United Nations
Educational, Scientific
and Cultural Organization

INTERNATIONAL HYDROLOGICAL PROGRAMME

Proceedings

Regional Aquifer Systems in Arid Zones – Managing non-renewable resources

International Conference
Tripoli, Libya, 20–24 November 1999

General Water Authority of
the Libyan Arab Jamahiriya

IHP-V | Technical Documents in Hydrology | No. 42
UNESCO, Paris, 2001

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The preparation of this volume has been supported by the Sahara and Sahel Observatory (OSS)



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Preface

The International Conference on "Regional Aquifer Systems in Arid Zones – Managing non-renewable resources" (Tripoli, 21-25 November 1999) marked a milestone in the review, discussion and analysis of the emerging concept of planned groundwater mining and made important progress in international exchange and co-operation towards an equitable and sustainable utilization of shared groundwater resources.

The Conference was jointly convened by the Divisions of Water Sciences and Earth Sciences of UNESCO and the General Water Authority of the Libyan Arab Jamahiriya. It was co-sponsored by FAO, OSS, IAH, IUGS, IWRA, ACSAD, ALECSO, CEDARE, IDB and the Great Man-Made River Authority.

The Conference starting point was Resolution XII-8 adopted by the Intergovernmental Council of UNESCO's International Hydrological Programme (IHP) at its XIIth session (UNESCO, 23-28 September 1996). The IHP Intergovernmental Council, considering that aquifer systems are often the main source of fresh water in arid and semi-arid zones, recommended to improve knowledge about "Fossil Groundwater in Sub-Saharan and Saharan Africa".

In many regions, water resources are stored in deep underground aquifers which are not recharged annually. This means that abstraction of such groundwater is equivalent to a mining exploitation. Many of these aquifers are extremely large and cover areas shared by several countries. How should the water resources of these aquifers be assessed? How should these non-renewable resources be managed to meet the increasing needs of populations with a high population growth? The Conference represented a step in the direction to give proper answers to all these questions.

More than 600 hundred participants from over 20 countries and regional and international organizations and associations attended the Conference. Fourty-eight papers were presented to elucidate and debate on the following themes:

- Geological characteristics of regional aquifer systems in arid areas
- Assessments methodologies and constraints for non-renewable water resources
- Principles of groundwater abstraction from fossil aquifers
- Environmental impacts of groundwater exploitation (desertification)
- Monitoring groundwater abstraction and environmental impacts
- National and regional policies concerning sustainable use of water

One of the direct achievements of the Conference is the Tripoli Statement which encourages countries to enter into negotiations with a view to reaching agreements on the development, management and protection of shared groundwater resources.

O. Salem
Director
General Water Authority of the
Libyan Arab Jamahiriya

Tripoli Statement

More than 600 hundred participants from more than 20 countries and regional and international organizations and associations attended the International Conference on

"Regional Aquifer Systems in Arid Zones – Managing Non-Renewable Resources"

Tripoli, 20-24 of November 1999.

We the Participants of the Conference recognize that:

1. In most arid countries the scarcity of renewable water supplies implies a serious threat to sustainable coupled and balanced socio-economic growth and environmental protection. This threat is clearly more pronounced in the less wealthy countries.
2. In many arid countries, however, the mining of non-renewable groundwater resources could provide an opportunity and a challenge, and allow water supply sustainability within foreseeable time-frames that can be progressively modified as water related technology advances.
3. The Conference marks a milestone in the discussion of the emerging concept of planned groundwater mining.

We the Participants consider that:

1. Adoption of this concept at national level could have international repercussions;
2. A national integrated water policy is essential with, where feasible, priority given to renewable resources, and the use of treated water, including desalinated water.

We recommend that:

a. Groundwater mining time-frames should account for both quantity and quality with criteria set for use priorities, and maximum use efficiency, particularly in agriculture;

b. Care should be exercised to minimize the detrimental impact to existing communities;

c. Consideration should be given to the creation of economical low water consuming activities.

We the participants further consider that in situ development, or development based upon transferred mined groundwater, depend upon many non-hydrogeological factors outside the scope of this Conference. Nevertheless, hydrogeological constraints need to be defined for both planners and the end users.

We recommend the participation of the end users in the decision making process and the enhancement of their responsibility through water use education and public awareness. We believe that for efficient water-use, cost recovery could eventually be necessary.

In recognition of the fact that:

a. some countries share aquifer systems;

b. international law does not provide comprehensive rules for the management of such systems as yet, and

c. clearly groundwater mining could have implications for shared water bodies;

We the participants draw the attention of Governments and International Organizations to the need for:

a. rules on equitable utilization of shared groundwater resources,

b. prevention of harm to such resources and the environment,

c. exchange of information and data.

We also encourage concerned countries to enter into negotiations with a view of reaching agreements on the development, management, and protection of shared groundwater resources.

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INTRODUCTORY PRESENTATION

Mohamed Bakhbakhi and Omar Salem***

Why the Great Man-made River Project?

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*** Director General*
General Water Authority
Tripoli, Libya

Abstract

Throughout history, Libya has witnessed severe water shortages resulting from long periods of drought. Massive migrations of people and animals to neighbouring countries took place keeping the local population below 1.5 million inhabitants.

Starting from the late fifties, and coinciding with oil exploration, the population has undergone steady increase along with rising income and improved standard of living. Large urban settlements began to form along the coastal belt, which represents less than 5% of the total surface area of the country.

The new situation has created large deficits in the water balance of the northern aquifers particularly in the Gefara plain, resulting in steady decrease in water levels and deterioration of quality.

Several steps were undertaken to minimize the effect of the diminishing water supply. They include expansion on seawater desalination and waste water treatment, improving irrigation practices, modifying agricultural policies, adopting necessary legislation and intensifying efforts in the field of water harvesting.

These measures fell short of closing the gap between water supply and demand and inter-basin water transfer was therefore contemplated.

Libya enjoys large reserves of fresh water bodies in the great sedimentary basins of Kufra, Sarir, and Murzuk. These Basins occupy the southern half of the country extending over an area of more than one million km^2 of the Sahara desert. For the last three decades, these basins were subjected to extensive hydogeological studies at regional and subregional scales. These studies indicated the possibility of their development much beyond the present level of exploitation and could therefor become a source for water conveyance northward.

Mathematical models were applied to simulate possible development schemes to meet pre-selected criteria which were carefully defined to cope with social, economical, and environmental objectives.

1. Introduction

The surface area of Libya is 1.750 million km^2 extending from The Mediterranean coast in the north to the Tibesti mountains in the south Figure 1, covering a great part of the Sahara desert. Libya enjoys a seashore along the Mediterranean of about 1950 km long with a coastal belt characterized by relatively good soils and suitable climatic conditions. These factors led to the rise of important economic activities and consequently to the establishment of relatively large population centers. Elsewhere, desert and semi desert climates prevail, causing lower population densities.

1.1 Climate

The Libyan climate changes rapidly and varies widely from north to south, influenced by the Mediterranean and the Sahara desert. The following climatic zones can be identified:

1. Mediterranean (Subtropical): limited to small areas in the Jabal Akhdar (NE)
2. Semi-Mediterranean: covering limited areas along the western and eastern coasts.
3. Steppe: in the northern slopes of Jabal Akhdar and Jabal Nafusa and western Gefara plain.
4. Desert: covering over 90% of the country to the south of the above zones.

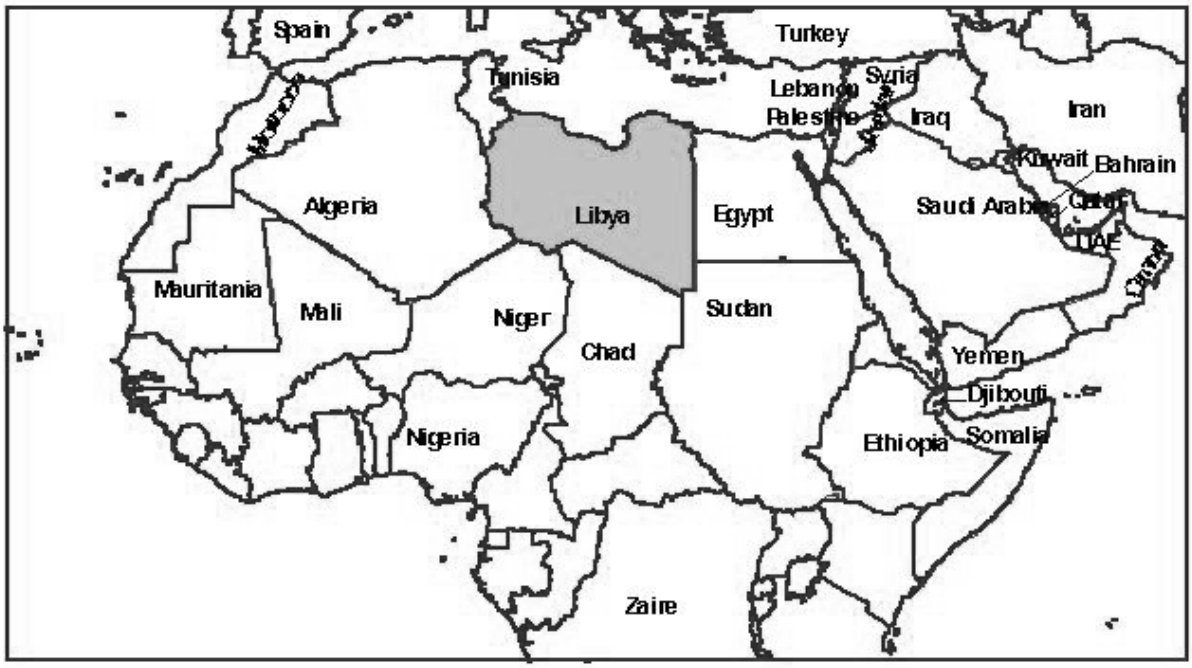


Figure 1: Location Map of Libya

1.2 Rainfall

Figure 2 shows the average rainfall distribution over the whole country. The highest rainfall occurs in the north western region (Jabal Nafusa and Gefara plain) and in the north eastern region (Jabal Akhdar), where the average yearly rainfall exceeds the minimum values (250-300) necessary to sustain rainfed agriculture.

Rainfall average is less than 100 mm per year over 93% of the country's land surface.

1.3 Population

In 1964, Libya's population amounted to 1.56 million, while according to 1973 census, this Figure increased to 2.25 million. In 1973 the western coastal area (gefara plain and misrata area) registered a population of 1.179 million out of which 551,477 are in Tripoli. The eastern coastal area is second in terms of population concentration with 585,648 inhabitants of which 282,192 are in Benghazi. This means that more than 75% of the population are concentrated over 1.5% of the total country area.

The 1984 census showed the Libyan population to be 3.6 millions, and the growth rates were steadily increasing as indicated by table 1 below

Table 1: Population growth rates

Period	Growth rate (%)
1954 – 64	3.9
1964 – 73	4.1
1973 – 84	4.2

However, according to the latest census conducted in 1995, The Libyan population is 4.8 million. This indicates a decline in the rate of population growth from 4.2% in (1973 - 1984) period to 2.8% in (1984 - 1995). This decline, beyond all previous estimations, is of great significance as it reflects a certain degree of public awareness, which could lead to a more effective control of the use of natural resources. Table 2 shows the predicted population growth until the year 2025.

Table 2: Population Growth based on adjusted rate of growth

Year	1995	2000	2005	2010	2015	2020	2025
Population (10^6)*	4.8	5.7	6.7	7.8	9.0	10.3	11.7

* Including non-Libyan population

It is worth mentioning here that more than 80% of the population lives in a narrow strip along the Mediterranean Coast.

1.4 Water supply

1.4.1 Surface water

Surface water resources are limited and contribute only a small amount to the total water consumption. The total average runoff for the northeastern and northwestern areas is estimated to be in the order of 200 million m^3 per year. Under natural conditions (without dams) the runoff water is partly evaporating and partly infiltrating in the spreading zones and this explains why so little water is usually reaching the sea.

Even assuming that 50% of the runoff water can be intercepted this makes an additional resource of 100 Mm^3/y. The total quantity of water recoverable from the surface reservoirs probably will not exceed 40 Mm^3/y representing the exploitable runoff water resources. However, some dams may have a negative effect if the water stored behind the dams minus evaporation in the dam reservoir is less than the water which was previously infiltrating in the spreading zones to recharge the aquifer underneath.

There are also more than 450 springs some are of continuous discharges while others are seasonal. Table 3 Summarizes the surface water resources in the five water zones or basins of the country, see also Figure 3.

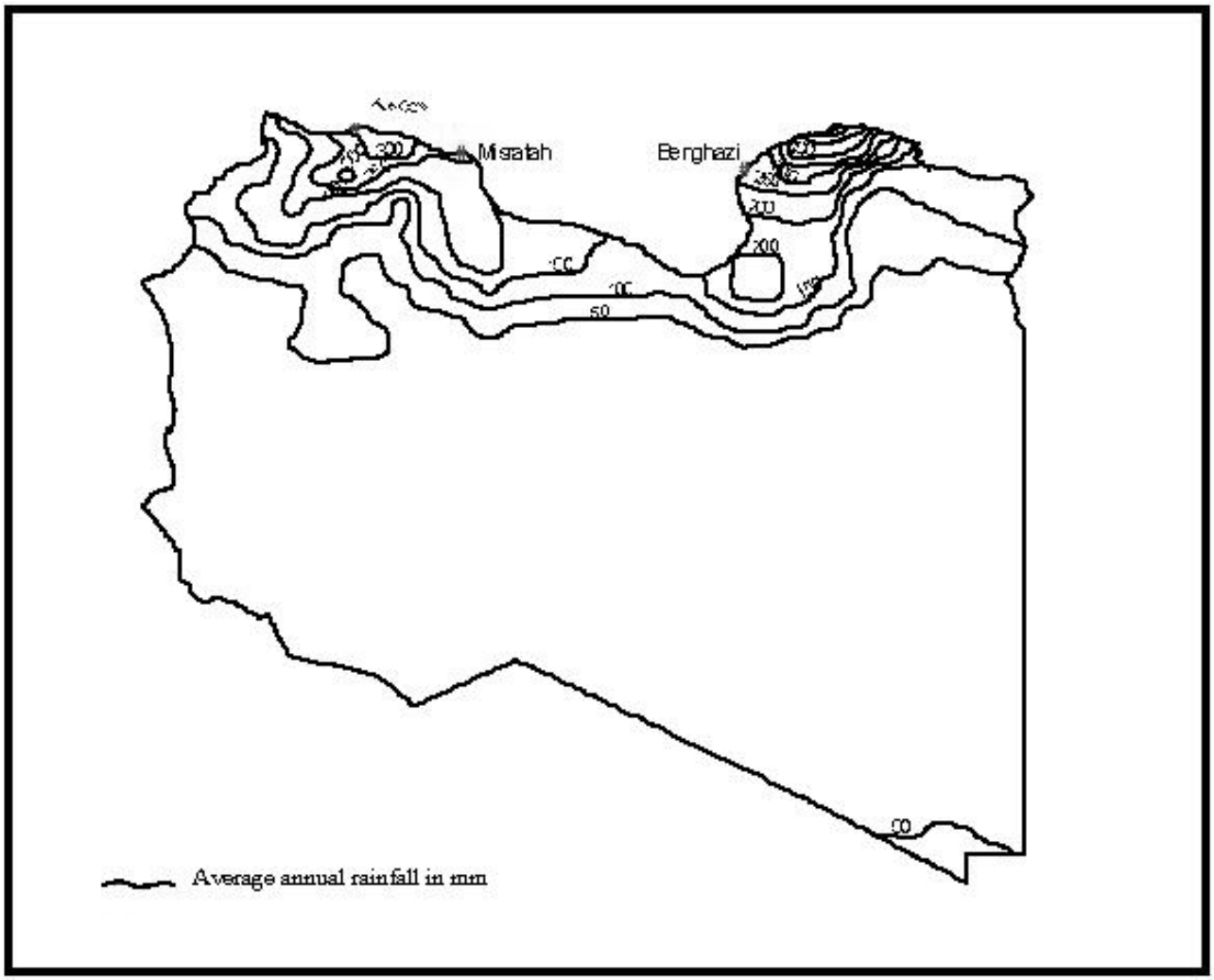


Figure 2: Annual average rainfall distribution

Table 3: Surface Water

Basin	Run off (Mm^3/y)	Springs (Mm^3/y)	Total (Mm^3/y)	Recoverable Quantity (Mm^3/y)
Gefara	87		87	52
Hamada	30	74	104	48
Jabal Akhdar	80	110	190	92
Murzuk				
Kufra and Sarir				
Total	**197**	**184**	**381**	**192**

1.4.2 Ground water

Libya depends heavily on groundwater which accounts for more than 97% of the water in use. Starting from the early sixties groundwater extraction rates accelerated rapidly to meet the growing water demand. Groundwater resources can be broadly divided into renewable and non-renewable. Renewable groundwaters occur in the northern aquifers of the Gefara plain, Jabal Akhdar and parts of Hamada and central coastal areas. Non-renewable groundwaters occur in the great sedimentary basins of the Kufra, Sarir, Murzuk and the Hamada. Table 4 shows the quantities available for annual use from the major ground water basins.

Table 4: Groundwater perennial yield

Basin	Volume of water available (Mm^3/y)
Gefara Plain	200
Jabal Akhdar	200
Hamada	230
Murzuk	771
Kufra and Sarir	563
Total	**1,964**

It should be noted that volumes indicated in table 4 for the Gefara Plain, Jabal Akhdar and partly Hamada basin are estimated on the basis of actual recharge, while in the case of Murzuq, Kufra and Sarir basins, they represent a mining yield with least negative effect.

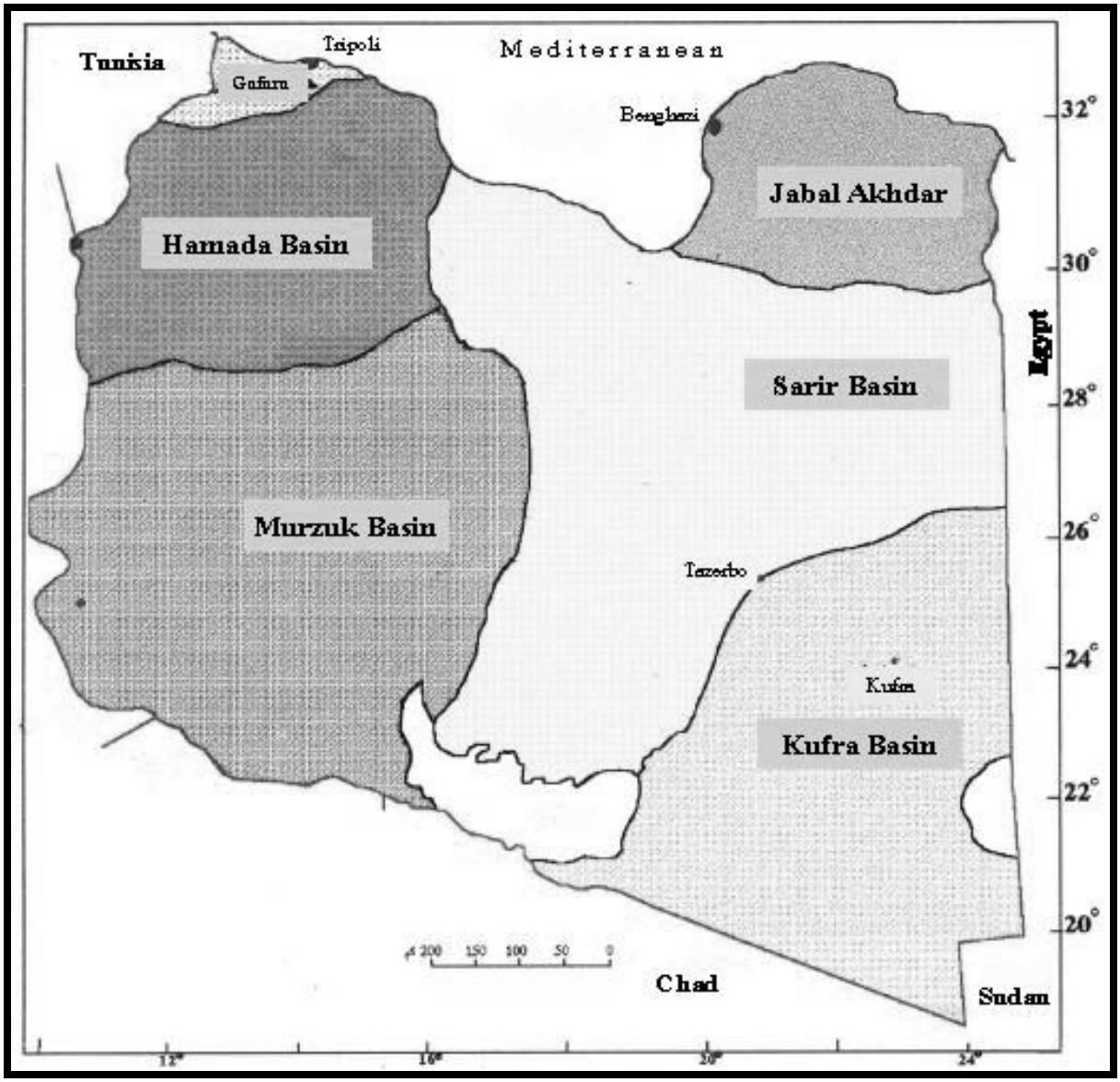


Figure 3: Groundwater basins in Libya

1.4.3 Unconventional water resources

A number of desalination plants of different sizes were built near large municipal centers and industrial complexes. Table 5 gives the location and capacity of existing plants. In addition, a number of small size units with capacities ranging from 100 to 6000 m^3/day are used for desalination and treatment of seawater and brackish water.

A number of sewage treatment plants are built and others are in the plan, when all the plants become operational, their total output will average 285,000 m^3/d.

Table 6 shows the total quantities of water resources available for use.

Table 5: Desalination plants

Location	Capacity (m^3/day)	Location	Capacity (m^3/day)
Zanzur	22,500	Ajedabia	35,000 **
Tajura	11,000	Susa	13,500
Suq el Khamis	42,000	Ras Lanuf	33,000
Zliten	18,000	Bomba	30,000
Sirte	18,000 *	New Zliten	30,000
N. Benghazi	48,000	Misurata	8,500
Derna	9,200	Steel Authority (Misurata)	33,000
Tobruk	24,000	Zwara	18,000 **
Ben Jawad	5,900		

* Replaced by a new plant with a capacity of 10,000 m^3/day. ** Presently out of order.

Table 6: Total supply in Mm^3/y

Source	Gefara Plain	Jabal Akhdar	Hamada	Kufra and Sarir	Murzuk	Total
Groundwater	200	200	230	563	771	1964
Surface water	52	92	48	-	-	192
Unconventional Sources	27.500	45.500	50.500			123.5
Total	**279.500**	**337.500**	**328.5**	**563**	**771**	**2279.5**

1.5 Water demand

Despite the scarcity of water resources, demand for water is rapidly increasing in Libya as a result of rising economic conditions, urbanization and improving standards of living.

1.5.1 Domestic use

In Libya, 85% of the population live in urban centers, varying in size from 5000 to 1,000,000 inhabitants. The average water consumption ranges from 150 to 300 l/c/d depending on the size of the city and location. In rural areas the average per capita consumption ranges from 100 to 150 l/c/d. Table 7 shows the existing and projected domestic water consumption in 1984 through 2025.

Table 7: Domestic water consumption (Mm^3)

Year	1984	1995	2000	2005	2010	2015	2020	2025
Population (million)	3.6	4.8	5.7	6.7	7.8	9.0	10.3	11.7
Domestic water consumption (Mm^3)	246.8	364	457	573	708	870	1060	1280

1.5.2 Industrial use

In 1995 the total industrial water use was estimated at 145 Mm^3. Industrial Water demand is expected to grow considerably within the coming years. An annual rate of increase in the order of 4% may be adopted as a representative scenario for future industrial water demand as shown in table 8.

Table 8: Industrial use (Mm^3)

Year	1984	1995	2000	2005	2010	2015	2020	2025
Water use (Mm^3)	90	145	176	214	261	318	386	470

Table 9 shows the municipal consumption as a sum of domestic and industrial use per basin.

Table 9: Total municipal consumption in Mm^3/y

Area	Year		
	1978	**1984**	**1995**
Gefara	97	177	235
Hamada	18.8	25.9	95
Jabal Akhdar	92	111	131
Kufra and Sarir	5	7	28
Murzuk	12.9	15.9	20
Total	**225.7**	**336.8**	**509**

1.5.3 Agricultural use

Agriculture being the major consumer is responsible for 85% of the water consumption. Irrigated agriculture is expanding in the north as well as in the oases and along wadies. At present it is estimated, Salem (1998) that between 350,000 and 400,000 h, are under irrigation. Their water requirement, vary from less than 10,000 $m^3/h/y$ to over 20,000 $m^3/h/y$ depending on the location, type of crop and irrigation method. Table 10 shows the yearly extracted groundwater for irrigation in each water zone.

Table 10: Extracted groundwater for irrigation in Mm^3/y

Area	Year		
	1978	**1984**	**1995**
Gefara	435	500	965
Hamada	173.1	241.2	360
Jabal Akhdar	79.5	150.5	469
Kufra and Sarir	216.5	535	535
Murzuk	372.5	551	751
Total	1276.6	1977.7	3080

Table 11 shows the yearly total demand of all the consuming sectors per basin

Table 11: Total demand

Area	Year		
	1978	**1984**	**1995**
Gefara	532	677	1200
Hamada	191.9	267.1	455
Jabal Akhdar	171.5	261	600
Kufra and Sarir	221.5	542	563
Murzuk	385.4	566.9	771
Total	1502.3	2314	3589

1.6 Water balance

In order to evaluate the water resources available for use in Libya, it is necessary to include and analyze the nonrenewable groundwater resources contained in the southern half of the country by allowing an acceptable rate of water level decline without exposing the aquifers to serious deterioration in quality. Accordingly a calculated volume of the nonrenewable groundwater could be safely used within a reasonable time scale. The volume of water that is available for use at an acceptable rate of depletion is estimated at around 4000 m^3/y. which is expected to change in time as a result of improvement in the state of knowledge on the aquifer conditions Table 12 below shows the water balance per basin.

Table 12: Water Balance in (Mm^3)

Basin		Year		
		1978	**1984**	**1995**
Gefara	Supply	279.5	279.5	279.5
	Demand	532	677	1200
	Balance	-252.5	-397.5	-920.5
Hamada	Supply	328.5	328.5	328.5
	Demand	191.9	267.1	455
	Balance	136.6	61.4	-126.5
Jabal Akhdar	Supply	337.5	337.5	337.5
	Demand	171.5	261	600
	Balance	166.0	76.5	-262.5

Table 12: Water Balance in (Mm^3) (continued)

Kufra and Sarir	Supply	535	563	563
	Demand	221.5	542	563
	Balance	313.5	21	0.0
Murzuk	Supply	771	771	771
	Demand	385.4	566.9	771
	Balance	385.6	204.1	0.0

1.6.1 Intensity of water shortage

The uneven distribution of population and the intensive agricultural activities in the coastal plains make the gap between supply and demand much wider in the Gefara and Jabal Akhdar plains as shown in Table 13.

Table 13: Water Balance per Basin showing the population and area affected

Basin		**Gefara**	**Jabal Akhdar**	**Hamada**	**Kufra and Sarir**	**Murzuk**	**Total**
Area km^2		18,000	145,000	215,000	700,000	350,000	
1978	Population*						
	Water balance **	-252.5	166.0	136.6	313.5	385.6	1001.7
1984	Population*						
	Water balance **	-397.5	76.5	61.4	21.0	204.1	-55.5
1995	Population*	2.24	1.27	0.92	0.13	0.24	4.8
	Water balance **	-920.5	-262.5	-126.5	0.0	0.0	-1309.5

* Population in millions. ** Water balance in million cubic meters/year

The imbalance between supply and demand is expected to grow much wider in the future especially for the northern basins. Table 14 below shows the overall water balance projected for the year 2025 after Salem (1998).

Table 14: Projected water balance

Year	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**
Supply (Mm^3)	2279.5	2279.5	2279.5	2279.5	2279.5	2279.5	2279.5
Demand (Mm^3)*	3885	4493	5128	5794	6495	7236	8022
Balance (Mm^3)	-1605.5	-2213.5	-2848.5	-3514.5	-4215.5	-4956.5	-5742.5

* Values for demand are after Salem (1998)

It should be noted that the values presented above are conservative estimates as far as demand is concerned; and is by no means representing the state of self-sufficiency in basic food production.

Self sufficiency in basic food crops is designated as a priority among agricultural policies of the country. If self sufficiency is sought, the deficit will be of course much greater. Two hypotheses have been considered for estimating the water demand if self sufficiency is sought:

1. A minimum hypothesis corresponding to the best irrigation practices.
2. Maximum hypothesis corresponding to the prevailing irrigation practices in Libya.

The results are shown in the table 15 and table 16 respectively and illustrated in Figure 4.

Table 15: Total deficit calculated on 100% self sufficiently Mm^3/y minimum hypothesis

Year	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**
Population in million	5.7	6.7	7.8	9.0	10.3	11.7
Supply (Mm^3)	2279.5	2279.5	2279.5	2279.5	2279.5	2279.5
Demand (Mm^3)	5985	7035	8190	9450	10815	12285
Deficit (Mm^3)	-3705.5	-4755.5	-5910.5	-7161.5	-8535.5	-10,005.5

Table 16: Total deficit calculated on 100% self sufficiently Mm^3/y maximum hypothesis

Year	2000	2005	2010	2015	2020	2025
Population in million	5.7	6.7	7.8	9.0	10.3	11.7
Supply (Mm^3)	2279.5	2279.5	2279.5	2279.5	2279.5	2279.5
Demand (Mm^3)	10117	11892	13845	15975	18282	20767
Deficit (Mm^3)	-7837.5	-9612.5	-11565.5	-13695.5	-16002.5	-18487.5

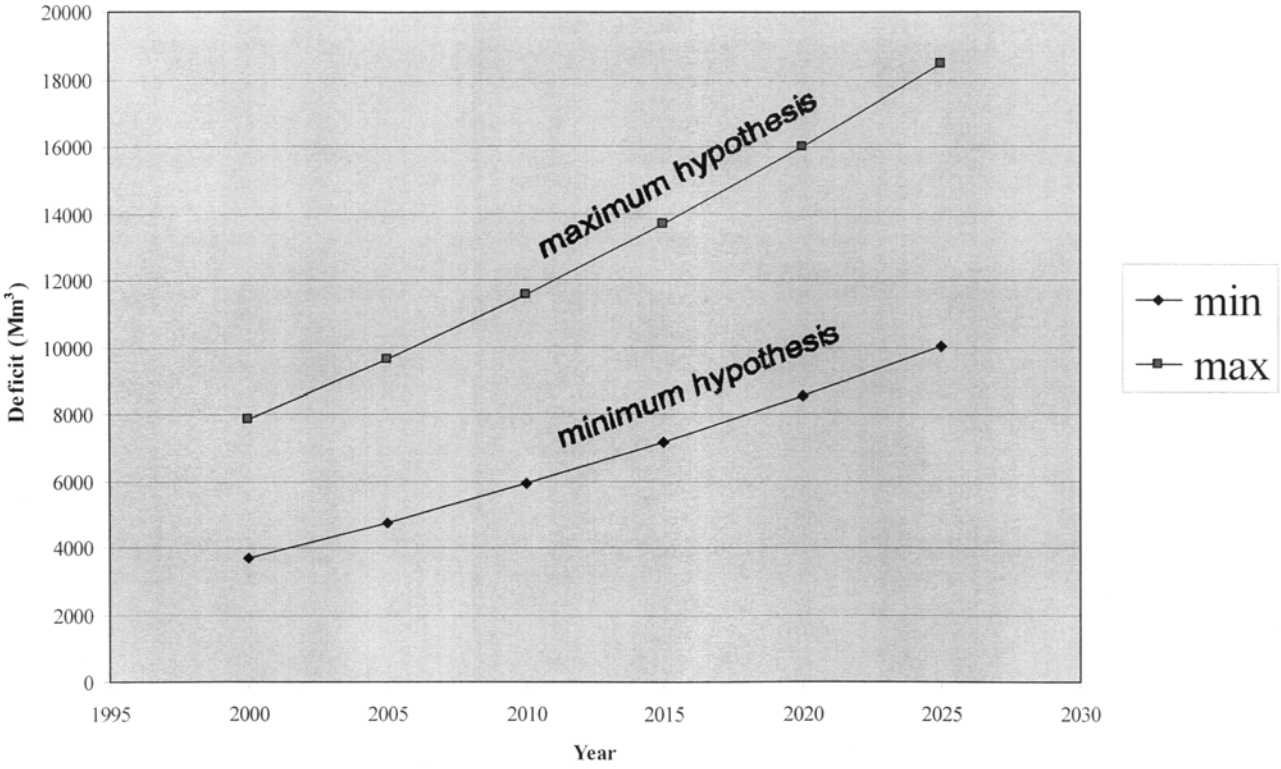


Figure 4: Total deficit calculated on 100% self sufficiency

1.7 Effect of over-exploitation

The large deficit in the water balance is compensated by over-exploitation on the coastal and inland aquifers resulting in:

1. a sharp decline in water levels, Figure 5, where water level has declined over 50 m in the deep aquifer and over 80 m in the shallow aquifer in the past 25 years;
2. seawater intrusion front along the north western coast, Figure 6. This front is advancing at an alarming rate. The effect of which is irreversible and threatens about half of the Libyan population and more than half the irrigated agriculture.

These two problems are responsible for other technical, social and economical difficulties. Among which:

1. Expensive cost of well construction.
2. High cost of pumping.
3. High cost of maintenance (wells, pumps, pipelines, irrigation networks, fittings, plumbing materials, heaters and boilers, etc…)
4. Use of small desalination units for houses, hospitals, public buildings, hotels, and other installations.
5. Higher application of irrigation water to avoid salt accumulation at root zones.
6. Low agricultural productivily.
7. Elimination of several fruit trees and crops that do not tolerate high salinity.

In view of the growing water scarcity problems presented above, it was deemed necessary to review the water situation and draw a long term policy to reduce the deficit in the water budget and minimize water quality deterioration.

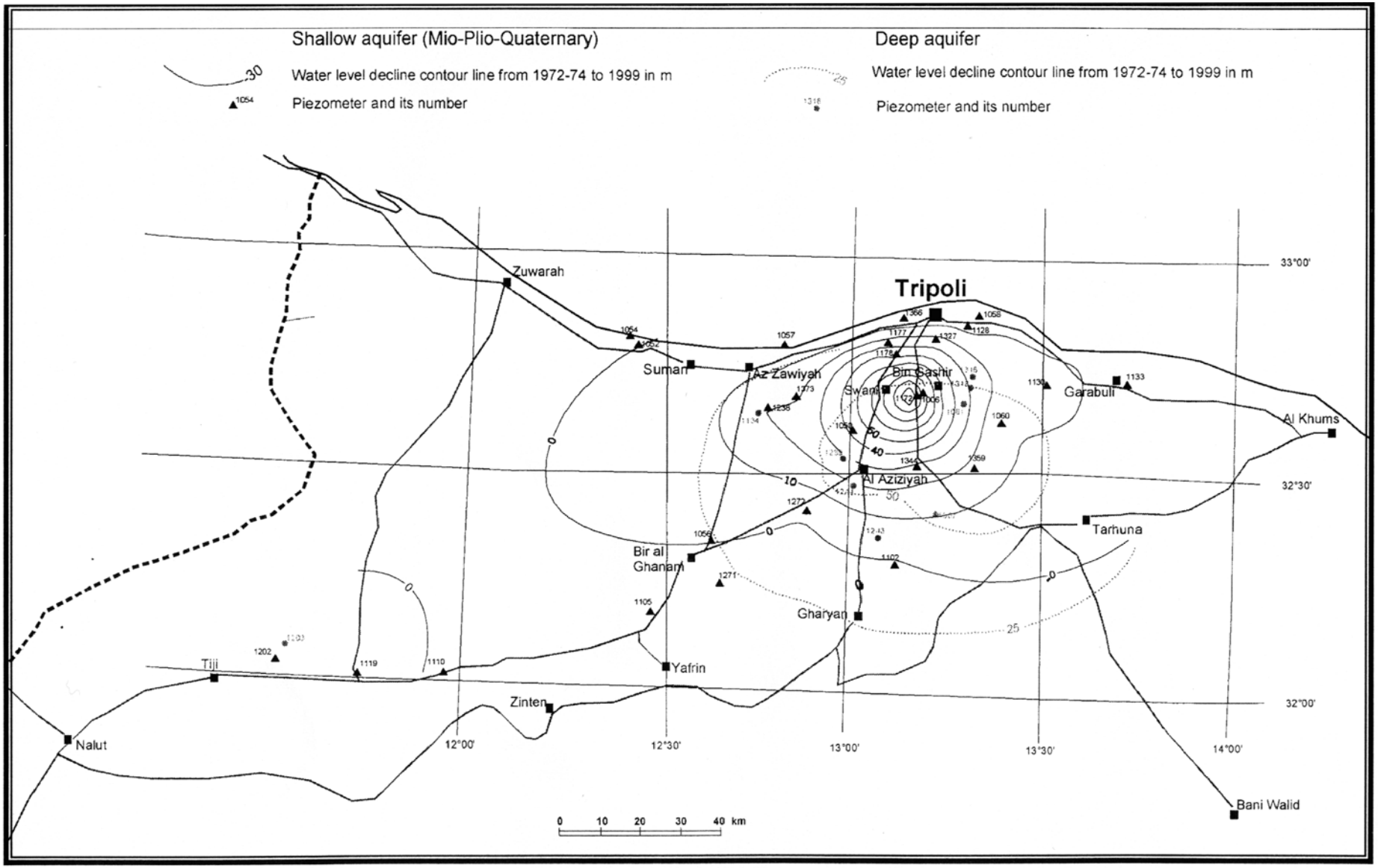


Fig (5) Water level decline from 1972-74 to 1999

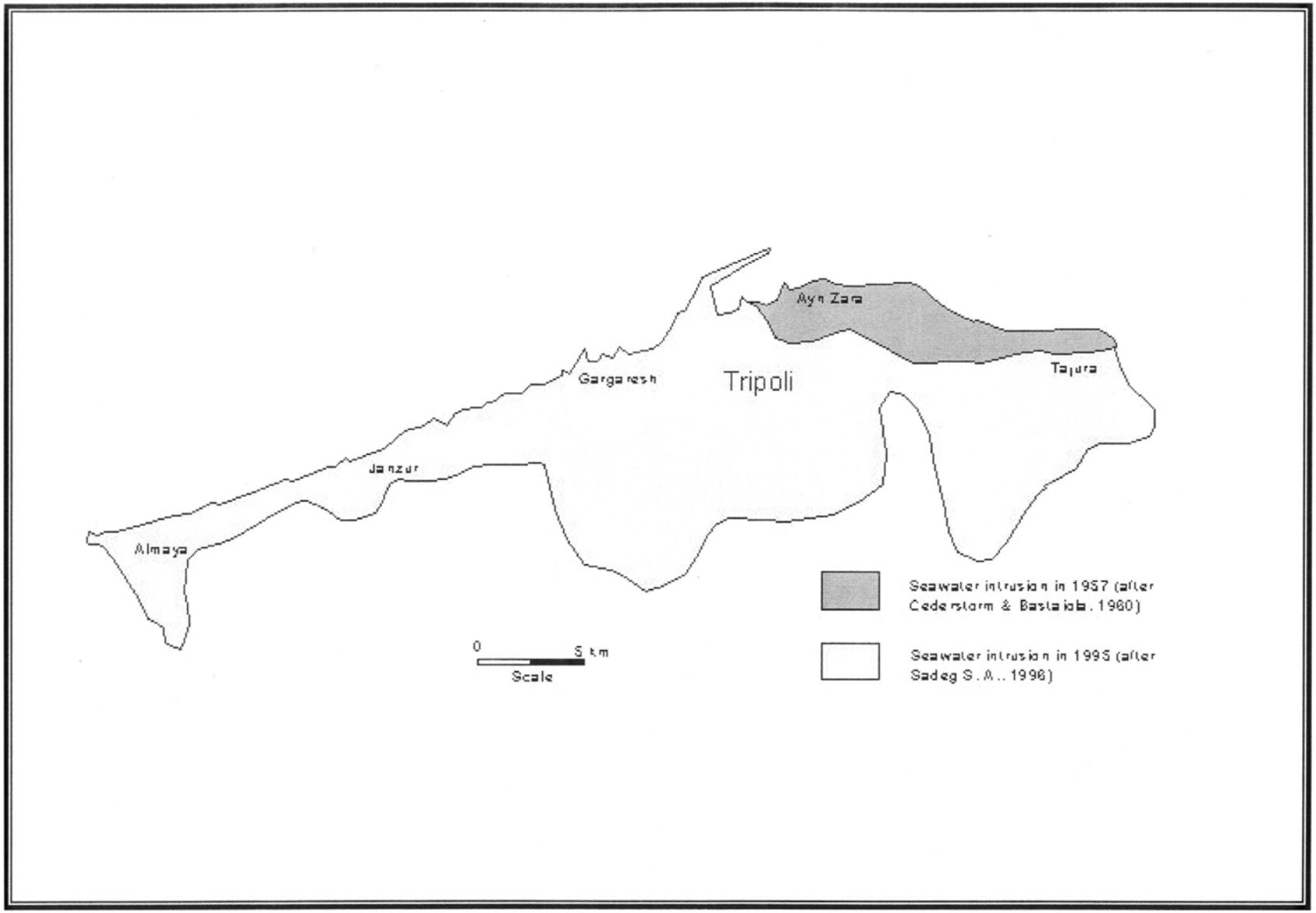


Fig (6) Sea water Intrusion

1.8 Water policy

1.8.1 Agriculture policies and practices:

Reduction of the water demand for agriculture could be attained by :

1. Upgrading irrigation techniques and gradual change of cropping patterns to maximize water saving.
2. Improvement of water productivity by increasing the agricultural yield per unit of water used.
3. Better rain water management in areas where rainfall is sufficient to sustain rainfed agriculture.
4. Organization of extension campaigns to educate farmers on efficient irrigation practices.

1.8.2 Domestic field actions

1. Raising the efficiency of water distribution and use. This requires monitoring of municipal networks for leak detection and repairs.
2. A water conservation policy be adopted with public awareness being a priority objective.

1.8.3 Legislative actions

Libya is among the first few countries in the region with modern water legislations, covering the following aspects of water resources: Ownership of water, responsibility of control and management, licensing for drilling, exploitation and use, pollution control and penalties. Other complementary legislations related to the water policy were also issued, among which:

1. The environmental protection law
2. The water well drilling law
3. The economic crimes law
4. The protection of ranges and forests law.

In addition several decrees and decisions were issued:

1. Ministerial decree for banning the drilling of new water wells in the Gefara plain and the surrounding mountains by the Secretary of Dams and Water Resources (1979).
2. Ministerial decree for controlling the plantation of citrus trees and banning plantation of tomatoes for manufacturing tomato paste and other crops demanding large supply of irrigation water (1976).
3. Decision of General People's Committee for adopting certain measures concerning the replanning and development of the coastal belt (1981).
4. Decision of the Secretary of Agriculture for regulating irrigation (1983).

1.8.4 Non conventional water resources

Contribution of the existing desalination and sewage treatment plants represents 39% and 32% of their installed capacity respectively, the production of these plants should increase to their installed capacity. If 50% of domestic water use is considered feasible for treatment, then by the year 2025, Libya should be able to produce around 500 Mm^3/y of waste water which could effectively contribute to the irrigation water supply. On the other hand desalination of seawater could offer the advantage of making almost unlimited amounts of water available, if costs were no constraints.

1.9 Interbasin water transfer

Studies of the county's large hydrogeological basins were given priority in implementation. Among these, the Murzuk basin in the SW and the Kufra and Sarir basins in the SE were investigated for the purpose of conveying water to the north, the results of which can be summarized as follows:

1.9.1 Groundwater occurrence

From the viewpoint of groundwater occurrence, Libya can be considered as a well-balanced country:

- In the north-western and north-eastern areas, storage capacity of the groundwater reservoirs is limited by both their physical dimensions and the presence of the sea threatening the aquifers, while the recharge is important and occurs every year, this creating important renewable resources.

- In the southwestern and south-eastern areas, yearly recharge is negligible if any, while the storage capacity of the groundwater reservoirs is huge. Large quantities of water accumulated during the pluvial periods of the quaternary are stored in these basins.

These considerations on groundwater occurrence were taken as a guideline for the investigations.

1.9.2 Investigations

Geological and hydrogeological investigations were carried out followed by detailed studies to determine the aquifers properties and to assess their reserves. Numerous sites were chosen for agricultural development. Hundreds of wells have been drilled during the seventies for local irrigation in Sarir, Kufra and at many localities in the Murzuk basin. Monitoring of the aquifers response to production from these wells is continuously recorded. In addition, observation in and around the well fields are monitored regularly for the preparation and updating of piezometric maps.

This relatively long period of record of abstractions and drawdowns, along with pumping tests results of exploratory wells, formed a good base for the construction and calibration of local and regional models. These models are considered satisfactory at this stage for simulating different abstraction alternatives.

It was found that the large sedimentary basins of the southern half of the country contained huge quantities of non-renewable groundwater that can be utilized by allowing an acceptable rate of water level decline without exposing the aquifers to serious deterioration. Several other factors control the rate of mining of these aquifers, among which, accessibility, quality, cost of production and use. The real problem in the development and management of groundwater resources in such an arid region is the difficult choice between two developments options:

- Large scale extraction of groundwater for maximum benefit of the present generation or
- Limited extraction that ensures sustainable development and conservation of resource base.

Nevertheless it was found technically feasible to extract 1 million m^3/d from West Sarir and 1 million m^3/d from Tazerbo and 2.5 million m^3/d from Murzuk in addition to quantities previously assigned for local irrigation in Sarir South, Sarir North, Kufra and many localities in the Murzuk basin.

These added quantities of water once transported to the north will definitely narrow the gap between supply and demand and minimize the deficit in agricultural water needs in addition to securing domestic water supply for a great number of coastal cities including Tripoli and Benghazi. With this in mind, economical analyses were carried out and cost comparison with desalination showed that it is feasible to transport these large quantities of water from the southern basins to the north.

Even though inter-basin water transfer based on nonrenewable groundwater is not a lasting solution but should be rather considered as a vital transitory stage for further detailed studies of these huge southern basins and during which a great effort should be placed on the development of desalination techniques in order to overcome the problem of high cost.

This resulted in what is called the “Great Man-made River Project” and once more *the Libyan Desert has come to rescue the Libyan people; first from famine in the fifties through desert oil discovery and now from thirst through its huge stored fresh water resources !*

2. The Great Man-made River Project (GMRP)

The conveyance of groundwater through large diameter pipelines for thousands of kilometers to bring good quality water to the suffering areas in the north is known as the “Great Man-made River Project“ which when completed will be able to carry more than 6 million m^3/d for the lifetime of the project estimated at 50 years at a cost much below the cost of desalination. This water is intended for minimizing the deficit in agricultural water needs in addition to securing drinking water supply for a great number of coastal cities including Tripoli and Benghazi.

2.1. Project components

The GMRP consists of the following five phases (Figure 7):

2.1.1 Phase I

In this phase a total of 2Mm^3/day will be conveyed to the coastal areas extending from Benghazi to Sirt. Two well fields are selected to provide 1 Mm^3/day each. The first is located in the Sarir area and consists of 126 production wells, 450 m deep, tapping the Post Eocene aquifers. The wells are arranged in 3 rows, 10 km

apart. The distance between wells in each row is 1.3 km and the static water level varies from 60 to 90 m.b.g.l. TDS ranges from 560 to 1,640 mg/l and all the wells are gravel packed and completed with stainless steel casings and screens.

The second well field is located near Tazerbo village, a transitional zone between Kufra and Sarir basins, and consists of 108 production wells tapping the Paleozoic aquifer. The wells range in depth from 500 to 800 m with static water level between 7 and 24 m.b.g.l. TDS is much lower than that in Sarir and is normally below 400 mg/l. The well field layout and well design is similar to that of Sarir. Both fields are designed with a number of observation wells distributed over the production zone.

2.1.2 Phase II

Under this phase, 2.5 Mm^3/day of water will be conveyed to the Gefara Plain in NW Libya from more than 500 wells tapping the Cambro-Ordovician aquifer at the NE part of Murzuk basin. The wells will vary in depth from 400 to 800 m and their static water level is expected to be from 80 to 175 m.b.g.l. Due to rough topography, production wells cannot be arranged in parallel rows; their distribution will be controlled to a greater extent by the shape and direction of local wadis.

Distance between wells will be around 1,500 m and a great percentage of them are planned to be completed “open hole”.

2.1.3 Phase III

Exploration being carried out in South of Kufra to investigate the possibility of transporting 1.6 Mm^3/day.

2.1.4 Phase IV and V

The last two phases of the project will not involve any additional water production. Instead, they are more oriented toward further extensions of the conveyance lines of phase I eastward to reach Tobruk and Westward to link with Phase II along the western coast.

3. Deficits of water supplies

When completed, the GMRP will therefore be capable of providing 6.1 Mm^3/day. Table 17 summarizes the total water demand in comparison with the available supply including the contribution of GMRP.

Table 17: Water balance including GMRP contribution in (Mm^3)

Year		1995	2000	2010	2020	2025
Demand		3885	4493	5794	7236	8022
SUPPLY	**Without GMRP**	2279.5	2279.5	2279.5	2279.5	2279.5
	With GMRP	2360.5	3912.0	4506.0	4506.0	4506.0
Balance		**-1524.5**	**-581**	**-1288**	**-2730**	**-3516**

Deficits in water supply as calculated in the above table are based on the lower limit of food production and conservative estimates as far as demand is concerned. If self-sufficiency is sought, the deficit will, of course, be much greater as shown in table 18.

Table 18: Total deficits calculated on 100% food self-sufficiency (Mm^3/yr) minimum hypothesis

Year	2000	2010	2020	2025
Total demand	5985	8190	10815	12285
Total deficit	2073	3684	6309	7779

4. Conclusion

In the early seventies, the Great Man-made River Project was deemed necessary to rescue the northern groundwater basins and to narrow the gap between water supply and water demand. The Project is by no means an everlasting solution to the chronic water shortage of Libya. The additional input from the project, if rationally used, could contribute to maintaining the present rates of development and offer an opportunity for the adoption of more practical and sustainable solutions.

Demand for water will continue to rise as a result of population growth and improving standard of living. Water supply should also be augmented by further development of the unconventional water resources, in particular sewage treatment and desalination, and the most important action of them all is the upgrading of irrigation techniques, gradual change of cropping patterns to maximize water saving, improvement of water productivity by increasing the agricultural yield per unit of water use and better rain water management in areas where rainfall is sufficient to sustain rainfed agriculture.

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THEME I: GEOLOGICAL CHARACTERISTICS TO REGIONAL AQUIFER SYSTEMS IN ARID AREAS

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Remote sensing of groundwater basins in the eastern Sahara

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Abstract

The eastern Sahara is the driest region on Earth. Although it is hyperarid and is subjected to the action of strong winds from the north, geological and archaeological evidence indicate that it hosted much wetter climates in the past. During moist episodes, inland basins must have stored much of the water in the underlying porous Nubian Sandstone. Such features are clearly depicted in the multi-spectral data of the Landsat Thematic Mapper (TM) as well as radar images from the Spaceborne Imaging Radar (SIR) of the American Space Shuttle and Radarsat of the Canadian Space Agency. These data provide unique perspectives that allow the recognition of regional influences on groundwater concentration, and particularly the unveiling of sand-buried channels of rivers that carried water during humid phases in geological past. In addition, an important factor to the potential of groundwater are faults that induce porosity along fracture zones. These have significant control on the trends of drainage channels, thus, on the enhancement of groundwater recharge into the substrate.

Keywords:
Eastern Sahara, sand seas, Landsat, radar images, palaeo-channels

1. Introduction

In the eastern Sahara of North Africa, the received solar radiation is capable of evaporating over 200-times the amount of rainfall (Henning and Flohn 1977). For example, in the southern parts of the Western Desert of Egypt rainfall is extremely variable and unpredictable; it rains only once in 20 to 50 years. This condition necessitated a complete dependence on groundwater resources for human consumption and agricultural activities.

Satellite images are used in this paper to view the regional setting of the eastern Sahara in terms of potential application to groundwater concentration. Although this region is now hyperarid and subjected to the action of strong winds from the north, geological and archaeological evidence indicate that it hosted much wetter climates in the past. Surface water during moist climates appears to have been responsible for the erosion, transportation and deposition of sand into inland basins. These basins would have stored most of the water in the underlying porous “Nubian Sandstone” rocks. During dry conditions that alternated with the wet climate episodes, the action of wind resulted in the formation of sand dunes and sandsheets.

Digital images from space were used to illustrate these relationships, including multi-spectral data of the Landsat Thematic Mapper (TM) as well as radar images from the Spaceborne Imaging Radar (SIR) of the American Space Shuttle and the Radarsat spacecraft of the Canadian Space Agency. These data provide unique perspectives that allow the recognition of regional influences on groundwater concentration, as well as the necessary information for detailed evaluation of the groundwater potential in a given area. This has been previously stated in several publications (e.g., El-Baz 1992 and 1998, Robinson and El-Baz 1998).

In addition to the primary porosity of the sandstone in the eastern Sahara, structural stresses result in the formation of faults, which induce porosity along fracture zones. The faults have significant control on the trends of exposed and sand-buried drainage lines, thus, on the enhancement of groundwater recharge into the substrate. Therefore, it would be prudent to apply the concept of fracture zone aquifers (Bisson and El-Baz 1991) to the exploration for groundwater in this desert.

2. Surface wind

In the eastern Sahara, the wind regime trends in an arcuate pattern that emanates from the coast of the Mediterranean Sea. The pattern changes from southward in the northern part of the desert to westward along the borders with the Sahel (Figure 1). Weather satellite images such as those of Meteosat of the European Space Agency (ESA) helped greatly in deciphering the details of this regional pattern (Mainguet 1995), which was first detected by Bagnold (1941, p. 235). Erosional scars throughout the desert suggest that this wind regime was effective during much of the Pleistocene.

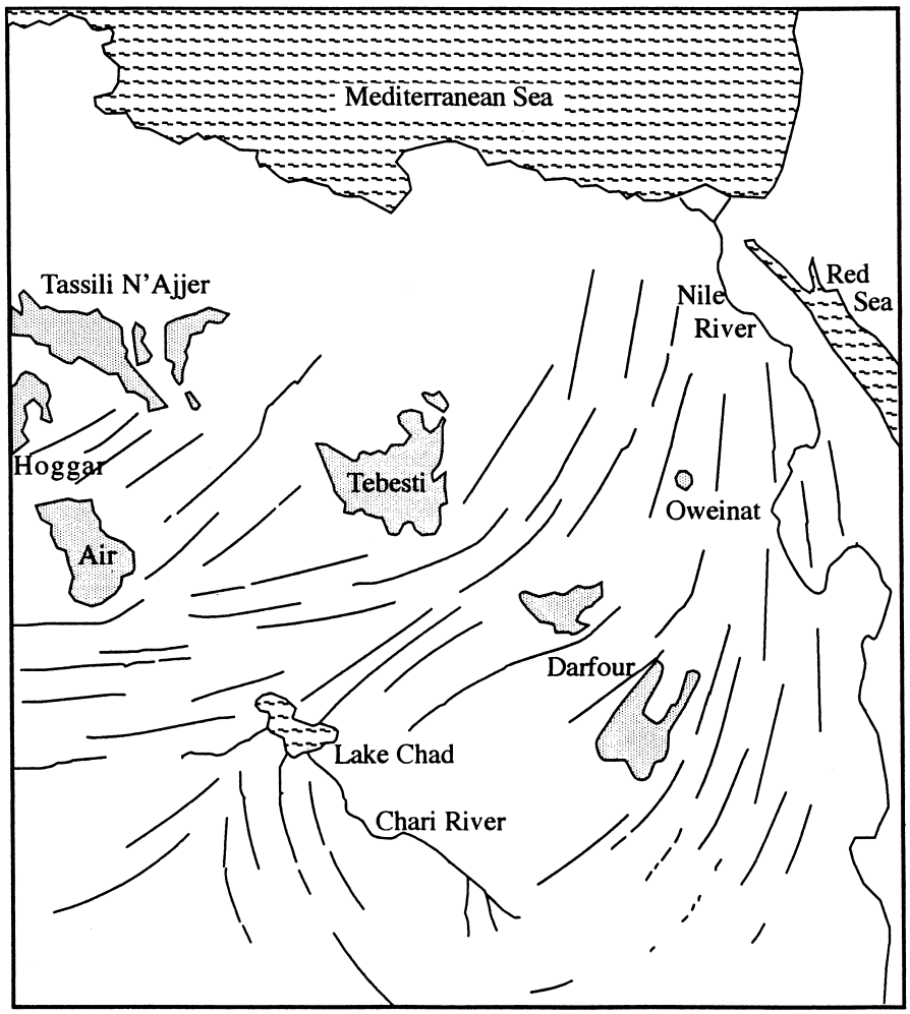


Figure 1: Major dune orientations in the eastern Sahara that affect wind directions.

Wind velocity and direction greatly affect particle transport and the formation, shape and orientation of dunes. In the case of the eastern Sahara, surface wind data were summarized for 42 meteorological stations between 15° and 35° N latitude and 15° and 41° E longitude (El-Baz and Wolfe 1982). Summaries presented as wind rose diagrams and sand-drift potential resultants agree with the basic pattern of a net southward direction of sand transport.

The sand-moving wind in this desert moves toward the south during most of the year, except where it is locally affected by topographic prominences (Manent and El-Baz 1980). Seasonal winds from the south do occur, particularly in the Spring, but these are not significant transporters of sand.

In addition to the fact that the wind in the eastern Sahara is northerly, two other observations must also be accounted for. The first is that sand accumulations in the eastern Sahara occur within or near topographic depressions. This must be explained in any theory regarding the origin of the sand and the evolution of the dune forms in space and time. The second is that the dune sand is composed mostly of well rounded quartz grains. The exposed rocks to the north of the sand seas are mostly limestones of Eocene or younger ages. The limestones could not have been the source of the vast amounts of quartz sand.

These observations discount the possibility of the origin of the majority of the sand by wind erosion and transportation from the north. The sand must have been formed by fluvial erosion of sandstone rocks in the south. Therefore, it is more likely that the areas presently covered by dune sand were relatively low areas

that received sediments from northward flowing stream channels in the geological past. When the conditions of climate changed, the wind sculptured these sand accumulations into the various dune forms and sand sheets.

3. Sand seas

Nearly 40% of the world's landmass may be called arid to semi-arid. Although half of that has been classified as desert, only about 4% is covered by sand (Petrov 1976). The eastern Sahara, in particular, encompasses the largest number of sand fields in any desert. The Western Desert of Egypt (Figure 2), for example, covers an area of 681,000 km^2, of which 159,000 km^2 (over 23% of the total area) is covered by sand.

As mapped from satellite images, the Great Sand Sea in Egypt that covers 72,000 km^2 (Gifford et al. 1997) is the largest dune field in this desert. It rests in a relatively low area bounded in the north by the escarpment of the Siwa Oasis and in the south by the Gilf Kebir plateau and the Oweinat Mountain (Figure 2). In the central region, dry courses of streams trend westward from the Farafra Oasis toward the area of the Great Sand Sea. Topographically, the lowest area in the region is a sand-free, flat playa just south of the extension of the Great Sand Sea into Libya. To the north of this playa, the dunes are densely distributed in complex forms; to the southeast, the dunes are linear forms with wide interdune corridors.

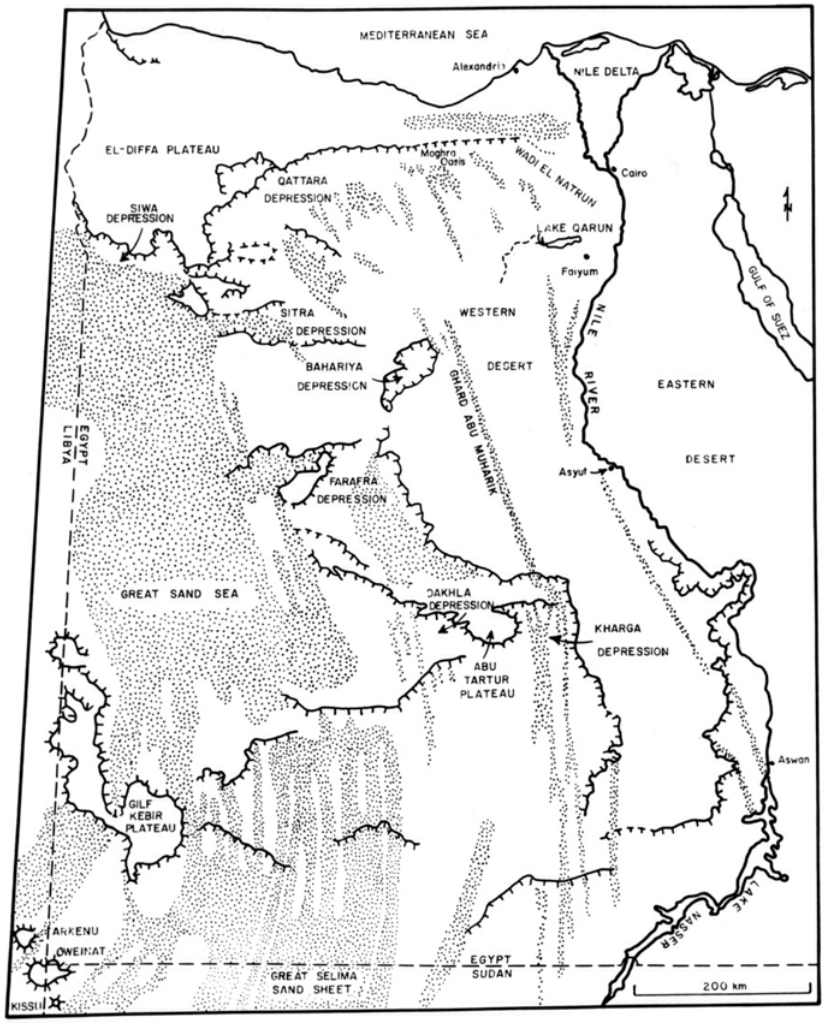


Figure 2: Distribution of sand deposits in the Western Desert of Egypt, based on interpretation of satellite images (after Gifford et al. 1979).

Dune patterns in the Great Sand Sea in particular support the present theory (El-Baz 1982). Its largest linear forms were called "whaleback" dunes by Bagnold (1941) who theorized that they grew so large that they no longer could move. Dunes, however, move when individual sand grains are dislodged by the wind, as Bagnold himself noted. Furthermore, cross-sections made into these dunes show that the sand is horizontally laminated rather than curved parallel to dune profiles as in the case of the nearby barchans and other wind-formed dunes (El-Baz et al. 1979). This suggests that what Bagnold named whaleback dunes are residual

sand ridges of horizontally laminated sand, left behind as the wind preferentially eroded the sand in what we see today as sand-free, interdune corridors.

Gifford et al. (1979, p. 219) stated that: "Factors controlling the occurrence and morphology of sand deposits are complex; they include the wind direction, strength and duration; the nature, extent and rate of erosion at the sediment source; the distance from the source; the grain and fragment size; the underlying and surrounding topography; the nature of the surface (rough or smooth); the amount and type of vegetation; and the amount of rainfall."

As recently realized, the single most important characteristic of areas with high concentrations of sand dunes, is the location within topographic depressions (El-Baz 1992 and 1998). Of twelve sand covered areas in the Western Desert of Egypt (Figure 2), ten occur in topographic basins; in the other two cases the sand emanates from low areas and is driven to level ground downwind.

4. Drainage patterns

It was previously theorized that the dune sand originated by fluvial erosion of sandstone rocks such as those of the Nubian Sandstone to the south of, or close to, the dune fields of the Western Desert of Egypt (El-Baz, 1982). Rounding of the grains must have occurred in turbid water as the particulate matter was transported during humid phases in rivers and streams (El-Baz, 1992 and 1998).

In this scenario, the sediment load must have been deposited in low areas at the mouths of the drainage channels. As the climate became drier, the particulate matter was exposed to the action of wind, which mobilized and sculptured the sand into various dune forms. The form of the dunes depended on the amount of available sand and the prevailing wind directions. During arid periods, it is likely that winds from the north caused the southward aeolian transport of the sand.

Archaeological evidence supports this hypothesis, particularly in the Western Desert of Egypt, where earlier periods of greater effective moisture are evident. In this desert, pre-historic sites are associated with remnants of playa or lake deposits (Haynes et al., 1989). An early Holocene pluvial cycle is well documented by geoarchaeological investigations at Neolithic playa sites throughout the eastern Sahara (Wendorf and Schild 1980; Pachur and Braun 1980). Late Pleistocene lake deposits with associated early and middle Paleolithic archaeological sites are best known from work in southwestern Egypt and northwestern Sudan (Haynes et al. 1989).

This archaeological evidence of previous human habitation, in addition to remains of fauna and flora, suggest the presence of surface water in the past. Indeed, remains of lakes and dry river and stream channels are exposed throughout the eastern Sahara. Playa deposits are particularly common beneath the dunes of the Great Sand Sea (Embabi 1999).

The Shuttle Imaging Radar (SIR-A) acquired in November 1981 images of a variety of features including faults, outcrops and dunes (Elachi et al. 1982). These images revealed, for the first time, sand-buried channels of ancient river and stream courses. Field studies indicated that these wide drainage patterns are buried beneath up to five meters of sand in the southwestern part of the Western Desert of Egypt near the border with Sudan (McCauley et al. 1982).

These findings increased the interest in the search for additional evidence of sand-buried river channels. More data were obtained by both the Spaceborne Imaging Radar (SIR-C) instrument that was flown on the Space Shuttle, in April and October of 1994, and the presently-active Radarsat of the Canadian Space Agency. These data revealed numerous rivers and streams throughout the eastern Sahara, including the following:

- In western Egypt, SIR-C data produced evidence of sand covered drainage in the southern part of the Great Sand Sea that emanate from the Gilf Kebir plateau. The plateau is bordered by numerous dry wadis, indicating that its edges were shaped by fluvial erosion. All the wadis have surface expressions and are visible on Landsat TM images. The radar data enhance their definition, especially in the surrounding plains (Figure 3).
- In northwestern Sudan, the Great Selima Sand Sheet is a sand covered plain that straddles the border with Egypt. Most drainage lines are covered by sand and invisible on the surface. Therefore, they become distinct only in radar images. Four major, NE trending drainage lines are revealed by SIR-C data (Figure 3). These broad channels must have formed under sheet flood conditions when surface water was plentiful.

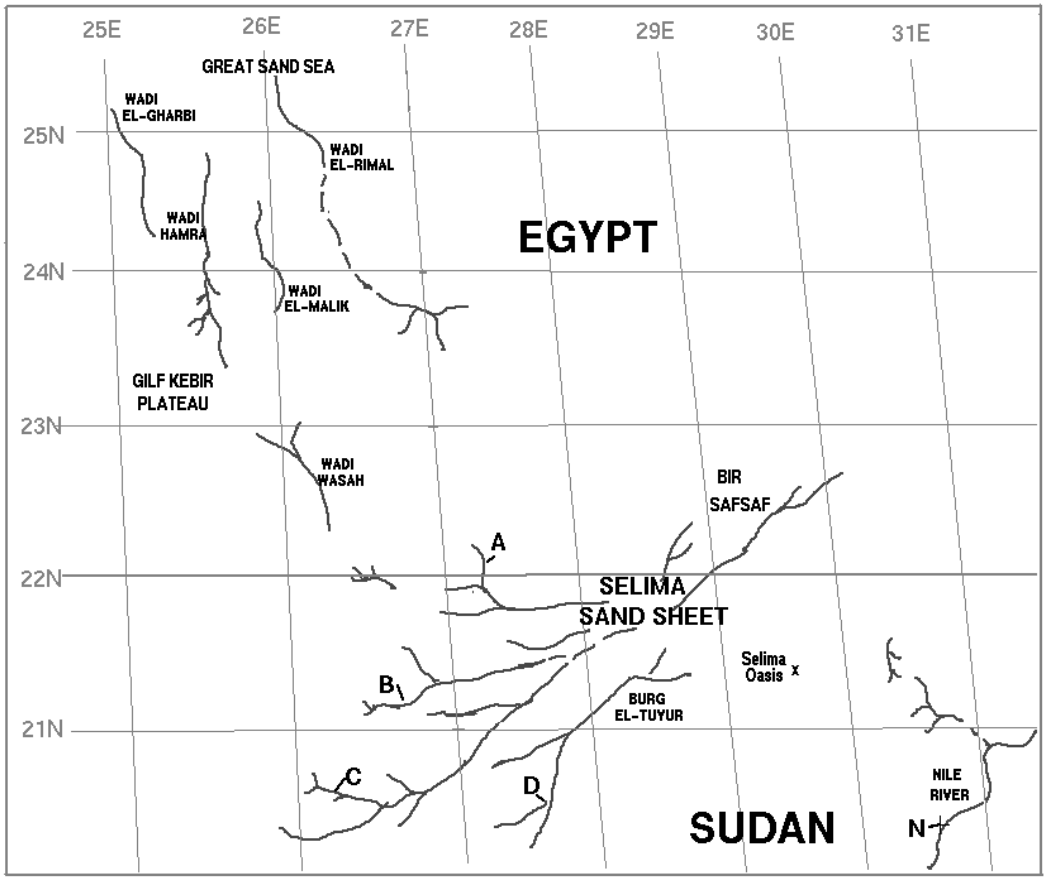


Figure 3: Map of radar-revealed paleo-channels, which trend northward toward the Great Sand Sea (upper left) and northeastward to the Great Selima Sand Sheet (modified from Robinson and El-Baz).

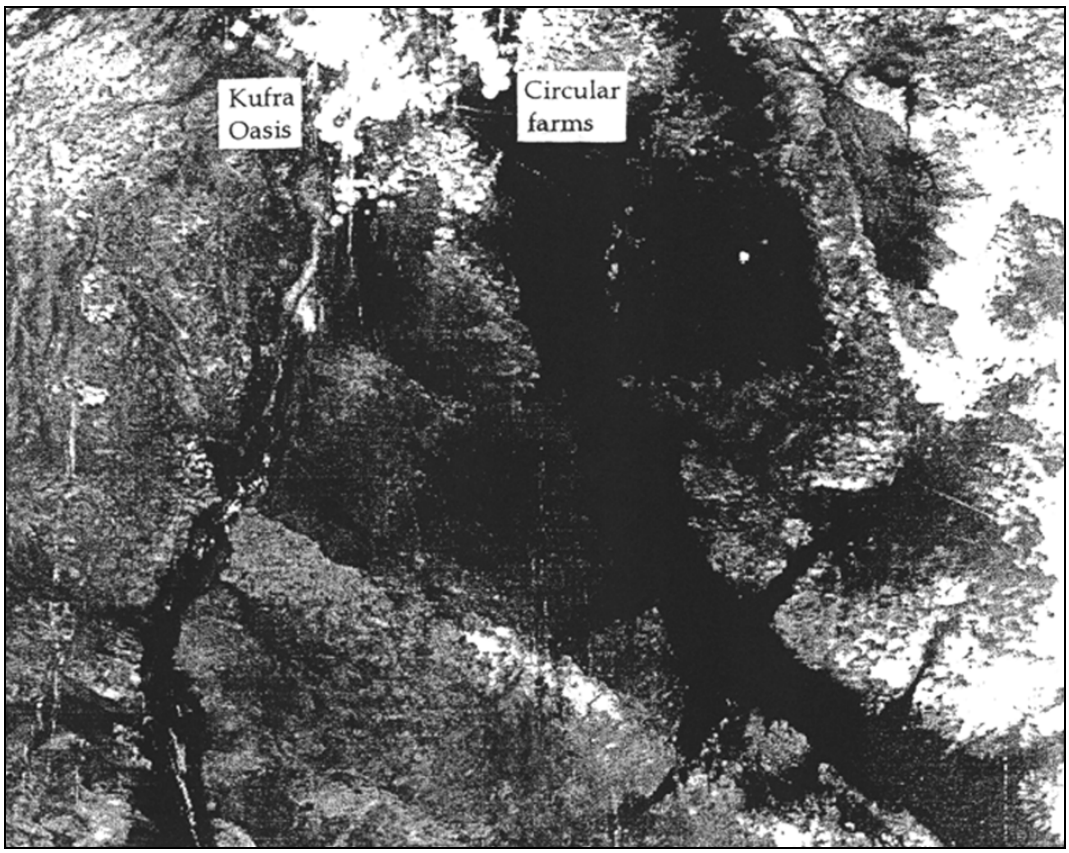


Figure 4: Two drainage channels leading to the Kufra Oasis region in southeastern Libya.

- In southeastern Libya, the Kufra Oasis is the only inhabited area in a vast plain. Numerous wells were drilled northeast of Kufra and a vast field of circular irrigation farms was developed. SIR-C data reveal the courses of two sand-buried palaeo-channels (Figure 4). The narrower channel passes through the Kufra Oasis and appears to originate from Chad's border at the southeast corner of the Tebesti Mountains. The wider channel is oriented NW-SE from the Gilf Kebir plateau and terminates in the area of the circular farms.

5. Groundwater concentration

The above-mentioned observations have far reaching implications to the concentration of groundwater resources in the eastern Sahara. Because the sand was transported by paleo-rivers, the depositional basins would have received vast amounts of fresh water. Much of that water would have seeped into the rocks beneath the sands. Thus, areas that encompass large sand dune accumulations in the eastern Sahara must host vast groundwater resources.

It is well known that the stratigraphic succession of the Nubian Sandstone in the eastern Sahara is mostly porous. It hosts an aquifer that has been tapped for groundwater in the past, particularly since the advent of deep-drilling technology. This is particularly true in the oases of western Egypt and eastern Libya.

Concentration of groundwater in topographic basins is particularly illustrated by the case of the Libyan Sahara. Because of the encroachment of sea water into the coastal groundwater aquifers, Libya had to transport sweet groundwater from the southern part of the country to where the population is concentrated along the Mediterranean seacoast. Hundreds of wells were drilled in the course of exploring for groundwater in five basins: Kufra, Sarir, Sirt, Hamra, and Murzuq (El-Baz 1991).

There are indications of a similar concentration in the Western Desert of Egypt. Two wells drilled for petroleum exploration near the edges of the Great Sand Sea proved the presence of vast amounts of water. These were drilled south of Siwa Oasis and west of Farafra Oasis to over one-kilometer depth and penetrated thick sandstone sequences that are saturated with groundwater. Water in these wells fountains under artesian pressure up to 40 meters into the air, indicating vast resources at depth.

In addition to the comparatively well-known horizontal aquifers in porous sediments, it is believed that groundwater is also channeled by fracture zones into the aquifers (Bisson and El-Baz 1991). Fracture zones are extensive, and nearly vertical zones in the rock. The fractures appear to form networks that would facilitate the transport of water and its storage. Thus, they would play a significant role in the localization of aquifers.

6. Conclusions

The hypothesis presented in this paper suggests that groundwater resources may be inferred from large accumulations of sand in the eastern Sahara. It is based on the study of satellite images followed by field work to confirm interpretations of the space-borne data.

Observations that support the hypothesis include: (a) the topographic confinement of the sand seas in depressions; (b) the consistent wind direction from the north during dry climates throughout the Pleistocene; (c) the quartz composition of the sand whose source is most likely a sandstone that is exposed only in the south, whereas rocks to the north are mostly limestones; (d) the ample archaeological proof of wet climates in the past as indicated by the evidence of pre-historic habitation by plants, animals and humans; and (e) the recognition, particularly in radar images, of sand-buried courses of paleo-rivers that terminate in inland depressions, which are surfaced by playa deposits.

The hypothesis relates the origin of the sand to fluvial erosion of the Nubian Sandstone, which is exposed in the southern part of the desert. It involves the down-gradient transport of the sand grains toward the north. This occured in the courses of ancient rivers that led to inland depressions, where the sand was deposited in horizontal laminae. The water that accumulated in the depressions during wet climate episodes would have seeped through the underlying rocks, through primary and/or fracture-induced porosity, to be stored as groundwater. As dry climates set in, the wind mobilized the sand and shaped it into various aeolian forms. Thus, the hypothesis implies that sand was born by water and sculptured by the wind.

Acknowledgements

Satellite image interpretations were part of the UNESCO-sponsored International Geological Correlations Program, Project-391. Field work was supported by the Arab League Educational, Cultural and Scientific Organization (ALECSO). Acquisition of Radarsat images was supported in part by the U.S. National Science Foundation (NSF) Grant INT-9515394.

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Geological elements for preparing regional hydrogeological studies, based on the Nubian Aquifer example

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Abstract

Regional hydrogeological studies of the scope of the Nubian Aquifer System cannot sucessfully be established with traditional hydrogeological methods which deal with groundwater at relatively small regional scales.

At the beginning of regional groundwater exploitation in Egypt and Libya it was commonly believed, that the groundwater of the Nubian Aquifer System is in equilibrium, what ever was produced was replaced by groundwater flowing in through the system from areas where present rainfall takes care of sufficient recharge. Within this picture no detailed regional knowledge of the geological situation was necessary as long as it was sure, that the outer part of the Aquifer System (basin!) reaches the areas of regular rainfall. Groundwater production consequently was reduced to a purely engineering procedure.

Reality unfortunately does not coincide with this positive expectation: Meanwhile we know, that recharge from the South is so slow, that it is only of academic interest. Most groundwater within the Nubian Aquifer System was recharged locally during different moist periodes of Holocene and Pleistocene times and consequently groundwater exploitation is mining groundwater. From a geological point of view this means, that relatively detailed knowledge of the overall structural situation of the system is necessary as well as knowledge of Aquifer thickness, characteristics and distribution. If the internal communication, the differences in depth and in reserves and especially the variations in hydrogeological characteristics of the different sediments shall be understood it is first necessary to interprete the geological development of the Aquifer System.

These first steps include interpretation of geophysical data (magnetometry, seismic, gravity) and drilling data in order to reconstruct the top of the impermeable basement and the thickness of the Aquifer System. Drilling data and data of surface geological fieldwork are needed to interprete and correlate the sedimentary column locally as well as throughout the Aquifer System. After this is carried out with professional methods used in oil geology hydrogeological interpretation summarizes or subdivides these stratigraphical/ sedimentological correlations under permeability and/ or transmissivity points of view based on test data from water or oil wells and laboratoy tests. A network of geological cross sections together with the reconstruction of the top of the impermeable basement and data of the surface geology make an undispensable prerequiside for a regional groundwater model. The main remaining problem is, that the large dimension of the Nubian Aquifer System and the scarce data available in some areas made approximations and generalisations necessary. Not all of them might be in accordance with reality, but because of the relatively unique structural and sedimentological situation of the Nubian Aquifer System we suppose that differences more or less equalize.

1. About the history of groundwater exploitation in NE Africa and their geological complications

There is a basic difference between groundwater and hydrocarbon exploration which should not be ignored any longer: When an oil company intends to explore a frontier basin, it normally begins its attempts with studies about the regional frame of the basin, its sedimentary content, its facies variations and its internal structural subdivision. In the ideal case some detailed geological fieldwork (often backed by remote sensing) and a first structural overview through regional airborn magnetic surveys leads to a substantial interpretation which becomes the base for concession application and later seismic as well as drilling activity. Parallel to these activities attempts are made to localize and characterize the potential source rocks of hydrocarbons, their regional variations and their quality. Exploitation of hydrocarbons, however begins, when commercial oil or gasfields are localized.

The history of groundwater exploration and exploitation in NE Africa was somewhat different from the more or less systematic development of hydrocarbons in the same general area. Similar to hydrocarbon exploitation groundwater production started where existence of reserves was expected: At the vicinity of

natural oasis where groundwater is or was at surface. But the pre-drilling procedures, all the different steps of exploration, were skipped. Within the Egyptian part of the Nubian Aquifer System the groundwater exploitation was not mainly focused on questions like availability and reserves of groundwater but more after infrastructural or traditional criteria independent from the groundwater situation. Moreover neither the sources of the groundwater were known nor the structural and sedimentological details of the basin. The subdivision of aquifers, aquitards and aquicludes was not carried out to the extent of regional correlation and consequent modelling of the interaction of groundwater within the different areas of the Nubian Aquifer System and between the different aquifers was not possible on a regional scale. It was the intensive geological reconnaissance carried out during the late 70ies and early 80ies, which let to the regional subdivision of the former Nubian Sandstone Formation into correlative sequences of Cambrian to Paleocene age and to the understanding of structural developments as well as rock-facies differences (Klitzsch 1994). These mainly geological exploration works became an important part for our groundwater model (Heinl and Brinkmann 1989, Thorweihe and Heinl 1989).

Within Libya the situation was somewhat different. In Murzuq as well as in Kufra Basin stratigraphy and facies distribution was much better understood when groundwater exploitation began; important geological criteria necessary for an exploration background were already assembled by the oil industry. I do not know to which extent they were used, but certainly the situation was different from Egypt. Different is also, that in the two Libyan basins the marine influence within the Paleozoics was stronger than in Egypt and consequently aquitards or aquicludes (mainly shale) are more frequent and generally thicker. And also saltwater becomes more extensive towards the inner parts of the basins. Not different was the fact, that in both countries it was difficult to convince the planing institutions, that the water is mainly fossil water formed locally during moist periods during and after the Pleistocene. It took time to make it clear, that Ambroggis (1966) postulation of continuous and sufficient recharge from areas further south was nothing but wishful thinking, steady state is not what is to be expected.

2. About the present day situation

It seems, that meanwhile it is generally accepted, that most of the groundwater in NE African basins is fossil water and groundwater exploitation consequently means mining groundwater. What are the most important geological elements under this aspect? As long as steady state conditions were believed to prevail it seemed to be satisfactory to know the aquifers capacity and its physical extension within the vicinity of the groundwater field under exploitation. In the case of Egypt connections of the aquifer to recharge areas in Ethiopia, Sudan or Chad were expected to be unproblematic (southward coarsening of Nubian Sandstone).

Reality soon proved slowly but constantly reducing pressure within the confirmed aquifers especially in the Kharga and the Dakha areas and rapidly decreasing groundwater table further south. Steady state conditions do not exist. Moreover, geological fieldwork resulted in the discovery of a number of “basment at suface” areas in southern Egypt and northern Sudan, which form local groundwater barriers. And the so-called Nubian Sandstone south of the border is mainly made of Permian to Lower Jurrasic mud stone interbedded with immature clastics, which are more a groundwater barrier than an aquifer connection to areas further south. In other words: even if the regional gradient would have been much steeper than it is, groundwater recharge from south would have been negatively influenced by permeability barriers.

Similar problems in the surrounding of the groundwater fields in the Kufra Basin part of Libya and the northern Murzuq Basin are not necessarily to be expected. But there the vicinity of saltwater needs a very detailed knowledge about facies changes within the aquifers, the distribution and regional extension of aquicludes and expecially the extension and variation of saltwater within aquifers. Moreover permeability values and gradients should not only be known from the groundwater field under exploitation but also from larger parts of the basins. Groundwater mining requests very qualified and rational exploitation wich is not possible without detailed knowledge of the geological conditions. To a certain degree it is comparable to the exploitation of an oilfield, there the results even within reservoires of equal quality range between 15 or 20 % in rapid and poorly controlled exploitation and 55 to 60 % recovery after exact planing.

3. Recommendations

The use of non-renewable groundwater reserves needs highly qualified exploitation, because it effects future generations at a very important issue: life without water is not possible. From a geological point of view groundwater exploitation of basins in arid or semiarid areas does not reach clear conceptions without careful exploration. In praxis that means, hydrogeologist and their engineer teams developing large basin areas should make use of some of the methods common in hydrocarbon exploration and they should, wherever possible, use the existing data and interpretations of the oil sector. It is not sufficient, to explore only the local

productivity of well fields by pumping tests and porosity as well as permeability studies. A regional picture should be achieved for example through aeromagnetic and/ or seimic data as well as by regional correlation of strata. It needs sufficient knowledge about stratigraphy, facies changes, structural developments and water chemistry. This regional reconstruction should make use of existing data and it should include the whole basin from which groundwater is extracted from the present well field or well fields to potential extention fields and to the edges of the basin. If there is interest in the groundwater development from fill up situation during the last moist period until now, quaternary geology has to be included like identification and age dating of ancient lake levels and exact identifications of their altitude. This at least is the way to reconstruct the groundwater situation through time and predict it – including development conceptions – to the future.

Figure 1 shows the kind of geological reconstruction and its hydrogeological interpretation which was used for the Nubian Aquifer model (Heinl and Brinkmann 1989, Hesse et al. 1987).

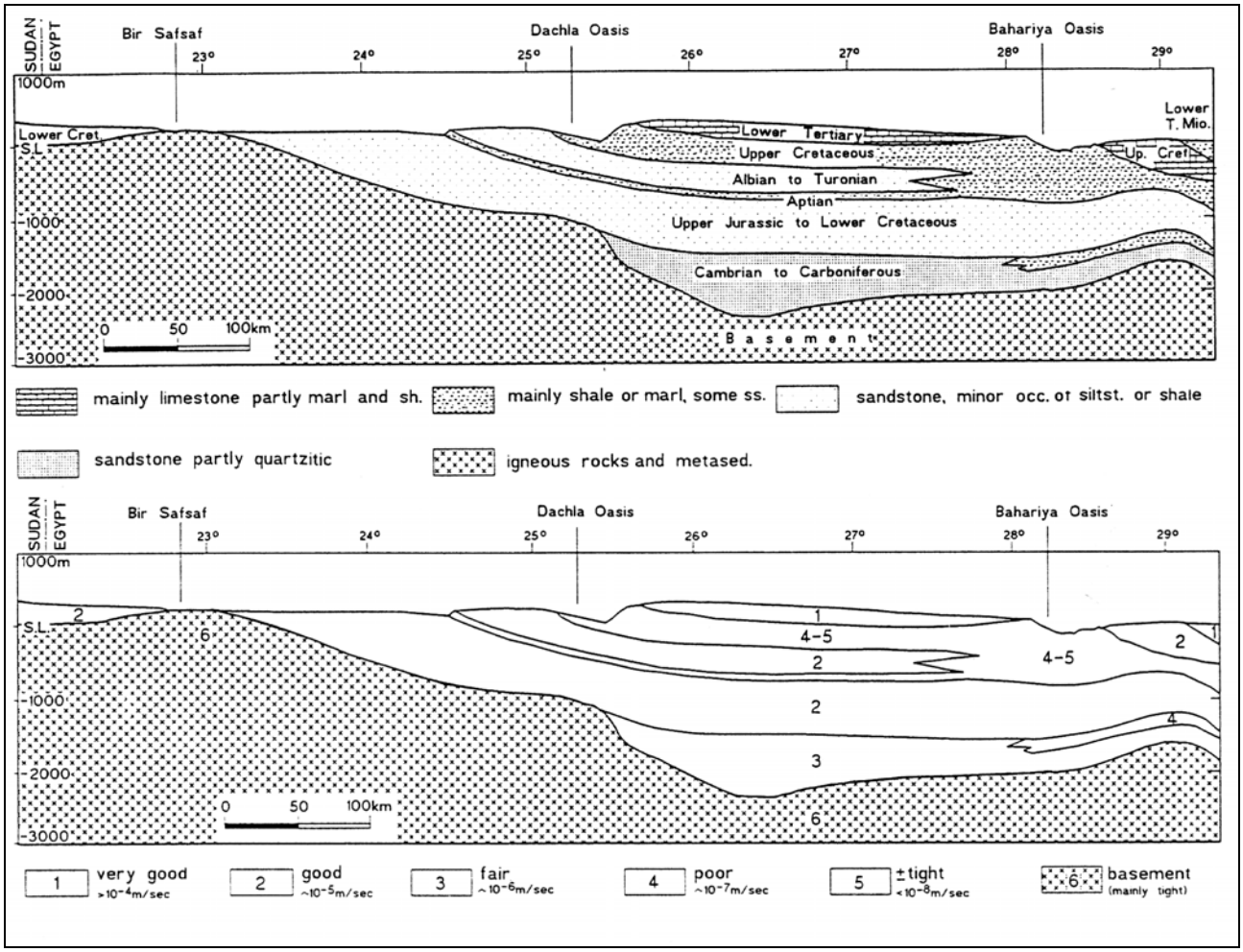


Figure 1: Generalized section through the Nubian Aquifer System from the Sudanese border to Bahariya area in Egypt. Upper part shows stratigraphy and lower part interpretation of permeability (modified after Hesse et al. 1987).

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Hans-Joachim Pachur

Palaeodrainage systems in the Eastern Sahara and groundwater recharge

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Abstract

Field research and palaeoenvironmental reconstructions have revealed that within less than 6,000 years the Eastern Sahara experienced a dramatic climatic change similar to that in the Western Sahara, passing from hyperaridity to semi-aridity (dry savanna) to its present hyperarid state. Groundwater levels started to rise about 9,300 years before present (14C-years B.P.), leading to the formation of a mosaic of freshwater lakes and swamps. Within a few decades the aquifers were loaded and the palaeo-piezometric surface was as much as 25 m higher than it is today. The uplands generated up to 900 km long fluvial systems which put an end to the endorheic drainage of Libya and NW-Sudan and functioned as migration paths for large savanna mammals. The palaeodrainage systems induced groundwater recharge and lake formation in the Kufrah basin and the Great Sandsea of Eppt.

In Western Nubia, Lake Ptolemy – a shallow freshwater lake – covered an area of more than 20×10^3 km^2 during early to middle Holocene time. Lake Ptolemy constitutes the eastern part of a chain of lakes that begins in the eastern Sahara, south of 20°N, and ends at Taoudenni/Mali, north of 20°N.

Changes in land-surface conditions such as palaeolakes, swamps and vegetation created water vapour sources that generated local rainfall and buffered short dry spells. Radiocarbon-dated charcoal indicates that Neolithic human occupation culminated during this early Holocene wet phase and ended c. 2,000 years after the fading of the wet phase at about 3,000 years B.P., when the shallow aquifers were exhausted.

Nicole Petit-Maire

Major recent palaeorecharge events in the Sahara: the example of Libya

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Abstract

Over the last 130 000 years, the global alternation of warm (interglacial) and cold (glacial) phases deeply modified the climate in the present-day arid area of Northern Africa and the Arabian Peninsula.

During the last two interglacial periods (peaking at c. 125 000 yrs BP and c. 9500-7000 yrs BP), both the activity and the northwards range of the African and Indian summer monsoons, as well as the Southern penetration of the Atlantic cyclones and Mediterranean winter rainfall widely increased. The desert belt considerably shrank, with aridity only persisting around of Tropic of Cancer.

In Libya, fresh water lakes existed, testifying for precipitation rates and aquifers rise much higher than nowadays. In the Shati Valley, presently receiving 30 mm mean annual rainfall, a fresh to brackish water lake, fed by local rainfall and the rise of the local aquifer, existed between 137 000 and 120 000 yrs BP. It was about 2000 km^2 large and 40 m deep.

The Holocene altithermal also induced an increase of local rainfall, however more modest, resulting into existence of numerous lakes or lakelets: in many of the troughs throughout the dune fields in Southern Libya, carbonate deposits with mollusc shells, testify the presence of surface fresh water, due to the outcropping of the dune phreatic nappes and thus to rainfall conditions much more favorable than nowadays.

Therefore, each recent global temperature rise has corresponded with a significant change in atmospheric circulation and in the Precipitation/Evaporation budget over Libya.

One may suppose that the expected global warming of +1° C to a few degrees, due to atmospheric pollution, will bring about the same effects as the past natural global warmings (even if not an analogue) and induce an increase of rainfall over the Libyan Sahara.

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Evidence of a large quaternary lacustrine palaeo-lakes in Libya and their importance for climate change in north Africa

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Abstract

In the endhoric Murzuq Basin three different lacustrine limestone deposits of presumed Tertiary or Quaternary age were investigated. New Th/U mass spectrometric age determinations produced Quaternary ages of three events with 128 ka, 240 ka and 380 ka. The size of the oldest "Lake Fezzan" 380 ka ago was about 120000 km^2 and vary to the youngest of about 3 000 km^2 128 ka ago. The oldest lake was twice the size of the largest recent African Lake Victoria. The water level of the three lake phases vary between 290 m and 520 m a.s.l. The distribution of cultural remnants of Palaeolithic and Mesolithic settlements is identical with the outline of the lake phases.

The aquifers were always totally filled during these humid phases corresponding with the warmer interglacial phases at the northern hemisphaere. The groundwater partly evaporated between each phase to give space for younger humid events. We expect groundwater remnants of these Quaternary humidic events in lower aquifers, new age determinations on deeper aquifers are necessary.

1. Previous geological investigations

Younger limestone bearing deposits were discovered in the endorheic Murzuq basin more than 60 years ago by Desio 1936. Later Pagni 1938, Bellair 1944-1953, Lelubre 1946, Collomb 1962, Hecht et al. 1963, Goudarzi 1970, Desio 1971, Klitzsch 1974, Bannerjee 1980, Domáci et al. 1991 and Grubic et al. 1991 presumed ages between Jurassic and Holocene.

First evidence for Quaternary age of one type of lacustrine limestones in the Murzuq basin was established by Gaven 1982 and Petit-Maire et al. 1980, Petit-Maire 1982 (Th/U-method, varying between 40 ka and 173 ka, with a cluster between 132 ka -136 ka).

2. New investigations

We identified three different types of lacustrine limestones in the Wadi ash Shati (northern Murzuq Basin), which can be distinguished by their topographical position, sedimentary structures, colours, impurities and geochemical isotopes (Thiedig et al. in press).

New results were obtained by mass spectrometric uranium-series (TIMS) disequilibrium dating (Ivanovich and Harmon 1992, Geyh 1994) on the lacustrine limestones of the Murzuq Basin. All three limestone types belong to the

Al Mahruqah Formation (Quaternary) (Thiedig et al., in press)

Brak Member c. 380 ka

Bi'r az Zallaf Mb c. 240 ka

Aqar Member c. 128 ka

The oldest and largest limestone of the **Brak Member** is situated at the highest topographical position (420 m to 520 m a.s.l.) covering different Palaeozoic units. It is a massiv partly brecciated limestone with thickness of about 10 m.

The limestone of the **Bi'r az Zallaf Member** is thinbedded with intercalations of gypsum. The topographical position is between 350 m and 410 m a.s.l.

The third **Aqar Member** is the youngest and topographically deepest lacustrine limestone, which consists mainly of coquina beds (shells of *Cardium glaucum)*, ostracods and foraminifers.The topographical position is between 290 m and 345 m a.s.l.

3. "Palaeo-Lake Fezzan"

We obtained three humid events: the Brak-, Bi'r az Zallaf and Aqar phases with ages of 380 ka, 240 ka and 128 ka of the Palaeo-Lake Fezzan (Thiedig et al. in press). The sizes of the palaeo-freshwater lake phases are between 3000 km^2 (Aqar phase), 30 000 to 50 000 km^2 (Bi'r az Zallaf phase) and about 120 000 km^2 (Brak phase) depending on the distribution and elevation of the limestone beds (Figure 1).

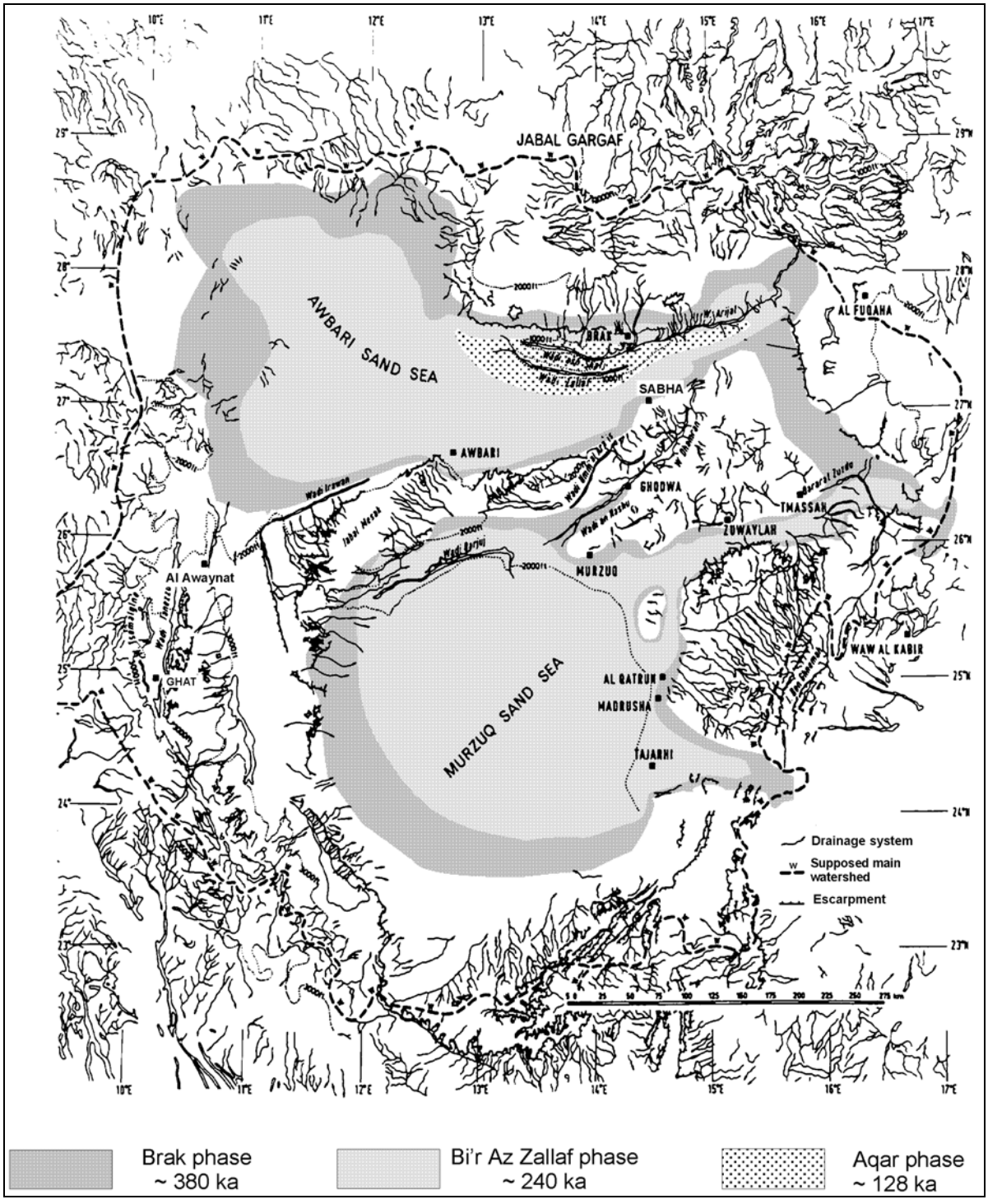


Figure 1: Size and distribution of the three phases of Quaternary Palaeo-Lake Fezzan in SW - Libya (Brak phase 380 ka, Bi'r az Zallaf phase 240 ka, Aqar phase 128 ka).

The water depth was mainly flat with a probable temporary maximum of about 100m in the largest lake.

All three lake phases developed in the same area covering each other. The distribution of tools made by “stone-age-people“ is identical with the shoreline of the “Palaeo-Lake Fezzan“ and evidence of Palaeo- and Mesolithic settlements close to the lake (Ziegert pers. comm.).

The Palaeo-Lake Fezzan was during his largest extension 380 000 years ago twice the size of the recent Lake Victoria (Figure 2).

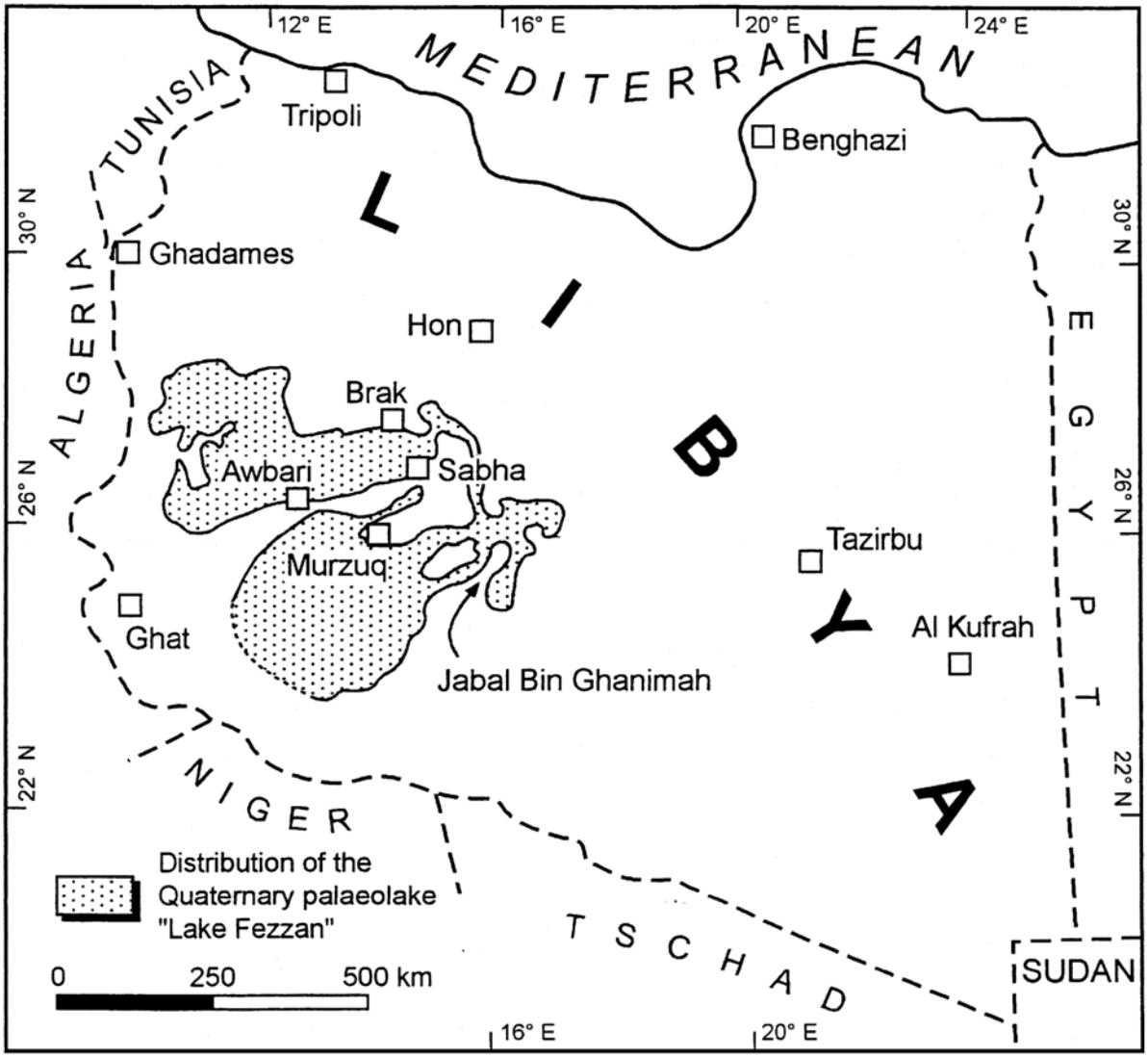


Figure 2: Position and distribution of the largest expansion of the Brak phase of Lake Fezzan in SW Libya, about 380 000 years ago

4. Conclusions

Different limestone deposits in the Murzuq Basin could be identified as remnants of one Quaternary palaeo-lake with three phases of 380 ka, 240 ka and 128 ka. Palaeo-lake sediments of the Murzuq Basin can be correlated with marine terraces around the Mediterranean. The ages of the 3 lakes correspond with the interglacial Quaternary events in Europe.

The ages fit very well into the isotopic stages of Deep Sea Drilling cores. Quaternary phases of higher precepitation in arid zones of today, the so-called “pluvials“ are not connected with cold glacial weather conditions but with warmer interglacial events (Kuklah 1978, Lézine and Casanova 1991).

Probably parts of the groundwater in the Libyan basins below the dated resources could be originated from the mid-Quaternary lakes of Libya. The shore lines of Lake Fezzan are identically with the distribution of Palaeo-and Mesolithic traces of settlements in the Wadi ash Shati and Wadi Hajal (Ziegert 1978 and pers. comm.). The water of the recent lakes in Awbari Sand Sea is not a relict of the palaeo-lakes but runs out of the same aquifer which existed long time ago (Chair 1984, El Chair 1991).

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THEME II: ASSESSMENT METHODOLOGIES AND CONSTRAINTS FOR NON-RENEWABLE WATER RESOURCES

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Environment Impact Assessment for groundwater management

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Abstract

Due to the finite and vulnerability resources of surface water groundwater plays, and will continue to play, a critical role in satisfying water requirements of most arid and semi-arid countries. Thus, sustainable groundwater development and presentation of groundwater quality should receive priority attention. The paper demonstrates the main aims of groundwater development and management and the process through which environmental impact assessment of groundwater development projects, and includes also a framework for environmental impact assessment. At the end the paper recommends such impact assessment of any groundwater development plan. The biggest challenge, however, will be how to manage groundwater properly.

1. Introduction

The realities of the water resources situation represent a serious challenge to water resources management in the twenty first century. In spite of the problems associated with water development, energy, domestic and industrial water supplies require that surface and groundwater resources be used much more effectively than at present. The challenge for water users, planners, policymakers is how best to achieve such development to contribute effectively to meeting social and economic goals, while maintaining water resources on a sustainable, high-quality basis, and avoiding serious degradation of the physical environmental and unacceptable social disruption.

Environmental quality was defined in terms of attributes which are the ecological, cultural and aesthetic. The most used methods for assessing the environmental impact of water related projects are checklists and matrix analyses. Throughout history groundwater has been an important source of water that has been extensively used for human consumption and for agricultural production. Even now, groundwater plays a critical role in satisfying the water requirements of many countries, both developed and developing. For example, 90% of rural population and 50% of the total population in the United States depend upon groundwater for their domestic water requirements. Similarly 73% of the population in West Germany, 70% in the Netherlands, 30% in the United Kingdom and a little percentage of the population in Sudan depend upon groundwater for irrigation and domestic purposes. In some parts of the world, as much as 75 to 80% of the water used for irrigation comes from groundwater. For storage purposes, the underground reservoirs have many advantages over surface reservoirs:

1. They cost nothing to construct.
2. They do not silt up.
3. They have no evaporation losses.
4. They have relatively uniform temperature and mineral quality.
5. They do not occupy the land surface that is useful for other purposes.
6. They are not relatively exposed to hazards of nuclear warfare.
7. They do not wear out if properly managed.

2. Groundwater in Sudan

The groundwater is found in the geological formation of the Nubian sandstone, the Umruaba series which both cover about 49% of the area of the country. The annual average recharge of the groundwater is about 4.9 milliards. For irrigated agriculture, alone the available water supply is 4.9 milliards being the groundwater recharge. Environment Impact Assessment is well taken care of in the Sudan and projects are evaluated on the merit of the technical, social, economic and environmental feasibility. The Urban Areas in Sudan are

supplied from surface and groundwater sources while in the rural areas where 35% of the rural population live are served with safe water supplies, there are 35 small dams having a total capacity of 20 million m^3 (Mm^3) and 99 haffirs (ponds) with a total capacity of 25 Mm^3. Water supplies from groundwater are obtained from some 7000 deep bores providing 150 Mm^3 per year in addition to some 5000 hand dug wells supplying some 10 Mm^3.

3. Groundwater in arid zones

Low average rainfall and the absence of perennial rivers characterize arid zones. Generally these basic criteria are correlated with high mean annual temperature and low atmospheric giving rise to high rates of potential evapotranspiration. Fresh groundwater in arid regions is characterized by a limited natural recharge. In the past, groundwater management strategies have focussed on the development of the resource to satisfy the increasing demand of the growing population. It was assumed that the resource is always available and that the main aim of plans is to make it available at the right time, the right place, and at properquantity and quality. In recent years, awareness has increased about the scarcity of groundwater and the challenge to develop sustainable strategies. Especially in arid to semi-arid regions, proper allocation of available resources requires planning to prevent competitive users from overexploiting the resource.

4. Objectives

- Identify and forecast the possible positive and negative impacts to the environment resulting from a proposed project.
- Provide for a plan which, upon implementation, will reduce or offset the negative impacts of a project resulting in acceptable environmental changes.
- To assist all the parties involved in the specific development project to understand their individual roles, responsibilities and overall relationships with one another;
- To identify adverse environmental problems that may be expected to occur;
- To involve the public in decision-making process related to groundwater management;
- To incorporate into the development action appropriate mitigation measures for the anticipated adverse problems;
- To examine and select the optimal alternative from the various relevant options available;
- To identify critical environmental problems which require further studies and monitoring; and
- To identify the environmental benefits and disbenefits of the project, as well as its social and environmental acceptability to the community.

5. General principles

Both human activities and natural phenomena can cause groundwater deterioration, but as a general rule it is human activities that contribute to maximum damage through over-exploitation and irrational use. **EIA** can be successfully used to identify adverse consequences of human activities, and is thus of prime importance to all parties involved in development planning and implementation of groundwater projects. It is equally applicable to all new development actions as well as to the expansion or modification of currently existing actions. Furthermore, in most developing countries few enviroumental considerations were incorporated in past development actions. There is thus a need to carry out environmental reviews of existing projects so that the major problems can be rectified.

EIA reports should be presented in a simple form so that decision-makers can readily digest and make use of the analysis in making rational decisions. However, EIA should aim at maintaining the availability and use of groundwater on a sustainable basis. Since environmental losses and gains cannot always be evaluated in straight economic terms, the expected changes in environmental values, which often can only be considered in a subjective way, have to be taken into account in the decision-making process.

EIA is already a legal requirement for water development projects in many developing countries, but it has to be admitted that its use thus far for groundwater development projects has been very limited. A legal

requirement by itself, through an essential first step, cannot ensure that EIA will actually be conducted, or that, if conducted, it is properly carried out and effectively used within the prescribed decision-making framework.

The interdisciplinary nature of groundwater problems means that close cooperation and coordination are essential among the various groundwater developments dealing with specific types of problem. Where expertise is not available within the government itself, it is necessary to consult with universities and other scientific establishments so that EIA can be properly conducted. The interdisciplinary nature of groundwater problems also means that the teams conducting EIA should also be multi-disciplinary and interdisciplinary.

To provide adequate environmental information for EIA, it is essential to set up national groundwater data banks, which can facilitate the use, the information available. The efficiency in the handling and of data is highly likely to increase significantly under such circumstances. Currently in many developing countries data are collected by various governmental authorities groundwater. Owing to the lack of appropriate interdepartmental coordinate, is often difficult-if not impossible-to obtaining an aggregate picture on data collected. This means that the available groundwater data may not be used for EIA. In some cases it could even result in duplicate data collection, which is a poor use of the very limited financial resources available in many countries.

Developing countries must carry out EIA of groundwater projects to the best of their national capability. Therefore it is urgently necessary to train our own experts in EIA. The involvement of local expertise will not only ensure that EIAs are carried out more relevant to local needs, but will also ensure a significant reduction in EIA costs when compared with those conducted by foreign experts.

6. Checklist and matrix analyses

Checklists evaluate the environmental 'without' and 'with' project in terms of scores that can be used for comparative evaluations of alternatives for one project or for comparing different projects. Several lists are used for environmental evaluation. Usually a hierarchical structure considers the environmental impacts in four categories; ecology, environmental pollution, aesthetics, and human interest, and assigns a number in the system which does not vary from project to project indicating its relative importance; these Parameter Importance Units (PIU) total 1000. Each Environmental Quality parameter (EQ) is scaled on a range of O to 1. The higher values indicate better quality. Each alternative is given a total scope by assessing each of the environmental parameters as follows:

EIU = PIU * EQ

Matrix analyses are commonly used to compare alternatives. This approach consist from a matrix with a number (depending on the author of the matrix; in the Lepold matrix 88) of existing characteristics and conditions of the environment and on a vertical axis about 100 proposed actions which may cause environmental impact. Thus a grid which in the case of Leopold matrix contain 8800 boxes. Each significant interaction between a proposed action and the environment is identified and their intersection corresponds to a box in the grid. Within this box, a number from 1 to 10 indicates the relative 'magnitude' of the impact, and another number from 1 to 10 indicates the 'importance' of the impact, with 10 representing the greatest impact and 1 representing the least.

7. Planning

Groundwater resources planning deals with the invisible part of the hydrological cycle. Therefore, availability and reliability of data and information are key issues for the success of plans.

The main information needed for planning include:

- Anticipated demand for groundwater.
- The configuration of the system, its present state (e.g. water levels, quality, volume in storage, discharge, boundaries, etc.) and its trend relative to the demand (the time factor).
- Controllable measures and corresponding actions to close the gap between supply and demand, and available resources.
- Anticipated exogenous inputs to the system (e.g. water and substances) which may affect the supply.
- Anticipate state and supply of the groundwater as a result of alternative courses of action.
- Benefits and adverse impacts of each alternative.

8. Environmental aspects of groundwater management

Groundwater has many implications if it is managed in an environmentally sound manner. The three main considerations for environmentally sound ground water management are:

1. Groundwater development must be sustainable on a long-term basis. This means that the rate of abstraction should be equal to or less than the rate of recharge. If the rate of abstraction is higher than the rate of recharge, it will result in groundwater mining, which can be carefully considered for some specific cases. If mining occurs, groundwater levels would continue to decline, which would steadily increase pumping costs, and then at a certain uses like agricultural production.
2. Human activities, which could impair the quality of ground water for potential future use, should be controlled. This would include leaching of chemicals like nitrates and phosphates form extensive and intensive agricultural activities, contamination by toxic and other undesirable chemicals from landfills and other environmentally unsound waste disposal practices, bacterial and viral contamination due to inadequate sewage treatment and wastewater disposal practices, and increasing salinity content due to inefficient irrigation practices.
3. Improper groundwater management often contributes to adverse environmental impacts. Among these are land subsidence in certain urban centers due to high rate of groundwater abstraction, and sudden strict control of groundwater abstraction, which allows groundwater table to rise steadily over its recent long-term levels which, could contribute to structural damages.

The main aim of groundwater development and management is to ensure the sustainability of the resource and developments based on it. This requires a good knowledge of the system configuration, present state, and response to future stresses. System configuration can be obtained by various methods, including geological and geophysical surveys and borehole drillings. The present state of the system involves determination of hydraulic parameters, groundwater quality, etc.

9. Purposes of Environmental Impact Assessment (EIA)

The EIA process makes sure that environmental issues are raised when a project or plan is first discussed and that all relevant concerns are addressed as a project proceeds towards implementation. Recommendations resulting from EIA may lead to redesigning some project components and suggests changes affecting project viability or causing delays in project implementation.

Corresponding to the World Bank Guidelines procedures for Environmental Impact Assessment should ensure environmentally sound and sustainable development. Any environmental consequences have to be recognized early and taken into account in project design. Main advantages of timely application of EIA are:

- Enable to take into account environmental issues at an early stage and in a systematic manner.
- Reduces the need for project conditionally and limitation.
- Help to avoid additional costs and delays in implementation.
- Provides a formal mechanism for inter agency coordination to deal with the concerns of affected groups and local Non Governmental Organizations (NGO's).
- Can play a major role in capacity building in the region or country of application.

The main purposes of EIA can then be stated in the following manner:

1. Identify and forecast the possible positive and negative impacts to the environment resulting from a proposed project.
2. Provide for a plan which, upon implementation, will reduce or offset the negative impacts of a project resulting in acceptable environmental changes.

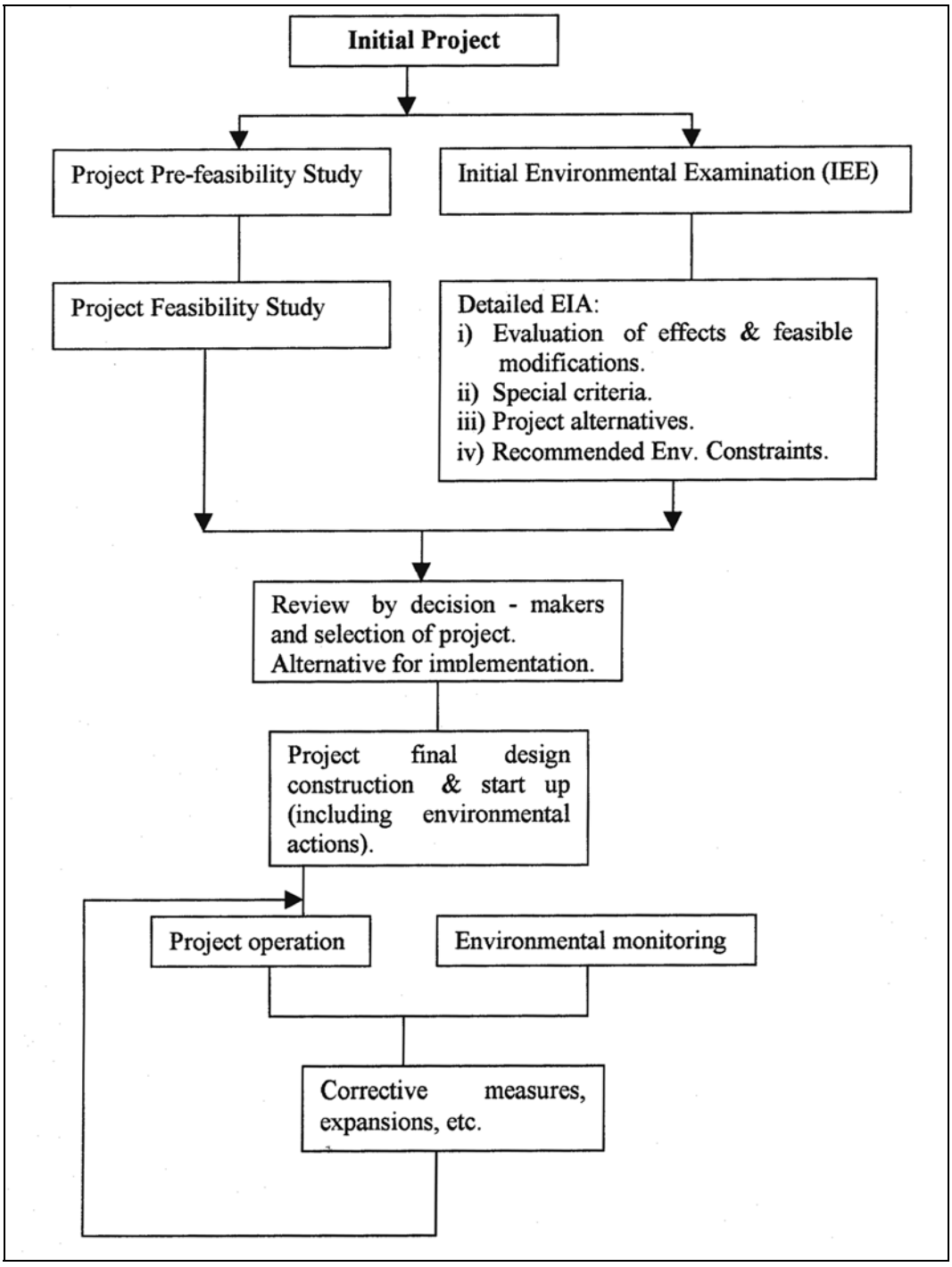


Figure 1: Relationshops of the EIA process to project planning and implementation.

10. EIA for developing countries

It is generally recognized that EIA can identify major areas ot environmental damage due to development activities in a systematic and comprehensive manner. However, not withstanding the intrinsic value of EIA, past experiences clearly indicate that there is an urgent need to develop procedures so as to make them more adaptable to conditions in developing countries. In adapting EIA for use in developing countries, it may be useful to take note of differing characteristics, such as limited resources in terms of information, technology, can be equally applicable to all developing countries. Various alternatives are available, and each country must choose its own system.

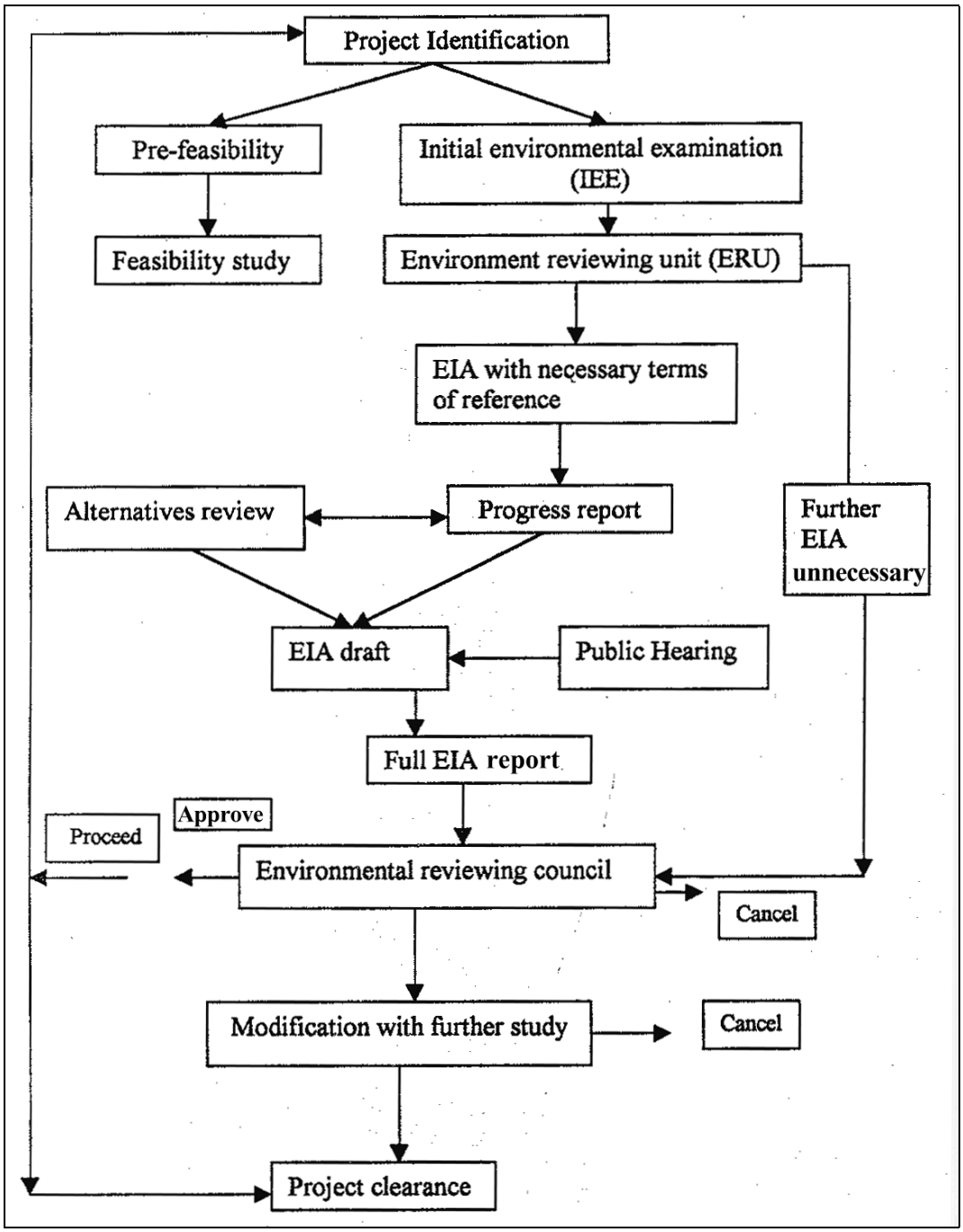


Figure 2: Flow chart of project analysis.

11. EIA Framework

In general terms, the framework for groundwater protection constitutes of a series of actions. Some are preventive while others are corrective. These should be directed to both the software as well as the hardware. An EIA procedural framework for groundwater development project is shown in Fig (2). A feasibility study of a project basically depends upon data and information on the technical, economic and social aspects of the project. To avoid higher cost and unnecessary time delays, EIAs of groundwater projects should be carried out along with the initial feasibility study.

Before going into detailed analysis, it is advisable that as soon as the project brief (e.g. nature, scale, location, time, frame, etc) is known, an initial environmental examination (IEE) of the project should be undertaken to determine whether it requires a full EIA. This activity is known as 'screening'. After an IEE is completed, it should be reviewed by an environmental reviewing unit ERU, together with the pre-feasibility study report, in order that the technical, economic, social as well as environmental aspects of the project can be carefully examined and evaluated in a comprehensive fashion.

If the reviewing unit finds no serious adverse environmental impacts, the project should be sent to the environmental reviewing council ERC for approval. If approved by the ERC, the project can be implemented, provided it complies with all existing environmental regulations. If, however, after deliberation the ERC requires further assessment on environment impacts, the developer and/or the environmental agency may prepare a detailed EIA with appropriate terms of reference (which may include baseline data requirements and the use of a particular ELA method).

Progress reports of the EIA study being undertaken should be submitted for review and evaluation at regular intervals so that the parties concerned are kept informed of the states of the analysis. Based on the study, on EIA draft should be prepared which should consider difference, viable alternatives available. Public hearings could be arranged to encourage and facilitate public involvement and participation in the EIA. Thereafter a full EIA report could be prepared. The report should then be reviewed by the ERC, which could either approve it or ask for further study and modification of it. The ERC can also recommend that the project be cancelled on account of highly undesirable environmental consequences.

In cases where further analysis is required the new EIA report has to be reviewed again by the ERC. After this review the project could either be approved for implementation, with or without suggestions for specific modifications, or be cancelled. After the implementation phase of a groundwater project is approved, it is essential that some institutional infrastructure exist which checks both that the recommendations made be the ERC are being actually carried out, and also that unexpected adverse environmental consequences which were not identified during the EIA are not occurring. Unfortunately in many countries, after EIA's have been carried out, no monitoring is generally done to ensure that ERC's recommendations are being observing developers.

12. Conclusion and recommendations

EIA may lead to redesigning some project components and suggests changes affecting project viability or causing delays in project implementation. Good environmental impact assessment has to be at the center of any sound groundwater management plan, because of the complexities and uncertainties that are invariably associated with groundwater regimes, it has generally been not possible to carry out proper environmental impact assessment of groundwater development projects in all developing countries. Accordingly, many such projects have proved to be neither sustainable nor environmentally acceptable on a long-term basis.

With substantial improvements in indigenous expertise on groundwater management, and with concomitant increases in interest in regular monitoring of the quality of groundwater, more and more developing countries. As EIA becomes an integral part of planning and management of groundwater management practices, there is no doubt that it can only be considered to be a beneficial development for all countries concerned.

The groundwater resources in general are naturally protected out of pollution but, if it is affected by pollution, it will be very costly to be reclaimed and in most cases it will be impossible to bring it back to normal.

There is a serious need to recharge the usable groundwater aquifers through the construction of dams and the recharge of wells in order to assure the sustainable safe yield needed for all forms of developmental projects.

To Identify and forecast the possible positive and negative impacts and to provide for a plan these are the main purposes of EIA.

The main aim of groundwater development and management is to ensure the sustainability of the resource and developments based on it.

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Ammar A. Ammar and Mohamed M. Yacoub***

Evaluation of the Catchment area of the Stuah Karst Spring Cyrenica, Libya

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Abstract

This study discussed and evaluated the results of geological, hydrological, hydrogeological analysis of the catchment boundaries of Stuah karst spring, the underground water shade has been determined by geomorphologic, geological and hydrological methods.The control used was the hydrologic inverse water budget analysis appropriate for karst basins with limited hydroclimateological data (Bonacci, Magdalene, 1993) and used (Turc, 1954) mathematical model to investigate the run off deficit and run off which reflected the estimate yield, the water losses might be recharged the adjacent aquifer to Stuah spring, and concluded relationships between estimated and measured yield, rain fall and run off deficit, estimated yield and precipitation, etc.

From the measurement of discharge of the study spring showed that it mainly uniform with average yield 25 liter per second, the optimum fluctuations of the yield reflected the fluctuations of the annual rain fall precipitation.

The catchment area zone is defined as 33 km^2, this spring has good discharge and acceptable water quality, it has never been utilized up to now with adjacent villages have scarcity of water.

1. Introduction

The Stuah spring is located in the northern part of Al-jable Al-Akhder Cryonics Libya (Figure 1), west of Ras Alhilal, east of Susa, north of hill of Sidi Masoud, coordinates latitude, longitude, altitude 290 meters above sea level, near the fault line of the northern flank of Al-jable Al-Akhder, there is no studies has been done on such area of the spring, the aim of the study is to evaluate the geologic, hydrologic and hydroclimatologic views of exploited area spring for domestic and irrigation use in the adjacent areas such Ras Al-Hilal and Susa which have water scarcity, and the ground water in these region is contaminated with sea water intrusion and the total dissolved salt exceed at 10,000 ppm, which disallowed for any development used.

2. Geologic description

The northern flank of Al jable Al akhder contains two major escarpments formed from tectoinic sequence events where formed sets of joints and faults therefore, it can be considered as an anticlinorium that is faulting mountain (Rolich, 1974; Figure 2).

The study area can be divided into two parts: geology of discharge area and geology of recharge area.

Geology of discharge area illustrate the out let spring which is located at the fault line of the first escarpment that formed from Apollonia formation which lies above Athrun formation of yellow to creamy color, fine-grain lime stone, compacted, hard, alternated with marly lime stone and chert Nodules as well as very thin beds.The layers of these formation are existed at the bottom and sides of the wadi, some how covered with quaternary sediments as wadi deposits, talus, debris, and soils. it can considered as an aquitard but effected by tectonic features as joints, faults and fractures. The sedimentary environment is from deep marine and eocene geologic time.

The geology of the recharge area represented in Derna formation lies above Apollonia formation; fine to coarse -grain lime stone enriched with nemolite fossils, interference with chalky lime to marly stone of

Apollonia formation (Ammar, 1993), affected with karst features, faults, joints, and is characterized by its moderate porosity and high transmassivety. These layers are considered as the main ground water aquifer of the spring. The sedimentary deposition occurred in shallow marine environment at eocene geologic time.

3. The hydrology

The studied base map (1:50,000) of the stream order, the catchement area and the stream divider, in addtion to the boundary of the catchment area (C.A) showed the west ridge of Sidi Masoud and the south Batoma up to main road of El-Beida Derna and the east Argob EL-Shafshaf and to the north El-Argob Alabid which is the south part of wadi El-Mahbol.

The C.A is about 33 km^2 (Figure 3).

From the geologic description and the structural geology of the studied area it has been found that the area is effected by two dense sets of joint the major set trends to the E-W and the minor one NW-SE (Figure 4).

These sets of joints are affective by the infiltration and the activities of the karst phenomenon in the lime stone.The C.A are formed from lime stone, dense joint of different directions, and the karst characterized by caves, sink hole, blind stream as a result of heavy rain which reached about 840mm one year during the study period Figure 5. Therefore, the run off at the study area and the northern flank of Al-Jable Al-Akhder is low according to the results from the equation of Turc (1954). Most of the rain falls water recharge the ground water aquifer infiltration (run off deficit). Stuah spring is classified as contact spring due to presence of fissures, and aquitard of Apollonia formation as the bottom of wadi which act as impermeable layers. Therefore, the water seeps from the side of wadi through the fissures to form the flow of the spring which is varies in depth from few centimeters to more then three meters with distance more 2.5km (Figure 3).Which ends, the water disappears in the wadi Mahbol due to the fissures and lack of ground water recharge as well as possibility of presence of blind stream so the spring water percolated to feed the ground water reservoir.

4. Hydrologic analysis and water budget

Water yield measured after 1991-94 and 98 monthly by two methods which are barrel and stream jet (Ammar and Chiblak, 1998; Table 1).

These two methods are not precisely accurate because the difficulty to collect all waters in the pipe to be measured and other lacks of water.

The hydroclimatic data of the annual mean temperature and accumulated rain fall and the C.A for the study area were founded to be vary yearly and can estimate the quantity of water of the C.A.

$$Q = P \times A \quad (1)$$

P = annual accumulated rain fall

A = total area catchment area

$$Q_{90} = 33 \times 1000 \times 839.4/1000 = 27700200 \ m^3$$

And can estimate the potential evapotranspiration Eto can be by (Penman-Montith, 1991) for the study area as Table 2; in the rain fall season can neglect the acctual evapotranspiration is neglected because of the short duration of rain fall, then the estimation of water yield of the spring by inverse water budget method (Boncci-Magdalenic,1993) is possible as considering the runoff deficit is the water infiltration. The amount of the run off deficit is:

$$I? = \frac{P}{\sqrt{0.9 + (P^2 / L^2)}}$$

$$L = 300 + 25t + 0.05t^3$$

Where *I* is the runoff deficit (mm), *p* is the yearly rain fall in the catchment area and t is the average yearly temperature of the C.A expressed in C–, the process consists of determining the catchment area which satisfies the water budget equation:

$$P = R + I$$

$$I = (Et + I)$$

Where R denoted runoff, I is the yearly infiltration, and Et is the actual evapotranspiration. The run off according to the inverse water budget is considered as estimate to the water yield of the spring.

$$R = \frac{60X\,60X\,24X\,365XQ}{A}$$

$$Q = \frac{R}{0.956}$$

Where Q is estimate water yield lit/sec, and A is the area of catchment (km^2) area.It was found statistical relationship between the weather information for 13 years (1986-1998) to evaluate the surface runoff deficit which identified in the equation of water budget for the amount of the deep percolation and actual evapotranspiration Et in the C.A. in the rain season, the amount of Eto will be the least as in Table 2, and Et can be neglected, due to lack of measuring instruments and the small size of wetted area of the spring flow in the catchment area and also because of the cracks and faults beside the karst phenomenon and shallow soil that showed infiltration during intensive rainy storm and the small allowable time for the actual evapotranspiration, therefore, the runoff deficit from water budget equation equal the amount of water infiltration as in model of Turc (1954). The runoff deficit has been evaluated as well as determining the relation with annual rain fall Figure 6 and it is as the following:

I =98.56 + 0.698 P, r =0.985

Where r is the correlation factor.The runoff deficit can be used to estimate water yield of the spring production in Figure 7 and it is as the following:

R = 357.5+1.86*I,* r = 0.924.

And there is a relation between the estimate of water yield and measuring the yield as Figure (8).

R = 23.49+0.019Rm, r = 0.806

Where Rm is the monthly measuring yield through five years; the variance between the estimated and measured discharge as well as the amount of the annual rain fall during the period of the study period can be explained and found the relationship as the following equations:

$$O_o = A_o + A_1P + A_2P^2 + A_3P^3 + ...$$

$$O_0 = \sum_{0}^{n} A_n + P^n$$

$$O_0 = (Rm/R) \times 100$$

$$r = 0.992$$

Where O_0 is the ratio of estimated and measured discharge, A is the changeable value of rain fall, infiltration and runoff. From their relation and the curve can justify the deficit of the measured or actual discharge. The values in the upper part of the curve showed the percentage deficit yield that feeds springs and adjacent ground water aquifer and the lower values represent the percentage of percentage the discharge and the annual rain fall. Figure 10 can be used to show the relation between the estimated discharge and the rain fall as:

R =0.3 –98 r=0.925

And the measured discharge and its relation with the relation with the rain fall as follow:

Rm =20.62+0.0075P r = 0.8

By subtracting the estimated discharge from the measured discharge the result will be as estimation of the amount of the feeding flow of the Stuha spring to the other small surrounding spring.

R* = R – Rm

Where R* is the annual water deficit from the spring stream to recharge the discharge surrounding area.

5. The water quality

From the periodical chemical analysis that taken monthly since 1981 till 1983 hydrogeo study, the total dissolved salt TDS showed 590 ppm, and from 1986 to 1998 the measured TDS value of 512 ppm. The biological analysis shows the water is free from pollution and no sign of bacterial effect therefor, the water is drinkable with good quality for other human use.

6. Conclusions

The catchment area is about 33 km^2 and all this area is covered completely by the karst phenomenon i,e karst factor F = the whole catchment area /the area that covered with karst=1.

The Turc (1954) has been used and it showed success in more then 255 studies similar to Stuah at various climatological regions worldwide. The water flows for more then 2.5 km then suddenly disappears in the wadi El-Mahbol as a result of lack of drainage in the ground water as well as possibility of presence of blind stream, joints and cracks, therefore, disappearance of the water could be a reason of feeding other ground water storage. Cleaning up and removing of quaternary deposits from the spring pathway can increase the spring.

From the geomorphological, structural geology studies and the hydrological calculations to the catchment area is characterized by dense infiltration (runoff deficit) and poorly runoff due to the presence the karst phenomenon and fissures, the runoff deficit estimated as 83% for the years of the study according to the model of (Turc, 1954).

The water is high quality chemically, biologically, and physically as well as high production, which is about 7.8 x 10^5 m^3 that can be invested for an estimation of 5000 people in the surrounding area that suffered of scarcity of water. The water can run to the coastal area with out pumps such as Ras-Alhilal and Susa (Apollonia) via pipes by gradient through wadi El-Mahbol. In addition, it can keep the environmental life through the spring pathway using it.

Acknowledgements

The authors would like to acknowledge Mr. E. Alkasseh, Fadel Gabaeli, S. H. Faaek and Libyan General Water Authority eastern zone as well as Shahat climatic station.

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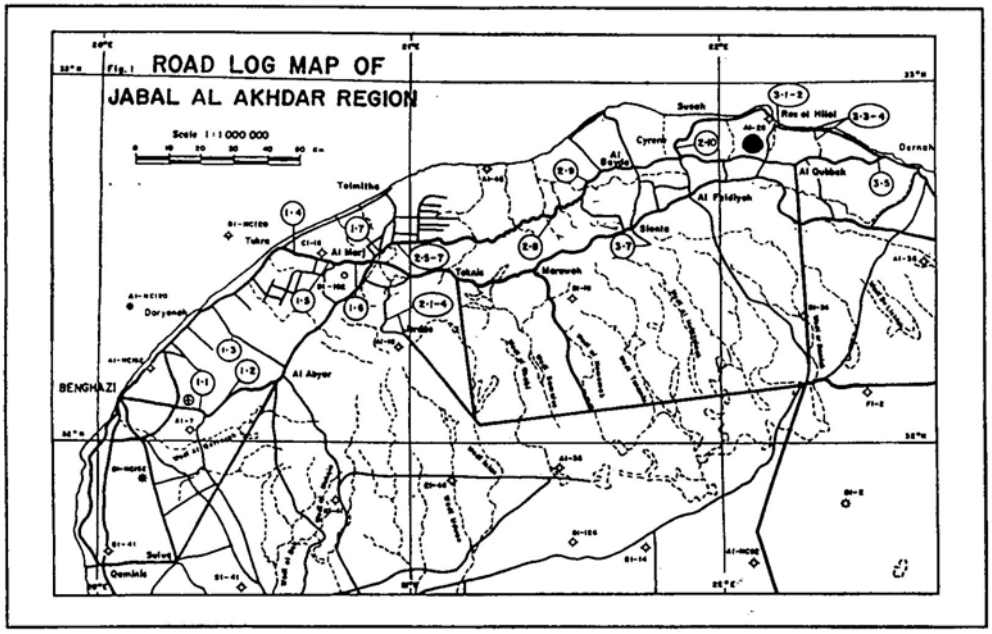


Fig (1) location map of Stuah spring

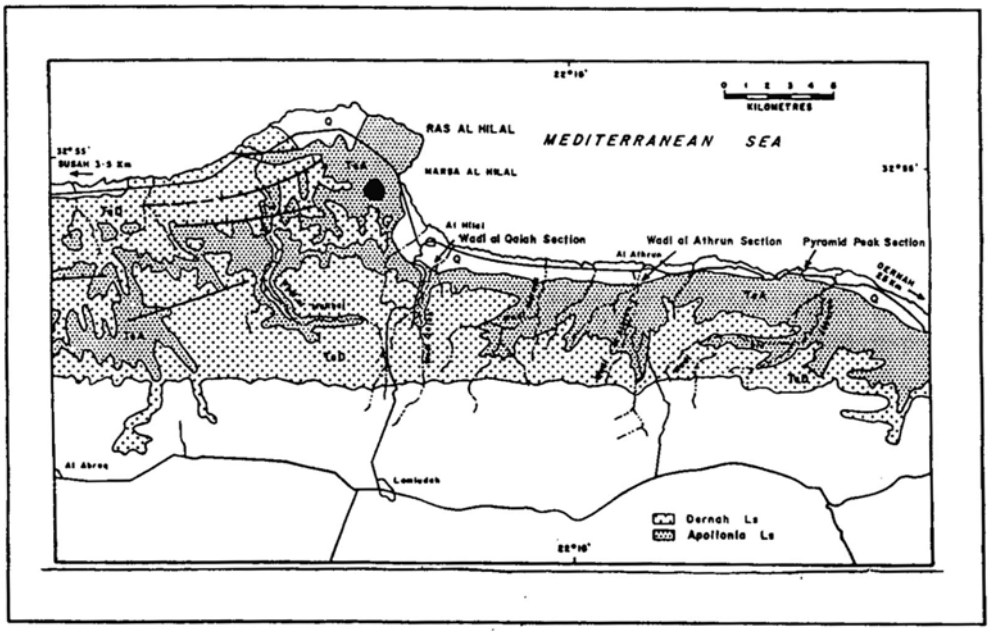
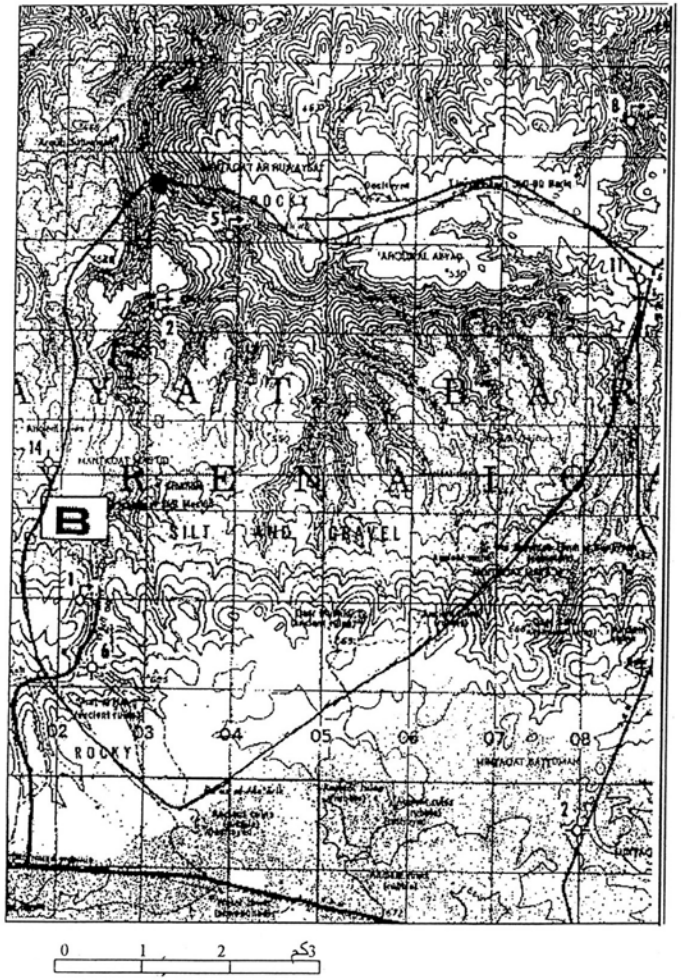
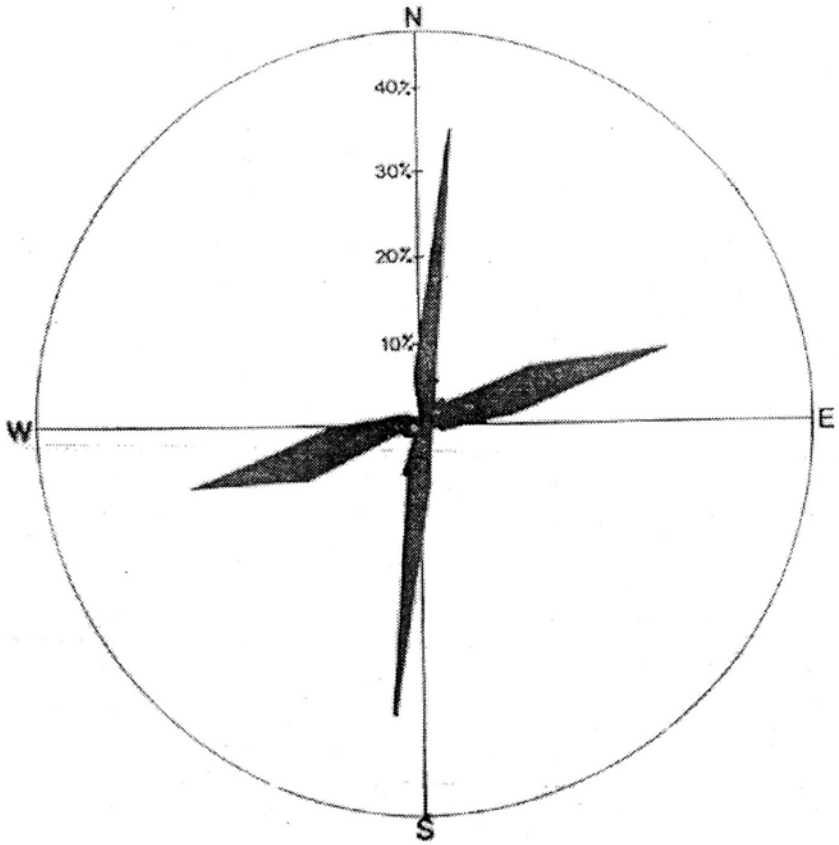


Fig (2) distribution of the Eocene rocks at study area after Rolich,(1974)



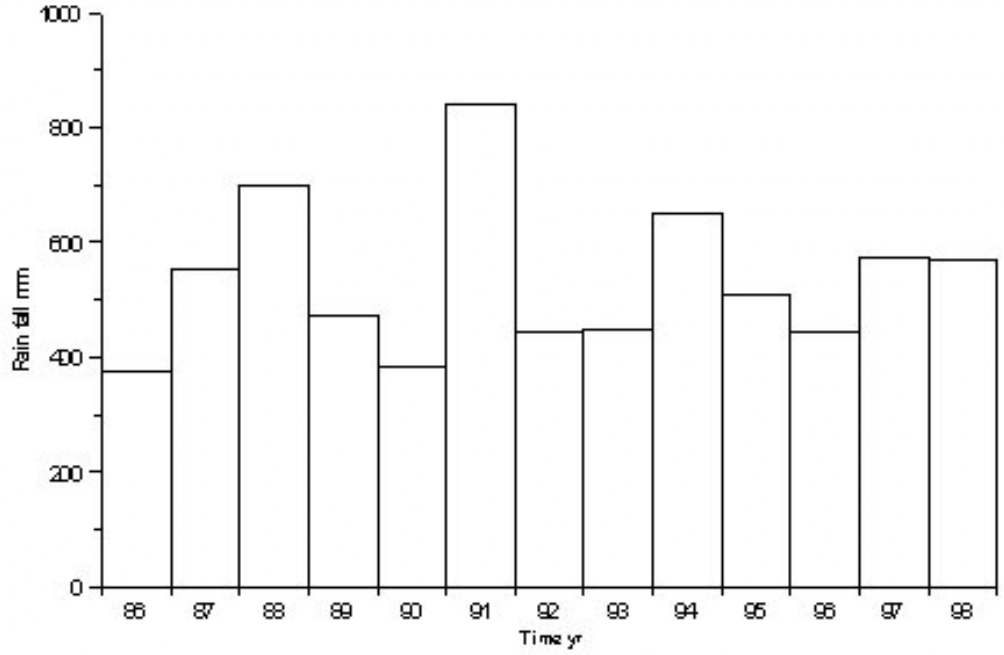
شكل (3) يبين حدود الحوض الصباب لعين استوة بشمال شرق الجبل الاخضر

Figure 3: Boundary of the catchment area for Stuah spring.



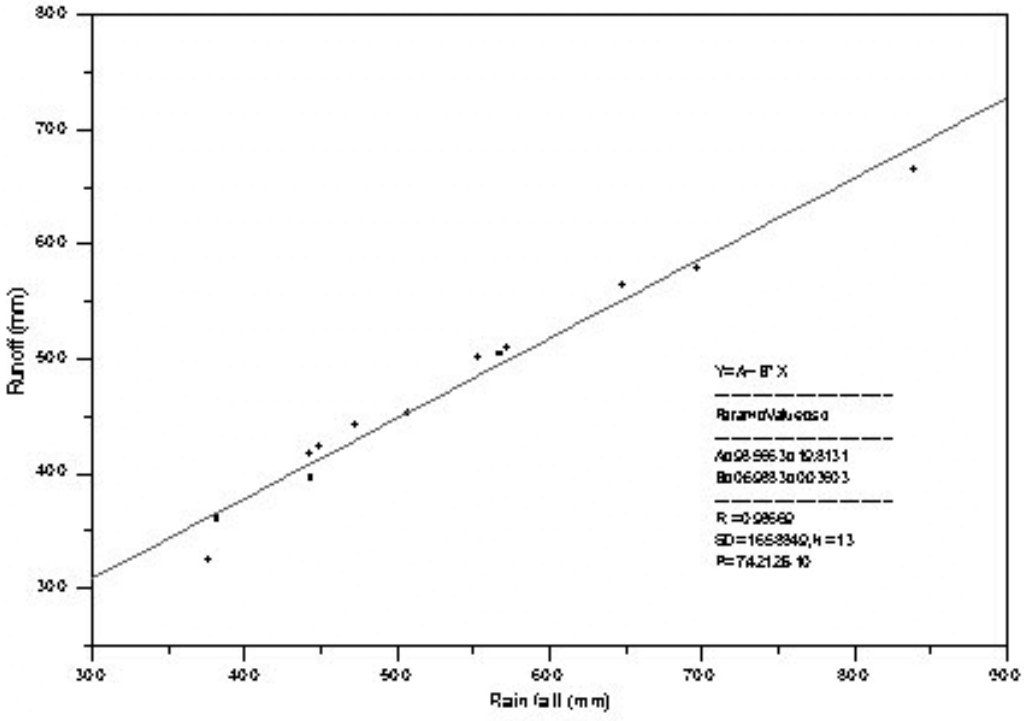
شكل (4) يبين اتجاه 200 فاصل مقاسة في منطقة الدراسة (Ammar, 1993)

Figure 4: Orientation of 200 joints measured at study area after Ammar (1993).

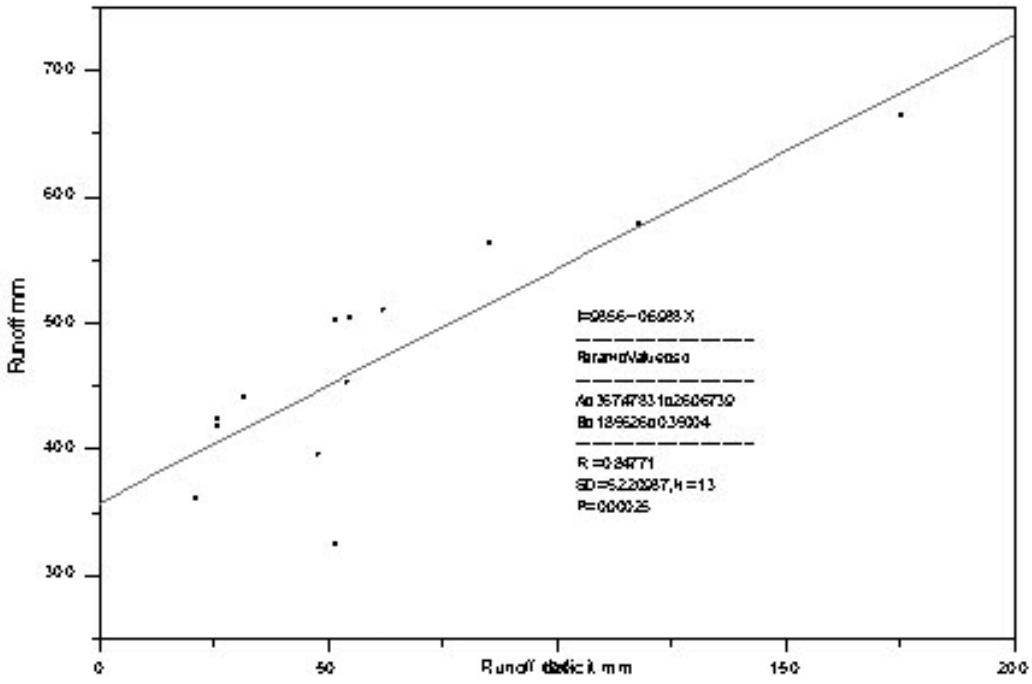


Time & Rainfall Relationship

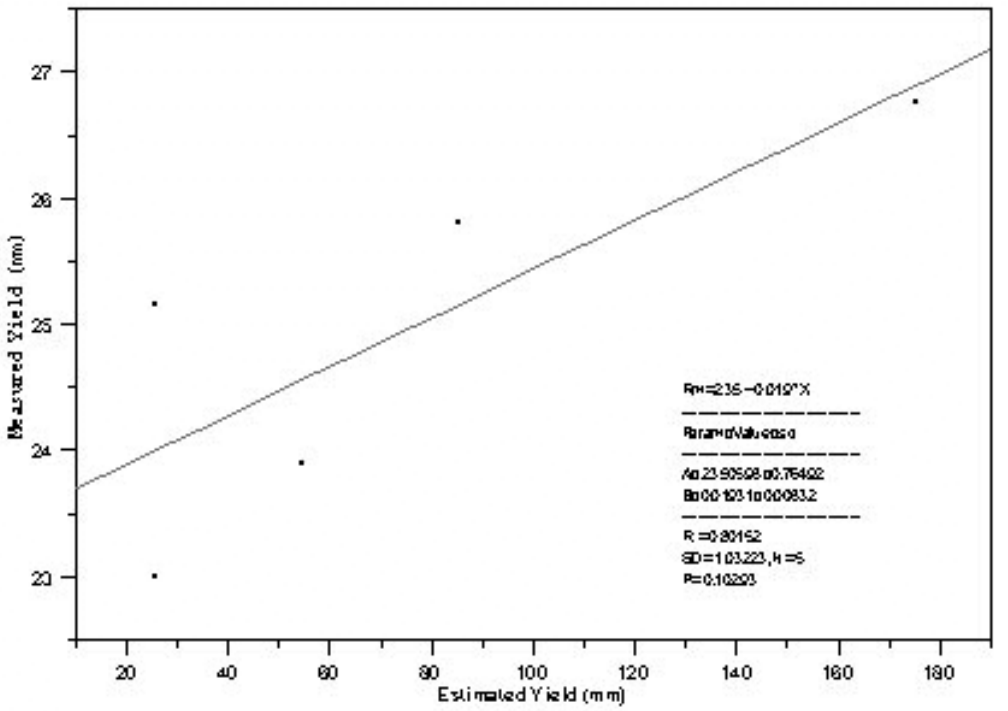
Figure 5



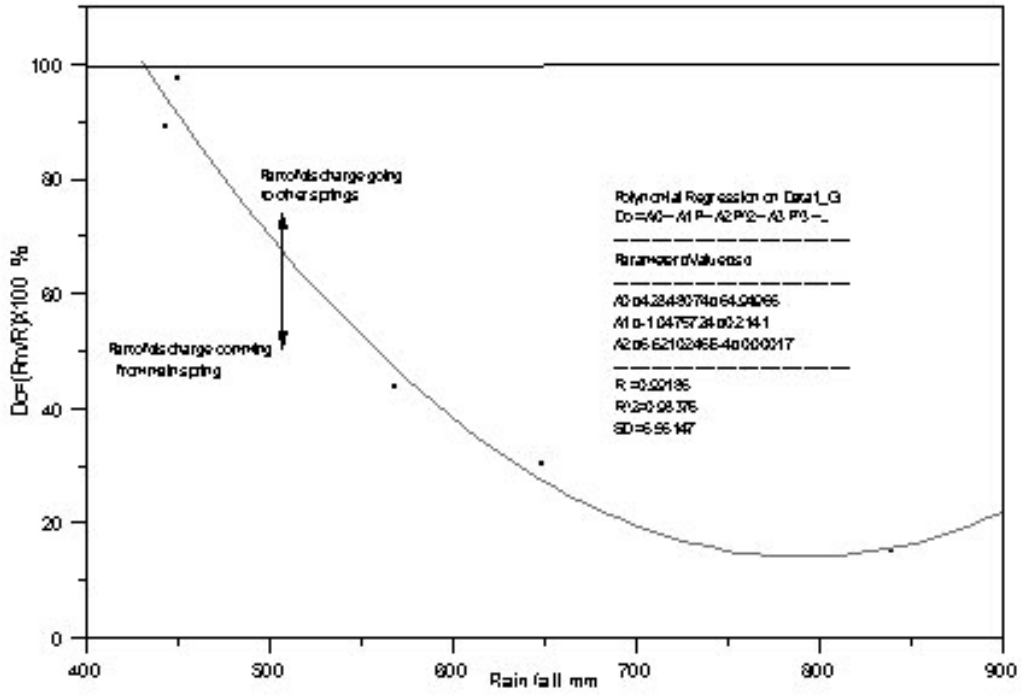
fig(6) Rainfall & Runoff relationship



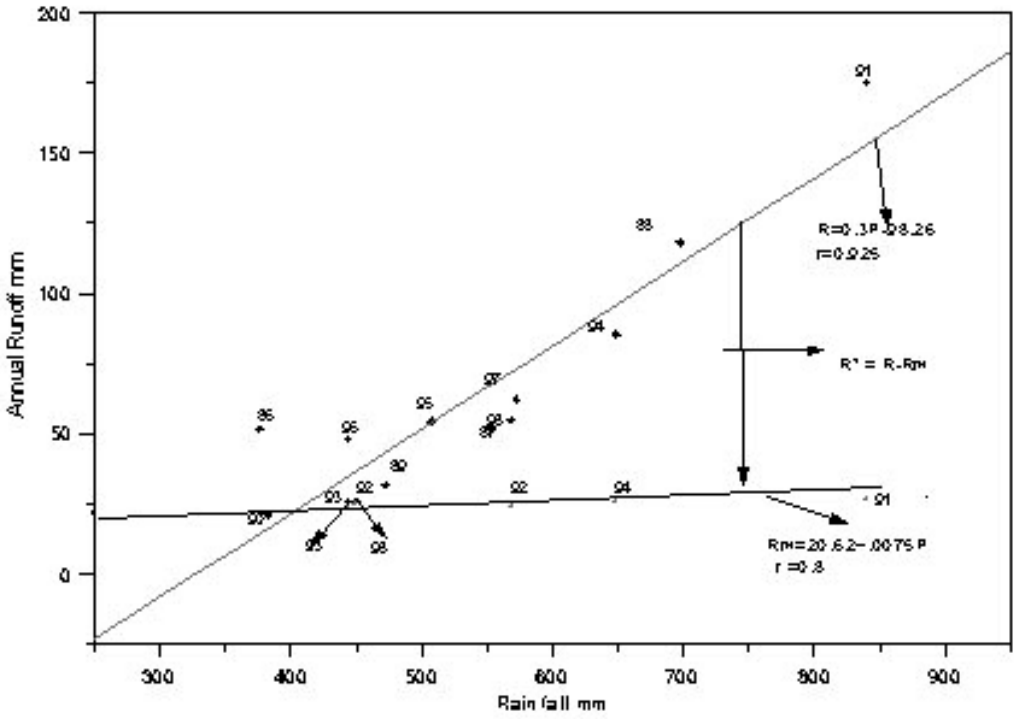
fig(7) Runoff deficit & runoff Relationship



fig(8) Estimated Yield & measured Yield Relationship



fig(9)contribution of the main spring to the other springs at zone



Fig(10) Annual rainfall &estimated and measuredyield realtionship

Year	Barrel method l/s	Stream jet method l/s
1991	28	26
1992	24	20
1993	26.3	22
1994	27	25
1998	25	23

Table 1: Measurement of Stuha Spring

year	Temperature C⁻	Rain fall mm	Runoff deficit mm	Runoff mm
86	16.09	376.0	324.48	51.52
87	17.27	355.2	501.71	51.49
88	16.55	697.1	579.01	118.09
89	16.80	472.3	441.67	31.63
90	16.84	382.2	361.05	21.15
91	17.50	839.4	664.24	175.16
92	16.40	443.2	417.51	25.69
93	16.67	449.8	424.09	25.71
94	17.43	648.6	563.34	85.26
95	15.24	507.5	453.13	54.37
96	16.66	443.8	395.84	47.96
97	16.26	572.7	510.47	62.23
98	16.47	567.9	504.16	54.74

Table 3: Values of estimated yield and infiltration according to Turc,1954

year	Estimated yield L/s	Measured yield L/s	Q_o= Rm/R X 100
86	13.16		
87	53.8		
88	123.5		
89	321.03		
90	13.35		
91	183.22	28	15.28
92	24.73	24	97
93	26.9	26.3	97.7
94	89.2	27	30.26
95	56.06		
96	25.41		
97	70.8		
98	57.26	25	43.66

Table 4: Relationship between measured and estimated yield

V. N. Bajpai, T. K. Saha Roy and S. K. Tandon

Hydrogeomorphic mapping on satellite images for deciphering regional aquifer distribution: case study from Luni river basin, Thar Desert, Rajasthan, India

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Abstract

Hydrogeomorphic mapping has been carried out using satellite images to understand the extent and distribution of aquifers in Luni river basin. Distinct hydrogeomorphic units identified on images are rocky tract, buried pediment, valley fill, flood pain, palaeochannels and dunal tract. These units have been found to control the extent and distribution of aquifer systems as evidenced on subsurface panel diagrams. While the concentric and linear patterns of aquifers are characteristic of pediments situated around ridges, linear pattern characterizes the extensive aquifer systems located along valley fills, flood plains and palaeochannels. Relatively less extensive aquifer systems have been found along major interdunal depressions. Analysis of panel diagrams in different directions indicates that the directional continuity of aquifers is maximum along NE-SW followed by E-W and NW-SE. It is interesting to find that these directions coincide with the extensive buried pediment – valley fill contacts formed by major tectonic lineaments.

1. Introduction

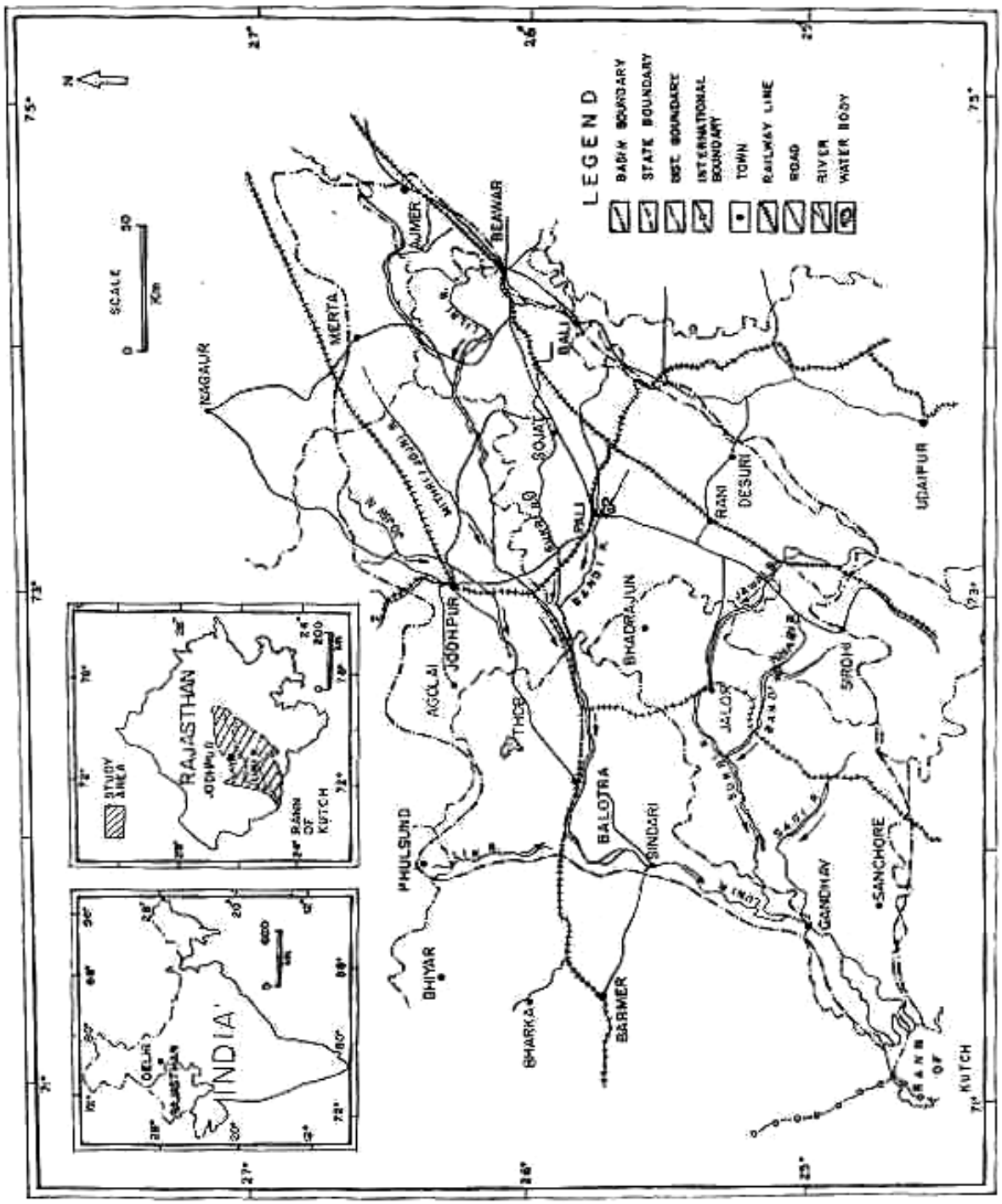
Luni river basin, located in the semi-arid zone of Thar desert in western Rajasthan (Figure 1) has distinct morphological variations ranging from high extensive ridges of hard rocks in the east to the vast alluvial plain blanketed by sand dunes and dotted with hills in the west. Deposition in the basin has taken place on an uneven basement and is the net result of the streams supplying material of all size grades, typical of arid / semi-arid zone, and the active tectonic conditions operating along major lineaments.

The basin is well known for its major Luni-Sukri lineament (Dhir et al., 1992) and seismic activity along the same (Ramasamy et al., 1991). Several graben structures filled with sediments are found coincident with the major tectonic lineaments in the basin (Bajpai et al., ms.). Lineaments have also influenced considerably the morphological processes and continue to exercise control on the present day channel behaviour (Kar, 1992, 1994).

Aquifer distribution being related to the zones of sediment accumulation, therefore requires to be understood in terms of the regional variations in the morphology and the prominent lineaments within the basin. Despite an extensive work carried out by scientists of Central Arid Zone Research Institute, Rajasthan on the part of morphology and lineaments in different parts of the basin (Singh 1977; Shankarnarayan and Kar, 1983, Kar 1994) no work is available in particular showing the relationship of aquifer geometry with the morphologic setting. Present work has been undertaken to have a clear understanding of the situation.

Geologically, the basin has the rocks of the Aravalli and Delhi Supergroups (Precambrian) along its eastern boundary, rocks of Malani Igneous Suite (Post Delhi: Precambrian) right from the north to the south, and rocks of Marwar Supergroup (Cambrian) in the northeast. The western and central part of the basin is occupied by desert sand, which overlies the Quaternary alluvium (Taylor et al., 1955; G.S.I. 1976; Gupta et al., 1980; Pareek 1981 and 1984, Dasgupta et al., 1993).

In the present work, hydrogeomorphic mapping has been carried out using satellite images to understand the major variations in morphology all over the basin, aquifer panel diagram has been prepared in a part of the basin to show the relationship of aquifer geometry with morphologic units, and the hydrogeologic sections are plotted to show the influence of major lineaments on the aquifer distribution. The panel diagram and the hydrogeologic sections are based on tubewell lithologs obtained from Ground Water Department, Rajasthan.



2. Hydrogeomorphic map

Hydrogeomorphic map has been prepared by using band 5 and band 7 of Landsat 1 and 2 images (acquired on October 30, 1972; January 9, 1973; December 29, 1976; January 15, 1977; and January 16, 1977). Selected areas have been mapped on IRS 1B-LISS 1 FCC images (acquired on February 4, 6 and 27, 1997) due to better contrast and clarity of features on them. The map showing major morphologic and lithologic units has been presented in Figure 2. As indicated on the map, the basin has been classified into following distinct hydrogeomorphic units (morphological units of hydrologic significance).

1. Rocky tracts
2. Buried pediments

3. Valley fills
4. Flood plains
5. Palaeochannels
6. Dunal tracts

2.1 Rocky tracts

Rocky tracts consist of hard rock ridges with alluvium in interridge areas. It is represented by granites in the southeastern and the central part, rhyolite in the northern, western and central part, quartzites in the northeastern part and the limestone and sandstone in the northern part of the basin. On imageries, the large patches and straight to curved ridges of the Sendra-Ambaji granite (Delhi Supergroup) have been observed near Sendra (Location 3, Figure 2 and location 5, Figure 4) and in Karan-Sadri region (Location 23 - 28, Figure 2), and of the Erinpura granite (Malani Igneous Suite) in the region to the west of Bera (Location 7, Figure 2) and to the northeast of Sirohi (Location 8, Figure 2) located in the southeastern part of the basin. Ridges of granite and gneiss of Delhi supergroup are found widely distributed in Desuri-Phulad-Sendra region (Location S 6-5-3, Figure 2 and Locations H and S, Figure 4). Massive, curvilinear and dissected ridges of Malani granite are also recognised on images to the south of Siwana (Location 13. Figure 2 and location R, Figure 3) and near Jalor (Location 11, Figure 2). Typical pinkish brown colour on FCC images, curvilinear to oval ridges with pincer type drainage and water bodies in the peripheral region of hills facilitate mapping. Rounded to oval and dark brown patches formed by curved and dissected ridges of Malani rhyolite (Locations RH, Figure 2) appear distinct on FCC images near Jodhpur (Location 17, Figure 2) and near Siwana (Location 13, Figure 2). Dark gray, curved and dissected ridges of rhyolite also appear distinct near Siwana on Landsat imagery (Location S, Figure 3). Straight to curved ridges of rhyolite with no preferred orientation are also observed at Bhadrajun (Location 14, Figure 2) and to its northeast towards Pali (Location 16, Figure 2) and to its southeast to the north of Sirohi (Location 8, Figure 2) and to the south of Bhinmal (Location 10, Figure 2).

Straight to curved and extensive ridges of quartzites of Delhi Supergroup have been observed on imageries right from the southeast of Sendra (Location 3, Figure 2) to the north of Ajmer (Location A, Figure 4) in Ajmer-Rir region (Location 1-25, Figure 2), extending to the northeastern boundary of the basin. The ridges appear more straight and continuous than that of granite and are in sharp contrast to their surrounding alluvium.

In general, the aquifer system in the rocky tract is located within the shallow alluvium filled in interridge areas, in the vicinity of fracture controlled bed rock channels, and within the fractured and weathered zone. Ridges also act as inhibitors of runoff and favour location of water bodies, providing recharge to the aquifers.

The depth zones of groundwater potential occur from 3 to 42 m in Jalor granite, from 6 to 57 m in Siwana granite, and from 3 to 60 m in Malani rhyolite. The average discharge per well (worked out on the basis of approximate hours of irrigation per day) has been found as 15,000 lph for Jalor granite, 11,400 lph for Siwana granite, and 7,300 lph for Malani rhyolite (Chatterji, 1969).

The aquifer system in quartzite has been formed in weathered, jointed and fractured rock, and in interridge alluvium. The wells tapping quartzite are more productive than those in granite. The yield from open wells in quartzite of Ajmer region ranges from 40,000 lpd to 1 lakh lpd (Tiwari 1987). The water quality in quartzite is generally fresh. The aquifers in interridge alluvium consist of sand, gravel and boulders and exist to a maximum depth of about 50 m. The productive aquifers are located in the alluvium of the tributaries of the Luni river in the region to the west of Ajmer, where yields of the wells have been found as 36,360 lph and 54,480 lph for the drawdowns of 3 m and 5 m respectively (Tiwari, 1987).

Limestone of Marwar supergroup has been observed on Landsat images in Gotan-Pundlu-Bilara region (Locations L and 21-22-26, Figure 2 Location G and B, Figure 4). Limestone terrain has been identified on Landsat images by its characteristic bedding and joint-controlled parallel drainages, irregular hummocky and rectangular to rounded blocks of light gray tone, longer main drainage connected with several parallel drainages from either side and discontinued drainage connected to sink holes (Locations T and S, Figure 4). Dark gray tone on band 5 due to vegetation along dry channels and in sink holes has facilitated mapping. Limestone in the region is dolomitic with alternate bands of siliceous and dolomitic limestone, and is highly folded and fractured. The thickness of limestone in the Bilara-Pundlu region ranges from 5 m to around 100 m. Being cavernous by nature, it contains a high aquifer potential. Sustained discharge of 400 klph corresponding to a drawdown of only 0.5 m has been reported by Central Ground Water Board, Rajasthan from a well of 10 m diameter in limestone at Borunda (10 km south of Pundlu). The yield from wells in limestone varies from 30 m^3/day to 900 m^3/day and the transmissivity of the aquifer is estimated as 2267.37 m^2/day (Henry and Mathur, 1994).

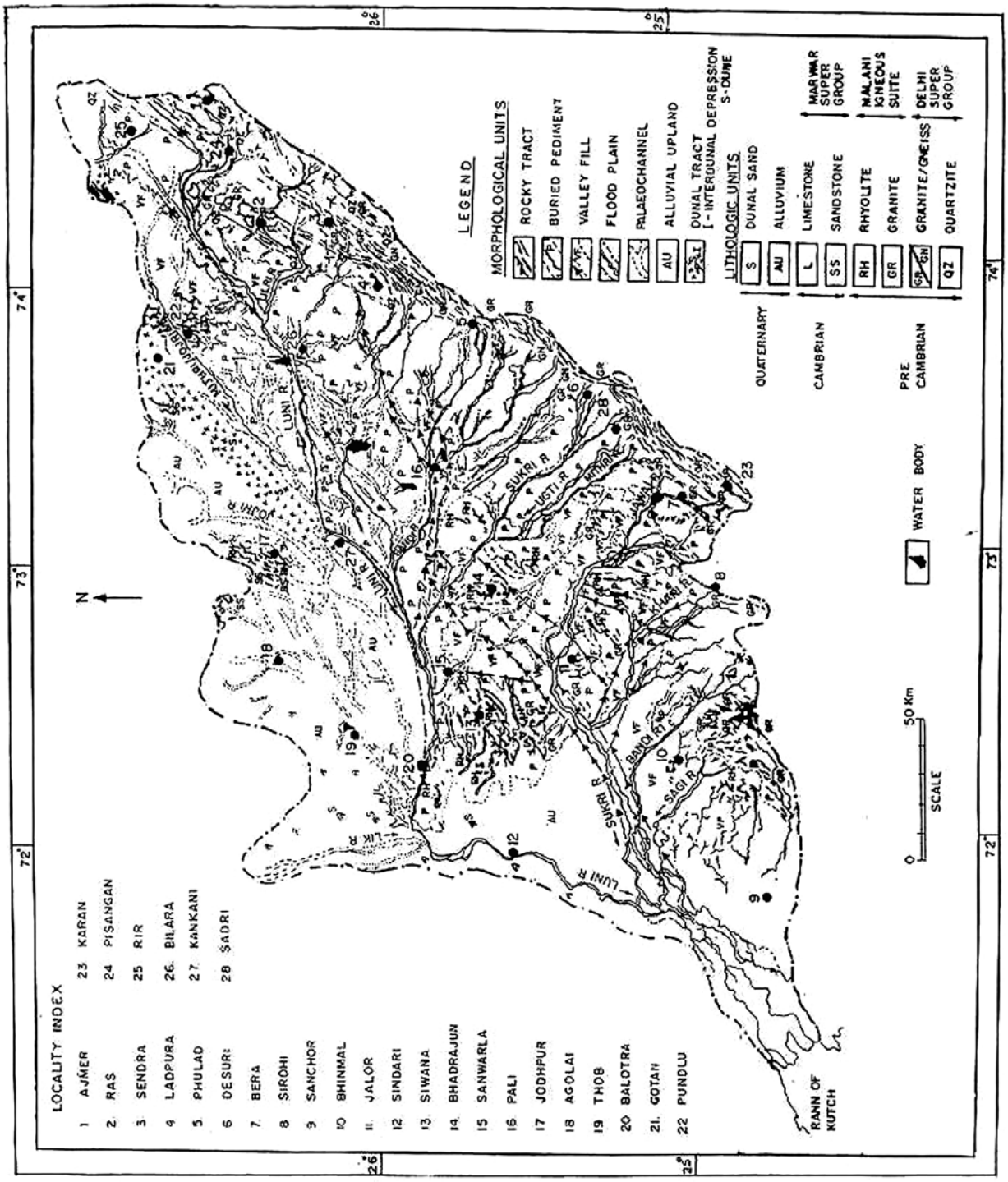


FIG 2. HYDROGEOMORPHIC MAP OF THE LUNI RIVER BASIN PREPARED BY USING SATELLITE IMAGES

Sandstones belonging to Marwar supergroup occur to the west and north of Jodhpur (Locations Ss and 17, Figure 2) and are identified on images as straight and extensive ridges and rectangular joint-controlled blocks with escarpments. Drainage is limited and follows rectangular pattern. They also occur as cappings on Malani rhyolite. The thickness of sandstone in Jodhpur region varies from about 40 m to 80 m and at places even more than 300 m. Sandstone is also intercalated with bands of shale and limestone. Zones formed by intersections of joint patterns are the sites of channel fills and promising aquifers. The aquifers in sandstone are highly productive and are semiconfined to confined in nature. The yield of the wells varies from 10m^3/day to 350 m^3/day. The transmissivity of aquifer varies from about 8.5 m^2/day to 1363.5 m^2/day and storativity ranges from 2.33 x 10^{-4} to 4.95 x 10^{-4} (Henry and Mathur, 1994).

2.2 Buried pediments

Buried pediments (Location P, Figure 2) are located in the peripheral regions of rocky ridges. These are basically the inclined rocky surfaces as extensions of ridges over which the alluvium and aeolian sand have been deposited. While extensive pediments all along the foot hill region are observed close to the eastern boundary of the basin, the same of circular to oval and elongated shapes are commonly distributed right from the southern part to the northern part of the basin. The boundary pattern of the pediments varies according to the running behaviour of ridges. The pediments of different ridges also appear as fused together. On IRS FCC images, the pediments are identified by their light greenish white tone in contrast to dark gray ridges on one side and dark greenish blue valley fill on the other. Several oval and elongated pediments of light gray tone are observed on Landsat images around ridges of granite situated to the south of Bhinmal (Location 10, Figure 2), north of Bera (Location 7, Figure 2) between Jawai and Ugti rivers, and to the south of Siwana (Location 13, Figure 2). Similar pattern has also been found around rhyolite ridges near Siwana and Bhadrajun (Locations 13 and 14, Figure 2). The pediment regions appear more distinct on band 5 imagery (Location P, Figs. 3 and 4) as compared to that on band 7 due to more contrast from dark gray ridges and valley fills.

The pediment material mostly consists of fine to coarse sand, gravel and rock fragments deposited by streams emanating from ridges. Many streams while flowing over the pediment disappear and disorganize due to limited amount of water and greater infiltration into the coarse granular material. At places, streams have also cut the pediment material exposing bed rock (Location 13, Figure 2). The thickness of pediment material increases to a maximum of around 30 m. In general, a good aquifer system has been formed in pediment zone and gets recharged by the streams from the rocky tract. The groundwater quality is normally good in pediment zone.

2.3 Valley fills

Valley fill zones are located adjacent to pediments. They are found mostly between the pediments and vary in shape and extent. Wherever, the pediments are of regional extent and are separated by major lineaments, wide and extensive valley fills are formed within the faulted grabens. These are indicated by dark arrows (Figure 2) and occupy the major lineaments of Luni-Sukri group with NE-SW trend and others with E-W trend. Minor and narrow valley fills are located along the dissected pediments. The valley fill zones are mostly occupied by major or minor streams. The streams show braiding, fanning, disorganization and disappearance in valley fill zones while flowing across them. They have been demarcated on the basis of their dark greenish blue colour on IRS FCC images and by dark gray tone on band 5 of Landsat imagery (Location V, Figs. 3 and 4).

The valley fill material consists of thick multistoried bodies of fine to coarse sand and gravel with rock fragments, separated by clay and kankar layers. The sand bodies show fining upwards. The thickness of alluvial fill ranges from 30 m to 300 m., the maximum being near Sanchore (Location 9, Figure 2) in the southwestern part of the basin. Productive aquifers are formed in the sand and gravel sequences, however, problem of groundwater salinity has been found associated with the deep valley fills.

2.4 Flood plains

Flood plains areas are situated on either side of the rivers. In most of the part of the basin, they are represented by the dry stream beds. The major flood plain areas have been mapped on satellite images along the main courses of Luni and Sukri-Jawai rivers (Location F, Figure 3) and the minor ones along the Mithri, Lilri, Khari, Bandi and Sukri rivers (Figure 2). While the dry sandy beds appear white on band 5 images and FCC, the moist areas with vegetation appear dark gray on band 5 images (Locations F, Figs. 3 and 4) and pinkish red on FCC. The flood plain areas also coincide with valley fills along the southwesterly courses of Jawai-Sukri river and Luni river along the Luni-Sukri lineament zone. In fact, the water of upper Luni used to discharge to Sukri river along this lineament passing through the west of Bilara and Jalor (Locations 26 and 11, Figure 2). A palaeodrainage and discharge of flood water of Luni along this NE-SW trending zone has been observed (Kar, 1999). The flood plain along the Luni river in Balotra-Kankani region (Location 20-27, Figure 2) also appears to be an active lineament controlled zone in which flood-disasters are also reported. Flood plain areas have high potential of groundwater, however, only shallow water bearing zone must be tapped to avoid saline water, as salinity increases with depth. Moreover, the areas near the confluences need to be particularly avoided as these are the locations of heavy silt depositions leading to hydraulic discontinuity with the main streams and thus promoting the salt concentration. Several such areas along the Luni, Jawai-Sukri and Khari rivers have been investigated for their high salt concentrations (Ghose, 1964).

2.5 Palaeochannels

These represent the former stream courses along which water may flow for a short distance during rainy season making the internal drainage. Such channels on the surface are almost disconnected with the main streams. The extent of channel continuity has been traced on band 5 and band 7 of Landsat imagery by their typical light gray to white tone for the dry part and dark gray tone for the part with moisture and vegetation. On false colour composites, the dry sections are indicated by their white to light greenish tone and the moist and vegetated sections by pinkish red tone. Several such channels have been mapped along the tributaries of Jawai-Sukri and Luni rivers in the eastern part of the basin.

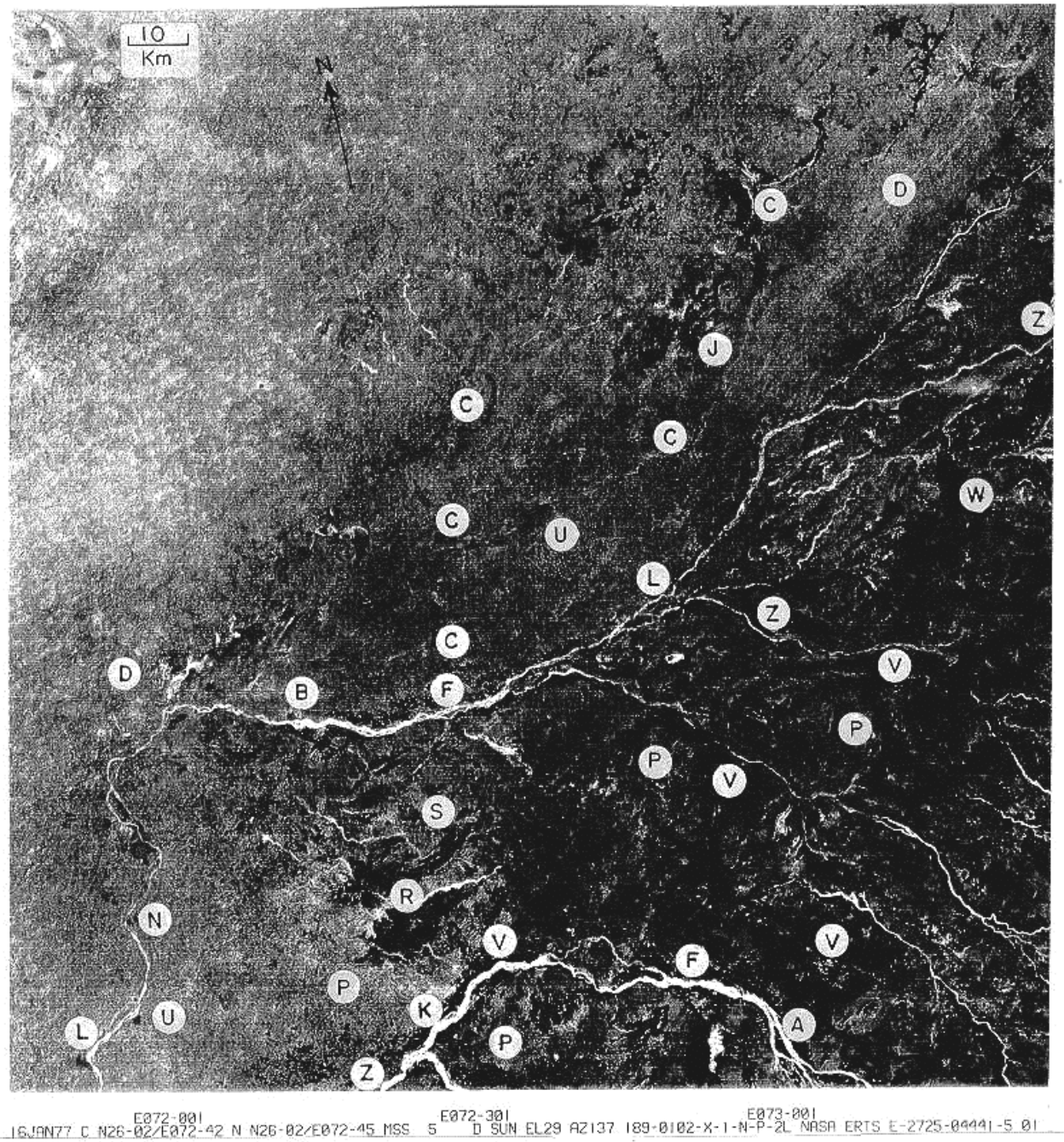


FIG. 3. Landsat MSS 5 imagery of a part of the Luni river basin showing rocky tract (R), pediment (P), valley fill (V), flood plain (F), palaeochannels of Jojri river system (C), alluvial upland (U), dunal tract (D), and Luni-Sukri lineament zone (Z-Z), J-Jodhpur, S-Siwana, N-Sindari, B-Balotra, L-Luni river, K-Sukri river, A-Jawai river, W-Water body.

It has been observed that in general the channels occupy the dissected pediments and get disorganised or extinct while reaching in valley fill zone. In the northern part of the basin these are represented by the former

tributaries of Mitrhi/Jojri river from its east (E and SW of Gotan, Location 21, Fig. 2) and (Locations G and C, Fig. 4) and by an extensive network of the Jojri river in the region from the NE of Jodhpur to the W of Balotra (Locations 17 and 20, Fig. 2 and Location C, Fig. 3). In the northwestern sector these are represented by the Lik river. The Lik river due to its bed heavily occupied by sand dunes in the past is almost extinct at present (Kar, 1988). The other abandoned channels of importance occur in the central part of the basin in the region from about 15km west of Bilara (Location 26, Fig. 2 and Locations B and C, Fig. 4) to about 15km northwest of Jalor (Location 11, Fig. 2). Through this sector upper Luni used to directly join the Sukri/Jawai river in the past (Kar, 1999).

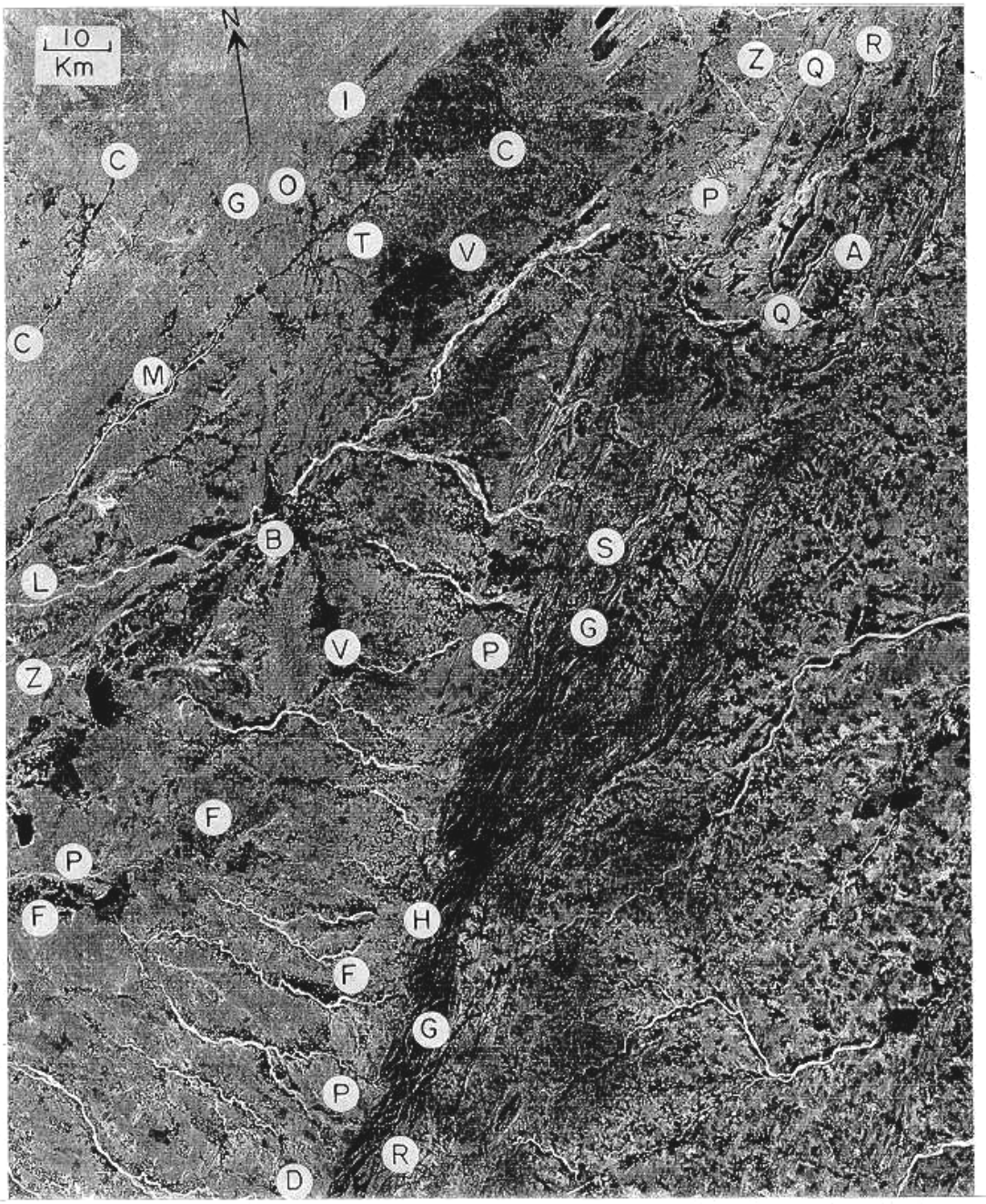


FIG. 4. Landsat MSS 5 imagery of the eastern part of the Luni river basin showing rocky tract (R), pediment (P), valley fill (V), interdunal depression (I), palaeochannels (C) and Luni-Sukri lineament zone (Z-Z). Limestone terrain (T) is visible with drainage connected sink holes (O). L-Luni river, M-Mithri river, Q-Quartzite, G-Granite, A-Ajmer, B-Bilara, G-Gotan, P-Pali, S-Sendra, D-Desuri, H-Phulad.

Extensive aquifer systems containing mostly fresh water have been formed along the palaeochannel belts. The fresh water occurrence is because of the regular flushing of the channels during rainy season. Still,

the water towards depth may be taken as brackish to saline. The promising aquifers in the channel belts of Jojri in Jodhpur district have been located by Remote Sensing Centre, Jodhpur and are being exploited for fresh water supply. The quality of water must be better in areas to the east of Jodhpur in the buried pediments of rhyolite and sandstone. The water reserves are also there in the northwestern part of the basin along the dry channels of Lik river and in the channels in the vicinity of Thob-Balotra region (Location 19-20, Figure 2). However, areas near the saline water depressions (ranns) formed at the junctions of the channels need to be excluded from exploitation due to saline water. The other promising channel belts, which can be exploited for fresh water exist to the east of Mithri / Jojri river in Jodhpur region, along the former course of the Luni river in the Pali-jalor region and in the area between the Mitri and Jawai rivers.

2.6 Alluvial uplands

These are distributed in the northern and western part of the basin in Jodhpur-Barmer-Jalor region. The vast flat uplands of older alluvium having regional slope towards the Luni river are formed by alternating thick sequences of clay, sand, gravel and pebbles deposited by the drainages operative in the past. The deposition has taken place into deep seated and extensive faulted-grabens represented by major lineaments: the Rabbasar – Baorli lineament passing through the area to the west of Agolai-Thob (Location 18-19, Figure 2) line in Jodhmer-Barmer region with roughly NE-SW trend and the Dugdava-Morsim lineament (Bajpai et al., ms.) traversing from the south of the Jawai-Sukri river to the southern border of the basin in the region to the east of Sanchore (Location 9, Figure 2). The influence of the Lik river appears to be prominent in deposition of coarse grained gritty gravels, indicated by southward palacocurrent directions in cross-bedded gravels near Sindari (Location 12, Figure 2) and in the region to its north. The thickness of fluvial sediments range from around 40 m in the northwestern part to more than 300 m in the southwestern part of the basin. The alluvial uplands are covered extensively by sand sheets and sand dunes, and are also dotted with salt water depressions (ranns).

The alluvial uplands are identified on the Landsat images by their typical moderately gray tone covered with NE-SW trending linear pattern of sand dunes of light gray to white tone (Location U, Figure 3). The moderately gray tone is smooth and even in Jodhpur region as compared to that in Barmer region, where the abundance of sand dunes is visible. The alluvial uplands are formed in older alluvium, which consists of sand and gravel mixed with calcareous material and rock fragments. At several places it contains thick calcrete zone in the near surface. Productive aquifer system have been formed in sand and gravel sequences. The water potential zone occuring within the older alluvium to a depth of 45 m gives the average discharge per well of about 3400 lph (Chatterji 1969). However, the problem of saline water has haunted the deeper aquifers. Shallow aquifers distant from the salt water depressions and the rivers with saline water are the only alternative for fresh water.

2.7 Dunal tract

This tract consisting of sand sheets, sand dunes and interdunal depressions is mostly distributed in northern and northwestern parts of the basin. The sand dunes and sand sheets blanket the alluvial uplands, western parts of the rocky ridges and their pediments. In fact, the peripheries of the sloping pediments are distinct on satellite images due to their sand cover appearing with light tone. The sand dunes in general are abundant in the western part of the basin in Barmer district. They rise to heights ranging from about 5 m to more than 50 m. The maximum height of about 70 m has been found in the vicinity of Lik river bed. Scattered sand dune ridges of about 25 m height are present near Sindari (Location 12, Figure 2) on either side of the Luni river and further downstream. The sand dunes are of linear and parabolic type and are also partly covered with vegetation. They are recognised on Landsat images with their linear and discontinuous patches of white tone with intermittent interdunal depressions, which appear as moderately gray to dark gray due to vegetation and water bodies within them (Location D, Figure 3 and Location I, Figure 4). On false colour composites, the sand dunes can be observed distinctly by yellowish green colour and linear to parabolic boundaries. The interdunal areas also appear dotted with pinkish red vegetation and light blue to dark blue water bodies. An extensive tract of parallel and linear dunal ridges, has been mapped on images (Location D, Figure 3 and Location I, Figure 4) in the region extending from the west of Gotan (Location 21, Figure 2) to the north of Kankani (Location 27, Figure 2). The aquifer potential is limited in the dunal tract and is only expected in the interdunal depressions. However, the infiltration through the sandy tract provides a good amount of recharge to the underlying aquifers.

3. Aquifer panel diagram

The aquifer panel diagram (Figure 5) has been prepared showing aquifer geometry across a part of the basin representing different types of hydrogeomorphic units. On comparing this diagram with the hydrogeomorphic map (Figure 2), it has been found that the aquifers related to pediments follow a laterally pinching and concentric pattern. This is evident in the aquifers formed in sand and gravel to the N and W of Siwana (Location 13, Figure 2 and Sections 2-3 and 6-7, Figure 5). As mentioned earlier that the circular to oval pattern of pediments are formed around the ridges of rhyolite and granite near Siwana.

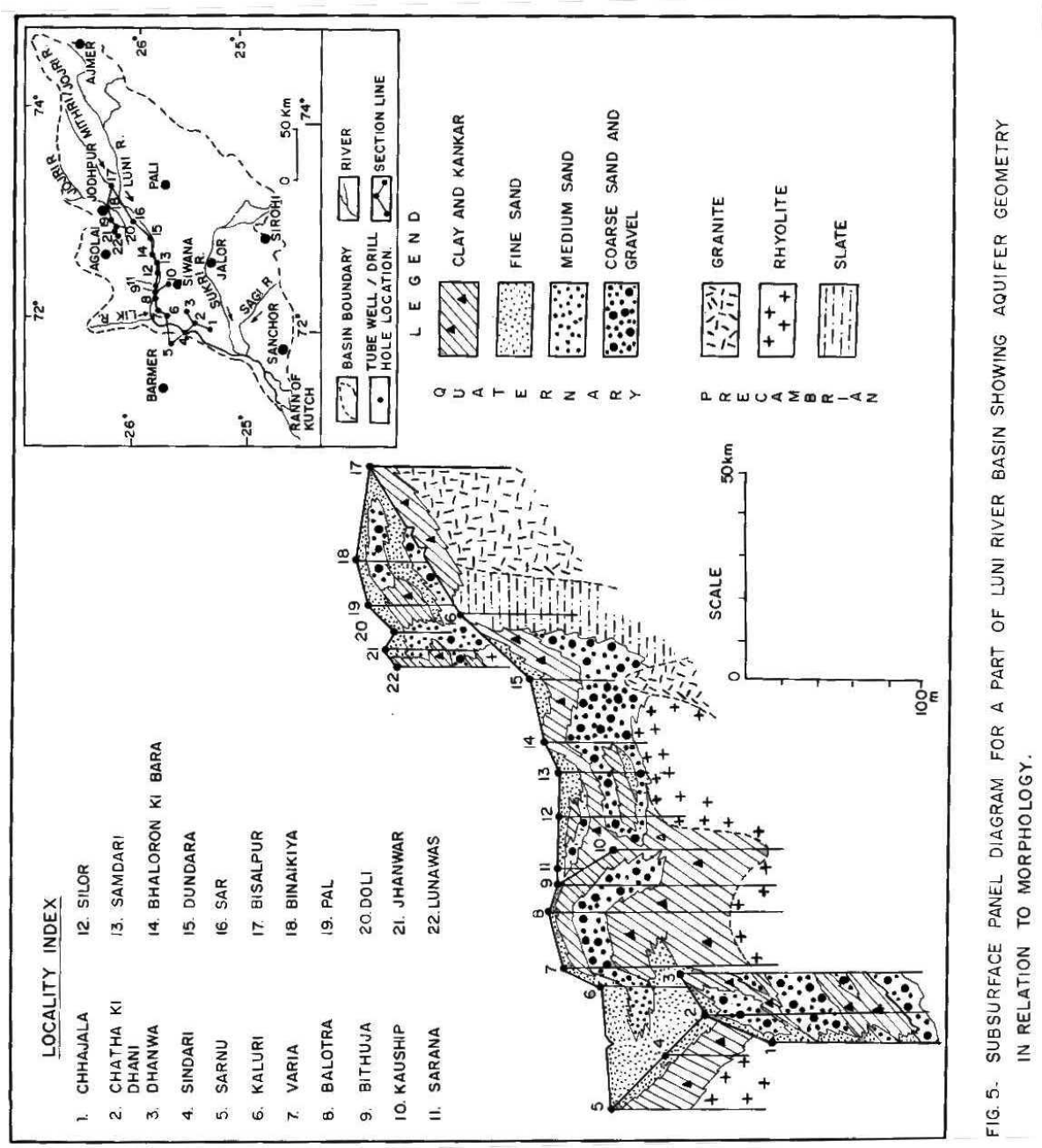


FIG. 5. SUBSURFACE PANEL DIAGRAM FOR A PART OF LUNI RIVER BASIN SHOWING AQUIFER GEOMETRY IN RELATION TO MORPHOLOGY.

Similar sand and gravel bodies are also disposed on pediments to the E and W of Jodhpur (Location 17, Figure 2 and Section 20-21-22, Figure 5). The sand bodies in general show fining upwards and in the distal region as well. Thick aquifers in the valley fill showing linear pattern are formed in multistoried sand and gravel bodies in Chhajala-Dhanwa region (selection 1-3, Figure 5). This region appears to be a wide valley fill (part of alluvial upland) located to the east of the Luni river passing through Sindari (Location 12, Figure 2 and Location 4, Figure 5) and extends to a depth of more than 150 m. The valley fill has been attributed to the intersections of major lineaments (faults), one along the NNE-SSW course of the Luni river and the other

passing through Sindari with roughly E-W trend (Bajpai et al., ms.). Extensive aquifers related to flood plain have been formed in the vicinity of Luni river in Balotra-Dundara region (Section 8-15, Figure 5). While the deep aquifers are thick and consist of coarse sand and gravel, the shallow aquifers are formed in fine to medium sand. The aquifers pinch out while being away from the flood plain as indicated by dominance of clay towards south of Bithuja (Section 9-10, Figure 5). The aquifers also show intersplitting by clay lenses.

Aquifers related to the palaeochannels of the Jojri river in Jodhpur region are indicated on the panel diagram (Section 17-22, Figure 5). These aquifers are formed basically along the dissected pediments and the buried pediment – valley fill contacts as indicated by the curvilinear channels of Jojri river to the east of Jodhpur (Location 17, Figure 2). The aquifers consist of coarse sand and gravel, and fine sand with rock fragments. The fine sand aquifer being shallow one extends to a depth of about 40 m and shows intersplitting by clay lenses. The deep aquifer in coarse sand and gravel extends from about 30 m to more that 60 m. The aquifer pinch out laterally showing the limits of channels. The aquifers in dunal sand are expected in Sarnu-Kaluri region (Section 5-6, Figure 5) and in interdunal depressions in Binaikiya – Bisalpur region (Section 17-18, Figure 5). Such aquifers are limited and are of perched nature, formed over the clay lenses.

4. Hydrogeologic sections

The sections are plotted along the Luni-Sukri Lineament zone in the northern part (Figure 6) and in the southern part (Figure 7) to understand the influence of Luni-Sukri lineament and the other lineaments passing through this zone on the aquifer disposition. The top lines in the sections indicate topography.

As evident from the section (Figure 6) the aquifer situation along the northern part of the lineament zone is not uniform due to interception by a number of subsurface ridges of granite and rhyolite. Two major sandy horizons appear in the section : one is of fine sand and the other is of coarse sand and gravel with rock fragments. While the fine sand horizon is continuous along the lineament zone and extends from the surface to a depth of about 10 m, the horizon of coarse sand and gravel disposed between 10 m and 30 m of depth is discontinuous. The discontinuity in the coarse sand layer is possibly due to the part of the section line (4-5-6-7-8, Figure 6) being deviated from the main zone. In fact, the deeper coarse sand and gravel layer is also extensive throughout the zone, however, its distribution is laterally narrower than that of the top fine sand layer. These continuous sand horizons basically show the connection of upper Luni to the Sukri in the past along Luni-Sukri lineament zone. The palaeodrainage analysis carried out earlier (Kar, 1999) also suggests the same. The promising aquifer formed in coarse sand and gravel thus follows the major Luni-Sukri lineament. Otherwise, the aquifers formed in the interridge areas in response to the minor lineaments (buried pediment – valley fill contacts) are of limited nature.

Hydrogeological section along the southern part of the Luni-Sukri lineament zone (Figure 7) indicates the disposition of thick and extensive aquifers formed in multistoried sand bodies. In this part, the Sukri river follows the lineament zone and captures the streams from the east. The other major lineaments (faults with downthrow towards south) with roughly E-W trend wherever intersect the Luni-Sukri lineament give rise to deep valley fills (Section 3-4-5 and 8-9, Figure 7). Besides, the major lineament with roughly N-S trend (Dugdava-Morsim lineament: Bajpai et al., ms) passing through the vicinity of Bijrol ka Golia (Location 2, Figure 7) has also intersected the Luni-Sukri lineament in this region resulting into deep valley fill extending to a depth of more than 300 m. The region is otherwise also well known for the intersection of major Jaisalmer – Barwani lineament and Luni-Sukri lineament at Jhab, located about 15 km NW of Bijrol ka Golia (Pal, 1991). Thus the increased channel activity together with the major sediment accumulation centre formed by intersections of major lineaments in this part of the basin has favoured the disposition of productive aquifers.

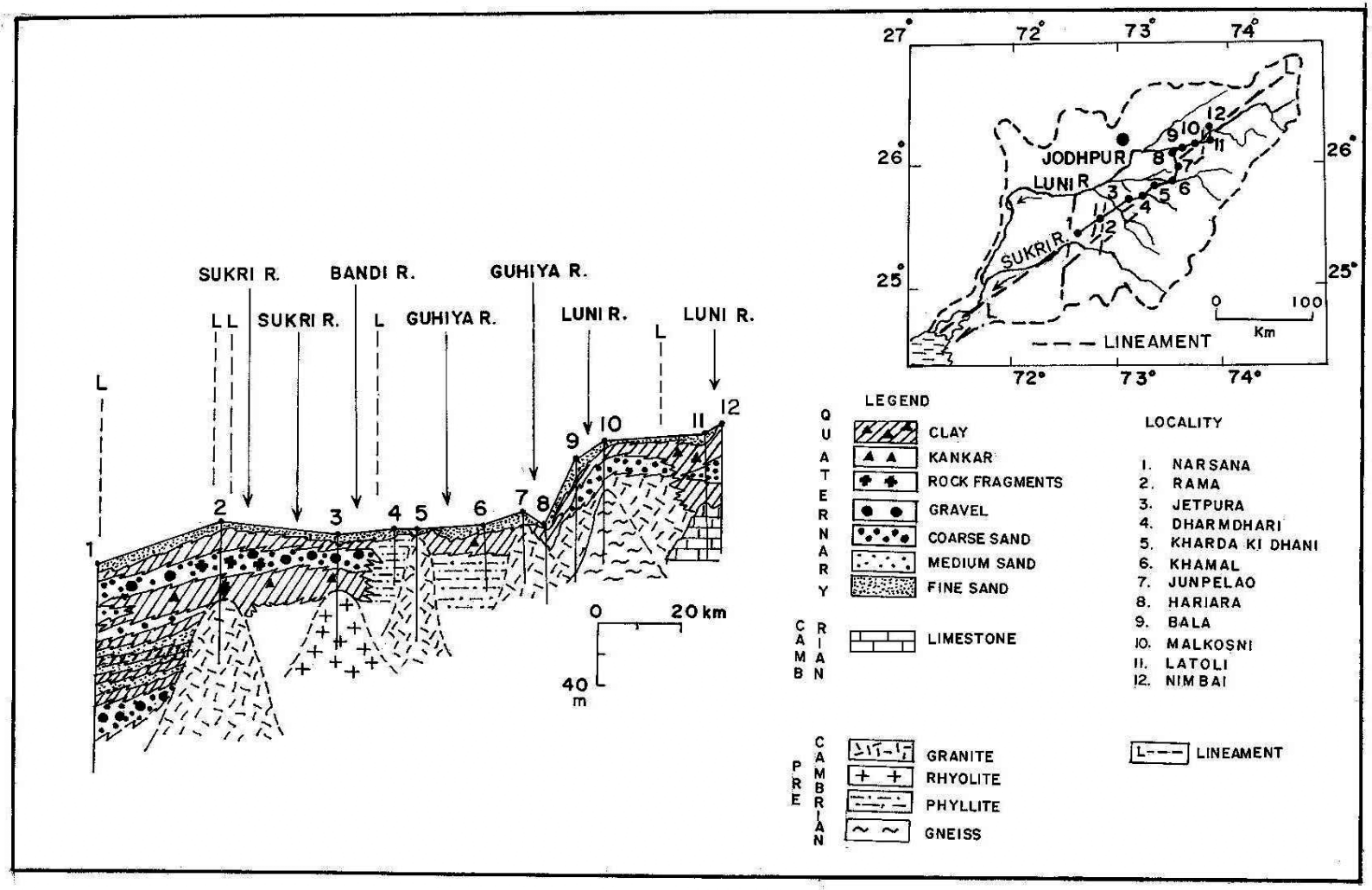


FIG.6. HYDROGEOLOGICAL SECTION ALONG LUNI – SUKRI LINEAMENT ZONE (L-L) SHOWING AQUIFER GEOMETRY (NORTHERN PART).

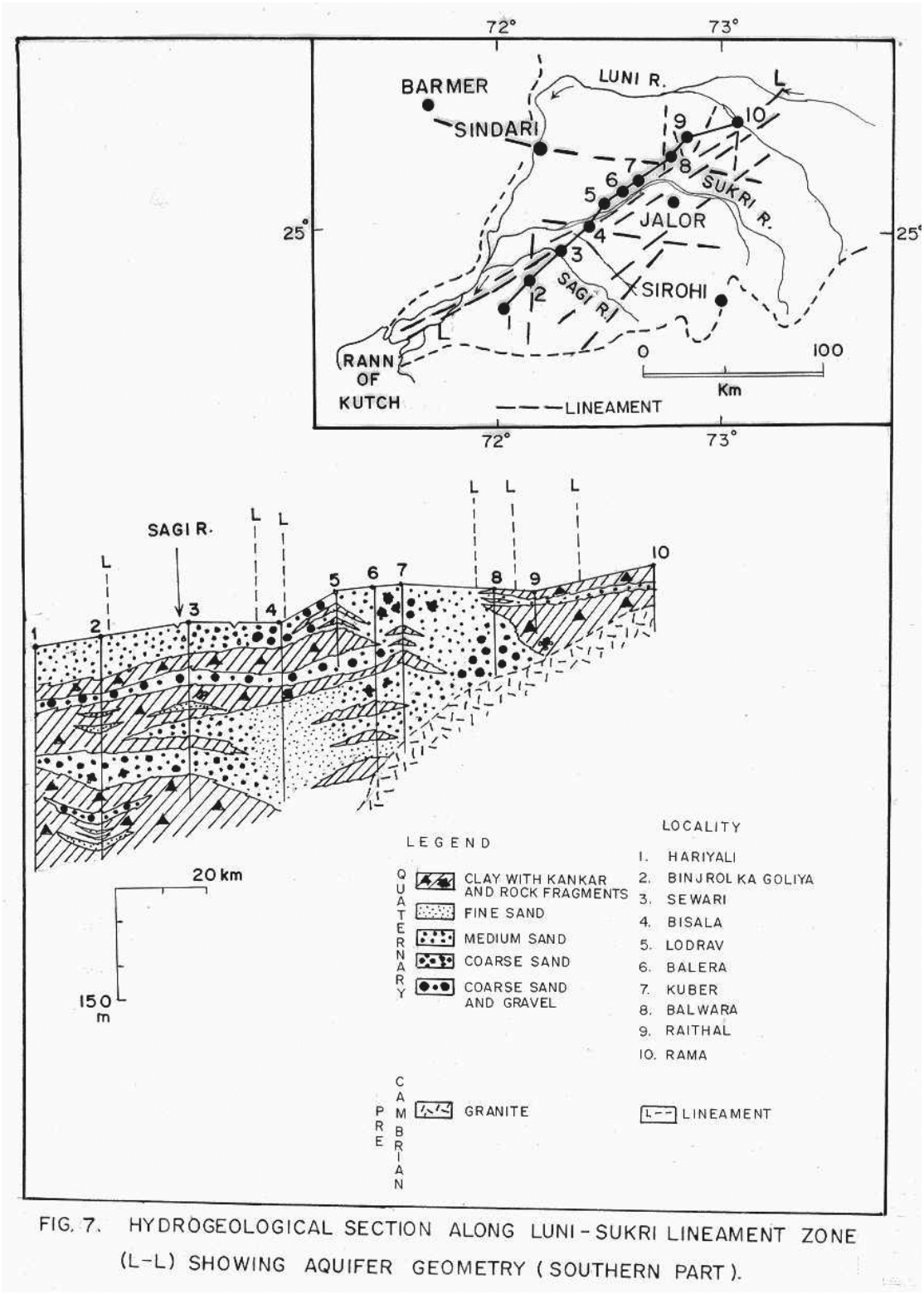


FIG. 7. HYDROGEOLOGICAL SECTION ALONG LUNI-SUKRI LINEAMENT ZONE (L–L) SHOWING AQUIFER GEOMETRY (SOUTHERN PART).

5. Conclusions

Following conclusions have been made in the present work:

1. Luni basin, an important geomorphic element in the Thar desert of India has distinct hydrogeomorphic units e.g. rocky tract, buried pediment, valley fill, flood plain, palaeochannels, and dunal tract. These units control the distribution of surface and subsurface water.
2. Subsurface panel diagram indicates that the disposition and pattern of the aquifers are in relation to the type and extent of hydrogemorphic units. Productive aquifers are found within the rocky tract in sandstones and limestone, in buried pediment, valley fill, flood plain and palaeochannels. Shallow aquifer system associated with buried pediments and palaeochannels can provide fresh water to a limited extent, otherwise water in deep valley fills and flood plain is mostly saline.
3. Productive aquifers are formed in the valley fills located along the NE-SW trending Luni-Sukri lineament zone. The aquifer potential is limited to the north of the Sukri river and increases along the Sukri river in the southern part of the lineament zone. The palaeochannel of the Luni river extending from the W of Bilara to the N of Jalor along this lineament zone is indicated by continuous layers of sand and gravel forming potential aquifers.
4. The NW-SE, N-S and E-W trending lineaments intersecting with Luni-Sukri lineament have progressively added to the thicknesses of sand bodies towards southwestern part of the basin forming extensive aquifer systems.
5. Pumping of fresh water without being mixed with saline water, exploitation of aquifers within the pediment region to avoid the flow of fresh water towards the aquifers of saline water in deep valley fill, and recharge to the palaeochannels are the essential practices required for an effective water management in the basin.

Acknowledgement

Authors are thankful for funding provided for the study under DST project ESS/CA/A3-08/92 to S.K. Tandon as Principal Investigator. Authors are also thankful to Dr. Amal Kar, CAZRI, Jodhpur for discussions and to Shri D.C. Sharma, Chief Hydrogeologist, Ground Water Department, Jodhpur for library consultation. Help given by Shri K.N. Kandwal, Sreeja. S. Nair and Priya Ranjan, Department of Geology, Delhi University in making diagrams is sincerely acknowledged.

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Habib Chaieb

Apport des modèles numériques à la planification des ressources en eau de la nappe du complexe terminal en Tunisie

(Mathematical models' contribution to the management of groundwater of the "Complex Terminal Aquifer" in Tunisia)

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Abstract

The "Complex Terminal Aquifer" is located in the Algerian-Tunisian Saharan area, extended to 350,000 km^2 and marked by their non-renewable water resources whose management was defined through mathematical models of simulation.

The first study was realised with analogical model (ERESS, 1972) and have come to the simulation models of the "Continental Intercalaire", the "Complex Terminal" and the "Djeffara" aquifers, which have been permitted the establishment of the exploitation programs of the groundwater in these large aquifer reservoirs.

The new hydro-geological information collected and the research works undertaking which permitted to give off new ideas about the hydraulic behaviour of these reservoirs, and the new economic conditions of the Saharian zones development, have required the focusing studies by the modelling of the Saharian aquifers and the re-actualisation of simulations, in order to achieve a better water resource management. So, in order to evaluate the hydrogeologic connection degree between the "Complex Terminal aquifer" of Nefzaoua and the surface aquifer levels, simulation models were realised in 1978 (Dh. Ben Salaih and J. Lessi), and showed that deep and phreatic aquifers were practically distinct except those near the Djerid Chott and at the peninsula of Kebili.

On the other hand, the data collected from realised wells since 1972, have put in question again the plausibility of the hypothesis formulated by the Water Resource Study of Northern Sahara (ERESS) and have led, in the framework of RAB/80/011 project, to the actualisation of the ERESS (1983), in order to reach a coherent politicy of water resources management for the distribution of drawings between different regions.

The actualisation of the "Complex Terminal model" (CT) have been taken up in 1984, so as to refine the computation with a variable stitch model integrating the Tunisian part of the reservoir of Nefzaoua-Djerid (Armines, ENIT), with more delicate stitching in the exploitation areas.

The recent simulations have been executed to analyse the piezometric effect of the future intensification of the drawings from the "Complex Terminal aquifer" in the Nefzaoua and in the Djerid regions, due to the creation of the new irrigated areas.

Résumé

La nappe du Complexe Terminal (CT) est localisée au Sahara Algéro-tunisien, elle s'étend sur une superficie de 350000 km^2 et est caractérisée par ses ressources en eau non renouvelables, dont la gestion et la planification ont été définies à travers les modèles mathématiques de simulations.

La première étude fût réalisée par modèle analogique (ERESS, 1972), et a abouti aux modèles de simulation des nappes du CI, du CT et de la Djeffara, qui ont permis l'établissement des programmes d'exploitation d'eau souterraine de ces grands réservoirs aquifères.

Les nouvelles informations hydrogéologiques recueillies et les travaux de recherches entrepris dans la région, ayant permis de dégager des idées nouvelles sur le comportement hydraulique de ces réservoirs, et les nouvelles conditions économiques du développement des zones sahariennes, ont nécessité la mise au point d'études par modèles des nappes du Sahara et la réactualisation des simulations, en vue d'une meilleure gestion des ressources en eau. Ainsi, dans le but d'évaluer le degré de liaison hydrogéologique entre l'aquifère du CT de Nefzaoua et les niveaux superficiels, un modèle de simulation a été réalisé en

1978 (Dh. BEN SALAH, J. LESSI), il a montré que les aquifères profonds et phréatiques sont pratiquement distincts sauf au voisinage du chott Djérid et dans la presqu'île de Kébili.

D'autre part, les données des forages réalisés depuis 1972, ont remis en cause la plausibilité de l'hypothèse formulée par l'ERESS et ont entraîné dans le cadre du projet RAB 80/011, à l'actualisation de l'ERESS en 1983, en vue d'une politique cohérente de gestion des ressources en eau pour la répartition des prélèvements entre les différentes régions.

L'actualisation du modèle du CT a été reprise en 1984, afin d'affiner les calculs, à l'aide d'un modèle à mailles variables, intégrant la partie tunisiennes du réservoir: Nefzaoua-Djérid (ARMINES–ENIT), avec un maillage plus fin dans les zones d'exploitation.

Les simulations les plus récentes ont été effectuées pour analyser l'effet sur la piézomètrie, d'une future intensification des prélèvements de la nappe du CT dans les régions de la Nefzaoua et du Djérid, due à la création de nouveaux périmètres irrigués (DGRE, 1997).

Mots clés :
Hydrogéologie, modèle mathématique, simulation, nappe, alimentation, exploitation.

1. Introduction

Les modèles mathématiques de simulation de nappes sont aujourd'hui des outils courants de gestion et de planification des ressources en eau. La bonne représentativité du modèle est liée à la qualité et à la masse d'informations disponibles sur les conditions aux limites et les paramètres hydrauliques du système aquifère. Lorsque les données manquent, la fiabilité de l'outil est amoindrie.

La mise au point d'un modèle nécessite la formulation d'un certain nombre d'hypothèses du fait de la dispersion et de l'hétérogénéité des données sur les réservoirs aquifères. Dans le but d'améliorer la représentativité du modèle, les études sont appelées à être réactualisées chaque fois que de nouvelles informations et données complémentaires sont disponibles.

Nous nous proposons dans la présente note d'exposer l'historique des différentes étapes et les objectifs de la modélisation de la nappe du Complexe Terminal.

2. Hydrogéologie

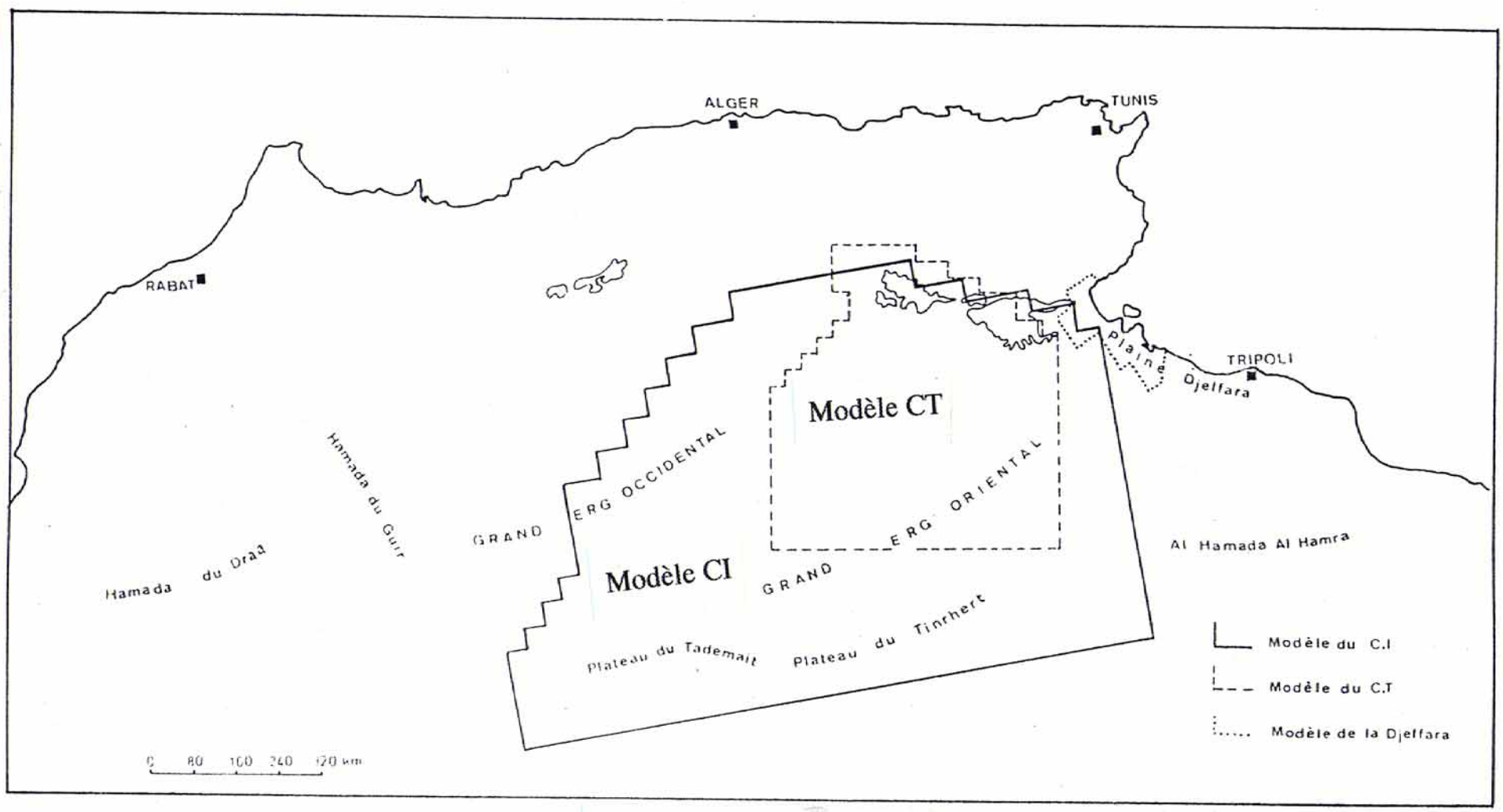
La nappe du Complexe Terminal est ainsi dénommée en raison de ses formations géologiques très diversifiées et hétérogènes qui se sont déposées au Bas-Sahara et dont l'âge va du Sénonien au Mio-Pliocène et qui constituent ainsi un complexe souvent interconnecté. Elle s'étend sur une superficie de 350000 km^2 dont une faible partie seulement se trouve en Tunisie où elle est représentée par deux entités: la Nefzaoua (aquifère calcaire du Sénonien) dont la profondeur moyenne est de 100 à 300 m et le Djérid (aquifère sableux du Pontien Inférieur) ayant une profondeur moyenne de 200 à 600 m.

La nappe du Complexe Terminal circule dans les formations carbonatées du Sénonien qui s'étend sur l'ensemble du bassin et de l'Eocène qui se situe au Nord et il est limité par la ligne Djamâa-Tozeur et les formations sableuses du Mio-Pliocène qui couvrent en discordance presque tout le domaine mais ils disparessent sur les bordures occidentale (M'Zab) et orientale (Dahar, Djebel Tébaga) du bassin.

Le remplissage du réservoir s'est fait pendant les périodes pluvieuses du Quaternaire. Actuellement la recharge de la nappe est assurée par l'infiltration des eaux de ruissellement en provenance des massifs montagneux : l'Atlas saharien, le M'Zab et le Dahar. L'écoulement général de cette grande nappe est de direction Sud-Nord, il converge vers les Chotts Melrhir en Algérie, Djérid et El Gharsa en Tunisie, qu'ils alimentent de bas en haut. Ces Chotts à sédimentation épaisse argilo-sableuse d'origine subsidente, constituent des machines à évaporation et sont considérés comme des exutoires de cette nappe. Les autres exutoires sont représentés par des sources importantes, autour des Chotts, comme les sources de Nefta (134 l/s, 1983) et de Tozeur (165 l/s, 1983) aujourd'hui en régression très importante à la suite de l'exploitation intensive de la nappe par forages artésiens ou pompés.

La salinité varie de 2,5 g/l dans le Djérid à 1,5 g/l dans la Nefzaoua, mais elle peut atteindre des valeurs plus élevées (4 g/l dans la presqu'île de Kébili, 8 g/l à El Hamma du Djérid).

L'exploitation est basée de plus en plus sur les forages artésiens ou pompés suivant les cas. On comptait en 1997, 216 sondages dans la Nefzaoua et 138 sondages au Djérid. Les prélèvements sont évalués à 14500 l/s.



CARTE DE SITUATION

3. Modélisation de la nappe du complexe terminal

3.1 Simulations ERESS (1972)

Le premier modèle mathématique du système aquifère du Complexe Terminal a été construit en 1972 dans le cadre du projet ERESS. Ce modèle a été subdivisé au départ en trois sous-modèles permettant de simuler le comportement de la nappe dans les régions de Ouergla, Oued Rhir en Algérie et de Nefzaoua-Djérid en Tunisie. Les opérations de calage ont nécessité la formulations de quelques hypothèses qui ont permit de surmonter les insuffisances enregistrées dues à la dispersion des informations et à la méconnaissance d'un certain nombre de paramètres structuraux de l'aquifère. Dans une seconde étape de cette étude, un modèle d'ensemble intégrant les résultats des trois sous-modèles, a été réalisé dans le but de simuler le comportement de toute la nappe. Les résultats obtenus des simulations ont servi pour orienter la politique de développement économique de la région dans les deux pays jusqu'en 1981. C'est ainsi que le plan directeur des eaux du Sud Tunisien (1975) s'est principalement référé aux résultats des simulations de l'ERESS.

3.2 Simulations DRES (1978)

Ce modèle qui intéresse la région de la Nefzaoua uniquement, a permis de simuler les incidences à moyen terme, d'une augmentation des débits d'exploitation dans cette partie de la nappe du Complexe Terminal. Il a déjà prévu que le comportement de la nappe devient préoccupant dès que l'exploitation serait portée à son maximum. Les risques d'une surexploitation de la nappe ne sont appréciés qu'au niveau des échanges avec l'aquifère superficiel. Les simulations prévisionnelles montrent aussi qu'une exploitation limitée à environ 4 m^3/s aurait des rabattements acceptables des niveaux piézométriques de cette nappe, même sous des hypothèses très pessimistes. D'autre part, ce modèle a permis d'évaluer le degré de liaison hydrogéologique entre l'aquifère du CT de Nefzaoua et les niveaux superficiels. Les simulations ont montré que les aquifères profonds et phréatiques sont pratiquement distincts sauf au voisinage du chott Djérid et dans la presqu'île de Kébili.

3.3 Simulations RAB 80/011 (1983)

Le modèle d'ensemble de la nappe du Complexe Terminal établi dans le cadre de l'ERESS a été actualisé en 1983 dans le cadre du projet RAB 80/011 (PNUD 1983) en reprenant la formulation des hypothèses des prélèvements futurs sur cette nappe et en tenant compte de son exploitation réelle entre 1971 et 1981, ainsi que sa réaction piézomètrique vis à vis des prélèvements. Au cours de cette étude, des simulations prévisionnelles basées sur de nouvelles hypothèses d'exploitation pour la période 1982-2010, ont été élaborées. Les résultats des simulations prises en compte devraient satisfaire aux critères suivants :

1. La réciprocité des effets des prélèvements additionnels d'un pays sur l'autre (Algérie et Tunisie).
2. La profondeur maximale de la surface piézomètrique ne doit pas dépasser en l'an 2010 la côte 60 m sous le niveau du sol (le Djérid en particulier) afin de garantir des conditions d'exploitation économiques acceptables et sans danger de salinisation de l'eau.
3. Limitation du niveau piézomètrique en 2010 dans la Nefzaoua, à l'altitude du Chott Djerid (22 m/NGM) afin d'éviter le renversement de l'écoulement entraînant la contamination de l'aquifère à partir des eaux salées du chott.

A la lumière de plusieurs simulations reflétant les préoccupations du développement dans chacun des deux pays, celle qui fût retenue est la simulation prévisionnelle CT13 qui correspond à l'évolution des prélèvements prévisionnels sur cette nappe en Tunisie et en Algérie entre 1981 et 2010 permettant de minimiser les effets de l'exploitation de part et d'autre de la frontière.

Tableau 1: Prélèvements prévisionnels selon la simulation CT13 en l/s (PNUD, 1983)

Années	1981	1985	1990	1995	2000	2010
Djérid	3175	3857	4548	4764	4892	4892
Nefzaoua	3484	3908	4554	6579	6617	6617
Total Tunisie	6659	7765	9102	11343	11509	11509
Total Algérie	8059	10290	13200	42937	44249	44249
Total CT	14718	18055	22302	54280	55758	55758

L'exploitation de la nappe du Complexe Terminal dans le Sud tunisien, prévue en l'an 2010 par la simulation CT13, est de l'ordre de 11509 l/s. Elle se répartie à raison de 4892 l/s dans le Djérid et 6617 l/s dans la Nefzaoua.

Cette simulation considère que les prélèvements sur les ressources en eau de cette nappe sont appelées à connaître à partir de 1990, une nette progression en Algérie où l'exploitation passerait de 13200 l/s en 1990 à 42937 l/s en 1995 puis à 44249 l/s en l'an 2000 pour rester constante jusqu'à l'an 2010. Dans le Sud tunisien, cette progression fait passer l'exploitation de 9102 l/s en 1990 à 11343 l/s en 1995, puis à 11509 l/s en 2000, et elle reste stable jusqu'à l'an 2010. Ainsi, les prélèvements sur les ressources de la nappe du complexe Terminal au Sud tunisien, ne représenteraient à partir de 1995, que le quart de ceux de l'Algérie.

Ces prévisions n'ont été effectivement respectées de près qu'en Tunisie où l'exploitation réelle en 1995 a été proche des prélèvements prévisionnels (14575 l/s), alors qu'en Algérie, l'exploitation de la nappe du Complexe Terminal en 1996 est de l'ordre de 18695 l/s, elle reste donc en deça des prévisions (42937 l/s) pour l'année 1995.

Les résultats de la simulation CT13 ont été jugées acceptables du point de vue des critères techniques établis dans le cadre de cette étude à l'exception de la région Nord de l'Oued Rhir (Algérie) où :

1. Le niveau piézomètrique dans la plupart des mailles se situerait en 2010 à des profondeurs supérieurs à 60 m par rapport au sol, entraînant des hauteurs de pompage de 75 à 80 m.
2. Le niveau piézomètrique en 2010, dans certaines mailles situées en bordure des chotts Melhir et Merouane, se situerait à plus de 20 m au dessous du niveau du chott, augmentant ainsi les risques de contamination des eaux de la nappe du Complexe Terminal à partir des aquifères superficiels très salés de ces chotts.

Tableau 2 : Résultats de la simulation CT13 en Tunisie (PNUD, 1983)

Régions		Rabattements 1981-2010 (m)	NP en 2010 (m/TN)	NP en 2010 (m/Chott)
Djérid	Hazoua	30 à 34	-13 à -4	-
	Nefta-Tozeur	22 à 43	-45 à -21	-
	Nord du Chott Rharsa	42 à 52	-60 à -36	-
Nefzaoua	Sud-ouest du Chott Dérid (Redjem Maâtoug)	12 à 27	+2 à +13	+13 à +21
	Douz – Sabria	11 à 13	-10 à +13	+21 à +28
	Kébili	9 à 11	-5 à +3	+6 à +16

En Tunisie, les résultats de la simulation CT13 se traduisent par des rabattement et une piézomètrie qui sont acceptables. Ainsi, le Djérid connaîtra une disparition de l'artésianisme avant la Nefzaoua. Cette situation s'est vérifiée à travers le tarissement du débit des sources dans les deux régions entre 1985 et 1988 et la baisse du niveau piézomètrique dans les forages devenus dans leur majorité pompés dans le Djérid. Cette baisse est restée jusqu'en 1995 dans les limites des prévisions de la simulation CT13 (de -39 à -2 m/TN).

3.4 Simulations ARMINES-ENIT (1984)

A l'initiative du Ministère de l'Agriculture, un autre modèle concernant la zone de Nefzaoua-Djérid fût élaboré en 1984, conjointement par ARMINES, l'ENIT et la DGRE afin d'affiner les calculs du projet RAB 80/011 dans la partie tunisienne de l'exploitation du Complexe Terminal (ARMINES-ENIT, 1984). Dans le cadre de cette étude, a été particulièrement vérifiée l'hypothèse de la disponibilité d'un débit de 2000 l/s dans la région de Redjem Maâtoug exploitable à l'aide des forages jaillissants avec une pression initiale de 2 à 3 kg/cm^2, un débit unitaire d'exploitation de 40 à 50 l/s et une salinité de l'eau de 1,8 à 2,5 g/l.

Quatre scénarios de prélèvement des ressources en eau du Complexe Terminal dans les régions du Djérid et de la Nefzaoua, furent simulés tout en respectant les conditions aux limites du modèle d'ensemble utilisé par l'ERESS et le RAB 80/011 et particulièrement l'hypothèse "CT13" prévoyant, entre autres, entre 1981 et 2010, le passage des prélèvements à partir de l'aquifère du Complexe Terminal dans le Sud tunisien, de 6659 l/s en 1981 à 11509 l/s en 2010.

Les quatre simulations retenues ont donné des résultats acceptables au niveau des rabattements engendrés.

Tableau 3 : Hypothèses des Prélèvements (l/s) des scénarios S1, S2, S3 et S4à Nefzaoua-Djérid (ARMINES-ENIT, 1984)

Années	**Scénarios**			
	S1	S2	S3	S4
1983	6740	6740	6740	6740
1984	6740	7510	7510	7510
1985	6740	8280	8280	8280
1986	6740	8280	8680	8680
1987	6740	8280	9080	9080
1988	6740	8280	9080	9210
1989	6740	8280	9080	9340
1990	6740	8280	9080	9470
1991	6740	8280	9080	9850
1992	6740	8280	9080	10230
1993	6740	8280	9080	10610
1994	6740	8280	9080	10990
1995	6740	8280	9080	11370

L'hypothèse qui a été jugée la plus représentative de la planification du développement de la région, prévoit une augmentation des prélèvements de 6740 l/s en 1983 à 11370 l/s en 2010 qui vérifie :

1. La réhabilitation des anciennes oasis et la création de nouveaux périmètres irrigués à Ibn Chabbat, Draa-Sud, Chott El Rharsa-Nord et Redjem Maâtoug ;
2. La maintenance de l'artésianisme jusqu'à l'an 2010 dans toutes les régions intéressées par le projet de Redjem Maâtoug ;
3. L'absence en 2010 de tout risque de pollution de l'aquifère par l'intrusion saline des eaux du Chott.

Sur la base de cette évaluation, il a été décidé de réaliser le projet agricole de Redjem Maâtoug s'étendant sur une superficie de 2500 ha dont 500 hectares au profit des habitants de la région et les 2000 hectares restants sous forme d'un projet dont l'exécution a été confiée à l'Office de Développement de Redjem Maâtoug (ODRM). La réalisation de ce projet est prévue en deux phases :

1. Une première phase de 750 hectares localisés au niveau des périmètres En Nasr, El Fardaous et Redjem Maâtoug ;
2. Une seconde phase de 1250 hectares répartis sur de nouveaux périmètres prévus entre Redjem Maâtoug et Matrouha.

La première tranche de ce projet a été réalisée suite à la création de 31 forages exécutés entre 1982 et 1992. L'exploitation de la nappe à Redjem Maâtoug a progressé de 49 l/s en 1982 pour atteindre 824 l/s en 1995. Cette progression des prélèvements s'est faite en fonction de l'avancement du programme de forages prévu pour cette première tranche du projet et leur adduction aux périmètres irrigués.

La deuxième tranche consiste à la création d'autres périmètres ce qui sera à l'origine de pousser l'exploitation de la nappe du Complexe Terminal entre Redjem Maâtoug et Matrouha jusqu'à 2000 l/s, soit une augmentation de 1176 l/s par rapport aux prélèvements de 1995.

Toutefois, l'évolution de l'exploitation de cette nappe a fait l'objet également d'un suivi de la qualité chimique de l'eau de la nappe qui exclue la tendance vers l'accroissement. Seule la partie de la presqu'île de Kébili, où la nappe est déjà avec un niveau piézomètrique plus bas que celui du Chott, montre une certaine croissance de la salinité qui a été entre 1950 et 1995 de l'ordre de 200 à 300 mg/l.

Les simulations d'une éventuelle contamination de la nappe du CT par les eaux salées des chotts, excluent dans la partie tunisienne, le danger de contamination de la nappe par les chotts. La méconnaissance de la nature de liaison existante entre le chott Djérid et l'aquifère du Complexe Terminal n'a pas permis d'approfondir la recherche à ce niveau et le risque de contamination par le chott Djérid n'a pas pu être quantifié. Les résultats du modèle ont mis en évidence le risque de contamination de la nappe du CT à partir des eaux sous-jacentes du Turonien.

Ce modèle de prédiction a été également utilisé pour évaluer l'impact du projet de la Mer intérieure sur l'aquifère du CT. Le projet consiste à relier la Méditerranée aux chotts algéro-tunisiens, l'influence de cette liaison se manifeste essentiellement dans la région des chotts.

3.5 Simulations DGRE (1997)

Les nouvelles simulations réalisées dans le cadre de cette étude ont pour objectifs d'analyser l'effet de l'exploitation supplémentaire (1176 l/s) sur la piézométrie de la nappe du Complexe Terminal, et ce à la lumière de la progression effective de l'exploitation de la nappe dans le Djérid et la Nefzaoua et de la piézométrie réelle mesurée sur le réseau de surveillance.

L'évaluation de l'exploitation réelle de la nappe du Complexe Terminal du Sud tunisien montre que les prélèvements réellement effectués sont conformes durant la période 1981-1995 dans le Djérid, aux prévisions de la simulation CT13 (4125 l/s exploités en 1995 contre 4764 l/s prévus). Mais dans la Nefzaoua les débits d'exploitation prévus par cette simulation durant la même période, ont été largement dépassés de 3871 l/s (10450 l/s exploités contre 6579 l/s prévus).

La réactualisation du modèle a permis de tester plusieurs simulations avec des conditions d'exploitation différentes, soit avec des prélèvements qui ne tiennent pas compte des pompages effectués par les sondes à main, soit avec les prélèvements réels évalués à la suite de l'inventaire effectué en 1995 et faisant intervenir ce type d'exploitation dans les régions du Djérid et de la Nefzaoua uniquement (Khalili B. and Hlaïmi A. 1997). Les prélèvement effectués sur le territoire algérien, sont supposés conformes aux hypothèses de la simulation CT13 adoptée par le projet RAB 80/011. Le domaine étudié correspond au sous-modèle Nefzaoua-Djérid élaboré dans le cadre du projet ARMINE-ENIT.

3.5 Résultats obtenus

La piézométrie simulée en 1995 donne des niveaux piézométriques variant de 12 à 40 m dans le Djérid, et de 24 à 66 m dans la Nefzaoua. A Redjem Maâtoug, les niveaux piézométriques sont à 57 et 59 m. L'analyse de la situation piézométrique de la nappe en 1995, montre deux sens d'écoulement :

1. De la Nefzaoua vers le Nord-ouest (El Ouediane et Tozeur-Nefta) où se situe l'exutoire des aïouns du Chott Djérid, schématisé par l'isopièze 30 m.
2. Du Sud-ouest vers le Nord-est à partir de la région de Redjem Maâtoug vers le Draa Djérid et l'exutoire secondaire du Complexe Terminal centré sur le Chott El Rharsa et qui correspond à l'isopièze 20 m.

La simulation prévisionnelle CT13 (1995) fait apparaître des niveaux piézométriques variant de 6 à 39 m dans le Djérid, de 32 à 72 m dans la Nefzaoua et de 58 à 59 m à Redjem Maâtoug.

L'écart entre la piézométrie calculée par la simulation CT13 et celle calculée par la présente simulation (-6 m au Djérid et +8 m à Nefzaoua), montre que la simulation CT13 est représentative et qu'une exploitation dépassant les prévisions dans la Nefzaoua, s'est traduite par une baisse plus accentuée. Alors qu'une exploitation en deça des prévisions de la simulation CT13, s'est traduite par des niveaux piézométriques plus élevés.

Il ressort que l'impact des prélèvements supplémentaires dus aux sondes à mains sur la piézométrie de la nappe dans la région, est maximal à Nefzaoua où les niveaux piézométriques subiront un rabattement supplémentaire de 4 à 12 m. Cette baisse de niveau engendrée par les prélèvements des sondes à main n'excédera pas les 2 m au Djérid et à Redjem Maâtoug.

3.6 Simulations prévisionnelles 1996-2010

Considérant que le modèle utilisé est suffisamment représentatif du fonctionnement hydraulique de la nappe, des nouvelles simulations prévisionnelles ont été réalisées avec les données de la deuxième hypothèse permettant d'estimer l'effet de l'exploitation future à Redjem Maâtoug. Deux hypothèses de prélèvements ont été adoptées :

1. Dans la Nefzaoua et le Djérid, l'exploitation est supposée rester constante durant la période 1995-2010 avec une valeur égale à celle de 1995, soit 4125 l/s au Djérid et 9626 l/s à Nefzaoua.
2. En Algérie, l'exploitation est supposée conforme aux hypothèses de simulation CT13, soit 42937 l/s en 1995 puis 44249 l/s à partir de l'an 2000 jusqu'à l'an 2010.

Dans un premier scénario, on a simulé l'option qui ne prévoit pas la réalisation de la deuxième tranche du projet de Redjem Maâtoug, c'est à dire maintenir l'exploitation dans cette région à 824 l/s. Ailleurs, dans le Djérid et le Nefzaoua, les prélèvements seront de 13749 l/s avec un léger dépassement par rapport à ceux prévus par la simulation CT13. Au second scénario, on a pris en considération la réalisation de cette deuxième tranche qui augmenterait progressivement les prélèvements dans la zone du projet jusqu'à 2000 l/s, à partir de l'an 2005.

La simulation du premier scénario a donné des niveaux piézométriques en 2010 variant de 50 à 53 m à Redjem Maâtoug, de 8 à 33 m au Djérid et de 20 à 56 m à Nefzaoua. Ce scénario donnera en l'an

2010 des rabattements de niveau piézomètrique de la nappe de l'ordre de 7 m par rapport à la situation de 1995, soit un rabattement annuel de 0,5 m.

La simulation du second scénario montre que de la réalisation de la deuxième tranche du projet de Redjem Maâtoug et l'augmentation de l'exploitation de la nappe engendrent des niveaux piézomètriques allant de 44 à 46 m à Redjem Maâtoug, de 2 à 30 m au Djérid et de 19 à 56 m à Nefzaoua. Ceci montre que la nappe subirait des baisses de niveaux plus accentuées que ceux obtenus au premier scénario. Les rabattements supplémentaires varieront de 6 à 7 m à Redjem Maâtoug, de 1 à 3 m au Djérid et d'environ 1 m à Nefzaoua où l'effet de cette extension sur la nappe est très réduit.

La comparaison des niveaux piézomètriques prévus par la simulation CT13 et ceux calculés au second scénario, fait ressortir un écart piézomètrique allant jusqu'à 24 m dans le Djérid, soit une piézomètrie calculée au scénario 2 plus élevée, résultant essentiellement d'une exploitation réelle au niveau de Chott El Gharsa-Nord, qui est de loin plus faible que celle prévue (329 l/s contre 779 l/s). Dans la Nefzaoua, cet écart varie de –23 à –8 m et traduit une baisse plus forte que celle prévue par la CT13; dans ce secteur l'exploitation enregistrée dépasse les prévisions (9626 l/s contre 4392 l/s en 2010). A Redjem Maâtoug, cet écart n'est que de –6 à –5 m, ce qui peut être peu significatif en raison de la répartition spatiale des prélèvements futurs entre 1995 et 2010 qui n'est pas la même pour les deux hypothèses.

Les résultats obtenus ont permis d'évaluer l'impact de la réalisation de la deuxième tranche du projet de Regjem Maâtoug sur la piézomètrie de la nappe du Complexe Terminal, les simulations ont fait apparaître une baisse piézomètrique à Redjem Maâtoug qui dans le scénario 2, dépasse de 6 à 7 m celle calculée au premier scénario. Ainsi, l'effet de la seconde tranche du projet est minime au niveau de la Nefzaoua où le rabattement supplémentaire n'excède pas les 2 m. Dans le Djérid, les rabattement supplémentaires par rapport à ceux prévus avec le premier scénario sont de l'ordre de 1 à 3 m.

Ainsi, la réalisation de la deuxième tranche du projet de Redjem Maâtoug n'influence le Djérid qu'avec un rabattement supplémentaire relativement négligeable, d'environ 0,3 m/an, quant au niveau de la Nefzaoua les rabattements supplémentaires seront de 5 à 11 m, soit 1 m/an.

4. Conclusion

L'étude hydrogéologique par modèles mathématiques de la nappe du Complexe Terminal a permis dans le cadre du projet ERESS, de simuler son comportement et d'orienter la politique de développement économique de la région aussi bien en Tunisie qu'en Algérie jusqu'en 1981. D'ailleurs, le plan directeur des eaux du Sud tunisien (1975) s'est principalement référé aux résultats des simulations de l'ERESS.

Le modèle DRES élaboré en 1978, constitue la première tentative d'actualisation de l'étude de la nappe du complexe terminal. Cette actualisation qui a été limitée à la région de la Nefzaoua, a permis de simuler les incidences à moyen terme, d'une augmentation des débits d'exploitation dans cette partie de la nappe du Complexe Terminal. Les simulations montrent que les aquifères profonds et phréatiques sont pratiquement distincts sauf au voisinage du chott Djérid et dans la presqu'île de Kébili et que le comportement de la nappe devient préoccupant dès que l'exploitation serait portée à son maximum. Avec une exploitation limitée à environ 4 m^3/s, les rabattements prévus seront acceptables.

L'actualisation des simulations prévisionnelles dans le cadre du projet RAB 80/011 est basée sur de nouvelles hypothèses d'exploitation pour la période 1982-2010. Les résultats des simulations prises en compte devraient répondre à plusieurs critères reflétant les préoccupations du développement dans chacun des deux pays. Cette étude a permis de déterminer le scénario qui correspond à l'évolution des prélèvements prévisionnels sur cette nappe, en Tunisie et en Algérie entre 1981 et 2010, permettant de minimiser les effets de l'exploitation sur la nappe, de part et d'autre de la frontière.

Les simulations ARMINES-ENIT élaborées en 1984, avaient pour objectif d'affiner les calculs du projet RAB 80/011 dans la partie tunisienne du Complexe Terminal. Il a été particulièrement vérifié l'hypothèse de la disponibilité d'un débit de 2000 l/s dans la région de Redjem Maâtoug exploitable par des forages jaillissants avec des conditions particulières de pression, de débit unitaire d'exploitation et de salinité.

Sur la base de cette évaluation, il a été décidé de réaliser le projet de développement agricole de Redjem Maâtoug s'étendant sur une superficie de 2500 ha. La première tranche de ce projet a été réalisée suite à la création de 31 forages exécutés entre 1982 et 1992. La deuxième tranche de ce projet consiste en la réalisation des autres périmètres ce qui sera à l'origine de l'augmentation de l'exploitation de la nappe du Complexe Terminal entre Redjem Maâtoug et Matrouha pour atteindre les 2000 l/s, soit une augmentation de 1176 l/s.

Toutefois, nous remarquons que l'évolution de l'exploitation de cette nappe a fait l'objet également d'un suivi de la qualité chimique de l'eau de la nappe qui ne montre pas de tendance nette vers l'accroissement. Seule la partie de la presqu'île de Kébili, où la nappe est déjà avec un niveau piézomètrique plus bas que celui du Chott, montre une certaine croissance de la salinité qui a été entre 1950 et 1995 de l'ordre de 200 à 300 mg/l.

D'autre part, Les simulations effectuées dans la partie tunisienne, excluent la possibilité d'une éventuelle contamination de la nappe du CT par les eaux salées des chotts. Quant au risque de contamination à partir des eaux sous-jacentes du Turonien, les résultats du modèle montrent que cet aquifère constitue une véritable source de pollution de la nappe du CT.

Le modèle de prédiction de la qualité de l'eau de la nappe du Complexe Terminal a été également utilisé pour évaluer l'impact sur cet aquifère, du projet de la Mer intérieure qui consiste à relier la Méditerranée aux chotts algéro-tunisiens. Il ressort que l'influence de ce projet se manifeste essentiellement dans la région des chotts.

Les nouvelles simulations réalisées dans le cadre de réactualisation de cette étude par la DGRE, ont pour objectifs d'analyser l'effet de l'exploitation supplémentaire (1176 l/s) sur la piézomètrie de la nappe du Complexe Terminal, et ce à la lumière de la progression effective de l'exploitation de la nappe dans le Djérid et la Nefzaoua et de la piézomètrie réelle mesurée sur le réseau de surveillance.

La réactualisation du modèle a permis de tester plusieurs simulations avec des conditions d'exploitation différentes, soit avec des prélèvements tels que évalués dans les annuaires d'exploitation des nappes profondes, soit avec les prélèvements réels évalués à la suite de l'inventaire effectué en 1995 et faisant intervenir les sondes à main dans les régions du Djérid et de la Nefzaoua uniquement.

Les simulations ont permis de conclure que la réalisation de la deuxième tranche du Projet de Redjem Mâatoug aurait des effets différents sur la nappe. C'est ainsi qu'au Djérid le rabattement supplémentaire est relativement négligeable, quant au niveau de la Nefzaoua les rabattements supplémentaires seront plus importants.

Les modèles mathématiques ont constitué pour la nappe du complexe un véritable outil à la fois de gestion des eaux souterraines et de prise de décision pour la réalisation de projet de développement agricole dans le Sud-ouest tunisien.

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Reévaluation des ressources d'un système aquifère profond sous contraintes physiques et chimiques : l'aquifère du Maastrichtien

(Reassessment of deep aquifer system resources under physical and chemical constraints: the Maastrichtian aquifer)

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Abstract

The deep and confined Maastrichtian aquifer contains considerable groundwater resources. It extends nearly 200,000 km^2 from Mauritania in the North to Guinea Bissau in the South where it became shallow. The reservoir is composed mainly of coarse sands and sandstone interbedded with some clay units.

The aquifer provides 40 % of total drinking water extracted from the different aquifers and 718 wells equally distributed operate only in the top 50 m of aquifer.

Despite the importance of these resources for providing water in rural and urban areas, the aquifer characteristics are not well defined. The present paper aims to define first the physical and chemical characteristics of maastrichtian aquifer. The reserve of aquifer initially estimated of 350 billions m^3, is reassessed using new data providing from cross sections realized as part of our research, through the Water Sectorial Project of the Ministry of Hydraulics.

Data from oil wells and geophysical logging are used to investigate the geometry of the aquifer and the position of the potable/salt water interface. The aquifer highest thickness is between 200 to 400 m and salt water occurs below the potable groundwater in the west side of the aquifer. In the Easten side, potable water lies directly above the basement. The thickness of the aquifer increases from the west to the center than decrease towards the shallow basement rock in the South East. The mean thickness is 250 m.

Chemical data coming from pumping wells indicate high chloride content (250 - 1600 mg/l) and fluoride content (1 - 5.5 mg/l). Therefore reassessment take into account chemical aspect of water.

Résumé

La nappe profonde et captive du Maastrichtien contient d'importantes ressources. Elle s'étend sur 200000 km^2, de la Mauritanie au nord à la Guinée Bissau au sud. L'aquifère est constitué principalement de sables grossiers et grès, avec des intercalations d'argile. Il fournit 40% de l'eau potable provenant de l'ensemble des aquifères du Sénégal ; il approvisionne près de 718 forages qui captent les 50 premiers mètres.

Les caractéristiques de l'aquifère sont mal connues, ainsi que ses possibilités. Dans cet article les données provenant, de forages pétroliers et de prospections géophysiques, ont été utilisées pour confectionner des coupes géologiques à travers le bassin sédimentaire sénégalais ; elles ont permis de déterminer la géométrie de la nappe d'eau douce. Les réserves de la nappe, qui étaient estimées à 350 milliards de m^3, doivent être revues à la baisse compte tenu des pollutions, saline et fluorée, qui affectent la partie ouest de l'aquifère. Ainsi le volume d'eau, mobilisable et de bonne qualité, a été estimé à 7 milliards de m^3.

Mots-cles

Aquifère, profond, caractéristiques, pollution, contraintes, réserve

1. Introduction

Au Sénégal 80 % de l'approvisionnement en eau potable provient des nappes d'eau souterraine. La nappe profonde du Maastrichtien, qui occupe près de 4/5 du territoire sénégalais (soit 155000 km^2), est la plus importante. Elle est captée par plus de 700 forages hydrauliques, dont les profondeurs moyennes sont autour de 250 m. L'aquifère présente un caractère régional puisqu'il occupe une grande partie du bassin sédimentaire sénégalo-mauritanien, et s'étend de la Guinée Bissau au Sud jusqu'en Mauritanie au Nord, en passant par la Gambie (Figure 1).

L'essentiel des informations disponibles sur la nappe est fourni par les forages hydrauliques qui sont surtout implantés au Sénégal. Ainsi sa partie inférieure est moins bien connue, puisque les ouvrages s'arrêtent dans les franges supérieures, où ils peuvent produire des débits ponctuels de l'ordre de 150 à 200 m^3/h.

L'objectif de cet article est d'abord de repréciser la géométrie de la nappe d'eau douce en s'appuyant sur des coupes géologiques réalisées dans le cadre du Projet Sectoriel Eau du Ministère de l'Hydraulique, et ensuite réévaluer les réserves de l'aquifère. On se proposera également d'exposer les caractéristiques physiques et chimiques de la nappe qui constituent autant de contraintes dans l'évaluation quantitative et qualitative des ressources de la nappe.

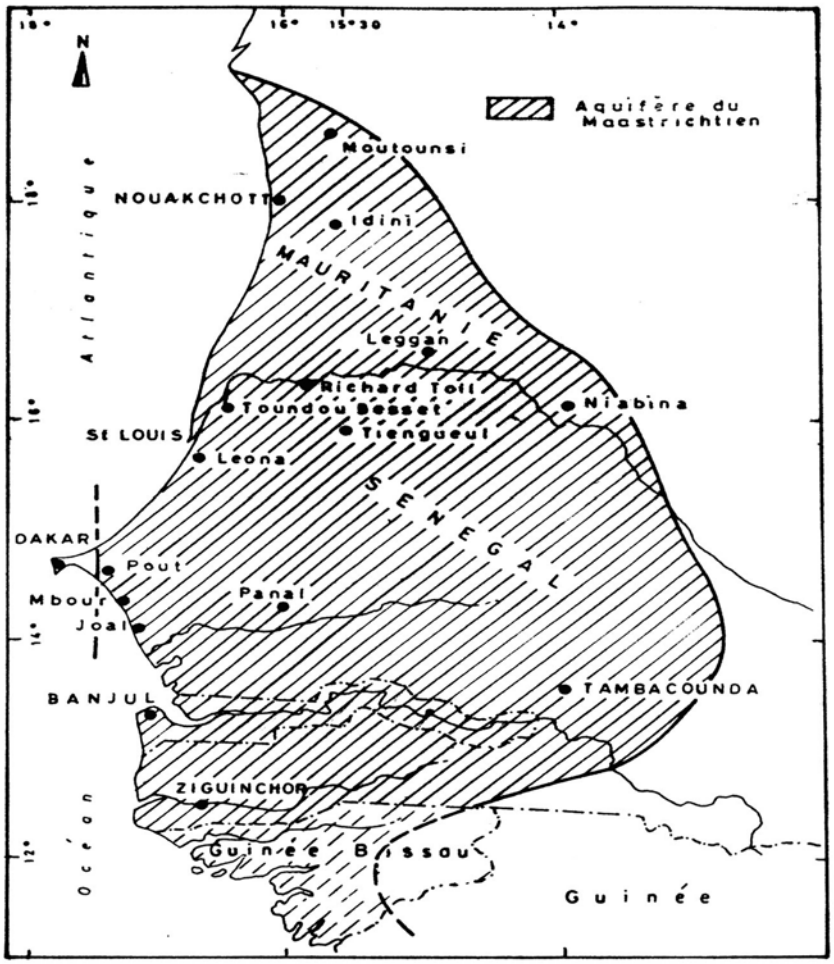


Figure 1 : Aquifère profond du Maastrichtien du bassin sénégalo-mauritanien (Forkasiewicz 1982, modifié)

2. Contexte geologique et hydrogeologique

Le bassin sédimentaire sénégalo-mauritanien est constitué essentiellement de formations secondaires et tertiaires. Celles-ci surmontent un substratum formé de roches cristallines d'âge primaire et antécambrien qui affleurent au Sud-Est et au Nord-Est du bassin.

La lithostratigraphie est connue depuis le Jurassique surtout grâce aux sondages de recherche pétrolière. Le Maastrichtien qui contient la nappe profonde du bassin affleure au niveau du horst de Ndiass sous forme de grès à ciment argilo – calcaire et d'argile sableuse. Au Sénégal, dans le Centre et l'Est du bassin, les sables dominent avec toutefois des intercalations d'argile. Des niveaux ligniteux minces s'observent vers le sommet de l'étage. A l'Ouest les faciès sont essentiellement sablo-argileux ; ils deviennent complètement argileux à l'ouest du méridien 17°30' (Doumouya 1988 ; Faye 1994).

En Mauritanie, le Maastrichtien est représenté par une formation argilo–sableuse azoïque (Bellion 1987). Toutefois les niveaux sableux prennent de l'importance à l'approche de la bordure orientale du bassin, leur épaisseur est faible (10 - 50 m). A l'Ouest des sables fins à grossiers alternent avec des argiles pyriteuses et parfois ligniteuses. Dans ce pays la nappe maastrichtienne y est d'intérêt très limité.

En Guinée Bissau par contre la nappe du Maastrichtien constituerait l'un des aquifères les plus importants. Elle serait contenue dans des sables fins à moyens, avec pyrite, glauconie et lignite, comme c'est le cas au Sénégal (Doumouya 1988). L'aquifère affleure à l'est et à l'ouest de ce pays ; il s'enfonce et devient captif au centre du pays.

La nappe ne se limite pas uniquement à l'étage dont elle porte le nom. En effet dans sa partie inférieure des niveaux aquifères sont attribués au Campanien, surtout dans la zone du horst de Ndiass ; de même vers la bordure orientale du bassin, la partie supérieure de l'aquifère est attribuée au Paléocène sus-jacent (Forkasiewicz 1982). Elle est captive sur l'ensemble du Sénégal, sauf dans le horst de Ndiass où elle est libre et en contact latéral avec les calcaires karstiques du Paléocène. Son toit est constitué de marnes ou argile du Paléocène. Elle est surmontée par un ensemble supérieur constitué par plusieurs aquifères, d'extension plus ou moins limitée. Ceux-ci sont rencontrés dans le Paléocène (calcaires karstiques des environs de Mbour), dans l'Eocène (calcaires lutétiens des environs de Louga et Kébémer), dans l'Oligo-Miocène (sables argileux des environs de Kaffrine, au centre-est du bassin), dans le Quaternaire (sables côtiers du nord – ouest et alluvions des grands cours d'eau).

3. Caractéristiques physiques et chimiques de la nappe

Les études réalisées sur la nappe maastrichtienne (Poul *et al.* 1971 ; Travi, 1988 ; Faye 1994) ont montré un relatif équilibre du chimisme de la nappe dans les 30 dernières années. Aucune évolution significative n'a été notée, la minéralisation totale reste stable. Les mesures effectuées à des périodes différentes donnent un aperçu de la composition chimique des eaux de la nappe (Tableau 1). On peut noter les forts taux de chlorures attestant de l'existence d'eaux saumâtres. Les valeurs moyennes de pH se situent à 5,8 vers les bordures est et ouest ; elles sont comprises entre 7,9 et 8,6 dans la partie centrale et nord (Faye 1994). La température varie entre 36 et 45° ; sa répartition suit approximativement la morphologie du toit de la nappe (Travi 1988).

Deux phénomènes majeurs caractérisent le chimisme de la nappe du Maastrichtien. D'abord sa minéralisation totale, qui varie entre 200 et 12000 mg/l (Travi 1988), permet de distinguer 3 grandes zones :

- à l'est du méridien 15°30 où la minéralisation est comprise entre 200 et 700 mg/l (Figure 2) ;
- à hauteur du horst de Ndiass, sur une bande étroite où la minéralisation est inférieure à 1000 mg/l ;
- une zone centrale, située à l'ouest du méridien 15°30' où les eaux chargées à fortement chargées se présentent sous un faciès chloruré sodique, avec des teneurs en chlorures comprises entre 250 et 1600 mg/l (SGPRE-COWI/POLYCONSULT, 1999).

Ensuite la pollution fluorée, qui est un phénomène assez répandu dans les systèmes aquifères du bassin du Sénégal, affecte aussi une bonne partie de l'aquifère. Une cartographie précise des teneurs en fluor a été élaborée par Travi (1988). Elle montre une évolution régulière (Figure 3), avec des valeurs qui augmentent des zones d'alimentation présumées (horst de Ndiass et bordure orientale) vers le Centre–Ouest. L'emplacement des taux élevés de fluor est associé à la présence de gisement de phosphates, dont l'un des minéraux en l'occurrence la fluor–apatite représente la principale source en fluor des eaux de la nappe (Travi 1988). Les fortes teneurs (1 - 5,5 mg/l) sont surtout retrouvées entre, d'une part la limite est du horst de Ndiass, et d'autre part le parallèle 15°30' ; ce qui correspond à la zone de forte minéralisation.

4. Géometrie de l'aquifère

L'essentiel des données disponibles sur l'aquifère profond du Maastrichtien concerne sa partie supérieure (50–100 m). Elles sont fournies, au Sénégal, par les forages réalisés pour satisfaire les besoins en eau potable des populations et quelques unités industrielles ou touristiques. Cette situation a toujours constitué un obstacle pour la détermination de la géométrie de l'aquifère, notamment l'extension verticale de la nappe d'eau douce.

Dans ce présent article les données provenant des forages pétroliers (qui traversent le Maastrichtien) ont été utilisées. Il s'agit d'une part de logs plus ou moins détaillés donnant la lithostratigraphie de la série sédimentaire très épaisse (le sondage le plus profond atteint 5395 m sur le littoral sud), et d'autre part de profils de résistivité et de polarisation spontanée (PS). Ces sondages sont, pour l'essentiel, situés dans la partie ouest du bassin et surtout sur le territoire sénégalais ; ce qui fait que la partie de l'aquifère située à l'Est, au Centre, et dans les pays voisins est moins bien connue. Néanmoins ils ont permis d'explorer la partie inférieure de la nappe. A ces données il faut ajouter celles provenant d'études géophysiques réalisées vers la bordure est et sud–est du bassin (DGRH 1990) ; elles ont permis de combler en partie le déficit d'informations dans cette partie du bassin.

Tableau 1 : Quelques exemples de la composition chimique (mg/l) des eaux de la nappe du Maastrichtien entre 1967 et 1994 (Travi 1988 ; Faye 1994 ; modifié)

Localité	Année	T°C	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	F^{-}	TDS
Diourbel	1967	-	-	8,2	2,42	484,1	16,6	475,7	43,2	466,7	2,1	1499,1
	1984	39°1	7,85	4,1	2,7	480	8,0	500	43,0	492,9	4	1534,7
	1994	-	-	-	1,7	315,3	-	480	65,0	440	-	-
Kaffrine	1970	37°	7,9	13,6	4,6	274	11,0	224	45,1	360	0,8	932,3
	1984	38°8	8,1	5,6	4,9	266	9,6	220	48,0	337,9	1,1	893,1
	1994	-	-	16,0	2,6	173,7	10,0	233,0	65,0	316	-	-
Kaolack	1967	39°	7,7	11,2	2,67	400,2	15,6	386,24	52,8	390,4	2,85	1262
	1984	37°9	7,93	4,0	3,3	440	20	330	73,5	416,03	2,78	1289,6
	1994	-	-	4,0	3,3	393,3	13,7	370,0	62,0	390	-	-
Linguère	1970	-	7,5	54,1	21,4	144	17,4	42,5	256,5	253,2	0,4	789,1
	1984	39°5	7,02	48,6	22,0	140	8	33	290	245,2	0,55	841,8
	1994	-	-	52,9	21,2	158	17,3	70,0	328,0	209	0,7	-

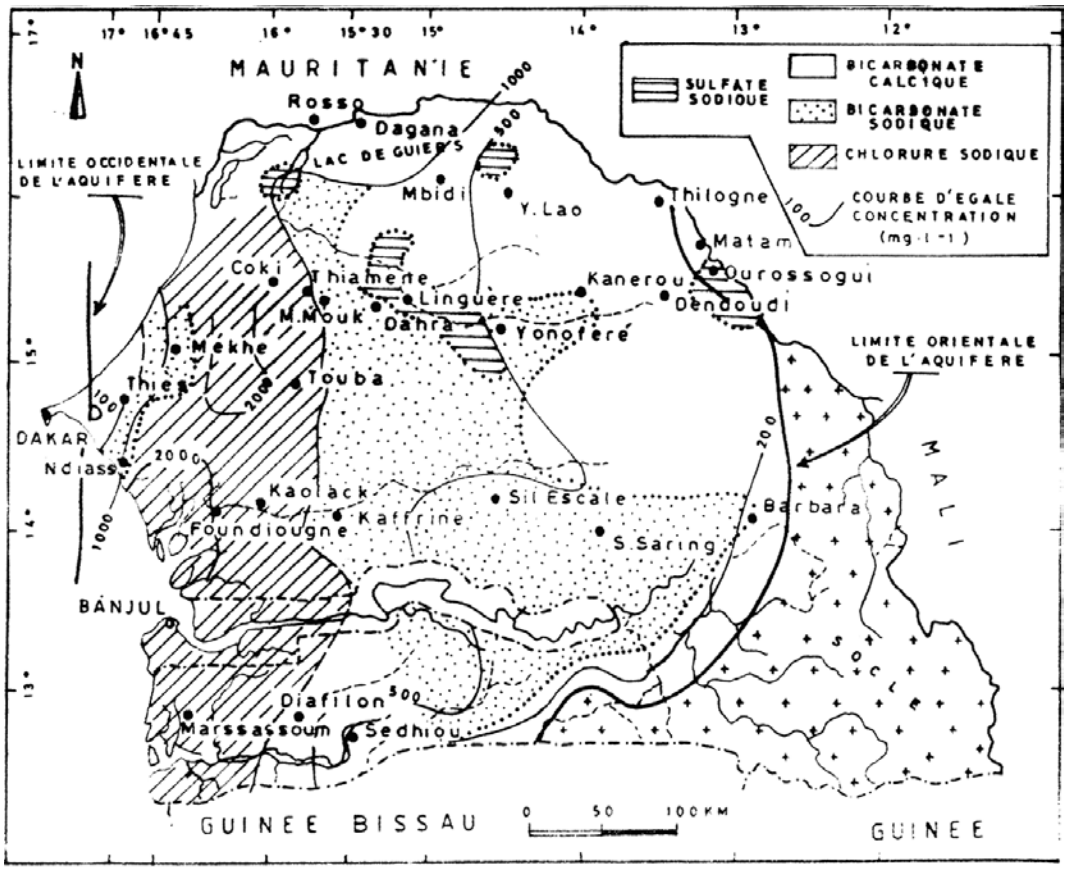


Figure 2 : Carte des courbes d'égale concentration (TDS) et des familles chimiques de la nappe profonde du Maastrichtien (Travi 1988).

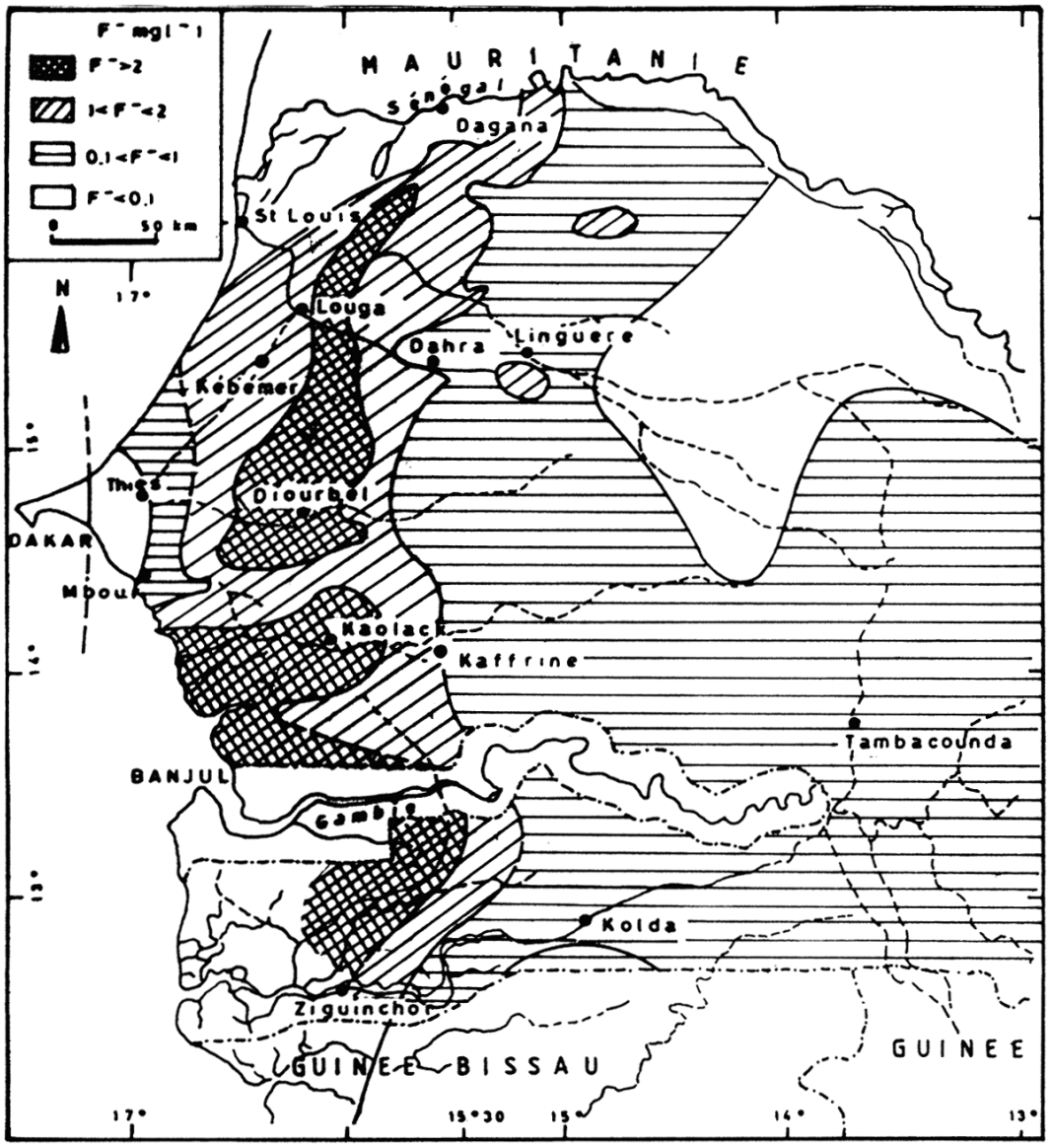


Figure 3 : Carte des teneurs en fluor de la nappe profonde du Maastrichtien (Travi 1988).*

Ainsi les coupes géologiques confectionnées (Figure 4) l'ont été sur la base, d'une part des données évoquées plus haut, et d'autre part de celles fournies par Le Priol et Dieng (1985) et Bellion (1987) sur la géologie structurale du bassin. Leur interprétation fait ressortir les observations suivantes :

- Le toit de l'aquifère est affecté par des jeux de failles qui ont entraîné l'effondrement du toit de l'est vers l'ouest (à l'exception du horst de Ndiass) où il est à plus de 500 m au dessous du niveau de la mer à Ziguinchor ;
- L'eau douce repose, à l'ouest et en partie au centre, sur l'eau salée ; tandis qu'à l'est elle repose directement sur le socle.

La carte isobathe du toit (Figure 5) montre aussi cette tendance générale d'augmentation de la profondeur du toit de l'est vers l'ouest, à l'exception d'une part du horst de Ndiass, et d'autre part du des environs de Tambacounda où un affaissement localisé du toit est observé.

La carte isopache donne une distribution plus générale des épaisseurs de la nappe d'eau douce (Figure 6). Elles sont relativement importantes au centre du bassin où elles atteignent 400 m par endroits, alors que vers l'ouest et vers l'est elles diminuent.

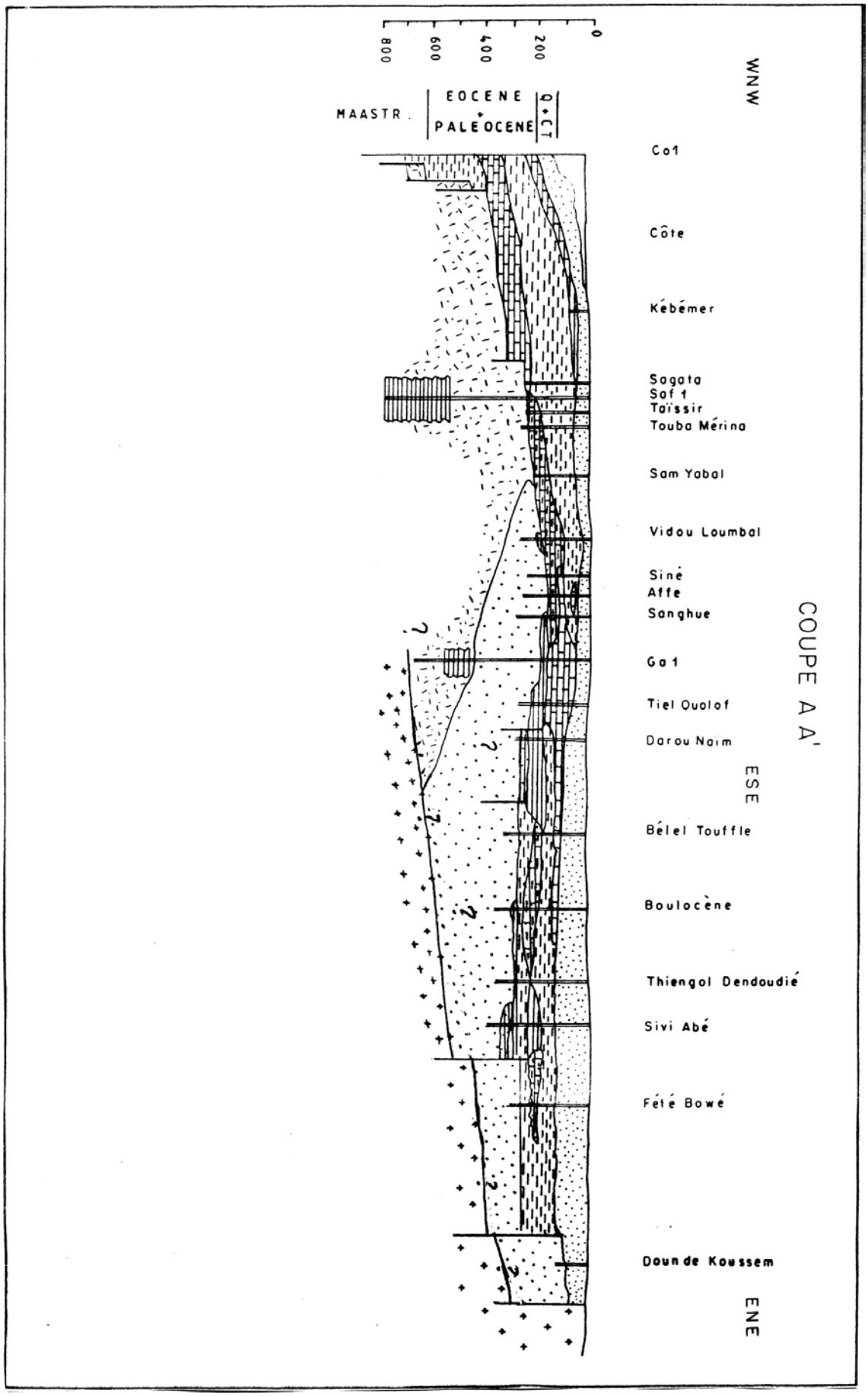


Figure 4a : Coupe géologique de la partie septentrionale du bassin sédimentaire sénégalais.

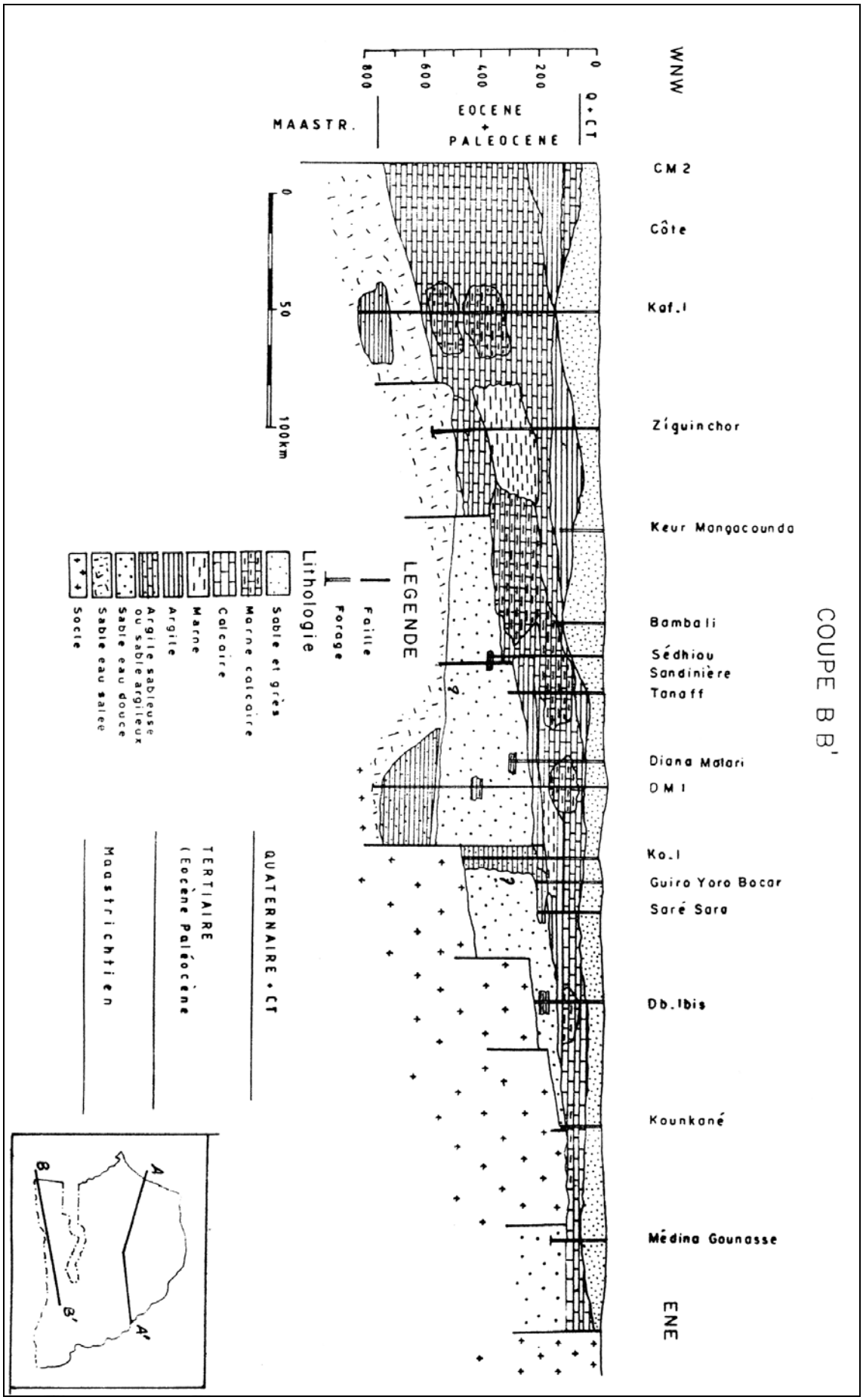


Figure 4b : Coupe géologique de la partie méridionale du bassin sédimentaire sénégalais.

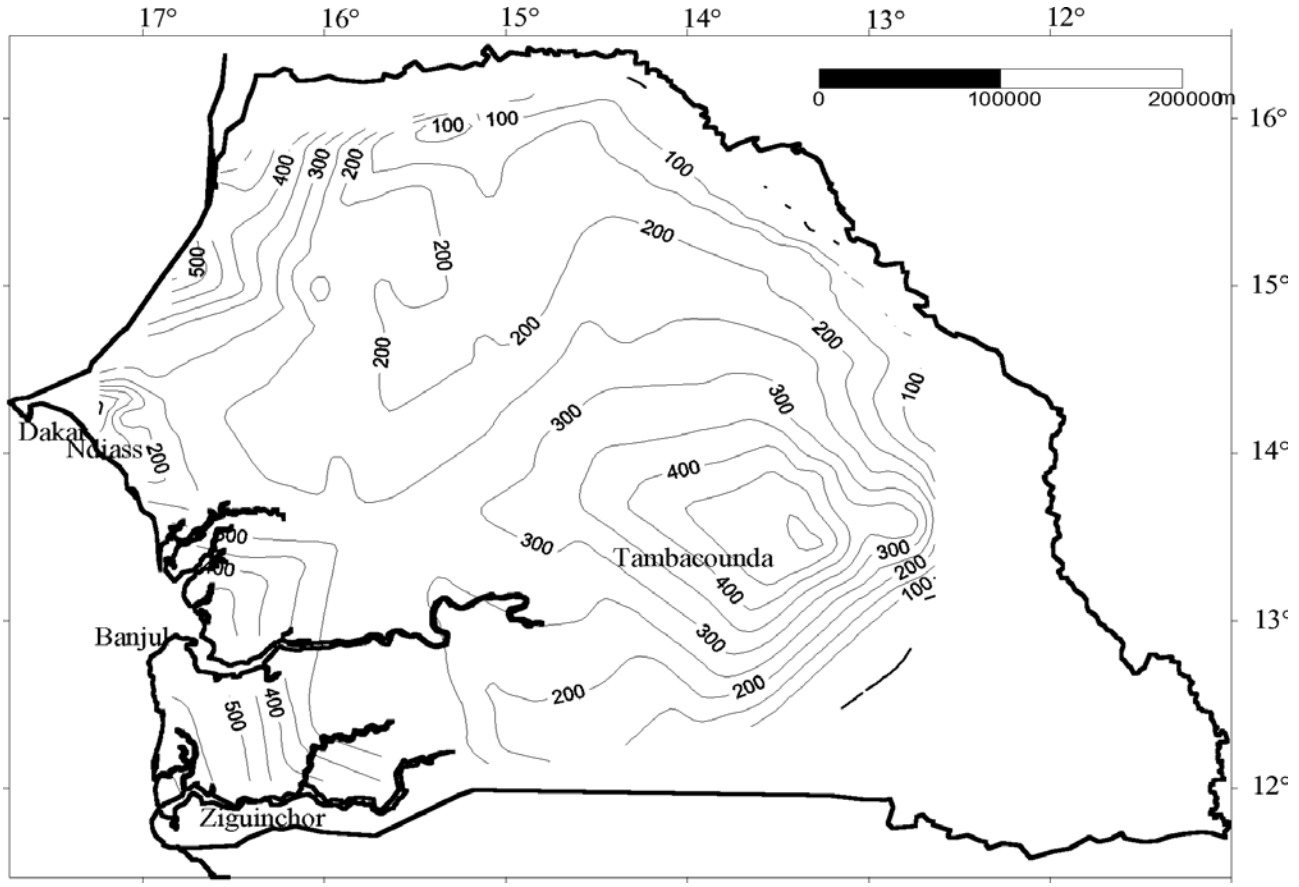


Figure 5 : Carte isobathe du toit de l'aquifère profond du Maastrichtien.

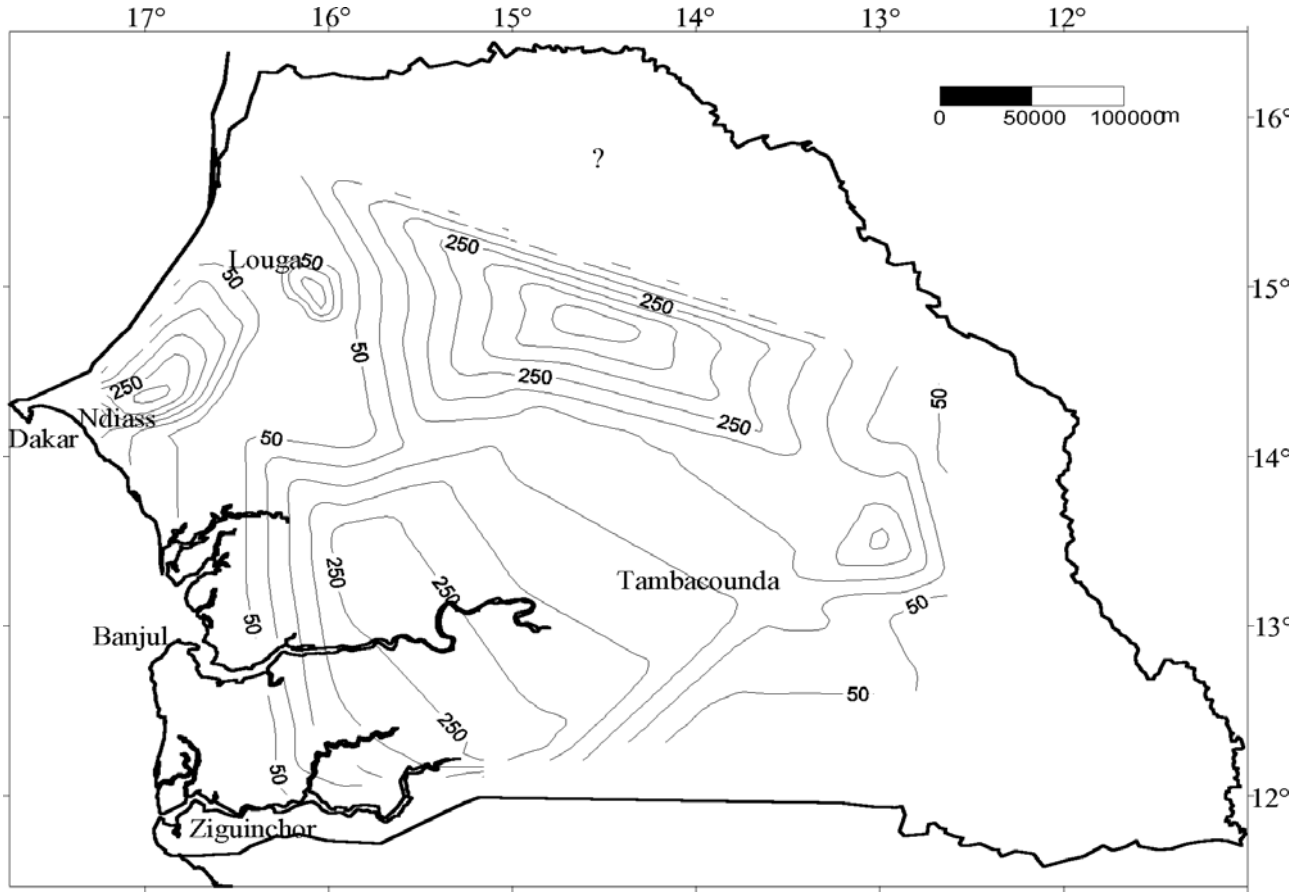


Figure 6 : Carte isopache de la nappe d'eau douce de l'aquifère profond du Maastrichtien.

5. Evaluation de la réserve d'eau douce

Une évaluation de la réserve en eau de l'aquifère profond du Maastrichtien se heurte à deux types de contraintes majeures.

5.1 Les contraintes chimiques

La forte minéralisation de l'eau de la nappe, ainsi que les taux élevés de fluor constituent des contraintes majeures qui sont nuisibles à la potabilité de l'eau. Une eau de boisson est jugée de bonne qualité si la concentration ionique est en dessous de 1000 mg/l, de même selon les normes internationales la concentration en fluor doit être en dessous de 1,5 mg/l. Dans ce contexte la partie de nappe comprise entre les parallèles 15°30' et 16°45' ne peut pas être considérée comme propre à la consommation. Il conviendra donc de prendre en compte cet aspect qualitatif dans l'évaluation des ressources de la nappe.

Ainsi les zones favorables au captage pour l'approvisionnement en eau des populations se situent d'une part, à l'est du parallèle 15°30' et d'autre part, à l'ouest du parallèle 16°45' (Figure 7).

5.2 Les contraintes physiques

Elles sont plutôt liées à la non - représentativité des données sur les paramètres hydrauliques de la nappe. En effet les essais de pompage sont réalisés sur des ouvrages qui captent généralement les 50 premiers mètres de la nappe ; ce qui est très faible par rapport à la puissance totale de l'aquifère. Ensuite les tests sont souvent de durée relativement faible, en conséquence les paramètres calculés sont plutôt représentatifs de l'horizon capté. Après corrections et extrapolations, Doumouya (1988) préconisent des valeurs de transmissivité comprises entre 10-3 et 4.10-2 m^2/s.

Par ailleurs le coefficient d'emmagasinement est plus difficile à cerner. En effet les essais de pompage sont le plus souvent effectués sans ouvrage d'observation, ce qui constitue un obstacle à la détermination. Les valeurs disponibles concernent, pour la plupart, le massif du horst de Ndiass où elles varient entre 1,5.10-4 et 8.10-4 (Arlab 1983 ; Dieng 1987). Dans le reste du bassin, seuls 2 forages situés au Centre (Kaolack) et au sud vers Ziguinchor disposent de données. Elles sont respectivement de 2,8.10-4 et 2,5.10-4. Ces valeurs disponibles laissent comprendre que ce paramètre varie peu à l'intérieur du bassin, comme l'a fait remarquer Dieng (1987). Pour les besoins de la présente étude nous retiendrons 2.10-4 qui nous paraît représentatif de de du centre du bassin, où on observe les épaisseurs les plus importantes.

5.3 Estimation de la réserve

L'évaluation de la réserve d'eau de l'aquifère du Maastrichtien prendra en compte la partie de la nappe, dont les caractéristiques chimiques sont compatibles avec celles d'une eau potable. Il s'agit d'une part, de la bande située approximativement entre les parallèles 16°45' et 17°, et d'autre part de la zone située à l'est du parallèle 15°30' (Figure 7). Ces deux parties réunies occupent une superficie de 123,400 km^2, sur une superficie totale occupée par l'aquifère de 176,650 km^2, soit 70 %.

La moyenne des épaisseurs révélée par les coupes géologiques, qui sont assez représentatives du centre et de la bordure sud du bassin, donne une valeur se situant aux environs de 270 m. Ainsi pour un coefficient d'emmagasinement de l'ordre de 2.10-4, la réserve totale de la nappe d'eau douce sera égale à 6,7 milliards de m^3. Ainsi donc il faudra retenir que sur les 350 milliards de m^3 souvent avancés comme réserve, environ 7 milliards de m^3 seulement sont de bonne qualité et mobilisables.

6. Conclusion

La nappe profonde du Maastrichtien constitue la plus importante source en eau potable du Sénégal, elle est captée par près d'un millier de forages hydrauliques. Cependant sur un tiers de l'aquifère, l'eau présente des caractéristiques physico-chimiques (taux de chlorures et fluorures élevés) incompatibles avec celles d'une eau potable. C'est pourquoi toute évaluation des ressources de l'aquifère doit prendre en compte cet aspect. Ceci nécessite, pour une gestion durable des ressources, de revoir à la baisse les réserves utiles de la nappe.

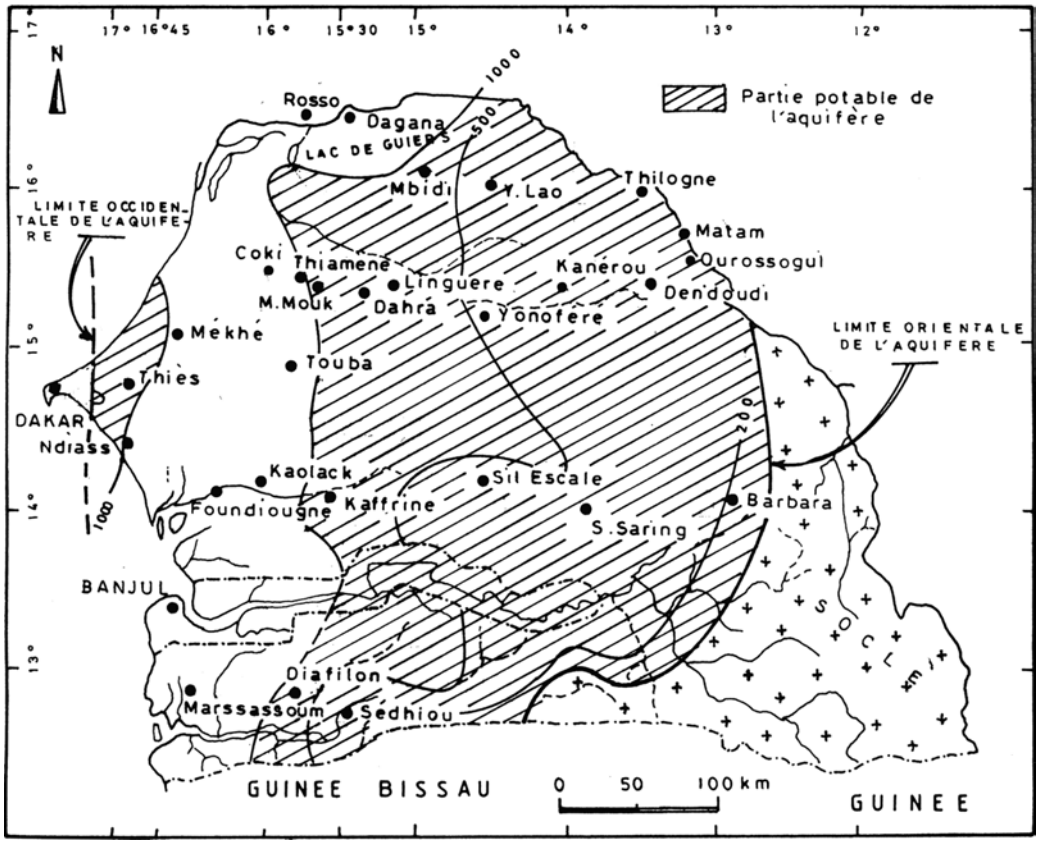


Figure 7 : Carte de situation de la nappe d'eau douce de l'aquifère profond du Maastrichtien.

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Mode d'alimentation des systèmes aquifères a pluviométrie contrastée – cas du système Annaba-Bouteldja : confirmation par les isotopes

(Supply mode of aquifers systems of contrasted pluviometry – case of the Annaba-Bouteldja system: confirmation through isotopes)

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Abstract

The pluviometric changes observed in the region, forced us to search for an explanation of the supply modes of the actual aquifer.

This research has become necessary especially after a succession of years of drought. The rain fall dwindled from 1000 and even 1200 mm/year to 400 mm/year. Knowing that, the waters of the region are meant for domestic use.

The environment isotopes can bring more valuable details to hydrogeological studies, especially concerning supply and the definition of aquifers conditions to limits.

In this study, new results have been obtained thanks to the use of the isotopes concerning:

1. the description of supply mode of the different aquifers,
2. the finding of two types of supply in the coastal aquifer of Bouteldja,
3. the identification of a recent supply of the superficial groundwater by the metamorphic formations.

One example of the aquifer system of Annaba-Bouteldja region of a Mediterranean climate, illustrates the concrete results that have been obtained from a relatively considerable amount of isotopic analyses. These results are to be taken into account when elaborating simulation models of aquifers for a non rational management.

Résumé

Les changements pluviométriques observés dans la région nous ont contraints à chercher l'explication du mode d'alimentation des nappes présentes. Cette recherche est devenue obligatoire surtout après la succession des années de sécheresse. Les précipitations pouvaient passer de 1000 voire 1200 mm/an à 400 mm/an. Notons par ailleurs que les eaux de la région sont destinées à l'A.E.P.

Les isotopes de l'environnement peuvent apporter des renseignements complémentaires précieux aux études hydrogéologiques, notamment en ce qui concerne l'alimentation et la définition des conditions aux limites des aquifères.

Dans cette étude, de nouveaux résultats ont été obtenus grâce à l'utilisation des isotopes, en ce qui concerne :

1. la description des modes d'alimentation des différentes nappes ;
2. la mise en évidence de deux types d'alimentation dans l'aquifère dunaire de Bouteldja ;
3. l'identification d'une alimentation récente de la nappe superficielle par les formations métamorphiques bordant la plaine.

L'exemple du système aquifère de la région de Annaba-Bouteldja, à climat méditerranéen, illustre les résultats concrets qui ont pu être obtenus à partir d'un nombre relativement important d'analyses isotopiques. Ces résultats sont à prendre en compte dans l'élaboration des modèles de simulation des aquifères en vue de leur gestion rationnelle.

1. Introduction

Les plaines de Annaba-Bouteldja, d'une superficie de près de 780 km^2, sont constituées par des sédiments mio-plio-quaternaires comblant une zone d'effondrement. L'hétérogénéité de ces dépôts détermine plusieurs horizons aquifères contenus dans des graviers et galets, dans les sables dunaires de Bouteldja et dans des niveaux discontinus de sables et d'argiles.

Des relations hydrodynamiques entre ces différentes nappes ont été mises en évidence par l'interprétation de plus d'une centaine de pompages d'essai. Ces relations impliquent en général, des transferts de débit issus des oueds, de la drainance d'aquifères annexes (alluvions des oueds) et de l'égouttement des niveaux aquifères superficiels, en particulier dans le massif dunaire et dans le secteur compris entre Chihani et Dréan.

Pour confirmer ces relations, nous avons fait appel aux analyses isotopiques, physico-chimiques et au calcul de la recharge pluviale.

Il est montré que ce sont principalement les précipitations à UT élevées qui conditionnent l'alimentation des nappes superficielle et dunaire. Par contre, la nappe "profonde" des graviers et galets est alimentée essentiellement par drainance, ce qui confère à l'eau son cachet ancien. Les deux phénomènes, recharge pluviale et drainance, peuvent contribuer à l'alimentation de la nappe des graviers et galets dans le secteur de Dréan-Chihani.

2. Situation géographique et géologique

La région d'étude est bordée à l'Ouest par les micaschistes et gneiss du massif de l'Edough, et par les alluvions de haut niveau du lac de Fetzara plus au Sud. Elle est limitée au Sud par le prolongement oriental de la chaîne numidienne des monts de la Cheffia, au Nord par la Méditerranée et à l'Est par les massifs numidiques de Bouteldja.

Dans ce secteur, des sédiments mio-plio-quaternaires sont venus combler une zone d'effondrement (Sonatrach, 1966 ; STROJEXPORT, 1975) comportant deux fosses séparées par une sorte de haut fond qui porte la butte de Daroussa et qui sont la fosse de Béni Ahmed, orientée Sud-Nord et la fosse de Ben M'hidi orientée Sud-Ouest - Nord-Est (Figure 1).

3. Contexte hydrogéologique du système aquifère

La géométrie des fosses a largement conditionné le remplissage par les apports de conglomérats et surtout par l'organisation du système aquifère de constitution lithologique assez complexe (Villa, 1980) en trois principaux horizons aquifères assez distincts.

4. Identification des modalités de transfert hydrodynamique

L'analyse de plus d'une centaine de pompages d'essai effectués dans les forages, a permis de déterminer trois types de relations :

1. Dans la région de Dréan, où les niveaux sont peu profonds (8 à 14 m), les pompages ont permis la mise en évidence des transferts hydrauliques verticaux consécutifs à un égouttement des formations alluvionnaires de la Seybouse, de faible perméabilité (1.10^{-5} m/s), mais à porosité importante (2%) suivant le schéma de Boulton. Ce schéma est également observé dans le massif dunaire de Bouteldja, où l'hétérogénéité granulométrique des sables plus fins dans la partie supérieure, induit un transfert des débits vers les formations grossières sous-jacentes.
2. Dans le secteur central de la plaine de Annaba, l'horizon des graviers est captif sous une couche plus ou moins sableuse épaisse de 26 m. Ces dernières sont imperméables et empêchent, du moins durant les pompages d'essai de 72 heures, toute relation hydraulique entre horizon superficiel et profond.
3. Enfin, une alimentation de l'aquifère graveleux à travers les argiles sableuses de 12 m et à partir d'une couche alluviale de 33 m qui joue le rôle d'un niveau d'eau constant. Cette alimentation est d'autant plus favorable que l'éponte semi-perméable est peu épaisse et que l'épaisseur des alluvions est importante. Ce cas de Figure est particulièrement concrétisé dans les forages situés sur la rive gauche de l'Oued Seybouse (à l'Ouest d'El-Hadjar).

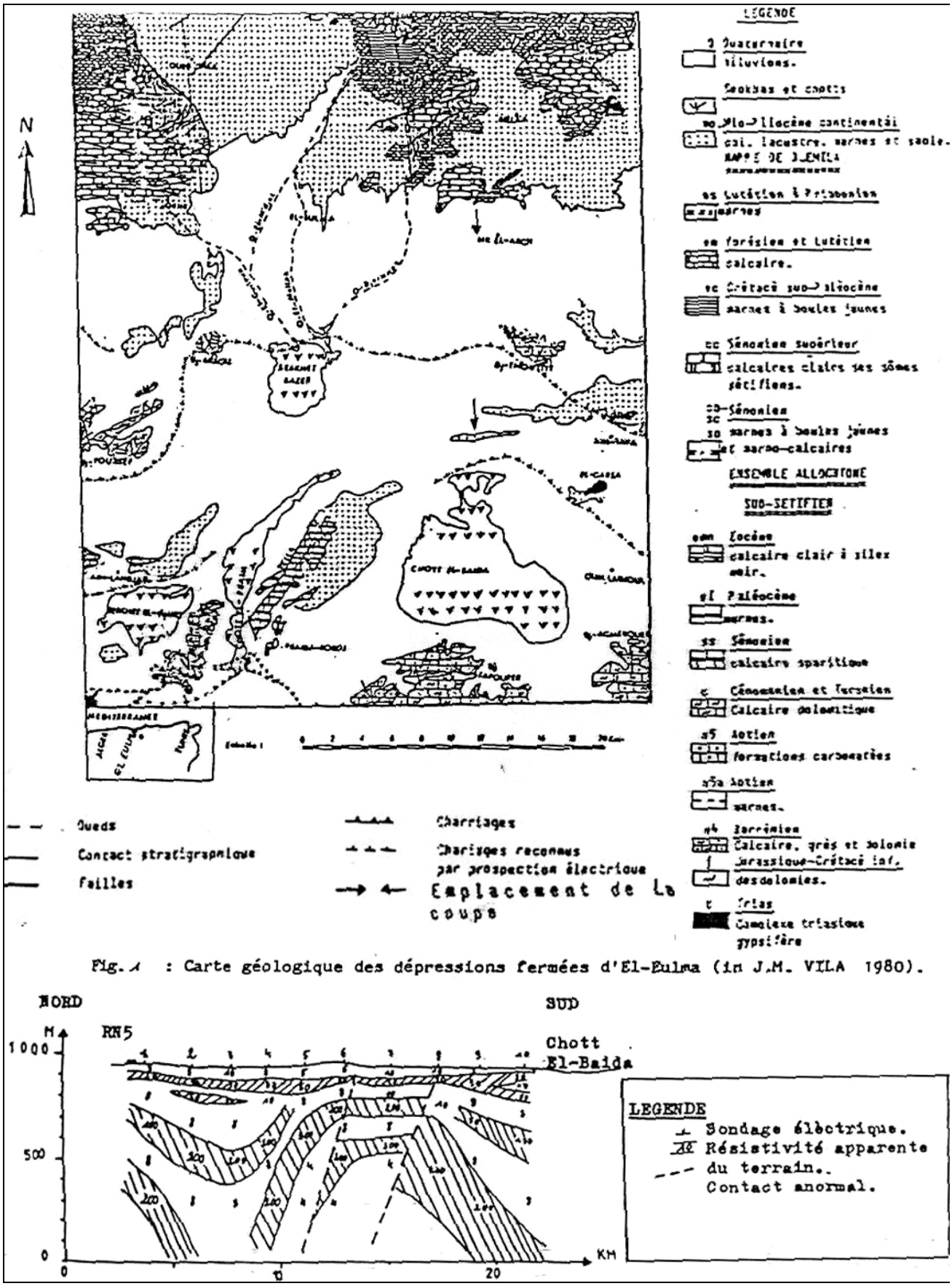


Fig. 1 : Carte géologique des dépressions fermées d'El-Eulma (in J.M. VILA 1980).

Figure 1 : Carte géologique des dépressions fermées d'El-Eulma (in J. M. Vila 1980)

5. Piézomètrie et conditions aux limites

Les cartes piézométriques établies à l'étiage (Octobre 1994) reflètent le mode d'écoulement des eaux souterraines dans les différents horizons aquifères. Les couches hydroisohypses de la Figure 4 permettent de relever les points suivants :

La nappe superficielle est caractérisée par :

1. un écoulement général du Sud vers le Nord,
2. l'Oued Seybouse alimente très fortement la nappe dans le secteur compris entre Chihani et Dréan,
3. la convergence des écoulements vers la zone des salinesprovoquée vraisemblablement par la mise en exploitation intensive de la nappe des graviers,
4. le gradient piézométrique est plus fort sur les bordures Sud que vers le centre de la plaine ; cela traduit à la fois une circulation des eaux plus rapide et une moins bonne perméabilité des alluvions de haut niveau, constitués essentiellement de graviers et cailloux à matrice argileuse.
5. un drainage des eaux souterraines par les oueds El Rhaim, Bouglez et Bourdim. Ce drainage est compensé en partie par les eaux de ruissellement sur les reliefs gréso-argileux du Nord-Est.

D'une manière générale, la morphologie de la surface piézométrique des nappes superficielles et dunaire reflète sensiblement la topographie de la zone d'étude ; ce phénomène marque certainement la forme de l'alimentation qui s'effectue principalement par la surface (recharge directe par la pluie).

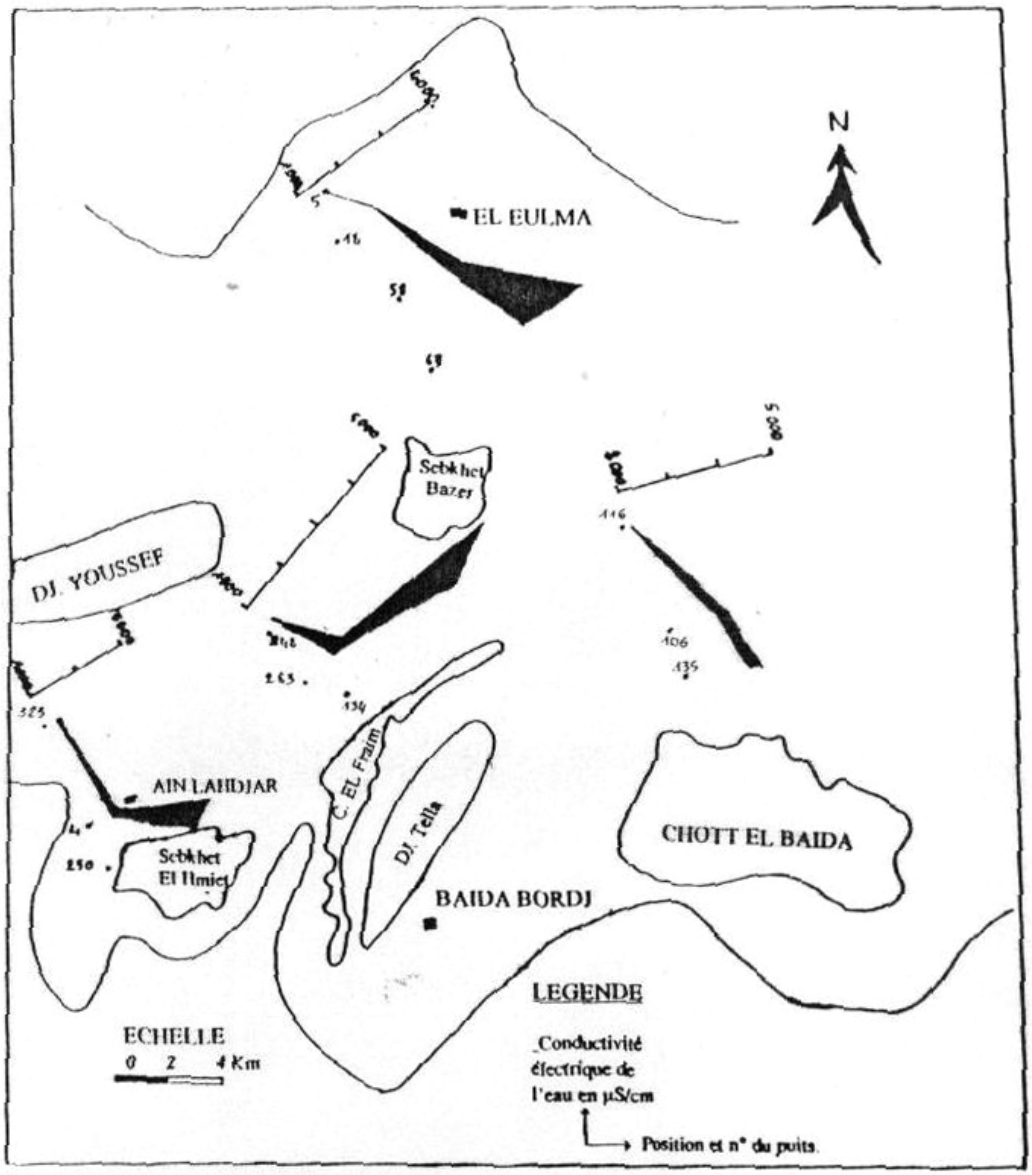


Figure 2 : Evolution de la conductivité électrique de l'eau entre septembre 1986 et septembre 1997

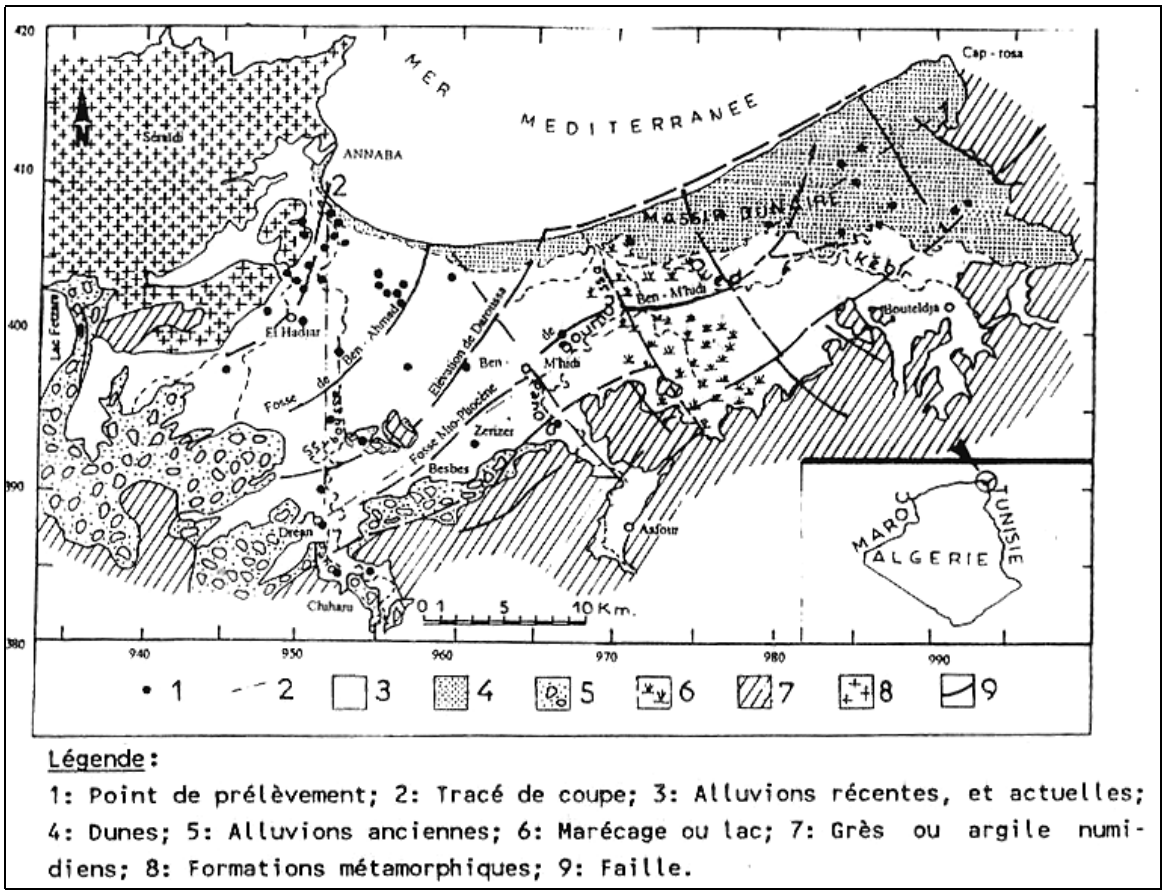


Figure 2a : Situation géographique et géologique des plaines de la région de Annaba-Bouteldja

6. Caractéristiques physico-chimiques

Partant des résultats analytiques effectués depuis 1982 sur les réseaux de surveillance du système aquifère Annaba-Bouteldja, les principaux processus responsables de l'évolution chimique observée au niveau de l'aquifère ont été identifiés :

1. Nappe du massif dunaire de Bouteldja : Ce sont les processus d'échange de base et d'évaporation qui sont responsables de l'augmentation en basses eaux de la minéralisation liée au calcium, sodium, potassium, chlorures et bicarbonates. Le pouvoir réducteur du milieu est responsable de l'augmentation des sulfates. Enfin, l'irrigation en période d'étiage est responsable de l'augmentation des nitrates.
2. Nappe des graviers ou nappe « profonde » de Annaba : Ce sont surtout les échanges cationiques et probablement l'influence de la mer qui sont responsables de l'augmentation de la conductivité électrique, représentée essentiellement par les chlorures et le sodium. L'absence, en certains secteurs périphériques du couvert argileux protecteur est également responsable de la pollution de la nappe par les nitrates.
3. Nappe superficielle de la plaine de Annaba : Les résultats obtenues par (L. Djabri, 1996) montre l'influence des apports des affluents de l'Oued Seybouse et du lac Fetzara et la proximité de la mer sur les eaux souterraines (impliquant une augmentation des chlorures). L'influence du trias gypsifère se manifeste par une augmentation très marquée des sulfates.

La faible profondeur du niveau piézométrique laisse présager également des fluctuations importantes de la qualité des eaux.

Pour mieux apprécier les principaux grands traits hydrochimiques et les rapports mutuels, les résultats analytiques effectués au mois d'octobre 1994, ont été représentés dans un diagramme de Piper (Figure 5). Ce dernier montre que les eaux de la région étudiée sont à dominante chlorurée à chlorurée calcique. Quelques échantillons sont chlorurés magnésiens.

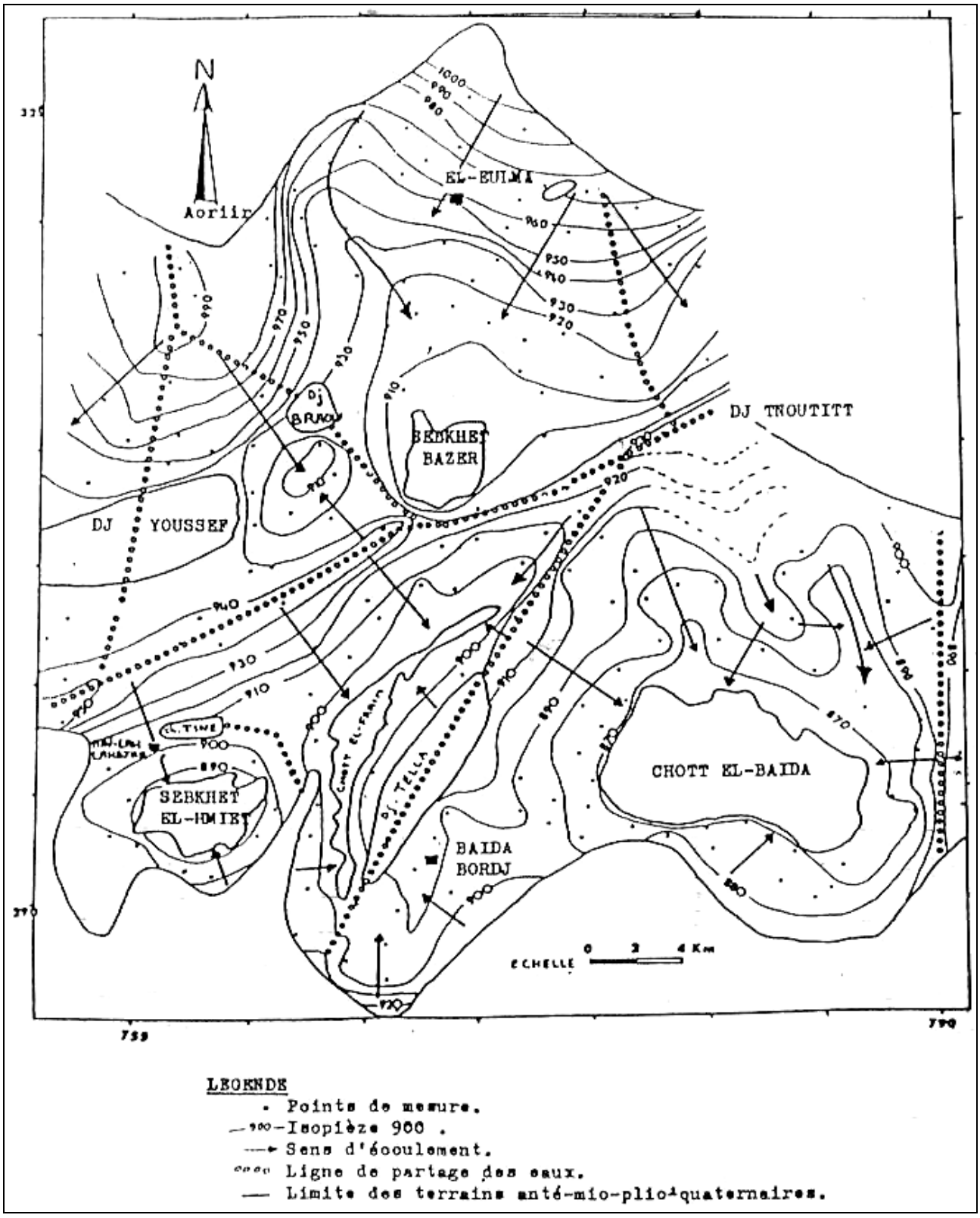


Figure 3 : Carte piézométrique de basses eaux (séptembre 1985)

6.1 Analyse isotopique

6.1.1 Teneurs en isotopes stables ^{18}O et ^{3}H

Cinquante et un échantillons (Figure 1 et 9) d'eaux du massif dunaire (11), de la nappe des graviers (23) et des eaux de la nappe superficielle (12) ont été analysés en oxygène 18 (^{18}O) et en tritium (Tableau 1).

Les teneurs en oxygène 18 des eaux varient entre -7% au niveau de la Mafragh (N¯18) à +0,12% à l'Oued Meboudja (41). Les points : 1, 2, 4, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20, 21, 22, 23, 24, 25, 26, 33, 42, 43, 44, 45, 46 sont homogènes, présentant des valeurs en oxygène 18 inférieures à -5%. Les autres points ont des teneurs supérieures à -5% et atteignent la valeur de +0,12%. Ce sont des eaux qui ont été réchauffées à des degrés divers et qui correspondent par conséquent à des eaux évaporées. Cette évaporation se fait par précipitations lors du ruissellement ou par réchauffement lors de l'utilisation.

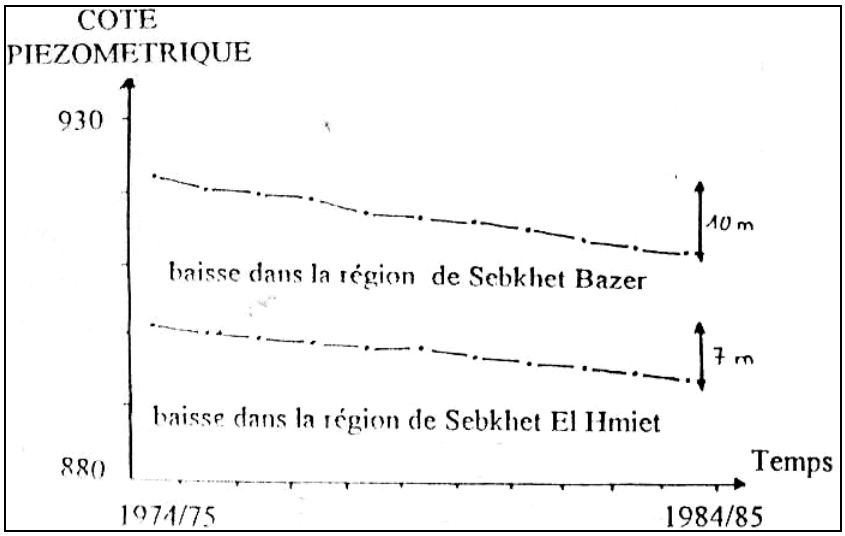


Figure 4 : Evolution de la piézométrie

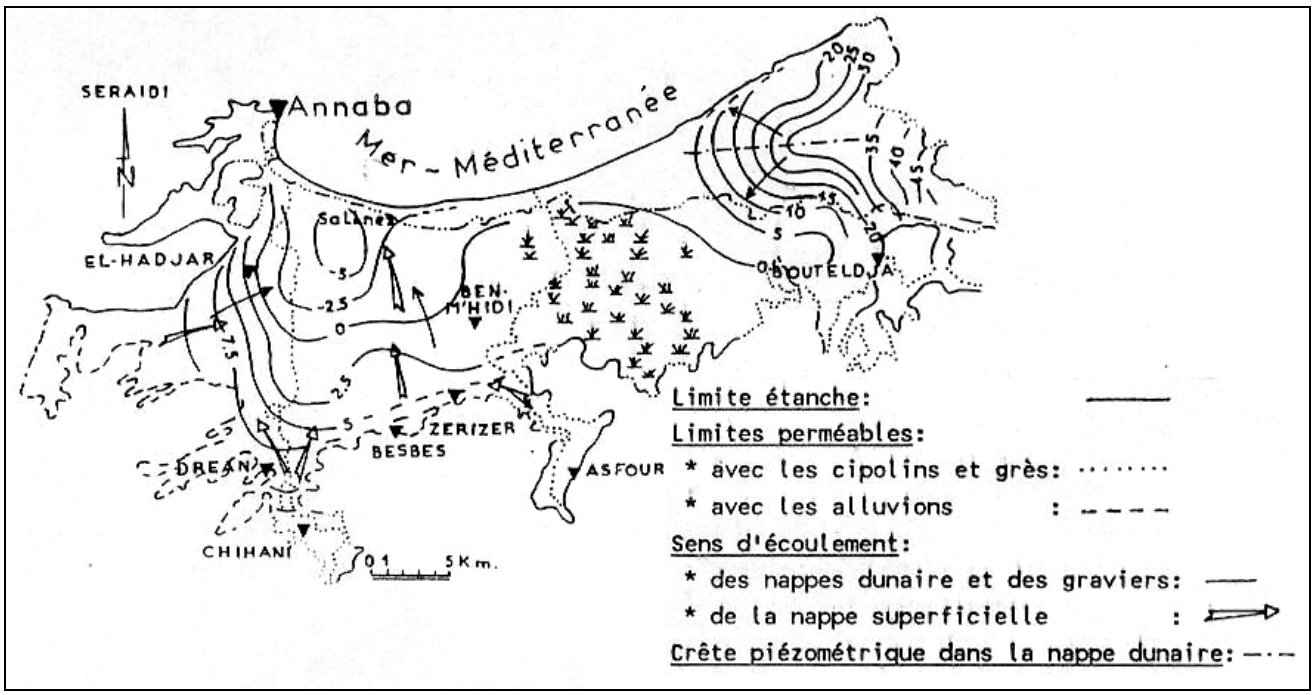


Figure 4a : Carte piézométrique des nappes du système aquifère Annaba-Bouteldja

6.1.2 Relation oxygène 18, conductivité électrique

Le graphique (Figure 6) montrant la relation entre l'oxygène 18 et la conductivité électrique, met en évidence trois familles d'eaux ; le domaine (1) des eaux homogènes qui n'ont pas subi d'évaporation. Dans ce cas les teneurs en oxygène 18 varient entre -5,5% et -7% . La conductivité électrique n'excède pas 1000 Ês/cm ; Ce domaine est composé par des eaux appartenant à la nappe dunaire (5, 6, 8, 14, 16, 18, 22, 24, 25, 33) et à la nappe superficielle (36, 42, 44, 45, 46). (Ces points appartiennent à la nappe des graviers qui devient libre dans le secteur de Dréan-Chihani). Ces points sont influencés par la géologie (sable) et par la proximité du

niveau piézométrique, ce qui implique une inflitration importante et rapide diluant la composition chimique des eaux. La deuxième famille concerne les eaux situées au-dessus de la droite ; c'est le cas des points (35, 39,40, 41) appartenant à la nappe superficielle. Leur composition chimique est influencée par les apports du massif de l'Edough (40, 41) de l'oued Meboudja (35) et de l'Oued Seybouse (39). Par contre, les points 30, 31, 32, 34, appartiennent à la nappe des graviers. Les teneurs en oxygène 18 varient entre -4% et -2% ; la conductivité électrique oscille entre 2000 ÊS/cm et 4000 ÊS/cm. Ce sont des eaux qui ont été réchauffées à des degrés variables avent leur utilisation, et qui correspondent par conséquent à des eaux évaporées. Ces points sont localisés au niveau de Annaba (zone industrielle) ; ces eaux ont été utilisées par l'industrie et rejetées après, ce qui explique le réchauffement. La troisième famille est essentiellement constituée par des eaux appartenant à la nappe des graviers dans sa partie confinée (Figure 9) ; c'est le cas des points (4, 19, 26, 27, 29). Les teneurs en oxygène 18 sont de l'ordre de -6,5% la conductivité électrique peut atteindre 9000 ÊS/cm, montrant que les eaux ont subi une dissolution et une évaporation, ce qui indique une infiltration faible, car elle n'influence pas la composition chimique des eaux.

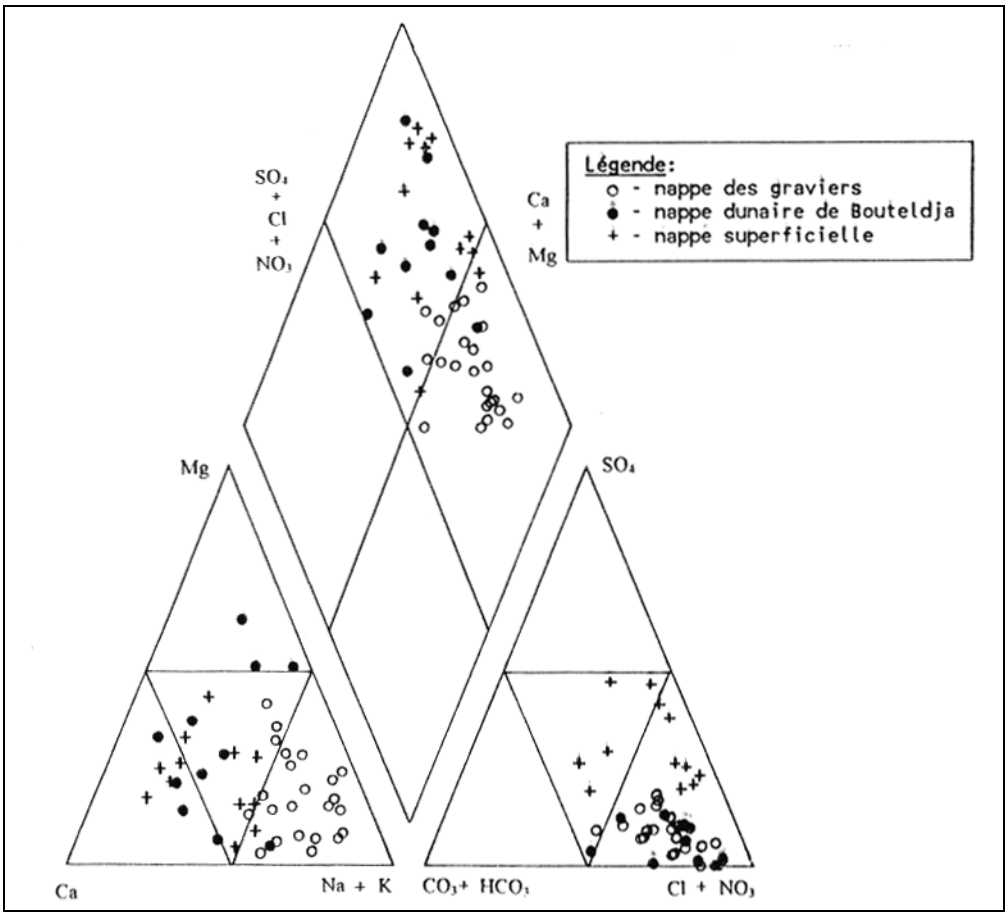


Figure 5 : Diagramme de Piper du système Annaba-Bouteldja

Le graphe de la relation oxygène 18-conductivité électrique (Figure 6) met en évidence l'influence de l'infiltration sur la composition des eaux ; cette dernière est fonction de la perméabilité :

1. Au niveau du massif dunaire constitué de sable de bonne perméabilité, on retrouve les eaux les moins chargées (1^{e} classe), ce qui peut s'expliquer par l'importance de l'infiltration qui représente près de 35% des précipitations.
2. La deuxième classe montre l'influence de l'industrie sur la qualité des eaux.
3. La troisième classe est influencée par l'existence d'un couvert argileux protecteur qui empêche toute infiltration.
4. Rapport entre les eaux des différents nappes.

Sur le diagramme de la Figure 7, nous avons reporté les teneurs en chlorures des eaux, en fonction des compositions isotopiques (^{18}O). Les points représentatifs s'ordonnent suivant un schéma triangulaire qui correspondrait à un mélange de trois types d'eau :

Une eau profonde bien homogénéisée, contenant près de 500 mg/l de chlorures et dont la teneur en ^{18}O est voisine de -6% qui correspond à des eaux du massif dunaire, la nappe des graviers et à un degré moindre, la nappe superficielle.

Une eau à caractère évaporé, relativement ancienne (teneur en tritium assez basse 7,9 et 8,8 UT), contenant près de 1600 mg/l de chlorures et dont la teneur en ^{18}O serait de -2%, qui correspond à une partie de la masse d'eau de la nappe des graviers, peu profonde sur les bordures Sud et Ouest de la plaine de Annaba.

Une eau à caractère évaporé contenant près de 400 mg/l de chlorures et dont la teneur en ^{18}O serait de -2,5% et représente les eaux de la nappe superficielle en relation avec l'Oued Seybouse.
Nous remarquons sur ce graphe que les points d'eau situés entre ces trois pôles correspondent à des eaux ayant des proportions de mélange liées à leur éloignement des différents pôles. Ces mélanges seraient liés à l'infiltration et aux apports par drainance au niveau des zones de captage de la nappe des graviers.

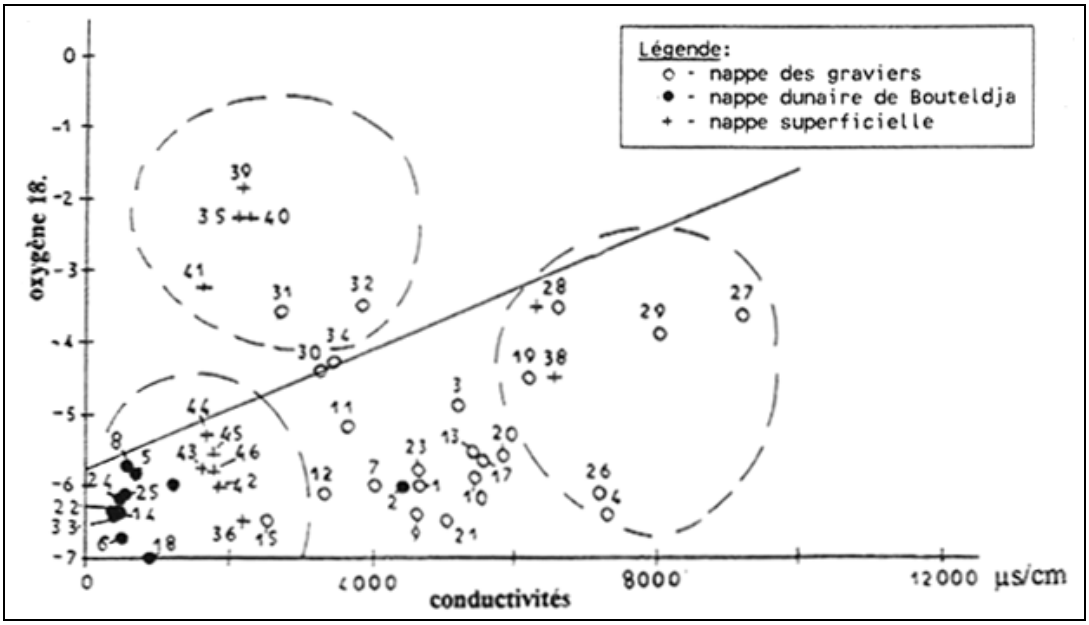


Figure 6 : Relation Oxtgène 18 - conductivité

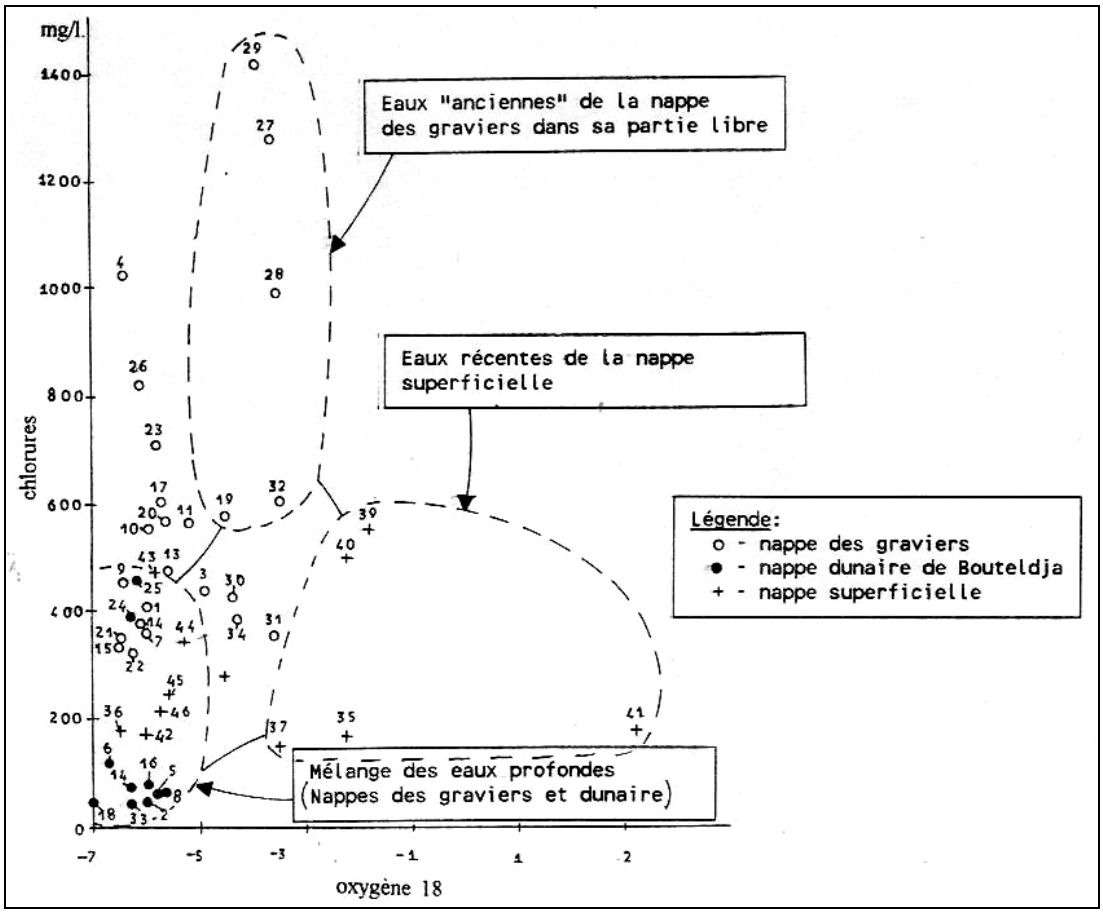


Figure 7 : Relation chlorures - Oxygène 18

6.1.3 Les teneurs en tritium

Le tritium indique le temps de séjour des eaux ; plus les UT sont élevées, plus l'eau est récente. Nous allons comparer les résultats obtenus au niveau des différentes nappes.

Douze points ont été analysés. Il ressort que les teneurs varient entre 5,6 et 24,5 UT. Cette variation nous a permis de dégager trois groupes :

- *1e Groupe* : Les teneurs supérieures à 15 UT correspondent au points d'eau 43.
- *2e Groupe* : Les teneurs comprises entre 6 et 15 UT. Il s'agit des points 35, 36, 37, 38, 39, 40, 42.
- *3e Groupe* : Les teneurs sont inférieures à 6 UT, c'est le cas du point 18.

Tableau 1 : Les eaux de la nappe superficielle de Chihani à Annaba

Groupe **Nature de l'échantillon**	**Groupe 1** **>15 UT**	**Groupe 2** **6<UT<15**	**Groupe 3** **<6 UT**	**Melange entre nappe superficielle et nappe libre**
Nappe ┌ Quaternaire └ Grés Numidiens	43	42		11,11%
Qued		35, 38, 39, 42, 45, 46		55,5%
Rejet		36, 37, 40		27,7%
Source			41	5,5%

Les eaux du 1e groupe ayant des teneurs en tritium élevées, sont considérées comme des eaux ayant la même valeur que celle des précipitations de la station de Tunis-Carthage (44,4 UT en 1975). Ces eaux sont récentes et correspondent aux dernières précipitations qui ruissellent et s'infiltrent directement dans le sous-sol vers les nappes phréatiques.

Par opposition, les eaux du 3e groupe sont considérées comme les plus anciennes du secteur. Leur origine est probablement antérieure à la période des années des essais thermonucléaires (années 50).

Dans le groupe 2, les points d'eaux ont des valeurs intermédiaires allant de 6 à 15 UT, correspondant à des eaux relativement récentes par rapport à celles du 3e groupe et plus anciennes que celles du 1e groupe. Dans ce groupe intermédiaire, plus la teneur est faible et plus l'eau est ancienne, avec l'existence de possibilités de mélanges. Cette catégorie de valeur intermédiaire indique un temps de séjour des eaux

Tableau 2: Les eaux de la nappe profonde, des graviers et de la nappe dunaire

Groupe **Nature de l'échantillon**	**Groupe 1** **>15 UT**	**Groupe 2** **6<UT<15**	**Groupe 3** **<6 UT**	**Melange entre nappe superficielle et nappe libre**
Forage ┌ Sables		6, 8, 12, 16 18, 25, 28	1, 2, 3, 4, 5, 7, 9, 10	23,5%
Grés		33	11, 13, 14, 15, 17, 19,	
└ Quaternaire			20, 21, 22, 23, 24, 26, 27, 29, 30, 21, 32, 34	76,3%

Trente quatre échantillons ont été analysés. L'observation nous a permis de dégager deux groupes :

- *1e Groupe* : Les teneurs sont comprises entre 6 et 15 UT et concernent les points 6, 8, 12, 16, 18, 25, 28, 33.
- *2e Groupe* : Les valeurs sont inférieures à 6 UT, cas des points : 1, 2, 3, 4, 5, 7, 9, 10, 11, 13, 14, 15, 17, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 34.

Les eaux de 1e groupe ayant des teneurs en tritium comprises entre 6 et 15 UT, indiquent des eaux relativement récentes par rapport à celles du 2e groupe. Dans ce groupe intermédiaire, plus la teneur est faible et plus l'eau est ancienne, avec l'existence de possibilitése mélange.

Les eaux du 2e groupe indiquent des UT inférieures 6, ce qui montre que les eaux sont anciennes, ce qui laisse présager une alimentation hors des précipitations, montrant ainsi la présence du phénomène de drainance.

La description précédente met en évidence deux types d'alimentation :

- L'infiltration touche particulièrement la nappe du massif dunaire et la nappe des graviers dans sa partie libre caractérisée par les points 12 et 28 (Figure 9).
- La drainance ; l'interprétation des pompages d'essai a démontré l'existence d'une drainance dirigée du haut vers le bas.

7. Analyse des résultats d'ensemble

L'analyse du cercle des variables (Figure 8) permet l'identification de trois familles selon les axes F1 et F2 ; le facteur 1 distingue les eaux initialement présentes dans l'aquifère (eaux de la nappe des graviers et quelques points de la nappe superficielle dans sa partie captive) des eaux diluées des nappes dunaire et superficielle. Ce facteur traduit donc l'origine spatiale des eaux.

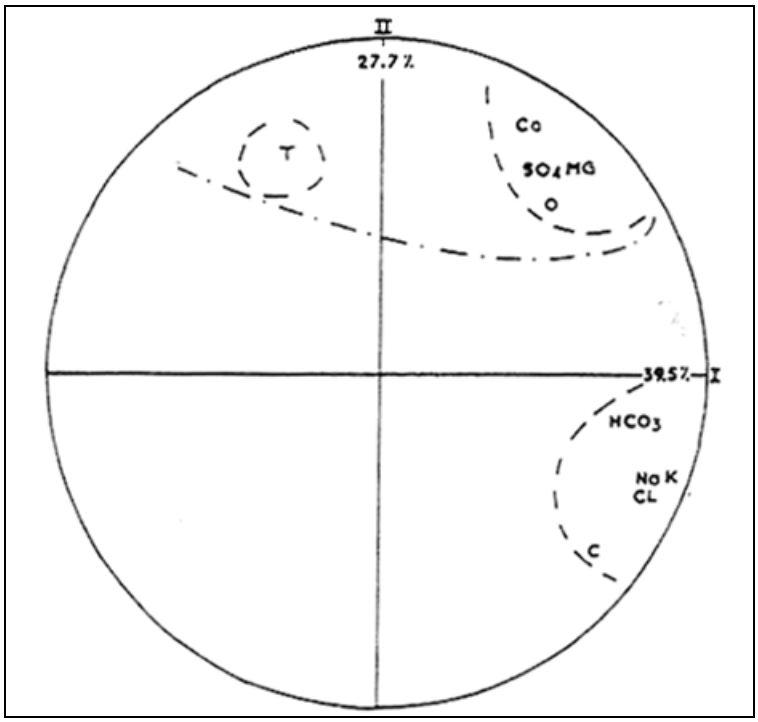


Figure 8 : Cercle ACP dans le plan factoriel (1, 2).
(C : conductivité électrique en µS/cm à 20° C, T : Tritium et O : Oxygène 18)

Le facteur F2 distingue essentiellement les eaux chlorurées sodiques à bicarbonatées de la nappe dunaire (dans sa partie confinée) et surtout de la nappe « profonde » des graviers, des nappes superficielles et dunaire.

Le graphe des individus (Figure 8a) met en évidence les répartitions décrites précédemment, à savoir :

- La famille des eaux riches en tritium : Les points se rapportant à ce groupe, appartiennent à la nappe superficielle et au massif dunaire dans sa partie libre, caractérisée par une forte infiltration.
- La famille des eaux fortement minéralisées : concerne deux groupes : le premier présente une minéralisation importante selon l'axe F1. L'axe F2 indique de fortes UT dans sa partie positive. Ce groupe d'échantillons appartient à la nappe superficielle et à la nappe des graviers.
- La famille des eaux à forte conductivité électrique : Ces eaux sont riches en HCO_3, NaK et Cl, ce qui entraîne une conductivité électrique plus importante. Les UT sont faibles, caractérisant ainsi une eau ancienne. Les eaux appartenant à ce domaine caractérisent la nappe des graviers, d'où l'origine des éléments chimiques observés (la nappe des graviers est libre).

- La famille des eaux faiblement minéralisées : Cette famille se caractérise par une faible minéralisation ; les UT sont faibles, ce qui indique des eaux anciennes et profondes, caractérisant le massif dunaire et la nappe des graviers profonde.

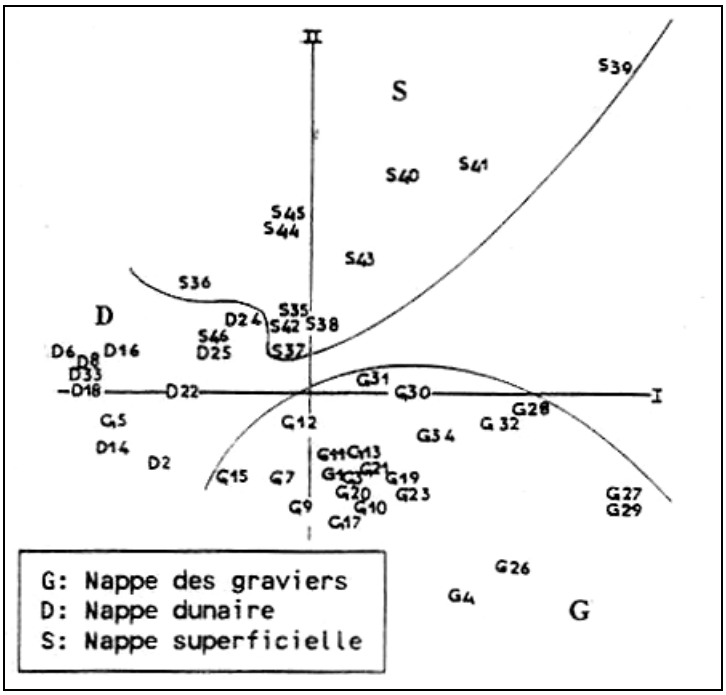


Figure 8a : Graphe des individus dans le plan factoriel (1, 2)

Si l'on tient compte des valeurs recueillies sur le tableau 1, la distribution des points d'eau et les principaux processus naturels et/ou antropiques on peut faire les considérations suivantes :

- Au niveau de la nappe superficielle se localisant à Annaba, on retrouve les eaux fortement tritiées et minéralisées. Cette minéralisation est due à la forte évaporation et à l'influence du lac Fetzara. Les UT sont dues à l'alimentation qui se fait par les précipitations.
- Au niveau du massif dunaire, on a deux familles d'eaux, c'est-à-dire, les eaux faiblement tritiées et faiblement minéralisées, ce qui indique une profondeur assez importante du niveau d'eau, et par conséquent un temps de séjour des eaux assez long, d'où modification de la composition chimique des eaux. Le deuxième groupe montre une minéralisation importante, liée certainement à la faible profondeur du niveau d'eau, ce qui entraîne une influence importante des facteurs climatiques sur la composition chimique des eaux. Les valeurs de tritium indiquent des eaux assez récentes, d'où l'importance de l'infiltration (partie libre de la nappe).
- Au niveau de la Seybouse, on retrouve des eaux récentes fortement minéralisées.

8. Conclusion

Cette étude a permis de mettre en évidence les différents modes d'alimentation dans le système aquifère Annaba-Bouteldja à savoir :

- L'alimentation de la nappe superficielle s'effectue de deux manières assez distinctes : par infiltration des précipitations efficaces et par le drainage des fractures des formations cristallines de Séraãdi.
- La recharge de la nappe des graviers s'effectue également par infiltration des précipitations dans le secteur compris entre Chihani et Dréan et par drainance des formations superficielles, comme cela a été confirmé par les résultats des pompages et des analyses isotopiques.
- Enfin, l'alimentation de la nappe dunaire s'effectue principalement par l'infiltration des précipitations à travers les couches sableuses et des eaux de ruissellement sur les formations gréso-argileuses des massifs numidiens dans sa partie Est. A l'Ouest, le confinement de la nappe dunaire permet d'obtenir une eau ancienne et par conséquent, l'alimentation s'effectue par drainance des formations superficielles.

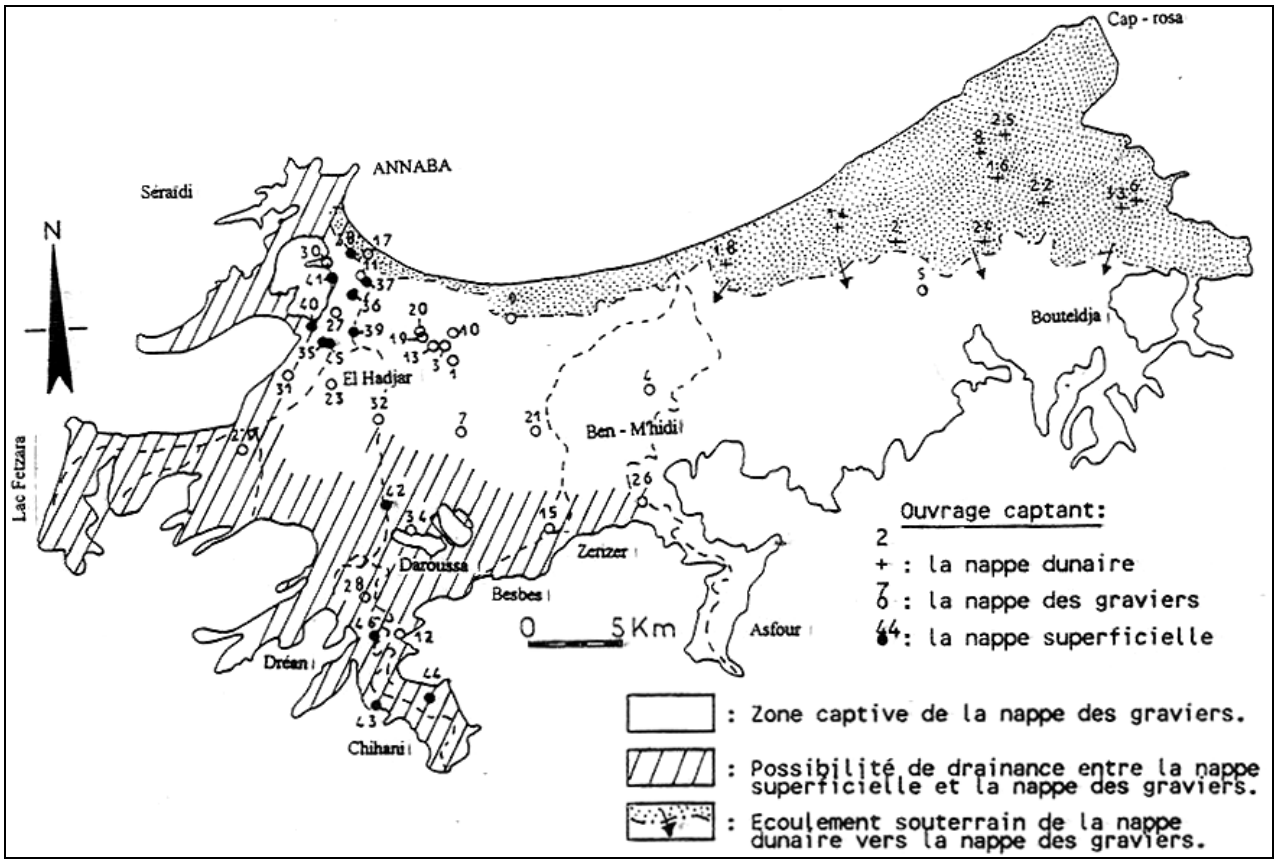


Figure 9 : Carte schématique des écoulements souterrains dans le système aquifère Annaba-Bouteldja.

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Integrated geochemical and isotopic evaluation of regional aquifer systems in arid regions

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Abstract

Some of the important issues relating to the development and management of groundwaters in the large sedimentary basins in arid and semi-arid zones may be addressed with the conjunctive use of inorganic chemical and isotopic tracers. These issues include; the detection of any modern recharge, what is the timing of any recharge, what is the explanation for 3-D variations in quality, how may water quality vary with time, what are the limits if any to potability from natural and anthropogenic causes. Tracers may be considered as inert (e.g. Cl, $\delta^{18}O$), or reactive (e.g. ^{14}C, major and trace cations). Inert tracers may be used to indicate the input conditions – past climate and environments, recharge amount and recharge temperatures as well as mixing relationships. Reactive tracers indicate the influence of the parent rocks on the groundwater chemistry as well as the evolution along lines of flow, as well as defining criteria for use. Under favourable conditions water in the unsaturated zone may record decade or century scale changes in the recharge history. Groundwaters in unconfined or confined strata provide evidence for major recharge episodes in the Holocene or Pleistocene.

It is concluded that the main water quality issues in the palaeowaters (as well as any modern recharge) contained in the major sedimentary basins are a) salinity; b) redox-related problems such as build up of some trace metals such as Cr in the aerobic sections; c) the presence of high NO_3 which may be preserved under aerobic conditions. Development of groundwater in such areas is generally stratified in respect to age and quality and care is required in well construction and development of the (finite) resources.

1. Introduction

The development of groundwater resources in arid and semi-arid regions often proceeds with a limited understanding of the resource base and its origins. Falling water tables in many areas testify to over-development of groundwater, specifically that the rates of groundwater abstraction exceed the rates of natural replenishment from current rainfall or, that a transient condition is produced where water level decline is proportional to the hydraulic diffusivity (transmissivity/storage) of the aquifer (Custodio 1992). Some of the produced groundwater may therefore not represent that which has been recharged during the modern era and in many semi-arid and arid areas the water resources are being mined from recharge from former less arid times.

Prior to human intervention, which has been restricted effectively to the past 50 years, groundwater systems had responded slowly to the hydrodynamic conditions produced by climatic changes over the Pleistocene and especially the Holocene. Small climatic perturbations at the century to decadal scale, such as the little ice age (1550-1800 AD) whilst leading to local variations in recharge rates, probably did not have any long term effects on aquifer storage. Many aquifers contain evidence of significant periods of recharge during the early Holocene or Pleistocene when the global climate and recharge patterns were significantly different from today. In addition, during most of the last 100 000 a sea levels were lower by up to 130m, allowing increased groundwater circulation in coastal areas. Around the time of the rise to modern sea levels by around 7000 BP some extreme wet periods occurred in the mid-Holocene in Africa and elsewhere, which resulted in the most recent recognisable and significant groundwater recharge episodes. Since about 4000 yr BP however the modern era has been characterised by much greater aridity in the Sahara/Sahel.

Aquifers in the large sedimentary basins in northern Africa and the Middle East therefore largely contain non-renewable waters under present day climatic conditions with modern rainfall often having only a marginal impact on the resources. The history of this groundwater emplacement under natural conditions and the interfaces between modern and palaeorecharge can be examined using isotopic and geochemical techniques. Problems exist regarding water sampling since well drilling has had the effect of penetrating aquifers which are naturally stratified both in age and in quality. Pumping invariably results in mixtures of groundwaters from the different layers.

The objective of this paper is to demonstrate and to review how geochemical and isotopic methods may be applied to improve the understanding of the origin and evolution of groundwaters in large sedimentary basins in arid and semi-arid regions. Usually it is possible to combine geochemical approaches with other hydrogeological evaluation, but in some areas (e.g. recharge assessment) geochemical techniques may provide a particularly attractive approach. Several key issues related to groundwater management are addressed in this paper:

1. is modern recharge occurring and if so, how much;
2. if non-renewable resources are proven, what was the timing and mechanism of the recharge event(s);
3. how does the water quality vary in three-dimensions and how may this be explained in terms of both input conditions and water-rock interactions in the aquifer;
4. how may the water quality change with time as development continues;
5. what water quality problems esist in these aquifers as a result of a) natural geological conditions and b) as the the result of human intervention.

Emphasis is placed upon an integrated approach using both chemical and isotopic methods. Illustrations are given using examples from arid or semi arid regions in the Mediterranean (southern Cyprus), and northern Africa (Senegal, Nigeria, Libya and Sudan) with a review in some areas of work in other parts of the world.

2. Available geochemical techniques

The methods available for isotopic and geochemical evaluation may be considered under two categories – inert and reactive tracers. Inert tracers are likely to record information about the inputs to the aquifer, mainly from the atmosphere and the surface environment. Reactive ions or tracers will have undergone some modification due to water-rock interaction and information regarding input conditions will be modified or erased. Nevertherless important information may be recorded related to residence time, subsurface mixing as well as the properties of the groundwater that relate to potability and use. A summary of the most commonly available tools used in groundwater investigations and their uses are summarised in Table 1. Stress is also placed on the need for adequate field measurements of well-head water temperatures (often a proxy for depth), pH, eH, dissolved oxygen and specific electrical conductivity.

2.1 Inert tracers

Chloride is undoubtedly the most useful single tool for water quality investigations. It is not involved in chemical reactions and may therefore be used in mass balance studies such as the assessment of groundwater recharge. It is an inexpensive tracer capable of being measured in most labotratories, although special care is needed to obtain accurate and precise results near the detection limit (Edmunds 1999). Inputs (especially rainfall Cl) and end-members of mixing series must be determined. The measurement of stable isotopes of Cl to a precision greater than 0.09‰ is now possible (Long et al. 1993) making this a useful tracer of Cl source. Chlorine 36 has also been used effectively as a tracer of modern Cl inputs although its reliability as a dating tool is limited by the in situ production of Cl in rocks with a high neutron flux.

Stable isotopes of water (^{18}O, ^{2}H) are well established tracers in groundwater hydrology especially in arid and semi-arid regions and give essential information on the moisture source, evaporative effects, climatic information and recharge history (Clark and Fritz 1997, Cook et al. 1999). Noble gas ratios provide important information on past groundwater recharge temperatures and have been used in demonstrating the amounts of atmospheric cooling during the last glacial maximum (Stute and Schlosser 1993, Loosli et al. 1998). Br/Cl ratios (see below) are also diagnostic of Cl source with Br an inexpensive natural tracer although requiring careful analytical technique at the low concentrations typical of fresh waters.

2.2 Reactive tracers

In some arid zone studies there has been a tendency to use isotopic techniques alone unsupported by geochemical (inorganic) studies. Both are needed since they provide separate but complimentary information on groundwater evolution. Isotopic fractionations resulting from water-rock interaction may also be used to unravel the geochemical processes occurring in groundwaters. In dating studies it recognised that a full understanding of the carbonate geochemistry including data on ^{13}C is required to interpret the measured ^{14}C activities (Clark and Fritz 1997). Both ^{13}C as well as trace elements such as Sr, Fe, released from the carbonates may be used to understand the reaction process where incongruent reactions lead to heavy

isotope or trace element impurities' rejection from the mineral lattice. Trace elements in groundwater form an important group of tracers which provide information on groundwater source rocks, as well as essential information on usage and residence times (Edmunds and Smedley in press). As well as Sr, other elements such as Li which are not affected by mineral solubility limits may build up in groundwater with time. Several isotope ratios (^{11}B, ^{34}S, ^{87}Sr) may also be used to assist interpretation of sources of solutes especially sources of salinity.

3. Renewable vs non-renewable groundwater

3.1 Modern recharge

The extent of any modern recharge is probably the foremost question in semi-arid zone water resources assessment. It is also important to be able to recognise the interface between actively recharged systems and paleowaters. Two main routes for recharge, by diffuse (direct) infiltration or preferential flow via fractured rock systems or wadi channels are possible. Estimates of direct recharge based on empirical formulae are inadequate for low rainfall areas with high evapotranspiration (Gee and Hillel 1988; Allison et al. 1994). One way to overcome this inadequacy is to use the unsaturated zone as a rain gauge. The concentrations of rainfall-derived chloride in the unsaturated zone are proportional to the precipitation less evaporation and under favorable conditions can be used as a long term (decadal scale) estimate of diffuse recharge rates. The chloride estimates may be supported by ^{3}H and $\delta^{18}O$ in cases where detailed studies have been carried out. There are now many examples of the use of chloride to measure recharge in most of the arid areas of the world, for example in north Africa and the Middle East: Edmunds and Walton (1980), Suckow et al.(1993), Edmunds and Gaye (1994), Bromley et al. (1997); in Australia: Allison and Hughes (1978), Allison et al. (1994); in India: Sukhija et al. (1988); in southern Africa: Selalo (1998) and in north America: Scanlon (1991) Phillips (1994), Wood and Sandford (1995).

Representative profiles from two semi-arid regions – the Mediterranean (southern Cyprus), west Africa (Senegal) illustrate the typical profiles observed in sandy Quaternary sediments found in many parts of northern Africa. Results from Cyprus are from Recent dune sediments from the Akrotiri peninsular are used to illustrate the basis of the chloride method (Figure 1). Samples were obtained from field-moist sands collected from a percussion drilled borehole. The overall results from several profiles from the same site are described in detail in Edmunds et al. (1988). The chloride concentrations below the zero flux plane (around 2 m in grass vegetation) oscillate about a mean value (C_s) of 200 mg l^{-1}. The oscillations in Cl have been interpreted in terms of seasonal variations related to periods of wet and dry years. The mean concentration can be interpreted to give the long term (50 yr average) value of recharge (see Figure 1) respectively of 34.4 mm a^{-1}, using a three weighted mean Cl concentration in the rainfall of 16.4 mg l^{-1} at this coastal site. Tritium profiles for this site act as independent confirmation of the recharge rates given by chloride, the peaks marking the position of the 1963 thermonuclear fallout maximum in the rain. The shape of the tritium peaks also confirm that downward movement of moisture (and solutes) is homogeneous with little or no by-pass flow. By-pass (or macropore) flow is restricted in these sediments to the upper 2-3 m and below this depth the water movement is homogeneous. The chloride peaks above 2 m in this and similar profiles probably represent some mineralisation in the soil zone where Cl, concentrated during evapotranspiration, becomes trapped in dead-end pore spaces.

A similar chloride profile was obtained from Quaternary dune sands from north-west Senegal where the water table was at 35 m and where the long term (100 year) rainfall is 356 mm a^{-1} (falling by 36% to 223 mm since 1969 during the Sahel drought). This Cl profile (Figure 2) is supported by ^{3}H and $\delta^{18}O$ profiles. The tritium profile also shows that diffuse recharge is occurring by piston type flow (Aronyossy and Gaye 1992); similar recharge rates are given by both tritium and chloride (Gaye and Edmunds 1996). Stable isotope profiles confirm the trends for evaporative enrichment given by Cl but cannot be used to derive rates of recharge. The average chloride concentration from 7 profiles at this site is 82 mg/l (13 mm a^{-1}).

Having established that all the Cl in this region of Senegal is atmospherically derived, it is then possible to extrapolate the unsaturated zone data to determine the spatial variability of recharge at a regional scale using data from shallow dug wells. 120 shallow wells were used to calculate the distribution of recharge over this 1600 km^2 area of NW Senegal. The regional recharge varies from 20 to <1 mm a^{-1}, corresponding to a renewable resource of between 13 000 and below 1100 $m^3/km^2/yr$ (Edmunds and Gaye 1994).

A limiting condition must exist in arid regions where modern rainfall becomes too low and other factors such as soil type intervene to inhibit any regional or diffuse recharge. Under this condition the unsaturated zone will become saline and geochemical reactions will lead to the formation of indurated crusts. Present day recharge in such areas may still occur via wadi systems. This is well illustrated at Abu Delaig in

the Butana region of Sudan, north east of Khartoum (Figure 3), where prior to 1969 the mean annual rainfall was 225 mm but for the following 15 years was only 154mm (Darling et al. 1987). Profiles drilled in interfluve areas comprising sandy colluvial clays of probable Quaternary age overlying Nubian (Cretaceous) sandstone give recharge rates of <0.1 to 0.78 mm a-1, being effectively zero. The overall recharge situation is shown in Figure 4. The wadi system at Abu Delaig flows for just a few days each year but this is sufficient to allow recharge up to 1 km laterally beneath the interfluves. This is confirmed by tritium which is detected up to 1 km from the wadi line. Wadi systems therefore represent potential recharge lines in areas where the soils or geomorphology are unfavorable for diffuse recharge. In indurated or fractured porous rocks more complex unsaturated zone profiles may develop with tritium penetrating to greater depths (Scanlon 1991, Wood and Sandford 1995). Similar high concentrations of chloride and low recharge rates similar to those described from Sudan have been recognised in Australia (Allison and Hughes 1978) and in southern USA (Phillips 1994).

3.2 Recent recharge history – unsaturated zone records

The unsaturated zone may, under favorable conditions, also preserve an archive of recharge rates and corresponding climatic events at the decadal scale or better, serving as the only part of the hydrological cycle, excepting ice cores, to provide this function. Inert tracers, especially chloride, can provide a record of oscillating recharge events during wetter or drier periods at time scales up to 500 years or more (Edmunds and Walton 1980; Allison and Hughes 1978; Edmunds et al. 1992; Cook et al 1992; Bromley et al. 1997). Much longer records, up to one thousand years, may be preserved in the unsaturated zone of more arid regions (Phillips 1994; Tyler et al 1996).

Under conditions of piston flow, solute (or tritium) inputs derived from the atmosphere should be displaced at regular intervals from the soil horizon into the unsaturated zone, with higher solute concentrations corresponding to lower recharge. The theory of the movement of solutes through the unsaturated zone and the transmission of solute peaks corresponding to recharge episodes, has been described and critically reviewed by Cook et al. (1992). Variations in chemistry will be preserved only if the time scale for hydrological change is large relative to the diffusive timescale. Using the model developed by Cook et al. (1992), a persistence time may be defined which represents the time that it takes for the relative difference in solute (chloride) concentration to be reduced to 20% of its original value (Figure 5). Thus a 20-year event such as the recent Sahel drought should persist at a recharge rate of 10 mm a^{-1} and at a moisture content of 5% (typical of fine grained sands) for around 800 years. The corresponding isotopic (water) signal will be significantly less due to some diffusion in the gas phase. Validation of the observed records over the past decades may be obtained using instrumental records.

An example is given from Senegal where several profiles have been interpreted as archives of recharge, climatic and environmental change for periods up to 500 years (Edmunds et al 1992). For the past 100 years, validation is provided by instrumental records for rainfall and river flow. In Figure 6, one profile (L3) has been calibrated using measured recharge rates, the 3-year record of Cl deposition (2.8 mg l^{-1}) and moisture contents. The profile record is thus calculated to be 108 years, assuming that the Cl flux of around 1g m^2 a^{-1} has remained constant. Assuming that the piston flow model applies, the peaks in Cl at 4-6 m and 6-13 m correspond to the periods of drought from 1970 to the mid-1980's and also in the 1940's; another peak in the 1900's also reflects a recorded drought period. The unsaturated-zone profile is compared (Figure 6) with the rainfall record at St Louis (some 80 km from the research site) dating back to the 1890's (Olivry 1983), and with the Senegal River with records over a similar period (Gac 1990). Whereas the correlation with the rainfall records is moderately good, the correlation with the river flow, representing the regional influence is much better. The correspondence with the main wet phase from 1920-1940 is well shown in all sets of data. During the dry episodes the recharge rate reduced to around 4mm a^{-1} but during the wet phases this rose to as high as 20 mm at this site. Some errors in the rainfall chemistry inputs over the long term might be expected and the rainfall and river flow data may also contain possible errors. Nevertheless, similar records are found in other profiles (Cook et al. 1992, Edmunds et al. 1992) and provide confidence to extrapolate further over longer time scales (over the past 500-2000 years) for which archives from semi-arid continental areas are generally scarce.

3.3 Recharge chronology for the Holocene and Pleistocene – the saturated zone

Isotopic methods have been used widely in arid and semi-arid regions to demonstrate the presence of palaeowaters as well as the timescales of recharge using in particular radiocarbon (see Fontes and Edmunds 1991, Clark and Fritz 1997). From a purely statistical viewpoint it is clear from the evidence now available from some hundreds of radiocarbon analyses that distinct episodes of groundwater recharge must have characterised the Holocene as well as the Pleistocene (Sonntag et al. 1978).

Evidence is found widely in unconfined aquifers in the Sahara and Sahel that groundwater at the immediate water table is of Holocene age (Fontes et al 1993). A good example is provided in the Surt Basin in east-central Libya (Edmunds and Wright 1979). During exploration studies in the mainly unconfined post-Middle Miocene (PMM) aquifer a distinct body of very fresh groundwater (<50 mg l^{-1}) around 100 m deep was found cross-cutting the general NW-SE trend of salinity increase (Figure 7). This feature, around 10 km in width, may be traced in a roughly NE-SW direction for around 130 km where the depth to the water table is currently around 30-50 m. Because of the good coverage of hydrocarbon exploration wells (water supply wells) in this region a three-dimensional impression can be gained of the water quality. It is clear that this feature is a channel that must have been formed by recharge from an ancient wadi. No obvious traces of this river channel were found in this area which had undergone significant erosion, although neolithic artefacts and other remains testified to settlement during the Holocene. Whereas the regional, more mineralised, groundwaters gave radiocarbon values of 0.7-5.4% modern carbon (pmc), the fresh waters gave values from 37.6-51.2 pmc and also were distinctive in their hydrogeochemistry. These younger waters gave ages ranging from 5000-7800 years (uncorrected ages since it was argued that any reaction with the solid phase would have been with active carbonates in the soil zone or with calcretes).

Evidence from shallow wells in the vicinity (Figure 7) proved that fresh and probably younger water was also present at the water table indicating that, simultaneously with the river flows, direct recharge was occurring at a regional scale. The groundwater radiocarbon ages from the area in general increase in age with depth (Edmunds and Wright 1979). Coinciding with the hydrogeological work, palaeoenvironmental studies were being carried out which traced the line of a large, now-inactive river system from the Tibesti mountains (Pachur 1974, 1980). Thus, converging evidence from both above and below ground demonstrate that in the middle Holocene a significant wet phase occurred. Recharge to the aquifer and perennial river flow probably only continued until around 5000 yr BP. Palaeontological evidence including that of large mammals shows that the wadi system was active until at least 3500 BP (Pachur 1975) after which time the present arid conditions (<20 mm yr) commenced with no recorded evidence of modern recharge having reached the water table.

Groundwater recharge, as indicated by ^{14}C data, may also have occurred during the Holocene from flooding as the result of higher river levels or from rivers changing their courses more frequently. This is probably the case for the Nile valley in northern Sudan as suggested by Pachur and Kröpelin (1987) and can be well demonstrated in the wetter Gezira region where dated palaeochannels (Williams and Adamson 1980) correspond to areas beneath which groundwaters of Holocene and Late Pleistocene age may be recognised (Malmberg and el Shafi 1975, Haggaz and Kheirallah 1988). Another example of selective (Holocene) recharge via no-longer-active river channels is provided from the arid region of north-eastern Kenya (Pearson and Swarzenki 1974). Similarly there is evidence of a northern extension of the Niger river in Mali during the Holocene and radiocarbon evidence confirms that this led to groundwater recharge (Fontes et al. 1991) to a distance of some 150 km northwest of the present Niger River bend.

Stable isotope ($\delta^{18}O$ and $\delta^{2}H$ signatures have been used in many studies to distinguish between water from the Holocene and present day from that of the Late Pleistocene. Light isotopic signatures, usually at least 2 per mil more negative in $\delta^{18}O$ characterise the main phase of recharge of most Sahara/Sahel aquifers during cooler climates of the last glacial period (references). This phenomenon is noted from Libya and areas of the central Sahara where values of $\delta^{18}O$ as negative as -11.5 are found (Edmunds and Wright 1979) and also Mali (Fontes et al. 1993) who propose a northward shift of the ITCZ (Inter-tropical covergence zone) producing more intense rains to explain the presence of isotopically light rains (after correction for evaporation effects).

In Sudan regional groundwaters of mainly Holocene age in the Abu Delaig area described in Figure 3 above have distinctive light signatures ($\delta^{18}O$ of -9 to greater than -10 ‰) which contrast with modern waters, including the river Nile (Figure 8). In this example the very distinctive isotopic compositions help to fingerprint the different water masses as well as the recharge processes (Edmunds et al. 1992). Rainfall measured locally shows highly variable composition close to the long term average for Khartoum (although in the drought years indicated here the rains were relatively enriched). Wadi flow lies close to the rainfall line. The River Nile also varies considerably in composition but baseflow from the White Nile with a compositon of up 5.4 $\delta^{18}O$ may be compared with that from the Blue Nile with origins in the Ethiopian Highlands, enabling the conclusion to be drawn that recharge to groundwater is drawn from both Nile sources. Modern groundwaters are however distinct from palaeowaters with the weighted mean composition of -2.2‰ $\delta^{18}O$ and -10‰ $\delta^{2}H$ a difference in $\delta^{18}O$ of almost 7 per mil. Groundwater in the unsaturated zone is highly enriched and in one profile (A) is related to the shallow groundwater. In the second example however, direct evaporation from the near surface palaeowater is indicated (B).

4. Water quality evolution in large regional aquifers

It has already been shown that groundwater mineralisation may be very low in those water bodies recharged during the Holocene. This is likely to be a reflection both of the sedimentary facies as well as the relatively high recharge rates during the pluvial episodes. Most parts of the Sahara south of latitude 28°N comprise continental sediments whereas to the north, marine facies may be found which contain formation waters and intra-formational evaporites contributing to salinity. This can be recognised for example in the Sirte Basin in the sudden change in chemistry (Mg, Sr) as groundwater moves north of latitude 28°30' (Edmunds 1980). In many of the large basins of the Sahara and Sahel therefore the groundwater chemistry, in the unsaturated zone at least, reflects to a significant extent the inputs from the atmosphere (Fontes et al. 1993) as noted earlier for the present day in the unsaturated zone. Superimposed are the effects of water-rock interactions in a mainly silicate dominated rock assemblage. Only in those areas with marine facies is there likely to be significant influence from the adjacent strata by diffusion or cross-formational flow except where faulting occurs.

Several inert tracers especially Br and Br/Cl ratios together with the other halogen elements may be used to follow the sources and evolution of salinity in aquifers where the stable isotopic signatures along with radiocarbon and noble gases can also be used to define the groundwater age relations (Edmunds 1996). An example is given from the Continental Intercalaire in Algeria (Edmunds et al. *in prep*) along a section from the Saharan Atlas to the discharge area in the Chotts in Tunisia (Figure 9). The overall evolution is indicated by Cl which increases from around 200 to 800 mg l^{-1}. The sources of salinity are shown by Br/Cl ratio; the increase along the flow lines for some 600 m is due to the dissolution of halite from one or more sources whilst in the area of the chotts some influence of marine formation waters is indicated (possibly from water flowing to the chotts from a second flow line). Fluorine remains buffered at around 1 mg l^{-1} controlled by saturation with respect to fluorite and iodine follows fluorine behaviour being released from the same source as F, possibly from organic rich horizons. The behaviour of Cl and Br are thus different from Cl and I.

Important changes in reactive tracers (major and trace elements) also occur due to various water-rock interactions which can be followed in (time-dependent) water-rock reactions. In addition to the chemical signature derived from atmospheric inputs, the chemistry of groundwater will be controlled largely during reactions taking place in the first few metres of the unsaturated or saturated zone and reflecting the predominant rock type. Any incoming acidity will be neutralised by carbonate minerals or, if absent by silicate minerals. In the early stages of flow the groundwater will approach saturation with carbonates (especially calcite and dolomite) and thereafter will react relatively slowly with the matrix in reactions where impurities (eg Fe, Mn, Sr) are removed from the minerals and purer minerals are precipitated under conditions of dynamic equilibrium towards saturation limits with other minerals (eg fluorite, gypsum).

During this period of time other elements may build up with time in the groundwater and be able to indicate if the flow process homogeneous or not; discontinuities in the chemistry are likely to indicate discontinuities in the hydraulic connections in the aquifer. An example is given here from the Continental Intercalaire aquifer in Algeria/Tunisia (Edmunds et al *in prep*) showing how the major elements may vary along the flow line (Figure 10). The use of ratios for example of a reactive versus an inert tracer is also helpful. The very constant Na/Cl ratio (wt ratio of 0.65) throughout the flowpath indicates the dissolution of halite with little reaction; at depth a different source is indicated. The Mg/Ca ratio indicates that saturation with respect to calcite (0.60) is approached after a short distance but that this is disturbed at depth by water depleted in Mg, probably the dissolution of gypsum. The K/Na ratio increases along the flow line from 0.05 to 0.18 suggesting a time dependent release of K from feldspars or other silicate source.

5. Water quality issues in arid and semi-arid regions

Exploitation of groundwater in semi-arid regions carries with it certain problems less likely to be met with in temperate areas where recharge is plentiful. Modern recharge rates are likely to be low and therefore salinity in low recharge areas is likely to be relatively high. Other problems relate to redox status of the groundwater, the possible build up of certain elements problematic for health due to long residence times and high nitrate. Problems may also be induced related to development and the protection of palaeowaters, including salinisation due to draw-down near discharge areas.

5.1 Salinity

The geochemical and isotopic approach to groundwater salinity investigations has been recently reviewed (Edmunds 1998) and is not discussed in detail here. In most field situations it is impossible to obtain a

resolution of salinity questions using a single tracer or indicator and conjunctive use of several tracers is required and recommended. The combined use of chloride and the stable isotopes of water ($\delta^{18}O$, $\delta^{2}H$), provide a powerful technique for studying the evolution of groundwater salinity as well as recharge/discharge relationships. A major challenge in the investigation of groundwater salinity is to be able to distinguish saline water of different origins, not least sea water of different generations. Here the ratio Br/Cl is an important tool for narrowing down different sources of salinity, discriminating specifically between evaporite and marine Cl sources. The relative concentrations of reactive tracers, notably the major inorganic ions, must be well understood as they provide clues to the water-rock interactions which give rise to overall groundwater mineralisation. The isotopes of Cl may also be used: ^{36}Cl to determine the extent of infiltration of salinity of modern origin and $\delta^{37}Cl$ to determine the origins of chlorine in saline formation waters. In addition several other isotope ratios: $\delta^{15}N$, $\delta^{13}C$, $\delta^{87}Sr$, $\delta^{11}B$ may be used to help constrain the specific origins and evolution of salinity.

The distribution of salinity in groundwaters of arid and semi-arid zones at or near the earth's surface is closely related to past and present climate since, as discussed earlier, over most of the continental areas of northern Africa and elsewhere solutes are dominantly of atmospheric origin and are concentrated in proportion to evaporation during recharge. Large freshwater reserves were established in the aquifers of arid zones during the late-Pleistocene and, with the lowered sea levels until 8-10 kyr BP, there was the opportunity in coastal areas for freshwater to displace salinity in the areas of former coastlines. The present day distribution of salinity in these areas therefore is mainly a legacy of the onset of periods of aridity since the LGM and especially during the past 4000 yr. It is therefore to be expected that some stratification in salinity of phreatic aquifer systems would be a natural and common occurrence. The recognition and understanding of such stratification is an important requirement for the management of fragile groundwater resources on semi-arid regions, especially the careful design of wellfields.

Human pastoral activities over recent decades, even millennia, have also led to slow changes in the salinity of groundwaters and these effects are clearly seen in the unsaturated zone records at the present day. The effects of population growth and settlement during the Holocene, notably the clearance of vegetation, have promoted land degradation. Where vegetation has been cleared this has had the effect of increasing recharge in some areas, initially releasing salinity but with the net effect of producing lower salinity in the diffuse recharge. In the past decades this is demonstrated most clearly in Australia where both Cl and ^{36}Cl have been used as tracers (Cook et al. 1994). However, in arid areas with shallow water tables the effect of clearance may have led to salinity increase due to rising water tables and increase in evaporative discharge.

5.2 Redox-related build up of inorganic ions

Groundwater in the phreatic sections and in parts of the confined sections of the large basin aquifers of north Africa and elsewhere have evolved under anaerobic conditions. Dissolved oxygen concentrations of several mg l^{-1} may persist in continental, non-carbonate aquifers for many thousands of years as reported from USA (Winograd and Robertson 1982), the Kalahari (Heaton 1984) as well as in red bed aquifers from other areas (Edmunds and Smedley *in press*). These persistent aerobic conditions maintain very low concentrations of dissolved Fe, but may favour the mobility of those elements such as As, Se, Mo, V, U, Cr which can form oxy-anion complexes such as MoO_4^-, CrO_3^{2-} and complexes with carbonate such as $UO_2(CO_3)^{2-}$.

An example in given (Figure 11) here from the Continental Intercalaire aquifer in Algeria/Tunisia (Edmunds et al *in prep*) where a chronology of the flow along the same line has been established (Guendouz et al 1998). A redox boundary is inferred from the abrupt concentration changes for example in Fe and NO_3. As a rule the measurement of both dissolved oxygen (DO) and redox potential (Eh) would define the boundary but in this case was not possible. The redox boundary is found some 300 km from the recharge area of the Saharan Atlas and some 200 km beyond the limit of modern or Holocene groundwaters (based on radiocarbon, stable isotopes, as well as noble gas data). The persistence of DO over this distance demonstrates that the aquifer must be virtually free of organic material, pyrite or other electron donors. In the aerobic section high concentrations of U and Cr are found. These high concentrations, restricted to the aerobic section may present a hazard for drinking water supplies and point to the need to consider a wide range of chemical parameters in evaluating waters from similar aquifers. In contrast it can be seen that Mn which has a wider eH-pH range of stability shows a progressive concentration increase with residence time across the aquifer.

Thus the evaluation of groundwater quality at the development stage should take account of a wide range of inorganic ions the behaviour of which may be predicted or understood based on geochemical principles.

5.3 Nitrate

The aerobic conditions which are found widely in unconfined and many confined continental regions of north Africa and elsewhere also favour the preservation of nitrate. Nitrate remains inert in the presence of dissolved oxygen and, as well as remaining a possible water quality problem during development, may also retain the signature of the environmental conditions at the time of recharge. In the Sirte Basin, Libya, NO_3-N sometimes in excess of 30 mg l^{-1} was originally considered (Wright and Edmunds 1969;) to have resulted from the contact with nitrate-rich shales (Hume 1915). However their widespread distribution later prompted the view that palaeo-environmental factors, related to former vegetation cover, in a region where there is no current recharge, were responsible (Edmunds and Gaye 1997). Near Khartoum in Sudan concentrations of NO_3-N up to 2800 mg l^{-1} were recorded in interstitial waters of unsaturated sediments. These were attributed to very low recharge rates and the accumulation from vegetation over many centuries (Edmunds et al. 1992). In the Kalahari, aerobic groundwaters contain between 4.8 and 37 mg l^{-1} NO_3-N (Heaton et al. 1983) and are explained by a natural origin from the soil. High concentrations of nitrate have also been found in desert soils in America (Marrett et al. 1990; Hunter et al. 1982) associated with vegetation and in Australia (Barnes et al. 1992) where nitrate fixation by cyanobacteria in soil crusts and bacteria in termite mounds are proposed as the most likely explanation. Naturally high nitrate therefore seems to be a common feature of groundwaters in certain arid and semi-arid areas low in organic carbon where aerobic conditions have persisted.

In Figure 12 dated groundwaters from Libya (Edmunds and Wright 1979), Niger (Andrews et al. 1994), Sudan (Edmunds et al. 1992), Mali (Fontes et al. 1991) and Algeria (Edmunds et al. in press) are shown and many of these contain nitrate close to or above the 11.3 mg l^{-1} NO_3-N drinking water limit (WHO 1993). The frequency of occurrence of high nitrate groundwaters appears to be regular through the Late Pleistocene and Holocene and is in line with evidence suggesting no major changes in plant communities, rather a shift northwards of the Sahelian vegetation zones some 500 km during the Holocene (Edmunds 1999). These concentrations are close to the baseline values observed for the region in modern groundwaters, although the cultivation of leguminous crops may lead to still higher NO_3 concentrations (Edmunds and Gaye 1997). Thus it seems that the high nitrate concentrations are an intrinsic property of these groundwaters supporting models of vegetation change and creating a higher baseline condition for nitrate than in temperate regions, with possible implications for water quality standards.

6. Human impacts and groundwater protection

From the previous discussion based on isotope and chemical studies of residence times it is clear that where recharge occurs at the present day rates of movement through the unsaturated zone of the mainly sandy sediments (which occur for example in the populated areas of the coastal Mediterranean) are low and thereby a degree of protection is afforded against diffuse or point source pollution. At the same time, under the widespread aerobic conditions at shallow depths, little attenuation capacity is provided and thus any contamination from agricultural fertilisers and chemicals will tend to accumulate. Significant threats come however from irrigation practices where return waters will increase salinity, and from waste water discharges, where transit times are likely to be rapid. It is beyond the scope of this paper to discuss the various forms of pollution, but it must be emphasized that groundwater protection policies in arid and semi-arid regions require separate consideration to those being formulated in temperate regions.

Salinity changes in stratified aquifers, noted above pose an additional problem for which chemical and isotopic studies are of particular value (Edmunds 1998). Fresh water lenses or layers only a few metres thick, related to modern recharge represent a fragile resource (in some coastal areas for example) and require careful well design and water quality monitoring. Similar problems are a feature of oases and sebkhat areas where shallow groundwater development is very vulnerable to salinisation.

Groundwater quality and water level have been proposed among a series of geoindicators, sensitive indicators of changes in geological systems in the past 100 yr (Berger and Iams 1996). Geoindicators may be linked to other indicators (bioindicators for example) to provide a measure of increase or decrease in management of the environment. Although the range of potential chemical and isotopic species considered separately or collectively is vast, the overall degradation due to human impact can be monitored effectively using a few “indicator” species. Of these, changes in Cl, DOC and HCO_3 invariably define overall trends in the groundwater quality due to human activities although other tracers such as Br and stable isotopes ($\delta^{18}O$, $\delta^{2}\rho$, $\delta^{37}Cl$ for example) may be needed to support conclusions on the origins of contamination.

7. Conclusions

Despite the very large resources of non-renewable palaeowaters in much of the Saharan/Sahel region of north Africa and the Middle East, signs are appearing in some areas that the life span of these is limited due to both quantity and quality. Geochemical and isotopic results provide an essential contribution to defining whether or not the resource is renewable, its origin and scale, as well as to locating the interface between modern and palaeowaters. The issues faced by society in areas where palaeowaters are the primary resource are different to those in areas where measurable recharge of aquifers takes place at the present day. In the latter case the ease of availability of water and the perception often held that water is an infinite resource and that groundwater especially is *per se* a pure resource, has led to carelessness resulting, notably, in pollution problems. In areas with finite, non-renewable resources it is important that the lifetime of the groundwater bodies are not further reduced by factors related to water quality. Some key points may be given in conclusion:

1. An integrated use of geochemical and isotopic methods is needed to interpret both the scientific and water quality issues relating to non-renewable water resources in arid and semi-arid regions
2. Cl, ^{18}O, ^{3}H unsaturated zone profiles can be used to demonstrate the limits to modern direct recharge and also that occurring through wadi systems.
3. Recharge history at the decadal scale may be recorded in the unsaturated zone whereas in the saturated zone millennial scale events can generally be resolved.
4. Water quality evolution occurs along flow lines with distinctive geochemical (major and minor elements) and isotopic trends related to initial inputs, reactions and mixing.
5. A number of quality issues related to natural geological conditions may be found in non-renewable or long residence time groundwaters in semi-arid regions, notably salinity problems, high nitrate and high concentrations of certain elements (eg F, Cr and possibly others)
6. Human impacts create problems by disturbing natural quality stratification, draw-down of saline waters, as well as direct contamination.

Acknowledgments

This overview paper has drawn upon several recent published sources as well as work in press and preparation. The co-authors cited in the bibliography are thanked for their contributions to the range of subjects forming this paper. This paper is published with the permission of the Director, British Geological Survey, Natural Environment Research Council.

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Table 1: Isotopic and geochemical tools used in arid and semi-arid zone investigations with emphasis on diagnostics for non-renewable waters

Geochemical or isotopic tracers	Uses of tracers in arid and semi arid zone basin studies
Inert Tracers	
Cl	Master variable: inert tracer in nearly all geochemical processes; use in recharge estimation and to provide recharge history.
^{36}Cl	Half life 3.01 x 10^5 a. Thermonuclear production. Main use in fingerprinting modern recharge. In rare cases may be used as long-life dating tool.
^{7}Cl	Fractionation in some parts of hydrological cycle allowing fingerprinting of salinity.
Br (Br/Cl)	Important for narrowing down the source of Cl.
NO_3	Inert tracer in aerobic environments. Records past environmental conditions.
$\delta^{2}H$, $\delta^{18}O$	Essential indicators of past climatic conditions (air mass sources and temperature), salinity source (marine vs non-marine) and evaporative enrichment
^{3}H	Half life 12.3a. Essential indicator of modern water.
Noble Gases	Noble gas ratios (Ne, Ar, Kr, Xe) provide groundwater recharge temperatures used in climate reconstruction. N_2/Ar provides index of denitrification in reducing environments.
^{81}Kr	Half life 2.1 x 10^5 a. Promising (if specialist and at present rather expensive tool) for dating of very old groundwaters (cf Great Artesian Basin, Australia)
Reactive Tracers	
Major ions and ratios eg. Mg/Ca	Essential for defining water quality and potability, source areas of recharge, extent of water-rock interaction.
Sr	Use in defining facies changes between carbonate and non-carbonate rocks.
$\delta^{87}Sr$	Indicator of source rocks; indicator of salinity sources.
Minor and trace elements	Indicators of water-rock interaction through release in incongruent reactions (e.g. Sr). Relative indicators of time through progressive build up in groundwaters. Indicators of redox reactions.
^{14}C, $\delta^{13}C$	Half-life 5730a. Carbon 14 essential indicator of groundwater residence times. ^{13}C is necessary for correcting raw ^{14}C data but also may be used independently to follow progressive reactions in the carbonate system.
$\delta^{11}B$	Additional indicator of salinity source.
$\delta^{34}S$	Characterisation of evaporite and other sulphate sources, and sulphur in reducing environments.
$^{234}U/^{238}U$	Residence time indicator for old groundwaters (up to 10000 a). Problems with interpretation due to chemical interactions
^{226}Ra	Half life 1630 a. Promising tool for dating (up to 3-5000 a) in non-carbonate aquifers

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Groundwater resources / Salinity model for Tripoli aquifer

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Abstract

Water Resources is major concern in arid countries. Over-exploitation of existing resources, either reservoir, river and groundwater, can lead to permanent loss and damage. A study has been undertaken for water management in Libya utilising 1 and 2 layered modelling techniques which have indicated groundwater resources will take many hundreds of years to recover from over-abstraction during the past thirty years.

What is essential therefore, is to develop an integrated strategy for agriculture and municipal/industrial supplies which balance the needs of current generations with that of future generations. Thus water resource management should embrace the principles of sustainable development.

This paper discusses the implications of over-abstraction with reference to the Tripoli situation, describing a novel 2 layer model approach to allow for salinity intrusion. The paper goes on to suggest how sustainable water management might be achieved in the region utilising database technologies, and strategic planning for abstraction.

1. Introduction

The Gefara Plain, located in the north western part of Libya, is an important agricultural and populated coastal area, with Tripoli as the principal city with 30% of Libya's 5.6 million population. Increased use of the Upper aquifer below the Gefara Plain for both municipal and agricultural purposes has led to severe depletion of the aquifer and the region has now been subject to several studies that seek to identify the most appropriate water resources strategies. A major consideration of these strategies is the Great Man Made River Project (GMMR), a major development to bring groundwater from sources in the central regions of Libya to the more densely populated coastal regions in the north.

This paper describes the application of a new 2D Groundwater model to the Upper aquifer to the Tripoli aquifer, a 300 km^2 area of the Gefara Plain and the upper aquifer. The study considers the long-term implications for aquifer recovery following the implementation of different water management strategies in the region. Water level and saline intrusion effects in the aquifer for different abstraction profiles are considered.

2. Geohydrogeology

The geology/hydrogeology for Northern Libya is complex. Two studies, (GEFLI 1972 and Krummenacher 1982), provide the most detailed accounts of the aquifer systems in the region. In summary several East-west faults run across the northern part of the country with the Nafusa fault and escarpment dominating the southernmost part of the Gefara Plain (Figure 1). The topography of the region rises from sea level to the north to 200 m above sea level, 50 km to the south.

The principal aquifer used by the population in the Gefara Plain and Tripoli area is the Upper Aquifer, which occur under an unconfined conditions, and consists of mainly Quaternary sandstones and riverine sediments underlain by Miocene sandstone with clay lenses located near the base. The thickness of the aquifer is variable, but is typically 150 m thick, lying immediately below the surface.

Groundwater level is generally between 20-60 m below ground surface, making it a readily available source for economical exploitation. The deterioration in groundwater quality in the immediate vicinity of the coast in recent years provides evidence that seawater intrusion is occurring along the northern coast.

3. Water Resources

The water balance of the Tripoli aquifer system, in terms of recharge and demand is critical in ensuring a sustainable use of any aquifer system. This is especially true of aquifers vulnerable to seawater intrusion such as the Upper Aquifer the subject of this study.

3.1 Rainfall

Average annual rainfall varies between 144 mm to 595 mm pa, but is typically 300-350 mm per annum (pa). Much of this is lost to evaporation and evapo-transpiration, with most studies (Pencol 1978, Krummenacher 1982) of the region estimating the recharge function to be between 5-15% of the rainfall, depending largely on soil moisture deficit for the prevailing year. For this study 37 mm (10%) of rainfall has been considered as recharge (10.36 Mm^3/yr). Recharge from river systems (or Wadis) is not considered to be significant in the Tripoli catchment, although in the wider Gefara Plain Upper aquifer, some recharge is known to take place.

3.2 Groundwater Abstraction

Water is used extensively in the Tripoli region for both domestic supply and agricultural irrigation. Most of this demand has been met until recently by the Upper aquifer, although some abstraction from lower aquifers is taking place. Demand has dramatically increased over the past 30 years and is expected to continue with population growth and agricultural development. The abstraction has been significantly reduced in the past year because of the GMMR project providing 91 Mm^3/yr with the possibility of increasing this to 116 Mm^3/yr. As this new supply is made available, less demand has been paced on the Upper aquifer. Table 1 illustrates the substantial increase in water demand.

Generally, about 45% of the water demand is for domestic supply, and given the current sewerage infrastructure for Tripoli, it is estimated that 25% of this water is returned to the aquifer via leakage and effluent seepage. The other 55% of demand is for irrigation, with 10% considered to be lost to the aquifer (FAO 1979; Krummenacher 1982). After 1996 the water demands from the aquifer has been considerably reduced because of the supplies from the GMMR project, yet recharge continue, because water demand has not been reduced.

4. The Model System

Several Models (Berney 1980; Krummenacher 1982; and NCB and MM 1994) have been developed in the past for the Gefara and Gefara aquifer systems. These have considered the overall water balance of the system in terms of demand recharge and subsequent behaviour of saline intrusion along the northern boundary of the models.

For the purposes of this study looking at the Tripoli aquifer, a new 2D horizontal finite difference model was developed. The model was developed generally so that the description of any 2D aquifer system including boundary conditions could be defined by the data input files alone. An indicator system was deployed to determine whether cells were confined/unconfined, constant head cells or no flow cells. A separate datafile describe the hydrogeologic features of the aquifer, abstraction locations and flows and recharge levels.

A forward time (explicit), but spatially centred, finite difference scheme was used for both the flow and solute equations (Wen-sen and Willis, 1985). The model employs the Gauss-Seidal interactive method for the flow equation, and upwind differencing for the advective components of the solute scheme. While dispersion is included, its effect was secondary to the predominant advection terms. A variable cell size feature that would give more detailed resolution in the region of the model closer to the coastal boundary is also included. The final grid designed for the aquifer simulation was 200 m by 1000 cell size with 24 columns and 72 rows as shown in Figure 2. The timestep for the model was determined using normal stability criteria:

$$\Delta t \leq 0.5 \frac{S}{T} \frac{(\Delta x^2 \Delta y^2)}{(\Delta x^2 + \Delta y^2)}$$

The model was rigorously tested for stability and accuracy for grids of varying sizes, ensuring the mass balance of flow and concentration remained conserved to less than 1% of the total mass of flow and solute.

Some concern might be expressed at the suitability of a depth averaged 2D grid for simulating saline intrusion, which is governed not only by aquifer hydraulic gradients, but also by the density gradients as

described (Reilly and Goodman 1985, Emliki et al. 1996). Indeed the approach here is a simplification of the 3D processes involved. The argument for the approach taken is that reliable data on salinity with depth is lacking because, first many of the boreholes with reported levels of salinity pumping from different levels within the aquifer, and, secondly the upper aquifer itself is a relatively shallow system 150 m compared with the modeled grid dimensions of 21 km by 14 km.

4.1 Model calibration

The northern boundary cells of the model maintained a constant head at sea level, while the eastern, western and southern boundaries were chosen as no flow boundaries. This assumption was based on groundwater levels data assessed and analysed by (Pencol 1978),

4.1.1 Hydrogeologic parameters.

Transmisivity (T) is calculated by multiplying hydraulic conductivity by the saturated aquifer thickness (aquifer height). The aquifer thickness is typically 150 m and therefore any variation in water table will have a significant effect on saturated aquifer thickness and subsequently on the value of Transmissivity. The model calculates the value of transmissivity at every timestep. The hydraulic conductivity is assumed to be a hydrogeological feature of the aquifer material based on the porosity and fissure characteristics of the medium. The value of 1.35 m is within other estimates of hydraulic conductivity (Anderson and Woessner 1992) and was found by the researchers (Berney 1980, Krummenacher 1982, NCB and MM 1994) to give drawdown profiles in keeping with field data. The model thus gave a better representation of the drawdown profile of around abstraction cells by reducing the value of T. Storativity was taken as 0.1, based on previous studies and Porosity as 0.3.

Abstraction was modeled at the cells shown on Figure 2 at locations where much of the region's abstraction takes place.

4.2 Predictive simulation

The purpose of the study is to examine the long-term implications for water quality in the aquifer for particular abstraction scenarios; three modeled scenarios are made, with all assume population will continue to rise at 1% from 1996 onwards (NCB and MM, 1994). The three scenarios are:

Scenario 1 - Abstraction continues for both municipal and agricultural supplies at early 1990 levels, based on the principal supply of water coming from the Upper Aquifer but supported by some lower aquifer supplies.

Scenario 2 - Abstraction for municipal supplies has effectively ceased in 1996 as a result of the GMMR project meeting domestic demands by supplying 91 Mm^3/yr. Under this condition, demand form the aquifer is assumed to drop by the equivalent amount while losses to the aquifer were maintained at 25% of the total water demand.

Scenario 3 - Extends the GMMR capacity yet further to 116 m^3/yr. Reducing the demand on the aquifer further, while maintaining the replenishment levels.

Each simulation starts in 1930 when demand on the aquifer was less than total recharge, giving the model the opportunity to 'warm up' to more representative groundwater levels than the water table at 5m below the surface as an initial start up condition.

4.3 Groundwater levels

Early years show a groundwater profile with flow in a northerly direction towards the coast. No sea water intrusion was reported in these early years. By 1960, the groundwater levels begin to slope in a southerly direction, giving rise to the start of model predictions of salinity in the northernmost cells. Drawdown in the region for the 1980s was widely reported as 4-5 m per annum, broadly similar to the model predictions for the same period.

The comparison of groundwater levels at cell (36,12) in the middle of the model is shown on Figure 3. Here the relative effects of each of the three abstraction and demand scenarios is shown. Scenario 1 with continued high level abstraction continues to show a lowering of groundwater levels, and, in some places, predicted aquifer drying. In reality abstraction would tend to fall off as the cost of abstraction from deeper groundwater levels and poorer quality groundwater became unsuitable for use. What is clear is that, from a water balance view, the continued use of the aquifer at 1996 levels is unsustainable. On the other hand, Scenario 2 shows recovery of the aquifer water levels. While Scenario 3 shows even further improvements in groundwater level recovery.

Figures 4 and 5 further illustrate this recovery. By 1990 the groundwater levels have fallen to 60m below sea level. However, for Scenario 3 in the year 2050, the ground water level is almost leveled with that of the sea, indicating that at this time onwards the levels will reverse saline intrusion. In fact saline intrusion will require greater gradients towards the coast in order to reduce the freshwater displacement caused by the vertical distribution of the more dense saltwater.

4.4 Salinity profiles

The salinity profiles predicted by the model over the 150 year period simulated by the model is shown on Figures 6 and 7 for Scenarios 2 and 3. Scenario 1 could not be shown because of extremely low water level predictions from 2000 onwards. For 1990 the model predicts concentrations of salinity greater than 5 g/m at 300 m from the coast. For Scenario 2, the region affected by concentrations grater than 5m extends 1 km inshore by 2080, although the rate of progress has almost ceased by 2080. For Scenario 3 the saline intrusion is shown to recede, indicating the aquifer is beginning to recover by 2050.

5. Conclusions

The study has shown that aquifers in arid and semi-arid regions where recharge is small will take many years to recovers, even if alternative supplies can be found as is the case for Tripoli. While groundwater levels may indeed return to some degree of normality after say 30 years or so, the problem of high salinity will persist for many years after, simply because the resources have been severely depleted and the recharge is insufficient.

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Hydrogeology of the Great Artesian Basin, Australia

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Abstract

The Great Artesian Basin is a confined groundwater basin, which underlies arid and semi-arid regions across 1.7 million km^2 or one-fifth of Australia. The basin's groundwater resources were discovered around 1880, and their development allowed the establishment of an important pastoral industry. Pastoral activity, town water supplies, mining and petroleum ventures are all totally dependent on artesian groundwater.

The Great Artesian Basin is a multi-layered confined aquifer system, with aquifers in Triassic, Jurassic and Cretaceous continental quartzose sandstones. Intervening confining beds consist of siltstone and mudstone; Cretaceous marine sediments form the main confining unit. The basin is up to 3000 m thick, and is a large synclinal structure, uplifted and exposed along its eastern margin and tilted southwest.

Recharge occurs in the eastern margin, an area of relative high rainfall, and the western margin in the arid centre of the continent receives minor recharge. Regional groundwater movement is towards the southern, southwestern, western and northern margins, where springs discharge and produce carbonate mounds. Potentiometric surfaces of the Triassic, Jurassic and Early Cretaceous aquifers are still above groundlevel, but pressure drawdowns of up to 100 m were recorded from 1880 to the 1980s in developed areas. Some waterbores ceased to flow, necessitating groundwater to be pumped.

Groundwater flow rates range from 1 to 5 m/year as determined from ^{14}C and ^{36}Cl isotopes. Isochrones derived from ^{36}Cl and ^{14}C data correlate with hydrodynamic calculated ages, and residence times range from several thousand years near the marginal recharge areas, to more than 1 million years near the centre of the basin. Environmental isotope and hydrochemical studies confirm groundwater flow patterns and recharge by meteoric water (as shown by ^{2}H and ^{18}O isotopes) from geological to modern times.

About 4700 flowing artesian waterbores were drilled in the main Lower Cretaceous-Jurassic aquifers at depths of up to 2000 m, but average 500 m. Individual artesian flows exceed 10 ML/day. About 3100 controlled and uncontrolled artesian waterbores remain flowing with an accumulated discharge of 1500 ML/day. About 35000 non-flowing artesian waterbores tap shallower Cretaceous aquifers, and each produce on average 0.01 ML/day using windmill operated pumps.

Groundwater quality of the Lower Cretaceous-Jurassic aquifers is good at 500 to 1500 mg/L total dissolved solids. Groundwater chemistry is of the Na-HCO_3-Cl type, and in the southwestern part of the basin of the Na-Cl-SO_4 type. Groundwater is suitable for domestic, town water supply and stock use, though unsuitable for irrigation in most areas. Groundwater temperatures at the boreheads range from 30° to 100° C, and are a potential geothermal energy source, but spring temperatures are 20° to 45°C.

The basin comprises abundant hydrocarbon reservoir (and some source) rocks, and commercial and sub-commercial oil and gas is produced from Jurassic and Cretaceous sandstones, contradicting earlier beliefs that the basin-wide groundwater throughflow had flushed out hydrocarbons.

Keywords:
Hydrogeology, artesian groundwater basin, hydrochemistry, isotope hydrology, groundwater assessment and management

1. Introduction

The Great Artesian Basin is one of the larger artesian basins in the world and is Australia's largest and most important groundwater resource. The Great Artesian Basin extends across 1.7 million km^2 or 22 percent of Australia, and underlies parts of the States of Queensland, New South Wales, South Australia and the Northern Territory (Figure 1). The Basin underlies arid and semi-arid regions and consist mainly of low-lying interior plains and is largely within Australia's rangelands. Highly variable and unreliable rainfall ranges from

an annual average of 600 mm near the eastern margins to less than 100 mm/year near the southwestern parts of the Basin, where evaporation reaches almost 4000 mm/year.

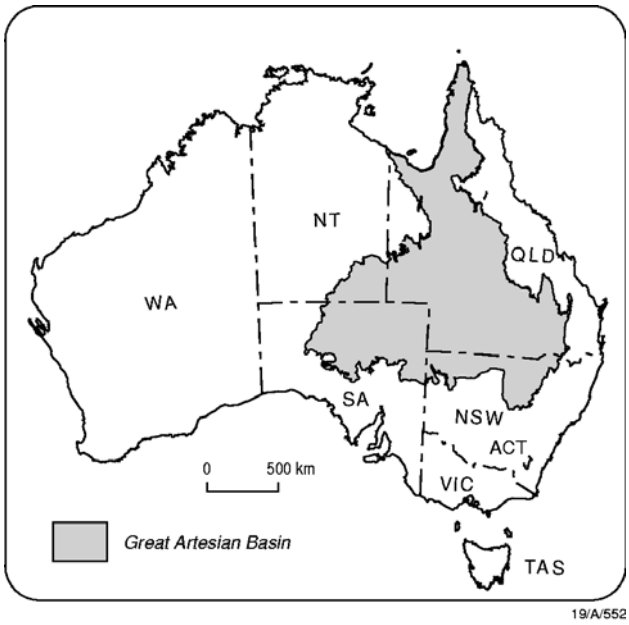


Fig. 1. Location and extent of the Great Artesian Basin, Australia.

The Great Artesian Basin is a confined groundwater basin comprising aquifers in quartzose sandstones of continental origin and Triassic, Jurassic and Cretaceous ages (Habermehl, 1980, 1996, Habermehl and Lau, 1997). The aquifers in the Great Artesian Basin are sheet-like sandstone deposits, which extend across parts or the entire basin. The Lower Cretaceous-Jurassic and Triassic aquifers alternate with confining beds of siltstone and mudstone with low permeability, which are of continental and marine origin and Triassic or Jurassic in age. Overlying the Lower Cretaceous-Jurassic aquifers is the main confining unit, a thick argillaceous sequence of sediments of marine origin and Early Cretaceous age, and these mudstones are overlain by the confined aquifers of Early to Late Cretaceous age (Figure 2).

The Basin is up to 3000 m thick, and forms a large synclinal structure, uplifted and exposed along its eastern margin, and tilted southwest. Recharge occurs mainly in the eastern marginal zone, an area of relatively high rainfall, and large-scale regional groundwater movement is generally towards the southwestern, southern, western and northern margins.

Recharge also occurs in the western margin of the Basin, and groundwater flow directions are towards the southwestern discharge margin. Natural discharge occurs in those areas from flowing artesian springs, most of which have built up mound-shaped deposits of sediments or carbonates. Discharge from the artesian aquifers near the discharge margins also occurs by diffuse leakage where the overlying confining beds are thin. Many springs are associated with structural features, such as faults, folds, monoclines and intersecting lineaments, and occur at abutment of aquifers against bedrock or where confining beds thin near the discharge margins.

Abundant artesian groundwater supplies of good quality are obtained from flowing artesian waterbores, and from pumped artesian waterbores in the Basin. Groundwater in the most exploited aquifers in the Lower Cretaceous-Jurassic sequence generally contains about 500 - 1500 mg/L total dissolved solids. It is of good quality, making it suitable for domestic and town water supply, stock use in the pastoral industry and water supplies for the mining and petroleum industries.

The Great Artesian Basin underlies arid and semi-arid regions, where surface water is sparse and unreliable. The discovery of the Basin's artesian groundwater resources around 1880, made settlement possible, and led to the establishment of an important pastoral industry. Pastoral activity and town water supplies are to a very large extent dependent on artesian groundwater in the Basin area. In recent years artesian groundwater has been used increasingly in the mining (since the 1980s and 1990s) and petroleum (since the 1960s and 1970s) industries located both inside and outside of the Basin area. Most of these industries are largely or totally dependent on the Basin's artesian groundwater resources, including the Olympic Dam copper-uranium-gold-silver mine and the associated town of Roxby Downs south of the Basin in South Australia, several copper-gold and silver-lead-zinc mines in the northwest margin of the Basin, and

oil and gas production in NE-South Australia, SW-Queensland and E-Queensland. Use of artesian groundwater in some areas for irrigation is also on the increase, though generally most of the artesian groundwater is unsuitable for irrigation because in much of the Basin area it is chemically incompatible with the dominantly montmorillonitic clay soils.

Hydrocarbon source and reservoir rocks are abundant in the sedimentary sequence of the Basin, and commercial and sub-commercial oil and gas discoveries have been made in several Jurassic and Cretaceous sandstones (and in underlying Permian and Triassic basin sediments). These contradict earlier beliefs that the Basin-wide groundwater flow had flushed hydrocarbons out of the system. Dissolved hydrocarbons in the artesian groundwater are generally dry gases and are useful petroleum exploration indicators.

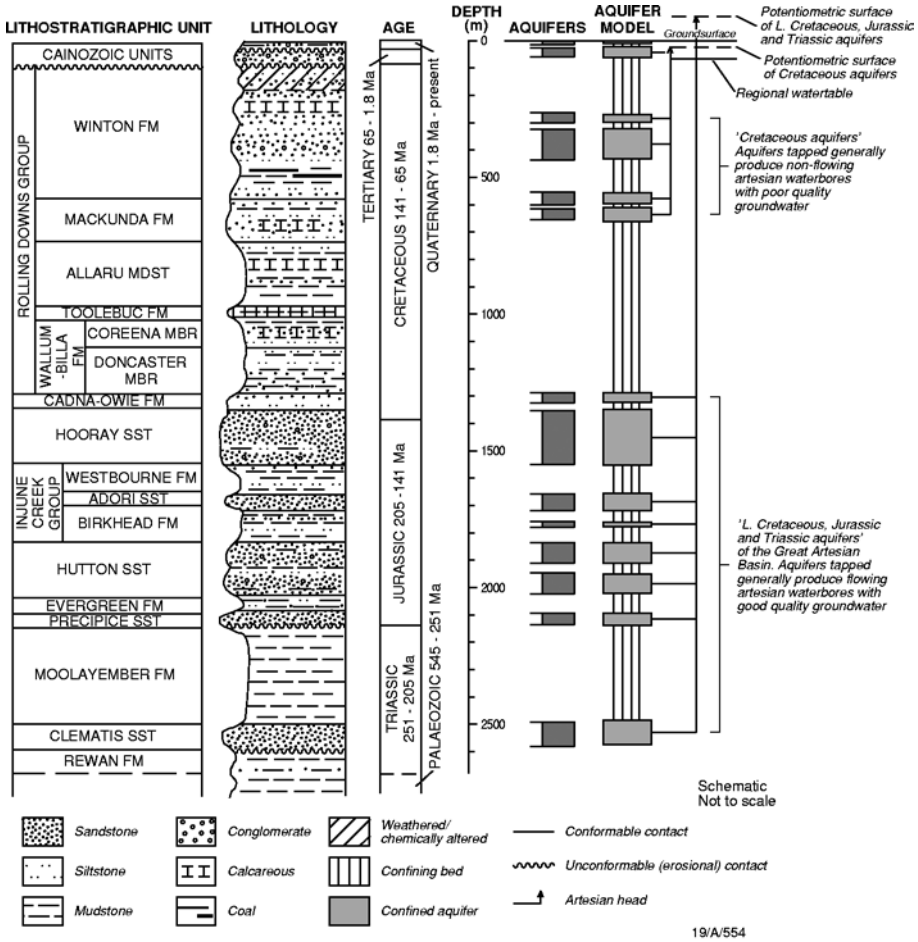


Fig. 2. Schematic lithostratigraphic column of the Great Artesian Basin, simplified aquifer groups and potentials of the main aquifers (after Habermehl, 1980).

2. Geology

The hydrogeological Great Artesian Basin comprises the sedimentary Eromanga, Surat and Carpentaria Basins and parts of the Bowen and Galilee Basins (Figure 3 and Habermehl, 1980). The geology of the Basins has been reviewed in Habermehl (1980, 1986, 1996). The constituent sedimentary basins are continuous across shallow ridges and platforms of older sedimentary, metamorphic and igneous rocks. The Basin consists of several broad synclinal structures trending north and northeast, overlying sedimentary, metamorphic and igneous rocks of pre-Jurassic or pre-Triassic ages.

The Mesozoic sedimentary sequence in the central part of the Basin reaches a maximum total thickness of about 3000 m. Parts of the marginal areas of the Basin have been eroded, in particular along the eastern border, which was uplifted during Cainozoic times. Sheet-like, conformable rock bodies extend relatively unchanged for hundreds of kilometres and are almost horizontal.

The Great Artesian Basin is an asymmetrical basin elongated northeast-southwest, and tilted towards the southwest. Four centres of basin subsidence are present, two coinciding with the Surat and Carpentaria Basins, and two within the Eromanga Basin, separated by the Birdsville Track Ridge, and

overlying the Permian and Triassic Cooper and Pedirka Basins (Habermehl, 1980, Habermehl and Lau, 1997).

Cainozoic and earlier uplift along the eastern margin, and subsidence in several parts of the Basin, particularly in the central and southwestern parts, led to the Basin's asymmetry.

Many of the near surface folds, particularly monoclinal features, grade downwards into faults and are the product of draping and differential compaction of the sediments over fault bounded basement blocks. Several major fault and fold systems occur in the Basin, in places forming en echelon structures.

Throws of up to 300 m affect some major faults, though the displacement of Jurassic-Cretaceous sediments along normal faults is usually much less.

The stratigraphic succession and the distribution and correlation of the rock units and their equivalents of Middle Triassic to Late Cretaceous ages in the constituent sedimentary basins in the Great Artesian Basin are given in Figure 3 and Habermehl (1980, 1986) and Habermehl and Lau (1997). Figure 2 shows the sedimentary sequence and hydrogeological units in the central Eromanga Basin part of the Great Artesian Basin. The Jurassic sequence comprises continental deposited quartzose sandstones, with lesser siltstone and mudstone. Siltstone, mudstone and lithic sandstone were deposited in shallow marine environments during Early Cretaceous times. During the Late Cretaceous more sandy sediments were laid down in lacustrine and fluviatile sedimentary environments.

The Eromanga Basin is deepest where it overlies Palaeozoic and older Mesozoic sedimentary basins. Thinner sequences are present across the shallow ridges and platforms connecting the Eromanga Basin with the Surat and Carpentaria Basins (Figure 3). The southeastern parts of the Great Artesian Basin includes the sedimentary Surat Basin, and the Coonamble Embayment, and consist of an alternation of Jurassic continental sandstone, siltstone, mudstone and some coal. The Cretaceous sediments are partly continental, but mainly shallow marine lithic sandstone and mudstone. The Carpentaria Basin contains continental rocks of Jurassic age, and marine sedimentary rocks of Cretaceous age.

The deeply weathered erosional surface of the Cretaceous sediments in these basins are overlain by Tertiary sediments, which are also partly weathered and silicified, and by mostly unconsolidated Quaternary sediments. The latter overlie parts of the Great Artesian Basin, and are usually up to several tens of metres in thickness, but form shallow basins as much as 150 m deep in some regions. Tertiary basalts cover some areas of Mesozoic rocks in the northeastern, eastern and southeastern parts of the Basin.

3. Hydrogeology

The confined aquifers of the Great Artesian Basin are present within a rock sequence, which, where complete, is bounded by the Rewan Group at the bottom, and the Winton Formation at the top (Habermehl, 1980, Habermehl and Lau, 1997 and Figure 2).

Aquifers are present in the Clematis, Precipice, Hutton, Adori and Hooray Sandstones, and the Cadna-owie Formation and their equivalents, and in the Mackunda and Winton Formations. Most of the individual aquifers are relatively uniform in their hydrogeological characteristics, and they are continuous and hydraulically connected across the constituent geological basins (Figs. 2, 3 and 4).

The major confining beds consist of the Rewan Group, Moolayember, Evergreen, Birkhead, Westbourne, Wallumbilla and Toolebuc Formations, and their equivalents, and the Allaru Mudstone, and parts of the Mackunda and Winton Formations.

The hydrogeological basement underlying the Basin comprises impervious sedimentary, metamorphic or igneous Mesozoic, Palaeozoic and Proterozoic rocks, and this basement forms in part an aquiclude or aquifuge.

The hydraulic characteristics of the confined aquifers have been determined since the early developmentof the Basin from a large number of periodic tests carried out on the flowing artesian waterbores, and during the last 30 years from rocksamples, and from wire-line logs obtained from 1500 waterbores (Habermehl, 2000), and from selected numbers of the 3500 petroleum exploration and production wells in the Basin.

Hydraulic conductivity values range from 0.1 to 10 m/day, the majority being in the lower part of that range, and mainly relate to the Cadna-owie Formation and Hooray Sandstone, and their equivalents including the Algebuckina and Pilliga Sandstones (Habermehl, 1980).

Transmissivity values ascertained from periodic systematic tests by the State Water Authorities, range from 1 to 2000 m^2/day. Storage coefficient values, as calculated from petroleum log data, range from 10^{-4} to 9 x 10^{-5}. Intrinsic permeability ranges from several tens to several thousands of millidarcys. Porosity

values range from 10 to 30 percent. Average vertical hydraulic conductivities of the leaky, very low permeable, confining beds range from 10^{-1} to 10^{-4} m/day. Hydraulic gradients of the potentiometric surfaces of the aquifers in the Lower Cretaceous-Jurassic sequence range from 1: 2000 to 1: 4000 in the central-southwestern part of the Basin. Hydraulic gradients of the aquifers in the upper part of the Cretaceous sequence are about 1: 1800 (Habermehl, 1980).

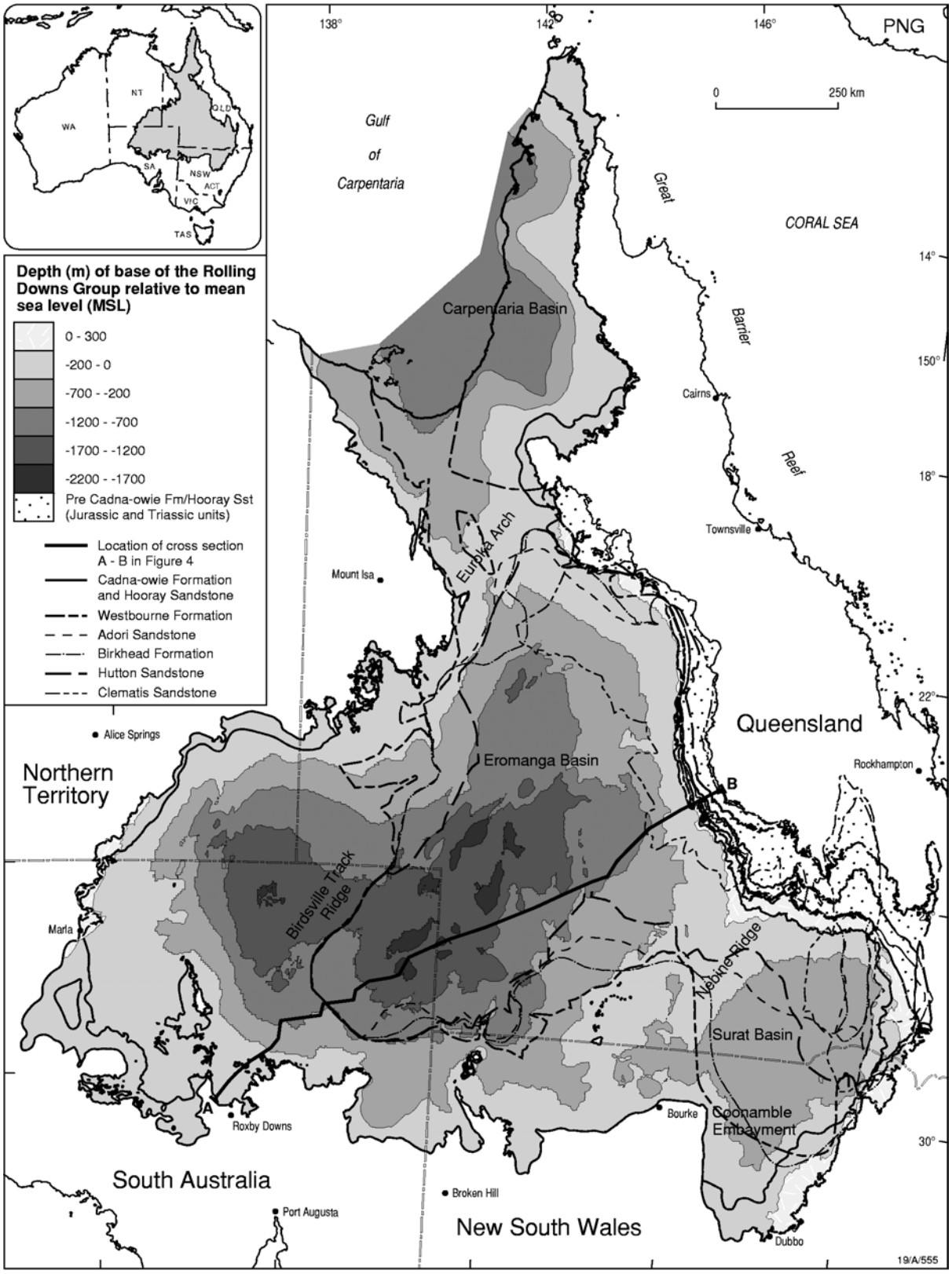


Fig. 3. Extent of the aquifers, and structure contours on the base of the Rolling Downs Group - top of the Cadna-owie Formation - Hooray Sandstone and equivalents.

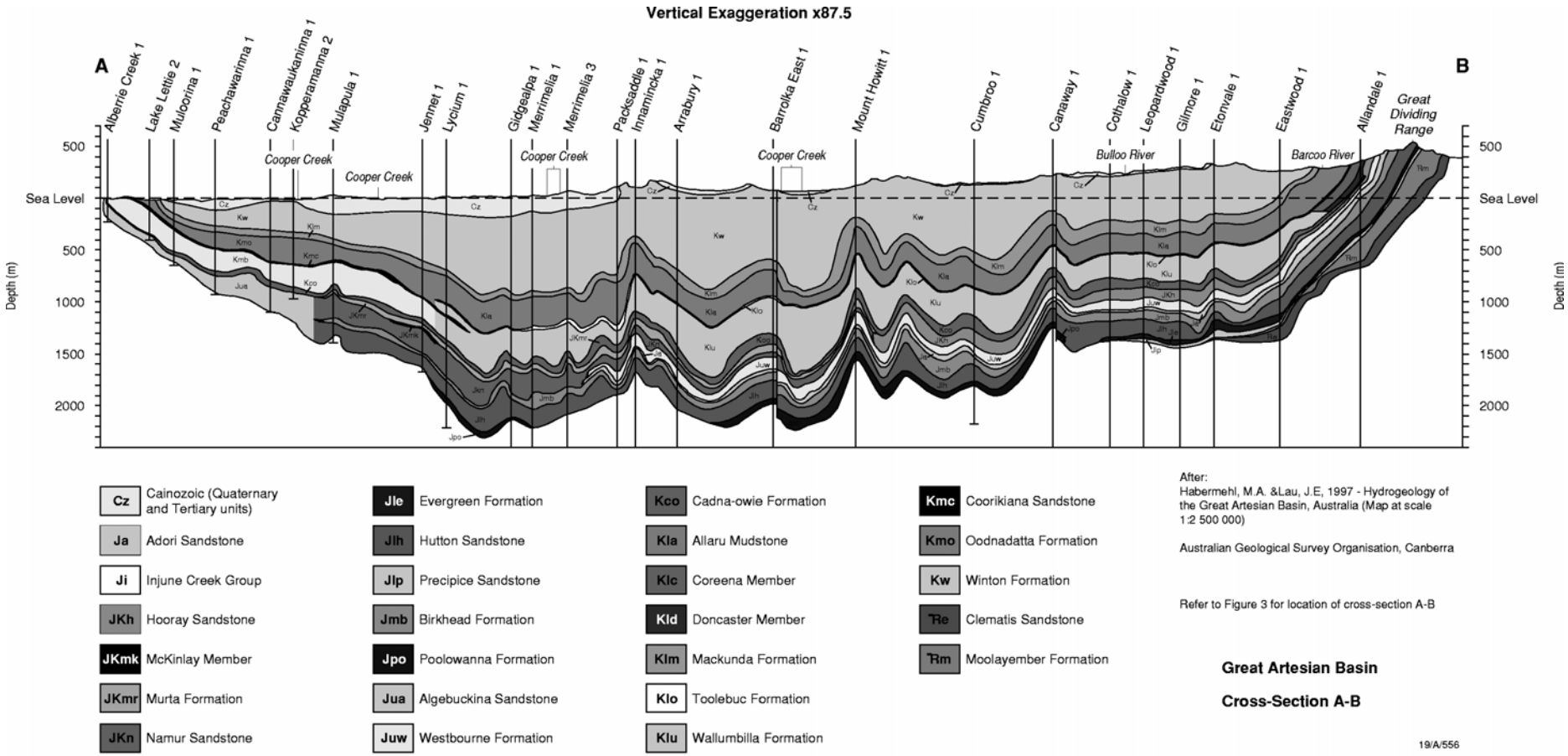


Fig. 4. Cross-section across the Great Artesian (refer to Fig. 3 for location of the cross-section A-B).

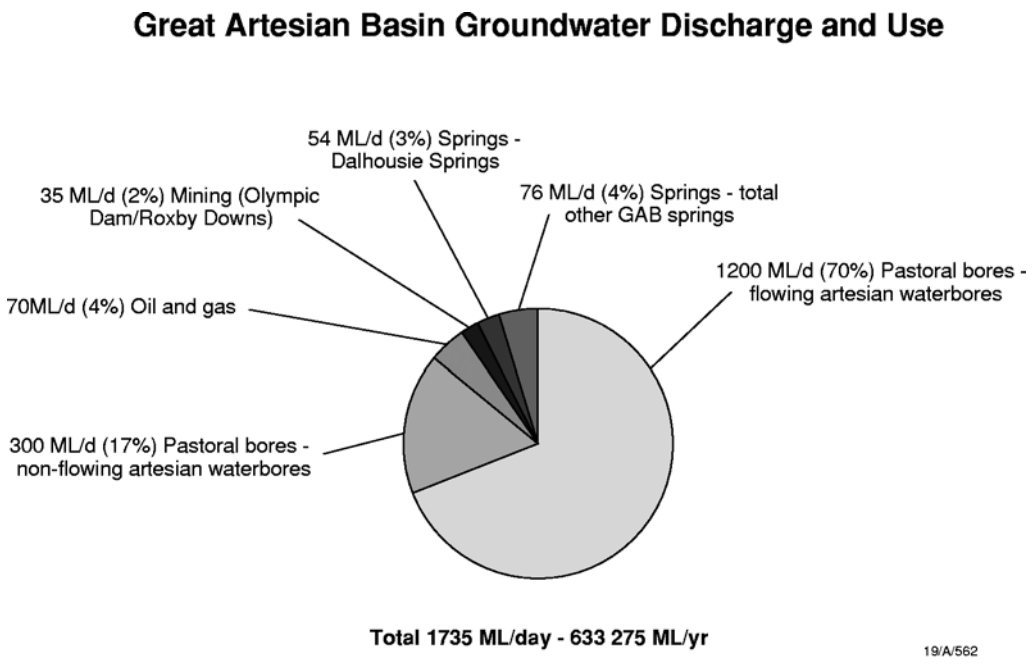


Fig. 5. Groundwater discharge and use in the Great Artesian Basin.

4. Recharge

Recharge of the aquifers by infiltration of rainfall into the outcropping aquifer sandstones and through unconsolidated sediments overlying the aquifers occurs mainly in the outcrop areas of the aquifers along the eastern, elevated, margins of the Basin, which mainly are located on the western slope of the Great Dividing Range. Recharge to the western margins of the Basin, in the arid centre of the continent, where aquifers are exposed or overlain by sandy sediments takes place from high intensity, short duration cyclonic summer rainfall, which occurs once every few years or once a decade or less.

Prior to development, the Basin was in a natural steady-state condition, with an equilibrium between recharge and natural discharge from springs and vertical upward leakage. Following development, natural discharge diminished. A visible effect has been the diminution in flow from springs in the south-central, southwestern and northern parts of the Basin. Abstraction by waterbores caused a large scale lowering of the potentiometric surface and a steepening of the hydraulic gradient, which allowed more recharge water to enter the system. Recharge has been estimated to have increased from 2200 ML/day to 3000 ML/day since the development of the Basin. At present a new approximate steady-state condition has been reached in which total recharge and discharge are approaching equilibrium again, and the sum of the discharges (Figure 5) and the vertical leakage are assumed to equal the recharge.

The discharge from waterbores equals about half of the recharge to the Basin, and based on rainfall and the areal extent of the aquifer outcrops, equals about 1 percent of the average annual amount of water available for recharge (Habermehl, 1980).

An approximate waterbalance for the Great Artesian Basin shows:

- Recharge (approximately 3000 ML/day) = Discharge (approx. 1750 ML/day, including springs and waterbores, Figure 5) + Vertical Leakage (approx. 1250 ML/day, including some subsurface outflow).

The potentiometric surface of the confined groundwater in the aquifers of the Lower Cretaceous-Jurassic rock sequence indicate the directions of flow of the groundwater (Figs. 6 and 7). Environmental isotope and hydrochemical studies of groundwater from drill-holes in the recharge areas, and from waterbores located downgradient of the recharge areas, and towards the centre of the Basin, have confirmed the increase in residence times and determined the flowrates and flowpatterns of the artesian groundwater predicted from the hydrogeological analyses and the potentiometric surfaces (Airey et al., 1979, 1983, Calf and Habermehl, 1984, Bentley et al., 1986, Torgersen et al., 1991, Herczeg et al., 1991, Habermehl et al., 1993, Cresswell et al., 1996, Radke et al., 2000). These studies show that the artesian groundwater is of meteoric origin and also support an assumption of continuing recharge from geological to modern times. More detailed studies of the recharge areas and quantification of the recharge are required and hydrogeological, hydrochemical and isotope investigations have been carried out during the 1990s and are continuing.

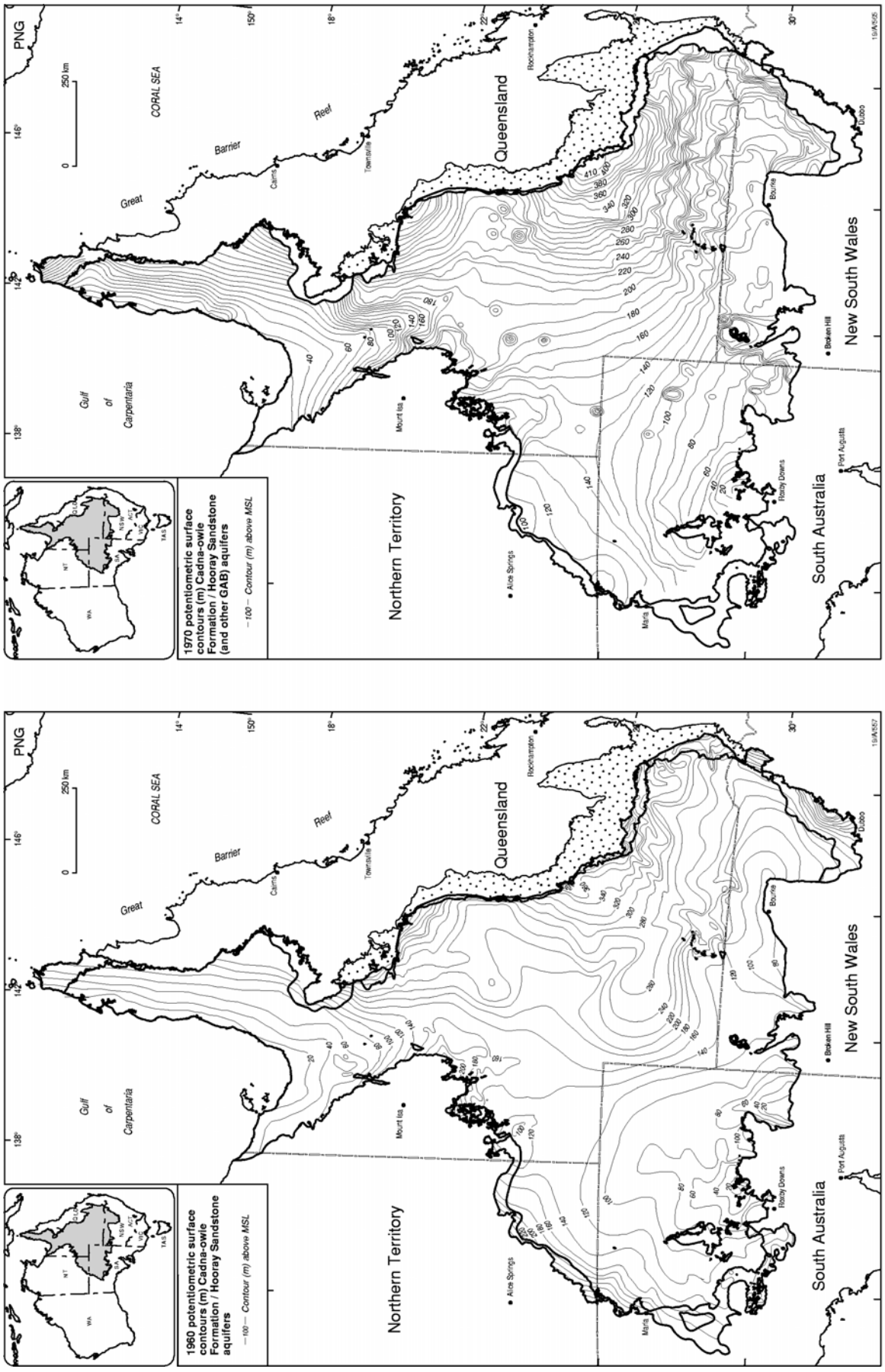


Fig. 6. Potentiometric surface map 1960 - Cadna-owie Formation/Hooray Sandstone aquifers (a), (after Welsh, in prep.); Potentiometric surface map 1970 - Cadna-owie Formation/Hooray Sandstone and other GAB aquifers (b), (after Habermehl, 1980).

5. Discharge

Discharge from the Great Artesian Basin aquifers takes place as natural discharge in the form of concentrated outflow from springs, vertical leakage from the Lower Cretaceous-Jurassic aquifers towards the Cretaceous aquifers and upwards to the regional watertable, subsurface outflow into neighbouring basins, and as artificial discharge by means of free or controlled artesian flow and pumped abstraction from waterbores drilled into the aquifers (Habermehl, 1980). Diffuse discharge from the artesian aquifers through the confining beds towards the groundsurface occurs in the marginal areas where the confining beds are relatively thin, potentials are high, and watertables shallow (Woods et al., 1990).

Springs and areas of seepage are abundant in the marginal areas of the Basin, particularly in the southern, southwestern, northwestern and northern areas. Most springs are concentrated in groups, covering relative small areas. Eleven groups have been identified in the main part of the Basin (Habermehl, 1982), and several springs exist in the far northern part of the Basin. Rates of discharge from the springs are generally low, and range from less than 1 L/s to about 150 L/s (the latter from a spring at Dalhousie Springs, northern South Australia). The temperatures of the springwater range from about 20^0 to 45^0 C. Total spring discharge is estimated at 130 ML/day (Figure 5), with 54 ML/day being produced from the Dalhousie Springs.

Springs are quite common in the recharge areas along the eastern margins, but most of these springs are the result of "overflow" or the "rejection" of recharge into the aquifers, or result from the intersection of the local topography and aquifers.

Flowing artesian springs within the Basin and in the discharge margins of the Basin are generally associated with structural features, such as faults, folds, monoclines and intersecting lineaments. Upwards groundwater flow along faults is the source of many springs, and also the abutment of aquifers against impervious bedrock, and pressure water breaking through thin confining beds near the discharge margins of the Basin. Many springs have built up conical mounds several metres to several tens of metres in diameter, and up to several metres high. The mounds are formed by deposition of particles brought up from the aquifers and the confining beds, and by the chemical and biological precipitation of solids dissolved in the artesian groundwater. The artesian springs are terminal evaporitic systems, usually comprising a central carbonate mound, with outer zones dominated by sulphate and chloride salts. Mound morphology is controlled by several factors, including groundwater discharge rates, hydrochemistry, evaporation, influence of inorganic versus organic carbonate precipitation, local subsidence of the mound and micro-tectonics. In some areas the mounds consist mainly of particles brought up from the confined aquifers and the confining beds, and form mud mounds and mud volcanoes. Many mounds, particularly those built by springs in the western and southwestern margin of the Great Artesian Basin, consist of carbonate. The latter are dominated by calcite and dolomite, and occur as tufa, travertine and very fine-grained or crystalline carbonate, which was deposited as a chemical precipitate out of the artesian groundwater, and precipitated by a combination of chemical, algal and bacterial action. Terraced mounds and waterfall or cascade deposits produced by algae are common, though many accumulations consist of steeply sloping mounds.

Artesian springs and their deposits in the Lake Eyre region in the southwestern part of the Basin range from topographically high springs to younger, topographically low springs as a result of the lowering of the land surface and spring outlet levels in Quaternary times (deposits of extinct pre-Quaternary springs occur more than 40 m above the present springs). This also indicates that the potentiometric surface in the Lake Eyre region has declined considerably during recent geological time (Habermehl, 1982). Morphological diversity and lithofacies patterns indicate that the spring complexes have developed over several climatic cycles. The ages of spring deposits range up to 700 000 years or more, and the ages of several basal spring deposits, as determined from ^{14}C, U/Th, thermoluminescence and palaeomagnetic studies suggest that some springs might have been (re-) activated as a result of major climatic changes.

Fossil carbonate spring deposits of Pleistocene ages, consisting of very fine-grained carbonates with abundant reed casts, gastropod shells and algal structures, rise several tens of metres above the present land surface where the present active springs (and Recent spring deposits) occur. The higher, older spring carbonates cap circular mesas and hills and overlie pedestals of Cretaceous mudstones.

Vertical leakage from the aquifers upwards through the semi-pervious confining beds occurs throughout the Basin, and despite the low percolation rates, involve a considerable volume of water, which constitutes a major part of the groundwater throughflow of the Basin. A deep phreatic surface, usually at several tens of metres (60 to 80 m) below the groundsurface, generally conceals the vertical leakage.

Groundwater in the Great Artesian Basin has been exploited from flowing artesian waterbores since artesian water was discovered in 1878, allowing an important pastoral industry to be established. Waterbores are up to 2000 m deep, but average about 500 m. Artesian flows from individual bores exceed 10 ML/day (more than 100 L/s), but the majority have much smaller flows. About 3100 of the 4700 flowing artesian waterbores drilled in the Basin, remain flowing. The accumulated discharge of these waterbores (including

some town water supply bores) is about 1200 ML/day, compared to the maximum flow rate of about 2000 ML/day from about 1500 flowing artesian waterbores around 1918.

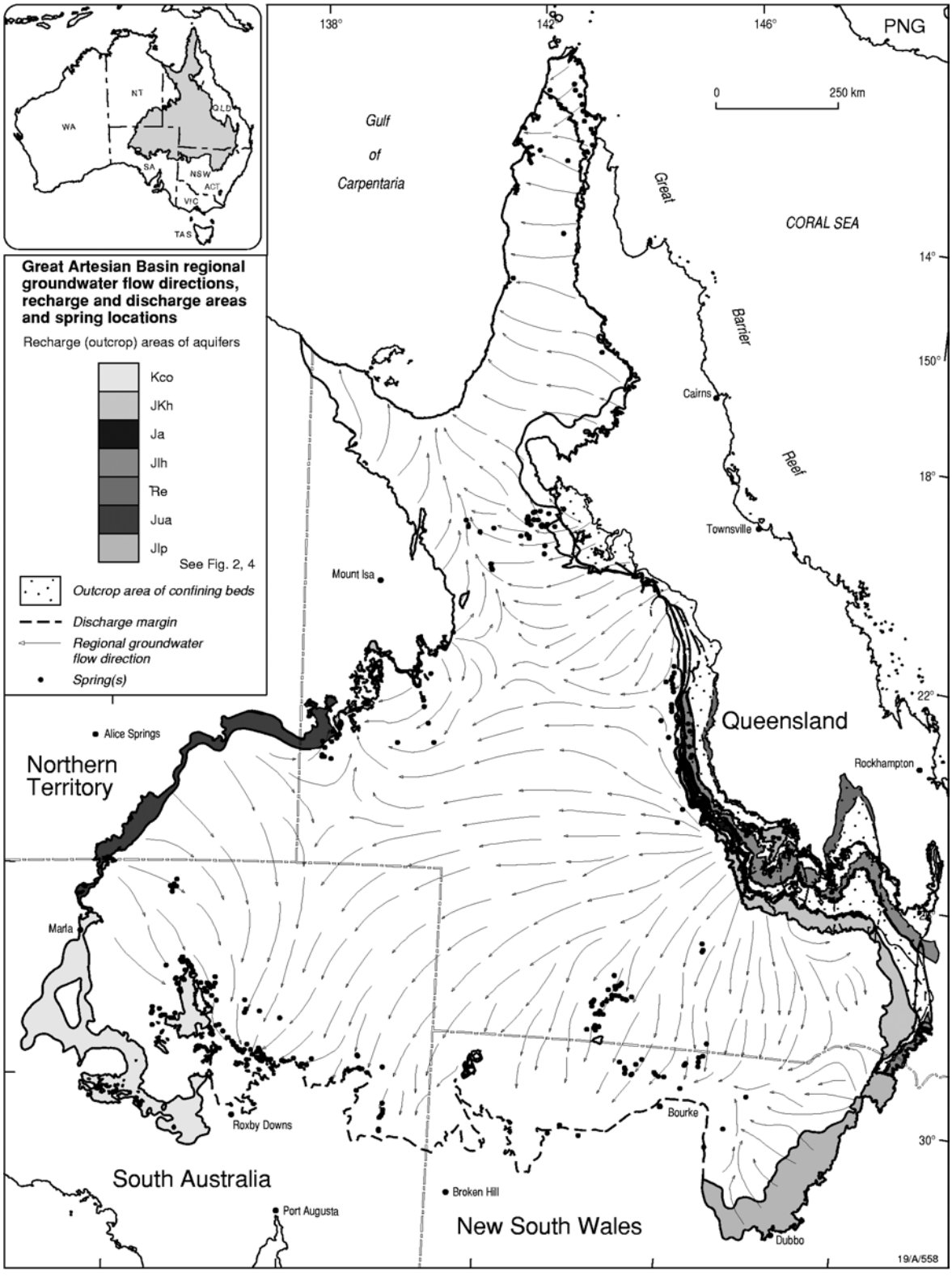


Fig. 7. Regional groundwater flow directions in the Cadna-owie Formation - Hooray Sandstone aquifers, recharge and discharge areas, and locations of flowing artesian springs in the Great Artesian Basin (after Habermehl, 1980, Habermehl & Lau, 1997).

Flowing artesian bores obtain their groundwater from aquifers in the Lower Cretaceous and the Jurassic sequence (mainly the aquifers in the Cadna-owie Formation, Hooray, Algebuckina and Pilliga Sandstones and their equivalents). The original non-flowing artesian waterbores generally tap the aquifers in the Winton and Mackunda Formations. These non-flowing bores, which number about 35000, are generally

shallow i.e. several tens to hundreds of metres deep. It is estimated that these generally windmill-operated pumped waterbores supply on average 0.01 ML/day, and produce a total of about 300 ML/day (Figure 5). High initial flow rates and pressures of artesian waterbores have diminished as a result of the release of water from elastic storage in the groundwater reservoir, and approach a steady-state condition in many areas. Exploitation of the aquifers has caused significant changes in the rate of various discharges in time (Habermehl and Seidel, 1979; Habermehl, 1980; Seidel, 1980).

Spring discharges have declined as a result of waterbore development in many parts of the Basin during the last 120 years, and in some areas springs have ceased to flow.

6. Groundwater movement

Regional lateral groundwater movement in the aquifers in the Basin has been interpreted from the potentiometric surface maps of the aquifers in the Jurassic and Lower Cretaceous sequences (Figs. 6 and 7). Flow directions are generally towards the south, southwest, west and north. In the western part of the Basin regional groundwater movement is towards the southeast and south. Groundwater movement is slow, and based on hydraulic data probably around 1 m/year, as hydraulic conductivities and gradients are low and porosities high.

Groundwater residence times determined from carbon-14 and chlorine-36 studies range from several thousands of years near the recharge areas to more than one million years near the centre of the Basin. The flow rates and groundwater residence times in the Lower Cretaceous-Jurassic Hooray Sandstone aquifer (and its equivalents) as calculated from hydraulic data are consistent with the residence times derived from environmental isotope studies carried out on artesian groundwater from flowing artesian waterbores tapping this aquifer throughout the Basin (Airey et al., 1979, 1983, Calf and Habermehl, 1984, Bentley et al., 1986, Torgersen et al., 1991, Herczeg et al., 1991, Habermehl et al., 1993, Cresswell et al., 1996, Radke et al., 2000).

The potentiometric surfaces of the confined aquifers in the Lower Cretaceous-Jurassic sequence were above the groundsurface over almost the whole of the Basin before exploitation began around 1880. Since then the regional potentiometric surface of the exploited aquifers in the sequence has dropped by several tens of metres in many heavily developed areas (Figure 8). It is still above groundlevel in most of the Basin, though in some areas flows from artesian waterbores ceased and water has to be pumped. The potentiometric surface of the confined aquifers in the upper part of the Cretaceous sequence (Winton and Mackunda Formations, Figure 2) has always been below the groundsurface, consequently waterbores tapping these aquifers are non-flowing artesian and have to be pumped.

Potentiometric maps showing the conditions during the early years of development and the 1970s for the main aquifers in the Lower Cretaceous-Jurassic sequence, which produce flowing artesian wells, are given in Habermehl (1980). These maps were produced from the results of the large number of periodic measurements carried out on the flowing artesian waterbores since the early development of the Basin, and computer simulation modelling of the hydrodynamics of the Basin (Seidel, 1980).

Development of the artesian groundwater resources has led to considerable changes in the patterns of the potentiometric contours, and the changes in waterlevels as a result of the regional drawdowns are shown in Figure 8 (after Habermehl, 1980). Predicted drawdowns, changes in discharges and predicted potentiometric surface maps as a result of possible future developments are shown in Habermehl and Seidel (1979) and Seidel (1980). Pressure drawdowns of up to 100 m were recorded between 1880 and 1970s/1980s (Figure 8), and also reflect the location and density of the flowing artesian waterbores in those regions (Habermehl, 1980, Habermehl and Lau, 1997). Recent MODFLOW modelling of the 1960 steady-state condition for the Cadna-owie Formation - Hooray Sandstone aquifers across the entire basin has produced a new potentiometric surface map for these aquifers (Welsh, in prep., Figure 6).

The confined aquifers in the Lower Cretaceous-Jurassic sedimentary sequence are sheet like deposits, which are relatively uniform, and extend for hundreds of kilometres. The aquifers are continuous across shallow ridges and platforms of older rocks. In some areas faults locally displace or disconnect aquifers, and obstruct part or all of the groundwater flow in the main Lower Cretaceous-Jurassic aquifers, which is normally directed to these structures. These faults could act as permeable or impermeable barriers, either to groundwater or to hydrocarbons migrating in the sandstones (Senior and Habermehl, 1980). Other impermeable barriers could occur in the aquifers, and be barriers of stratigraphic or diagenetic origin. Part of the north-south striking Canaway Fault (east of Canaway-1 in Figure 4) appears to be a preferential permeable zone along which groundwater moves from Jurassic aquifers upwards into Cretaceous aquifers (Habermehl, 1986). Upward vertical leakage from the Lower Cretaceous-Jurassic aquifers into the aquifers of the Winton and Mackunda Formations probably accounts for a substantial part of the groundwater discharge from the former aquifers and influences groundwater movement on a local and regional scale.

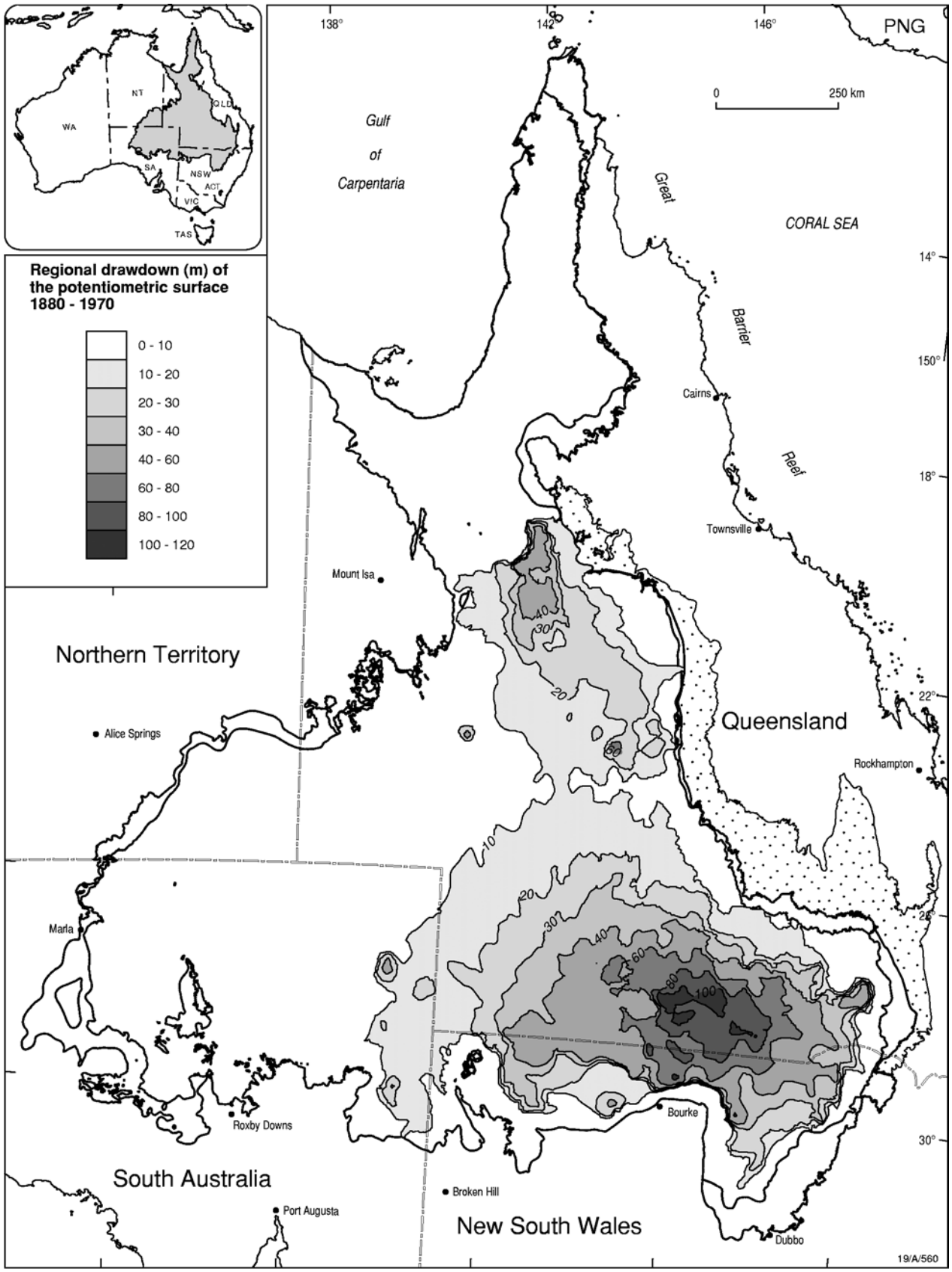


Fig. 8. Regional drawdown of the potentiometric surface of the Cadna-owie Formation - Hooray Sandstone aquifers in the Great Artesian Basin for the period 1880 - 1970 (after Habermehl, 1980, Habermehl & Lau, 1997).

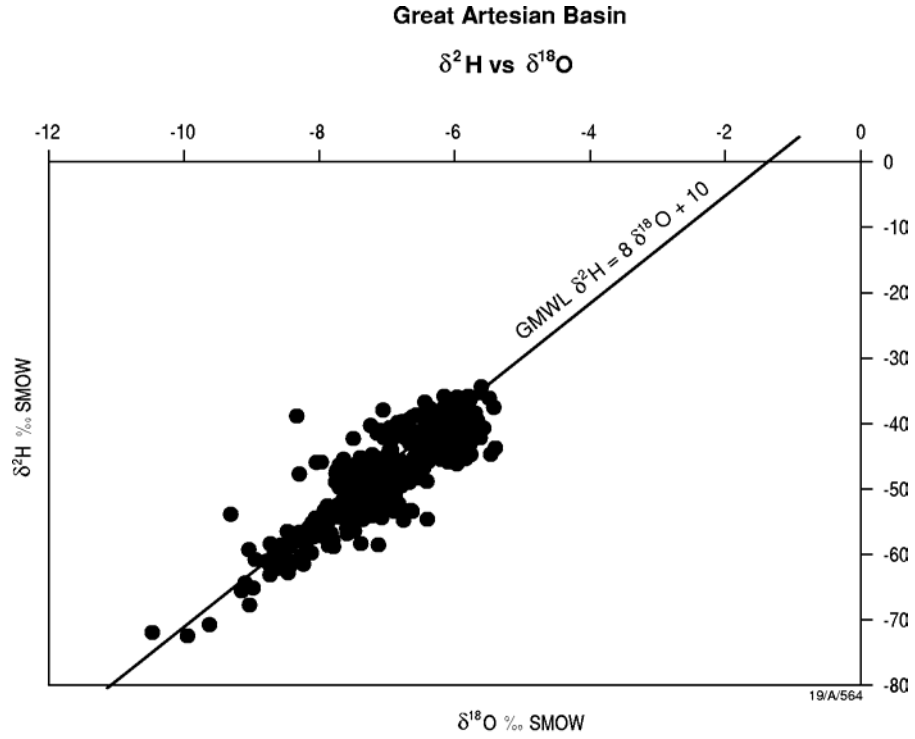


Fig. 9. Deuterium - oxygen-18 stable isotope composition of groundwater from flowing artesian waterbores in the Great Artesian Basin.

7. Isotope hydrology

Isotope hydrology studies on the artesian groundwater from the Lower Cretaceous-Jurassic aquifers in the Great Artesian Basin have confirmed recharge areas and regional groundwater flow patterns, and the sources and origin of the artesian groundwater.

Studies of stable isotope ratios D/H and $^{18}O/^{16}O$ show that the artesian groundwater is meteoric in origin, and nearly all values plot on the (global) meteoric waterline (Figure 9).

Samples downgradient from the recharge areas show decreasing percentages of modern carbon, from high values in the exposed aquifers in the recharge areas to background levels further downgradient in the Basin (Figure 10a), and carbon-14 derived isochrones have been determined (Calf and Habermehl, 1984). The carbon isotope ratio $^{13}C/^{12}C$ increases basinwards, as does alkalinity, and the variation of $\delta^{13}C$ is closely related to the changes in HCO_3 (Calf and Habermehl, 1984, Herczeg et al., 1991).

The age and residence times of the artesian groundwater, and the groundwater movement rates and flow patterns in the Great Artesian Basin have also been determined with carbon-14 and chlorine-36 isotopes (Figure 10). The data points include approximately 350 ^{14}C and approximately 360 ^{36}Cl analysis results from more than 800 samples (analysed for stable isotopes $^{2}H/H$, $^{18}O/^{16}O$ and ^{13}C and for detailed hydrochemistry results including major and minor ions, metals, trace elements, gases and hydrocarbons) collected from waterbores and springs in the Basin by the author (data in Radke et al., 2000).

Chlorine-36 has a longer half-life than carbon-14, is highly soluble in water, has a relatively conservative behaviour in groundwater and has a simpler geochemistry than ^{14}C. The application of ^{36}Cl as a dating tool for the very old groundwater in the Great Artesian Basin has many advantages, and is well suited for the high ages of the slow moving artesian groundwater in this large groundwater basin, as it has a potential range of more than 2 million years.

Groundwater ages from the Great Artesian Basin determined from the chlorine-36 results (Figure 10) are in general in good agreement with the calculated ages, suggesting that the flow conditions of the artesian groundwater have remained largely unchanged during at least the last one million years (Bentley et al., 1986, Torgersen et al., 1991, Habermehl et al., 1993, Cresswell et al., 1996, Radke et al., 2000).

Alternative explanations for the ^{36}Cl derived age have been discussed by Andrews and Fontes (1993) and Torgersen and Phillips (1993). Bethke et al. (1999) modelled groundwater flow and ^{4}He distribution in the Basin. Fabryka-Martin et al. (1985) determined iodine-129 levels in the Basin.

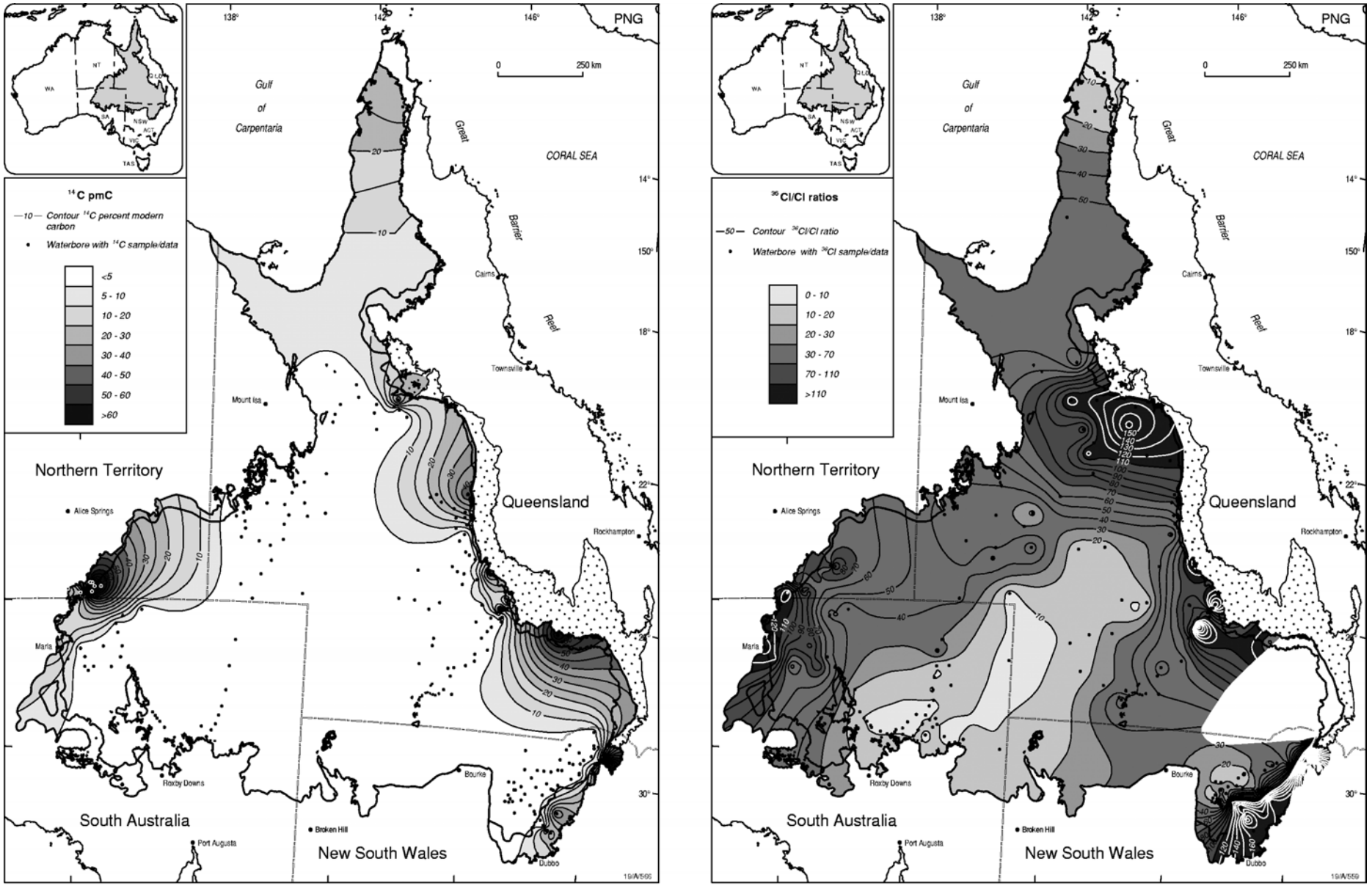


Fig. 10. Contours of 14C pmC (a) and contours of 36Cl/Cl ratios (b) in the Great Artesian Basin.

8. Hydrochemistry

Groundwater in the most widely exploited confined aquifers in the Lower Cretaceous-Jurassic sequence generally contains about 500 to 1500 mg/L total dissolved solids. Artesian groundwater has pH values that are almost uniformly between 7.5 and 8.5.

The artesian groundwater is chemically of the Na-HCO_3-Cl type, and these ions contribute more than 90 percent of the total ionic strength of solutes in the main Basin area (Figure 11). Evolution of the groundwater chemistry along the flowlines is characterised by the removal of Na and K by reconstitution reactions involving kaolinite, a Na-smectite and illite (Herczeg et al., 1991, Radke et al., 2000). In the southwestern part of the Basin the groundwater is characterised by Na-Cl-SO_4 type water, and the two regional groundwater flow directions show different hydrochemical characteristics, with westward flowing water being of the Na-HCO_3-Cl type and eastward flowing water being of the Na-Cl-SO_4 type. These flows, within the same aquifer meet and mix, and are directed towards the main discharge area near the Basin's southwestern margin (Habermehl, 1986).

Near the recharge areas Ca, Mg and SO_4 concentrations are proportionally higher, but these decrease basinwards. Variations of the major ion concentrations and ratios occur along the flowlines. Na and HCO_3 concentrations generally increase along the flowlines in most parts of the Basin. Cl and SO_4 also increase in most areas, though an initial decrease occurs basinwards of the northeastern marginal area. Along the southerly directed flowpaths from the northeastern recharge area to the New South Wales border, concentrations of all four ions decrease, and then increase or remain approximately constant. In the centre of the Basin some deep waterbores with high Cl concentrations occur, and very low to semi-stagnant flows along the deep and long flowpaths might account for these high Cl concentrations and high salinity values. In the northwestern part Na, HCO_3 and Cl increase along the flowlines, but SO_4 concentrations are constant (Habermehl, 1983, 1986, Radke et al., 2000).

Observed systematic variations in the chloride levels could reflect variations in the rate of recharge and infiltration of recycled salt throughout the late Quaternary. The minimum and maximum in the chloride curve correlates with the last glacial and interglacial period respectively (Airey et al., 1979).

Total dissolved solids values generally show an increase downgradient in the Basin. This is probably the result of mixing of the dilute recharge water with more saline groundwater in the deeper parts of the Basin, diffusion of ions out of the mudstones of the confining beds containing higher salinity water, and dissolution of evaporites, carbonate minerals or incongruent dissolution of feldspars, micas or clay minerals (Herczeg et al., 1987, 1991).

The increase in alkalinity and decrease in SO_4 concentrations in the Basin might result from biochemical reduction of carbon dioxide to produce methane rather than the dissolution of carbonate minerals. The aquifer system is open to CO_2 and the addition of CO_2 is accomplished by fermentation processes occurring in situ. Some of the added CO_2 is a by-product of methanogenesis. The addition of CO_2 drives the carbonate dissolution reaction, and so exerts an important control on the evolution of the Na-HCO_3 groundwater within the Basin (Herczeg et al., 1991).

Fluoride values in many parts of the Basin are high, with values up to 10 mg/L and more, which is a problem for domestic and stock water supplies. High fluoride concentrations in the artesian groundwater have been attributed to groundwater being in contact with underlying basement rocks, in particular igneous rocks (Evans, 1995, Habermehl and Lau, 1993, Habermehl et al., 1996).

Contact of the artesian groundwater with igneous rocks has been interpreted to be the reason for the occurrence of surprisingly unradiogenic $^{87}Sr/^{86}Sr$ ratios (Collerson et al., 1988).

Cretaceous aquifers have higher salinities and Cl values than the Lower Cretaceous-Jurassic aquifers, and the high Na-Cl values in the Cretaceous aquifers probably reflect the non-flushing characteristics of these mainly isolated and lenticular shaped aquifers. The marine origin of the adjoining mudstones in the Cretaceous sequence might also contribute.

The Lower Cretaceous-Jurassic aquifers can be distinguished from the Cretaceous aquifers based on their hydrochemical characteristics, but the distinction between individual aquifers in the Lower Cretaceous-Jurassic sequence is less obvious (Muller, 1989, Quarantotto, 1986, 1989). Mixing of groundwater from the latter aquifers occurs where intervening confining beds pinch out and the aquifers are in contact. The upper parts of the Cadna-owie Formation and Hooray Sandstone aquifers are influenced by the downward diffusion of ions from the marine mudstones of the Rolling Downs Group.

Most artesian waterbores produce varying amounts of gases. The main constituents of the gases include N_2, CO_2, Ar and small amounts of H_2 and He. In addition many waterbores produce artesian groundwater containing small amounts of hydrocarbons. The hydrocarbons are mainly CH_4 and lesser amounts of C_2H_6 to C_7H_{16} but liquid hydrocarbon fractions have also been detected (Habermehl, 1986, 1989).

Hydrocarbon source and reservoir rocks are abundant in the sedimentary sequence of the basin. Commercial and sub-commercial oil and gas discoveries have been made in several Jurassic and Cretaceous sandstones, and in particular in the underlying Permian and Triassic sediments, contradicting earlier beliefs that the basin-wide groundwater flow had flushed hydrocarbons out of the system. Dissolved hydrocarbons in the artesian groundwater are generally dry gases and are useful petroleum exploration indicators.

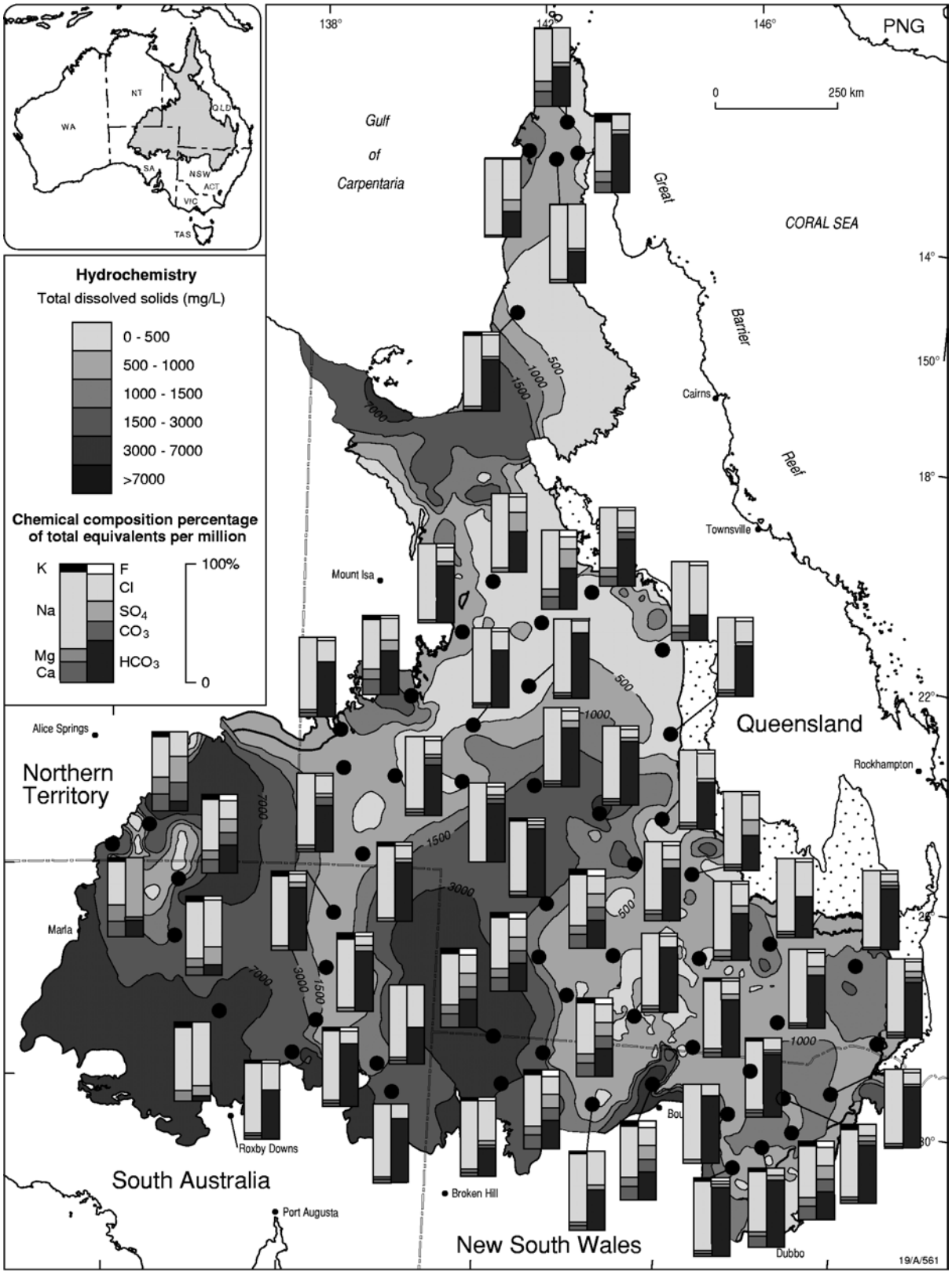


Fig. 11. Groundwater quality (Total Dissolved Solids) and major ion hydrochemistry (chemical composition of groundwater) of selected flowing artesian waterbores in the Great Artesian Basin (after Habermehl, 1980, Habermehl & Lau, 1997).

Water quality improves with the lower stratigraphic location of the aquifers in the Lower Cretaceous-Jurassic sequence, with groundwater obtained from aquifers in the older part of the Lower Cretaceous-Jurassic sequence having better quality water than the upper aquifer. The latter underlies the main confining bed of Early Cretaceous age and marine origin and is probably in part affected by diffusion of salts from these Cretaceous mudstones. Groundwater from all of the aquifers in the Lower Cretaceous-Jurassic sequence are of good quality and suitable for domestic, town water supply and stock use, though it is generally unsuitable for irrigation because in much of the Basin area it is chemically incompatible with the dominantly montmorillonitic swelling clay soils. Water from the upper, Late Cretaceous, Winton and Mackunda Formation aquifers has a higher salinity, though it is still acceptable as stockwater.

Reverse osmosis desalination plants upgrade the quality of groundwater used at the town of Roxby Downs and some of the mines in the northwestern margin of the Basin. Other towns and homesteads use the artesian groundwater directly, usually after cooling.

9. Groundwater temperatures

Groundwater surface temperatures of waterbores tapping aquifers in the Lower Cretaceous-Jurassic sequence generally range from about 30^0 to 100^0 C, and springs have temperatures from about 20^0 to 45^0 C. Geothermal gradients show a wide range and give a mean of about 39^0 C/km, and a range of about 15^o C/km to 100^o C/km (Polak and Horsfall, 1979), as obtained from temperature wireline logs in waterbores (Habermehl, 2000). Surface temperatures of the waterbores and geothermal gradient maps are shown in Habermehl (2000). Waterbore values for the geothermal gradients, though internally consistent, are too high, based on data from deeper petroleum exploration wells in the central part of the Basin (Cull and Conley, 1983). Geothermal gradients derived from petroleum exploration wells are given in Pitt (1986). The heat flow in the Basin is attributed to heat produced in the earth crust by uranium and thorium, and by recent volcanic activity (Torgersen et al., 1992). The effects of temperature variations on the hydrodynamics of the Great Artesian Basin have long been recognised, and have been incorporated in computer based simulation modelling.

10. Assessment and management

A long history exists of interstate cooperation in the management and systematic investigation of the Great Artesian Basin since the early 1900s, though the States of Queensland, New South Wales and South Australia and the Northern Territory have separate and different legislation and management strategies. The States are responsible for water matters under the Australian Constitution, and this includes water resources management. Water, including groundwater is vested in the Crown. All bores in the Great Artesian Basin need to be licensed.

The Great Artesian Basin Consultative Council, established in 1997, developed a strategic management plan for the whole of the Great Artesian Basin in 2000. The Council, with representatives from Federal, State and Local Governments, pastoral, petroleum and mining industries, traditional landholders, community and conservation groups, has an opportunity with the strategic management plan to address Basin-wide management issues, sustainable development and use of the artesian groundwater.

Further decrease of the diminution of the artesian pressures and the reduction of the uncontrolled discharges are achieved since the introduction of the Federal and State Government subsidised Great Artesian Basin Bore Rehabilitation Program in 1989. The Program aims to rehabilitate waterbores in poor condition and place control valves on free flowing artesian waterbores without control mechanisms (Hillier et al., 1995, Reyenga et al., 1998). Flowing artesian waterbores are important for the pastoral industry in the Basin area. About half of the 1200 uncontrolled or corroded waterbores have been rehabilitated (1999), at an average cost per bore of about $ 50 000 plus headworks. Completion of the Bore Rehabilitation Program and a follow-up program, the Great Artesian Basin Sustainability Initiative introduced in 1999, to accelerate bore rehabilitation and bore drain replacement, should result in better control and management of the flowing artesian waterbores and their discharges, particularly if a Basin-wide management program is implemented. Artesian pressures in most areas should thus increase significantly because of the increase in fully controlled flowing artesian waterbores and reduced outflows, and already important results of increased pressures and flows have been achieved in some areas.

The past and present distribution of artesian groundwater by the main users, the pastoral industry, from the flowing artesian bores by open earth drains is extremely wasteful, owing to seepage, transpiration

and evaporation of the water. Boredrains have lengths of many tens of kilometres, up to 100 km, and a total length of 34 000 km. This causes wastage of more than 95 percent of the groundwater produced. Introduction of (polythene) piping to replace the earth drain reticulation system will significantly reduce the demand on flowing artesian waterbores for groundwater, and could almost eliminate the wastage of water, if piping is combined with float valve controlled tanks and trough systems. Piping of the water will also reduce the environmental effects caused by the introduction of large amounts of water and watering points in the semi-arid and arid landscape. The availability of water in these areas has resulted in land degradation, the spread of introduced weeds, shrubs and trees, greatly increased numbers of feral and native animals attracted by the water, and affected the biodiversity around waterbores and boredrains, and near springs with reduced outflows (Noble et al., 1998).

Reduced demand also provides resources for alternative industries, and in recent years mining and oil and gas production have become significant users and producers of artesian groundwater (Figure 5). Groundwater extraction by these industries has caused results similar to effects of the groundwater development for the pastoral industry, ie. significant drawdowns of the potentiometric surfaces, which affect other users and naturally occurring flowing artesian springs. Other environmental geology issues include the changes to the eastern recharge areas caused by land use changes, and the possible effects on groundwater recharge and groundwater contamination. In Situ Leach (ISL) uranium mining techniques have been introduced in the South Australian part of the Basin area. However, the ISL is carried out in a confined Tertiary aquifer on the surface of the Great Artesian Basin, which is hydraulically separated from the Basin's aquifer.

Acknowledgments

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Ghanim M. Ibrahim, Mahmud B. Rashed***

Groundwater situation in a region of north-west Libya

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Abstract (see full text in Arabic at the end of this volume)

In the Al-Jafra plane in the North-West of Libya is situated one of the country's most important groundwater reservoirs. To assess the groundwater resources both in field experimental work and surveys have been carried out.

The work has consisted of measuring the static and dynamic groundwater level in the main wells supplying Zwara City together with their discharges. The measurements were carried out under different sequences of observation operations.

The analysis of the field data has clarified the groundwater hydraulics essential for the water use. The results show a continuous decline in groundwater level, especially from January to April 1998. In this short period, the decline was 120 cm contrary to 62 cm for the period 1992–1997. The well-productivity was found to have decreased in comparison to the design discharge. The maximum decrease reached 31.5%. Well-interference was also found to be a major problem.

J. Naji-Hammodi and H. R. Kahpood***

Anisotropy coefficient-mean apparent resistivity method – A sucessful tool to explore karst groundwater resources in Iran (abstract)

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Abstract (see full text in Arabic at the end of this volume)

The application of cross-square arrays resistivity traversive in fissured and fractures formations is described. The Schlumberger square array is considered to be the most applicable for the resolution of hard rock and karst groundwater resources.

In the square array six types of resistivity location can be measured providing a comprehensive data spread.

The method is described for the Arak area of Iran which consists of lower Cretaceous materials that have been heavily fractured and crystalized.

Measurements of 100 m spreads were carried out at 41 locations with supporting spreads at 35 m. Seven electrical profiles were prepared as a result of the field work.

The results have provided a distribution of apparent mean resistivity and anisotropy coefficients, the difference between the two being taken as an indication of major fracture, or fissure location and hence a preferred location for exploitable groundwater investigation.

Philippe Pallas and Omar Salem***

Water resources utilisation and management of the Socialist People Arab Jamahiriya

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This paper is a summary of a document which is being published by UNESCO under the same title.

1. Projected food and water demand

1.2 Population distribution and forecast

In 1964, Libya's population amounted to 1.56 million; according to the 1973 census, this number has increased to 2.25 million. Libya's population in 1995 was estimated at 5.205 million (4.39 million Libyans according to census plus some 800,000 non-Libyans).

In 1995, 54 % of the population lived in the western coastal area (Jifarah plain and Misratah area). The eastern coastal area (Al Jabal al Akhdar) is the second area of population concentration with 21 % of the Libyan population living there. This means that 75% of the population is concentrated over 1.5 % of the total area of the country.

The average annual Libyan population growth (excluding non-Libyans) during the 4 periods between the census, was as indicated in Table 1.

Table 1: Annual population growth of Libya

Period	Annual population growth in %
1954 - 1964	3.8
1964 - 1973	3.4
1973 – 1984	4.2
1984 - 1995	2.8

Assuming a constant rate of growth equal to 2.8 % over the next 30 years, starting from 1995 census would bring the population of Libya (Libyans only) to approximately 10 million in 2025 or some 11.9 million including the non-Libyans. United Nations projections, based on 1995 estimates predicted a 2025 Libya's population of 12.9 million (including non-Libyans). It is likely that the rate of growth will rather decrease with time and a reasonable estimate of the 2025 Libya's total population might be around 11.9 million, of which more than 90 % would be urban.

1.3 Food balance (FAOSTAT)

Food supplies provided 3438 kcal per caput per day in 1980, 10.4 % (89 g) of this being provided by protein and 29.2 % (112 g) from fat. By 1996 (average 1994-1996), food supplies provided 3137 kcal, 9 % (73 g) protein and 31% (113 g) fat. In 1994-96 (average), cereals contributed 47.5 % (193 kg/caput/year) of the total energy supply, vegetables and fruit 10.8 % (231.5 kg/caput/year), animal products[1] 9.7 % (117.8 kg/caput/year), added fats and oil 21.8 % (28.3 kg/caput/year) and sweeteners 9.3 % (30.2 kg/caput/year). While total energy supply exceeds total requirements, the degree of need satisfaction and quality of diet at the household or individual level varies widely because of current food habits and lack of nutritional awareness.

[1] Including milk (81 kg/caput/year) representing 4.2 % of the daily calorie intake in Libya

1.4 Food supplies

Libya is still importing food. In 1994 (FAOSTAT), food imports made up almost 20% of total imports. Production, consumption and self-sufficiency percentages for principal commodities are indicated on Table 2.

Table 2: Production, consumption and self-sufficiency

Product	Average production 1994-1995 in 1000 tons	Waste in 1000 tons	Average consumption including animal feed and seed 1994-1995 in 1000 tons	Self-sufficiency %
Wheat	163	86	1332	12
Barley	149	16	522	28
Fruits	454	45	446	100
Vegetables	421	33	590	71
Meat and fish	158	0	174	91

1.5 Cereals production and future requirements

Cereal utilisation includes human consumption, animal feed, seed and waste. In 1995, the total food grain consumption in Libya was 2.3 million tons (Mton), including 1 Mton for human consumption, 1 Mton for feed grain and 0.3 Mton for seed and waste. Assuming that the Libyan diet in 2025 will have approximately the same structure as in 1995, with perhaps a slightly lower percentage of cereal product (45 % instead of 48 % today) and daily calorie intake (3000 kcal/caput/day instead of 3137 today) the domestic cereal consumption in 2025 would be as indicated in Table 3. Table 3 shows also the expected vegetable and fruit consumption in 2025 on the basis of the present consumption (231.5 kg/caput/year).

Table 3: Projected cereal and vegetable requirement in 2025

Product	Food grain consumption in million tons/yr	Feed grain consumption in million tons/yr	Seed and waste		Total expected domestic consumption in million tons/year
			%	million tons/yr	
Cereals	2.1	1.9	17	0.7	4.7
Vegetables and fruit	3.5	0.0	40	1.4	4.9

Now in Libya 52% of the meat consumed is made of poultry which can be fed with grain and is a better water converter than the other categories of meat. Part of the other animals which are included in the Libyan diet are fed with fodder crops (alfa alfa, berseem). When taking into account the contribution of 900,000 ha of rainfed grazing land to feed animals in Libya, it may be assumed that only 25% of the meat requirement will be produced under irrigation corresponding to 0.11 million tons on the basis of an average meat requirement of 36.8 kg/cap/yr.

The equivalent water demand in 2025 may be calculated on the basis of average water requirement to produce one ton of cereal, one ton of fruit and one ton of meat under Libyan climatic conditions. Table 4 summarises the order of magnitude of the water demand to support agricultural self-sufficiency in Libya in the year 2025.

Table 4: Water requirement to support food self sufficiency in 2025

Product	Total requirement in 2025 in 1,000 tons	Water equivalent in 1000 m^3 per ton of product		Corresponding water requirement in km^3/year	
		Present agricultural practice	High level of irrigation management	Maximum hypothesis	Minimum hypothesis
Cereals	4.7	1.5	1	7.0	4.7
Vegetables and fruit	4.9	1	0.5	4.9	2.5
Meat fed with irrigated fodder crops	0.11	30	20	3.3	2.2
Total				*15.2*	*9.3*

1.6 Expected municipal water demand in the year 2025

A recent estimate of the domestic water supply in Libya is summarised in Table 5, which indicates a total municipal water demand in 1998 of 435 x 10^6 m^3/yr

Table 5: Present domestic water supply in Libya from all sources of water (1998 estimate)

Water province	Population 1997 incl. Non Libyans		Average water supply in m^3/day			Total water supply in Mm^3/yr	Average water consumption in l/day/cap
	Number x 1,000	Percentage	GMRP*	Groundwater	Desalination plants**		
Al Jabal al Akhdar	1,380	26.5	188,000	347,945	14,000	201	399
Al Kufrah - As Sarir	280	5.4	70,000	33,108	1,500	38	374
Jifarah	2,300	44.2	300,000	387,576		251	299
Hamada el Hamra	890	17.1		123,288	33,000	57	176
Murzuq	350	6.7		158,904		58	454
TOTAL	*5,200*	*100*	*558,000*	*1,050,821*	*48,500*	*605*	319

* Great Manmade River Project

** Probably overestimated since most of the desalination plants are not in good operating conditions

Assuming that 90% of the population will be urban in the year 2025 and assuming a water consumption rate of 300 litres/capita/day (1/c/d) for the urban population and 150 l/c/d for the rural population, the total domestic water consumption in the year 2025 would be 1,240 x 10^6 m^3/yr, approximately 2 times the 1998 water demand. It should be noted however that part of the water "consumed" can be and certainly will be treated so that part of it, say 50 % or 620 x 10^6 m^3/yr can be re-used for agriculture.

1.7 Industrial water demand

Most of the industrial water is used for oil industry (injection, processing and some domestic use). The Libyan National Oil Company (NOC) estimates the total water consumption for oil industry in 1998 at 117 x 10^6 m^3/yr. Other industries are reported to consume 5 to 10 x 10^6 m^3/yr. Even if the industrial water demand grows considerably within the coming years, the quantity of water involved will always remain negligible when compared to the agricultural consumption. It is considered here that the future industrial water demand will be within the margin of error of the agricultural water demand estimate.

2. Surface water

2.1 Rainfall

The highest rainfall occurs in the northern Tripoli region (Jabal Nafusah and Jifarah Plain) and in the northern Binghazi region (Al Jabal al Akhdar), these two areas being the only ones where the average yearly rainfall exceeds the minimum values (250-300 mm) which are considered necessary to sustain rainfed agriculture. Rainfall average is less than 100 mm per year over 93% of the land surface. In addition to its scarcity, the rainfall in Libya shows an extreme variability from year to year and from place to place.

2.2 Surface runoff

A very small amount of runoff water reaches the sea and it is considered that most of the runoff water is either evaporated or infiltrated in the wadi beds for recharging the underlying aquifers. The total mean annual runoff water calculated or measured at the entrance of the wadis in the plains (or spreading zones) is roughly estimated at 200 x $10^6 m^3$/year

3. Groundwater

3.1 Groundwater occurrence and geology

The main features of the geology and hydrogeology of Libya have been described and illustrated with cross-sections in the 1980 publication (Pallas P., 1980). The following description summarises the main characteristics of the groundwater occurrence in Libya.

1. South of lat 29° N, an important development of Palaeozoic and Mesozoic continental sandstones enabled water to be stored safely during the long periods of the late Quaternary when the climate turned extremely arid.
2. From the 29th to the 32nd parallel, in the central and eastern zones, the Tertiary deposits form the main groundwater reservoir, which is more than 1000 m thick but contains an important proportion of evaporites which -have deteriorated its quality.
3. In the western zone, **north** of lat 29', the main groundwater reservoir is composed of lower Mesozoic sandstones, but in correspondence with Jabal Nafusah, the present recharge from rainfall is superimposed on several perched groundwater systems in the Cretaceous formations over the main water body. Along the coast and mostly around Tripoli, Plio-Quaternary deposits form another important groundwater system which is well recharged every year by rainfall.
4. In the eastern zone, north of lat 32', the geology is dominated by the anticlinorium of Al Jabal al Akhdar. The main groundwater system in the Eocene limestones follows the geological structure with a radial flow around the core of the jabal.
5. In addition to these main features, it is worth mentioning some areas of persistent uplift conditions which are lacking a substantial accumulation of sediments. These include the Tibisti and Jabal al Awaynat where almost no ground water exists.

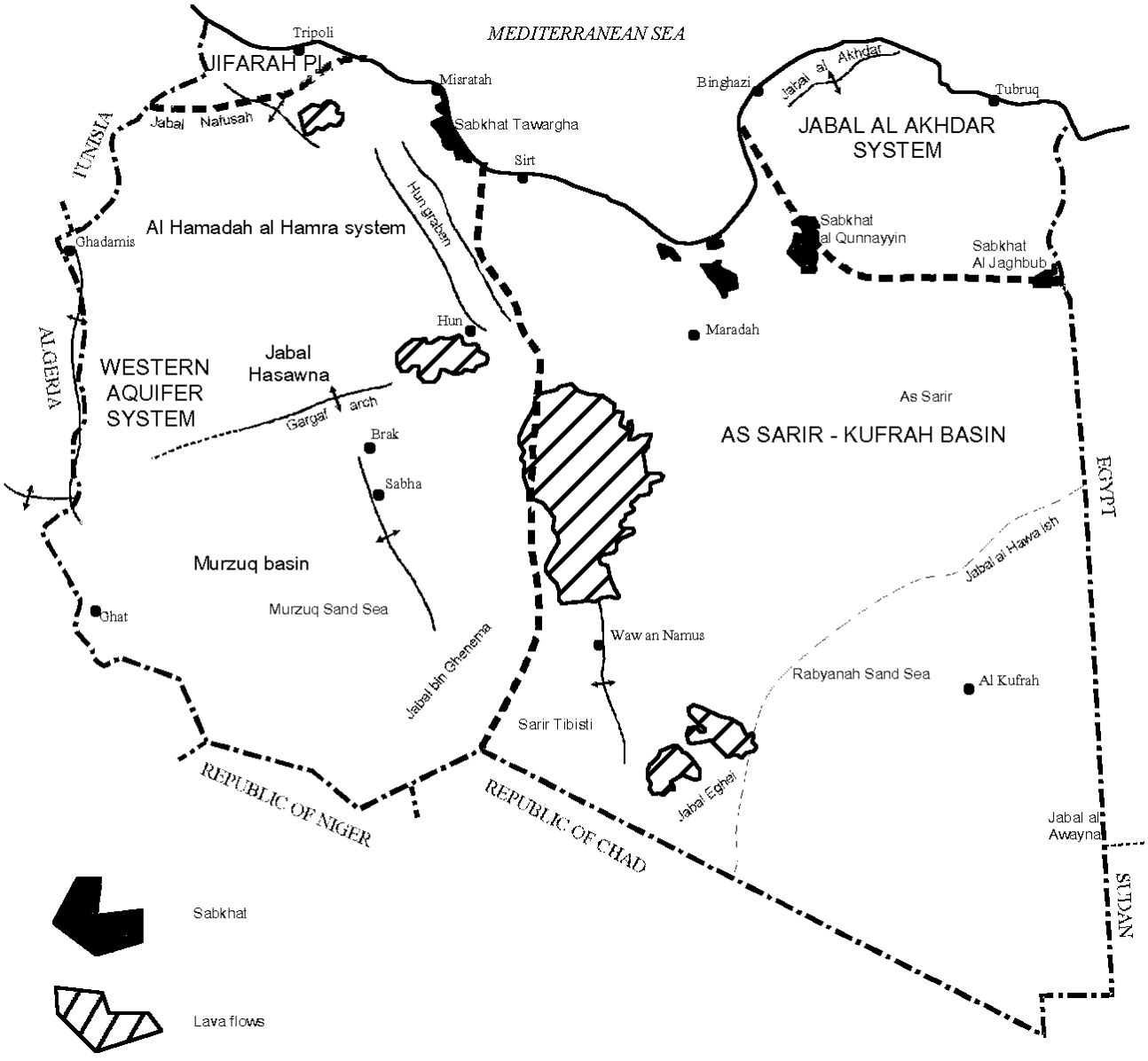


Figure 1: Groundwater systems in Libya

3.2 The different groundwater systems

It is possible to group the groundwater provinces where hydraulic connections exist between them and to limit their number to only four, relatively independent from each other:

1. the Western Aquifer system including three sub-systems interconnected:
   - The Murzuq basin
   - Jabal Hasawnah which is going to play an important role in the future as water source for the western water transport system
   - Al Hamadah al Hamra system including the Jabal Nafusah - Suf-Ajjin-Tawurgha sub-basin, Ghadamis sub-basin and Al Hamadah al Hamra system
2. the Jifarah Plain system;
3. As Sarir-Al Kufrah basin system;
4. the Al Jabal al Akhdar system.

The limits of these groundwater systems are indicated on Figure 1. The following sections will deal with each of the groundwater systems separately.

4. Murzuq Basin

4.1 General Description of the Area

Limit of the area considered. The area considered includes the south-western quarter of Libya. It is limited (Figure 3) to the north by lat 28* N corresponding to Jabal Fazzan-Jabal Hasawna, to the east by long 16° E, to the south by the political border with Niger and to the west by the political border with Algeria.

Groundwater reservoirs and geology. Two main groundwater reservoirs can be considered in the Murzuq basin. They have been described and illustrated with cross sections in the 1978 publication (Pallas P., 1980). in the 1980 publication (Pallas P., 1980):

1. *The lower groundwater reservoir*. It includes the Siluro-Devonian and Cambro-Ordovician sandstone. Available piezometric data in Wadi ash Shati, Wadi Tanezzuft and in Algeria indicate a hydraulic gradient from South to North and would suggest some groundwater flow from Wadi Tanezzuft to Wadi ash Shati through the Cambro-Ordovician sandstone. A peculiarity of the distribution of the piezometry of the lower reservoir is the dome corresponding to Jabal Fazzan-Jabal Hasawna, as if this area was still acting as a water reservoir feeding the aquifers located to the north and to the south of it.
2. *The upper groundwater reservoir*. It includes the continental formations of the Triassic, Jurassic and Lower Cretaceous usually known as the Post-Tassilian and Nubian series. It consists of alternating clay, loose sand and sandstones. The total saturated thickness of the reservoir exceeds 1000 m over a large area in the centre of the basin and even in the north western part of it (Wadi Barjuj).

4.2 Present water extraction

4.2.1 Lower groundwater reservoir development

Because of the great depth to the lower reservoir from the ground surface, the water development is limited to the areas located along the edge of the basin where the aquifers are easily accessible by wells. The three main zones of groundwater development are Wadi ash Shati, Ghat-Wadi Tanezzuft and recently Jabal Hasawnah which is actually located between the Murzuq basin and the Hamadah al Hamra system. Moreover, some water is being withdrawn from the Devonian aquifer in Al' Awaynat.

Wadi ash Shati. Three major agricultural projects based on the Lower Groundwater Reservoir have been implemented in Wadi ash Shati:

- Ashkidah, implemented in the late 70s was designed to produce vegetable and fruit over 3000 ha. The project is facing serious problems of well corrosion causing continuous leaks and damages to the soil, and of water shortage which leads the farmers to irrigate only part of their farm.
- Wadi al Aril implemented in the 80s, located on the extreme east of Wadi ash Shati was designed as a state operated project consisting of 125 pivots of 40.5 ha each for a total of 5062ha.
- Dubwat project implemented in the 80s consists of 22 production wells and 6 wells for utilities. The total irrigated area of the project was planned to be 660 ha.

Present irrigated area in the agricultural projects is approximately estimated at 4200 ha (in winter).

Private agriculture originally based on flowing wells but now on pumped wells in most areas, has significantly increased in Wadi ash Shati although no precise data are available neither on the extension nor on the water used per unit area. However a recent inquiry by GWA within a UNDESA project provided an approximate figure of 11,900 ha of private irrigated area for Wadi ash Shati.

Effect of the water abstraction on the aquifer. Several piezometers distributed along Wadi ash Shati were observed a few times since 1974 or since the implementation of new projects. Figure 2 shows some examples of the aquifer response to water development in the new agricultural projects

Ghat-Wadi Tanezzuft-Al 'Awaynat. The two existing projects in Wadi Tanezzuft are not very active. Their irrigated area is estimated at 240 ha.

Private agriculture has developed in Ghat area and its present extension is estimated at 2670 ha.

Conclusion on the Lower Reservoir. The main extraction zone from the Lower reservoir is located along Wadi ash Shati – Wadi Aril. The various projects and private farming systems deepened the depression of the piezometric surface caused by the natural water extraction due to evaporation in the sebkhas. The present additional decline of the piezometric level may be estimated at 30 to 40 m in the deepest depression centred on Ashkidah project. Another 40 to 50m decline is expected to take place in Wadi Shati, mainly in the area of Brak and Wadi Aril, essentially resulting from the effect of the water production in Wadi ash Shati itself. The effect of the huge water production planned in Jabal Hasawna for water transport to the coast which will be described in the next section, would not be critical according to the simulations made on mathematical model.

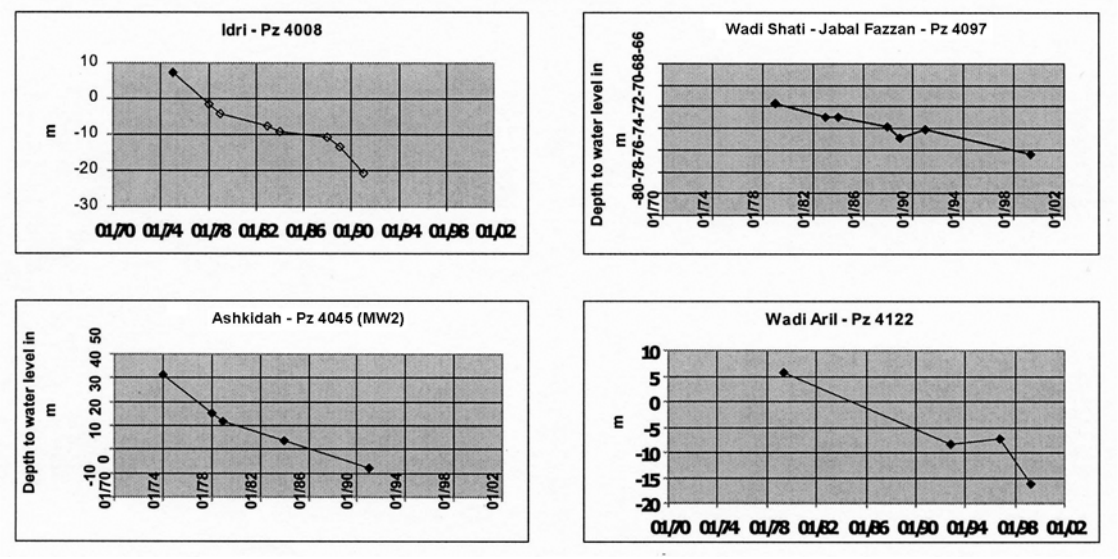


Figure 2: Wadi Shati - Wadi Aril - Piezometric fluctuations

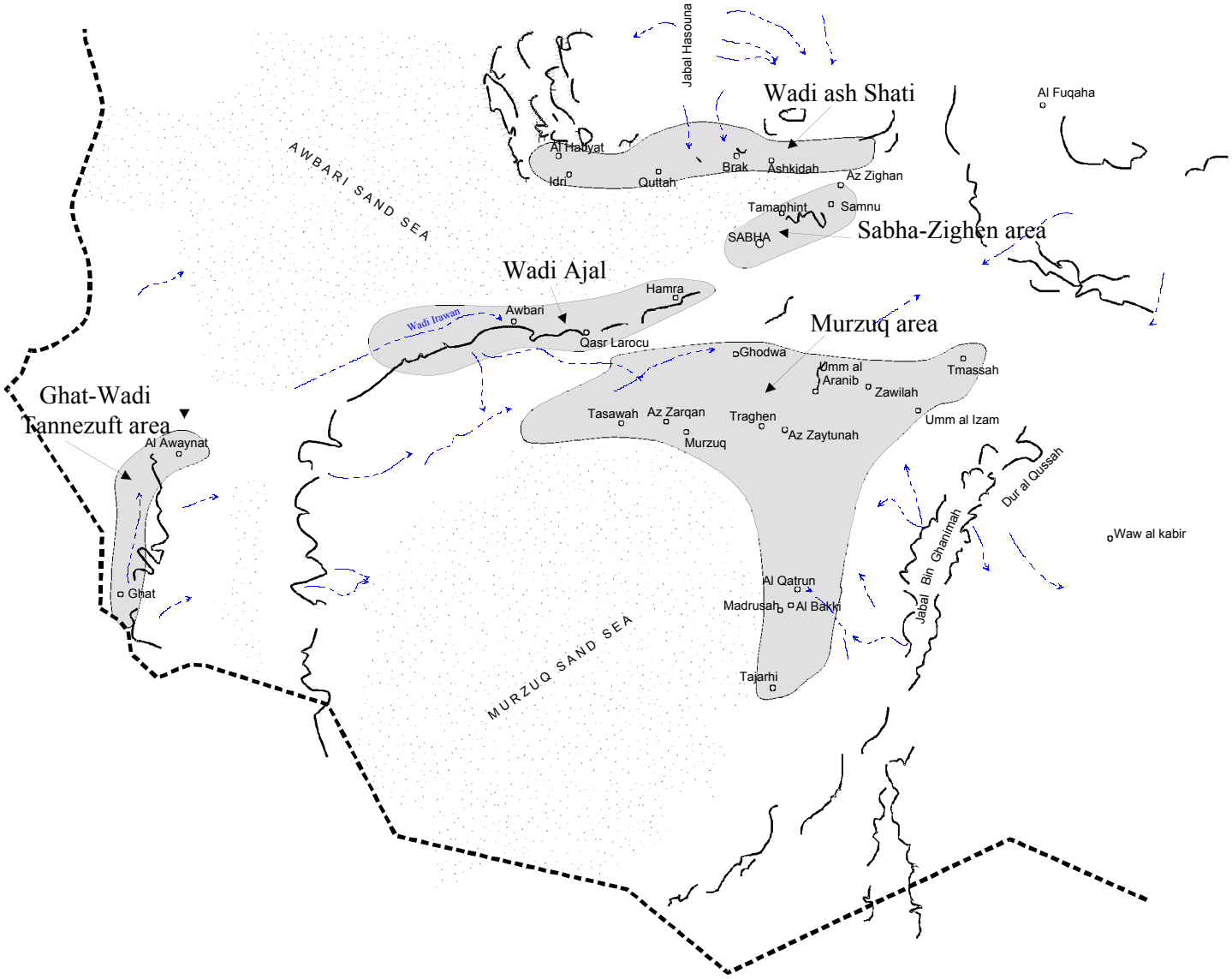


Figure 3: Murzuq basin

4.2.2 Upper Groundwater Reservoir

The water extraction is concentrated in the depressions where the water level is close to the surface and where the best soils are:

Wadi al Ajal – Wadi Irawan - Sabha. The area is located in the vicinity of the northern limit of extension of the upper reservoir (presumably under the Awbari sandsea) and the percentage of clay in the continental deposits is much higher than in Murzuq area. This explains the relatively low transmissivity values ranging from 1 to 8 x 10^{-3} m^2/s in Awbari and from 4 to 11 x 10^{-3} m^2/s in wadi Irawan. Also the TDS shows higher values than in Murzuq area: 300 to 380 ppm in Wadi Irawan and 100 to 400 ppm in Awbari.

The state operated projects implemented in the years 70s show an important decline of the irrigated area, from 6,842 ha at the origin to 4,091 ha now. Many wells are not operating anymore, probably because of lack of maintenance of the pumping equipment.

An important development of private farms has taken place in Wadi Ajal and in Sabha area.

Murzuq area. In 1978, a few agricultural projects were operational: Zuwaylah, Humayrah, Umm al Aranib and Ghudwa essentially, for a total irrigated area of some 3000 ha using approximately 50 x 10^6 m^3/yr of water. During the 80s, important new irrigation projects were implemented. The most important are those implemented in Maknussah and Wadi Barjuj areas. Irrigated area in the agricultural projects show a slight decrease when compared to the situation at the implementation stage: 10,089 ha in 1999 compared to 12,179 ha in the 70s-80s

Private irrigation spread also in Murzuq area. A field inquiry conducted in September 1999 by GWA (under a UNDESA project) made it possible to estimate the present irrigated area in the state implemented projects (10,089 ha) and in the private farms (14,630 ha).

Figure 4 shows the water level decline resulting from the water abstraction in the most important projects for which data are available.

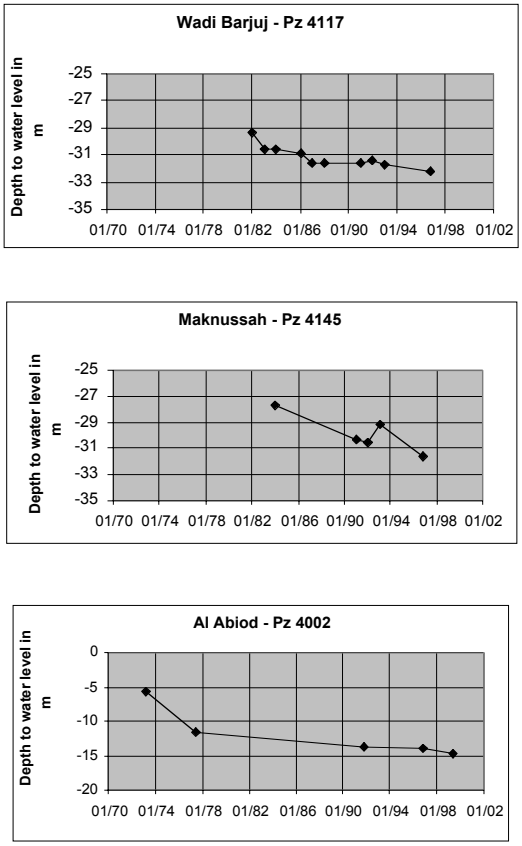


Figure 4: the water level decline

4.2.3 Summary of water use estimates in Murzuq basin

Table 6 summarises the irrigated area and water use estimates by groundwater reservoir and area for the whole Murzuq basin, not including Jabal Hasawna, which is considered in the next chapter.

Table 6: Irrigated area and water use in Murzuq basin in 1998-1999

Area	Domestic water supply	Agricultural Projects			Private agriculture			Agricult. water use in Mm^3/yr	Total water use in Mm^3/yr
		Irrig. Area winter (ha)	Irrig. Area summer (ha)	Water use	Irrig. Area winter (ha)	Irrig. Area summer (ha)	Water use		
Lower groundwater reservoir (Paleozoic sandstone)									
Wadi ash Shati - Wadi Aril	5	4,199	1,571	58	11,888	10,190	258	316	321
Wadi Tannezuft - Ghat	3	240	160	7	2,668	1,778	50	57	60
Upper groundwater reservoir (Mesozoic sandstone)									
Sabha-Zighen	30	604	287	10	19,440	16,200	411	421	451
Wadi Ajal - Wadi Irawan	10	3,487	1,562	52	18,684	15,570	395	448	458
Murzuq area	10	10,089	3,633	144	14,634	12,195	310	454	464
Total	58	18,619	7,213	271	67,314	55,933	1,425	1,696	1,754

5. Jabal Hasawnah

The Great Manmade River Project Phase II. Jabal Hasawnah consists of a large Cambro-Ordovician outcrops, north of Wadi ash Shati, extending over more than 20,000 km^2. The area was selected for the implementation of an important water development project – the Great Manmade River Phase II – designed for transporting water to the Jifarah Plain. Jabal Hasawnah project consists of two well fields respectively located north-east and east of Jabal Hasawnah. The two well fields are planned to produce 2.5 million m^3/day

Well completion design. One of the problems experienced in Wadi ash Shati in agricultural projects is the high degree of corrosivity of the water from the Palaeozoic formations. The problem was overcome in Jabal Hasawnah by using fiberglass material (Glass Reinforced Resin – GPR) for lining the pumping chamber of the wells. Typically the wells are drilled at approximately 500m total depth and cased down to approximately 300m. The producing zone (from 300 to 500m) is left in open hole.

Long term effect of the water extraction in Jabal Hasawnah. A multi-layer mathematical model covering the western side of the Libyan territory was run in 1992 (Geomath, 1994) with the view to (a) predict the long term effect of water abstraction, (b) decide the amount of water to be extracted, (c) design the well field layout. The finite element model used for the exercise is described in other papers papers presented at the Conference (Pizzi G., El Sonni A.). The final scenarios simulated in the model consisted of a water abstraction of 2 and 2.5 x 10^6 m^3/day. Table 7 summarises the long term (year 2046) water level decline in the two well fields.

Table 7: Long term effect of water abstraction in Jabal Hasawna

Well field		Simulation 11 – no production from Hasawna	Simulation 6 – total production = 2x10^6 m^3/day	Simulation 10– total production =2.3x10^6 m^3/day
North-eastern	Water production in 10^6 m^3/day	0	0.517	0.517
	Water level decline in m in 2046	5	75-102	75-105
Eastern	Water production in 10^6 m^3/day	0	1.482	1.784
	Water level decline in m in 2046	5 - 10	56-80	60-90

Present water development. Part of the first 90 wells located in the north-east well field, drilled in 96-97 are operating since September 1996 at an average discharge rate of 50 l/s and produce now approximately 300,000 m^3 /day conveyed to Tripoli as First Water to Tripoli Project. The 33 month operation of the north western well field (from September 96 to June 99) at an average rate of 275,000 m^3/day has produced the following drawdown in the three piezometres located within the well field: Pz5: 2.54m, Pz 31/83: 0.34m, Pz 32/83: 3.92m.

5. Al Hamadah Al Hamra

5.1 General description of the area

Limits of the area considered (see Figure 5). The area considered in this section includes the northwestern quarter of Libya excluding Jifarah plain. The area considered is limited

1. to the north by the crest of Jabal Nafusah from Nalut to Al Khums, then by the Mediterranean Sea from Al Khums to Bin Jawwad;
2. to the west by the Tunisian and Algerian borders;
3. to the east by long 18° E;
4. to the south by lat 29° N, immediately north of Jabal Hasawnah.

Rainfall. Only the southern and eastern slopes of Jabal Nafusah receive a significant amount of rainfall ranging from an average of 100 to 300 mm per year. The remaining area (Al Hamadah al Hamra, western Sirt basin, except a very narrow strip along the coast) receives less than 50 mm average rainfall per year.

Geology and hydrogeology. The water development which took place since 1978 did not really generate new hydrogeological concepts in the distribution of the aquifers and their inter-relation. The description of the groundwater occurrence in the 1980 paper (Pallas P., 1980) is still valid.

5.2 Present groundwater development and use

Al Khums-Misratah-Tawurgha. In that area several agricultural projects were implemented, in the 70s, some of them (Taminah and Kararim) based on very old projects. In Wadi Kaam, the water from the spring originating from Upper Cretaceous limestone aquifer, supplemented by 12 wells, is used for irrigating two projects totalling 1362 ha. Three agricultural projects, Ad Dafniyah, Taminah and Kararim are now suffering from the reduced number of wells in operating conditions (only 30 well are working now out of 65 at the origin of the projects), and from the bad water quality (1700 to 5000 ppm, approx. 3000 ppm as an average). Tawurgha spring discharging some 60 x 10^6 m^3/yr in the 70s was used for the irrigation of a 2286 ha project. No discharge measurement is available now, but the proximity of 8 deep artesian wells discharging each one some 400 to 450 m3/hr to supply water to Misratah did certainly affect the discharge of the spring. The area comprised between Al Khums and Misratah is characterised by an important development of private irrigation based on the shallow aquifers (Mio-Plio-Quaternary) usually of poor quality. The recent acceleration of the water abstraction by private farmers has produced a significant water level decline.

Wadi Suf Ajjin basin. Deep wells tapping Mesozoic sandstone (Kiklah) aquifer were drilled in Wadi Suf Ajjin and its tributaries Wadi Mardum and Wadi Maymun. Most of the wells were free flowing at the origin and were used to supply water to agricultural projects. As a consequence of poor management and lack of maintenance, many of these wells started flowing without control (due to heavy corrosion of the well head). The project of Wadi Maymun has been completely abandoned. In Wadi Mardum, while the discharge of the artesian wells decreased in relation to the piezometric level decline ranging from 33 to 36 m in less than 20 years, private irrigation developed on the basis of shallow wells tapping the upper aquifer (Upper Cretaceous essentially). Private irrigation is estimated to be around 1000 ha, mostly in Wadi Mardum in Bani Walid area.

Al Jufrah (west and southwest of Suknah). In Al Jufrah area, groundwater is produced from a dolomitic aquifer (probably Senonian) recharged by upwards leakage from the Cambro-Ordovician sandstone aquifer. Two projects (Al Hammam and Al Farjan) are operating since the late 70s. Originally the wells were free flowing, now, only the wells of Al Hammam project are still artesian. Total present water production for the two projects is estimated at 62 x 10^6 m^3/yr compared to 158 x 10^6 m^3/yr originally produced by the artesian wells. Water level decline in Farjan project from the implementation of the project is ranging from 30 to 32 m. The lack of drainage facilities in these two projects has induced important waterlogging and salinisation of the soils. Moreover the lack of maintenance of the water distribution system lead to the flooding of large areas of the projects due to the deterioration of the canals. Besides the poor success of the state implemented projects, private irrigation has developed around the small cities of Waddan, Hun and Suknah, based on shallow wells tapping the upper aquifers (Oligocene), in spite of the very poor quality of the water. It is estimated that 9,000 ha of private farms are now irrigated.

In Zallah area water is found in a thin Oligocene sandy layer located at a depth ranging from 30 to 150 m below ground surface and within a narrow graben of northwest-southeast direction. The Oligocene deposit overlies thick evaporitic series of the Eocene. The water in the main well field is of medium quality (2000 ppm TDS on average) but the eastern part of the well field shows a higher salinity. A 1200 ha agricultural project was implemented, based on 43 wells. Most of the wells are still in operation today.

Eastern flank of Hamadah al Hamra. An old hydrographic network has cut the eastern side of the Hamadah and created long southwest-northeast valleys in which deep wells were drilled down to 1000 to 1500m in order to tap the Mesozoic sandstone (Kiklah) and even the Palaeozoic in the most southern wadis.

Several agricultural projects were implemented in the 70s and in the early 80s, based on deep artesian wells. However because of heavy corrosion most of the wells could not be controlled properly and some started flowing uncontrolled. Moreover the high temperature of water was another difficulty which led to the progressive abandonment of part of the original hydraulic equipment which is still producing water, flowing in the wadis. In wadi Zamzam private farmers started drilling shallow wells 100 to 120 m deep tapping Upper Eocene aquifers and developed a flourishing private agriculture producing fodder, vegetable and water melon essentially. The same evolution is observed although to a lesser extent in Wadi Washkah and Wadi Mrah.

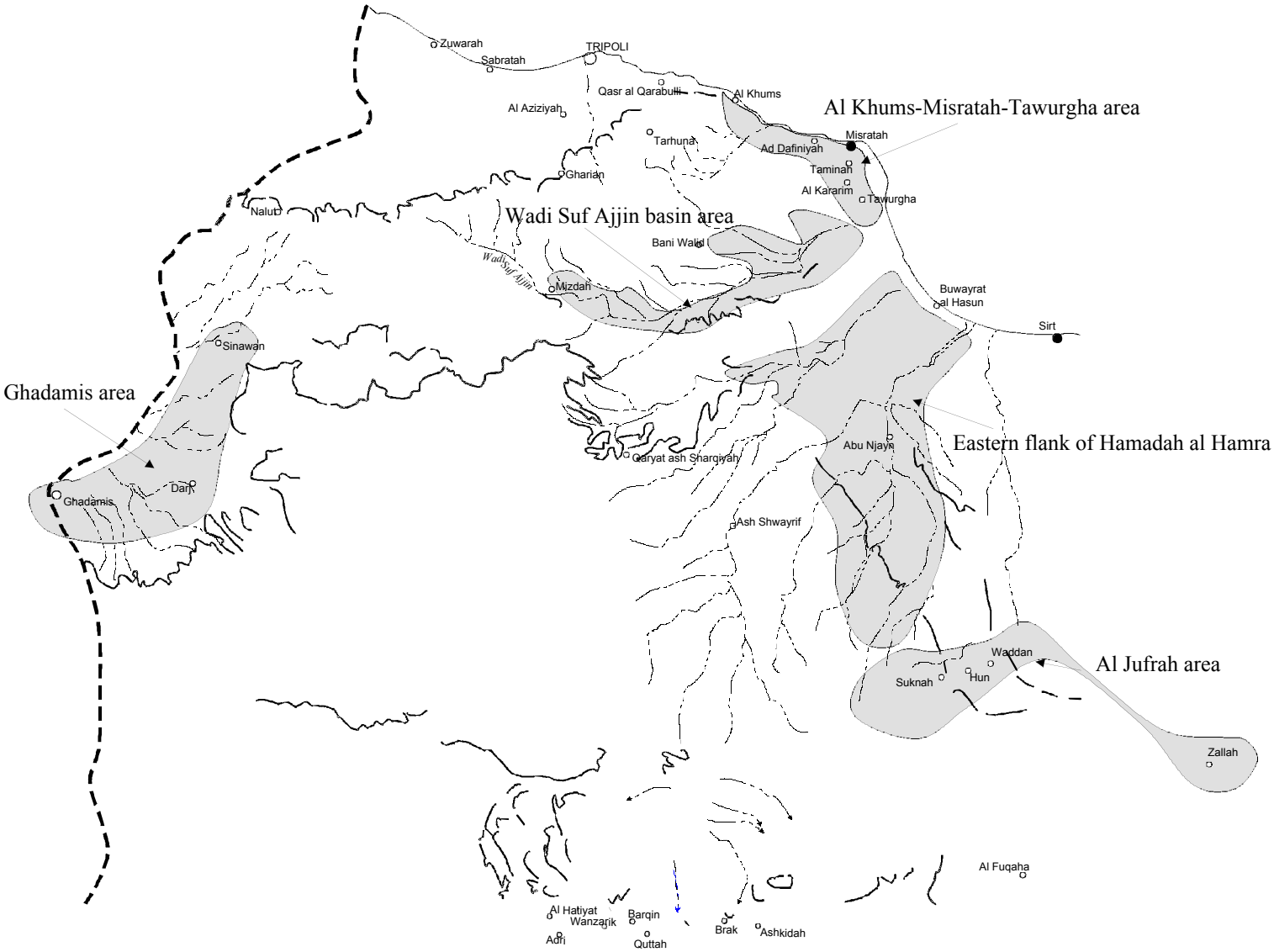


Figure 5: Hamadah el Hamra

Ghadamis. There are no agricultural projects in that area. An important project of water transport to the western coastal area is under study but will not be operational before 4 to 5 years.

5.2.1 Summary of groundwater use in the Hamadah al Hamra basin

Table 8 summarises the best estimates of the present irrigated areas and related groundwater abstraction as well as the domestic and industrial water supply estimates based on a 1998 inquiry of the Water Resources Committee.

Table 8: Hamadah al Hamra - Summary of groundwater use in 1998-1999

Area	Domestic and industrial water supply	Agriculture						Total water use x 10^6 m3/yr
		Agricultural projects		Private irrigation*		Total agriculture		
		Irrigated area (ha)	Water use	Irrigated area (ha)	Water use	Irrigated area (ha)	Water use	
Al Khums-Misratah-Tawurgha area	37	5,258	74	5,000	50	10,258	124	161
Wadi Suf Ajjin basin	3	1,087	20	1,000	20	2,087	40	43
Eastern flank of Hamadah al Hamra	1	2,990	58	1,440	30	4,430	88	89
Al Jufrah - Zallah	2	3,418	84	9,000	190	12,418	274	276
Ghadamis	2			200	4	200	4	6
Total	45	12,753	235	16,640	295	29,393	530	575

6. Jifarah Plain

6.1 General Description of the Area

Limits and population. The Jifarah Plain is a triangular area of about 20 000 km^2, bounded on the north by the Mediterranean sea, on the south by Jabal Nafusah and on the west by the Tunisian border.

The Jifarah Plain is heavily populated and contains the city of Tripoli and the towns of Zuwarah, Sabratah, Az Zawiyah, Qasr al Qarabulli, Bin Ghashir and Al Aziziyah. Approximately 44% of the Libyan population lives in the Jifarah Plain (1997 estimate).

Rainfall. The rainfall varies between, an average of approximately 300 mm/year in Tripoli and an average of less than 100 mm in the south western part of the plain.

Surface runoff. Part of the precipitation falling on Jabal Nafusah reaches the plain as surface runoff through many wadis, the length of which does not usually exceed a few kilometres.

Main Aquifers. The aquifers which play an important role in the groundwater flow and storage in the Jifarah Plain are as follows:

1. The Quaternary-Pliocene-Upper Miocene aquifer consisting of sand, calcarenites and clay extends over the area of the Miocene transgressive series (north of Al Aziziyah parallel). The saturated thickness of the aquifer varies from 10 to 150 m
2. A thick series of sandstones from Upper Triassic (Abu Shaybah Formation) to Lower Cretaceous Upper Jurassic (Kiklah Formation) forms another important aquifer in the central and eastern part of the plain. Moreover, the upper part of this sandstone series often directly underlies the Miocene sandy limestones and calcareous sandstones This geological forms a single hydraulic unit usually under a confined condition (below the clays of the Middle Miocene) except in the stretch between the southern limit of the extension of the Miocene and the foot of the jabal.
3. Aziziah dolomitic limestone (Middle Triassic) forms another aquifer well developed in the south-central and south-western part of the Jifarah. The formation is outcropping along the foot of the jabal where the Tertiary formations are absent.

6.2 Hydraulic Behaviour of the Aquifers – Water balance

Agricultural water demand. The agricultural sector consists almost exclusively of private farms. Several projects were implemented but most are suffering from insufficient water supply and their consumption is almost negligible when compared to the private sector.

The groundwater abstraction in 1998 for agriculture use is estimated at 900 x 10^6 m3/yr.

Municipal water demand. Groundwater consumption for urban and industrial use is dominated by that of Tripoli, Az Zawya and Jabal Gharbi (Jabal Nafusah). The total municipal abstraction in 1992 was approximately 473 000 m^3/day or 173 hm^3/yr of which 350 000 m^3/day were used by Tripoli. For the Jefara Plain as a whole, the municipal abstraction was estimated by Mott Mac Donald at 200 hm^3/yr in 1992. On september 1996, the Great Manmade River Project water from Jabal Hasawna reached Tripoli and made it possible to reduce the groundwater abstraction from the municipality well fields (Swani well field already strongly affected by seawater intrusion was closed at that time as well as Ayn Zara well field). The Committee on Water Resources estimated in 1998 the municipal water demand in the Jifarah Plain at 242 x 10^6 m^3/yr :

Today the water supply to Tripoli from Jabal Hasawna through the Western Jifarah System (WJS) has increased to approximately 300,000 m^3 per day.

6.2.1 Summary

Various authors have estimated the groundwater abstraction at different periods since 1960. Table 9 shows the rapid increase of the water use for the domestic and agricultural sectors:

Table 9: Groundwater abstraction estimates in Jifarah Plain since 1959 in 10^6 m3/yr

Year	1959/62	1972	1973	1975	1978	1992	1998
Author	USGS	GEFLI	FAO	GEFLI	FAO	Mac Don.	
Agriculture use	195	313	336	475	435	802	900
Municipal use	15	65	?	92	97	200	141*
Total	210	378		567	532	1002	1041

* Groundwater abstraction only without the contribution of GMRP

6.2.2 Water balance in 1992

Mott Mac Donald tentatively estimated the water balance of the Jifarah Plain (Mott Mac Donald, 1994) with the help of a mathematical model consisting of two layers: the upper layer, unconfined representing the Mio-Plio-Quaternary deposits covering the Jifarah, north of the Al Aziziyah fault; the lower layer representing several aquifers assumed to be in hydraulic continuity.

The most remarkable information provided by the model concerns:

- the release from storage which is estimated at 584 hm^3/yr in spite of a high assumption for the aquifer recharge related to irrigation and municipal losses (since more than 15 years, low water consumption irrigation methods such as sprinkler or drip, have developed in the Jefara and perhaps do not originate such high losses). 584 hm^3/yr as release from storage should therefore be considered as a minimum.
- the inflow from the sea, estimated as 166 hm^3/yr, which gives rise to the deterioration of the water quality around Tripoli.

Consequences of water unbalance in the Jifarah Plain. The water unbalance has the following main consequences:

- the inflow from the sea induced a strong deterioration of the water quality in Tripoli area and a few km inland due to seawater intrusion into the shallow aquifer.
- the release from storage induced a steady decline of the water level mainly in the areas of high groundwater abstraction (triangle Swani-Bin Gashir-Al Aziziyah) where the cone of depression reached 50 m in 1992 and approaches 60m today, leading to the depletion of the upper Plio-Quaternary aquifer (Figure 6).
- The mathematical model run by Mott Mac Donald indicated that, from the beginning of the development up to 1993, 13.0 km^3 of water have been abstracted (net abstraction taking into account the return flows), out of which 8.8 originate from storage. The model also shows that even **if abstraction was completely stopped, it would take in excess of 75 years before the aquifer returned to pre-development levels, without much improvement in water quality** from the present situation. This conclusion indicated how difficult and how long will be the process of restoring the aquifers even through a dramatic reduction of the abstraction, without the assistance of artificial recharge.

6.2.3 Water quality

Where not affected by seawater intrusion, water from the upper aquifer is usually of good chemical quality with an electrical conductivity ranging from 0.5 to 1 dS/m. The lower aquifer system generally shows much higher values of salt content with EC ranging from 1.5 to 5 dS/m.

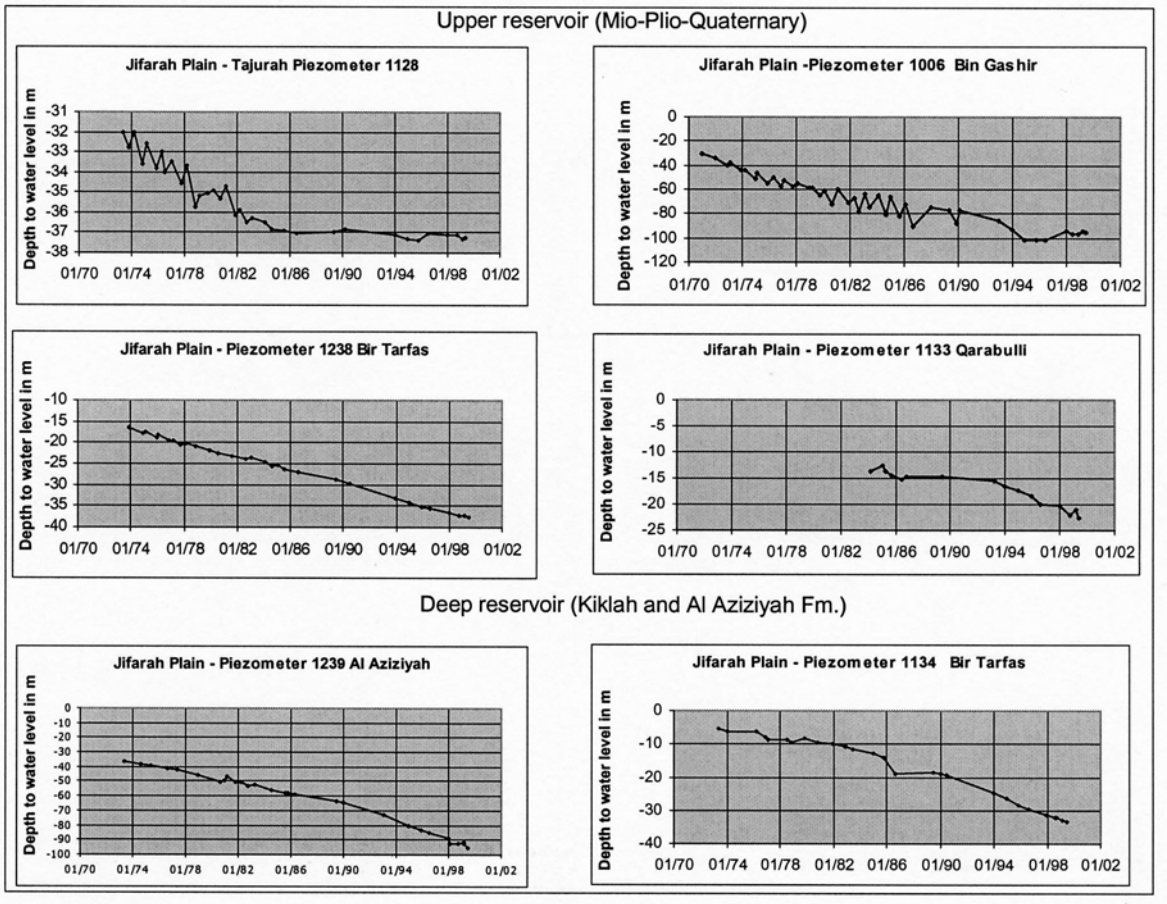


Figure 6: Jifarah Plain – piezometric fluctuations

7. As Sarir – Kufrah Basin

7.1 General description of the area

Limits of the area considered (Figure 9). The area corresponds to the eastern and south-eastern part of Libya. It is limited to the north by the depression marked by several sabkhas along the parallel 30°N, to the east, south-east and south, respectively by the Egyptian, the Sudanese and the Chadian borders, to the west by long. 17°30 E and along the western slope of Jabal Haruj and the eastern flank of Jabal Ghanimah. It is part of a much larger hydraulic system, the Nubian Aquifer System extending over most of the Egyptian territory, the north-western part of Sudan and the north-eastern part of Chad.

Groundwater reservoirs. The area considered in this section includes several sub-systems hydraulically connected, namely:

- The Kufrah sub-basin in the south east,
- The Sarir-Tibisti area in the south-west
- The Sarir in the north-east
- The Sirt sub-basin in the north-west

7.2 Kufrah sub-basin

It is delineated in its periphery by Paleozoic outcrops composed mainly of continental sandstone and clayey sandstone, except for the Carboniferous which shows shaly horizons which may isolate the Cambro-Ordovician from the Devonian aquifers over large areas. The central part of the basin (more than 250,000 km^2) is occupied by Mesozoic continental deposits, usually called Nubian Sandstone. Kufrah sub-basin forms a large fresh water reservoir as deep as 3,000 m in its centre. Groundwater investigations were carried out mainly in Kufrah area in relation to the agricultural development and in Tazirbu area for the design of the well field

7.2.1 Present water extraction and aquifer response in Kufrah area

Kufrah Production Project (KPP) consists of 102 production wells drilled by the end of 1972, which are used to irrigate 100 hectares each by the pivot system. The wells are 350 m deep with a pumping rate of 76 l/s each. Kufrah Settlement Project (KSP) originally consisted of 35 wells which are 457m deep; later on, in 1978, 22 wells were added to KSP well field.

Recent information from GWA indicate that most of the wells of KSP have now been abandoned by the farmers because of unreliability of the water supply and the water production from KSP is now considered as nil.

On the contrary the wells of KPP keep on working and the annual withdrawal from KPP is shown on Figure 8. In addition to the projects, a significant development of private agriculture is now taking place in Kufrah from 60 to 100 m deep wells, but no estimate of the irrigated area nor of the water withdrawal is available so far. It is considered that the private irrigated area is in the order of 5000 ha using some 75 x 10^6 m^3/yr.

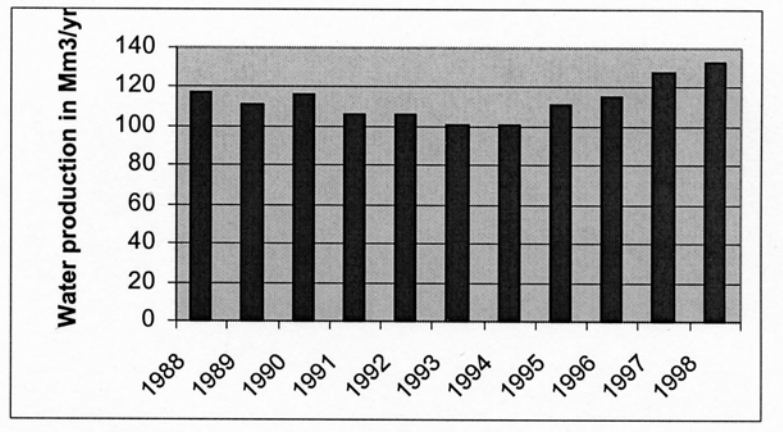


Figure 7: Kufrah Production Project - Water production in Mm^3/yr

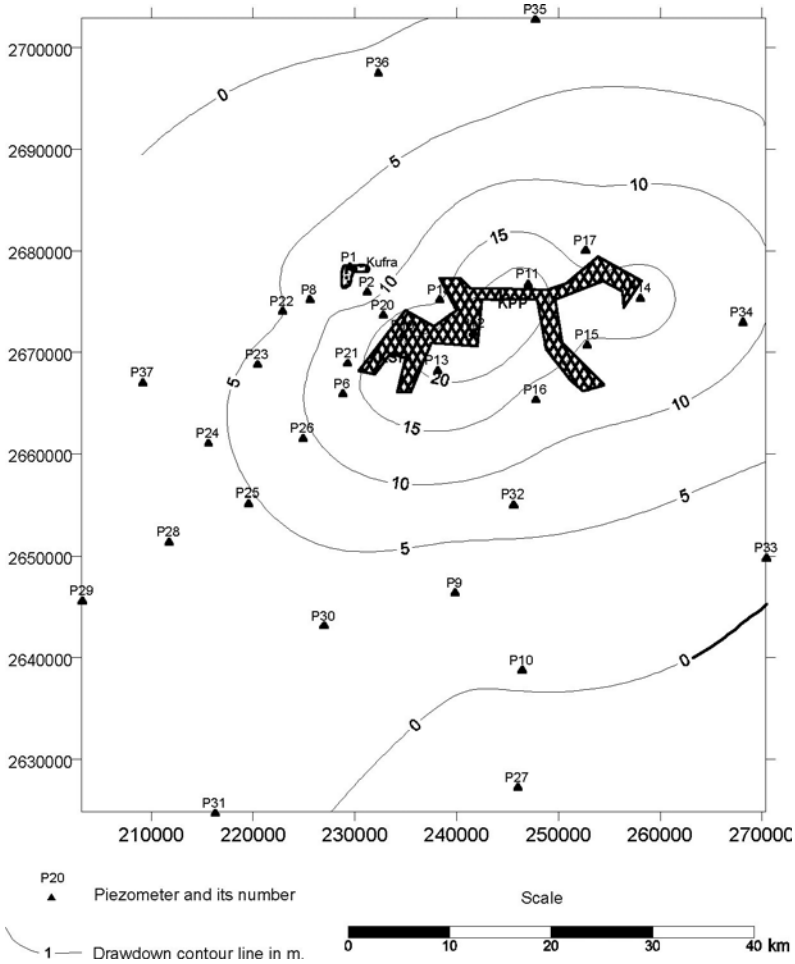


Figure 8: Kufrah agricultural projects - Drop in water level from 1968/1971 to 1998 (from deep piezometers readings)

The map of Figure 8 shows the drop of water level in the deep observation wells from the beginning of the operations (1968-1971) to 1998. Within the well fields, the water level decline in the deep piezometers is ranging from 15 to 25m in almost 30 year operation. The iso-drawdown contour line 1m is located about 20 km from the edges of the well field while the drawdown at 30-40 km away from the limits of the well fields is limited to 0.2 to 0.3m. No information is available on the dynamic water level in the wells while pumping.

The mathematical model carried out by several authors and calibrated on the data of a few year operation (Ahmad 1983, Abufila 1984, Johnson 1977, German Water Group 1977) obtained a good match between observed and calculated drawdowns which would make their predictions reasonably reliable. However, in view of the uncertainties on the actual water discharge which is likely to be lower than assumed in the models and on the behaviour of the production wells, there is still some uncertainty on the drawdown predictions made so far. Unless a serious effort is made to monitor the water abstraction mostly by the private farmers and the water level in Kufrah area, it will be difficult to draw reliable conclusions on the real water development potential of the Kufrah basin.

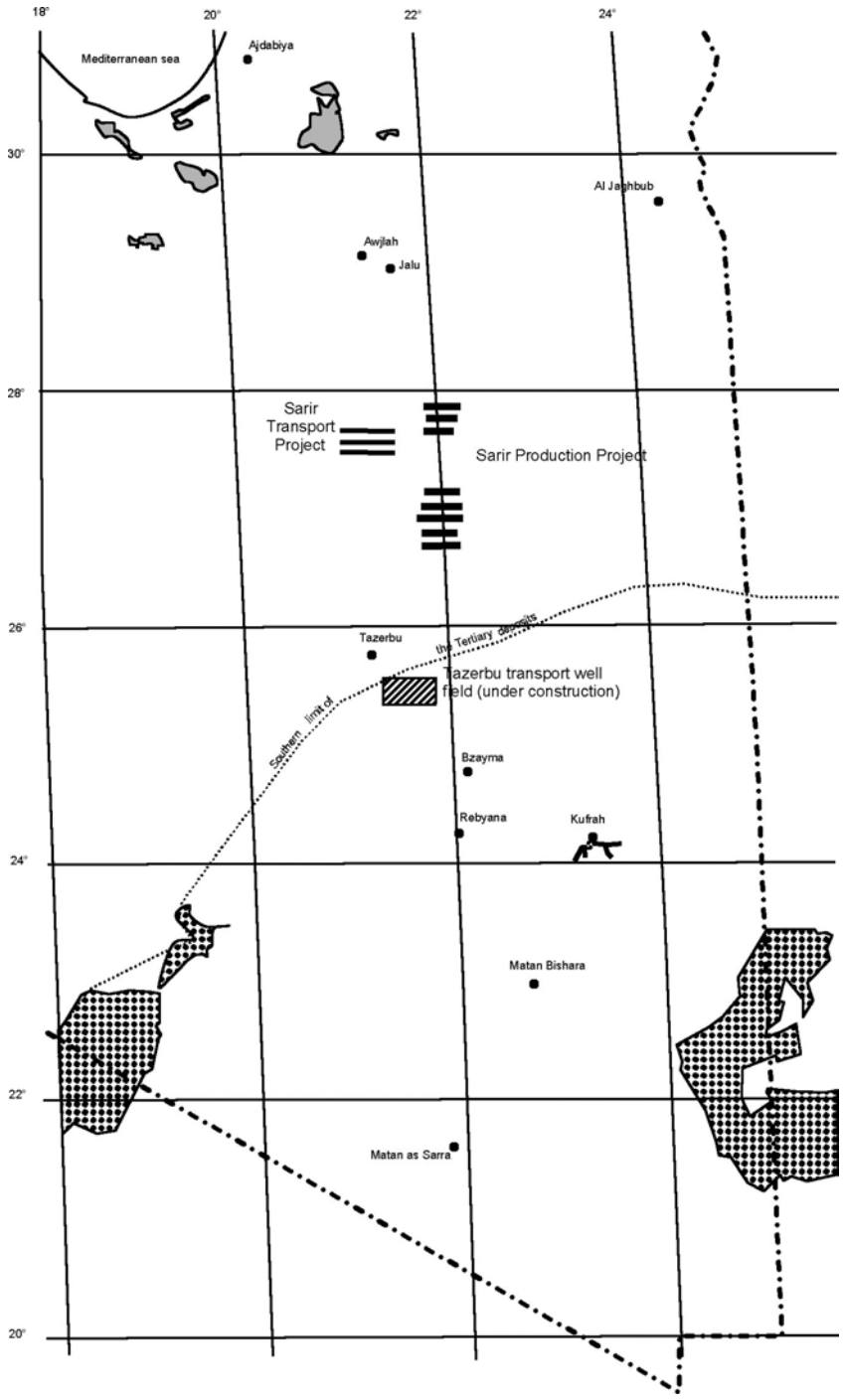


Figure 9: Sarir-Kufrah basin

7.2.2 Water development plans in Al Kufrah sub-basin

Tazirbu well field is under construction and is planned to produce 1 million m^3/day which will be added to Sarir production and conveyed to the coast. The production wells are under construction now, on the basis of a series of investigations (16 exploratory wells drilled earlier) and additional test holes recently drilled with the view to define more precisely the well field layout and the well completion design.

Phase III of GMRP is expected to develop a new important **well field South-West of Kufrah** projects. The water production from this new well field under study is expected to be some 1.68 x 10^6 m^3/yr.

7.2.3 Water quality

In Kufrah sub-basin the water quality is always excellent and the TDS from the main aquifers, both in Kufrah and Tazerbu is usually ranging from 100 to 400 ppm.

7.3 Sarir sub-basin

Two important well fields are now in operation in Sarir sub-basin: Sarir Production Projects (SPP) and Sarir Water Transport, located about 30 km west of SPP.

Sarir Production Projects are composed of two well fields which were set up in the years 70s and aimed at agricultural production.

South Sarir Well Field consists of 160 wells and the North Sarir Well Field consists of 80 wells. Each well was designed to produce 76 l/s and is fitted with a self-propelled sprinkler which irrigates 80 ha for winter and summer crops.

Figure 10 shows the water production from both well fields from the start of operation to 1998-99. Figure 13 shows the water level decline in November 98 compared to the initial water level and related to the deep aquifer tapped by the production wells. The water production is continuously decreasing since 1990 and was only 71 x 10^6 m^3/yr in 1998 (195,000 m^3/day). In November 1999 only 120 wells were working out of 240. The water abstraction resulted, in almost 25 years operation, in a drawdown, within the well fields, ranging from 4 to 7 m in Sarir North and from 3 to 5 m in Sarir South. A similar exercise made in 1996 with the 1994 piezometric data indicated a slightly higher decline of water level in Sarir South (4 to 8 m) which confirms that the rate of discharge since 1994 has decreased.

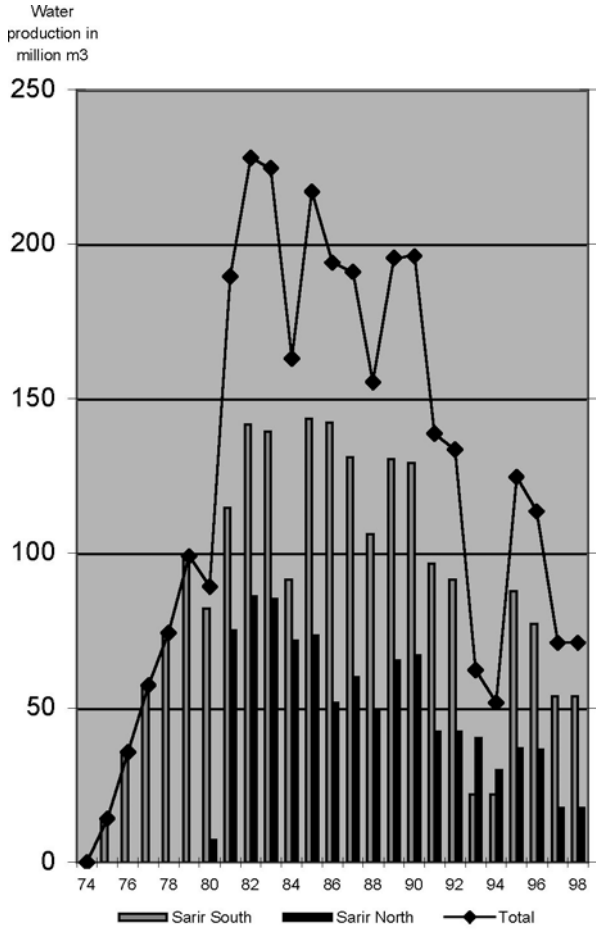


Figure 10: Water production of SPP from 1974 to 1994

7.2.1 Sarir GAMRP Phase I well field

Sarir well field for the water transport consists of 126 wells in three parallel rows set in east-west direction. Each row consists of 42 wells, 1.3 km apart from each other. The distance between rows is 10 km. Each well was originally designed to produced 92 l/s, 113 wells being operated at the same time, with 13 wells in standby. The well field was designed to produce 1,000,000 m^3 /day.

The well field is now under operation (at around 25-30 % of its capacity) since 1993. Figure 11 shows the history of the water abstraction from the well field from 1993 to 1998 . At present, only 25 % of the wells are operating at a rate varying from 210,000 to 250,000 m^3/day according to the demand. 97 % of the water produced is used for domestic water supply, 2 % for agriculture and 1 % for animal watering. The water is distributed according to a pattern which may slightly vary from day to day.

Figure 12 shows on the same map as Sarir Production, the response of the aquifer in Sarir Transport Project area. The drop of water level indicated on the map referred to the deep piezometers readings in April 1999 compared to the initial situation of the well field before 1993, date of the beginning of significant water production. It is worth to note that the cones of depression due to the effect of the three well fields are connected and form a unique large depression of more than 25,000 km^2. The three well fields are surrounded by the iso-drawdown contour line 2m

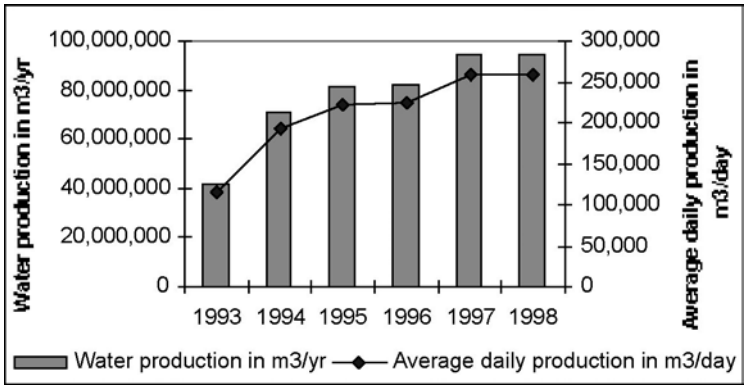


Figure 11: Sarir water transport - Water production

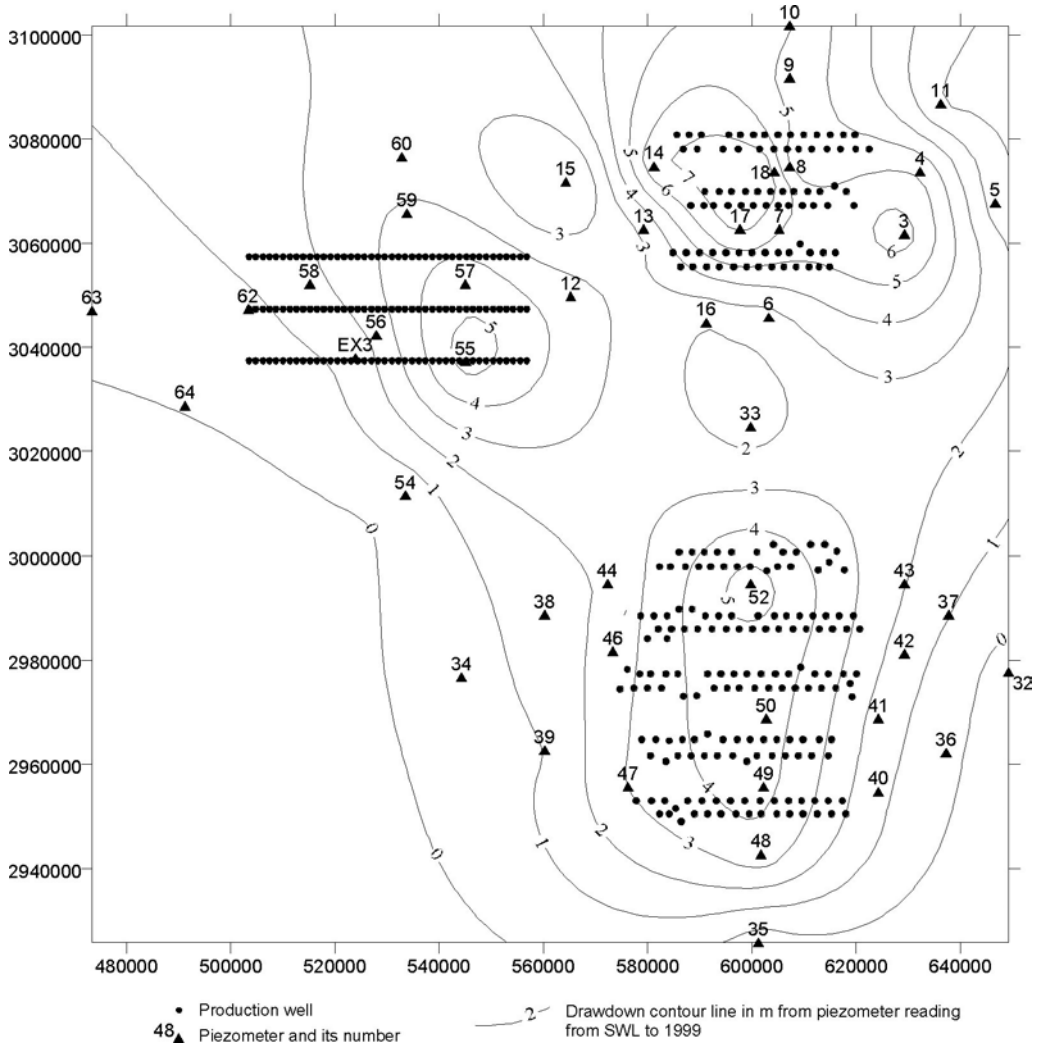


Figure 12: Sarir Production Projects and Sarir Transport Project - Water level decline in winter 1998-99 referred to initial situation (1971-75 for Sarir Production and 1990 for Sarir Transport)

7.3 Jalo-Awjlah oasis

In the area of Jalo-Awjlah, a state project was implemented in the early 80s, consisting of 101 farms of 6ha each. Water was to be supplied by a well field located a few km to the south where water was found of better quality in the Post Middle Miocene. 33 wells in 3 parallel rows of 11 wells were drilled from 1977 to 1981 but only 11 wells of one row were connected to the irrigation network of the farms. Now only 4 out of the 11 wells are in operating conditions and each well has a capacity of approximately 50 l/s. In view of the insufficient amount of water available for irrigation, the farmers drilled their own wells at depths ranging from 60 to 100m but supplying water of poor quality (2.5 to 5 g/l TDS) to be mixed with the better quality water from the deep wells. Through verbal communication from agricultural engineer working in Jalo, it seems that most of the 600 ha originally planned are now under irrigation, mostly with shallow wells.

Private irrigation has rapidly developed in Jalo-Awjlah based on shallow drilled wells each with a capacity ranging from 4 to 7 l/s but with a poor quality water. Nevertheless, the private irrigated area is now estimated at 3500 ha (approximately 2000 in Jalo, 1000 in Awjlah and 500 in Jekara). The main crops grown with the brackish water are date palms and tomatoes. The average yearly water abstraction may be estimated at some 60 to 80 x 10^6 m^3/yr.

7.4 Summary of irrigated areas and water use in the Kufrah-Sarir basin

Table 10 summarises the information available on water production by area and by sector in the Kufrah-Sarir basin.

Table 10: Water production in Kufrah-Sarir basin in Mm^3/year in 1998-1999

Area	Water transport in Mm3/yr	Domestic and industrial water supply	Agriculture						Total water use x 10^6 m3/yr
			Agricultural projects		Private irrigation*		Total agriculture		
			Irrigated area (ha)	Water use	Irrigated area (ha)	Water use	Irrigated area (ha)	Water use	
Kufrah		6	9,200	132.60	5,000	75	14,200	207.60	214.0
Tazerbo					200	3	200	3.00	3.0
Sarir Production Project			9,600	71.10			9,600	71.10	71.1
Sarir Transport	94.11	2					0	0.00	96.1
Jalo					3,500	70	3,500	70.00	70.0
Water supply small cities		4							4.0
Total	94.11	12	18,800	203.70	8,700	148	27,500	351.70	458.24

* Figures related to private agriculture are very approximate

8. Jabal Al Akhdar system

8.1 General description of the area

Limits of the area considered (Figure 14). This area covers the north-eastern part of the country, immediately to the north of the Sarir basin. It includes the Jabal al Akhdar, its southern flank ending in the depression along lat. 30° and desert land up to the Egyptian border.

Hydrographic network. It reflects the morphological features of both flanks: to the north, the valleys are short and deeply cut and reach the sea after a few tens of km; to the south, the valleys are wider and they progressively become large spreading zones, at the breaking slope of the jabal, where water evaporates.

Rainfall. The average rainfall ranges from 200 to 600 mm in the mountainous part of the area. To the south, the precipitation becomes negligible along the southern limit of the area.

Groundwater reservoirs. Fractured carbonate rocks of the Eocene and Miocene are the main aquifers of the Jabal al Akhdar. Both are heterogeneous and anisotropic karstified aquifers, hydraulically interconnected on a regional scale. A sharp decline in water level elevation of more than 400m over a short distance from the axis of the Jabal takes place in both a northern and southern direction. The crest of the Jabal also represents a surface water as well as a groundwater divide with flow taking south and north directions in the central part and becoming radial with a more relaxed gradient at the eastern and western flanks.

8.2 Groundwater resources

Since 1978 when comprehensive studies of the water resources of the western part of Jabal Akhdar was carried out by General Water Authority (Khan, M.Y., Raju, T.S. and Ghosh, A.K., 1978 and Guerre, A.

1977a,b,c), only one hydrogeological survey was performed in Baydah-Al Bayyadah area (Hydrogeo, 1992) consisting of an inventory of wells, geophysics, submarine springs investigations, mathematical model of the main aquifer and climatic and hydrological measurements in the years 1982-84. The conclusions of this study are completely different from those reached by GWA in 1977-78 as shown on Table 25: aquifer recharge estimated by Hydrogeo is 3 times less than GWA's and the water abstraction through wells is estimated at 16 x 10^6 m^3/yr (including 13 x 10^6 m^3/yr for Baydah water supply) by GWA as compared to 8 x 10^6 m^3/yr indicated by Hydrogeo. Both conclude however that large amount of groundwater is lost to the sea: 76.7 x 10^6 m^3/yr according to Hydrogeo and probably much more for GWA. The water balance components estimated by GWA for the other units of Jabal Akhdar are also indicated on Table 11. No new estimates are available today.

Table 11: Water balance of Jabal Akhdar

Name of the area	GWA estimates (1977-78)				Hydrogeo estimates (1982-84)	
	Average rainfall surplus x106 m3/yr	Runoff x10^6 m^3/yr	Groundwater discharge (1977-78)		Aquifer recharge (equivalent to rainfall surplus - runoff - springs) x10^6 m3/yr	Water abstraction through wells x106 m3/yr
			Springs	Wells		
Binghazi-Al Marj-Tulmaythah	265	20	90	112		
Al Bayda-Al Bayyadah-Al Qubbah	275	5	11	16	98.1	8
Darnah-Bomba-Tubruq	60	17	10	7.5		
Southern flank	175	35	0	0		
South-western coastal area	50	1	0	?		

8.3 Present groundwater use and aquifer response

The last decade was marked by the rapid development of the private agriculture, particularly:

- Around Binghazi, in Hawari, Beninah and Sidi Mansur
- Around Al Marj
- North of Al Bayda

and by the increasing water demand for the urban agglomerations.

Binghazi Plain and Al Marj (Unit 1 on the map of Figure 14). The water abstraction increased significantly in the Binghazi Plain during the last decades, as indicated in Table 12.

Table 12: Water abstraction in Binghazi Plain (Sources: Khan, M.Y. et al. 1978 for 1967 and 1977 estimates. GWA estimates for 1993 and 1999)

Year	Domestic water supply	Industry	Irrigation	Total
1967	7.4		3.6	11.0
1977	48.0	1.7	35.8	85.5
1993	170.0	5.0	100.0	275.0
1999	50.0	5.0	114.2	169.2

Note: Until 1993, before water to Binghazi came from GMRP, the water abstraction was higher since Beninah well field was operating and producing some 120 x 10^6 m^3/yr.

In Al Marj area, the water abstraction increased from some 10.4 x 10^6 m3/yr in 1976 (Guerre, A., 1976a) to some 45 x 10^6 m^3/yr (GWA estimate from number of licences issued) in addition to some 10 x 10^6 m^3/yr for the water supply to the city.

Comparing the water abstraction estimates in Binghazi and in Al Marj with the GWA recharge estimates, would clearly suggest an overexploitation of the aquifers in that area. This conclusion is also confirmed by the water level decline in the most solicited areas and primarily by the general water quality deterioration in the Binghazi Plain. Figure 13 shows two examples of substantial water level decline in the western plains of Jabal Akhdar.

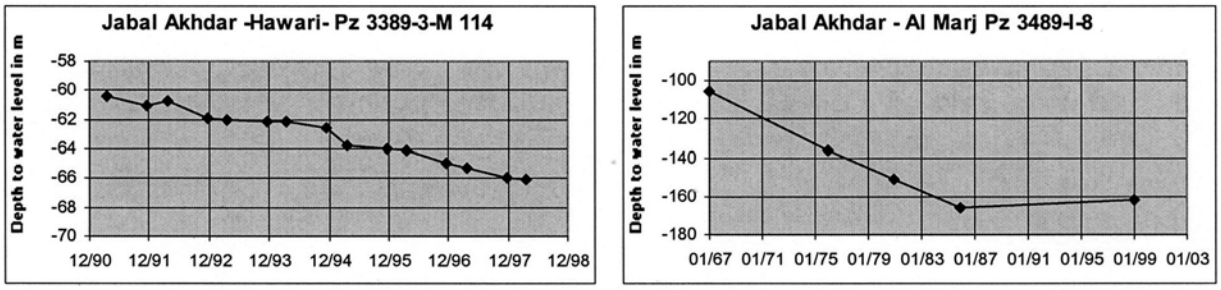


Figure 13: Examples of water level fluctuations in Binghazi-Al Marj area

Some electrical conductivity measurements in September 1999 showed a significant increase of the salinity in Beninah (from 2500 ppm in 1978 to approx. 4000 in 1999) and in Kuwayfiyah (from 2000 ppm in 1978 to more than 4000 today) areas.

Al Bayda-Al Bayyadah area (Unit 2 on the map of Figure 14). In that area the private agricultural development increased rapidly during the last decade mostly in the depressions of the lower plateau north of Al Bayda. Vegetable production proved to be a very profitable activity when modern irrigation techniques allow high yield. Many wells were recently drilled that brings the total number of drilled wells in operation in the area to approximately 600. On the basis of the number of wells for which licences have beenissued, and on the average discharge and pumping hours per day, GWA estimates the water abstraction at some 50 x 10^6 m^3/yr. This amount includes the production of new wells drilled for the water supply to the cities. When adding the old estimates, the total water abstraction may be roughly estimated at:

- 31 x 10^6 m^3/yr for agriculture
- 35 x 10^6 m^3/yr for domestic water supply
- 11 x 10^6 m^3/yr as natural discharge from springs

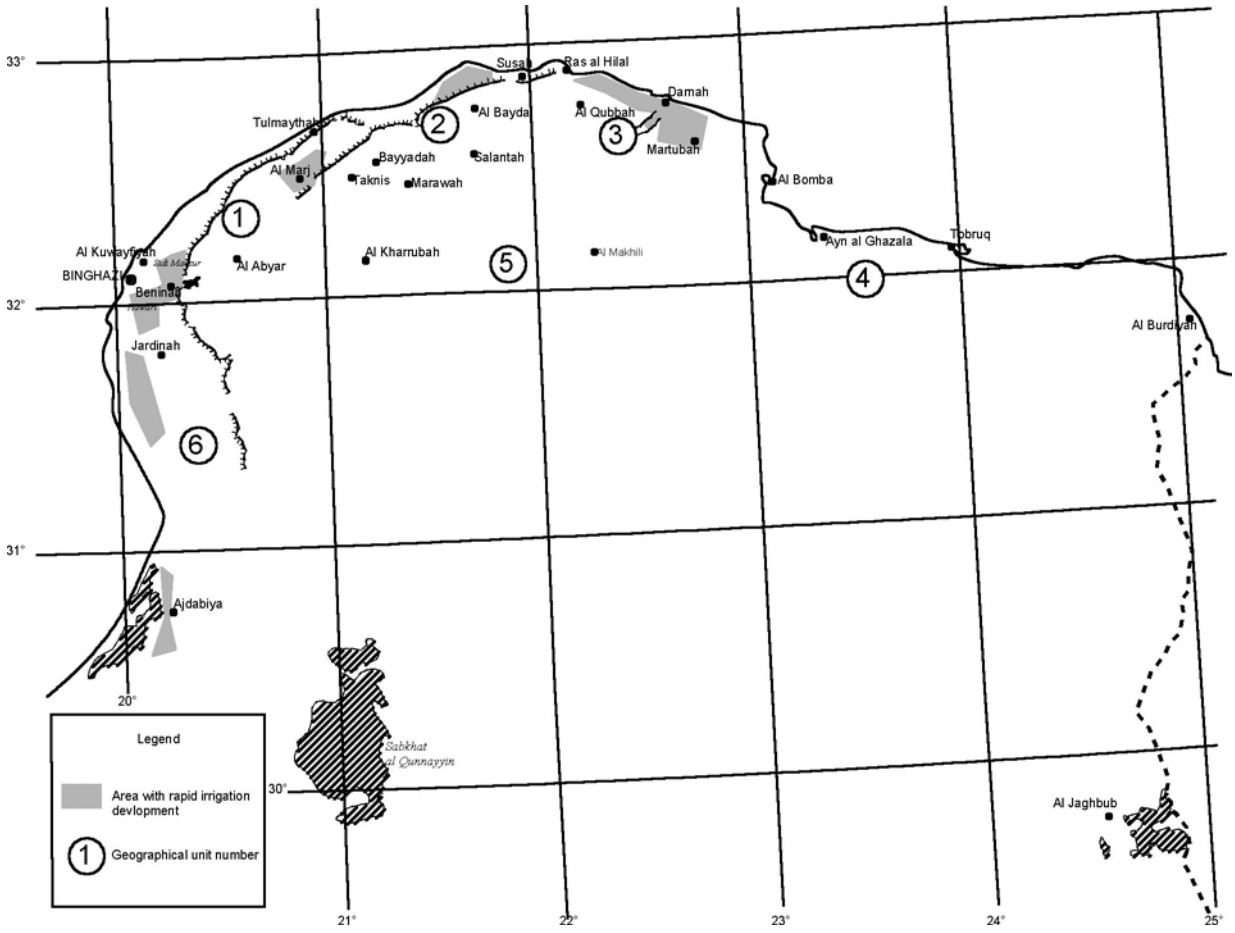


Figure 14: Jabal Akhdar - Areas showing rapid development of private irrigated agriculture

Ras al Hilal-Darnah-Martubah area (Unit 3 on the map of Figure 14). Also in that area, private irrigated agriculture has developed significantly. On the basis of the number of licences issued, GWA estimates the total water abstraction at some 40 x 10^6 m^3/yr , in addition to some 10 x 10^6 m^3/yr natural discharge from springs. A rough distribution of the water production in 1999 could be as follows:

- 20 x 10^6 m^3/yr for agriculture
- 20 x 10^6 m^3/yr for domestic water supply
- 10 x 10^6 m^3/yr as natural discharge from springs

Al Bomba-Tobruq area (Unit 4 on the map of Figure 14). Water abstraction in the area seems to be essentially limited to that needed for the water supply to the coastal cities (Al Bomba, Ayn al Ghazala, Tobruq) estimated at some 5 x 10^6 m^3/yr. This limited water abstraction is due to the high salinity of groundwater (more than 4 g/l) in most of the area, except in the valley bottoms where fresh water lenses may exist.

Southern flank of Jabal Akhdar (Unit 5 on the map of Figure 14). Some hundred production wells were drilled in Al Kharruba-Al Mekhili areas, following a water resources survey carried out by Franlab (Franlab, 1974 and 1976). However the irrigation network has not been implemented and the water abstraction in that area is almost nil.

South-western coastal area: Soluq-Ajdabiya (Unit 6 on the map of Figure 14). South west of Binghazi, in Soluq-Jardinah area, groundwater is brackish, usually more than 2.5 g/l . However many wells are reported to be drilled and used for irrigation in that area. No estimate of water abstraction is available which is however probably less than 10 x 10^6 m^3/yr. Now the city of Ajdabiya is supplied with water from the Great Manmade River.

Table 13 summarises the groundwater use estimates in 1978 and 1999. Even if the figures are very rough estimates they clearly indicate the significant increase of water abstraction both for water supply and private irrigation. It is likely that a significant part of the water balance in Unit 1 is coming from the storage and from the sea.

Table 13: Jabal Akhdar; Groundwater use estimates

Area	Groundwater use estimates (1978) from springs and wells				Groundwater use estimates (1999) from springs and wells			
	Domestic and industrial water supply	Agriculture		Total	Domestic and industrial water supply	Agriculture		Total
		Private	Projects			Private	Projects	
Unit 1: Binghazi Plain-Al Marj-Al Abyar - Coastal area from Sidi Khalifa to Tulmaythah	53	57	2	112	55	114.2	0	169.2
Unit 2: Al Bayda-Al Bayyadah	23	4	0.6	27.6	46	31	0	77
Unit 3: Ras al Hilal-Darnah-Martubah	14	3.5	0.1	17.6	20	30	0	50
Unit 4: Al Bamba-Tobruq					4	1	0	5
Unit 5: Southern flank of Jabal Akhdar	0.5	0	0.1	0.6	1	0	0	1
Unit 6: South-western coastal area; Ajdabiya-Suluq	2	12	0.2	14.2	1	20	0	21
Total	**92.5**	**76.5**	**3**	**172**	**127**	**196.2**	**0**	**323.2**

8.4 Pollution of the groundwater

Pollution of the groundwater is a very serious problem in Jabal Akhdar. The sewage collection and treatment system of most of the cities are not in operating conditions. Thus the sewage effluents are either discharged into nearby wadis (Al Marj, Al Bayda), spread in the fields around the city or directly injected in karstic caves in communication with the aquifer (Binghazi).

9. Conclusions

9.1 Renewable water resources

The total renewable water resources in Libya are usually estimated at 600 x 10^6 m^3/yr. This means that 87% of the present groundwater use is coming from non-renewable resources.

9.2 Present water use in Libya

Three main events have marked the water history in Libya during the last decade:

- the increasing demand for water supply in the coastal cities and the coincident deterioration of the water quality in the coastal aquifers;
- the starting operation of the water transfer from the desert accelerated by the water shortage in the cities along the coast;
- the rapid development of private agriculture

9.3 Irrigated agriculture

The total net irrigated area (irrespective of when the irrigation occurs) is estimated at 310,000 ha (Table 14). However because of the importance of the private irrigation representing some 84% of the irrigated area in Libya, the figure of 310,000 ha should be considered as a very rough estimate, probably underestimated. It should also be mentioned that the area equipped for irrigation is probably much bigger, say in the order of 450,000 ha since only part of it is actually irrigated.

Table 14: Irrigated area in Libya in ha

Area	Irrigated area in ha			% of the private irrigation
	Projects	Private irrigation	Total	
Al Jabal al Akhdar	0	24,000	24,000	100.0
Al Kufrah - As Sarir	18,800	8,700	27,500	31.6
Jifarah	0	142,000	142,000	100.0
Hamada el Hamra	12,753	16,640	29,393	56.6
Murzuq	18,619	67,314	85,933	78.3
Total	50,172	258,654	308,826	83.8

9.4 Domestic water supply

More than 30% of the present domestic water demand is supplied by the Great Manmade River Project. The contribution of the existing desalination plants is almost negligible and it is even probably less than indicated on Table 15 since most of the desalination plants are not in good operating conditions. The domestic water supply shown on Table 15 includes some 5 to 10 x 10^6 m^3/yr of water used for industry which cannot be precisely identified.

Table 15: Domestic water supply including some industrial water demand in the cities (1998-1999 estimate)

Domestic water supply	Origin of water			Total
	GMRP	Local groundwater	Desalination plants	
In m^3/day	558,000	1,050,821	48,500	1,657,321
In Mm^3/year	204	384	18	605

9.5 Industrial water use

Most of the industrial water is used for oil industry (injection, processing and some domestic use) and was estimated in 1998 at 117 x 10^6 m^3/yr.

9.6 Summary of water abstraction

Table 16 summaries the various estimates of water abstraction by area and by sector. Agriculture is the larger consumer and represents some 82% of the total groundwater withdrawal. The figure corresponding to “Others (evaporation)” is indicative and has been estimated only in Wadi Shati. It should also include the

volume of water evaporated in the sebkhas connected to the groundwater and may be substantial but no precise estimate is available today.

Table 16: Groundwater abstraction by area and sector objective in Mm^3/yr

Area	Domestic and industrial water supply		Identified industrial water supply	Agriculture			Others (evaporation)*	Total
	Water transport	Local production		Agricultural projects	Private agriculture	Total		
Al Jabal al Akhdar	0	127		0	196	196		323
Al Kufrah - As Sarir	94	12	117	204	148	352	?	575
Jifarah	0	141		0	900	900		1,041
Hamada el Hamra	0	45		235	295	530	?	575
Jabal Hasawna	110					0		110
Murzuq	0	58	0	271	1,425	1,696	70	1,824
Total	204	384	117	710	2,964	3,674	70	4,449

* Evaporation in sebkhas in Al Kufrah-Sarir and Hamada al Hamra basins may represent a significant amount of water

9.7 Projected water requirement to meet the expected domestic water demand and to support food self sufficiency in 2025

Depending on the assumptions made on water productivity in agriculture, the total water requirement to support the basic food self sufficiency and to meet the domestic water demand in the year 2025 is estimated to be ranging between 10.5 and 16.4 km^3/year. Present groundwater abstraction is in the order of 4.4 km^3/yr. When the Great Manmade River will be fully operational, the total amount of water available for all uses, assuming that the present groundwater production equipment will be maintained until 2025, will be in the order of 6.4 km3/year and will probably hardly cover 50% of the total water requirement to support the basic food self sufficiency and meet the domestic water demand

9.8 Water issues

9.8.1 Water resources issues

a) Uncontrolled groundwater development from the coastal aquifers exceeding the annual replenishment has caused severe water level decline and seawater encroachment, making the coastal groundwater resources almost unusable because of their high salinity;

b) The difficult water supply situation along the coast has accelerated the process of water transfer from the South where huge amount of water has been stored since the late Quaternary. The response of the aquifers to the first years of pumping in the two well fields operated by GMRA, Jabal Hasawna and Sarir, seems to be reasonably close to the prediction in terms of water level decline. However,
   - The data collected need to be used to verify the calibration of the simulation models and to check the reliability of the long term predictions on which the project is based;
   - The well field of Sarir is not fully safeguarded from an unexpected increase of water salinity due to up-coning from the brackish aquifers located underneath;

c) Most of the groundwater monitoring network in Libya is focused on the control of large water development projects (for agriculture or water transport). Groundwater abstraction from private farms, which corresponds to 47% of the total present and planned abstraction and is now, and will probably be, in the future, the main sector of water use, is almost completely lacking of water resources monitoring system.

Table 17: Relative importance of the various categories of water use

	Water production in Mm^3/yr	%
GMRP well fields when fully operational	2,300	36.2
Domestic and industrial water supply	384	6.0
Private farms	2,964	46.6
Agricultural projects	710	11.2
Total	6,357	100.0

9.8.2 Environmental issues

a) Inadequate sanitation system in the urban agglomerations (mostly in Jabal Akhdar) leads to severe pollution of the shallow aquifers around the cities;

b) Important water abstraction either for local agricultural projects or for water transport to the coast, will cause a significant water level decline in the aquifer, due to the non renewable character of the water resources. This will slowly induce the disappearance of natural vegetation which is still important in Wadi ash Shati or Ghadamis oasis;

c) Improper irrigation and drainage practices has resulted in substantial degradation of soil in the south-western part of Libya. The planned use of transport water for irrigation along the coast of Sirt where brackish aquifers exist at shallow depth may also result in waterlogging and salinity problem if appropriate irrigation and drainage techniques are not applied.

9.8.3 Food security and non-renewable water resources

Food security is felt as a moral imperative for the Libyan leaders and huge efforts were accomplished in the 70s and 80s to develop irrigated agriculture based on local water resources, and in the 90s to create the conditions for the rehabilitation and development of the coastal agriculture through water transport from the south.

However,

a) Food security is distinctly different from food self sufficiency which is now impossible and will be more and more difficult to achieve in Libya;

b) Rapidly growing urban water demand will need to be met increasingly from transfers from irrigated agriculture. This is clearly the case in the Jifarah Plain where the domestic water demand in the year 2025 will be in the order of 2 million m^3/day, i.e. almost the whole amount of the planned water transport from Jabal Hasawna. This means that the planned use of the GMRP water for agriculture will have to be progressively but drastically reduced even when taking into account the re-use of sewage water unless other sources of water are put into operation for the domestic demand (seawater desalination);

c) A debated question is whether irrigation, mostly that based on costly water transfer, remain justified in situation of scarcity where the only source of water is non-renewable and where economic return from other sectors (oil industry) would allow an easy access to international food market;

d) In view of the important expected drawdown in the wells of Jabal Hasawna, it might be difficult to maintain the foreseen pumping rate beyond the expected life time of the project, i.e. 50 years, and it might also be difficult to find an alternative location for a new well field in the same area (Jabal Fazzan). The Murzuq basin still offers a large potential of freshwater but this alternative would require a completely new design for the water conveyance and may provoke strong reactions from the local water users.

e) The Kufrah basin is the only area which offers a huge potential for the very long term groundwater development with the possibility to accommodate several successive well fields when one is facing problems of excessive drawdown.

9.9 General conclusion

Irrigated agriculture in Libya can hardly expand to meet a significant portion of the long term food demand for a number of reasons: growing urban water demand competing with the agricultural demand, limited opportunity of extending the life time of the water transport system beyond 50 years, soil degradation. Water saving and re-cycling may certainly extend the life time of irrigated areas and help sustaining the agricultural activities but the only long term options which can reasonably envisaged now are:

- Sea water desalination which can certainly alleviate the weight of the domestic water demand along the coast
- Creation of job opportunities which are not water consuming in order to develop economic sectors which do not require water for their activity.

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Modeling of the Western Jamahiriya Aquifer System

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Abstract

The Western Jamahiriya System (WJS) forms Phase II of the Great Man-made River Project in which 2 million m^3/day of groundwater is to abstract from the Fezzan aquifers to be conveyed to Tripoli and Jeffara Plain.

The Western Jamahiriya Aquifer System has been modelled using a quasi-three-dimensional finite element flow model, simulating multilayered aquifers with vertical and lateral hydraulic interconnections. The steady-state model calibration was made with reference to the natural state of the aquifer system prior to its modern development (year 1970), the non-steady-state model calibration was made by matching the history of the exploitation in the period 1970-1990. After the calibration process, the model has been used to optimise the WJS wellfield layout. The most favourable solution for the WJS wellfield development was considered to water from the Cambro-Ordovician Devonian aquifer in the east and north-east Jabal Hasouna. Long term forecasting simulations, representing 440 individual wells pumping between 45 and 56 l/s, were performed over a period of 50 years to optimise the WJS wellfield layout. The identification of the most cost effective solution for gathering and conveying the ground water from the wells to the main conveyance pipeline required to link the hydrogeological model with a pipeline network analysis model and a costing program.

This model has been recently used in the framework of the Ghadames Water Supply Project. Scope of the work is to design the most economic layout of wells and collector pipes which will supply 90 million m^3/year of groundwater from the Triassic Jurassic Lower Cretaceous aquifer in the Ghadames-Derj area.

Keywords
Aridity, groundwater abstraction, modelling, planning, regional aquifer, Western Jamahiriya System.

1. Introduction

General surveys and detailed studies of the water resources of the Fezzan have been performed since 1950 by many Authors and Companies. The first works (Tibbits 1966, Jones 1969, Regwa 1973) are mainly concerned with the exploration and the development of groundwater from the more promising areas. Only after 1973, when the hydrogeological conditions of the area were known in their main outline, did the need for a long term forecasting of the aquifers behaviour arise and it was proposed to construct a regional model of the Fezzan area (Burdon 1974). Some local models were thereafter performed by Italconsult (1975), German Consult (1975) and Holzmann-Wakuti (1975) in order to predict the long term effect of the water abstraction in Wadi Ash Shati and Al Jufrah. Comments on these models have been made by Pallas (1975a, 1975b) who essentially pointed out the substantial arbitrariness in the choice of the boundary conditions and the unrealistic assumption of some physical parameters utilised in the construction of these models. He also suggested that a regional model should be constructed, taking into account the whole groundwater system and its actual hydrodynamic behaviour. This suggestion was considered by the General Water Authority of Libya (GWA) in the specifications of the project "Hydrogeological study of Wadi Ash Shati, Al Jufrah and Jabal Fezzan Area", namely:

1. The model must reach the limits of the physical system and the hydrodynamic conditions prevailing in these limits must be assigned as boundary conditions.
2. The model must take into account the main features of the groundwater system (multilayered regional aquifer, lateral connections between aquifers, leakage trough aquitards, confined and unconfined zones of the groundwater system).

In the framework of the above study, realised by Idrotecneco (1982), a quasi three-dimensional finite element flow model of the Western Libya Groundwater System was performed (Pizzi and Sartori, 1984), taking strictly into account the above specifications. The feasibility of huge water abstraction from the Jabal Hasouna water table aquifer was first demonstrated utilising the above model (Pizzi and Brandi, 1981).

In the period 1980–1985, the geological and hydrogeological situation prevailing in the area was clarified by several exploratory wells drilled by GWA in the north and east Fezzan. Additional findings of these wells resulted in some changes in the Fezzan. geological and hydrogeological interpretation. Moreover El Sonni and Aboulkheir (1988) developed a new interpretation of the northern Murzuq basin between Sarir Qattusah and Maknussa area. This interpretation leads to a double layered concept for the Nubian aquifer in this area.

As a result of the above interpretation changes, the Idrotecneco model was no longer appropriate to be used in the area under consideration. Therefore the Management and Implementation Authority of the Great Man–made River Project (GMRA) required the construction of a new regional numerical model with the objective to demonstrate, by computer simulations, the effects on the aquifer system of future groundwater abstraction from the WJS wellfields and from other existing and planned projects in the area.

The specifications and the mathematical tools used in this work, realized by Geomath for Brown and Root and GMRA, (Geomath 1994), are of the same type utilised in the Idrotecneco study. However, a much greater detail has been required in the project area and in the WJS wellfields, which also cover a greatly increased area. Moreover, due to the additional data, the hydrogeological interpretation of the aquifer system was augmented. During the course of the project, six additional exploratory wells were drilled in the unconfined zone of the Cambro Ordovician Devonian aquifer in the east Jabal Hasouna area, which allowed the transmissivity map and the substratum elevation in the above area to be refined.

Recently, the above regional flow model has been used, in conjunction with a local two dimensional flow and solute transport model, by the Engineering Consulting Office for Utilities (ECOU), in the framework of the Ghadames Water Supply Project. The WJS model has been considerably improved (Geomath 1997) as a result of the additional hydrogeological data concerning the TRJLC aquifer in the north-western Libya (Salem and El Baruni 1990) and southern Tunisia (Mamou 1990).

2. Hydrogeological outline of the Western Jamahirya Aquifer System

The WJS aquifer system extends over 864,000 km^2 between the Agmuid fault (west), the Atlas Flexure and the Gafsa-Homs fault (north), the Hun graben (east) and the basement outcrops surrounding the Murzuq basin (south). Within this area, Cambrian to Tertiary sediments overlie Precambrian Basement. The Qarqaf uplift divides the area into two basins: the Hamadah Al Hamra basin to the north and the Murzuq basin to the south. Alternating cycles of erosion and deposition have resulted in complex layering and interconnections between the three aquifers which occur in each basin. The occurrence areas of these aquifers are reported in Figure 1. Three schematic hydrogeological cross sections of the WJS aquifer system are reported in the Figure 2.

2.1 Aquifers

The Upper Cretaceous (UC) aquifer occurs in the Hamada Al Hamra - Al Jufrah area and corresponds to the upper aquifer in this area. The water bearing formations consist of fractured dolomitic limestones with marl, shale and gypsum of Late Cretaceous age. This aquifer includes the Mizda, the Tigrinna and Nalut aquifers as described by Pallas (1980).

The thickness of this aquifer ranges from 100 to 250 m. The field transmissivity is low (50 m^2/day) except where the limestones are fractured as in the Al Jufrah area, where the transmissivity is very high (2600 m^2/day). The UC aquifer outcrops in Jabal Nefusa and in a small area north of Adrar Bendrich; elsewhere, it is partially confined by tertiary formations. The field storativity is high (up to 10^{-1}) in the outcropping areas, where the aquifer is unconfined, and ranges from 1.7 10^{-2} to 2.6 10^{-4} in the confined zones.

The Jurassic-Lower Cretaceous (JLC) aquifer occurs in the central Murzuq basin and corresponds to the upper aquifer in this area. The water bearing formations are continental sandstones of Jurassic-Lower Cretaceous age. The thickness of this aquifer ranges from 100 to 700 m. The field transmissivity is very high (1500-3000 m^2/day). This aquifer is phreatic throughout its extent, therefore the field storativity has unconfined values (up to 10^{-1}).

The Triassic-Jurassic-Lower Cretaceous (TRJLC) aquifer occurs in the Hamda Al Hamra basin and corresponds to the middle aquifer in this area. The water bearing formations are continental sandstones of the Triassic, Jurassic and early Cretaceous age and include the Kikla aquifer (Pallas 1980) and the Continental Intercalaire aquifer (Unesco 1972). The thickness of this aquifer ranges between 200 and 500 m. The field transmissivity is very high (2600-3000 m^2/day) in the central and eastern zones of the aquifer and lower (500 m^2/day) in the western zone. The TRJLC aquifer outcrops near the Adrar Bendrich, in Jabal Tuil el Hira and in Jabal Nefusa. The field storativity is high (up to 10^{-1}) in the outcropping areas, where the aquifer is unconfined, and ranges from 0.9 10^{-4} to 2.0 10^{-4} in the confined zones.

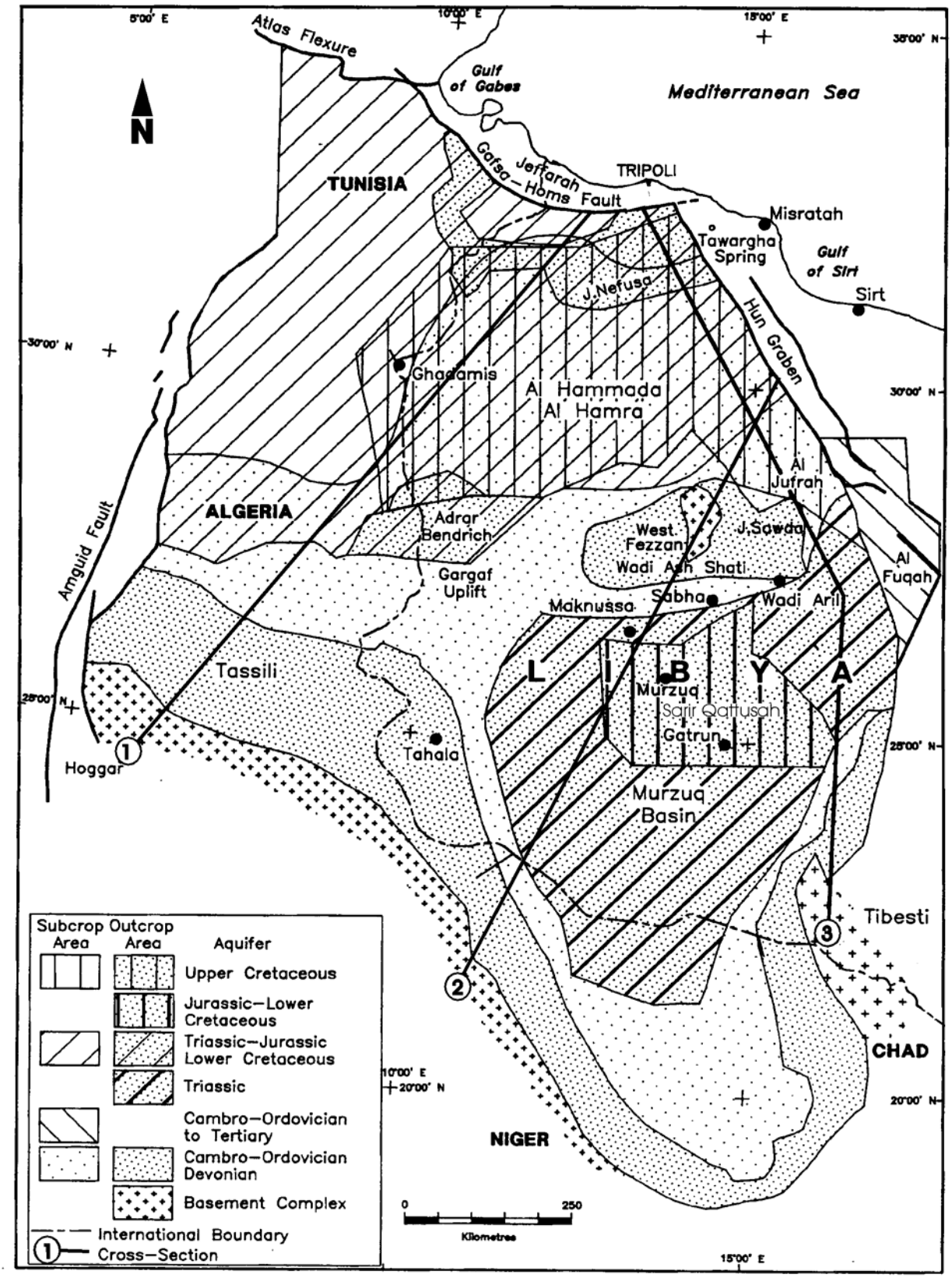


Figure 1: Hydrogeological outline of the WJS aquifer system

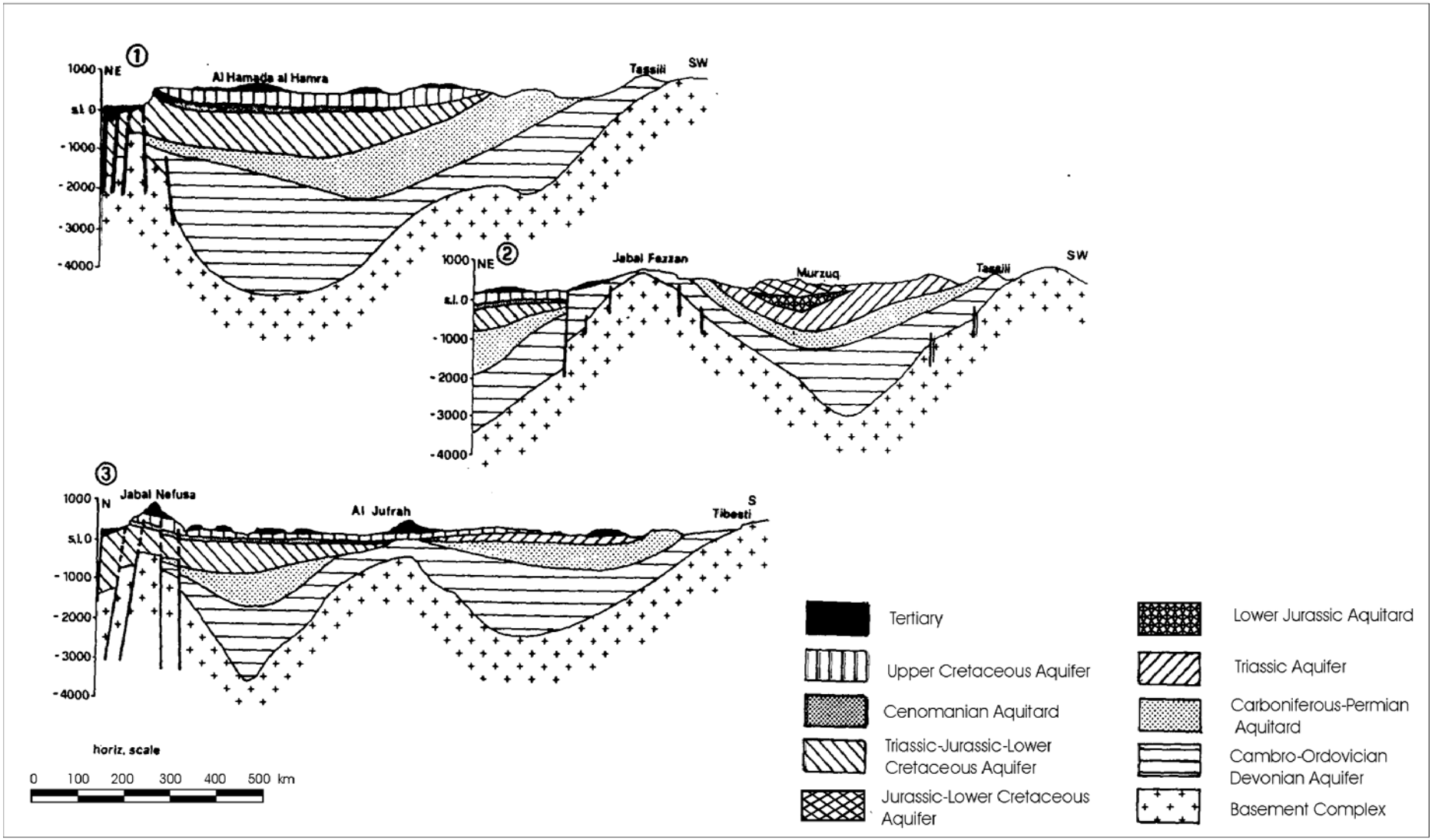


Fig. 2: Hydrogeological cross sections of the WJS aquifer system

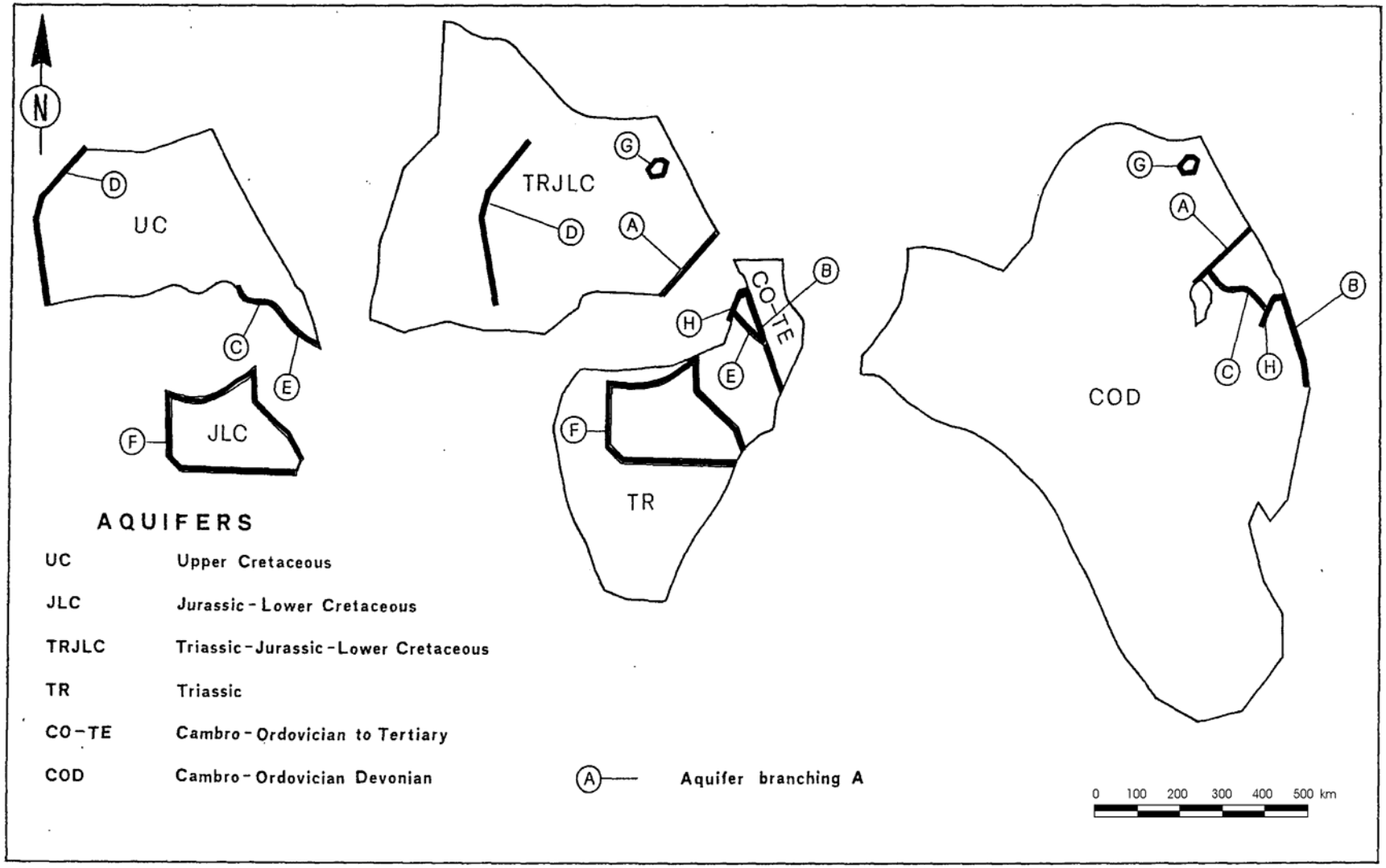


Fig. 3: Lateral connections among the aquifers of the WJS aquifer system

The Triassic (TR) aquifer occurs in the Murzuq basin and corresponds to the middle aquifer in this area. The water bearing formations are continental sandstones of Triassic age. The thickness of this aquifer ranges between 200 and 1400 m. In the centre of the basin, this aquifer underlies the JLC aquifer. The field transmissivity is good (1500-3000 m^2/day) througout its extent. The Trassic aquifer is phreatic, except in the central zone, where is kept in pressure by the Lower Jurassic aquitard. The field storativity ranges from 0.8 10^{-4} to 2.1 10^{-3} in the confined zones, while in the unconfined zones is much higher (up to 10^{-1}).

The Cambro-Ordovician Devonian (COD) aquifer occurs with continuity in both the Hamada Al Hamra and Murzuq basins and corresponds to the lower aquifer of the WJS aquifer system. The water bearing formations are continental sandstones of Cambro-Ordovician, Late Silurian and Early Devonian epoch. The thickness of this aquifer ranges between 500 and 1500 m. The field transmissivity is good (1500-3000 m^2/day) over a large area in the centre of the aquifer (Wadi Ash Shati-Al Jufrah area) but becomes increasingly low in its peripheral zones. The COD aquifer outcrops all around the Murzuq basin and in Jabal Fezzan. The field storativity ranges from 2.2 10^{-5} to 2.0 10^{-3} in the confined zones and from 2.7 10^{-2} to 6.4 10^{-2} in the unconfined zones. In consideration of the importance that the specific yield has for the future water abstraction from Jabal Hasouna wellfields, laboratory determinations of specific yield have been done on 44 core samples randomly selected from boreholes in this area. The average value resulted S_y=10.4 %.

The Cambro-Ordovician to Tertiary (CO-TE) aquifer occurs in the area east of the Hun Graben-Al Fuqaha fault. This aquifer, composed of sandstones, fractured dolomite, limestones and chalk, alternating marl, shale and gypsum, ranging from Cambro-Ordovician to Tertiary age, has been considered as a single layer confined aquifer in contact along the fault with the COD and the TR aquifers. The thickness of this aquifer ranges between 500 and 1500 m. No field transmissivity and storativity data are available for this aquifer.

2.2 Aquitards

The Cenomanian aquitard is represented by a thin (50–100 m) marl and gypsum horizon of Cenomanian age (Yafrin member) lying in the Hamadah Al Hamra basin, and in the Al Jufrah–Al Fuqaha area. In the Hamadah Al Hamra basin this aquitard is interbedded between the UC and the TRJLC aquifers. Westward of the Cenomanian aquitard limit (Touil El Hira – Adrar Hendrich line) the above mentioned aquifers are in direct hydraulic contact. In the Al Jufrah area the Cenomanian aquitard is interbedded between the UC and the COD aquifers. Along the south–western limit of the Cenomanian aquitard, the above aquifers are in direct hydraulic contact. In the Al Fuqaha area the Cenomanian aquitard is interbedded between the UC and TR aquifers. Along the southern limit of the Cenonamian aquitard, the above aquifers are in direct hydraulic contact.

The Lower Jurassic aquitard is represented by the impervious Lower Jurassic horizon of the central Murzuq basin (El Sonni and Aboulkheir, 1988). The thickness of this horizon ranges between 200 and 1000 m. This aquitard is interbedded between the JLC and the TR aquifers, in the central area of the basin. All around the border of this aquitard, a lateral contact of the above aquifers exists.

The Carboniferous–Permian aquitard is represented by a thick (500–1000 m) shale horizon of Carboniferous and Perman period, which occurs in both the Hamada Al Hamra and Murzuq basins.

In the Hamada Al Hamra, this aquitard is interbedded between the COD and the TRJLC aquifers, while in the Murzuq basin is interbedded between the COD and the TR aquifers. The Carboniferous–Permian aquitard is missing in the Jabal Fezzan (where the COD aquifer outcrops) and in the Al Jufrah area. In this latter zone the Carnbro–Ordovician sandstones are in direct hydraulic contact with the Mesozoic formations.

2.3 Aquifer branchings

Aquifer branchings are distinctive features of the interconnected groundwater systems. They can be found in any geological situation where aquifers divide or meet. The different aquifers of the groundwater system are therefore hydraulically connected vertically by leakage through the aquitards and laterally through the aquifer branchings. The aquifer branchings existing among the different aquifers of the WJS aquifer system are the following (see Figure 3):

A. North Fezzan branching: occurs between the COD and the TRJLC aquifers, north of Al Jufrah, along the limit of the Carboniferous–Pernian aquitard.
B. Haruj branching: occurs between the COD, the TR and the CO-TE aquifers, south of Al Jufrah in the Haruj area, along the limit of the Carboniferous Permian aquitard.
C. East Fezzan branching: occurs between the COD and UC aquifers, east of the.Jabal Fezzan, along the limit of the Cenomanian aquitard.

D. Ghadames branching: occurs between. the TRJLC and UC aquifers, in the Ghadames region, along the western limit of the Cenomanian aquitard.
E. Dur Al Ghani branching: occurs between the TR and the UC aquifers, along the southern limit of the Cenomanian aquitard in Dur Al Ghani area.
F. Murzuq branching: occurs between the JLC and TR aquifers in the Central Murzuq basin, all around the limit of the Lower–Jurassic aquitard.
G. Tawarga window branching: occurs between the COD and the TRJLC aquifers, in the NE area, of the aquifer system, in correspondence of a small zone where the Carboniferous–Permian aquitard is missing.
H. South Fezzan. branching: occurs between the COD and the TR aquifers, in correspondence of the limit of the Carboniferous–Permian aquitard, along the alignment Wadi Aril–Al Jufrah.

As shown in the Figure 3, the above aquifer branchings mostly represent situations where deposition of an aquifer has occurred on an unconformable surface beyond the limits of an underlying aquitard.

3. The quasi-three-dimensional flow model of the Western Jamahiriya Aquifer System

The quasi–three-dimensional finite element flow model of the WJS aquifer system has been realised utilising the program GEASS. This code is an improved version of IGROSS (Pizzi and Sartori 1984), which was used for the Idrotecneco study.

3.1 The structure of the model

The quasi-three-dimensional scheme of the WJS aquifer system, utilised for the model construction, consists of three aquifer units separated by two aquitards:

- the upper aquifer unit is represented by the UC aquifer in the Hamada Al Hamra and the JLC aquifer in the Murzuq basin;
- the upper aquitard is represented by the Cenomanian aquitard in the Hamada Al Hamra and the Lower Jurassic aquitard in the Murzuq basin;
- the middle aquifer unit is represented by the TRJLC aquifer in the Hamada Al Hamra and by the TR and CO-TE aquifers in the Murzuq basin;
- the lower aquitard is represented by the Carboniferous-Permian aquitard;
- the lower aquifer unit is represented by the COD aquifer.

The quasi-three-dimensional finite element network of the WJS aquifer system has been obtained taking into account the topological relationships of the three aquifer units and of the interbedded aquitards. The network density was decided on the basis of the project's requirements. The generated network is reported in the Figure 4. As shown in this Figure, five detailed study areas where considered. In these areas, the grid elements were set at 6.25 km^2. It is noteworthy that in the transition zones between areas of different densities and along the external and internal boundaries, intermediate size elements have been automatically generated. The aquitards have been simulated connecting the nodes of superimposed aquifers by means of vertical linear macroelements, each one composed of four linear elements.

The generated network is composed of 12048 triangular elements ranging from 6.5 to 3200 km^2, for the six aquifers identified, 10536 linear elements for the aquitards and 513 aquifer branching nodes. This feature of the grid network has enabled the model to reach the physical boundaries of the aquifers, far outside the main zones of interest, thus providing both a general overview of the groundwater flow on a regional scale and detailed results in wellfield areas.

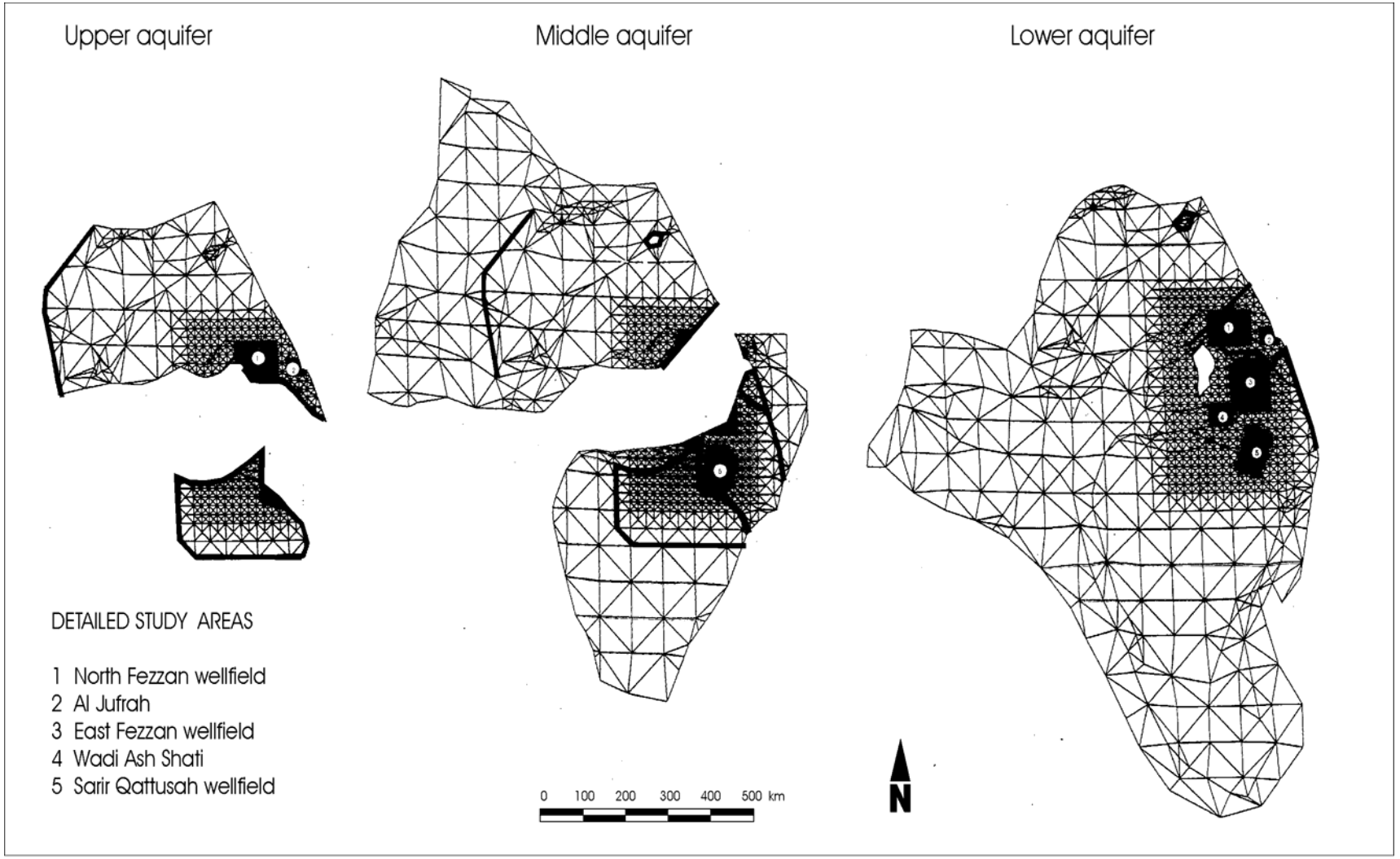


Fig. 4: Quasi-three-dimensional finite element network of the WJS groundwater flow model

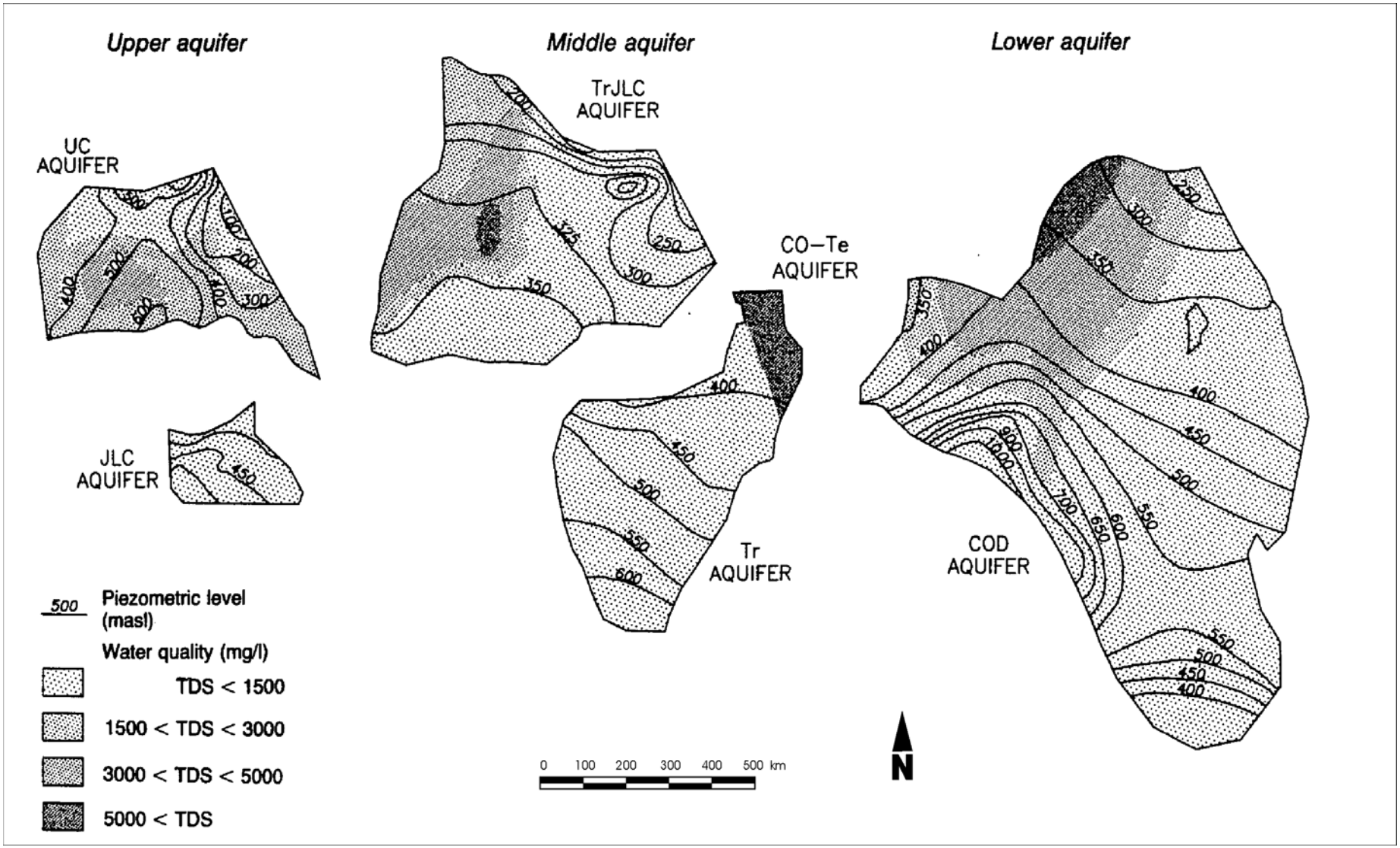


Fig. 5: Observed hydraulic head and water quality of the WJS aquifer system in the year 1970

3.2 The natural regime of the WJS aquifer system: Steady-state model calibration

The first step towards model calibration was the reproduction of the system's state prior to its modern development, when it was subjected only to the natural regime.

Recharge studies in arid zones (Lloyd et al. 1966) have shown that no recharge by direct infiltration takes place when rainfall is less than 200 mm. As a consequence of the region's climate, rainfall infiltration takes place only in the northern zone of the groundwater system (Jabal Nefusa, Jabal Tuil el Hira, 200–250 mm rainfall). In the remaining area, characterised by less than 50 mm rainfall, infiltration cannot be considered as an important source of recharge. On the other hand, the regional distribution of the hydraulic head, observed in the year 1970, prior to the modern development (see Figure 5), clearly shows that the drive of the system originates in the southern outcrop area of the aquifers, where presumably no present recharge occurs. A regional isotopic study confirmed that these outcrops were certainly recharged during the last pluvial age (Salem et al. 1978).

As shown by Pizzi and Sartori (1984), the natural regime of the WJS aquifer system is a result of a long lasting depletion of the system, through its natural outflows, since the last pluvial age. Moreover the natural regime of the WJS groundwater system can be assumed as pseudo-steady, characterised by a gravitational depletion of the highlands water table aquifers that takes place with linear hydraulic head decline (dh/dt=const).

The reproduction of the state of the system prior to its modern development was therefore obtained with steady-state calculations. The reference piezometric configuration, utilised for the steady-state calibration of the model, was the one observed in the year 1970 and reported in the Figure 5. Only the natural outflows of the groundwater system have been considered, imposing for each aquifer the hydraulic head in the corresponding points (including the sebkas and springs lying inside the study area). The zero flow-rate condition has been imposed along the impervious boundaries of each aquifer. It is important to note that, in correspondence to aquifer branchings, the aquifers' continuity is automatically taken into account and therefore no boundary condition must be imposed.

The natural depletion of the phreatic aquifers' outcrops, where the drive of the groundwater system originates, has been taken into account introducing a distributed source term equal to the reservoir depletion S(dh/dt) of the concerned zones (not depending on time in the assumption of pseudo-steady-state regime).

Steady-state model calibration was performed with the usual trial-and-error procedure, adjusting the transmissivity of the aquifers and the vertical hydraulic conductivity of the aquitards until the computed steady-state hydraulic head configuration approached the observed one. A total of 174 steady-state calibration runs were needed to obtain a satisfactory fitting.

Table 1: Steady-state water balance of the WJS aquifer system (Year 1970)

AQUIFER	INFLOW (MCMY)		OUTFLOW (MCMY)	
UC	Infiltration (Jabal Nefusa)	54. 86	North-East boundary (Tawarga)	21.45
	Reservoir depletion (Adrar Bendrich)	39 47	South-East boundary (Hun)	10.01
	Dur Al Ghani branching (from TR)	6.41	Ghadames branching (to TRJLC)	6 66
	East Fezzan branching (from COD)	1.24	Sinawan sebka	56.49
	Leakage (from COD)	0.07	Leakage (to TRJLC)	7.44
		102.05		102.05
JLC	Reservoir depletion (Sarir Qattusah)	102.16	Germa sebka-oasis	21.95
	West Murzuq branching (from TR)	19.80	Sebha sebka-oasis	1.55
	South Murzuq branching (from TR)	15.53	Thamenint sebka-oasis	0.70
			Godwa sebka-oasis	5.80
			Terbuo sebka-oasis	9.26
			Murzuq sebka-oasis	40.34
			East Murzuq branching (to TR)	15.49
			North Murzuq branching (to TR)	42.24
			Leakage (to TR)	0.16
		137.49		137.49

AQUIFER	INFLOW (MCMY)		OUTFLOW (MCMY)	
TRJLC	Infiltration (Jabal Nefusa-Jabal Tuil El Hira)	154.21	Jeffara boundary	181.82
	Reservoir depletion (Adrar Bendrich)	44 77	North-East boundary	103.40
	Leakage (from UC)	7 44		
	Leakage (from COD)	0.12		
	North Fezzan branching (from COD)	14.30		
	Ghadames branching (from UC)	6 66		
	Tawarga window branching.(from COD)	33 18		
	North-West boundary	24 5li		
		285.22		285.22
TR	Reservoir depletion (Murzuq basin)	175.23	Wadi Adjal sebka-oasis	94.99
	Leakage (from COD)	0.15	Semnu sebka-oasis	2.90
	Leakage (from JLC)	0 16	Gatrun sebka-oasis	43 18
	North Murzuq branching (from JLC)	*42.24*	Tmessah sebka-oasis	7.24
	Sarir Qattusah branching (from JLC)	15.49	Germa sebka-oasis	10.17
			Haruj branching (to CO-TE)	27.59
			West Murzuq branching (to JLC)	19.80
			South Murzuq branching (to JLC)	15.53
			South Fezzan branching (to COD)	5.46
			Dur Al Ghani branching (to UC)	6.41
		233.27		233.27
CO-TE	Haruj branching (from TR)	27. 59	Sirte basin boundary	43.98
	Haruj branching (from COD)	34. 17	Hun graben boundary	17.78
		61. 76		61.76
COD	Reservoir depletion (Tassili-Tibesti)	388.36	Idri sebka	22.02
	Reservoir depletion (Jabal Hasouna)	26.27	Al Mahruqah sebka	52.23
	South Fezzan branching (from TR)	5.46	North-East boundary	2.60
			Amguid fault boundary	142.32
			Tcad basin boundary	117.69
			North Fezzan branching (to TRJLC)	14.30
			East Fezzan branching (to UC)	1.24
			Haruj branching (to CO-TE)	34.17
			Tawarga window branching (to TRJLC)	33.18
			Leakage (to TRJLC)	0.12
			Leakage (to TR)	0.15
			Leakage (to UC)	0.07
		420.09		420.09

Table 1 illustrates the volumetric balance of the WJS aquifer system, resulting from the steady-state model calibration. As can be seen in this table, the yearly infiltration on in the Jabal Nefusa-Jabal Tuil El Hira totals 209.1 MCMY (million cubic metres per year), equivalent to 2.35 mm/year over the outcrop areas of the UC aquifer and 11.8 mm/year over the outcrop areas of the TRJLC aquifer. The reservoir depletion of the southern unconfined zones of the WJS aquifer system totals 710.5 MCMY, equivalent to 2 mm/year. The reservoir depletion of the Jabal Hasouna totals 26.3 MCMY, equivalent to 1.5 mm/year. In Table 2, the comparison between the field and model values of the main natural outflow in the year 1970, is reported.

Table 2: Comparison between the field and model values of the main natural outflow in the year 1970

Aquifer	Location	Flow rate (MCMY)	
		Field	Model
JLC	Murzuq	(*) 40.00	40.14
	Godwa	(*) 10.00	5.80
TR	Wadi Adjal	(*) 89.00	94.99
	Gatrun	(*) 28.80	43.18
COD	Wadi Ash Shati	(*) 85.40	74.25

(*) Source: Brown and Root

3.3 The artificial groundwater abstractions in the period 1970–1990: Non-steady-state model calibration

The artificial groundwater abstractions in the Saharan oases started in the year 1970. At approximately the same time, oil production started in the Edjeleh area (Algeria). In Figure 6, the main abstractions from the WJS aquifer system in the year 1990, are reported.

The non-steady-state calibration of the model consisted in the reproduction of the WJS aquifer system's past history during the industrial exploitation period 1970-1990. Therefore, together with the natural outflow, all the artificial groundwater abstractions that took place during this period were taken into account.

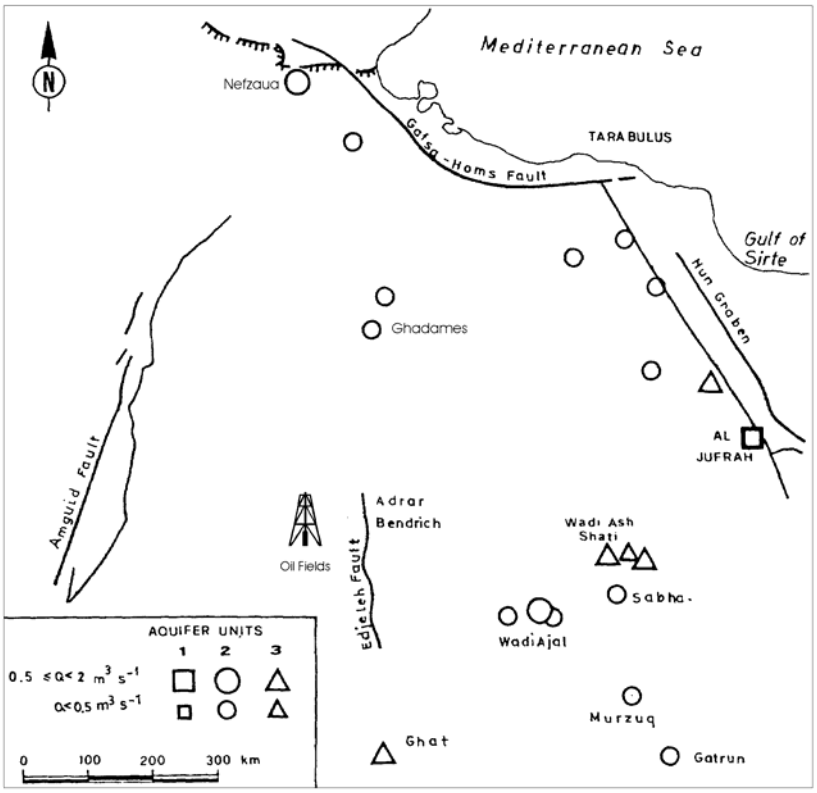


Figure 6: Main abstractions from the WJS aquifer system in the year 1990.

The initial condition assumed for the non-steady-state simulations over the period 1970-1990 was the hydraulic head configuration resulting from the steady-state model calibration. The boundary conditions were the same utilised in the steady-state case. As for the springs and the sebkas inside the study area, in order to exactly take into account the decay of their outflow due to artificial abstraction, a head-dependent discharge rate has been imposed.

The hydraulic parameters adjusted during the transient calibration of the model were the storage coefficient (the specific yield for outcropping zones) of the aquifers and the specific storage coefficient of the aquitards. A total of 14 transient simulations were run to reach a satisfactory fitting between the computed and observed past history of the WJS aquifer system. In Figure 7, two examp1es of fitting between computed and observed well hydrographs, are reported. The calibrated specific yield value is 8 %, for the

southern unconfined zones of the WJS aquifer system while is 5%, for the Jabal Hasouna water table aquifer.

One of the most interesting results of the non-steady-state model calibration was the possibility to reconstruct the original hydraulic head (corresponding to the natural state of the system) for the control wells drilled after the year 1970 (Al Jufrah, Wadi Ash Shati, Wadi Aril). For these wells, as shown in the Figure 7, the hydraulic head of the first measurement is lower than the original hydraulic head. This result allowed an understanding to be reached regarding some atypical residuals found in the steady-state model calibration in correspondence of several control wells, drilled after the start of the industrial production.

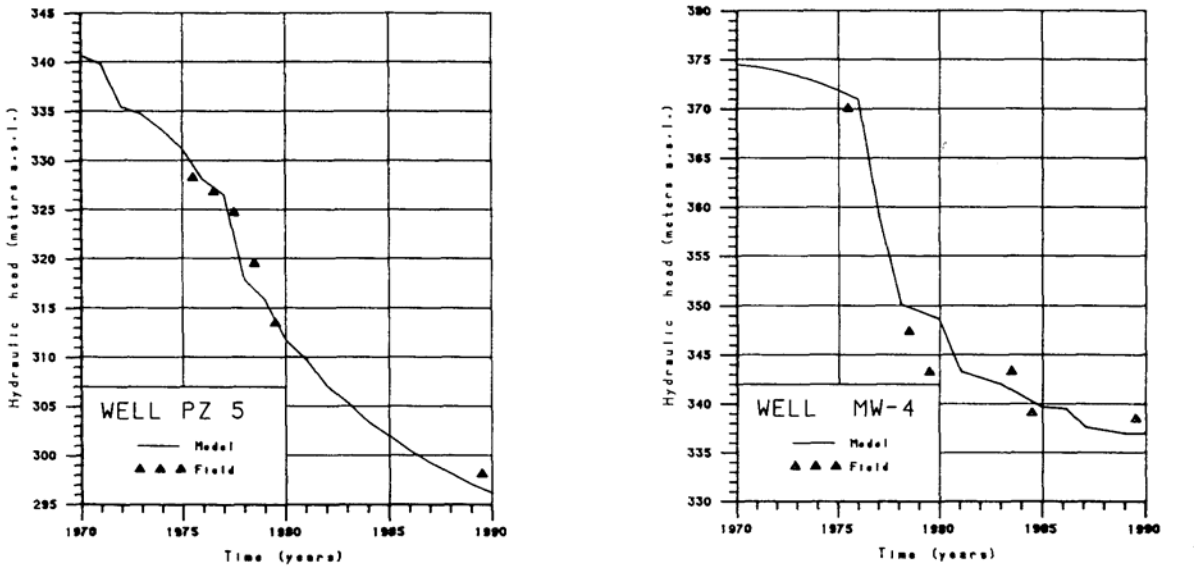


Figure 7: Non-steady-state model calibration - computed vs. observed well hydrographs

3.4 Sensitivity tests

Sensitivity tests were carried out after the model calibration. The main outcome of the steady-state sensitivity tests was to confirm (within the range of ±20 %) the calibrated transmissivity and reservoir depletion values of the COD aquifer in Jabal Hasouna area. The main outcome of the non-steady state sensitivity tests was to confirm that the calibrated specific yield (Sy=5 %) of the COD aquifer, in Jabal Hasouna area, represents a lower limit (conservative value) for this parameter. Moreover the non-steady-state sensitivity tests confirmed that the model is not sensitive to 5%-10% increase of the extension of the COD water table aquifer in the north and east Jabal Hasouna. This result is important because confirms that the expansion of the water table area of the COD aquifer beyond the present limits, due to future abstractions, will have no significant effects on model predictions.

3.5 Forecasting simulations

After the calibration process, the rnode1 was assumed as representative of the WJS aquifer system and was therefore used to find the best area in which to place the WJS wellfield for 2 MCMD bulk abstraction and to forecast the wellfield performance, taking into account all the currently p1anned domestic, agricultural and industrial groundwater abstraction up to the year 2046.

In the preliminary long term forecasting simulation, all the potential wellfield areas were considered (Sarir Qattusah, Maknussa, Wadi Aril, West Fezzan, North Fezzan and East Fezzan). Following the results of the above simulations and of the preliminary geological and hydrogeological assessment of the project area, GMRA, GWA, Brown and Root and Geomath considered the most favourable solution for the WJS wellfield development was to abstract water from the COD aquifer in the area extending from the north of Wadi Aril to the north-east of Jabal Hasouna. In most of this area the COD aquifer is unconfined, the hydraulic parameters (transmissivity and storativity, resulting both from field tests and model study) are high

and the water quality is acceptable. Other potentially exploitable wellfield were discarded on the basis of geological, hydrogeological and economic considerations.

Predictive simulations therefore concentrated on the north-eastern area of Jabal Hasouna. Twenty-two long term forecasting simulations up to the year 2046 were performed, simulating different WJS wellfield layouts and bulk abstraction ranging between 2.0 and 2.5 MCMD from the COD aquifer. In the above simulations, the planned abstractions from existing wellfields were left unchanged. A reference forecasting simulation was also made, simulating only the planned abstraction from existing wellfields up to the year 2046.

From an hydrogeological stand point, the most suitable WJS wellfield layout for 2 MCMD bulk abstraction from the COD aquifer is composed of 440 production wells with 133 wells at 45 l/s and 20 wells at 56 l/s, located in the North-East Jabal Hasouna (NEJH), and 287 wells at 56 l/s, located in the East Jabal Hasouna (EJH). The WJS wellfield layout is completed by 44 additional standby wells (10 % increment), mainly located along the spines of the collector system. In the Figure 8, the retained WJS wellfield layout and the computed drawdown in the year 2046 for 2 MCMD bulk abstraction from the COD aquifer, are reported.

3.6 Wellfield optimisation

The wellfield optimization included to identify, in addition to the most suitable wellfield layout from an hydrogeological stand point (pre-eminent in the scope of the work), the most cost-effective solution for gathering and conveying the abstracted water from the wells to the main conveyance pipeline. The wellfield optimisation required to link the hydrogeological model with:

1. a water network hydraulic model to provide the steady-state network analysis of the collector system and to generate pipe sizes and hydraulic elevations;
2. a costing program to compute the comparative net present value of the capital and operating costs for different network configurations, discount rates and energy costs.

For the steady-state network analysis of the WJS collector system, the computer program WATNET-4, developed by Water Research Centre (UK), was used. The hydraulic scheme utilised for the WJS collector system has been obtained connecting the wells of the WJS wellfield layout with a system of longitudinal collector pipelines crossed by 3 main gathering pipelines (spines), located respectively in the northern, south-eastern and south-western zones of the wellfield layout. Each pipeline has been simulated with a series of pipe joints of assigned characteristics. Three fixed head reservoirs (Fezzan regulating tank, EJH and NEJH forebay tanks) and two pump-stations(EJH and NEJH) have been considered in the WJS collector system.

A total of 78 hydraulic simulations, corresponding to different collector configurations and operation modes were performed. For 35 of the above simulations, a workable hydraulic collector system was achieved.

A costing program has been developed to compute the present value of the capital and operating cost of the WJS layouts of wells and collector pipes, for different discount rates and unit energy cost. The capital cost and present value of the operating and maintenance costs over the period 1997-2046 was then computed for the 35 workable hydraulic collector systems generated. The finalised WJS wellfield layout and collector configuration is reported in the Figure 9. The corresponding project cost assessment is reported in the Table 3.

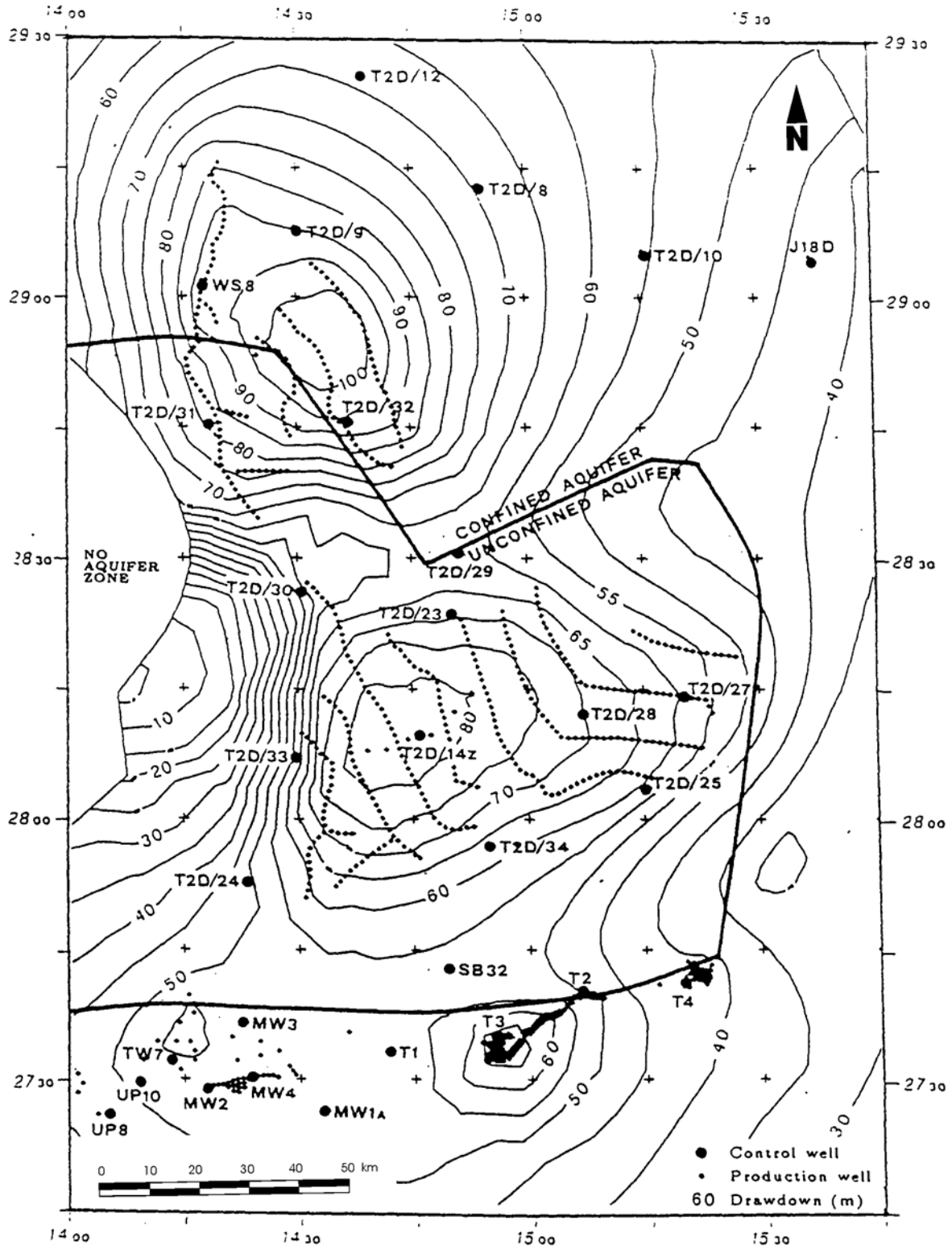


Figure 8: WJS wellfield layout and computed drawdown in the year 2046 for 2 MCMD bulk abstraction from COD aquifer in Jabal Hasouna.

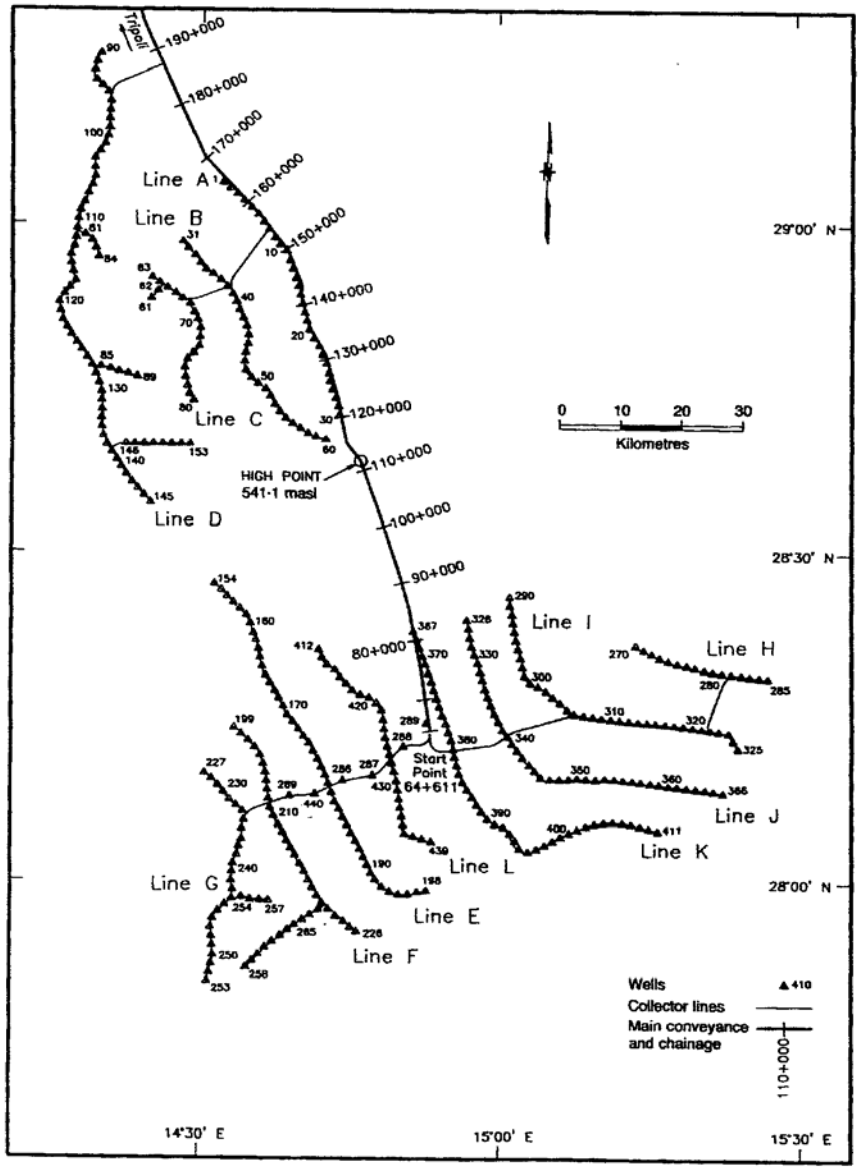


Figure 9: Finalised WJS wellfield layout and collector configuration for 2 MCMD bulk abstraction

Table 3: Cost assessment of the finalised WJS wellfield layout (million $)

Discount rate: 5 % Unit energy cost: 0.12 $/kWh		
	Pipelines	855.540
	Wellfield	499.869
	Booster pumps	92.133
	Roads	76.575
	Electrical lines	202.473
	Tooling requirements	4.724
Capital cost		1731.313
	Wellpumps substitution	96.611
	Booster pumps substitution	75.889
	Energy wellpumpss	1372.051
	Energy booster pumps	224.938
	Maintenance cost	159.699
Operating cost (Net Present Value)		1929.188
Total (Net Present Value)		3660.501

4. The Ghadames water supply project

The WJS model has been recently used, in conjunction with a local two dimensional flow and solute transport model, by the Engineering Consulting Office for Utilities (ECOU), in the framework of the Ghadames Water Supply Project. The regional WJS model has been considerably improved (Geomath, 1997) as a result of the additional hydrogeological data concerning the TRJLC aquifer in the north-western Libya (Salem and El Baruni, 1990) and southern Tunisia (Mamou, 1990).

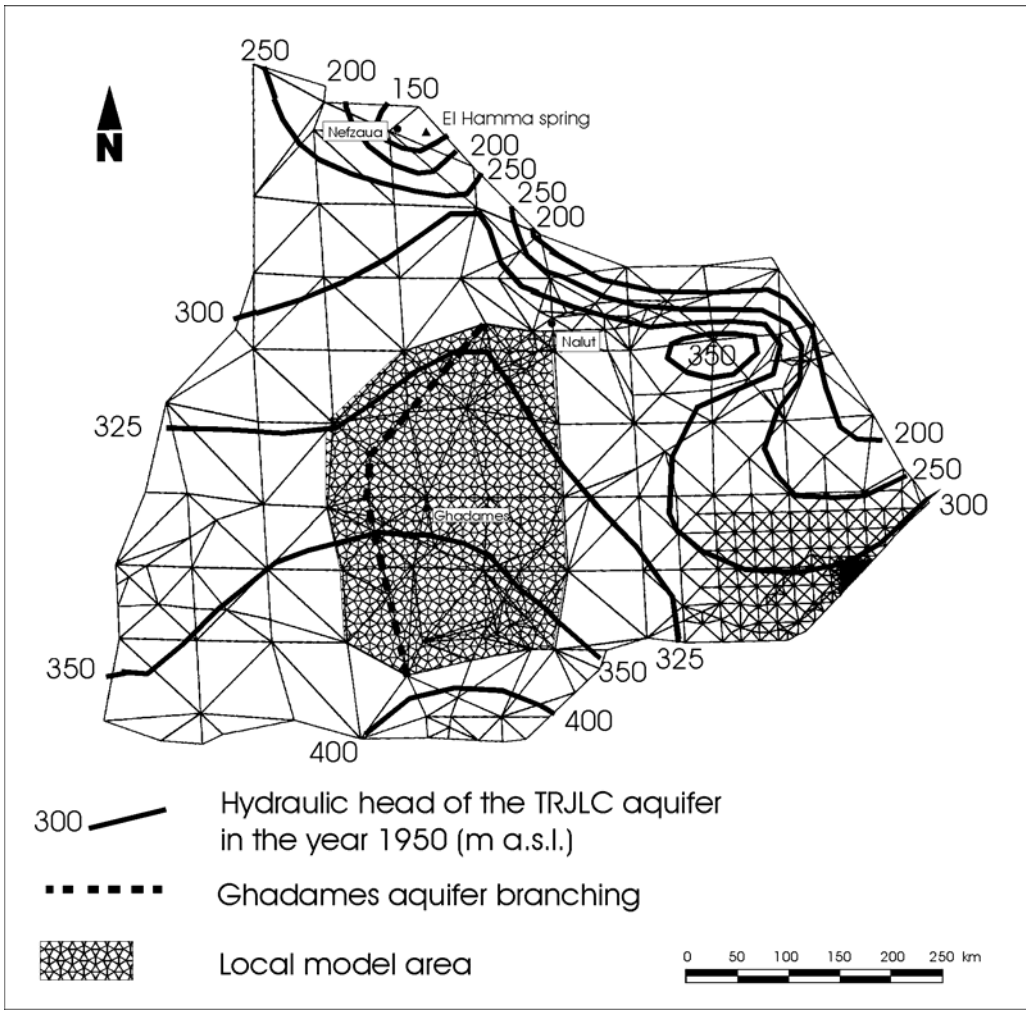


Figure 10: TRJLC aquifer: Observed hydraulic head in the year 1950, regional WJS model network and local model area.

The main changes of the TRJLC aquifer hydrogeological data were the following:

- The year 1950 instead of the year 1970 has been assumed as the starting date of the artificial groundwater abstraction, because in Tunisia the TRJLC exploitation dates back to the fifties.
- The reference piezometric configuration of the TRJLC aquifer was substantially changed in Ghadames-Derj area and in southern Tunisia, as can be seen comparing the Figures 10 and 5.
- The recharge has been increased of 18 MCMY to take into account the TRJLC outcrops in Fedjej area, not considered in the former model.
- The natural discharge has been increased by adding the natural outlets of El Hamma spring (6.3 MCMY), Chot Fedjej (9.5 MCMY) and Northern sources east of Nalut (1.2 MCMY).

The new data have been taken into account to improve the steady-state and the non-steady-state calibration of the regional WJS model in Ghadames-Derj area and in southern Tunisia.

The local two-dimensional groundwater flow and solute transport model of the TRJLC aquifer in the Ghadames area, has been constructed to overcome two main limitations of the regional WJS model:

1. The finite elements network of the WJS model is very coarse in the Ghadames area (see Figure 10): the local model will allow studying with a finer grid the groundwater flow in this area (water levels, drawdown, wellfield optimisation).
2. The regional WJS model simulates only the groundwater flow: the local model will allow to simulate the water quality changes, which may take place in the TRJLC aquifer as a result of long term abstractions in the Ghadames area.

As shown in the Figure 10, the external boundary of the local model is composed by a succession of element sides of the regional WJS model. The hydraulic heads assigned on this boundary; have been derived from the regional model nodes. This procedure allows to take correctly into account the hydraulic relationships of the TRJLC aquifer in the Ghadames area with the WJS aquifer system. Similarly have been derived from the WJS model and imposed to the local model, the flow rates exchanged between the TRJLC aquifer and the UC aquifer along the Ghadames aquifer branching and the flow rate coming by leakage from the UC aquifer trough the Cenomanian aquitard. As shown in Figure 11, the local flow model has been satisfactorily reconciled with the WJS model both in steady and non-steady conditions.

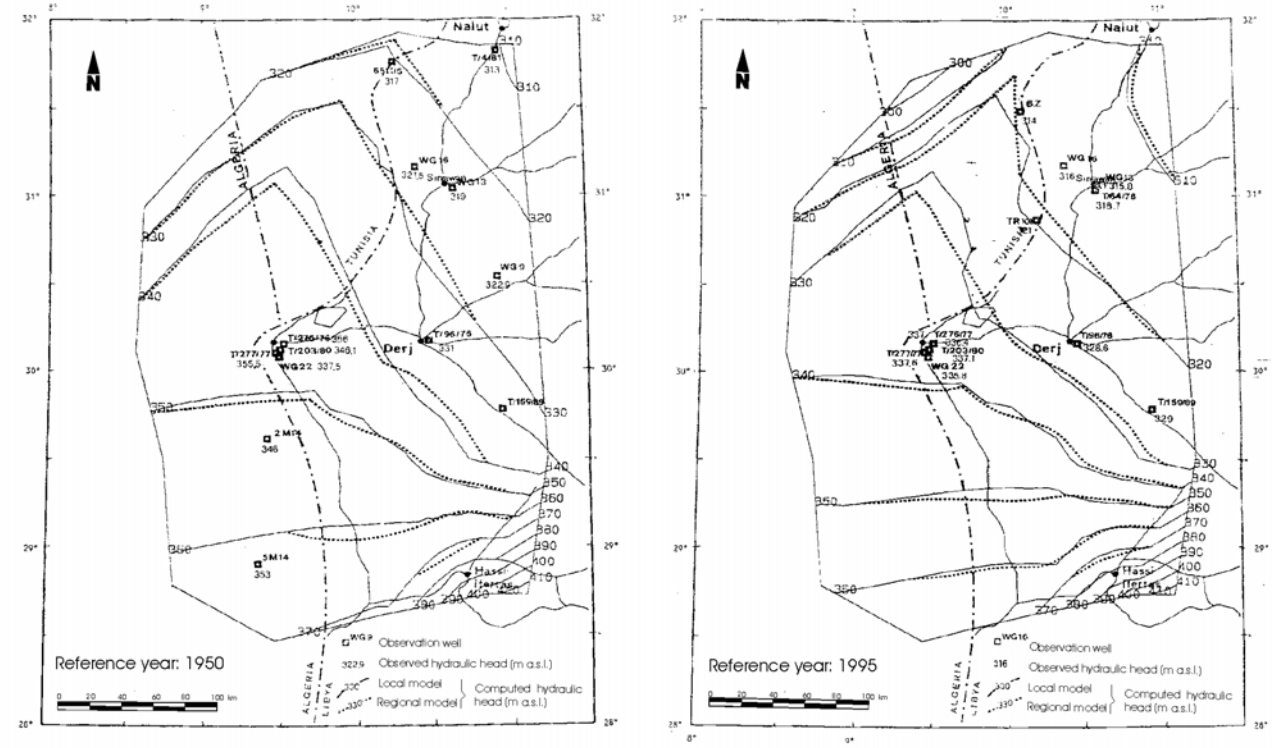


Figure 11: Steady-state (left) and non-steady state (right) reconciliation between the regional WJS model and the local model of the TRJLC aquifer in Ghadames area

The local model was then implemented for solute transport simulation. The condition of assigned salt concentration has been imposed to the external boundary. The flow rates encroaching into the TRJLC aquifer from the UC aquifer, both trough the aquifer branching and by leakage, have been considered with the related salt content.

Five long term forecasting simulations up to the year 2050 were performed, simulating different wellfield layouts and bulk abstraction of 90 MCMY from the TRJLC aquifer in Ghadames-Derj area. In the above simulations, the planned abstractions from existing wellfields were left unchanged.

A reference forecasting simulation was also made, simulating only the planned abstraction from existing wellfields up to the year 2050. The above simulations have been run by using both the regional WJS model and the local model.

The objectives of the WJS regional long term forecasting simulations are the following:

- To forecast the effects of future groundwater abstraction from TRJLC aquifer in the Ghadames area, taking into account all planned abstractions from the WJS aquifer system (WJS wellfield in Jabal Hasouna included);
- To derive the hydraulic head on the nodes of the WJS model, to be imposed as boundary condition to the local model;

- To derive the lateral flow encroaching into the TRJLC aquifer from the UC aquifer through the Ghadames aquifer branching, to be imposed to the local model;
- To derive leakage flow rates exchanged between the TRJLC aquifer and the UC aquifer through the Cenomanian aquitard, to be imposed to the local model;

The objectives of the local long term forecasting simulations are the following:

- To simulate the groundwater flow in Ghadames-Derj area (water levels, drawdown, wellfield optimization) with a greater detail than the one of the WJS regional model
- To simulate the water quality changes, which can take place in the TRJLC aquifer as a result of long term exploitation in the Ghadames-Derj area.

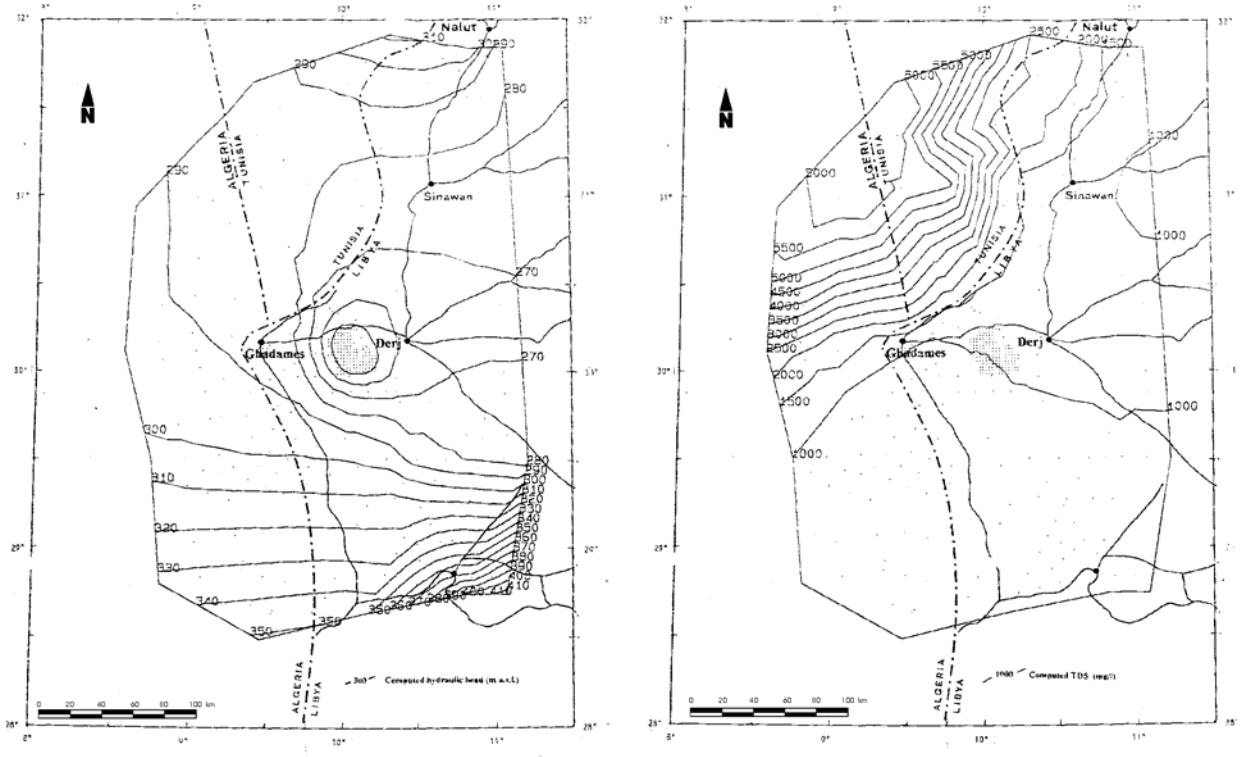


Figure 12: Computed hydraulic head (left.) and TDS (right) configurations in the year 2050 for 90 MCMY bulk abstraction from the Ghadames-Derj area.

In the Figure 12, the computed hydraulic head and TDS configurations in the year 2050, are reported. for 90 MCMY bulk abstraction from the Ghadames-Derj area. The simulated wellfield layout is composed of 144 production wells at 20 l/s and 15 standby wells assembled in a square grid of 2 km.

Acknowledgements

The author thanks the Libyan Authorities for their kind permission to publish this paper. Particular thanks are due to A. S. Kuwairi, O. Salem, A. El Sonni, A. Binsariti, J. W. Lloyd, H. Moorwood and C. del Giudice for their contribution to the work.

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The use of mathematical modeling techniques for managementof non-renewable resources

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Abstract (see full text in Arabic at the end of this volume)

The recharge of the large Arab groundwater reservoirs is extremely limited or negligible, therefore the development and rational management of groundwater resources is diispensable. Modelling techniques are recommended for the management of these resources.

A mathematical model has been prepared to set up an appropriate development plan for the exploitation of non-renewable groundwater resources for the different activities in the Syrinn Steppe including agricultural, industrial, tourism, and others. A comprehensive conceptual hydraulic model was designed, based on all available geologic and hydrogcolngic studies of the project's region and surrounding areas. Partial differential equations for the unsteady state were used. The numeric solution was based on finite difference implicit scheme. The model was calibrated and tested, then prediction runs were carried out for the development plan.

It has been found out that, the proposed scheme conforms to the hydrogeologic conditions of the region, and it serves the current and future requirements for the different activities. As the area is charactarized by its tectonic structure and its complicated effects on groundwater system, continuous assessment of non-renewable resources is required, to reach the almost complete simulation which closely represents the actual hydrogeological conditions. Therefore periodic measurements are essential for the continuous re-calibration of the model during the execution of the proposed development scheme.

The mathematical modeling can be considered as a practical tool for the groundwater management in arid zones, since the model can be applied for continuous assessment of the non-renewable resources.

Gerhard Schmidt, Manfred Hobler and Bernt Söfner

Investigations on Regional Groundwater Systems in North-East Africa and West-Asia

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1. Introduction

During the last decades various groundwater systems in the region of North-East Africa and West-Asia have been investigated by different companies and national and international institutions. Within the framework of Technical Cooperation Projects several studies were carried out and supported by the Federal Institute for Geosciences and Natural Resources (BGR) of Germany.

Long-term activities of BGR were concentrated on selected areas of this region, e.g., in Djibouti, Egypt, Jordan, Niger, Saudi Arabia (Hamad Basin), Sudan, Syria (e.g. Palmyra Basin) and Yemen. A reference list about major projects with contributions of BGR to groundwater investigations in the area is attached to this paper. Selected contributions to groundwater investigations in Jordan are reported in chapter 2.

Additionally, a Tentative Equipotential Map of the PUC (Nubian)-Aquifer System in the Western Desert of Egypt is presented in *Annex 1, chapter 3*. This map reflects the knowledge of the ground-water flow pattern in the fresh water bearing Pre-Upper-Cretacious sandy sediments as derived from information of oil and water exploratory studies and own field investigations by a BGR-team as part of the Joint Venture Qattara in 1976/77 in the frame of a feasibility study of the possibility to use the Qattara Depression for electric power generation.



Figure 1: Groundwater investigation areas (location of BGR cooperation projects)

2. Groundwater investigations in Jordan

Hydrogeological investigations in Jordan have provided basic information for the National Water Master Plan of the Hashemite Kingdom. In cooperation projects with the Water Authority of Jordan (WAJ) various types of geohydraulic modelling studies have been carried out and groundwater resour-ces of northern and southern Jordan have been assessed with respect to water quantity and quality.

The South Jordan Model is an example of a fairly generalized groundwater flow model for the entire aquifer system. It has been set up to improve the understanding of the overall hydraulic situation in central

and southern Jordan and represents an example of transboundary flow. In contrast to this, the Siwaqa-Qatrana-Hasa Model has been prepared for the detailed study of the effects of groundwater withdrawal from the A7-B2 aquifer on the well fields in central Jordan. This type of model can be used as an efficient tool for well field management.

2.1 South Jordan Model

The three-dimensional South Jordan Model permits the simulation of the complex structure of the entire aquifer system. The model covers an area of approximately 57 000 km^2 and includes the entire central and southern part of Jordan, from the Azraq Oasis in the north to the border with Saudi Arabia in the east and to the south (*Figure 2*). For hydraulic reasons the model boundaries also include some parts of Saudi Arabia (Tabuk and part of the Wadi Sirhan area).

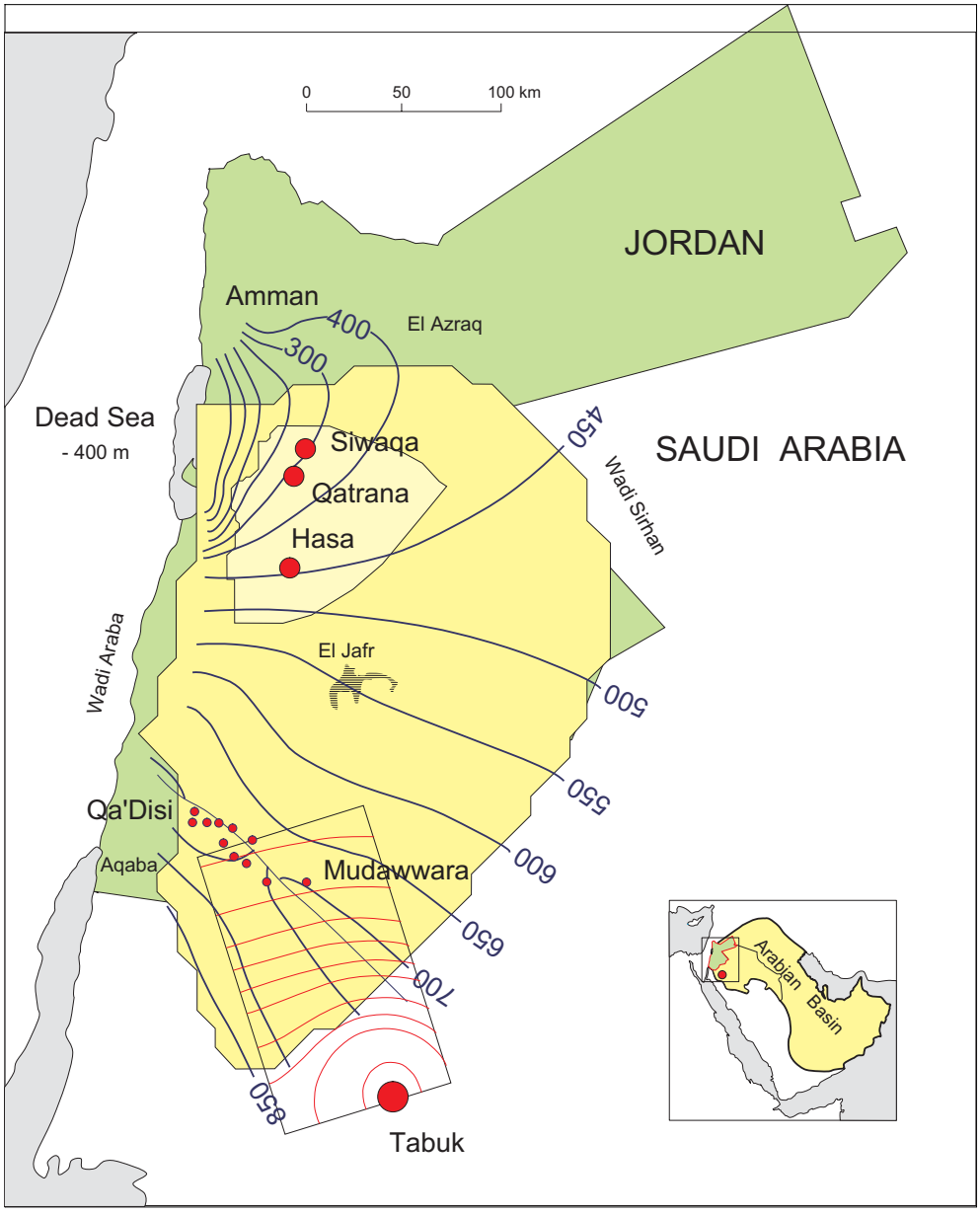
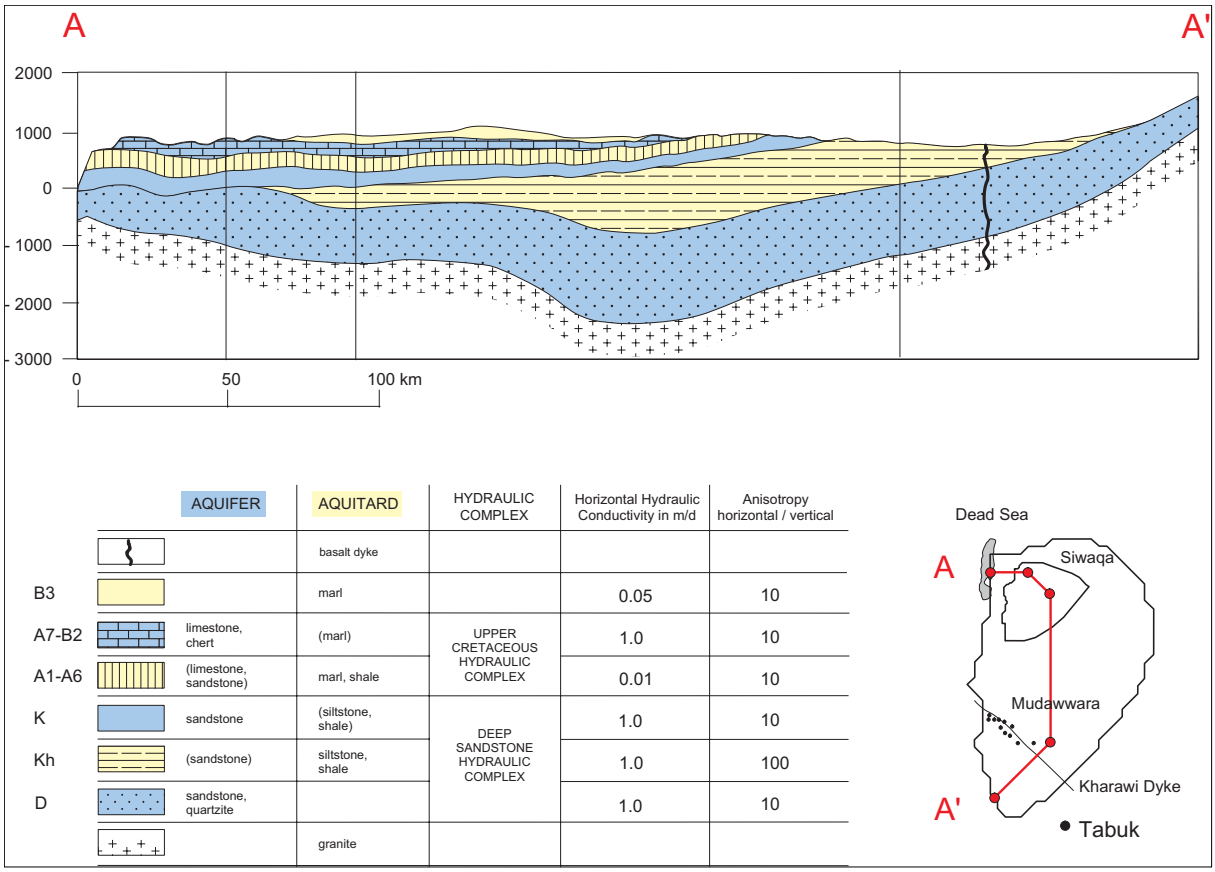


Figure 2: Model investigation areas and groundwater flow pattern of the deep sandstone aquifer (equipotential lines with elevation in metres ref. to mean sea level)

The geometry of the aquifer system in the model area is based on structure contour maps of each hydrogeological unit down to the top of the crystalline basement complex. *Figure 3* shows the vertical distribution of the main hydrogeological units in a cross-section through the model area. This section is representative for the model area and illustrates the wide variations in thickness and depth of the

hydrogeological units. The total thickness of the model aquifer system varies between 200 and 5500 m and generally increases from west to east.



	AQUIFER	AQUITARD	HYDRAULIC COMPLEX	Horizontal Hydraulic Conductivity in m/d	Anisotropy horizontal / vertical
		basalt dyke			
B3		marl		0.05	10
A7-B2	limestone, chert	(marl)	UPPER CRETACEOUS HYDRAULIC COMPLEX	1.0	10
A1-A6	(limestone, sandstone)	marl, shale		0.01	10
K	sandstone	(siltstone, shale)	DEEP SANDSTONE HYDRAULIC COMPLEX	1.0	10
Kh	(sandstone)	siltstone, shale		1.0	100
D	sandstone, quartzite			1.0	10
		granite			

Figure 3: Generalized Hydrogeological Cross-Section

The model boundaries were selected taking the hydraulic situation in the sandstone aquifer system into account. The boundaries of the outcrops of this aquifer, east of the Wadi Araba Escarpment, are the western model boundaries. The southwestern model boundary lies in the area where aquifer saturation ceases. Based on the groundwater flow pattern in the deep sandstone aquifer (*Figure 2*), the eastern and northern boundaries follow a flow line which runs from the Tabuk area in Saudi Arabia to the northeast through the northern part of Wadi Sirhan and turns in a wide arc towards the Dead Sea in the west. The boundary conditions have been selected in such a way that the model can be viewed as hydraulically isolated. No groundwater enters or leaves across the lateral boundaries or the base of the model area. Groundwater turnover is restricted to the surface of the system and the groundwater movement is determined by the distribution of recharge and discharge areas (*Figure 4*).

One of the main purposes of the model was to study the natural long-term depletion of the deep sand-stone aquifer system. Therefore, model calculations were started at the end of the last humid period, about 5000 years ago, where a relatively clear hydraulic situation can be recognized (*Figure 5*). It is assumed that the aquifers were saturated at that time. The Dead Sea with water level of about 400 m below sea level forms the main base level for the system and therefore has been simulated by a constant head boundary. Wadi Sirhan in the east, the Jafr Basin and the Disi/Mudawwara area were secondary discharge areas at higher elevations. High evaporation rates in those areas contributed to the consumption of the near-surface groundwater. These factors particularly influence the initial stages of the model calculations.

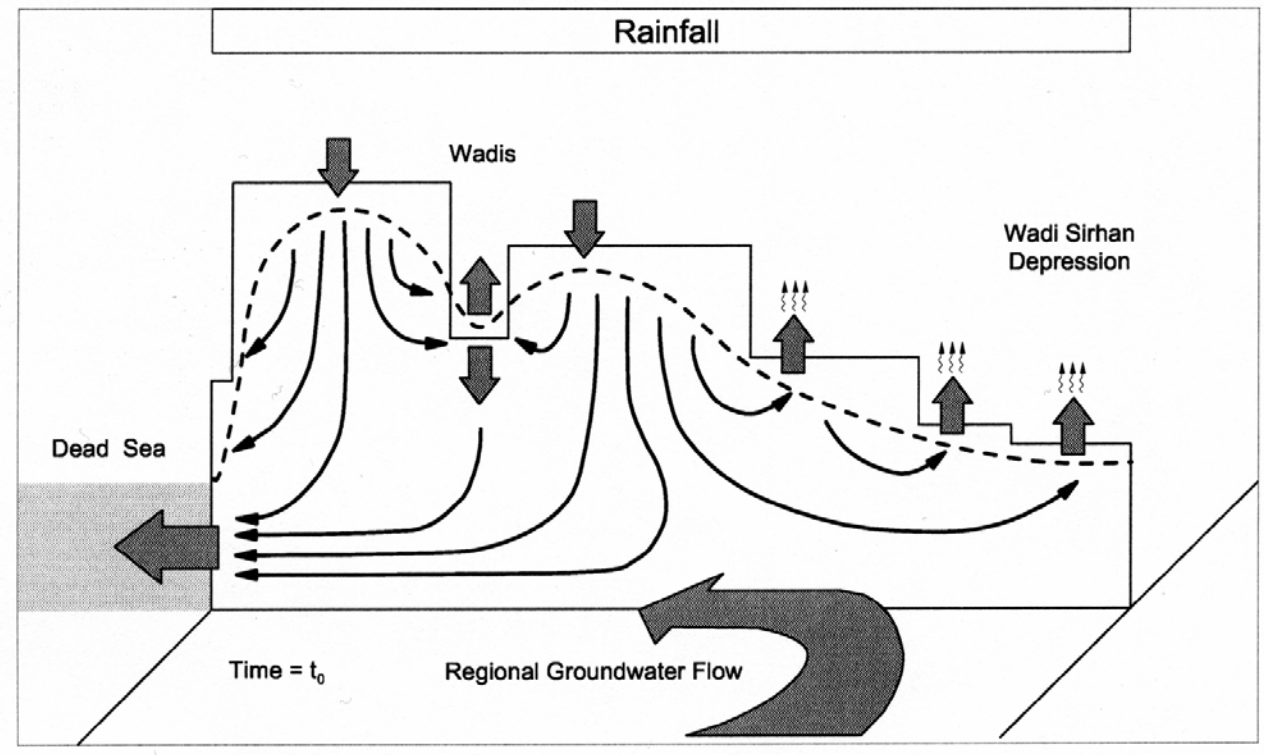


Figure 4: Generalized flow components

The initial stationary conditions of the hydraulic system at the end of the last humid period, 5000 years ago, determine the process of natural depletion of the sandstone aquifer. For a more accurate definition of the hydraulic boundary conditions several model calculation runs have been carried out. The input data represent possible conditions as they may have prevailed at the end of the last humid period, at the model time t_0 , and during the time of aquifer depletion (*Figure 5*). The assumptions for the initial model conditions include the following :

- complete saturation of the aquifer system; groundwater levels are at the same elevation as the land surface and
- calculated initial water levels which have been modelled using a mean annual recharge rate which can be assumed under the humid climatic conditions of the pluvial.

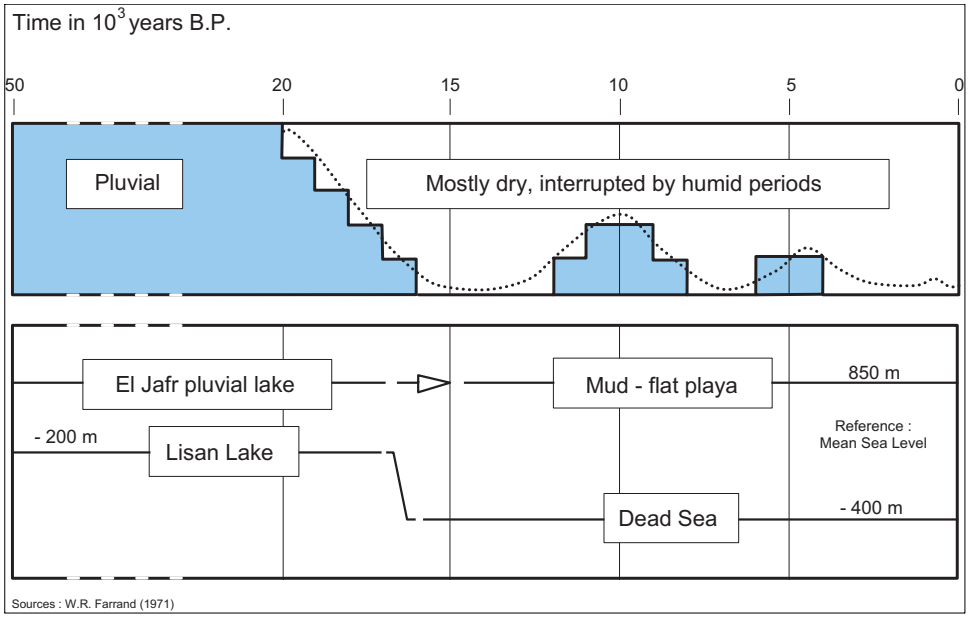


Figure 5: Generalized climatic fluctuations before present (B.P.)

Climatic changes from humid to arid conditions affected the original groundwater balance. The natural depletion of the groundwater system started with the reduction or cessation of recharge. Consequently, groundwater flowing to the Dead Sea had to come from storage. For the simulation of the long-term depletion, model runs have been carried out without recharge as well as with the present recharge conditions in southern Jordan.

The modelling results show that under natural conditions the whole aquifer system is being continuously drained to the Dead Sea. However, the actual rate of natural loss of groundwater is gradually decreasing. The model simulations indicate that natural groundwater discharge, after 5000 years of depletion, may be approximately 500 million m^3/year, most of it in the form of undetected discharge. Considering a relevant surface area of the Dead Sea of roughly 500 km^2, the above amount would raise the sea level by about 1 m/year. Without considering all aspects of water level fluctuations of the Dead Sea, it can be assumed that there is a corresponding rate of evaporation from the Dead Sea.

The hydraulic parameters of the rock formations (conductivity and storage coefficient) have an essen-tial effect on the model results. Sensibility studies have been carried out in order to define the order of magnitude of regional hydraulic parameters more accurately. According to the results, the regional aquifer parameters shown in *Figure 3* appear to be plausible. Specific storage coefficients S' for the deep aquifer system seem to be in the range of $S'=10^{-4}$. In the upper part of the system (B4-B5, A7-B2 aquifers) values of $S'=10^{-3}$ might be more realistic. The model results also indicate that the im-portance of recent groundwater recharge appears to be overestimated.

The numerical model calculations of the present distribution of piezometric levels, after 5000 years of natural discharge, compare fairly well with the observed or assumed current situation. It should be kept in mind that in large parts of the study area, especially in the east, geohydraulic observations are missing. Therefore, a calibration of the model in the true sense is not possible. The South Jordan model however can be considered as a possible and plausible representation of the interplay of hy-draulic parameters and external conditions.

2.2 Siwaqa-Qatrana-Hasa Model

The two-dimensional horizontal Siwaqa-Qatrana-Hasa Model covers a region of 5700 km^2 in central Jordan and includes the most important well fields of Jordan (*Figure 2*). In 1989, approximately 15 million m^3 of groundwater was withdrawn for the water supply of Amman and more than 10 million m^3 for the phosphate mining industries in Hasa and Abiad.

The model simulates the flow of groundwater in the A7-B2 limestone aquifer taking the vertical hydraulic contact with the sandstone aquifer via the A1-A6 aquitard (downward leakage) into account. Apart from the northern boundary, where the 600 m water-table contour line is used as a constant head boundary, the boundaries of the model are based solely on natural conditions (flow lines or outcrops of aquifers). The geometrical discretisation of the model area was done with the help of an irregular triangular grid which is much finer in the immediate vicinity of the well fields. In this way it was possible to calculate the drawdown around each single well.

The groundwater budget includes amounts of the water withdrawn, the vertical leakage down to the sandstone sequence, the horizontal flow across the boundary of the model in the direction of Azraq and Wadi Sirhan, and the recharge. In the Siwaqa-Qatrana-Hasa model groundwater inflow is not to be considered because of the favourable choice of model boundaries. In the model the hydraulic re-gime was simulated on the basis of the groundwater contour plans of the limestone and sandstone aquifers as well as an initial distribution of hydraulic conductivities. Approximation of the calculated water levels to the observed level of the water table was obtained by model calibration runs with varying aquifer parameters. This led to the following spatial distribution of the transmissivity values in the model: in about one third of the area the transmissivity is below 100 m^2/d, in more than half of the area between 100 and 400 m^2/d and in about 10% of the modelling area in excess of 500 m^2/d. This area of high transmissivity coincides with the zone effected by the Karak fault and associated fault zones. Over much of the model area the average horizontal hydraulic conductivity is just under 1 m/d. It is assumed that the vertical conductivity reaches only 1% of the horizontal conductivity. The underlying aquitard A1-A6 is characterized by horizontal and vertical conductivities of $9x10^{-3}$ m/d and $4x10^{-6}$ m/d respectively.

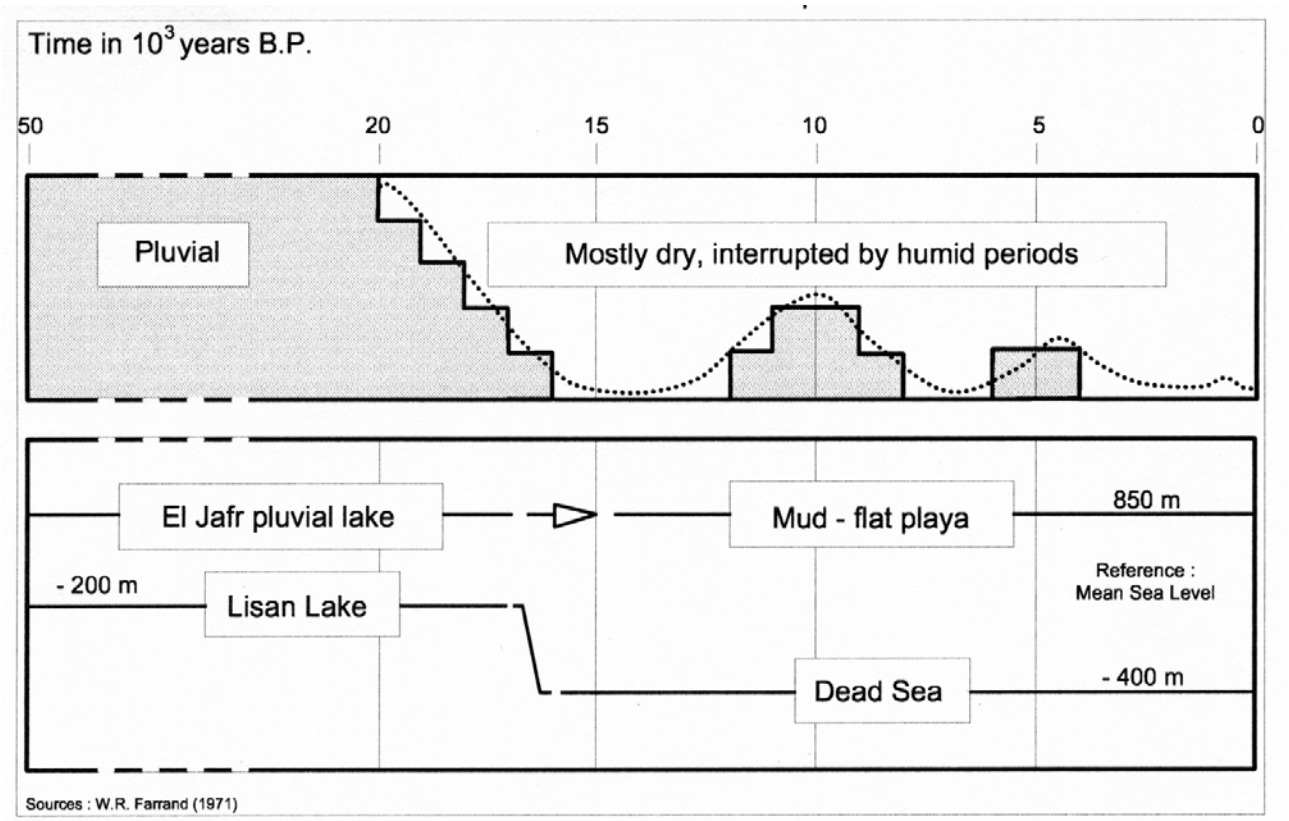


Figure 6: Calculated groundwater budget of the A7-B2 aquifer in million m^3/year. Results from the two-dimensional simulation model with consideration of the vertical leakage to the Kurnub sandstone aquifer via the A1-A6 aquitard.

The calculated groundwater recharge is 39 million m^3/year. In comparison, the amount reaching the sandstone aquifer is estimated to be 12 million m^3/year. Groundwater losses across the model boun-daries are in the range of 27 million m^3/year: 11 million m^3/year at the northern margin, 11 respectively 5 million m^3/year into Wadi Mujib and Wadi Hasa. The calculated groundwater levels closely correspond with the distribution in the general groundwater contour plan. However, the groundwater observation network is insufficient for the detailed model calibration under transient flow conditions, because only four monitoring wells with long-term head observations were available.

On the basis of time dependend simulations carried out over a period of five years (1984-88) and using relatively well known withdrawal rates, the storage coefficient was calculated at about 0.01. The simulation and prediction of the groundwater behaviour begins in 1984. After ten years the drawdown in the main well fields reaches 20-30 m and another ten years later 30-40 m. According to the ground-water budget (*Figure 6*) water is drawn from aquifer storage (i.e. ground-water mining). The reduction in outflow across the boundaries of the area is of very little importance. The model results also indicate that drawdown in the areas between the existing well fields will be comparatively small during this 20 years time period.

However, the required long-term exploitation of groundwater resources from the existing well fields in the limestone aquifer will become problematic relatively soon. The water levels in the production wells currently range between 130 and 160 m below land surface. The large-diameter casing which is intended to accommodate the pumps, only reaches down to a depth of 140-200 m. The simulation results demonstrate that these depths are only sufficient for 10-20 years to compensate the drawdown. This problem should be tackled by improved well construction and the development of well field management strategies based on the model results.

2.3 Possible conflicts (hydraulic interactions) between well fields in South Jordan and Saudi Arabia

In the Disi/Mudawwara area groundwater is being pumped from the Disi aquifer for local demand, municipal supply for Aqaba and irrigation by private companies. Exploitation started in 1977 and was about 2.3 million m^3/year in the period until 1981. At the end of 1981 the well field for the water supply of Aqaba came into operation and total annual withdrawal increased to 5.9 million m^3 in 1982 and 9.2 million m^3 in 1983.

Groundwater abstraction by private companies for irrigated agriculture started in 1985 and reached about 55 million m^3 in 1990, bringing the total withdrawal from the Disi aquifer to about 65 million m^3.

The South-Jordan model makes it possible to predict the future lowering of the groundwater level. Assuming a continuous production rate of 40 million m^3/year for the irrigation of agricultural land over a period of 25 years, the groundwater level would be lowered by up to 30 m at a regional scale.

Larger quantities of groundwater are being pumped from the Saq sandstone aquifer in Saudi Arabia. In the Tabuk area, approximately 70 km south of Mudawwara, groundwater exploitation in the TADCO well field almost tripled from 53 million m^3 in the growing season 1983/84 to 140 million m^3 in 1988/89. The total abstraction in the larger Tabuk area exceeded 215 million m^3 in 1990.

As a first estimate of the possible influence of the large groundwater production in the Tabuk area on groundwater levels in the Mudawwara well field, a simple analytical model has been calculated assuming the Saq aquifer to be homogeneous and confined and to be of infinite extension in northern, southern and western direction (*Figure* 2). A Transmissivity of about 35 m^2/day and a storativity of 0.0008 are assumed to be uniformly distributed. Since the model calculations were only aimed at an estimate of the overall influence of the pumping in Tabuk on the Mudawwara area, abstraction in the model has been concentrated on the immediate sourroundings of Tabuk without consideration of the exact location of the various well fields. Based on these assumptions, the model indicates that ground-water withdrawal in Tabuk will affect the Mudawwara well fields. This drop of water levels could reach a range of a few tens of metres during the next decades, depending on the abstraction rates in Tabuk.

The results of this simple model show qualitatively the degree of interference of groundwater withdrawal in Saudi Arabia on the well fields in southern Jordan. More detailed predictions would need new modelling investigations incorperating bilateral data. Future models should be based on additional information and, most important, on groundwater head observations from the area between Mudaw-wara and Tabuk. Consequently, further groundwater investigations and groundwater management will need international cooperation.

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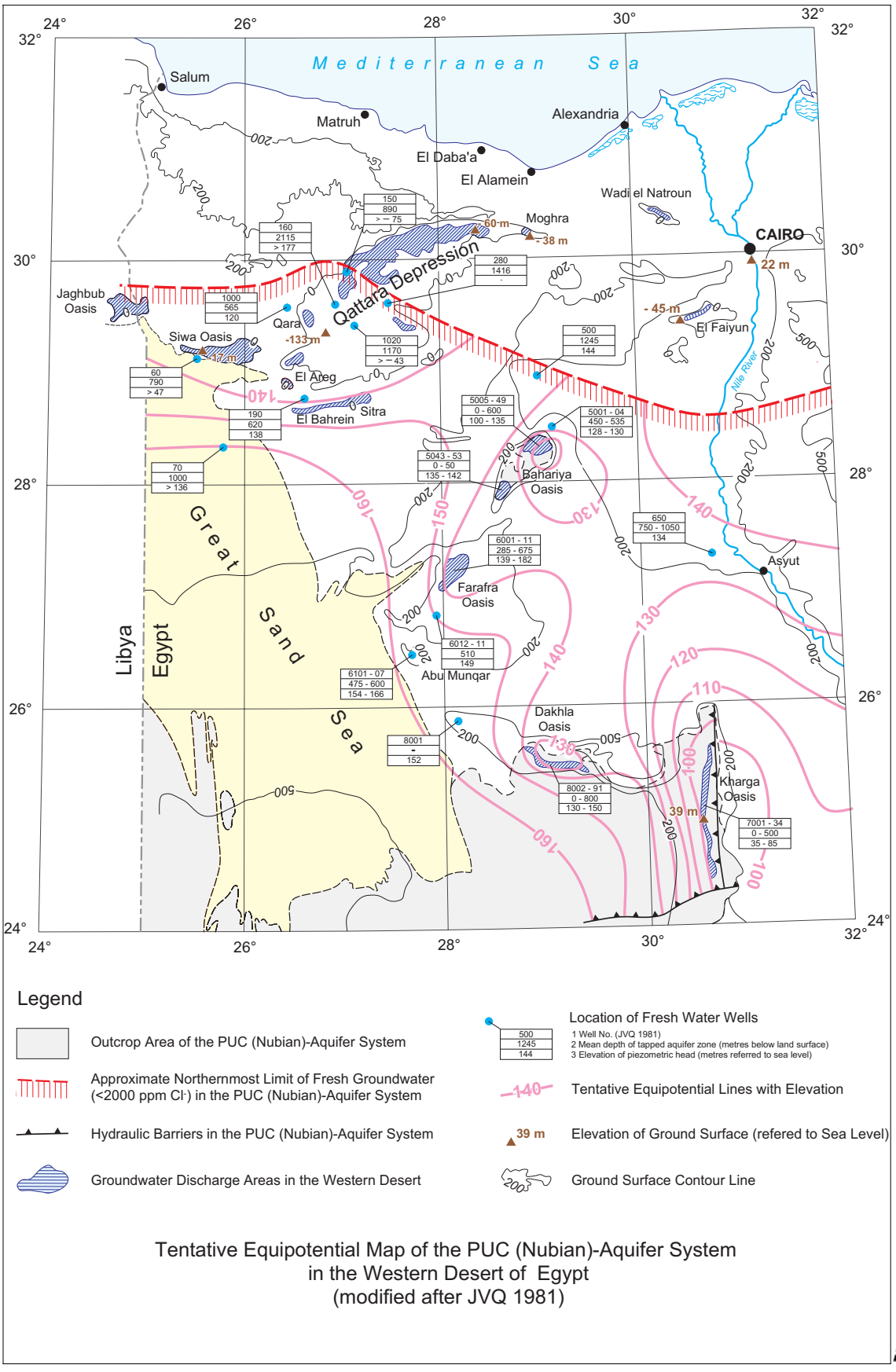
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Annexes

Annex 1: Qattara Depression



Legend

- Outcrop Area of the PUC (Nubian)-Aquifer System
- Approximate Northernmost Limit of Fresh Groundwater (<2000 ppm Cl^-) in the PUC (Nubian)-Aquifer System
- Hydraulic Barriers in the PUC (Nubian)-Aquifer System
- Groundwater Discharge Areas in the Western Desert
- Location of Fresh Water Wells
  1 Well No. (JVQ 1981)
  2 Mean depth of tapped aquifer zone (metres below land surface)
  3 Elevation of piezometric head (metres referred to sea level)
- Tentative Equipotential Lines with Elevation
- Elevation of Ground Surface (refered to Sea Level)
- Ground Surface Contour Line

Tentative Equipotential Map of the PUC (Nubian)-Aquifer System
in the Western Desert of Egypt
(modified after JVQ 1981)

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Assessment methodologies: isotopes and noble gases in Saharan palaeowaters and change of groundwater flow pattern in the past

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Abstract

Environmental isotopes (^{14}C, ^{13}C, ^{3}H, ^{2}H, and ^{18}O) and noble gases (He, Ne, Ar, Kr, and Xe) dissolved in Saharan groundwaters are presented and discussed, particularly those from the Eastern Sahara (Libya, Egypt).

These Saharan palaeowaters show almost late-pleistocene ^{14}C-ages of 20,000 y to 50,000 y B.P., which compare with He-ages derived from radiogenic He accumulated in groundwater. Because of their stable isotope pattern across the Sahara with pronounced West to East decrease of δD and $\delta^{18}O$, these palaeowaters have been formed by infiltration of local rainfall from the Western Drift, i.e. Mediterranean winter rain climate has prevailed in Northern Africa in last glacial time. Palaeowaters from holocene humid phases appear to be relatively rare, particularly in the Eastern Sahara, where this can be explained as an artefact of non-representative groundwater sampling.

Autochthoneous palaeowaters in widely extended deep aquifers like the Nubian Aquifer System do not contradict the existence of large-scale flow from (rainy) montain ranges at the southern margin of the Sahara, as for example from Tibesti across Southern Libya into the Western Desert of Egypt, under the present arid climate. This paradox is explained by the change from fast small-scale groundwater circulation pattern under full reservoir conditions at humid climate into slow large-scale circulation at arid climate,when the shallow aquifer systems and their densely distributed discharge locations have progressively fallen dry. At present, about 5,000 to 6,000 years after the end of the last pluvial phase, this large scale is given by the mean distance between the various Saharan depressions, where deep ground-water discharges by evapotranspiration. The depressions in the Eastern Sahara extend over 5 percent of the total area. The estimate of approx.10 mm water /y for the annual mean evapotranpiration rate there corresponds to a regional mean groundwater drawdown rate of 0.5 cm/y, if 10 % by volume is taken for the effective porosity of the sediments.

The groundwater flow from the catchment area to the individual depressions implies a regional mean effective transmissivity of the sediments of ca. 500 m^2/day.

1. Introduction

Since the beginning of ^{14}C groundwater dating a lot of isotope-hydrological investigation was done in Northern Africa, where huge fresh water reserves are stored in aquifer systems of very wide and deep Saharan sediment basins (Figure1a). In the Eastern Sahara, the Nubian Aquifer System (NAS) extends over the North Sudan-, Kufra-, Dakhla- and North Egyptian-Basin, where sediment thicknesses up to several thousand meters are reached in the basin centres (Figure6). The groundwater reserves of the Middle Sahara are contained in upper and deep aquifers of the Murzuk- and Homra-Basin with the Grand Ergs on top, and of the Tchad- and Niger-Basin at the southern margin. The sediments of the Taoudeni-, Tindouf- and Ferlo-Basin form big groundwater reservoirs of the Western Sahara.

Estimates of the Saharan groundwater reserves have increased from $15x10^6$ Mill. m^3 (Ambroggi 1966) to $60x10^6$ Mill. m^3 (Gischler 1976). If these quantities are divided by the number of 4.5 Mill. km^2 representing the areal extension of all sediment basins mentioned above, water column heights of 3.3 m and 13 m are obtained, which are to be compared with the global mean of 55 m (Sonntag 1978). With an effective porewater content of 10 % by volume for slightly consolidated sandstone (like Nubian Sandstone) in use, water columns such high can be stored in the pore space of sandstone layers of 33 m and 130 m thickness only. Thus, for the estimates above, only exploitable groundwater contained in the upper part of the sediment basins have been considered.

For long time the Saharan groundwater reserves were believed to be in steady state, i.e. the natural discharge of many Mi. m^3 water per year by evapotranspiration in depression areas should be compensated by an equivalent groundwater formation rate in rainy mountaineous terrain along the southern margin of the

Sahara and along the southern slopes of the Atlas mountain range. This groundwater replenishment was estimated to be about $4 \cdot 10^3$ Mill. m^3/y. Related to the numbers for the Saharan groundwater reserves above, this regional recharge/discharge rate gives mean residence times of ca. 4000 y and 15 000 y, which represent rough estimates of the mean groundwater age.

The hypothesis of allochtoneous groundwater origin would imply the existance of large-scale flow of the deep groundwater before pumping. If so, a continuous increase of the groundwater ages were to be expected from young groundwater in the infiltration areas to approx. 1,0000 y over a mean flow distance of 500 km. This gives a distance velocity of v_d =50 m/y or a Darcy filter velocity of $v_f = v_d/n$ = 5 m/y based on an effective porosity of n =0.1 for the aquifers. Using a mean hydraulic gradient of $i=1 \cdot 10^{-3}$, an average hydraulic conductivity of K_f =5,000 m/y $=1.6 \cdot 10^{-4}$ m/s is obtained, which appears, however, to be by an order of magnitude too high for the large Saharan aquifer systems (e.g. Nubian Sandstone).

Dating experience in the Sahara tells that there is no increasing groundwater age along the large-scale flow lines, for example from North Sudan through the Western Desert of Egypt to the Mediterranean or from the Tibesti through Kufra Basin and Serir Calancio into the Western Desert (see Figure1b). This means much lower or even negligible groundwater replenishment compared to natural discharge and thus unbalanced groundwater conditions under the present arid climate.

2. Environmental isotopes and noble gases in Saharan palaeowaters

The environmental isotope and noble gas data presented and discussed in this chapter provide strong arguments that the Saharan palaeowaters have mainly been formed by infiltration of local precipitation during moist climatic periods in the past. . If this hypothesis of autochthoneous groundwater is correct, one may ask for the last pluvial, when full groundwater reservoirs prevailed. This last pluvial has ended with the beginning of the present arid climate at some 5,000 y to 6,000 y B.P. Since that time, unbalanced groundwater discharge has caused decreasing groundwater levels (hydraulic heads) in the catchment areas around the various morphological depressions, where groundwater evaporates from barren soils, wild vegetation, and even from groundwater lakes. This exponential hydraulic head decay is discussed in Chapter 3 in context with the hydraulic interpretation of the isotope and noble gas ages of Saharan palaeowaters.

2.1 ^{14}C-groundwater ages

Figure 2 shows the frequency distribution of the ^{14}C-ages of 328 Saharan groundwaters. These ages are based on an initial ^{14}C-content of 85 percent modern carbon (pmc), i.e. the carbonate hardness effect is accounted for by a constant reduction of 15 pmc, no other age corrections have been made.

This statistical presentation reflects the alternating sequence of humid and arid periods in the Late Pleistocene and Holocene. The deep groundwater from continental sediments of Paleozoic and Cretaceous Age have mainly been formed in humid periods of the time slice from >50,000 y to 20,000 y B.P., whereas shallow groundwaters, which are found here and there in late Tertiary and Quaternary sediments, show ^{14}C-ages less than 12,000 y B.P. The time slice between 20,000 y and 14,000 y B.P. is less populated. The average population of this frequency minimum is significantly lower than that of the adjacent time periods, and there is no doubt that, during maximum glaciation, groundwater formation in the Sahara was low (Sonntag 1980).

As can be seen from the regional groundwater age distributions (Figure 3), this frequency minimum seems to exist everywhere in the Sahara, even in the Southern Sahara and in the Sahel Zone, although the statistical significance is fairly poor there. The long dry period (20,000-14,000 years B.P.) in the region south of the Sahara is also indicated by low levels of African Lakes, Lake Tchad for example (Gasse 1979).

The age spectrum of the Southern Sahara includes the ^{14}C groundwater data of the Ferlo Basin (Castany 1974). Its deep groundwater in the Maastrichtian formation shows an age increase which indicates groundwater flow from the rivers Senegal and Gambie at the periphery towards the basin center, with a main flow from SE to NW. We believe that the deep groundwater of the Ferlo Basin mainly originates from these rivers. This conclusion is supported on the one hand by the hydrochemical data which changes from bicarbonate-type groundwater in the south-eastern part of the basin to sulfate-type and finally chloride-type groundwater in the basin center under continuous increase of the total dissolved substance (TDS) from 250 ppm to 2,000 ppm (Castany 1974). On the other hand, the groundwaters show a uniform deuterium and oxygen-18 content, which is expected for rain in the catchment area of the rivers, but being too low for rainfall in the Ferlo Basin. It is surprising that the ^{14}C-age spectrum of the Ferlo groundwaters seems to show also the frequency minimum in the time-slice of the ice-age maximum. If so, reduced flow rate of the rivers has to be concluded for that time span.

Altogether the ^{14}C groundwater data indicate that this long semi-arid or even arid period has affected whole Northern Africa down to about 20 degrees northern latitude.

In opposite to other Saharan regions, however, holocene palaeowaters seem to be minor frequent in the Eastern Sahara or even absent like in the Western Desert of Egypt (see Figure3), where the hatched part of the frequency presentation is entirely due to groundwater from the Qattara Depression. This water contains appreciable bomb tritium and was thus considered either as modern groundwater from infiltration on the fractured limestone plateau at the northern margin of the depression or as mixtures of palaeowaters with this modern water. The absence of holocene palaeowater in the Eastern Sahara, however, is contradicted by many indicators for humid climate in early and mid holocene time (Pachur 1987), which are as frequent there like elsewhere. There is some evidence now, that missing the holocene waters seems to be an artefact of groundwater sampling (see chapter 3).

2.2 Continental effect in Deuterium and Oxygen-18

As can be seen from the isoline-presentrations in Figure 4, the heavy stable isotope content (deuterium and oxygen-18) of Saharan palaeowaters shows a significant decrease from west to east, which is similar to the one observed in European winter-precipitation and in shallow groundwater. This effect is called „Continental Effect“ in δD and $\delta^{18}O$, which denote the commonly used permille deviations between the isotope ratios R_{sample} and R_{smow} for HDO and $H_2{}^{18}O$ in the water sample and in Standard Mean Ocean Water (SMOW). The negative δD-values result from progressive isotopic depletion of precipitating air masses along their path-way across the continent. The δD pattern of the Saharan palaeowaters leads to the conclusion that the Sahara was influenced by westerly winds which have carried moist Atlantic air masses across the Sahara. There has been enough precipitation for groundwater formation by local infiltration. A simple model treatment of the continental effect based on progressive Rayleigh condensation steps in a closed air-mass system (no vertical water vapor exchange, and no exchange between rain and water vapor assumed) gave an estimate of the mean palaeowinter-precipitation across the Sahara. As an example, a paleowinter-precipitation of 600 mm at Agadir would lead to about 250 mm in the Murzuq Basin which agrees suprizingly well with the precipitation estimate of Pachur (Pachur 1969) obtained from ^{14}C-dated fluvial and limnic deposits and from the water demand of the palaeofauna and –flora.

Since groundwater, once formed, does not change its heavy stable isotope content under normal geochemical conditions, the continental effect in Saharan groundwaters proves their autochthoneous origin (local infiltration). Long-range groundwater movement can only be assumed to exist along isolines of the stable isotope pattern, for example along the isoline from Tibesti Mountains via the oases Kufra and Farafra to Bahariya (Figure4). A significant ^{14}C-age increase along these lines, however, has not been found yet.

Figure 4 suggests that moist air masses from the Western Drift seem to have brought palaeo-precipitation to the Sahara down to about 20 degrees northern latitude. At lower latitudes, the δD- and $\delta^{18}O$-data of palaeowaters and of modern groundwaters (bomb tritium!) from the Sokoto-, Tchad- and Bara Basin show meridional variations which indicate their tropical convective origin (moonsun rains).

These waters show also a slightly higher deuterium excess $d = \delta D - 8 \cdot \delta^{18}O$ (see below) in comparison to the Northern Saharan palaeowaters. This higher deuterium excess is typical for tropical summer rains. Thus, the region south of the Sahara, in particular the Sahel Zone, has received tropical rain in all time periods. However, the late-pleistocene palaeowaters of the Sahel Zone appear to be isotopically depleted (by about –15 to –20 permille in deuterium),if compared with modern groundwaters at the same locality. This is also observed in European palaeowaters and modern groundwaters (Rozanski 1985). We do not believe that the lower stable isotope content of the palaeowaters has been caused by greater isotopic fractionation factors due to lower temperatures in the past. It might rather be due to a steeper inland decrease of the mean annual precipitation, which could have led to a steeper continental effect of δD and of $\delta^{18}O$ in the past.

The heavy stable isotope data of the Saharan palaeowaters and of modern European groundwaters is presented in the δD versus $\delta^{18}O$ diagrams of Figure 5. As can be seen from these presentations, the data points of the modern European groundwaters fall on the classical “Meteoric Water Line“ (MWL), $\delta D = 8 \cdot \delta^{18}O + 10$, which at $\delta^{18}O = 0$ shows a deuterium excess of d =+10 permille. The variance of the data points from this regression line is very small. The Saharan palaeowaters, however, fall on a straight line parallel to the MWL, intersecting the dD-axis at d =+5 permille only. The higher variance of the data points around this line may indicate slight kinetic re-evaporation effects as to be expected under Savanna climate: Evaporation loss of rain drops falling through a relatively dry atmosphere and/or evaporation loss at the soil surface before infiltration. In both cases, the residual rain water, which was originally on the MWL, will become isotopically enriched along evaporation lines of gradient 3-6 in the $\delta D/\delta^{18}O$-diagram, i.e. the data points are shifted to the right, off from the MWL.

We do, however, not believe that the lower apparent deuterium excess of the Saharan palaeowaters is exclusively due to kinetic- re-evaporation, since the data from the Eastern Sahara (Kufra Basin, Western Desert of Egypt) shows a variance from the regression line as low as the European waters, but nevertheless a smaller deuterium excess.

It is commonly assumed that the deuterium excess of meteoric water is due to kinetic isotope fractionation in the evaporation of sea water. The data of a wind/water tunnel experiment in our institute is in agreement with the issue that the deuterium excess decreases with decreasing moisture deficit of the air over the ocean (Münnich 1978). The smaller d of the Saharan palaeowaters would correspond to a moisture deficit of 15 percent in the marine palaeo-atmosphere to be compared with approx. 22 percent today.

2.3 Noble gases dissolved in groundwater

The concentrations of the noble gases He, Ne, Ar, Kr and Xe dissolved in Saharan ground-waters (cc STP gas /g H_2O) give additional information on the groundwater age and on the soil temperature in the recharge area at the time when the groundwater was formed.This is possible since the physical solubility of the heavy noble gases Ar, Kr, and Xe is temperature dependent, and atmospheric noble gases once dissolved in groundwater are kept there, even in case of geothermal heating (Mazor 1972). The precision of this „noble gas thermometer“ is ± 0.5 centigrades (Rudolph 1984). Information on the groundwater age can be derived from radiogenic helium. Deep ground-waters of high ^{14}C-age show He-contents, which exceed the one expected for atmospheric He in dissolution equilibrium ($4.5 \cdot 10^{-8}$ cc STP He/g H_2O) often by orders of magnitude. This “excess He” is due to the accumulation of radiogenic He from the ⁄ -decay of uranium and thorium in the minerals of the aquifer („in situ produced He“) and due to fluxes of helium released from the outer earth crust and, here and there, also from the earth mantle.

Mantle helium can be identified by its high isotope ratio in the order of $^3He/^4He = 3 \cdot 10^{-5}$, whereas crustal helium ($^3He/^4He = 2^* \cdot 10^{-8}$) is also radiogenic and, therefore, cannot be distinguished from in situ produced He (Mamyrin 1984). Assuming a constant accumulation rate for radiogenic He along the groundwater pathway, the excess He increases linearly with the groundwater flow age. Using reasonable numbers (i) for the in situ production rate depending on the U-,Th-, and porewater content of the aquifer rocks, (ii) for the crustal He-flux, and (iii) for the vertical extension of the aquifer, the He-accumulation rate can be calculated. Then the He-accumulation age desired is given by the ratio of the “excess He”-concentration in the groundwater sample and the this accumulation rate.

Most of our noble gas data for Saharan palaeowaters stem from artesian wells in the Western Desert of Egypt (Rudolph 1984) and from deep wells in Eastern Libya (Kufra Oasis, Sarir Well Field, Tazerbu area). Moreover, some samples from Algeria (Grand Erg Occidental) and from NE Nigeria (Chad Basin) have been analyzed.

The noble gas temperatures derived from these data are ranging between 20.9 and 26.0 centigrades. Their mean value of 23.2 ^oC compares with the mean annual temperature of today or may even be slightly higher (Bahariya Oasis 21.8 ^oC, Kharga Oasis 23.5 ^oC), whereas by about 5 - 7 ^oC lower values were to be expected for palaeowaters of last glacial time. This discrepancy was explained as being due to the fact that in semi-arid/arid regions the mean soil temperatures exceed the annual mean air temperature by a few centigrades (Dubief 1957). Moreover, the deep groundwaters analyzed are considered as to consist of different age components. For the palaeowaters from the large depressions in the Western Desert of Egypt, where natural discharge from the Nubian Aquifer System occurs, an age composition of 34 % holocene plus 53 % late pleistocene water has been estimated, the rest is older than 50 000 years. Under the assumption that the temperatures in holocene wet periods have been close to the present Saharan temperatures, the palaeotemperature calculated for the glacial component is indeed by at least 4 ^oC lower than the present local temperature.

This temperature assumption for the holocene wet periods seems to be supported by the noble gas temperature data of the shallow groundwater from Tazerbu TSW 1 and TSW 3, which shows holocene ^{14}C-ages and noble gas temperatures by 3 ^oC higher than the present mean annual air temperature as to be expected from Dubief’s finding. These groundwater samples from Eastern Libya were collected on our sampling campaigns in 1982/83, which were initiated and arranged by Mr. Fathi Salloum/Bengazi. The results of this isotope and noble gas investigation has been presented in a technical report to the Libyan Authorities, but this data has not yet been published.

In this report He-accumulation ages of palaeowaters from the Tazerbu-, Sarir- and Kufra-well fields are presented which were calculated with a fixed accumulation rate of $1.4 \cdot 10^{-12}$ cc STP He/ g H_2O/year for in situ He production in use. This rate is based on Uranium- and Thorium-contents of 3 ppm and 12 ppm for the sediments, on a rock density of 2 g/cm^3 and on a total porosity of 10 % by volume for the various aquifers. In the case of the shallow groundwater samples TSW1 and TSW3 from Tazerbu area, these in “situ He

accumulation ages"of 4,100 y and 4,600 y B.P. agree with the ^{14}C-ages of 4,400 y and 5,000 y B.P. The deep groundwater samples TX170 and MT1 from Tazerbu show He-ages of 74,300 y and 59,000 y B.P., which are considerably higher than their ^{14}C-ages of 38,600 y and of 37,500 y as well. These higher He-ages might be due to the presence of crustal helium, which has not yet been considered in the He-production rate above.

In case of the two deep groundwater samples from KPP E13 and KSP 2151 in the area of Kufra, however, the age discrepancy is the other way round. May be that the in situ helium production rate is considerably lower there than the number quoted above, and that their ^{14}C-ages are by about 5,000 y too high. But anyhow, the low excess helium in the deep groundwaters from Kufra suggests that the influence of the crustal helium is negligible small. This suppressed crustal He-flux seems to indicate an effective deep groundwater flow, which is strong enough to carry off all crustal flux helium before it penetrates into the pumped aquifers above.

3. Estimating the groundwater balance of the eastern Sahara

3.1 Natural discharge of east Saharan palaeowaters

As mentioned in the first chapter, the groundwater reserves of the Eastern Sahara are mainly contained in the Nubian Aquifer System (NAS) which extends over an area of approx. 2 Mi. km^2 (Thorweihe 1988), including the Kufra Basin. The isotopic finding suggests that these palaeowaters have been formed by local infiltration during humid periods in late pleistocene time. However, as already mentioned in chapter 3, palaeowaters of holocene ^{14}C-age seemed to be missed in the Eastern Sahara. This problem turned out to be an artefact of groundwater sampling. In the Eastern Sahara, particularly in the Western Desert of Egypt, the water wells are located in the large depression areas which are deeply cut into the land surface. In these topographic lows, the hydraulic head is close to the ground surface or even above (artesian groundwater). Thus natural groundwater discharge occurs either by capillary rise from the groundwater table or by ascend of confined or artesian groundwater through leaky confining beds followed by water vapour diffusion through top layers of dry soils and by transpiration of wild vegetation. In the vicinity of these discharge centers of NAS, holocene palaeowaters, which were originally there, have already disappeared or form a small admixture to much older groundwater. They should, however, still exist in the vast desert area outside the depressions. This hypothesis is supported by isotope dating of unconfined groundwater from relatively new wells in the catchment area of the fairly flat Bir Tarfawi/Bir Safsaf depression in the hyperarid Southwest of Egypt, the groundwater balance of which is discussed below.

The natural groundwater discharge from East Saharan depression areas occurs at a total rate of approx.$1 \cdot 10^9$ m^3/y (Ahmad 1983). In comparison to this, groundwater replenishment under the present arid climatic conditions by infiltration of episodic local rainfall and by subsurface inflow from rainy mountaineous terrain at the southern margin of the Eastern Sahara is negligible (Sonntag 1986). If this unbalanced groundwater discharge is related to the areal extension of NAS mentioned above, an areal mean discharge rate of D=0.5 mm water/year is obtained. Negligible replenishment means an areal mean recharge rate which is by at least one order of magnitude smaller than D, i.e. R<0.05 mm water/y. Hydrological estimates of extremely low groundwater recharge like this are very difficult and need many convincing arguments.

3.2 Exponential decay of the hydraulic head

Under the assumption of negligible recharge since the beginning of the present arid period at 5,000 y to 6,000 y B.P., the hydraulic head has exponentially been decreasing, $h(t) = h_o \cdot \exp(-t/\Downarrow)$, from its initial level h_o close to ground surface (full groundwater reser-voirs) to the present one at about h(t) = 60-70 meters depth below ground. The time constant $\Downarrow = g \cdot (n \cdot L^2)/(K_f \cdot H)$ depends on th one hand on the hydraulically dischargeable groundwater mass, which is represented by the effective porosity n, the by initial value h_o of the hydraulic head with the depression surface as reference level, and by the length scale L of the area of influence around the individual depression. On the other hand, the time constant depends on the areal mean effective transmissivity $K_f \cdot H$ (K_f= hydraulic conductivity of the sediments, H= penetration depth of the groundwater flow), which determines the groundwater flow towards the depression. The dimensionless geometrical factor g depends on the morphological shape of the depression and of the catchment area around. In case of cylindrical depressions (radius r) with ring shaped catchment areas (outer radius R), see Figure 6, L has to be replaced by the depression radius r, and in g the ratio R/r of the radii comes into play; for example: R/r=4.3 gives g=8.2. Using R=130 km, r=30 km, n=0.1, $K_f = 1.2 \cdot 10^{-5}$ m/s, and H=500 m as typical numbers for groundwater discharge from large East Saharan depressions, a time constant of $\Downarrow$=3,900 y is calculated for the hydraulic head decay in the catchment areas around (Sonntag 1986).

If steady state groundwater circulation at full reservoirs (pluvial period) is considered, this hydraulic time constant is equivalent to the mean groundwater age in the hydraulically dischargeable sediment layers above the depression floor, which are h_o meters thick. The groundwater, however, which has reached the depression area, has passed through a much larger reservoir of h_o+H meters vertical extension, where H denotes the mean penetration depth of the groundwater circulation below the depression floor. With h_o=100 m and H=500 m in use, this total reservoir is six times the dischargeable one. Since the ratios of the reservoirs and of the mean groundwater ages therein are identical, mean groundwater ages in the order of 6·4,000=24,000 years are to be expected for deep groundwater ascending to the depression surface. However, this is an hydrodynamic estimate of the deep groundwater age in pluvial time. In the arid period like now, this mean age is higher by the actual duration of the arid period, i.e. by 5,000 y to 6000 y.

It should be mentioned here that the number H=500 m used for the penetration depth of the deep groundwater circulation stems from Burdon (Burdon 1977). Multiplied with the K_f-value above, a mean areal transmissivity of $T=1.2\cdot10^{-5}\cdot500=6\cdot10^{-3}$ m^2/s=520 m^2/d is obtained, which seems to be reasonable.

3.3 Exponential model for the tracer flow

However, in case of steady state groundwater (mass)- and radiotracer-flow (here ^{14}C of mean life $\Downarrow_{14}$=8,300 y), the exponential model, which is adequate here, yields $c_m=c_o*(1+\Downarrow\Downarrow_{14})^{-1}$ for the mean ^{14}C-content c_m of the groundwater body. Continuous tracer input by the recharge water of c_o=85 pmc leads to c_m=21.3 pmc for $\Downarrow$=24,000 y, whereas the ^{14}C-data of the groundwater samples from wells in the depressions are ranging between 7 and 0.5 pmc only (apparent ^{14}C-groundwater ages between 20,000 y and >41,000 y B.P.!). Mean (steady state ^{14}C-contents c_m such high have existed until the end of the last humid period some 5,000 y to 6,000 y B.P. Under the assumption of no groundwater recharge over the present arid period, the mean ^{14}C-content has decreased by radioactive decay to about one half of the original steady state value c_m, i.e. to about 12 pmc. The remaining discrepancy between model estimate and ^{14}C-groundwater data may have various causes which, however, cannot be further discussed here.

3.4 Discrepancy between the ^{14}C- and He-Ages of Saharan palaeowaters

Finally, the discrepancy between (i) the apparent ^{14}C-groundwater ages and our model estimate of the mean ^{14}C-groundwater age on the one hand, and (ii) the much higher He-accumulation ages mentioned in the previous chapter on the other hand can be explained as being due to slight admixtures of quasi-stagnant or even syngenetic porewater from sediment layers below the penetration depth H. If this “immobile” deep water has an age of, let us say, 10 Mi. years, an admixture of 10 percent to the groundwater sample would have negligible influence on its ^{14}C-content, but it would cause an apparent He-accumulation age of 1 Mi.y. Slight admixtures of very old groundwater beyond the upper limit of ^{14}C-dating are also predicted by the exponential model. The exponentially decreasing groundwater flow time spectrum means, that groundwater of 24,000 y mean age is composed of holocene water by 34 %, of late pleistocene water (10,000 y to 50,000 y B.P.) by 53 %, of water between 50,000 y and 100,000 y old by 11 % , and of water older than 100,000 y by 2 %. We believe, that mid holocene groundwaters, which have not been found yet in the Western Desert of Egypt, should exist in the vast desert area along the groundwater sheds in between the depressions. However, there are more or less no wells, except the wells in the small catchment area around the discharge locations Bir Tarfawi/Bir Safsaf in SW Egypt.

4. Groundwater balance of the Bir Tarfawi/Bir Safsaf-area in SW Egypt

Palaeowater of holocene ^{14}C-age was found in the catchment area around the flat Bir Tar-fawi/Bir Safsaf depression in SW Egypt. The groundwater balance of this area has been estimated by the following independent approaches:

1. In the *hydrological approach*, the present groundwater discharge has been determined directly. This was done by assessing the evaporation from bare soils as a function of ground-water depth and soil type (Christmann 1987) which have carefully been mapped, and by assessing the water consumption of the (mapped) wild vegetation by means of biometric methods (Kontny 1992). The total discharge rate of $D=3.6\cdot10^6$ m^3/y obtained for the depres-sion gives an areal mean groundwater drawdown rate of 1.2 mm/y, if related to the catchment area of 30,000 km^2.
2. The *palaeohydrological approach* is based on the assumption, that the groundwater surface has exponentially been decreasing from ca. h_o=10m to h(t)=30m below ground surface over the past 5000 years, which gives a mean drawdown rate of 4 mm/a. With a time constant of $\Downarrow$=3000 y for the exponential decay of the hydraulic head in use, the drawdown rate has decreased from 8.2 mm/y at

the beginning to 1.6 mm/y now. This time constant has been calculated with reasonable numbers for the geohydraulic parameters n, L, K_f and aquifer thickness H in use, which were introduced above.

3. The initial groundwater drawdown rate of 8.2 mm/a correponds to the mean infiltration rate, which has kept the groundwater level high during humid periods, particularly in the last one, which ended approx. 5000 y B.P. This number compares fairly well with an independent infiltration estimate derived from the vertical distribution of ^{14}C in the unconfined groundwater of the area.

4.1 Groundwater conditions in Eastern Libya before pumping

Piezometric contour line presentations of the groundwater levels in Eastern Libya (Pallas 1980, Ahmad 1983) suggest a large-scale groundwater flow from the groundwater divide along the mountain range in the South (approx. 21° N latitude) towards the oasis belt at about 25° N latitude, where considerable discharge by evapotranspiration has existed already before human interference. In opposite to Ahmad's idea of steady state groundwater conditions in the time before pumping, this natural discharge is not balanced by inflow from the South, i.e. the regional groundwater flow has caused continuously decreasing hydraulic heads. In the Kufra Basin this flow is divided into a NE directed branch to the Dakhla Basin (Western Desert of Egypt) and into a branch northwards through the southern part of the Sirte Basin to the wide sabkha belt at about 30 N latitude, where most of the natural discharge occurs.

Under the assumption of negligible groundwater replenishment over the last 5,000 y - 6000 y, the groundwater drawdown in the region south of the oasis belt is estimated as follows: The catchment area for the palaeowaters, which are being dicharged from the oasis belt, is considered here as to extend from 18 to 24 E longitude and from 21 to 25 N latitude, i.e. over $F=620 \cdot 450=2.8 \cdot 10^5$ km^2. The distance between the oasis belt and the groundwater divide in the South is approx. 450 km. If h(t) denotes the time-variant elevation of the mean ground-water level in the catchment area above the mean water level in the oasis belt, the hydrauli-cally dischargeable groundwater mass is given by $M(t)=n \cdot F \cdot h(t)$, where n stands for the mean effective porosity of the aquifers. Full system conditions, i.e. groundwater levels close to ground surface everywhere, assumed for the beginning of the present arid period gives $h_o=h(t=0)=200$ m. This maximum mean groundwater level in the catchment area has exponentially been decreasing over the past t=6,000 years by about 50 meters to h(t)=150 m at present. This hydraulic head decay is controlled by a fairly large time constant of $\Downarrow$=20,800 y. The groundwater drawdown rate has also been exponentially decreasing from $(dh/dt)_{t=o}=-h_o/T=-0.96$ cm/y at the beginning to $(dh/dt)_{t=6000}=-0.72$ cm/y now. Using n=0.1 for the aquifer porosity, the present drawdown rate corresponds to a mean areal groundwater loss of 0.72 mm water per year, which gives a total discharge from the catchment area of $2.0 \cdot 10^8$ m^3 water per year or 6.4 m^3/s. This paleohydraulic estimate of the groundwater discharge from the Kufra Basin is by an order of magnitude smaller than the number for the discharge from the oasis belt plus subsurface outflow into the Dakhla Basin quoted in Ahmad's regional groundwater model. Our number for the discharge, however, is high enough to provide a groundwater flow of 2 m^3/s into the Sirte Basin, which is needed to maintain steady state groundwater conditions in the Post-Eocene aquifers there (see model estimate for case c) in Wright 1982).

At given hydraulic gradient the discrepancy between our and Ahmad's discharge estimate implies an equivalent discrepancy in the numbers used for the regional mean transmissivity T_r which determines the groundwater flow to the oasis belt and to the northern and eastern margin of the Kufra Basin. If r=450 km (distance oasis belt/groundwater divide), n=0.1, g=0.41 (geometrical factor in the formula for the time constant in the 1-dimensional case), are inserted into the formula for the time constant $\Downarrow$ for the hydraulic head decay, the number of $\Downarrow$=20,800 y quoted above yields a mean regional transmissivity of $T_r=4.0 \cdot 10^5$ m^2/y=1,100 m^2/d=0.013 m^2/s. This number is indeed by at least one order of magnitude smaller than the transmissivity value which Ahmad has used (see Figure7 in Ahmad 1983). Our smaller number supports the idea, that the regional groundwater circulation has a penetration depth H of a few hundred meters only, whereas the sediment fill of the Kufra Basin reaches thick--nesses up to more than thousand meters. If so, the effective mean regional transmissivity can be written as $T_r=K_f \cdot H$. Then Tr =0.013 m^2/s yields $K_f=2.5 \cdot 10^{-5}$ m/s for H =500 m.This number compares surprisingly well with hydraulic conductivity data reported for Nubian Sandstone in the Western Desert of Egypt (Hesse 1987).

5. Changing groundwater circulation pattern in the past

The environmental isotope and noble gas data presented and discussed in Chapter 2 provide strong arguments that the Saharan palaeowaters have mainly been formed by local infiltration during moist climatic periods in the past. This autochthoneous groundwater origin excludes large-scale groundwater circulation in the time of groundwater formation and also in the early phase of the following arid period, when the reservoirs were still well filled. High ground-water levels everywhere in that time imply a hydraulic head

surface which has followed even small-scale topographic ups and downs of the (palaeo-)groundsurface. Thus strong small-scale hydraulic gradients have driven small-scale groundwater circulations with discharge in many topographic lows, which have fallen dry one by one in the course of the present arid period; i.e. most of them have already disappeared. At the beginning, small-scale cells of intensely circulating shallow groundwater have penetrated even through thick leaky confining beds. Thus large-scale groundwater flow driven by the regional hydraulic gradient like now was suppressed. However, in the present arid period, which lasts since 5,000 y or 6,000 y, hydraulic head decay has smoothed out small-scale topograhic variations of the hydraulic head. This implies that the small-scale, but intense circulation of the shallow and of the deep groundwater as well has ceased, so that larger or even regional scale flow has come up. This large-scale flow is less intense than the former circulation cells of the deep groundwater, i.e. there is no increase of the groundwater age along the regional flow lines. Due to the local groundwater formation everywhere in the Palaeo-Sahara and particularly in last pluvial time, there is an increase of the groundwater age with depth below ground rather than a lateral increase in the direction of the present regional flow. The regional flow shifts this age profil only through the sediment package with a low distance velocity.

The vertical groundwater flow through the confining beds downward and upward, so that last glacial ages appear in the confined aquifer, need leakage coefficients for the confining beds in the order of 10^{-9} to 10^{-8} m/s and, of course, hydraulic gradients for driving the deep ground-water by small scale circulations, which are about one order of magnitude larger than the regional hydraulic gradient. If 0.3 permille is taken for the hydraulic gradient forcing the regional groundwater flow, then palaeo-gradients of 3 permille should have existed to drive the small-scale circulations of shallow **and** deep groundwater in the past.

This picture of changing groundwater circulation patterns over the palaeoclimatic history of the Sahara follows the idea of Toth (Toth 1963). Figure 7 has been taken from his paper, but slightly modified to illustrate changing circulation pattern during Saharan pluvial and arid periods.

(See Figures 1-7 on following pages)

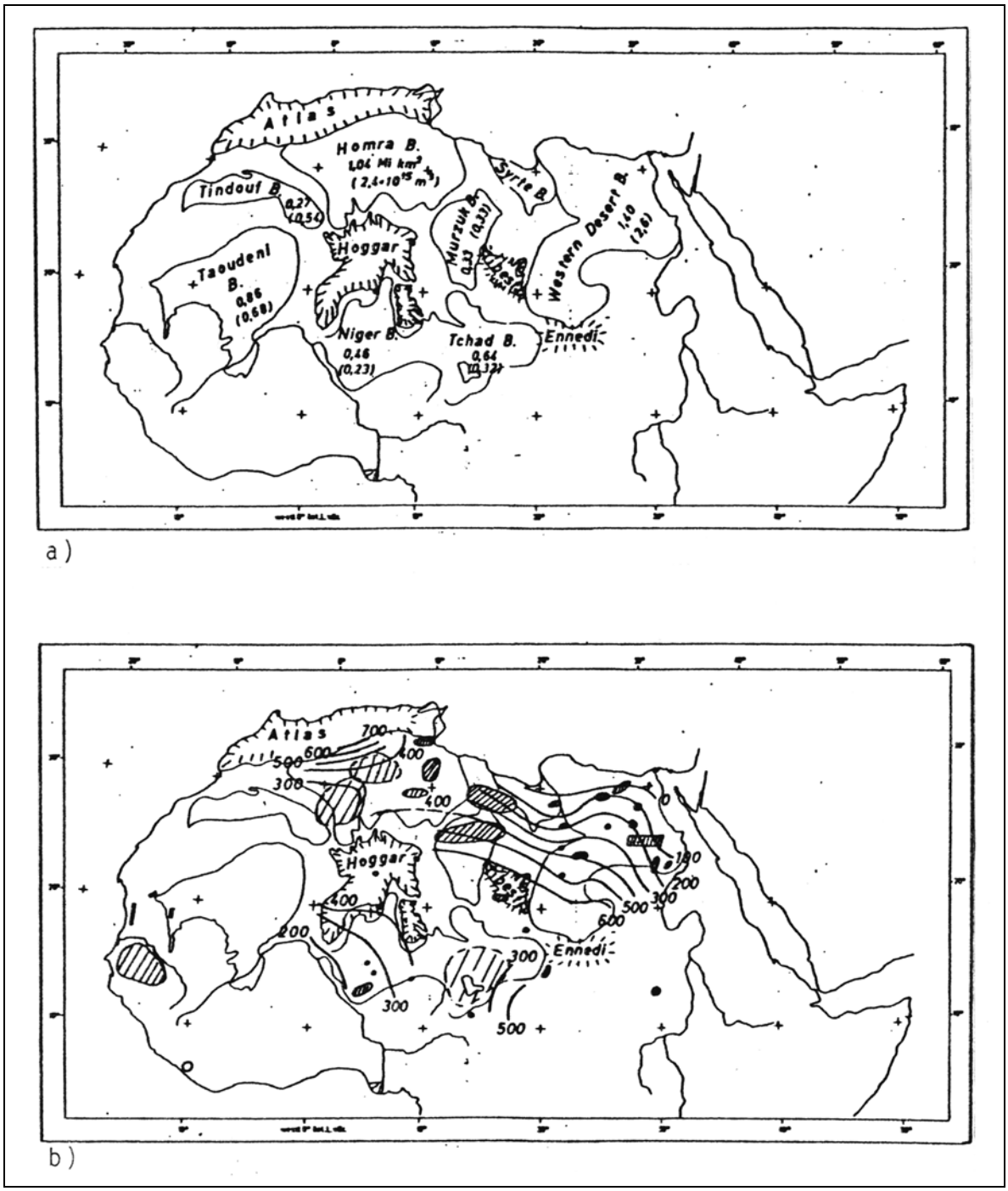


Figure 1: a) Saharan sediment basins after the tectonic map of G.Choubert and A. Faure Muret 1968. The areal extension of the basins is given by the inserted numbers in 106 km^2, whereas the numbers in brackets represent the volume of the sediments fills in 1015 m^3.
b) Hydraulic head contour lines giving information on the direction of large-scale circulation of the deep groundwater, in particular for the Eastern Sahara.
The hatched areas, black dots and short bars indicate the locations where isotope work was done.`

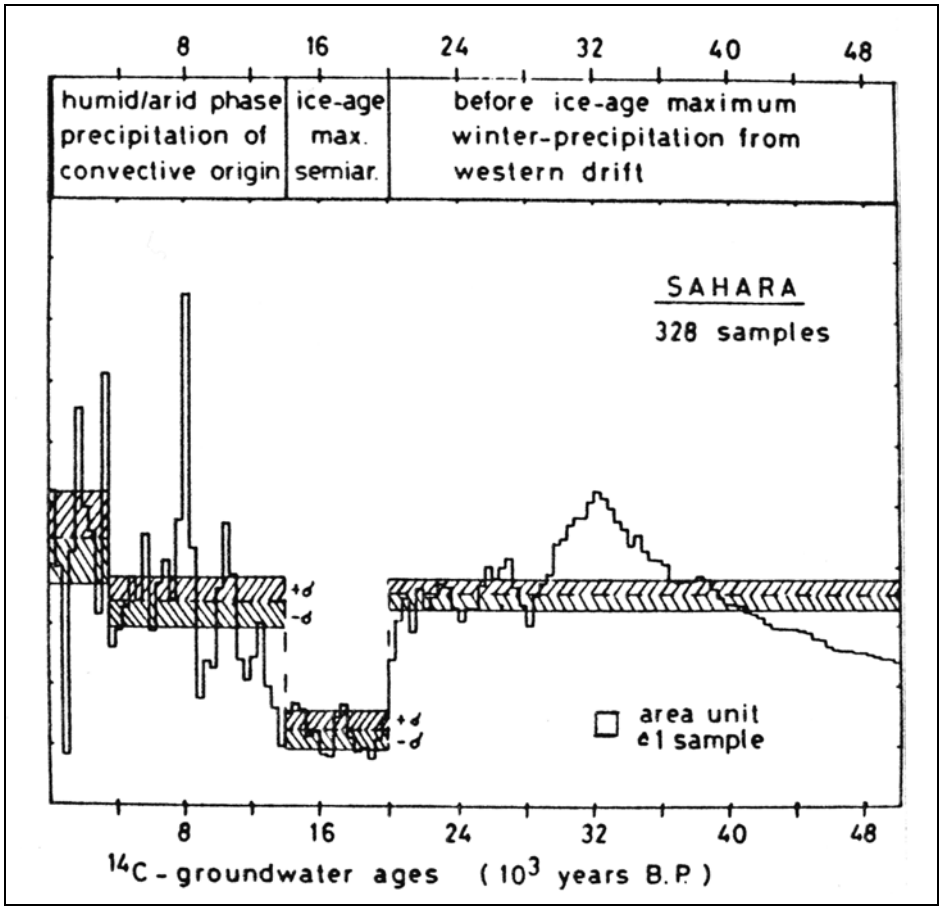


Figure 2: Frequency distribution of apparent ^{14}C-ages of Saharan groundwaters based on an initial ^{14}C-content of 85 pmc, no other age corrections made. The unit area representing one sample is always a rectangle; its width on the time axis is the ±sigma dating uncertainty. Therefore, at low dating precision (high age) the area representing one sample is broad and flat, at high precision narrow and high. The ±⇑ range on the ordinate indicates the statistical error of the frequency distribution for the individual age periods.

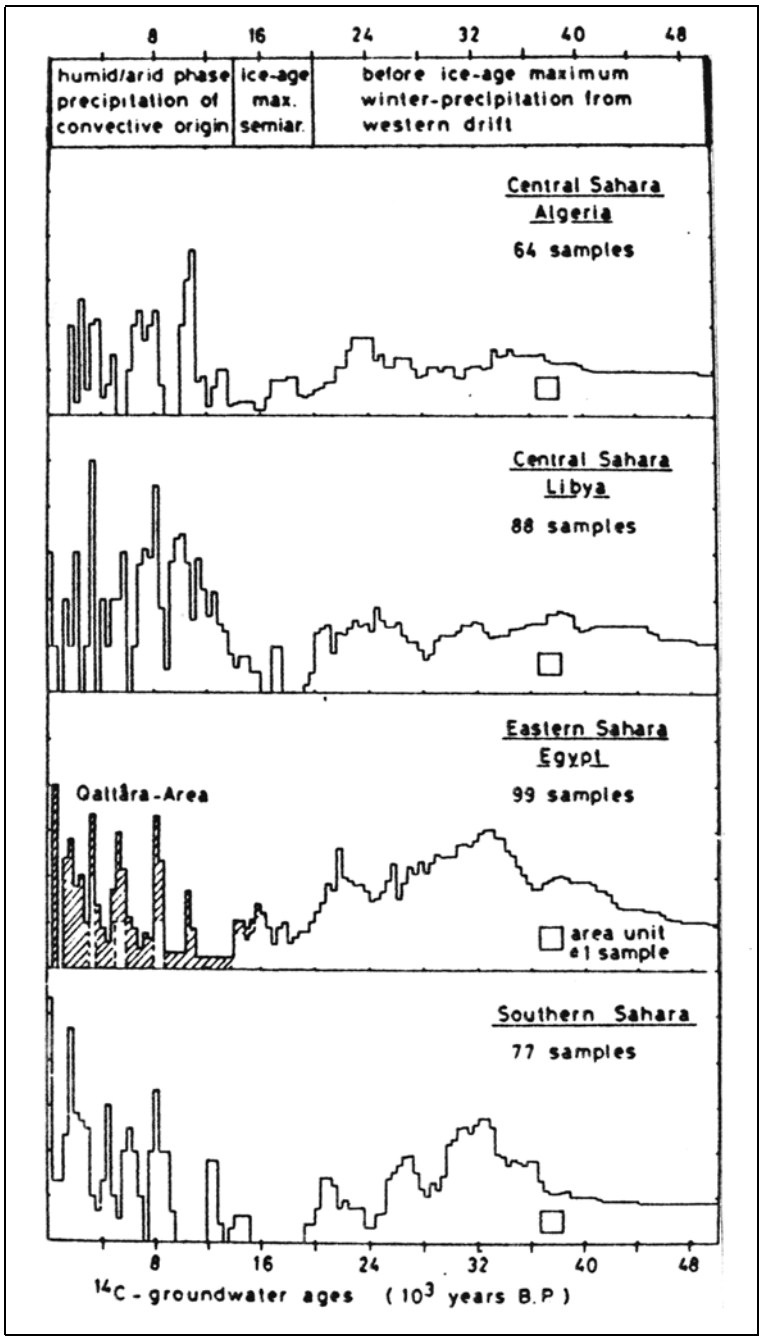


Figure 3: Regional frequency distributions of apparent ^{14}C-ages of Saharan groundwaters. The Southern Sahara diagram includes the Sahel Zone.

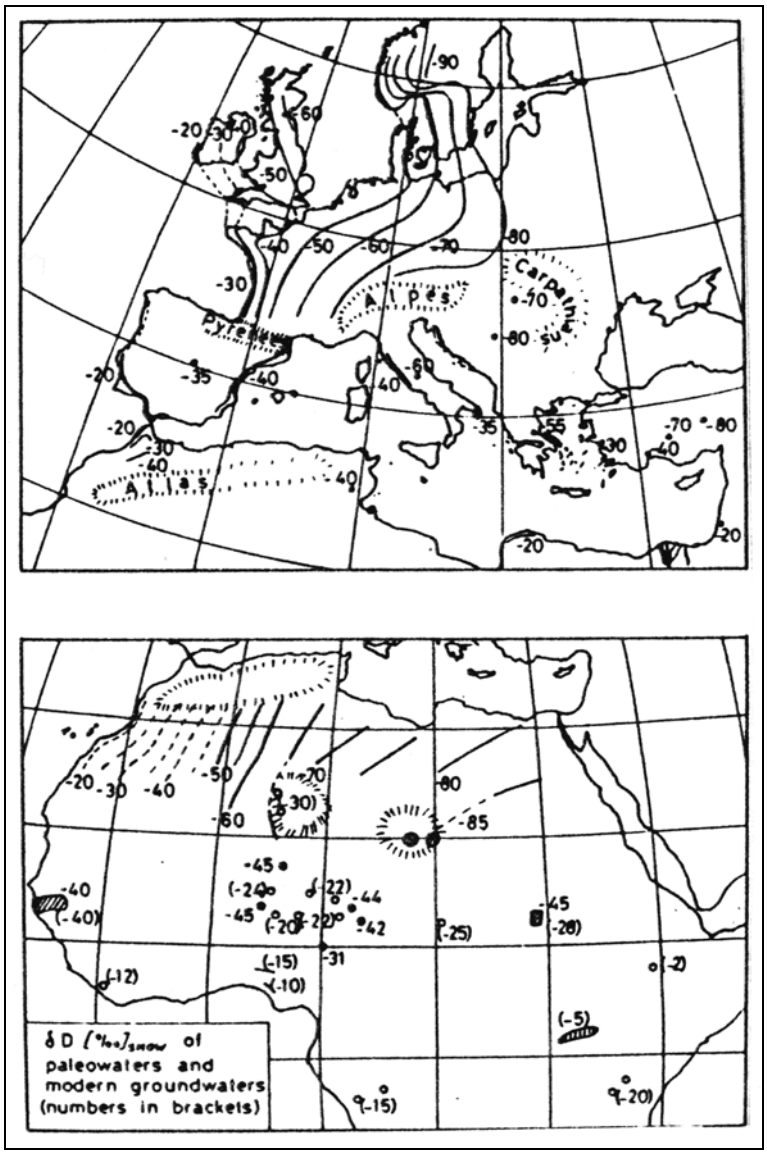


Figure 4: δD-isoline presentation of modern European and fossil Saharan groundwaters respectively. For Central Africa, the mean δD of modern (and fossil) groundwater (in the dotted areas) and of the mean weighted annual precipitation (heavy full dots, numbers in brackets) is shown. The European data points uniquely fall into distinct isozones, the resolution across the isolines (excluding the influence of altitude effects) may turn out to be not much more than ⇑ Ξ ± 50 km or about ±2 ‰ in δD.

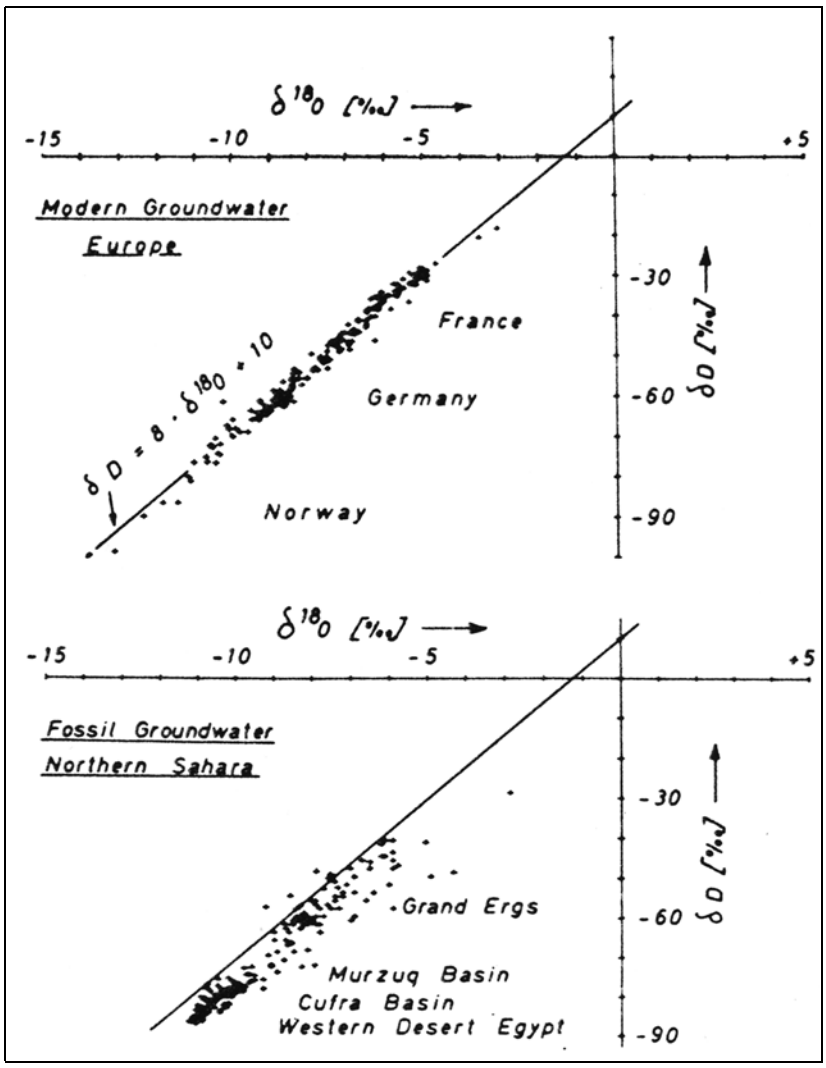


Figure 5: δD versus $\delta^{18}O$ diagram of modern European and fossil Saharan groundwaters. In case of the European groundwaters the spread around the regression line is dominantly due to the analytical precision of ±1 ‰ for deuterium.

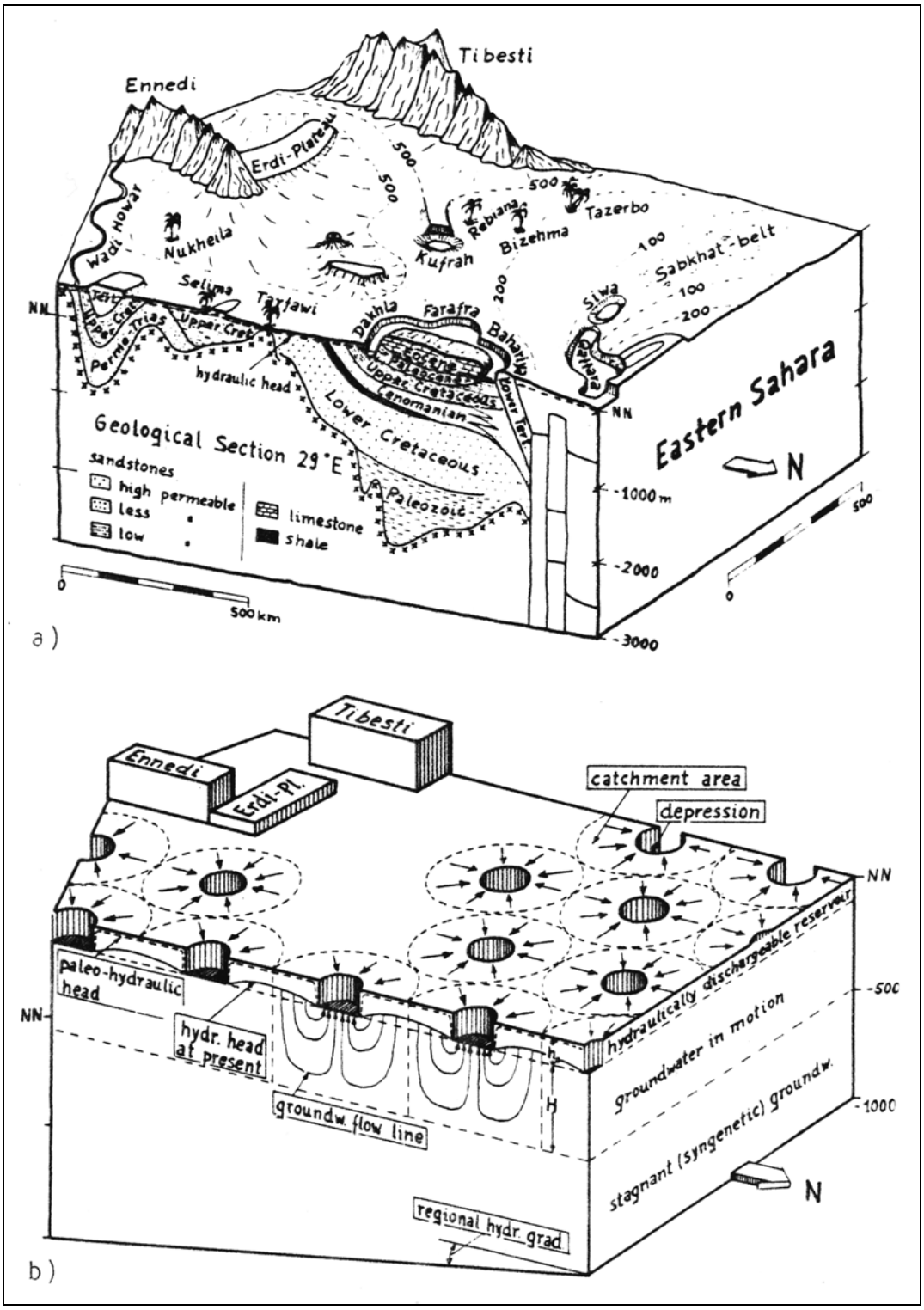


Figure 6: Eastern Sahara
a) Simplified presentation of the geological basin structure and of the surface morphology with emphasis of the depressions, where palaeowater evaporates.
b) Schematic sketch of provincial groundwater flow towards the individual depressions, which causes hydraulic heads being continuously decreasing at a rate of about 0.5 cm/y at present time.

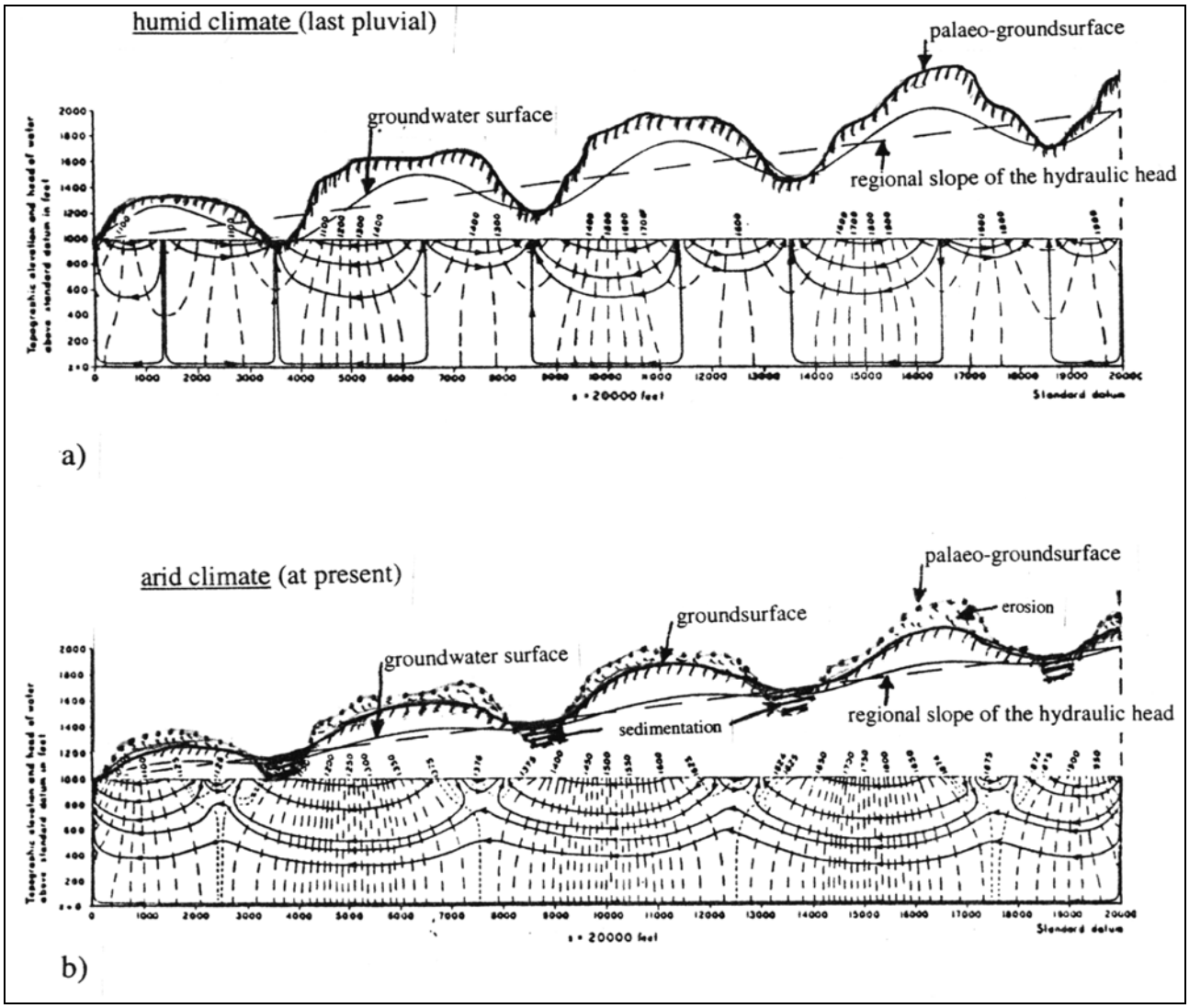


Figure 7: Changing groundwater circulation pattern.
a) Pluvial climate: Small-scale shallow and deep groundwater circulation cells at full reservoirs due to groundwater recharge by local infiltration. Local haudraulic gradients exceed the regional mean slope of the hydraulic head surface.
b) Arid climate: Hydraulic head decay due to continous groundwater discharge without recharge has smoothed the hydraulic head surface, so that small scale groundwater circulation has disappeared and regional flow of the deep groundwater has come up. This drying up of the ground surface was associated with flattenting of the surface topography by erosion and sedimentation.

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Optimisation of artificial recharge using well injection

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Abstract

In the field of water management, artificial recharge is used widely over the world for many purposes. One of the most important goals of artificial recharge is the storage of water in wet seasons to be used in dry seasons.

There are many methods of artificially increasing groundwater supplies. In this study, a better management of surface water and groundwater using artificial recharge by well injection has been proposed. To reach this objective, some combined tool of optimisation and simulation for groundwater has been used. This gives the minimum amount of water necessary to be injected by respecting some constraints related to the drawdown of the aquifer. This optimal solution generates also the number of wells and their locations.

Many simulations have been done for different sets of constraints. The results obtained show very forte non linearity in the relation between the total injection rate per year and the duration for the exploitation of the aquifer (an augmentation of the injection rate by 13% could increase the duration of exploitation by 220%).

Sensitivity analysis study has been done to show the consequences of an error concerning the data field measurements on the results. The conclusion is that, an error in estimation of hydraulic conductivity is tolerable while the results depend closely on the value of the porosity.

The recommendation given from this study is: injecting the maximum amount of water possible is better. The use of optimisation tools will show the locations and rates of wells.

Keyword

Artificial recharge, well injection, optimization, modeling

1. Introduction

The management of groundwater resources is becoming now a very necessary and important subject because of the increased demand of groundwater caused by the rapid development of the society.

It is important to be mentioned that only 0.6% of the total quantity of water on the earth is fresh and liquid water (not ice or vapour). This quantity corresponds to $8.5 \times 10^{15} m^3$ where 98% of this amount is groundwater. Moreover, half of this groundwater occurs at a depth of more than 800 m below ground surface, where its salt content is often too high and nearly all cases recovery is too expensive. It is so clear that the available fresh water on earth is really a very precious commodity. Water has become also gradually an economic commodity and one of the main “fuels” for development. It now plays different roles in every-day’s life: as a source of water for domestic use and irrigation; as production and cooling water in industry; as an essential element for navigation, fishery and recreation; as a source of energy; as an agent to dispose of sewage and other waste.

Compared with the use of surface water from rivers and lakes, groundwater has many advantages for public and industrial supplies. It has a constant chemical and physical composition, it is free from the pathogenic micro-organisms, so it can be used mostly without any treatment. But in the other hand, from the hydrological cycle we can easily conclude that the average detention time of groundwater surpass a span of 300 years. As a consequence, processes in groundwater tend to be very slow; e.g. horizontal velocities of groundwater are typically within the range of a few metres to a few hundred metres per year. Hence, we can say that the groundwater is a resource, which is **not renewable** in a short term.

One of the fundamental causes of today’s water resources problems is the fact that steadily increasing water demand are not balanced by an equivalent increase of the earth’s water resources. On the contrary, the usable reserves rather trend to diminish as a result of depletion and pollution.

When we over exploit an aquifer, the deficit is then taken from the storage, continuously lowering the groundwater table and allowing such abstractions for a limited period only. That also has bad effects on the environment.

Hence, a rapid intervention of men becomes primordial to save this precious resource of water. This could be done by the implementation of projects in order to have best management of water resources.

In this study I propose a better management of surface water and groundwater using artificial recharge by wells injection. In order to reach this objective, I used some tools of optimisations and simulation for groundwater. This led to minimising the water rate injected in an aquifer located in a region with very important seasonal variations of natural recharge. This optimal solution gave also the number of wells and their locations for defined constraints. Some important results were obtained and there will be discussed later in this rapport.

2. Objectives of this study

In the management of water resources, artificial increasing of the amount of surface water entering an aquifer is practised to allow a larger rate of groundwater abstraction. In many regions all over the world, river discharges show great seasonal variations. The average flow is perhaps large enough, but in dry periods the flow may be too small to provide a proper dilution of waste discharges or to allow abstraction of water needed for drinking or irrigation purposes. These problems may be solved by taking water from the river in wet periods, using *artificial recharge* for storing this water underground in neighbouring aquifers and abstracting it again to supplement low river flows in dry periods.

The reasons of using the artificial recharge, generally say, could be resumed by the following:

1. Purification and equalisation of water quality,
2. Storage of water in wet seasons to be used in dry seasons,
3. Transportation of water,
4. Maintenance of groundwater levels,
5. Disposal of unwanted water (to prevent salt-water intrusion in a coastal aquifer, for example).

“Considering all the variable present in a water resources system, we may observe that some of these variables can not be changed by current technical means (e.g. mean sea level, regional rainfall distribution),others are easily modified by human interference (e.g. groundwater abstraction, groundwater level, surface water storage, soil moisture constant). The later group of variables are called *decision variables*, because the value of these variables can be modified on the basis of decision taken. No rational decisions can be made without specific objectives in mind; and criteria are needed for evaluating to what extent these objectives are satisfied by the proposed or implemented decisions.

Searching for optimal values of the decision variables is called *optimisation*. Also optimisation can be done by trial and error, a methodologically more elegant procedure is followed by so called *optimisation models*. These models maximise or minimise an objective function that states the objectives in mathematical terms. The boundary conditions that have to be satisfied are called constraints” (Van der Gun, 1994).

The objective of this study consists of finding better management of water resources in a region where big quantity of water is available in wet period and not enough of it in dry period. In order to reach this aim, an artificial recharge using well injection is used. Detail about the different methods used for artificial recharge is done in the next paragraph. But let us mention here the advantages of using this method, which could be resumed by:

1. No loss in evaporation as the case in the other method;
2. Less effects on the environment;
3. Can be applied for all aquifers, confined and unconfined, situated at any depth below ground surface.

In this study, I was looking for optimal solution in order to minimise the water injection rate. That means also we minimise indirectly the cost of the project as we will see later in this study.

3. Literature review

There are many methods of artificially increasing groundwater supplies but they may all be classified in two main groups: *indirect methods and direct methods [Ref. 2]*.

3.1 Indirect Methods

It consist of increasing recharge by locating the means for groundwater abstraction as close as practicable to areas of rejected recharge or natural discharge.

The most common method of indirect recharge consists of setting a gallery or a line of wells at a short distance (~50 m) parallel to the bank of river or lake.

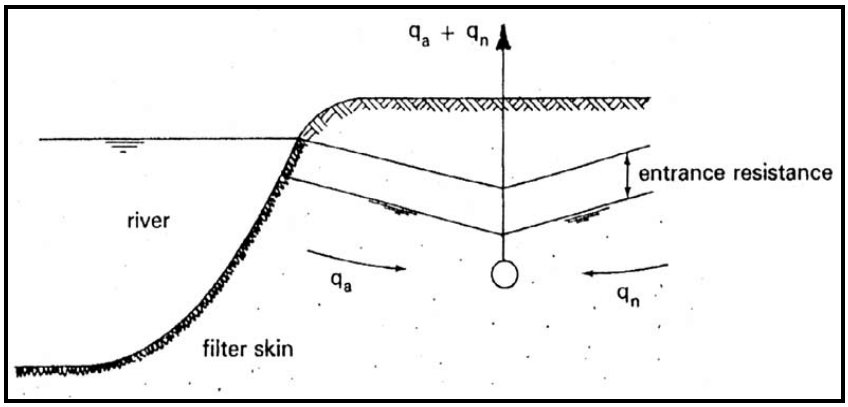


Figure 1: Indirect method of artificial recharge (from Ref. 2).

The Figure 1 shows the indirect method of artificial recharge where the total pumping rate is equal to the discharge coming from the aquifer $\mathbf{q_n}$ and this coming from the river $\mathbf{q_a}$. Deep inspection reveals that success of this method depends on the permeability of the river bed and this is the weak link in the system.

The most serious risk today to the applicability of this method for public water supplies is the present danger of a catastrophic pollution of river water by any accidental event.

3.2 Direct methods

In this method water from surface sources is conveyed, sometimes over big distances, to suitable aquifers where it is made to percolate into a body of groundwater. For direct recharge many methods are available, which may be classified in three groups:

1. When the aquifer extends to or near to ground surface, water spreading may be applied, intentionally by flooding (Figure 2), or by conveying water to basins (Figure 3).
2. An aquifer situated at a moderate depth below ground surface may be recharged with the help of pits and shafts (Figure 4).
3. Where the overburden is very thick, recharge can only be accomplished by injecting the water directly into the aquifer using wells (Figure 5).

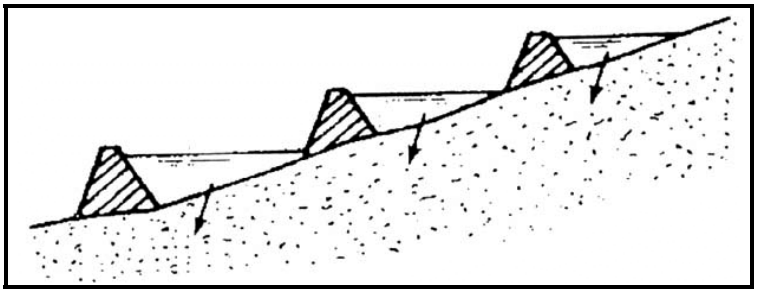


Figure 2: Artificial recharge by flooding (from Ref. 2).

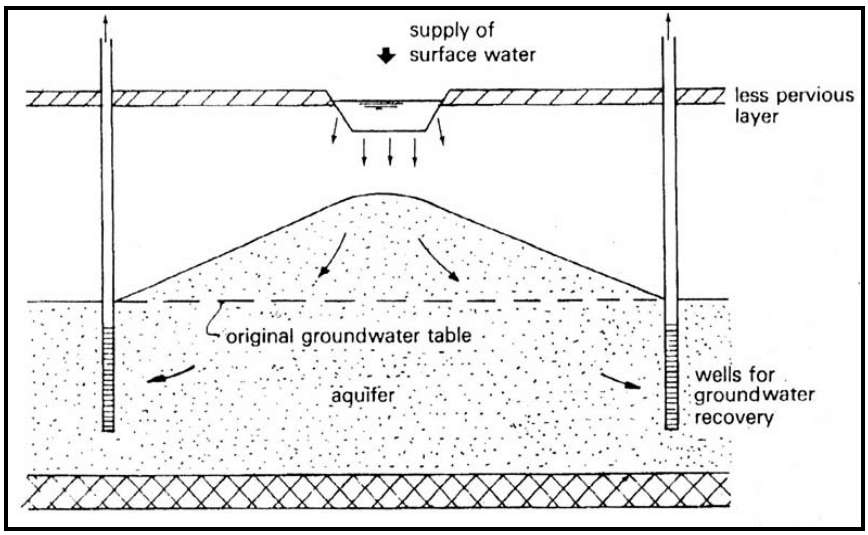


Figure 3: Spreading water with basins (from Ref. 2).

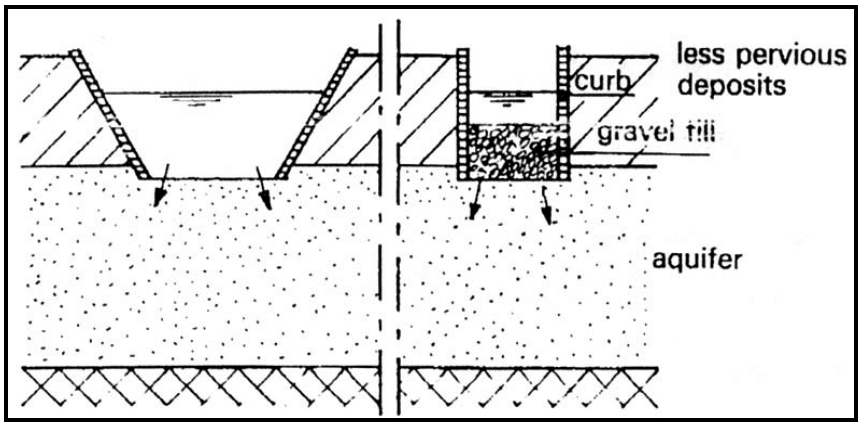


Figure 4: Artificial recharge using pits and shafts (from Ref. 2).

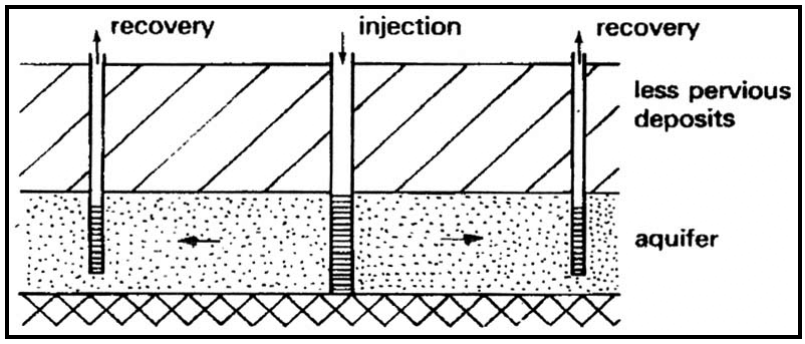


Figure 5: Artificial recharge by using wells injection (from Ref. 2).

3.3 Studies on Optimisation of Artificial Recharge

Concerning the optimisation of artificial recharge, some search studies were made in the IHE of DELFT within the framework of Master Degree Search. I would like to mention here briefly two of them:

1. The first one was done by A. Jonoski where the aim consist of maximising the total abstraction rate while respecting two constraints: a) the drawdown in the vicinity of the system shouldn't overlap 2.5 cm. b) the travel time of the infiltrated water from the pond to the pumping wells should be at least 60 days. The artificial recharge was done by circular pond system and island system (water spreading method). The optimisation, in this study, has been done in steady state [Ref. 3].
2. The second was done by C. K. Vidanaarachchi where the aim was the same as this of the previous study and for the same region but the optimisation was done by using infiltration galleries [Ref. 7].

4. Tools for simulations

The mathematical modelling has become an essential part of groundwater resources evaluations. The execution of a model several times results different scenarios, which could be compared. But this approach does not give the optimal management alternatives. In order to optimise management of water resource systems, a combined model is required. This model sound from one hand considers the hydro geologic aspects, and determines the optimal operating strategy given the constraints and objectives specified by the water manager from the other hand.

Three codes were used here in order to accomplish this study:

1. ***MODFLOW*** *(McDonald and Harbaugh 1988)*: It is a finite difference model developed by the *United States Geological Survey*, and it is able to be used for three dimensional, steady or transient flow simulations.
2. ***MODMAN*** *(MODflow MANagement, Greenwald 1994)*: The purpose of this package is to give the possibility of optimisation of ***MODFLOW*** groundwater flow model. In fact, the MADMAN code is used only to generate the *response matrix* through series of MODFLOW simulations, and for defining the optimisation problem.
3. ***LINDO***: It is an optimisation program recommended for use with the optimisation module. LINDO has the ability to read output from MODMAN (MPS format), to solve then the **L**inear **P**rogram (**LP**) and linear **M**ixed-**I**nteger **P**rogram (**MIP**) and to create output suitable for post processing by MADMAN.

The Figure 6 illustrates the diagram of the optimisation procedure from the beginning till the end.

4.1 Concept of the response matrix

A response matrix, generated on the basis of linear superposition, allows drawdown induced by one or more wells to be calculated with matrix multiplication. For example, drawdown at three control locations, induced by two wells in a steady-state system, is calculated as follows:

$$\begin{vmatrix} S_1 \\ S_2 \\ S_3 \end{vmatrix} = \begin{vmatrix} R_{1A} & R_{1B} \\ R_{2A} & R_{2B} \\ R_{3A} & R_{3B} \end{vmatrix} = \begin{vmatrix} Q_A \\ Q_B \end{vmatrix}$$

Drawdown vector, response matrix, well rate vector
Where:
$\mathbf{S_i}$ = drawdown at control location ***I*** (1,2, or 3)
$\mathbf{Q_j}$ = rate at well ***j*** (A or B)
$\mathbf{R_{ij}}$ = drawdown response at location ***I*** to a unit stress at well ***j***.

Once the response matrix is known, any set of well rates may be entered and the resulting drawdowns calculated. With a response matrix, drawdowns induced by wells are defined as linear combinations of well rates. This allows implementation of linear programming methodology, with well rates as the decision variables.

I limit myself with this brief explanation about the response matrix. For more detail, the reader could consult the MODMAN Documentation and User's Guide (R. M. Greenwald 1993).

5. Hydrological and hydrogeological characteristics

In this section, the hydrological and hydrogeological characteristics of the area will be presented. The area studied is a square 4000 m x 4000 m as shown in the Figure 8. The aquifer considered, which is unconfined, has homogeneous characteristics with the following values:

- the horizontal conductivity is K_h = 50 m/d;
- the vertical conductivity is K_v = 20 m/d;
- the effective porosity is n = 0.2;
- the storage coefficient is S = 0.000001.

The natural discharge is estimated at *NR = 0.00026 m/d* over the total surface of the area. This recharge is applied during 90 days representing the wet period. In the rest of the year this value is nil.

The thickness of the aquifer is 50 m. The ground surface is at '0' level and an impervious layer is located at -50 m (see Figure 7).

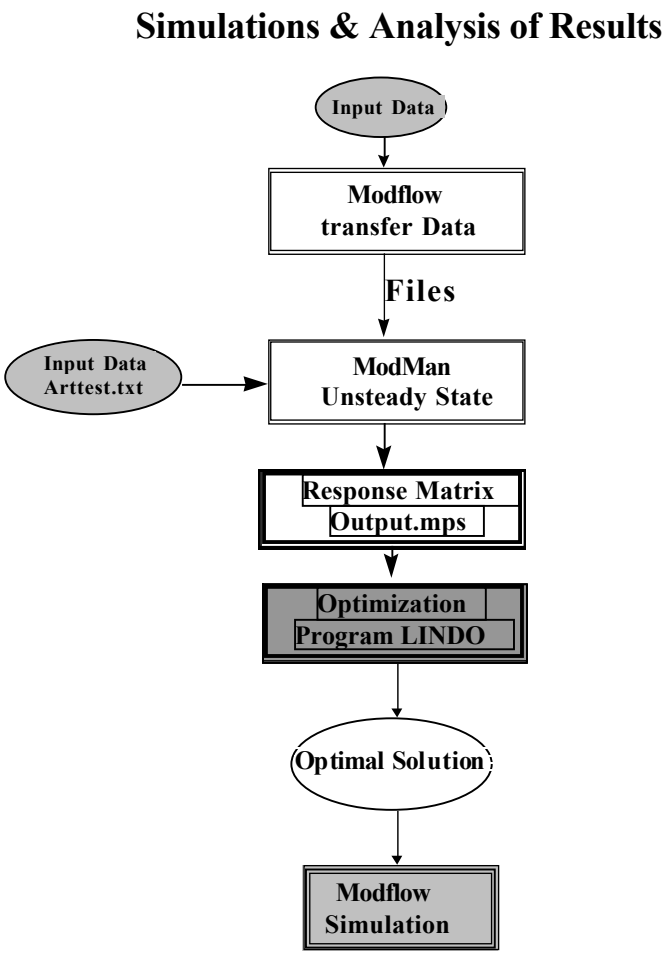


Figure 6: Diagram of optimization procedure

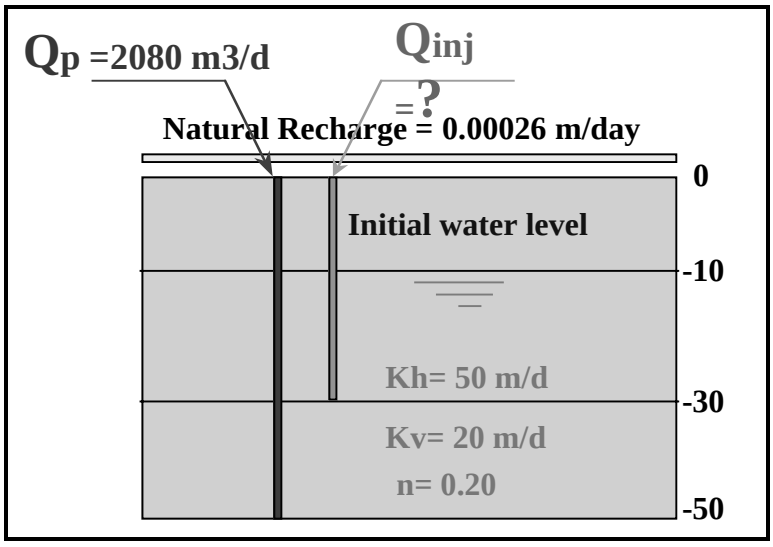


Figure 7: Conceptual model and vertical section

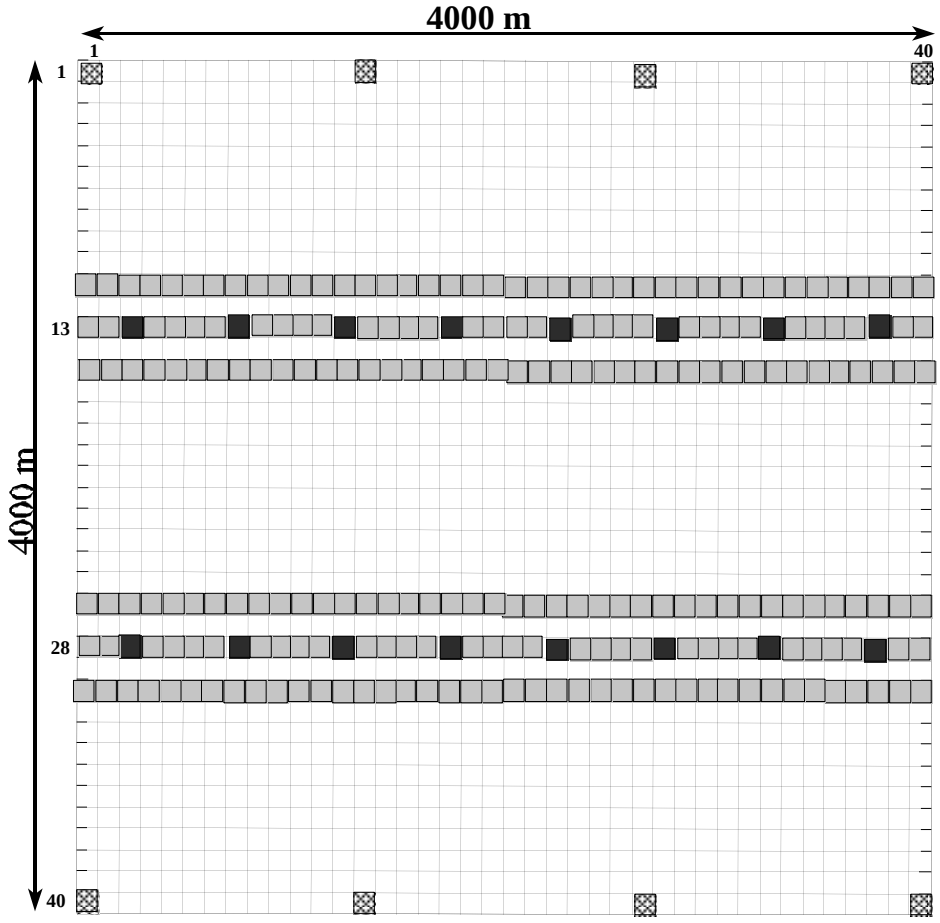


Figure 8: Plan of the conceptual model

6. Description of the mathematical model

The aquifer has been divided into two layers for modelling purposes. The first layer is located between the level '0' and -30 m and the second one is situated between -30 and -50 m. This division allows the implementation of injection wells in the first layer and the pumping wells in the second layer (see Figure 7).

Each layer has been divided to 1600 grid cells (40 x 40). The dimension of each one is 100 m x 100 m. Hence, the total number of cells in the model is 3200 cells.

6.1 Initial conditions

The water table over the total area of the aquifer was situated, initially, at 10 m below the ground surface. This is valid for all performed simulations in this study.

6.2 Boundary Conditions

The studied aquifer is bounded by impermeable layer around its four sides. So, we have here closed boundary type with flow nil. The same conditions are applied in the bottom of the aquifer due to the impermeable base.

7. Simulations and results

All simulations was done in transient state with natural recharge *NR = 0.00026 m/day* applied only during 90 day (wet period). Pumping rate from 16 wells located in the second layer was considered with a discharge Q_{pump} = *2080 m^3/day* for each. So the water balance over one year for the area, *without any artificial recharge*, could be written as following:

IN: NR x Area x Duration = 0.00026 x (4000 x 4000) x 90 = 374400 m^3/year.

OUT:16 x 2080 x 270 = 8 985 600 m^3/year.

DEFICIT:8 985 600 - 374400 = 8 611 200 m^3/year.

Concerning the injection wells, *224 potential well locations* were considered. LINDO should give the optimal number of well on duty, their locations and the rate for each one. The maximal value for each injection well is *4000 m^3/d* and the minimum is nil (that means no well in this location). Note that MODMAN gives the possibility to solve the problem by assigning, for any potential well, fixed rate Q_f (4000 m^3/d for example) or zero (no well) without any possible intermediate value; but, in this study I opt to not use this solution. The reason for that is, if the optimal value of the total injection rate is not a multiplication of Q_f (for example, Q_{opt}=16100 m^3/d) the program will add a value in order to have a multiplication of Q_f (20000 m^3/d for the given example).

The first simulation was performed considering only the natural state of the system aquifer (without any artificial recharge). This simulation showed that the drawdown in the control locations is equal approximately 233 cm at the *end of the first year*. This first simulation gave us the amplitude of depletion which help us later to define reasonable values for the constraints concerning the drawdowns. Also an other important information was provided by this simulation which was the duration of exploitation of the aquifer without any intervention. This simulation showed that it is possible to exploits the aquifer, in the present state, during 12 years only. (See Figure 12).

After the first simulation, six other simulations were done but with artificial recharge these times. The injection rates and the locations of wells has been obtained from *MADMAN* and *LINDO* by defining different constraints values concerning the drawdown. These value are the following : 75, 100, 125, 150, 175 and 200 cm for the eight control locations. The optimisations were done over one year with 90 days of natural *and* artificial recharge but *without* any pumping. The rest of the year (270 days), pumping rates were considered for the sixteen wells (2080 m^3/day for each), but without any artificial or natural recharge.

As an example, the Figure 13 shows the locations of the injection wells which are given by LINDO for the case of $(Ddown)_{max}$ =75 cm. All results about values of injection rates and locations are given in the appendix.

Table 1 resumes the results obtained from these simulations. In this table, three information are given for each value of drawdown allowed at the end of the first year of exploitation.

Table 1: Results of simulations

Drawdown	OBJ (m^3/day)	Total number of used wells	Duration of Exploitation (Years)
75	89777	27	118
100	80803	22	53
125	71830	21	35
150	62858	18	27
175	53886	16	21
200	44915	15	18
233	0	0	12

In the Figure 9 there is two graphs: the first one represents the relation between the number of wells used and the duration of exploitation of the aquifer. The second graph shows the minimum injection rate necessary for different duration of exploitation of the aquifer. These curves merit some comments:

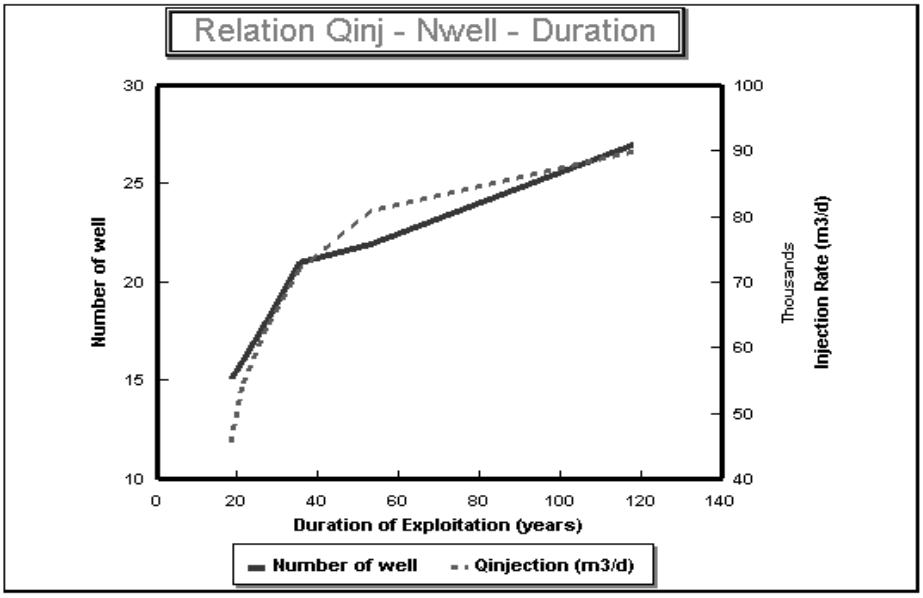


Figure 9

- The shape of the two curves is nearly similar with some small differences. This means that the trends of these curves are the same. Hence, when we minimise the total injection rates, the number of wells will almost be minimised.
- It is obvious the strong non-linearity between the duration of exploitation from one hand and the injection rates and the number of wells on the other hand. If we compare the two first lines of the table 1 we note that an increasing of 13% of the injected rates could increase by 220% the duration of exploitation of the aquifer! This could be very important factor when someone want make economical analysis and study different alternatives for the water management resources.

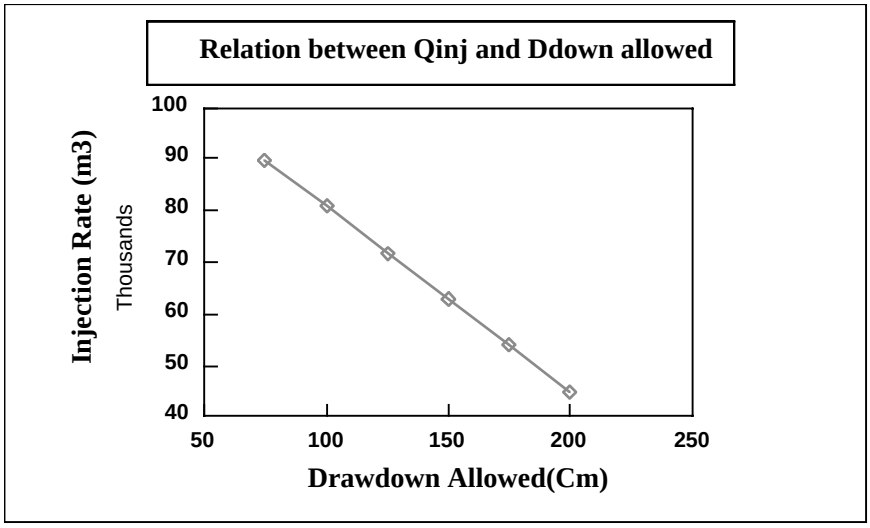


Figure 10

The Figure 10 gives the relation between the drawdown allowed in the control locations and the minimal total injection rate required for satisfying this condition. It is obvious, from this Figure, the perfect linearity between them.

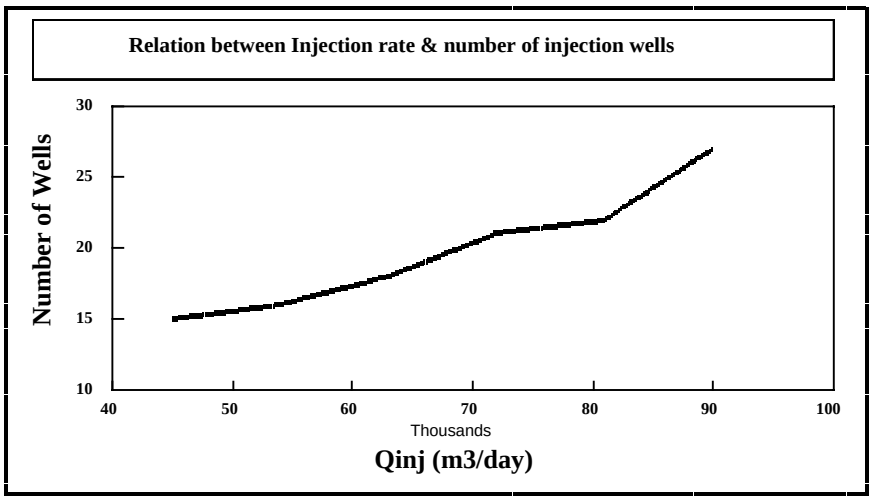


Figure 11

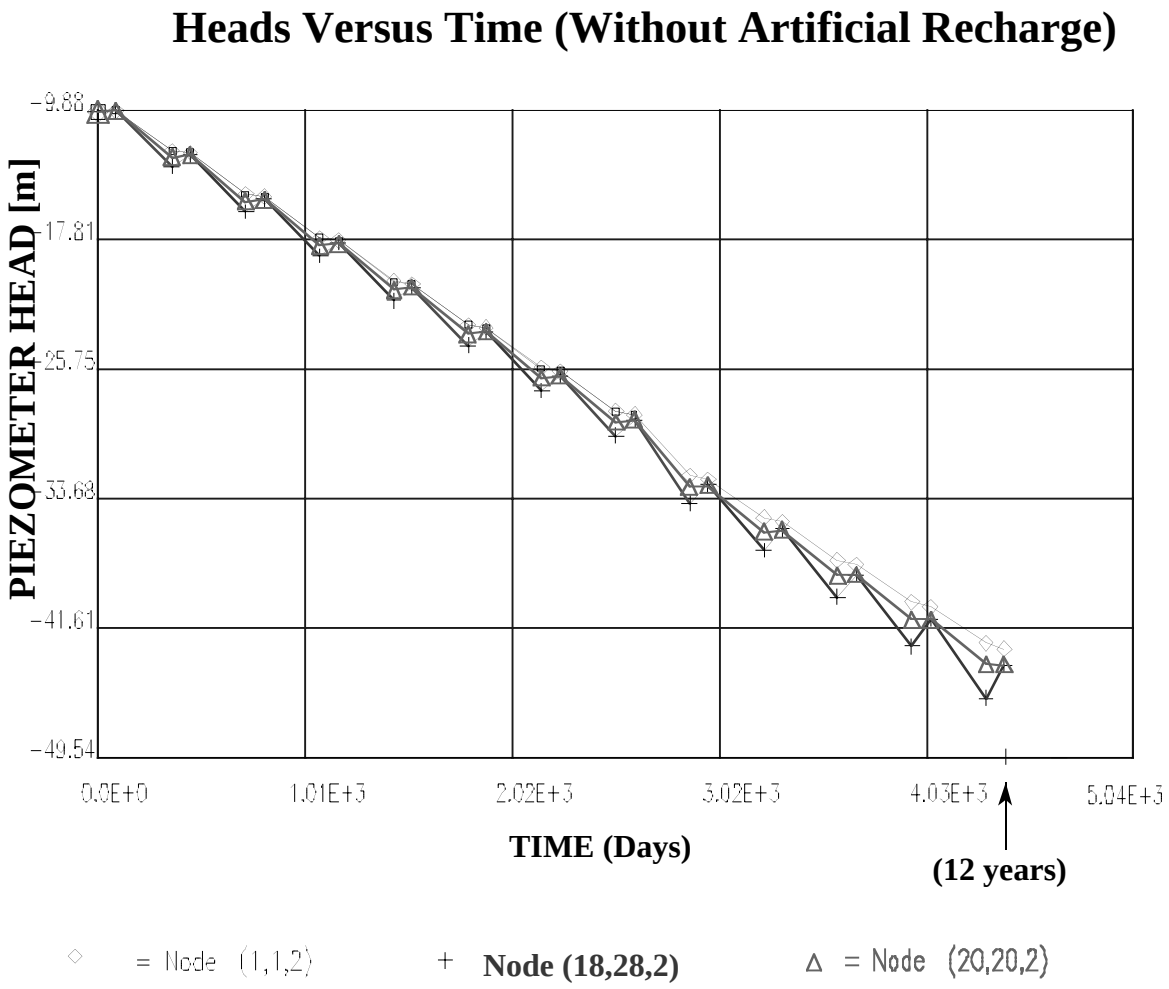


Figure 12: (*Note: The notation "Node(18,28,2)" means : The node located in Row 18, Column 28 and Layer 2)

The Figure 11 illustrates the relationship between the number of wells and the injection rates for the differences simulations. We can conclude that this relation is quasi-linear. The no complete linearity might be due to the fact that the optimal solution gives in some case small injection rates for some well far from the maximum possible value (4000 m^3/d in this study).

The Figures 14 to 19 show the depletion of the water table with the time for the different optimal solutions. In these Figures, we note that curves become steeper when the water levels become below the bottom of the first layer. This is due to the fact that the injection is done only in the first layer. Also I want

mention here that MODFLOW becomes not very accurate, in case of unconfined aquifer, when the relation [(S/H)<<1] becomes no more valid, where S is the drawdown and H is the head. This is related to the assumptions done in MODFLOW which consist of a linearisation of the equations of the groundwater flow for an unconfined aquifer.

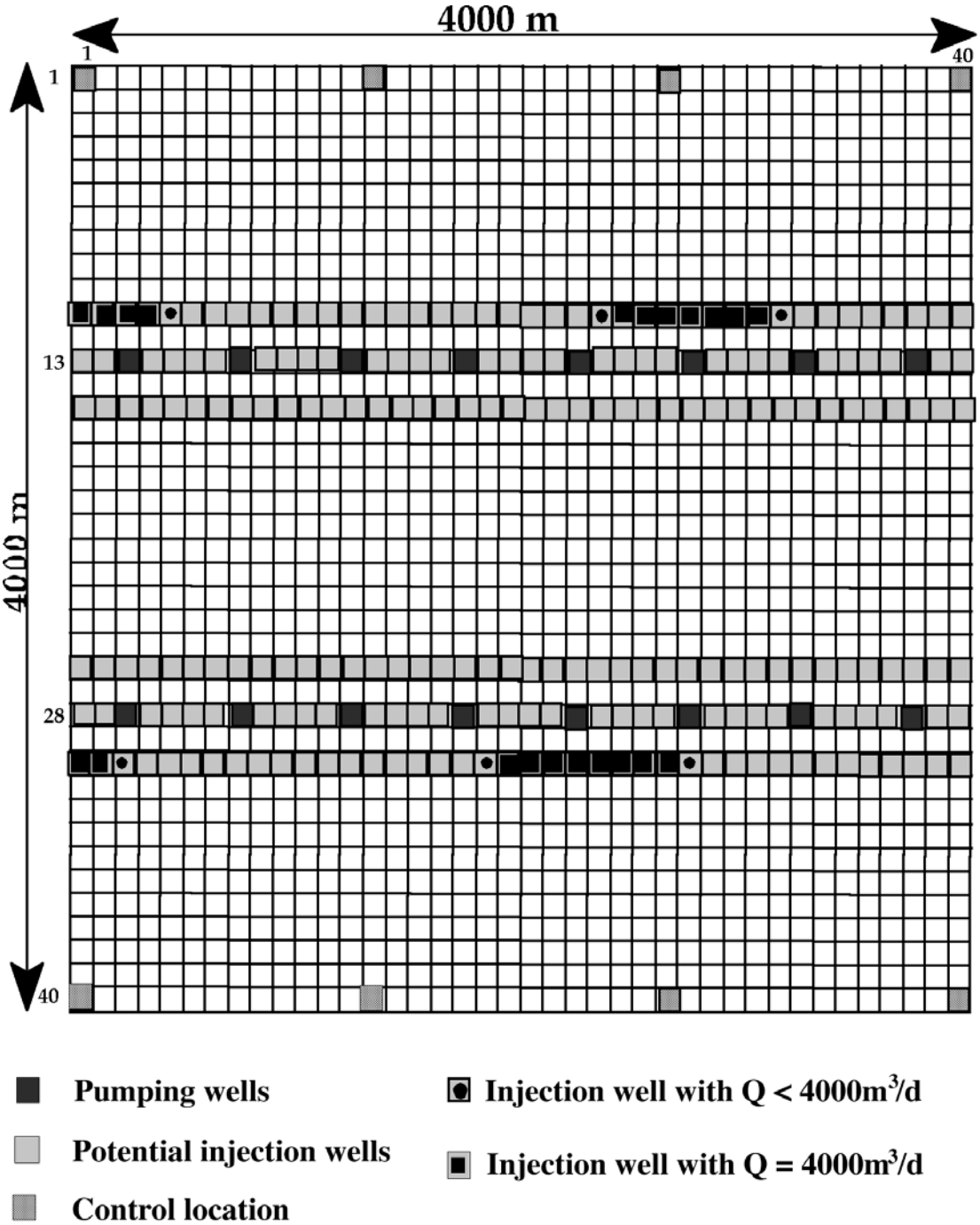


Figure 13: The locations of wells injection for **Ddown <= 75 cm** in control locations

HEAD VERSUS TIME (Drawdown 75 cm)

Qinj = 89776 m3/days *With 27 wells*

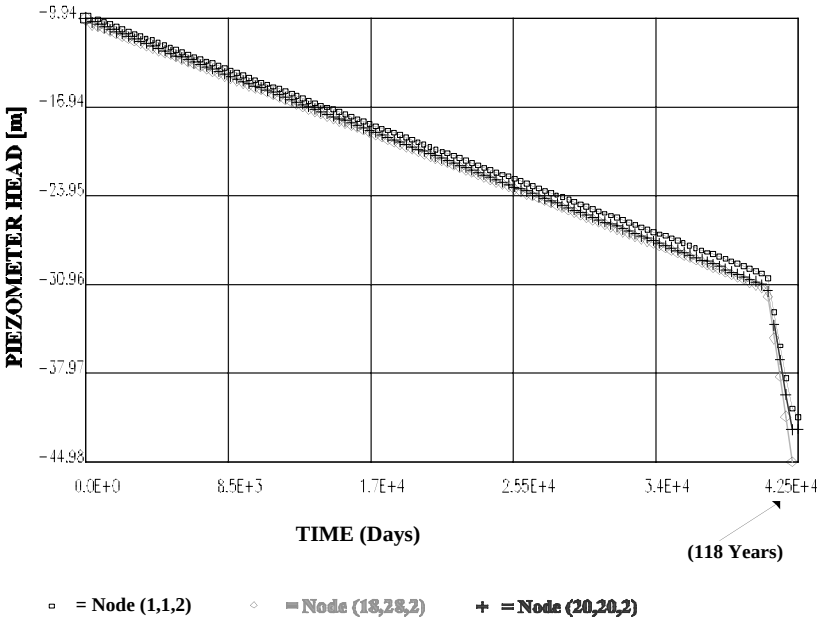


Figure 14

HEAD VERSUS TIME (Drawdown 100 cm)

Qinj = 80803 m3/days *With 22 wells*

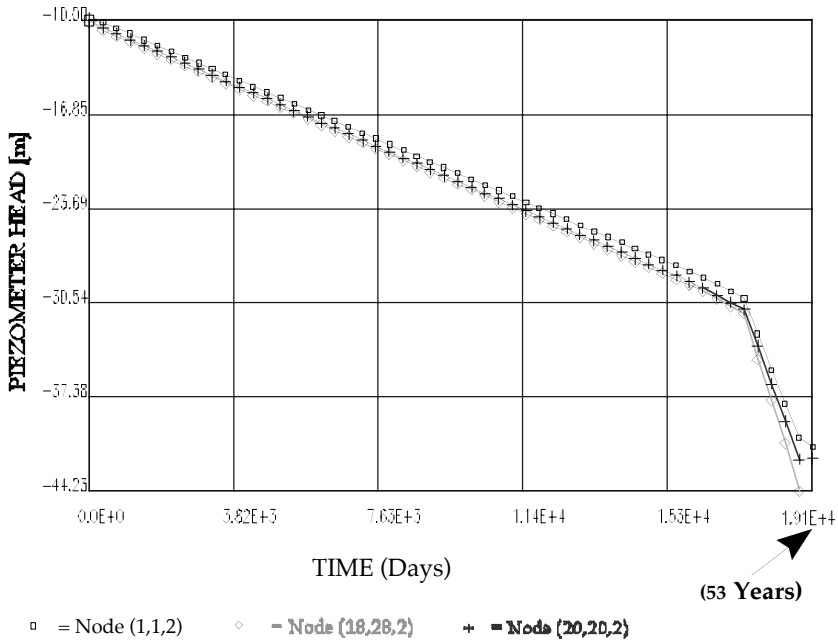


Figure 15

HEAD VERSUS TIME (Drawdown 125 cm)

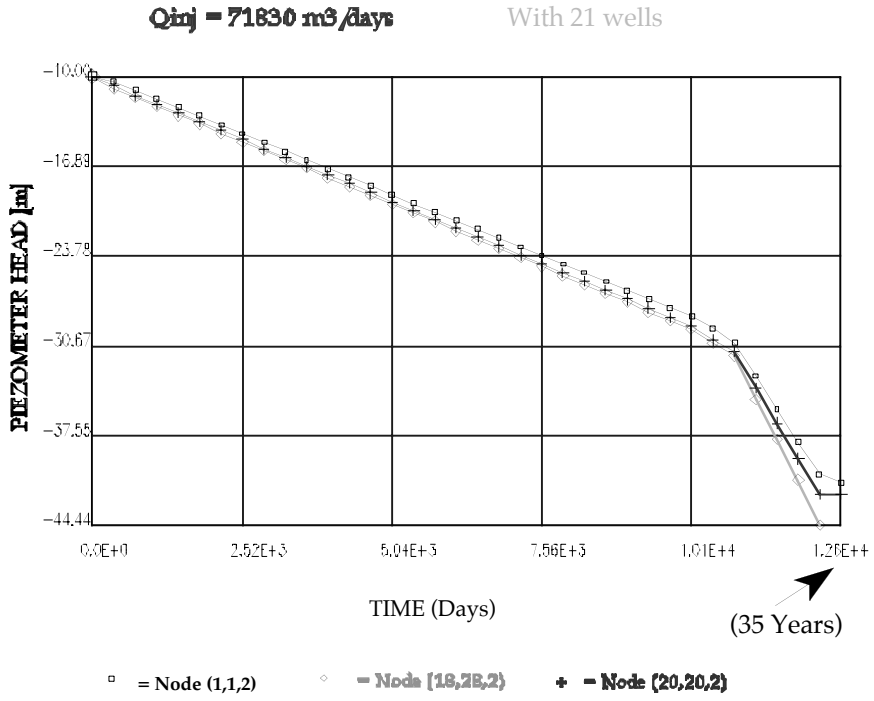


Figure 16

HEAD VERSUS TIME (Drawdown 150 cm)

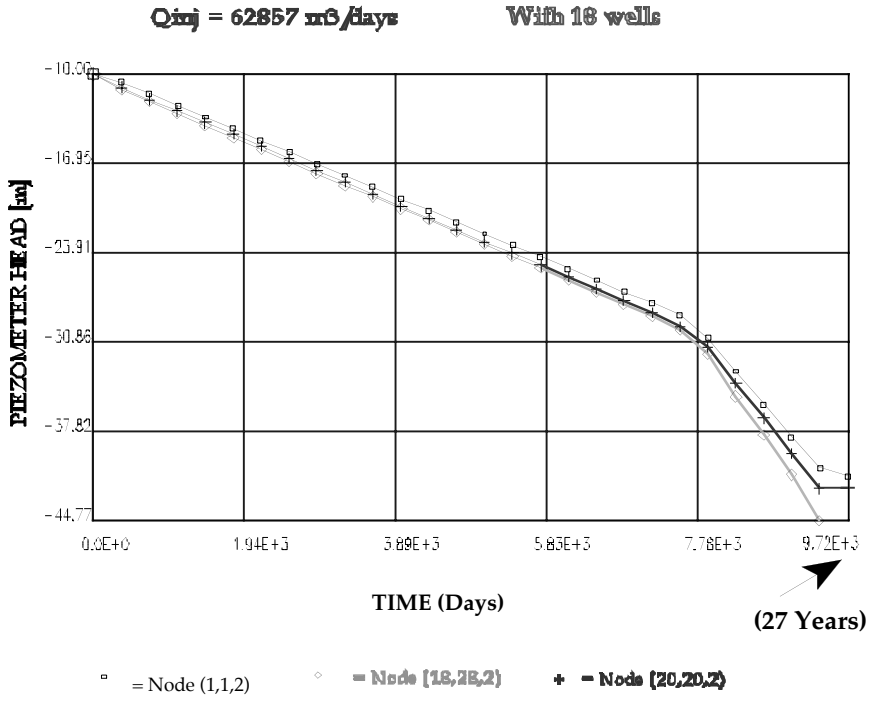


Figure 17

HEAD VERSUS TIME (Drawdown 175 cm)

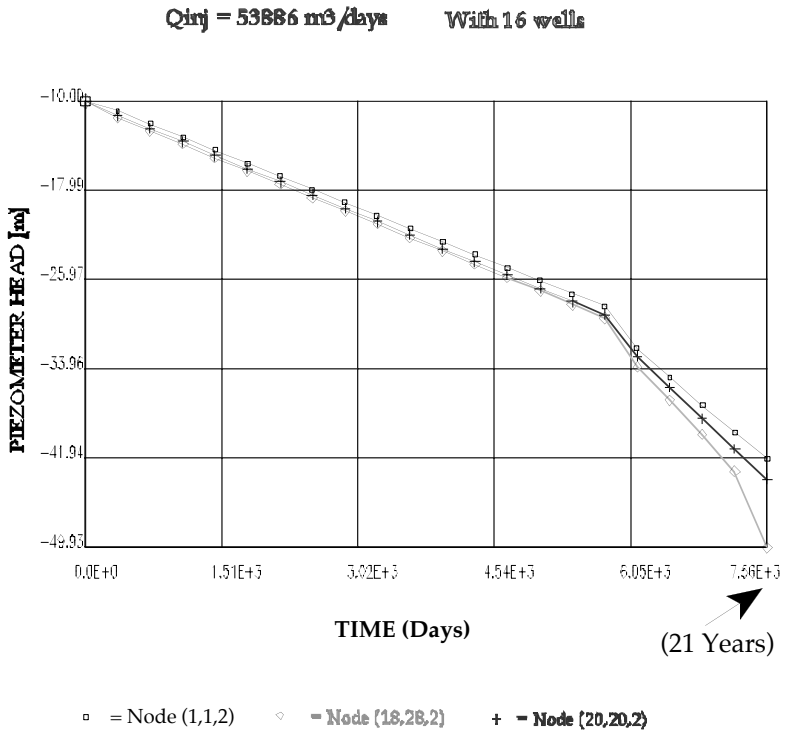


Figure 18

HEAD VERSUS TIME (Drawdown 200 cm)

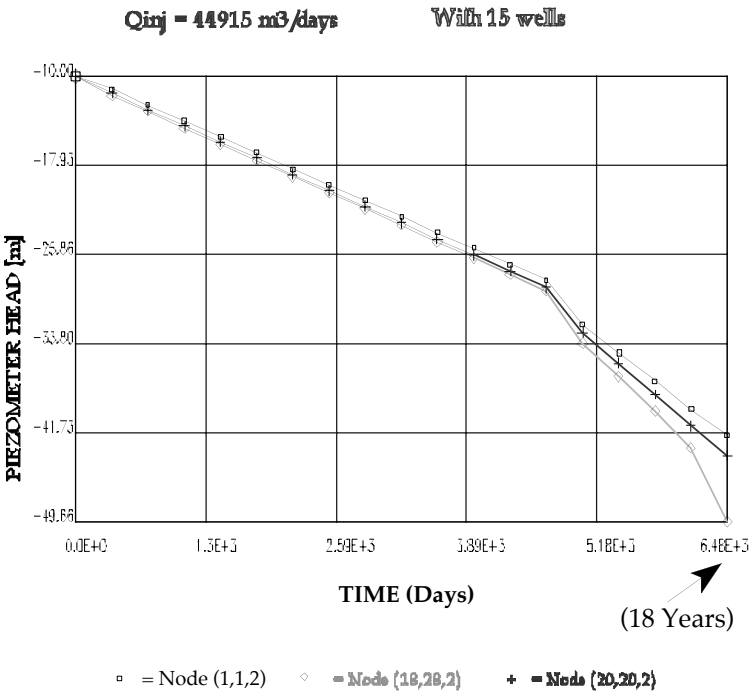


Figure 19

8. Sensitivity analysis

In contrast to surface water, groundwater can not be observed directly because it is hidden inside the rocks of the outer earth crust. The domain where groundwater does occur is extensive, both in lateral direction and with depth. Access for making observations is relatively difficult and expensive. Consequently, available field data are seldom sufficient to derive by simple interpolation a representative picture of the groundwater system. This means that the interpretation depends strongly on geological and hydrological knowledge and judgement. So, errors in estimation of hydraulic parameters of an aquifer may occur.

From what is mentioned above, it may be important to investigate how could an error in field data measurements affect the results concerning the duration of exploitation of the aquifer.

Two parameters has been considered in this sensitivity analysis study: the hydraulic conductivity (horizontal and vertical) and the effective porosity. In the first stage, the hydraulic conductivity was maintained as before (K_h = 50 m/d, K_v = 20 m/d), but the effective porosity has been reduced by 20% (from 0.20 to 0.16). In the second time, the hydraulic conductivity has been reduced by 20% (K_h = 40 m/d, K_v = 16 m/d), and the effective porosity was maintained at n = 0.20.

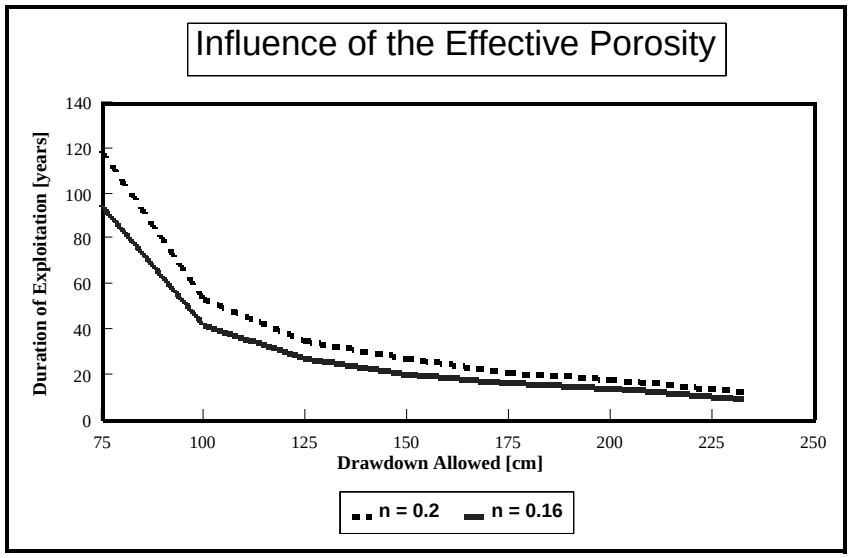


Figure 20: Duration of exploitation for different values of the effective porosity.

Table 2: Influence of the effective porosity

Drawdown	Dur. for S =.2	Dur. for S =.16	OBJ (m3/day)
75	118	94	89777
100	53	42	80803
125	35	27	71830
150	27	20	62858
175	21	16	53886
200	18	14	44915
233	12	9	0

A new set of simulations has been done by using MODFLOW in order to obtain the duration of exploitation of the aquifer with its new parameters. In these simulations the previous values for injection rates were used (obtained from optimisation with K_h = 50 m/d, K_v = 20 m/d and n = 0.20). The reduction of the hydraulic conductivity didn't cause any change in the previous results shown in the **Table 1**. While the reduction of the effective porosity by 20% decreases the duration of exploitation of the aquifer by the same ratio approximately as it is shown in the **Table 2** and **Figure 20**.

9. Conclusion

By approaching the third Milliner, water becomes more and more a subject of conflict between different countries. The reason of that is that water resources are limited and important population occurs specially in developing countries.

Problem of water does not concern only developing countries but also developed ones. The problem in the last is rather problems of quality than problem of quantity even if sometimes leakage of water occurs during drought years. This leakage happened in Europe (France for example) in the last few years where authorities imposed some rationing of water during the summer. Worst situation exists in other place in the world for the distribution of international water resources. This last will be, believe many observers, the first reason of wars in the next century.

"In general, the awareness of people and of politicians for water issues is small, except in those parts of the world where water shortage is strongly felt. In day life, people appear to take water for granted and don't seem to be aware that the limit of water resources development are within reach" (Savenaije, 1995).

Coming back to the present study, the conclusion could be resumed by the following:

1. The effective porosity plays a key factor for the duration of exploitation of the aquifer. So, an accurate information about it is very necessary.
2. The cost of pumping water increases when the water table decreases. So the injection decreases indirectly the cost of exploitation of the aquifer.

From what is mentioned above we can say, "*Prevention is better than cure*". This proverb indicates very well my recommendation in this study: I advise to opt for the maximum injection possible. The non-linear relation between the injection rates and the duration of exploitation could justify this.

Finally, in real case study, a complete economical analysis should be done for the different alternatives possible which was not possible within the framework of this study because of the limited time.

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Appendix

*MODMAN VERSION=3.01 **(OBJ=89776.0 m^3/day)***
*Robert M. Greenwald **No of wells = 27***
*GeoTrans, Inc. **Ddown = 75 cm***

layer	row	col	stress rate	well no.
1	11	1	4000.00513	17
1	11	2	4000.00513	18
1	11	3	4000.00513	19
1	11	4	4000.00513	20
1	11	5	147.31439	21
1	11	23	0.00000	39
1	11	24	572.46649	40
1	11	25	4000.00513	41
1	11	26	4000.00513	42
1	11	27	4000.00513	43
1	11	28	4000.00513	44
1	11	29	4000.00513	45
1	11	30	4000.00513	46
1	11	31	4000.00513	47
1	11	32	162.04395	48
1	28	22	0.00000	186
1	30	1	4000.00513	201
1	30	2	4000.00513	202
1	30	3	2503.54346	203
1	30	18	0.00000	218
1	30	19	721.93182	219
1	30	20	4000.00513	220
1	30	21	4000.00513	221
1	30	22	4000.00513	222
1	30	23	4000.00513	223
1	30	24	4000.00513	224
1	30	25	4000.00513	225
1	30	26	4000.00513	226
1	30	27	4000.00513	227
1	30	28	1669.28857	228

****

*MODMAN VERSION=3.01 **(OBJ=80802.9m^3/day)***
*Robert M. Greenwald **No of well = 22***
*GeoTrans, Inc. **Ddown = 100cm***

layer	row	col	stress rate	well no.
1	11	1	4000.00513	17
1	11	2	4000.00513	18
1	11	3	4000.00513	19
1	11	4	2579.14355	20
1	11	24	0.00000	40
1	11	25	3099.59692	41
1	11	26	4000.00513	42
1	11	27	4000.00513	43
1	11	28	4000.00513	44
1	11	29	4000.00513	45
1	11	30	4000.00513	46
1	11	31	2715.19653	47
1	28	40	0.00000	200
1	30	1	4000.00513	201
1	30	2	4000.00513	202
1	30	3	1205.09387	203
1	30	19	0.00000	219
1	30	20	3994.39038	220
1	30	21	4000.00513	221
1	30	22	4000.00513	222
1	30	23	4000.00513	223
1	30	24	4000.00513	224
1	30	25	4000.00513	225
1	30	26	4000.00513	226
1	30	27	3209.45825	227

*MODMAN VERSION=3.01 **(OBJ=71829.92m^3/day)***
*Robert M. Greenwald **No of wells 21***
*GeoTrans, Inc. **Ddown 125 cm***

layer	row	col	stress rate	well no.
1	11	1	4000.00513	17
1	11	2	4000.00513	18
1	11	3	4000.00513	19
1	11	4	1000.65210	20
1	11	5	0.00000	21
1	11	25	1600.37708	41
1	11	26	4000.00513	42
1	11	27	4000.00513	43
1	11	28	4000.00513	44
1	11	29	4000.00513	45
1	11	30	4000.00513	46
1	11	31	1304.55676	47
1	11	32	0.00000	48
1	30	1	4000.00513	201
1	30	2	3865.15942	202
1	30	3	0.00000	203
1	30	20	3479.06250	220
1	30	21	4000.00513	221
1	30	22	4000.00513	222
1	30	23	4000.00513	223
1	30	24	4000.00513	224
1	30	25	4000.00513	225
1	30	26	4000.00513	226
1	30	27	580.03424	227

****

*MODMAN VERSION=3.01 **(OBJ= 62857.5 m^3/day)***
*Robert M. Greenwald **No of well = 18 wells***
*GeoTrans, Inc. **Ddown 150 cm***

layer	row	col	stress rate	well no.
1	11	1	4000.00513	17
1	11	2	4000.00513	18
1	11	3	3431.52441	19
1	11	24	0.00000	40
1	11	25	112.76048	41
1	11	26	4000.00513	42
1	11	27	4000.00513	43
1	11	28	4000.00513	44
1	11	29	4000.00513	45
1	11	30	3872.43750	46
1	28	40	0.00000	200
1	30	1	4000.00513	201
1	30	2	2523.44238	202
1	30	19	0.00000	219
1	30	20	3302.50342	220
1	30	21	4000.00513	221
1	30	22	4000.00513	222
1	30	23	4000.00513	223
1	30	24	4000.00513	224
1	30	25	4000.00513	225
1	30	26	1614.76208	226

*MODMAN VERSION=3.01 **(OBJ=53885.99m^3/day)***
*Robert M. Greenwald **No of wells 16***
*GeoTrans, Inc. **Ddown 175 cm***

layer	row	col	stress rate	well no.
1	11	1	4000.00513	17
1	11	2	4000.00513	18
1	11	3	1854.92542	19
1	11	25	0.00000	41
1	11	26	2656.83301	42
1	11	27	4000.00513	43
1	11	28	4000.00513	44
1	11	29	4000.00513	45
1	11	30	2416.91406	46
1	28	40	0.00000	200
1	30	1	4000.00513	201
1	30	2	1152.40149	202
1	30	19	0.00000	219
1	30	20	3573.13647	220
1	30	21	4000.00513	221
1	30	22	4000.00513	222
1	30	23	4000.00513	223
1	30	24	4000.00513	224
1	30	25	2231.72241	225

*MODMAN VERSION=3.01 **(OBJ=44915.04m^3/day)***
*Robert M. Greenwald **No of wells 15***
*GeoTrans, Inc. **Ddown 200 cm***

layer	row	col	Stress rate	well no.
1	11	1	4000.00513	17
1	11	2	4000.00513	18
1	11	3	274.12109	19
1	11	25	0.00000	41
1	11	26	1205.75354	42
1	11	27	4000.00513	43
1	11	28	4000.00513	44
1	11	29	4000.00513	45
1	11	30	959.85046	46
1	28	40	0.00000	200
1	30	1	3726.68408	201
1	30	18	0.00000	218
1	30	19	564.04376	219
1	30	20	4000.00513	220
1	30	21	4000.00513	221
1	30	22	4000.00513	222
1	30	23	4000.00513	223
1	30	24	2184.54150	224

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Groundwater Resources of the Nubian Aquifer System

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Abstract

In the Eastern Sahara, in south-eastern Libya, north-eastern Chad, northern Sudan and Egypt the Nubian Aquifer System occurs, which is formed by predominantly continental sandstone of Mesozoic and Palaeozoic age (pre-Senonian strata). Its major structural elements are the Kufra Basin in south-eastern Libya and the Dakhla Basin in south-western Egypt, each with an aquifer system up to 4,000 m thick. Based on effective porosities of 7 to 10 % of the sediments, the total groundwater storage amounts to 150,000 km^3, a giant groundwater resource, which has been developed partially since 1960 in particular project areas in the Kufra Basin in Libya and in major oases of the New Valley in Egypt.

In the frame of a joint research programme on geoscientific problems in arid and semiarid areas, carried out in the eighties by the Universities of Berlin and different partners in the region, the evaluation of the groundwater resources in the Nubian Aquifer System - its development history and utilisation strategy - was one major emphasis of investigation. In that programme, the groundwater research was based on two scientific sectors: isotope technique and numerical flow simulation. The isotopes have proven, that the groundwater in the Nubian Aquifer System was formed by wet Atlantic air masses transported by western drift. Groundwater recharge has taken place during different wet periods in the past. Radiocarbon age dating indicates the groundwater formed in the Late Pleistocene older than 20,000 years and in the Holocene between 14,000 and 4,000 a b.p. This distribution of periods of groundwater recharge is in accord with the Quaternary geological findings in the region as well as in areas in central and western Sahara.

Keywords

Groundwater management, non-renewable groundwater resources, isotope hydrology, numerical flow simulation

1. Introduction

The Nubian Aquifer System is the Sahara's most easterly groundwater province. It covers south-east Libya, Egypt, north-east Chad, and north Sudan with a total area of about two million square kilometres. To the east, the border is formed by basement outcrops of the Nubian Plate, to the south and west by the basement outcrops of the Kordofan Block and the Ennedi or Tibesti Mountains (Figure 1). In the north and north-west, the pore volume of sediment is filled with saline water that entered the system either via an intrusion of Mediterranean sea water from the north or is groundwater that has not flushed out since the sedimentation of marine deposits. This interface between fresh and saline water forms the system's border in the north and north-west and is considered spatially stable in its position although slow movement is conceivable. The Nubian Aquifer System is therefore a broadly closed system. Only in the south-east there is a groundwater inflow from the Blue Nile/Main Nile Rift System (Salama 1985).

The Kufra Basin in south-eastern Libya, north-eastern Chad and in furthest north-western Sudan, and the Dakhla Basin in south-western Egypt are the dominant elements of the aquifer system. Both contain sediments with thicknesses of 4,000 to 4,500 m and maximum aquifer thicknesses of about 3,500 to 4,000 m. Compared to them, the Aswan Platform, which is east of the Dakhla Basin, and the North Sudan Platform, which borders to the south, contain comparatively small groundwater resources due to the low sediment thickness of a few hundred meters only. North of the Dakhla Basin lies the Northwestern Basin of Egypt, with sedimentary thicknesses of over 4,000 m. Only the southern part of this structure, however, is within the Nubian Aquifer System, and is therefore only of marginal importance for the hydrogeology of the study area.

Since the early 1960's, groundwater has been developed to a great extent for agricultural and to a lesser degree for mining purposes in the Kufra Oasis in Libya and in the oases of the New-Valley in Egypt, a

chain of depressions in the Dakhla Basin that runs roughly parallel to the Nile and includes the Kharga, Dakhla, Farafra and Bahariya Oases.

During planning it has been generally assumed that the groundwater inflow from the south more or less balanced the groundwater discharge in the depressions. In other words the groundwater flow was in a steady-state, which would not be disturbed by artificial groundwater extraction. However, hyper-arid climatic conditions prevail in the study area, except in the most southern areas of the Nubian Aquifer System. Groundwater recharge from recent precipitation is only conceivable in mountainous areas or south of the Wadi Howar (Sonntag 1985). Even without precise knowledge of the hydraulic parameters, based on Darcy's law the estimated groundwater flow time from there to the development projects is several hundred thousand years. During this time different wet periods have occurred during which groundwater formation by local precipitation has taken place over the entire area. Due to these climatic changes from humid or semiarid conditions to arid climates and vice versa, the groundwater system cannot attain a steady-state flow.

It must be assumed that even with regional groundwater inflow from present infiltration areas the groundwater in the Nubian Aquifer System is fossil. In other words, it is a groundwater deposit that would be depleted through natural and artificial processes. For this reason, choice of development area and production rate must be planned carefully even during the exploration phase, in order to avoid a breakdown in groundwater exploration projects over short- or long-term.

Responsible use of the groundwater requires a profound study of its origin and formation taking into account the quantitative hydraulic parameters of the aquifer system and the development of the groundwater flow considering extractions already started.

2. Geological Outline

The dominant geological units of the Nubian Aquifer System, the Kufra and Dakhla Basins, have undergone different geological development. The formation of the Kufra Basin began in the Early Paleozoic and was completed at the end of the Lower Cretaceous. Through regional marine transgressions during the Lower Silurian and Upper Carboniferous, which intercalated the far-reaching ccontinental sedimentation, thick, vastly differentiated predominantly Paleozoic sediments are found here. On the other hand, the Dakhla Basin was presumably formed at the beginning of the Cretaceous, at least its southern part. North of the Dakhla Oasis latitude, Paleozoic sedimentation can be found.

The Nubian Aquifer System is subdivided by uplifts (Figure 1): The Cairo-Bahariya Arch separates the Northwestern Basin of Egypt from the Dakhla Basin. The Kharga Uplift forms the eastern margin of the Dakhla Basin. The Uweinat-Bir Safsaf-Aswan Uplift separates the Dakhla Basin and the Aswan Platform from the North Sudan Platform. The Howar-Uweinat Uplift forms the eastern border of the Kufra Basin. A separation of the Kufra Basin from the Dakhla Basin caused by an uplift is not evident. At least since the Mesozoic, the transition area (more or less along the Libyan-Egyptian border) was a common sedimentation area.

3. Hydrogeology of the Nubian Aquifer System

The sediments of the Nubian Aquifer System were deposited in predominantly continental environments. Meandering rivers and deltas were the usual transport mechanism, which were spatially effective in different times. Due to this environmental history, correlation from one aquifer outcrop to the next is generally difficult since sedimentation at one location occurred probably in the same period when adjacent areas were eroded. Furthermore, the different development history of the sub-units of the Nubian Aquifer System is extremely critical for the hydrogeological interpretation, concerning thickness and extension of lithological units.

3.1 Groundwater Volume

Details about the groundwater resources in the Sahara have been published repeatedly. The best known are from Ambroggi (1966), who estimated the total groundwater reservoir of the Sahara at 15,000 km^3, and from Gischler (1976), who includes at least 60,000 km^3. Both could carry out only vague estimates, since at that time the data situation in many areas of the Sahara was still very unreliable. In the Nubian Aquifer System area, imperative geophysical studies on volume calculation were first carried out in the Kufra Basin at the end of the 1960s and in the Dakhla Basin at the end of the 1970s in the course of oil explorations.

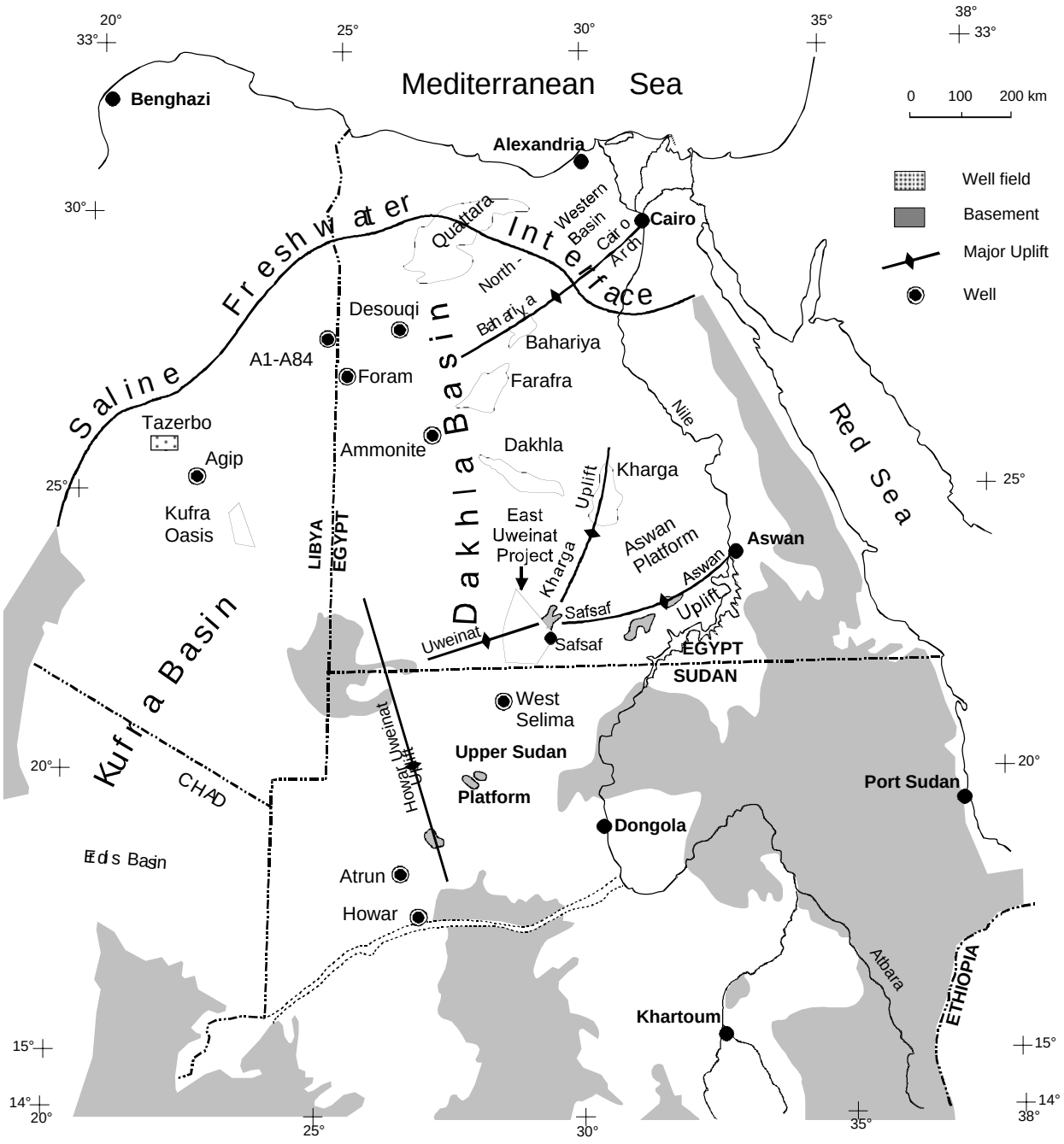


Figure 1: General map of the Nubian Aquifer System area. (Position of saline-freshwater interface after: Klitzsch 1972, BGR 1976)

Based on updated subsurface data, the Nubian Aquifer System groundwater volume can be calculated at 150,000 km^3 Figure 2), a very large amount of water largely exceeding previous estimates. This value corresponds to Nile discharge of 1,800 years or to a water column of 75 meters over the entire study area of 2 mill. km^2. Since it is economically unreasonable and infrastructurally impossible to obtain groundwater from great depths over broad areas of the aquifer system, the total volume of the groundwater resources is only of academic interests. For the interpretation of groundwater ages based on radiocarbon analyses, however, it is very important to have an idea of the groundwater's mean residence time, which is dependent on water volume and discharge rate.

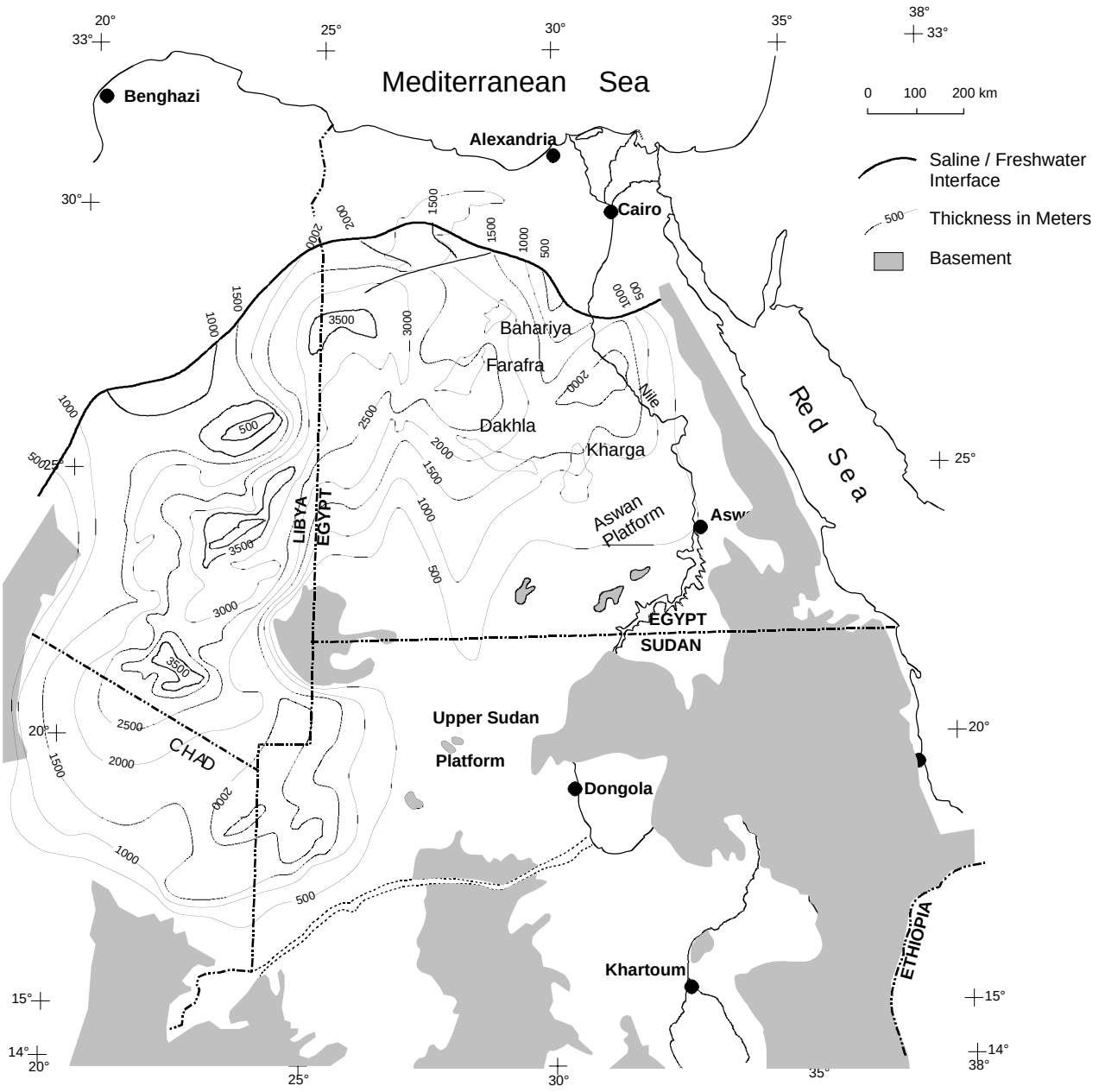


Figure 2: Thickness of the Nubian Aquifer System

3.2 Hydraulic Conductivities

Registering geohydraulic parameters presents a great problem in the study area, since first of all, little to no lateral or vertical hydrogeological data is available in large areas and, secondly, the measurements do not always reach the desired quality standard or are poorly documented. On the other hand, a reasonable homogenous geology occurs in the study area; in other words, the aquifer system is composed of relatively large units with the same lithology.

In order to model groundwater flow and draw-down in the Nubian Aquifer System it was necessary to evaluate the hydraulic conductivity variability of the entire study area: they depict the hydrogeological input data for the numerical simulations. Hydrogeological data processing must be adequately exact to be able to detect lateral changes in transmissivity for each lithological unit within acceptable errors.

The values for hydraulic conductivities were obtained from pumping tests which have recorded only the Mesozoic sediments in the aquifer system. There are no test records available for the Paleozoic deposits. The hydraulic conductivity for these sediments can only be determined through evident comparison with Mesozoic sediments of similar composition. That holds large subjective misinterpretations.

The interpretation of the hydraulic conductivity in the Nubian Aquifer System in a resolution of one order of magnitude is shown as fence diagram in Figure 3. It shows the hydrogeological interpretation with regard to the transmissivity of individual lithological units in the various hydrogeological provinces. Concerning the transmissivity values, this interpretation is the basis input for the numeric simulation of the groundwater flow.

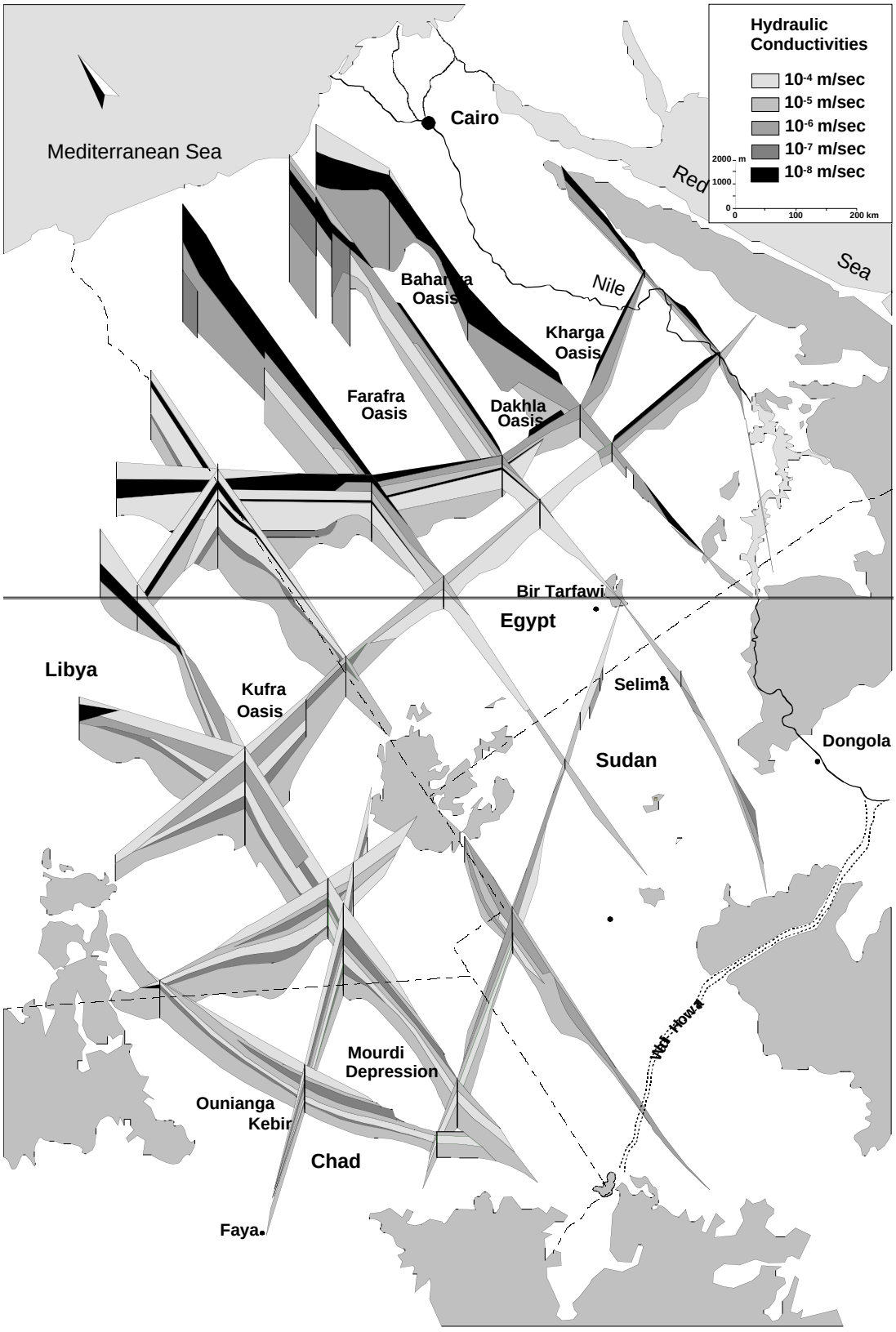


Figure 3: Fence diagram of hydraulic conductivities for the Nubian Aquifer System.

4. Groundwater Formation

There are three possible ways of groundwater recharge:

1. Seepage of Nile water
2. Regional groundwater influx from areas with modern groundwater recharge
3. Local infiltration through precipitation during wet periods in the past

4.1 Nile Water Seepage

Nile water seepage into the Nubian Aquifer System is possible only when both, geological conditions (permeability) and hydraulic conditions (level of the Nile higher than the groundwater table) are favourable. The geological conditions are provided between Wadi Halfa in northern Sudan and Qena in Egypt as well as between Khartoum and Karma (southern rim of the basement outcrops north of Dongola) in the transition zone to the Blue Nile/Main Nile Rift System. Hydraulic conditions in the area mentioned above are only favorable south of the mouth of the Atbara river, in the Dongola area and artificially along Lake Nasser.

4.2 Groundwater Influx from Areas of present Infiltration

A possible groundwater influx mechanism within the Nubian Aquifer System is the regional groundwater flow from areas with precipitation, sufficient for groundwater recharge. It is certainly very difficult, to obtain a hard and fast formula to determine at which precipitation rate groundwater can be formed. This is highly dependent on precipitation distribution and on the climatic, hydraulic and pedologic conditions.

It can be assumed that there is groundwater recharge through infiltrating precipitation on the southern edge of the study area. The flow time of the groundwater from these infiltration areas to the discharge areas in the north can be roughly calculated. Based on rough estimates of the regional hydraulic parameter of the Nubian Aquifer System (groundwater table gradient: $3 \cdot 10^{-4}$, hydraulic conductivity: $1 \cdot 10^{-5}$ m/sec; effective porosity: 10%) with the simple application of Darcy's Law, one arrives at a field velocity of about 1 m/year. Using these Figures, this means that the groundwater from the southern edge of the Nubian Aquifer System to the Qattara Depression in the north would need about one million years. During this time many climatic changes including wet periods occurred, which supplied plenty of precipitation to suffice for local groundwater formation.

4.3 Local Infiltration during Wet Periods in the Past

Isotope analyses (radiocarbon age dating in combination with deuterium and oxygen-18) of groundwater have made an important contribution to clarifying the history of groundwater formation and origin during the Late Pleistocene and Holocene.

4.3.1 Stable isotopes D and ^{18}O

The deuterium and oxygen-18 content (_D and _^{18}O) of the northern Saharan groundwater, the radiocarbon age of which is primarily more than 20,000 years b.p. shows a distinct west-east gradient like in European winter precipitation and groundwater (SONNTAG et al., 1982). This isotope distribution pattern thus indicates that the northern Sahara received winter rains from the western drift before the culmination of the last glacial period, which led to local groundwater recharge. Further south, the groundwater becomes isotopically heavier, which indicates that the southern Sahara always received tropic convective summer rains from humid air masses from the Indian Ocean, the African rain forest or further west from the Gulf of Guinea during past wet periods.

If the piezometric data in the Nubian Aquifer System were considered as a cause for a regional groundwater flow as described by BALL (1927), this flow would run in a north and north-east direction and therewith actually more or less along the iso-contours of stable isotopes. For that reason, a possible regional groundwater flow in the eastern Sahara can not be excluded on the basis of stable isotope contents in D and ^{18}O.

4.3.2 Radiocarbon groundwater age

The age distribution of radiocarbon dated groundwater from the Sahara (Figure 4 presents the variation of the Nubian Aquifer System) shows a long wet period ending approximately 20,000 years ago. Between 20,000 and 14,000 b.p. there was a significant minimum of groundwater recharge representing a semiarid or

arid climate period. Later, after 14,000 b.p., numerous radiocarbon datings register a wet period from the beginning of the Holocene, providing groundwater recharge.

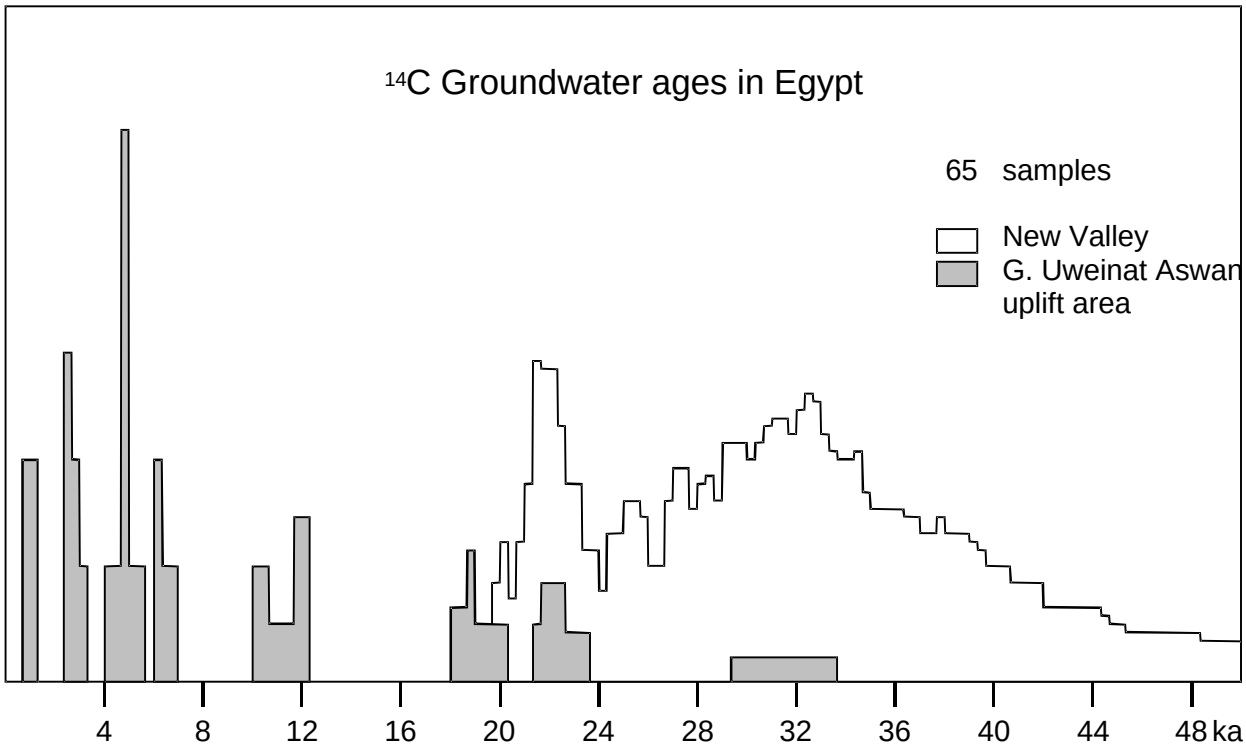


Figure 4: Frequency distribution of apparent ^{14}C ages of groundwaters in the Nubian Aquifer System (Thorweihe 1986).

A significant direction of age increase of the groundwater in the study area based on radiocarbon activities could not be proved, which should indicate the presence of groundwater flow. However, there is also no difference in the radiocarbon content between the groundwater in the unconfined and confined parts of the aquifer. This fact proves, that also in the confined part of the aquifer system groundwater recharge must have taken place through leakage from the confining beds, i.e. infiltration from local precipitation. That stands in superb agreement to the results of the numeric flow model.

The proof of radiocarbon in confined parts allows no quantitative estimate of the groundwater recharge through leakage. The qualitative piece of evidence supports, however, that vertical groundwater transport from the confining beds must be taken into consideration.

4.4 Regional Flow vs. Local Infiltration

The question whether the groundwater encountered today in the Nubian Aquifer System has been formed during former more humid climatic periods by local infiltration or whether it is still flowing from more humid areas in the south, can also be investigated using the dynamics of groundwater flow.

The more traditional view of regional flow goes back to Ball (1927) and Sandford (1935). They found a regular gradient from south-west to north-east, and concluded that groundwater comes by regional flow from some "intake beds" in the south. Although the theory of transient groundwater flow has developed further, Ball's concept was the basis for most of the mathematical flow models, which were set up until today. The considerable transmissivity and the existing gradient support this view. They show clearly that regional flow from south to north exists. But it has been mentioned above, that the travel velocity is so slow, that climatic changes also have to be considered.

In the Nubian Aquifer System the slope of the ground level is in the same direction as the gradient of precipitation, from south to north. This can mislead to the conclusion, that there is continuous recharge. South of the Sahara the conditions are inverse. The climate becomes more humid towards the lower areas, e.g. the Bahr El Arab. Here we find still a very small gradient from the more elevated arid to the more humid southern areas (HEINL and THORWEIHE, 1993). The mathematical groundwater model for the Nubian Aquifer System can help to quantify the ratio of regional and local flow.

5. Numerical groundwater Model

A two dimensional horizontal Finite Element Model was chosen as a basic tool for the simulation of the Nubian Aquifer System. The Finite Element grid covered an area of two million square kilometres. Thus, large distance flow from the Chad to the Qattara depression could be modelled as well as the transition from semiarid climate to the present hyper-arid conditions during several thousand years, which is the flow time of the large distance flow.

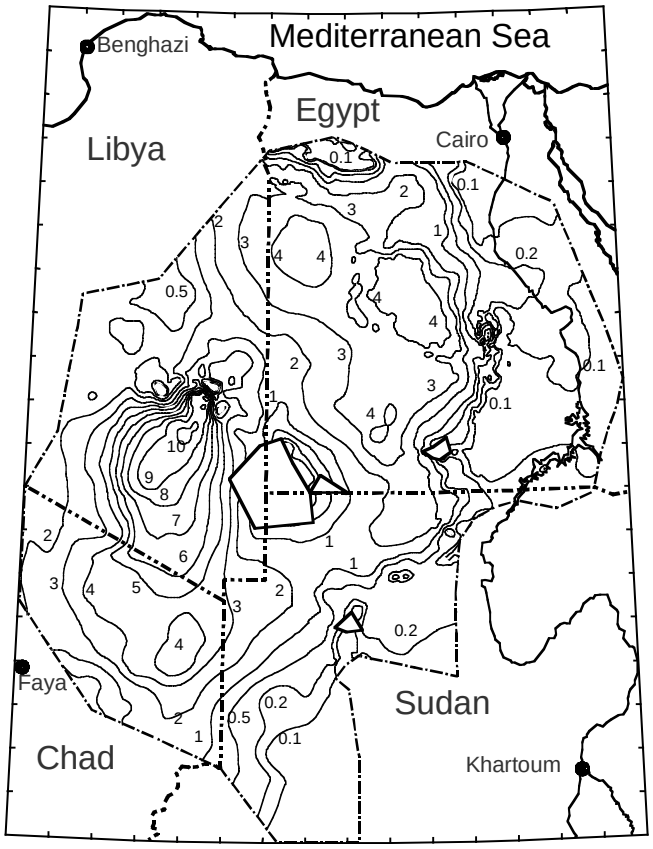


Figure 5: Contour lines of the calibrated transmissivity in 1,000 m^2/day.

The model was designed as a closed system. In this way, reliable no-flow boundary conditions could be identified at the outcrops of the basement, i.e. the natural boundaries of the system. All groundwater flow, recharge and discharge occurred within the model area.

The confined part of the system in the north was considered as “leaky aquifer”, allowing vertical water exchange between the Nubian aquifer and overlaying sediments: Exfiltration in the large Egyptian depressions like Kharga or Dakhla and also possible infiltration from highlands. Horizontal flow in the post-Nubian sediments was not simulated, because available data are not sufficient.

The basic geological input to the model was the hydraulic conductivity (Figure 3). In a first step, the horizontal permeabilities of the different Nubian layers were integrated over the entire sediment thickness resulting in the transmissivity distribution along the axes of the cross sections. In geologically homogeneous areas, the transmissivity values then were attributed to the model elements. During the calibration of the model these values have been modified in certain areas, predominantly SW-Egypt. The final transmissivity of the groundwater model is shown in the contour lines of Figure 5.

5.1 Simulation Results

The simulation consisted of three parts:

1. Steady-state conditions during semiarid climate, 8,000 years ago
2. Long-term simulation of the aquifer behaviour, due to climatic change
3. Short-term simulation of the Egyptian New-Valley Project 1960-1980

All three phases were simulated in the same model. Only different time-steps (100 years and 52 days respectively) were used in the long-term and short-term calculations.

5.1.1 Steady-state filled-up conditions

The climatic change in the Sahara resulted in a delayed lowering of the water table. It was intended to simulate the development of groundwater flow from a situation under humid conditions to the current hyper-arid conditions.

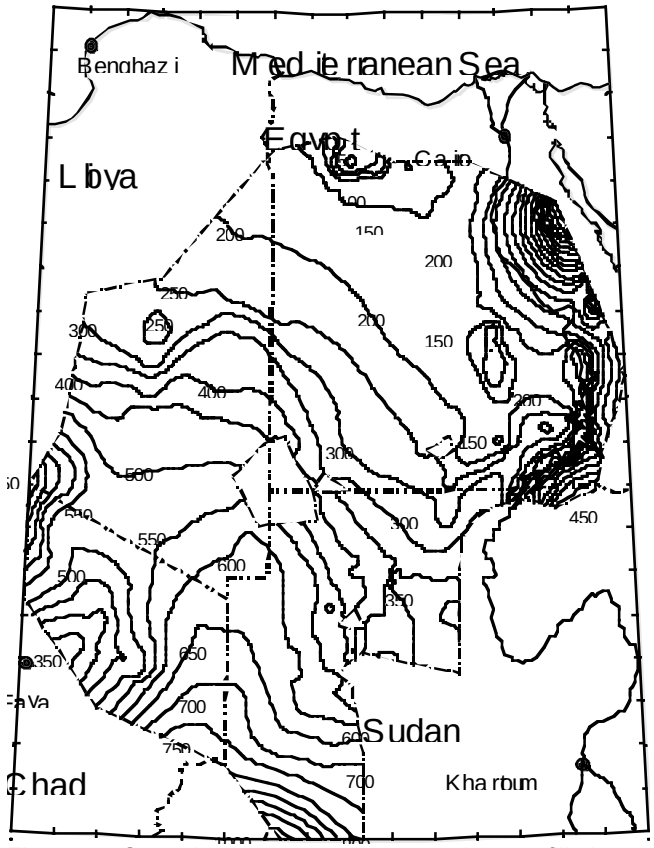


Figure 6: Groundwater contour lines, steady-state filled-up conditions.

Starting point for these calculations was a filled aquifer system that existed at some earlier time (Figure 6). Filled-up conditions mean that the water-bearing sandstone were saturated up to the surface and that the potential water head was located at surface or slightly below. Such a state is likely to have existed some 8,000 years ago. Even under wetter conditions of a semi-arid climate, the water table could not rise considerably above the present ground because it would have been carried away by surface run-off or evapotranspiration.

The resulting groundwater contour lines are plotted in Figure 6. It may surprise, that a recharge of a few mm/year is sufficient, to keep the groundwater level near the surface. This is the maximum flow, the system could carry on a regional scale. Higher recharge would induce higher local flow rates with discharge areas nearby.

5.1.2 Long-term decline due to climatic change

The purpose of the long-term simulation was to show the time scale of the aquifer reaction on climatic change. At the same time it produced initial conditions for short-term simulations of groundwater extraction.

The simulated draw-down shows a different behaviour of the aquifer in elevated and low areas respectively. After the stop of infiltration, 8,000 years ago, the groundwater dropped rapidly in the elevated recharge areas. In the unconfined section, where the initial recharge had been 10 mm/year, groundwater level dropped 60 m in 1000 years in Ennedi and Gilf Kebir. In the Tibesti mountains and the Red Sea Hills it dropped more than 100 m. In the confined part, groundwater level in elevated areas of downward leakage (recharge) dropped as well. On the plateau east of the Kharga Oasis, the draw-down was 60 m in 1,000 years. During the second millennium, when the climatic conditions remained unchanged, the draw-down was much less. Flow conditions were still clearly transient even after 8,000 years.

The steady-state results indicated that even very little recharge can keep the Nubian Aquifer System in equilibrium conditions, but that without recharge in major parts of the system, groundwater would decline.

The transient simulation shows that the Nubian aquifer system already was in an outflow process before the New-Valley project and other development projects started. The decline of the groundwater surface started about 8,000 years ago, but it was slowed down or interrupted by local infiltrations occurring in the central highlands and other parts of the system. Steady-state and transient simulations both indicate that the pre-development situation cannot be considered as equilibrium condition. The long-term transient simulation gives the (transient) initial condition for the simulation of the subsequent extraction projects.

5.1.3 Short-term simulation of the New-Valley Project, Egypt, 1960-1980

In order to get more reliable transient results, the model was calibrated in a limited area and time interval. For this purpose data of the New-Valley extraction and draw-down from the period 1960-1980 were used. The transmissivity distribution resulting from the calibration was already shown in Figure 5.

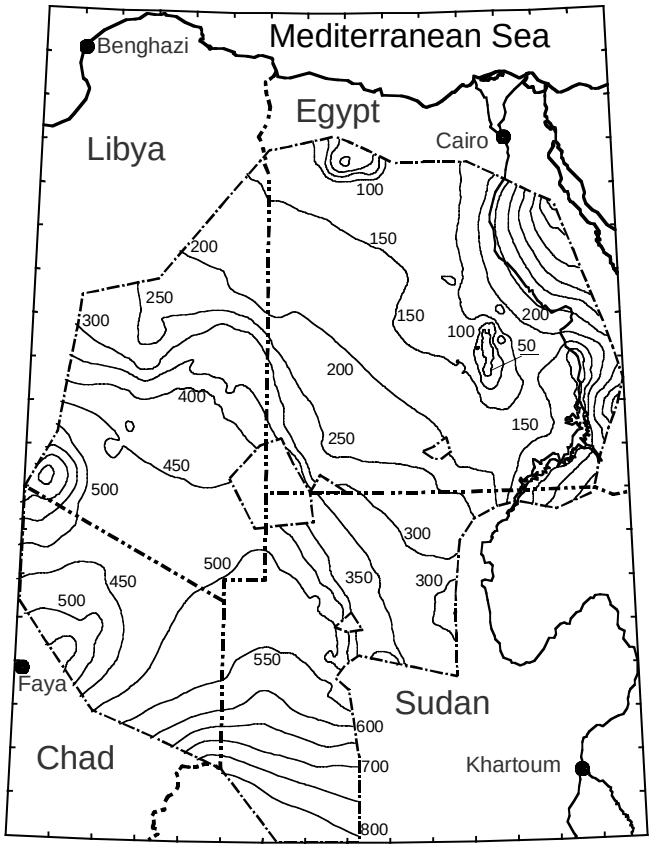


Figure 7: Groundwater contour lines at the end of the short-term simulation (in the year 1980).

The main change compared to the values presented in the final report is a reduction of permeability of the Six-Hills formation by 30%. The leakage coefficients have been reduced considerably. Storativity was reduced in a transition area south of Dakhla and west of Kharga.

The calculated contour lines for 1980, at the end of the short term simulation, are shown in Figure 7.

5.2 Groundwater balance for the transient development

A more general picture of the behaviour of the aquifer system can be obtained by integrating the different flow components of the entire system. Thus, the rather complex picture of groundwater level change, recharge and discharge for each element can be simplified into one diagram.

Figure 8 shows the different flow components, and, in the lower part an integrated volume curve. The total change of storage as well as extraction is shown in a different time scale for long-term and short-term changes (before and after 1960).

In general, the natural discharge does not directly depend on climatic conditions. For a given set of transmissivities it depends on the distribution of potential heads, i.e. the groundwater surface. Since this does not change all of a sudden after transition to arid conditions 8,000 years b.p., discharge continues in the first instant at the same level. The lacking groundwater is replaced from the storage. Only after decline of the groundwater level, discharge starts to diminish and slowly approximates the actual recharge.

In the long-term simulation recharge is reduced 8,000 years b.p. by 1,463 mill. m^3/a from 2,369 to 906 mill. m^3/a (in the Ennedi mountains). Thus, 1,463 mill. m^3/a is taken immediately from storage after the change. After 1,000 years the change in storage is reduced to 906 mill. m^3/a, therefore, groundwater discharge has been reduced to 700 mill. m^3/a. The first part of the storage curve has an exponential shape. After 4,000 years, when recharge in the Ennedi mountains stops, the change in storage suddenly increases to 1,300 mill. m^3/a. At the end of the long-term simulation it has diminished to 550 mill. m^3/a.

6. Assessment of Groundwater Resources in the Nubian Aquifer System

Before evaluating the groundwater resources in the Nubian Aquifer System, the results of the numerical simulation are reviewed. The model revealed some general dynamics of the Nubian Aquifer system:

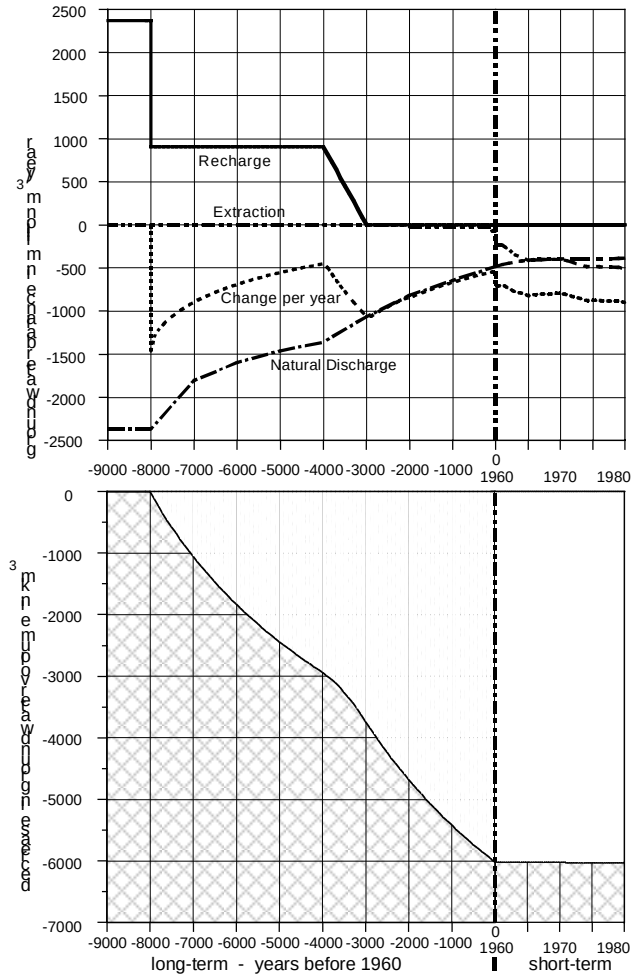


Figure 8: Groundwater balance for the Nubian Aquifer System

Based on paleoclimatic evidence (Pachur et al. 1987) it is assumed, that there has always been a change between humid and arid phases, each lasting for several thousand years. After an arid depletion of the aquifer system, the groundwater is quickly replenished over large areas in the entire unconfined part as soon as humid climatic conditions set in. This filling process ends when recharge and discharge balance each other, i.e. in a humid or semi-arid steady-state. Such state probably existed 8,000 years ago.

It may be maintained with as little as 10 mm/year recharge in the highlands. No recharge does then occur in depressions and plains. Recharge and large scale flow are limited by relatively small gradients. Most of the recharged water flows to discharge areas nearby; only a minor part reaches more distant areas at a lower level. The Nubian Aquifer is a continuous system. However, the regional flow across the system is very small compared to the flow within sub-regions of the system.

The water balance for steady and transient conditions shows a deficit in the confined part, which is compensated by regional flow from south to north because of the higher average elevation of the unconfined part. Under arid conditions, water comes mainly from unconfined storage.

Infiltration, supporting equilibrium conditions, stopped some 8,000 years ago, but continued on a minor scale in different areas and time intervals. Possible subrecent groundwater recharge in central or southern highlands are small and difficult to assess.

Present recharge in Wadi Howar or the Tibesti mountains is only relevant for natural flow conditions in geological time scales. For artificial extraction it is negligible. The river Nile acting as a drainage channel does not recharge the system.The natural system with a timescale of thousands of years is under unsteady conditions. For artificial extraction in timescale of tens of years these may be regarded as quasi steady initial conditions. However, in any case artificial extraction leads to a highly unsteady situation with almost the entire extracted water taken from storage.

Sophisticated small scale extraction schemes require detailed modeling. Boundary and initial conditions for such models may be determined by the regional model. They have to account for the non-equilibrium of the pre-development state. When calculating the artificial draw-down, the "natural" decline of the groundwater level may be neglected. A steady-state calculation of initial conditions, however, will result in transmissivities too high, if it is based on extraction Figures. Still, any prediction of draw-downs for high extraction rates over 100 years will be biased since only small extraction rates or none have been measured over a short period of time.

It has been shown that recent groundwater recharge is negligible, and that extraction from the Nubian Aquifer System is mining of an non-renewable resource. Nevertheless, the large amount of groundwater allows for reasonable exploitation.

In general, the extraction has to be very much restricted to limited areas. Although the groundwater reserves under the Sahara are immense, they are not sufficient for irrigation of large areas. The available groundwater volume corresponds to an average water cover of about 75 m. This has to be compared to the water consumption of green vegetation which is about 1.5 m/year. Even if all the groundwater could be extracted, this would be a very limited supply. Therefore, the extraction has to be limited to a few pumping centres.

These pumping centres form extraction cones. Groundwater from the surrounding 100 or 200 kilometres flows into these cones. The water which had been recharged in the surrounding areas thousands

of years ago is consumed within a much shorter period in the centre of such cones (e.g. New-Valley or Kufra). The disposable water for such a project is not the whole groundwater body, but only the amount of water stored in the extraction cone.

For a feasibility study of a certain project a more detailed groundwater model is needed. The regional model helps to supply boundary conditions for such a detailed model. The predictions of the impact of planned extractions give an idea of the draw-down to be expected. With the results of a detailed model, pumping costs and feasibility can be evaluated.

Acknowledgement

The Nubian Aquifer System has been investigated in the frame of the joint research project “Geoscientific problems in arid and semi-arid areas”, carried out 1981 to 1995 in north-east Africa. It was sponsored by the Deutsche Forschungsgemeinschaft, Germany.

OSS (Observatoire du Sahara et du Sahel) has initiated the programme “Aquifers of Major Basins” for the region of the Saharan countries and adjacent areas. In the frame of this programme, OSS asked the authors to present a study of state of art for the Nubian Aquifer System, which has been submitted in 1996 with the financial support of BGR (Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany). The paper presented here is a synthesis of this study.

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Hydrogeoelectric investigations conducted at Wadi Hodein, Wadi Ibib and Wadi Serimtai, located in the South Eastern part of Egypt

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Abstract

The present work is a result of a hydrogeophysical study for the groundwater exploration in the area under consideration. Three wadis were chosen to be investigated using Schlumberger four-symmetrical electrodes array. The first one is the upstream of Wadi Hodein near to Wadi Abu Saafa where the Nubia Sandstone crops out. A total number of 8 Vertical Electrical Sounding (VES) were carried out and three productive wells were drilled at sites chosen according to the results gained from the VES mentioned above with productivity of 15 m^3/h and salinity of 578 ppm at well number 5, but salinity increases at well number 4 to be 1428 ppm. At well no. 8 it is 1780 ppm as it increases downstream.

Wadi Ibib is the second investigated wadi. It lies about 60 km south of Shalatin town. This wadi runs in the territory of basement rocks, where they are exposed on the surface. Six VES were carried out in the course of this wadi where the sedimentary cover was determined and the salt water intrusion in the wadi was accurately located. The results were matched with the geological and structural factors affecting the area. Proposed locations for drilling were recommended.

Wadi Serimtai is the third investigated wadi. The wadi is located about 12 km to the south of Abu Ramad town, adjacent to Gebel Elba. The trend of the main wadi runs almost N 45°E parallel to the trend of a major fault (Conoco map, 1987). Self potential measurements as well as ten VES were carried out at the Wadi, where a hand-dug well Sararat Serimtai is located in the fractured basement. Three water bodies could be recognized which having low values of true resistivity. The salt water intrusion was located and delineated in the area. Also the direction of groundwater flow was able to be determined easily in the field as well as in the geoelectric section.

1. Introduction

At the far southeastern corner of Egypt, located a small triangular area which is named as Halalb-Shalatin. It is a strategic frontier lies between longitudes 34°30` - 36° 52`E. and latitudes 22°00`- 23° 07` N (Figure1).

The area of study is surrounded by the Red Sea Coast to the East, the Red Sea Mountains and the Nile Valley hydrographic basin to the west and the Egyptian-Sudanese border to the south at latitude 22° 00`.

Recently, the area has got more attention as a promising region for different developmental activities as tourism, fishery, animal husbandry mining and for its importance as a trading route between Egypt and Sudan. The growth of such activities requires a simultaneous strategies for using and development of the available water resources of the area of study.

The present work summarizes the prevailing hydrogeologic conditions via three geoelectric Sections carried out in the vicinity of the area of study.

2. Climate

The area of study is situated within the arid belt where sporadic rainfall may occur from time to time and accompanied by flash floods. Sometimes an extremely rainless or shortage in rainfall may continue for years, reaching six or eight years.

Halaib-Shalatin area occupies a part of the arid zone of Egypt and is characterized by hot summer with an average temperature of about 32"C and cool winter with an average temperature of about 19°C. The net humidity is about 43-49% while evaporation rate is about 16.8 mm./day (table 1).

The rainfall is scarce over most of the year . The average rainfall rates are about 25 mm./year. The rainfall increases southward towards Gebel Elba and Red Sea Mountain Chains. Occasionally rainfall exists in the form of storms which are associated with the south eastern winds which represent the prevailing winds

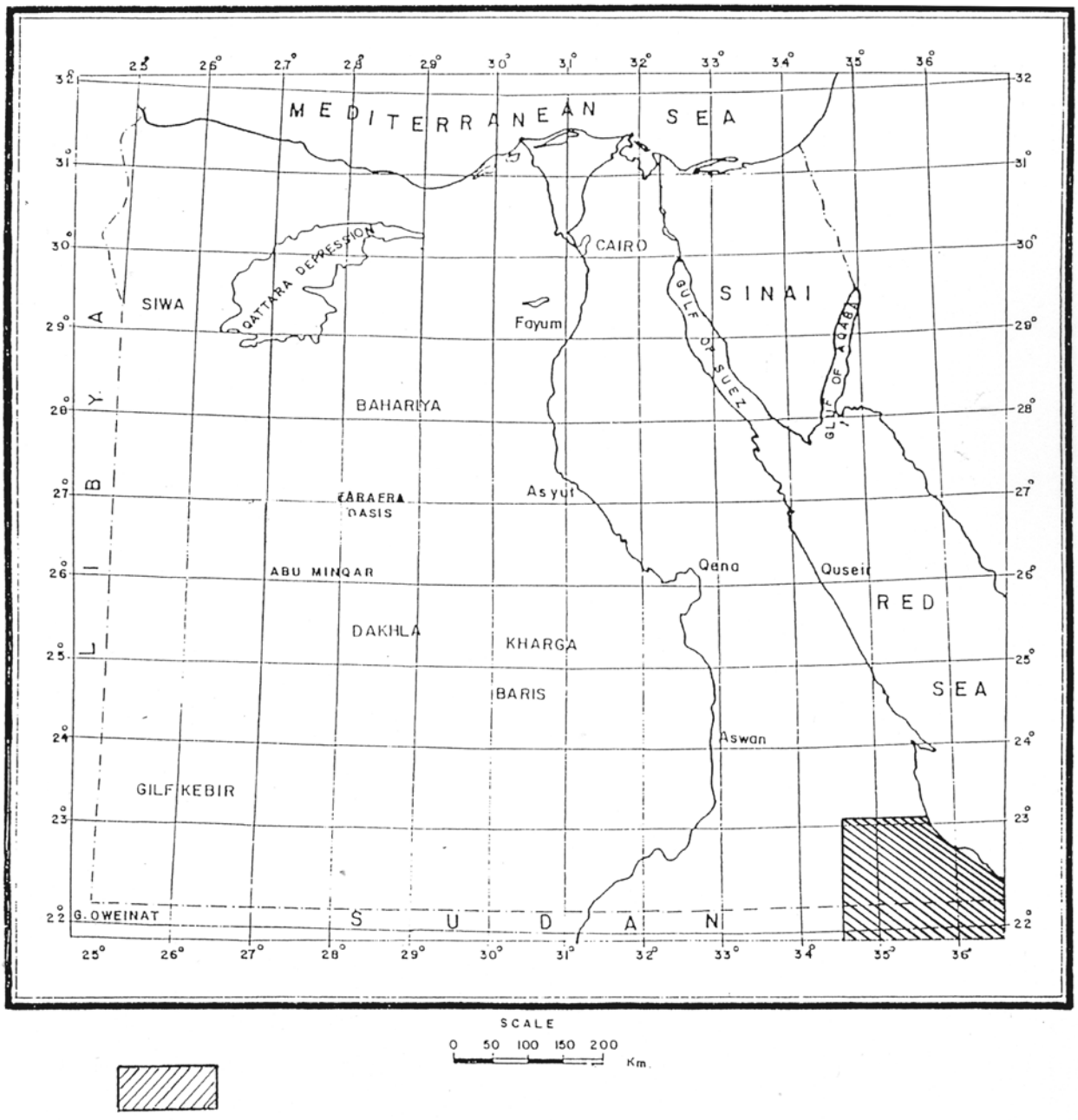


FIG: 1 LOCATION MAP OF THE AREA STUDIED

Table 1: Climatological data of the southern Red Sea region (after Pirard, 1980)

Meteorologic Station	Max. Temp. (°C)	Min. temp. (°C)	Av. Rainfall mm/year	Relative Humidity %	Evaporation mm/day
Ras	32.4	19.1	7.6	43	16.8
Quseir	42.6	4	3.4	49	11 .1

3. Geological Setting

To the west of the coastal zone, the area is covered completely (except area of Gebel Abraq and the upstream portion of Wadi Hodien) by basement rocks, Figure(2), which consists mainly of granites, gneisses, schists and quartzites of Precambrian age. These basement rocks are unconformably overlain by about 430m. of thick sandstone section of Nubia facies which refer to the Paleozoic to Upper Cretaceous ages.

The sandstone section consists of three formations namely; Abu Agag, Timsah and Umm Barmil at the top (Klitzsch, 1986). Towards the northwest, the sandstone in general clips due the east and southeast.

Isolated patches of Miocene sediments are located to the west of Abu Ramad and Halaib areas and mainly consists of alternating limestone and marl of Gebel El-Rusas Formation.

Quaternary sediments of wadi fills and alluvial wadi deposits cover a vast areas. Most of the wadis are filled with alluvial deposits with thickness that varies between a few meters and about 20 meters. Generally, the thickness increases from west to east.

Numerous traverse faults have a NW-SE and E-W directions. On the other hand, a small group of minor faults exists with a NE-SW direction and extend perpendicular to the Red Sea rifting system (NW-SE direction).

4. Hydrogeolocical Setting

4.1 General Outline

The hydrogeology of Halalb-Shalatin area represents the hydrogeological setting of arid zones with scarce rainfall and high evaporation rate. Occasional flash floods events sporadically take place causing mostly annual recharge of the existing previous formations. Due to the nature of those floods, a limited part of rains recharge the subsurface formations as the greater part flows as surface runoff to the Red Sea.

4.2 Hydrogeologic Units

In the study area, four litho-stratigraphic units (Zaghloul et. al. 1997) possess some suitable properties to form groundwater aquifers. These aquifers are from older to younger:

1. Fractured basement rocks of Pre-Cambrian age.
2. Nubia Sandstone of Paleozoic-Upper Cretaceous ages.
3. Carbonate rocks of Miocene age.
4. Quaternary deposits.

4.3 Hydrologeological characteristics of fractured basement rocks aquifer

Outcrops of the basement rocks cover great parts of the mountainous blocks to the west of the coastal plain. Basement rocks consist of granites, gneisses, schists and quartzites.

Groundwater in the basement rocks depends on several factors, among them:

- The weathered mantle which is being formed by means of continuous physical and chemical weathering processes acting on the existing rocks. The thickness of the weathered mantle determines or assesses the rocks as aquifers.
- Fracturing system (faults, joints and fissures) are of secondary origin and create a secondary porosity for the basement rocks with no primary one.

Intrusive dykes which collect groundwater on their upstream sides and direct the movement of such water.

In Halaib-Shalatin area, the above mentioned three factors exist at several localities and many shallow wells are being dug by the local inhabitants. The depth to water in basement aquifer generally varies between 3 m (Bir Bitan) and 22 m (Bir Sararat Serimtai) and the groundwater is fresh where salinity varies between 480 ppm (Bir Gahelia) and 11722 ppm (Salalat Lasilai).

Recharge to such isolated aquifers may be increased by controlling the surface runoff. Figure(3) shows the distribution of the existing water wells.

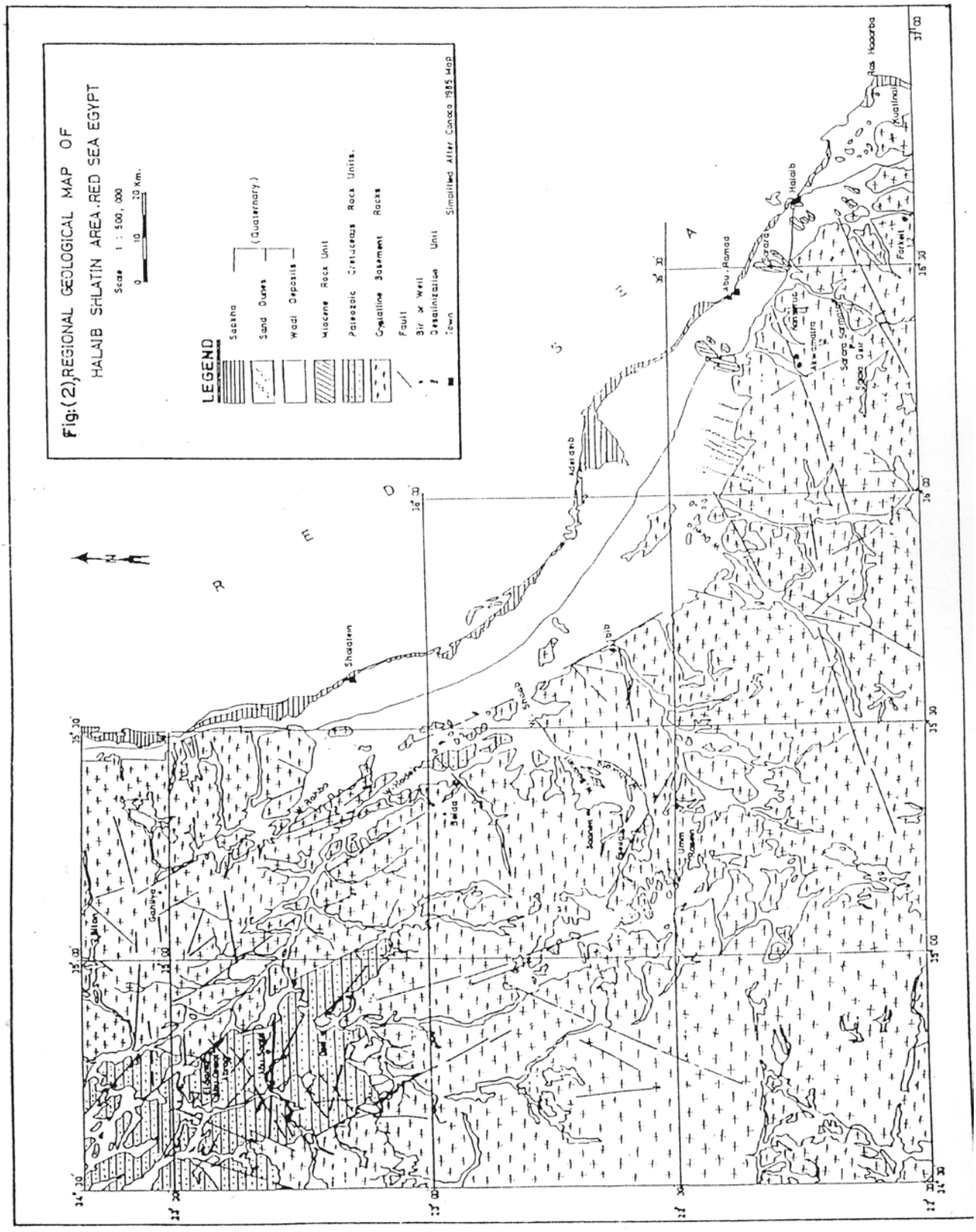


Figure 2: Regional geological map of Halaib Shlatin Area, Red Sea, Egypt

4.4 Hydrogeology of the Nubian Sandstone Aquifer

The Nubia Sandstone aquifer occupies mostly a great area of Wadi Hodien basin. These rocks are faulted and slightly folded which are structural features associated with the Red Sea Rifting blocks. These blocks act as independent aquifers which are drained naturally in the form of minor springs with discharge rates up to 21m^3/h (Abu Saafa springs). Groundwater in the Nubia Sandstone is slightly fresh with salinity varies between 528 ppm (Abu Saafa production well no. 5) and 2810 ppm (Abu Saafa production well no. 8).

The recharge is by direct infiltration of direct rainfall and partly from the surface runoff in the fractured sandstone. This may be proved by the continuous discharge through the springs and wells at Gebel Abrq and Abu Saafa areas. The existing springs are structurally controlled.

4.5 Hydrogeology of the carbonate rocks of Miocene Aquifer

This rocks are located at the south eastern parts as limited areas at Wadis Sarara, Abu Ramad and Emblacit where alternating beds of limestone and marl of Gebel El-Rusas Formation which form a localized aquifer.

The Miocene aquifer is of limited productivity and poor quality which is attributed to the its marine origin of lithological environment of deposition. The depth to water is about 5.72 m (Bir Abu Ramad no. 1) while the groundwater salinity is about 14818 ppm.

4.6 Hydrogeology of Quaternary Aquifer

The Quaternary deposits exist in the form of alluvial deposits, which consist of pebbles, gravels and boulders derived from basement rocks.

5. Geoelectrical Measurements

5.1 Methodology

The surface electric resistivity method is widely used for groundwater exploration. The importance of this method was discussed by many authors such as Keller (1966), Kuenetz (1966), Bhattacharya and Patra (1968) and Koefoed (1968).

The observed field curves were constructed by using bilogarithmic paper with modulus 625 mm. The values of mean apparent resistivity were plotted against the distance AB/2 m. (half the spacing between the two current electrodes A^+ and B^-). Three pseudo geoelectric sections are constructed, namely A-A`, B-B` and C-C`. For each section, the interpreted section is also constructed.

Vertical Electrical Sounding (VES) were measured through wadis mentioned before, oriented parallel to their main course. The Schlumberger Symmetrical Four Electrodes Configuration was used. The Number of measurements was not less than seven ones per period cycle. Each individual reading was measured twice by changing the current intensity. The difference between both results of pt for each measured point is less than 5 % and the mean value was calculated. Double measurements for two successive points for overlap for each successive segment of the observed field curve were done. Figure 3 Shows the site locations of these VES. The data gained were interpreted both quantitatively and qualitatively.

The main task of the present work was to investigate the water content of the water-bearing layers, or in the fractured bed rock aquifers, its real extension, its quality and quantity and the prevailing hydrological and hydrogeological condition.

Two techniques were used for quantitative interpretation of the measured VES. The first one was by using Pilaeve Catalogue and the models obtained for each observed curve were refined by using computer technique. The second technique - by using computer- was by using computer programs (Zohdy, 1989 and Resist, 1988).

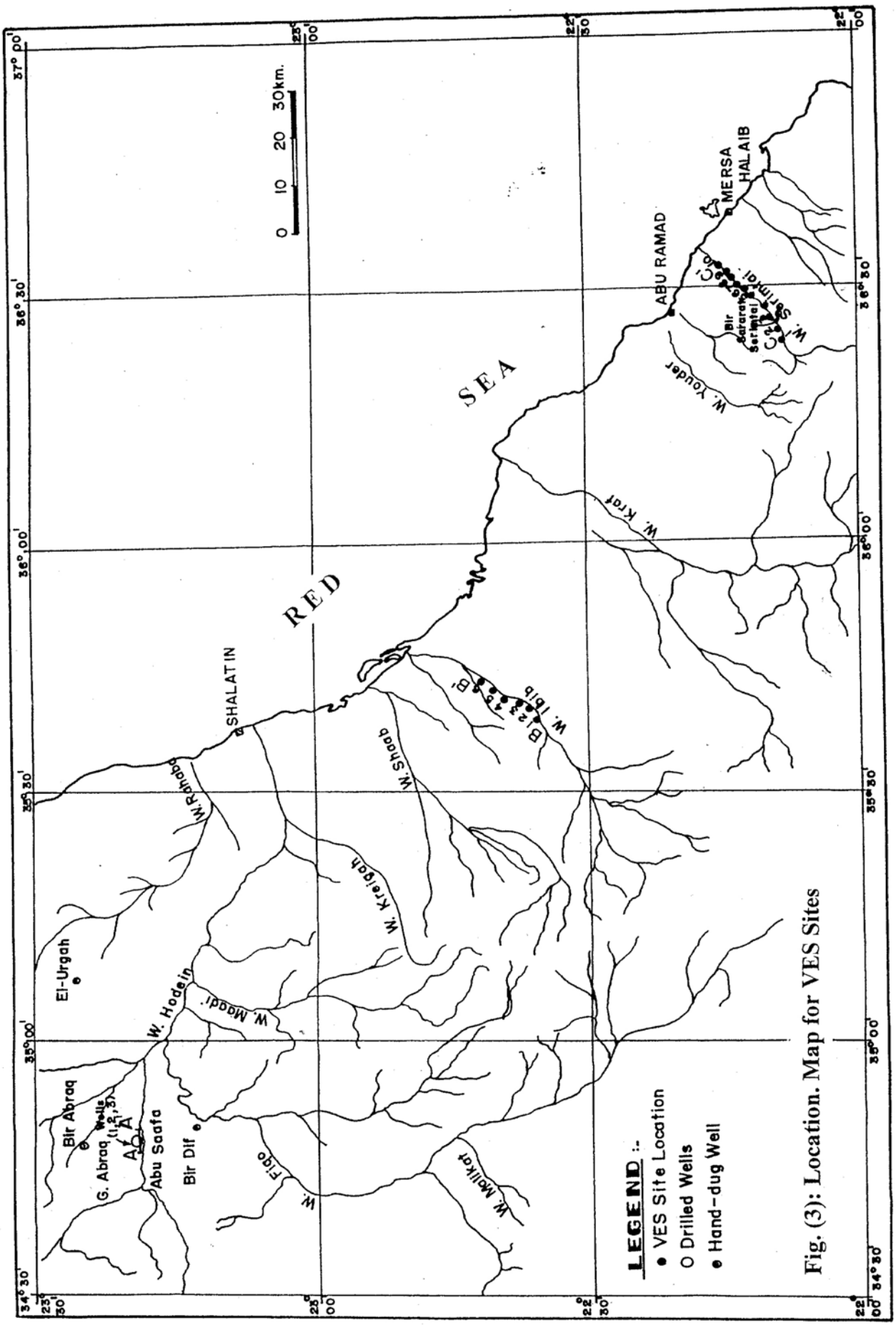


Fig. (3): Location. Map for VES Sites

5.1 Wadi Abu Saafa

Wadi Abu Saafa is the western extension of Wadi Hodein From its upstream direction. This wadi is considered as one of the most important wadis that runs in the sandstone territory due the west of wadi Hodein as the latter runs in the basement complex region . Three natural springs are present in the area and are called Ayoun Abu Saafa (that lie at the intersection of longitude 34° 43' 54 and latitude 23°18 6 and lies in the proper sandstone region where Um Barmil Formation (Kub) and timsah formation (Kux) of the upper Cretaceous age are the most dominant outcropping sandstone formations (Conoco Map, 1987) There is a contact fault that trend N 30° W and separates the sandstones and the basement complex rocks that outcrop in the area from its eastern side. Wadi Abu Saafa runs almost E - W at its upstream then merges to run S 30° E to Join Wadi Dif that lies south to it, then heads towards Wadi Hodein.

This studied wadi was planned to investigate and to delineate its groundwater potentialities in order to be used for drinking and irrigation purposes, if possible, as water is badly needed in this area.

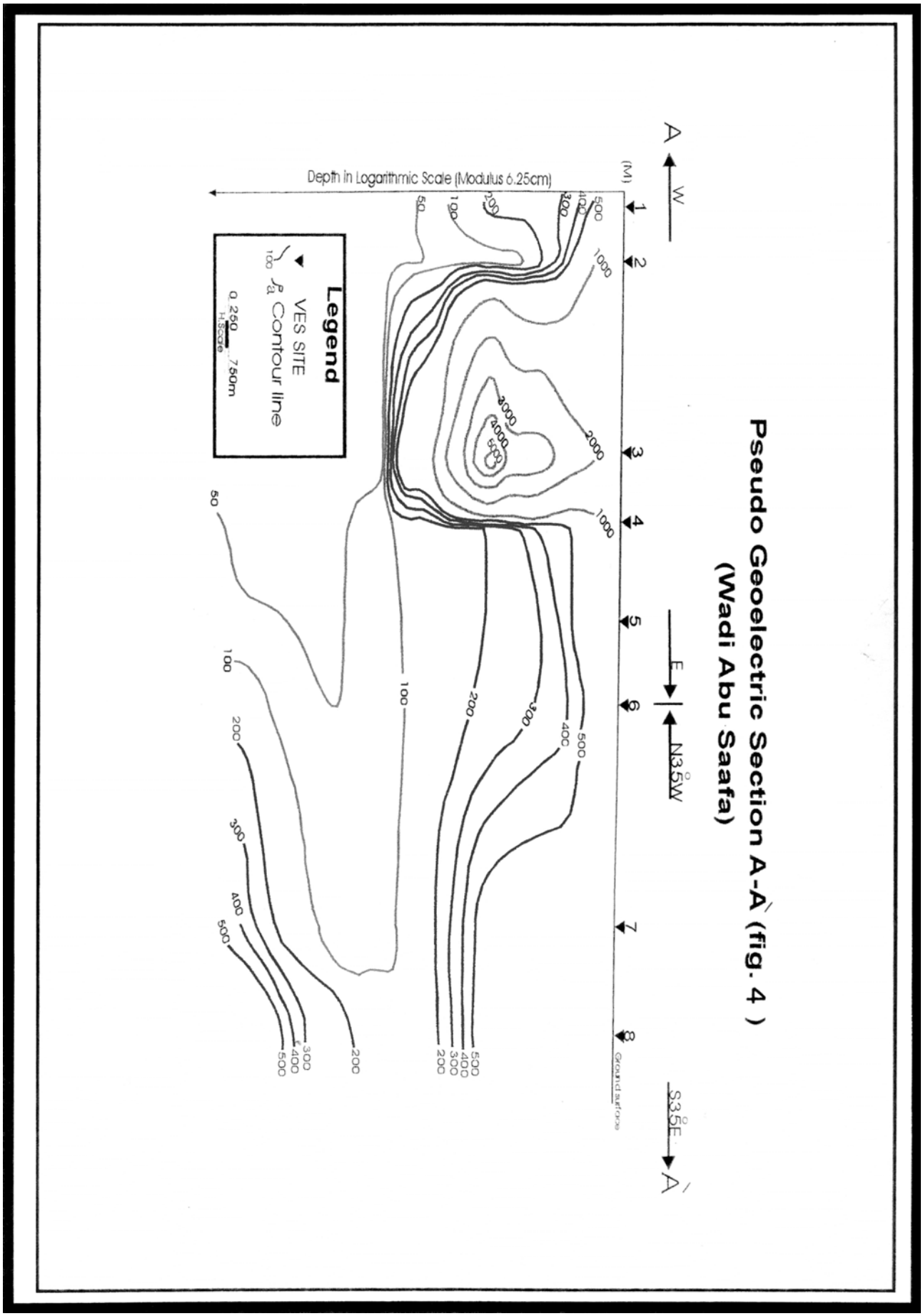
5.1.1 Geoelectrical Investigations:

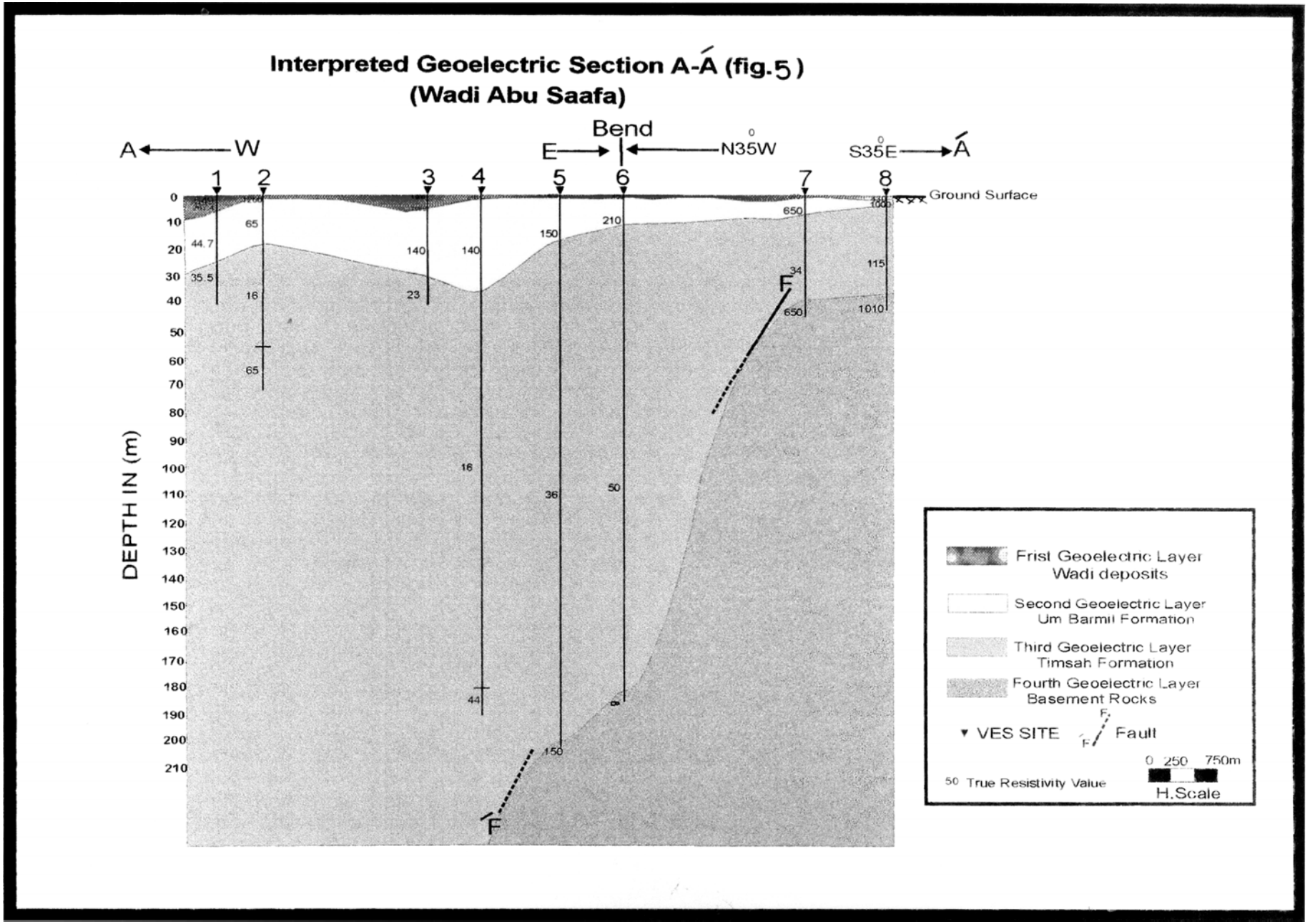
Many VES were carried out to cover the area between Ayoun Abu Saafa and the entrace of Wadi Dif, from which eight VES (Vertical electrical soundings) are selected to represent the area of study of this present work. The promising results obtained from this geoelectrical study has encouraged the decision to drill some exploratory/ productive wells in the area studied. Table 2, presents the quantitative interpretation for these VES.

Table 2: Quantitative Results obtained for the interpreted geoelectric section A-A' (Figure 5).

VES No	Trend & Type	1st Geoelectric layer		2nd Geoelectric layer		3rd Geoelectric layer		4th Geoelectric layer	
		Thic. (m.)	*ρt (Ωm)*	*Thic. (m.)*	*ρt (Ωm)*	*Thic. (m.)*	*ρt (Ωm)*	*Thic. (m.)*	*ρt (Ωm)*
1	E-W QQ	0.6 6.3	649.1 267.4	17.7	44.7	∞	35.5	____	____
2	S75°E QH	0.85	1260	17.15	65	35 ∞	16 65		
3	N60° W KQ	1.45 3.65	1900 7500	24.9	140	∞	23		
4	N60°W QH	1.50	600	33.5	140	145 ∞	16 44		
5	S80°E QH	1.40	600	16	150	182.5	36	∞	150
6	N75°E QH	1.30	480	9.8	210	168.5	50	∞	∞
7	S30°W KH	0.38	400	6.22	650	31.4	34	∞	650
8	E-W KH	0.21	430	3.59	1000	31.2	115	∞	1010

Noteworthy that the sites of drilling were at VES sites numbers 1, 3, 5 and 8. The last site was drilled to get a dry hole that would locate the eastern limit of the water-bearing layers. In order to delineate the vertical and the horizontal extensions of the geoelectric layers along this wadi, both pseudo and interpreted geoelectric sections A-A' (Figure 4 and 5) are constructed.


Pseudo Geoelectric Section A-A` (fig. 4)
(Wadi Abu Saafa)
A
W
E
N35°W
S35°E
A`
Depth in Logarithmic Scale (Modulus 6.25cm)
(M)
Legend
VES SITE
Contour line
H Scale
0 250 750m
Ground surface


Interpreted Geoelectric Section A-Á (fig.5)
(Wadi Abu Saafa)
A
W
Bend
E
N35W
S35E
Á
1
2
3
4
5
6
7
8
Ground Surface
DEPTH IN (m)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
44.7
35.5
65
16
65
140
23
140
16
44
150
36
210
50
150
650
34
650
115
1010
F
F
Frist Geoelectric Layer
Wadi deposits
Second Geoelectric Layer
Um Barmil Formation
Third Geoelectric Layer
Timsah Formation
Fourth Geoelectric Layer
Basement Rocks
VES SITE
Fault
50 True Resistivity Value
0 250 750m
H.Scale

5.1.2 Description of the pseudoqeoelectric section A-A' (Figure 4)

This Section is very simple and is characterized by the presence of very high values of ⇦a (apparent resistivity) concentrated near-surface at the area from VES 2 to VES 4 having the form of a local syncline-like shape with maximum value of contour line 5000 and the value of ⇦a decreases slowly very fast to reach the value of 50 and less than 50 Km. at depth . The values of ⇦a are high and very high for both the most upper and the most lower parts of the rest of the section specially at the site of VES 8. Lower values (50 Km. and 100 Km.) are found in between. From this, it is expected to find a very local structure between the sites of VES 2 and VES 4, also the geoelectric layers are expected to be very resistive at very shallow depths along the section and also at depth near by VES 8. It is worthy to mention that this section runs W-E-S 35° E following the route path of the wadi and Covers a distance of ∠8 Km. The least spreading used was AB/2 = 400 m. and the maximum was 700 m.

5.1.3 The Description of the interpreted geoelectric section A-A' (Figure 5)

The results obtained from the interpretation of the forementioned VES are reported in Table 2. These values are used to build this section. Four main geoelectric layers are recognized. From top to bottom they are:

The first (Shallow) main geoelectric layer (red-colored):
This layer extends through the whole section and is characterized by its high ⇦t values and thin thickness. The true resistivity values ranges between 267.4 Km. and 7500 Km. and is subdivided into two very thin layers at VES 1 and 3. Its Minimum thickness is 0.21m. and a maximum of 5.1 m. This layer could represent the wadi deposits.

The second main geoelectric layer (yellow-colored):
This layer extends through the whole section and is characterized by its moderate ⇦t values except at both VES 7 and 8. The values of ⇦t range between 44.7 Km. and 1000 Km. The thickness of this layer ranges between 3.59 m. and 33.5m. The lower surface of this layer is undulating to form the shape of an anticline - like structure at VES 2 and a syncline - like structure at VES 4. This layer could represent Umm Barmil Formation which is consisted mainly of fluviatile sandstone and is water-bearing as revealed from the wells drilled in this area except at VES 8.

The third main geoelectric layer (gray-colored):
This layer extends through the whole section and is characterized by its very huge thickness that reaches to ÷ and by its relatively low true resistivity values that range from 16 Km. and 115 Km. Both water content and the presence of clay layers that intercalates the sandstone layers are responsible for the low interpreted resistivities. Water potentiality decreases east and southeast wards until its diminishing at VES 8 as proofed by drilling and operation of an open hole test However, the lower boundary of this layer was detected for the far eastern side of this section by this present work in addition to the dry hole drilled at VES 8. This boundary was detected for VES 6 through 8 as shown in Figure 5. As the basement rocks expose due north and northeastern side from these investigated sites and at a distance of an average of ± 500 m., this mentioned lower boundary of this third geoelectic layer which is at the same time the upper boundary of the fourth geoelectric layer is affected by a very much predicted fault (F-F). This layer could represents Timsah Formation.

The fourth main geoelectric layer (purple-colored):
This fourth layer is defined by the interpretation of the measured VES number 5 through 8 and is proven by drilling at VES 8. The top surface of this layer is located at shallow depths at both VES 7 and 8, and at far more deeper distances heading west. The true resistivity of this layer ranges between 150 Km. and ÷ K m.

5.1.4 Hydrogeological data

As mentioned before, four drilled wells were carried out in the study area, one of them was merely a dry hole that proofed the presence of basement rocks at shallow depth (35 m from ground surface).

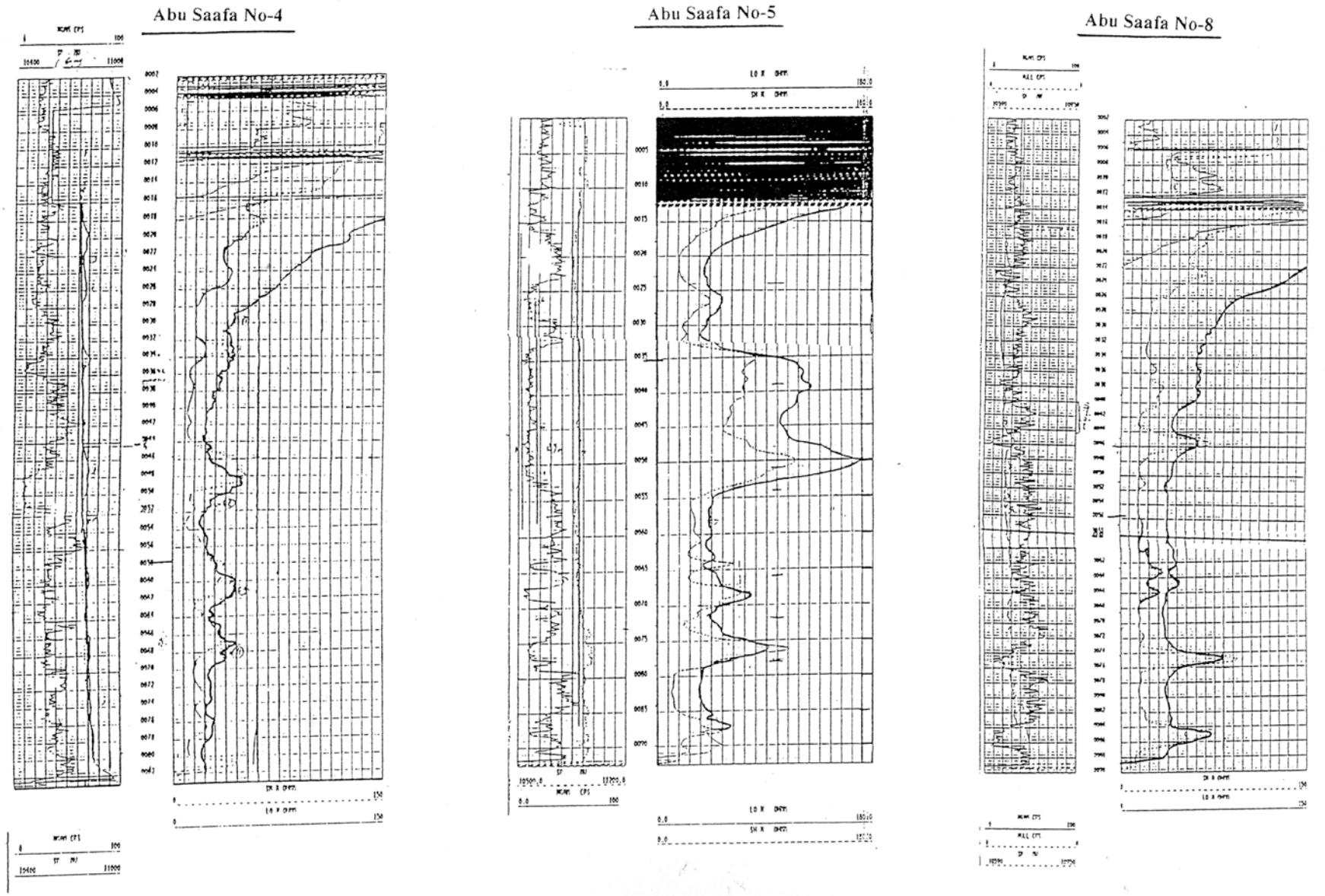


Fig. (6) : Electric Logs for Boreholes Drilled in W. Abu Saafa

Sandstones and gravels, white to yellow in color are dominant in the first layer (6 m) followed by sandstone and sometimes with silt till the depth of about 30 m. then there are sandstones alternated with clay layer, sandy clays, silty sandstone are present till the depth of 93 m (the maximum drilled depth). Groundwater is present in these drilled wells named Abu Saafa 5, Abu Saafa 4 and Abu Saafa 8. Figure (6) shows the borehole geophysics (logs) done for these wells. Water samples were collected from these wells and their chemical analyses was presented in the following table:

Table 3: Chemical analyses of water samples

Well No.	T.D.S. ppm.	units	Cations				Anions				Ph
			K^+	Na^+	Ca^{++}	Mg^{++}	HCO_3^-	CO_3^{--}	Cl^-	SO_4^{--}	
5	578	mg/ l	8.7	82	36.8	33.04	144	--	128	100	6.48
		m.eq./ l	0.222	3.567	1.836	2.716	2.36	--	3.61	2.082	
4	1428	mg/ l	15.6	320	38.4	60.64	168	--	440	250	7.36
		m.eq./ l	0.399	13.92	1.916	4.985	2.753	--	12.408	5.205	
8	1780	mg / l	6.4	650	27.2	6.8	220	--	680	300	8.16
		m.eq./ l	0.163	28.27	1.357	0.559	3.605	--	19.176	6.246	

From this table, it is clear that the total dissolved solids increase towards the downstream. And from the pumping tests conducted to these wells, it was found that the safe yield for these wells is 15 m^3/h.

5.1.5 Conclusions

1. The least affected measured field curves are those oriented E-W, which leads to conclude that most of the dominant faults in the area are oriented E-W.
2. The eastern boundary of the sedimentary cover is delineated by both geoelectric work and also by drilling.
3. The sedimentary cover is composed of wadi deposits, Umm Barmil Formation and Timsah Formation and this is a water-bearing as proofed by drilling.
4. The salinity increases downstream.
5. The safe yield for the drilled wells is 15 m^3/h.
6. Local geological structures are delineated.

5.2 Wadi Ibib

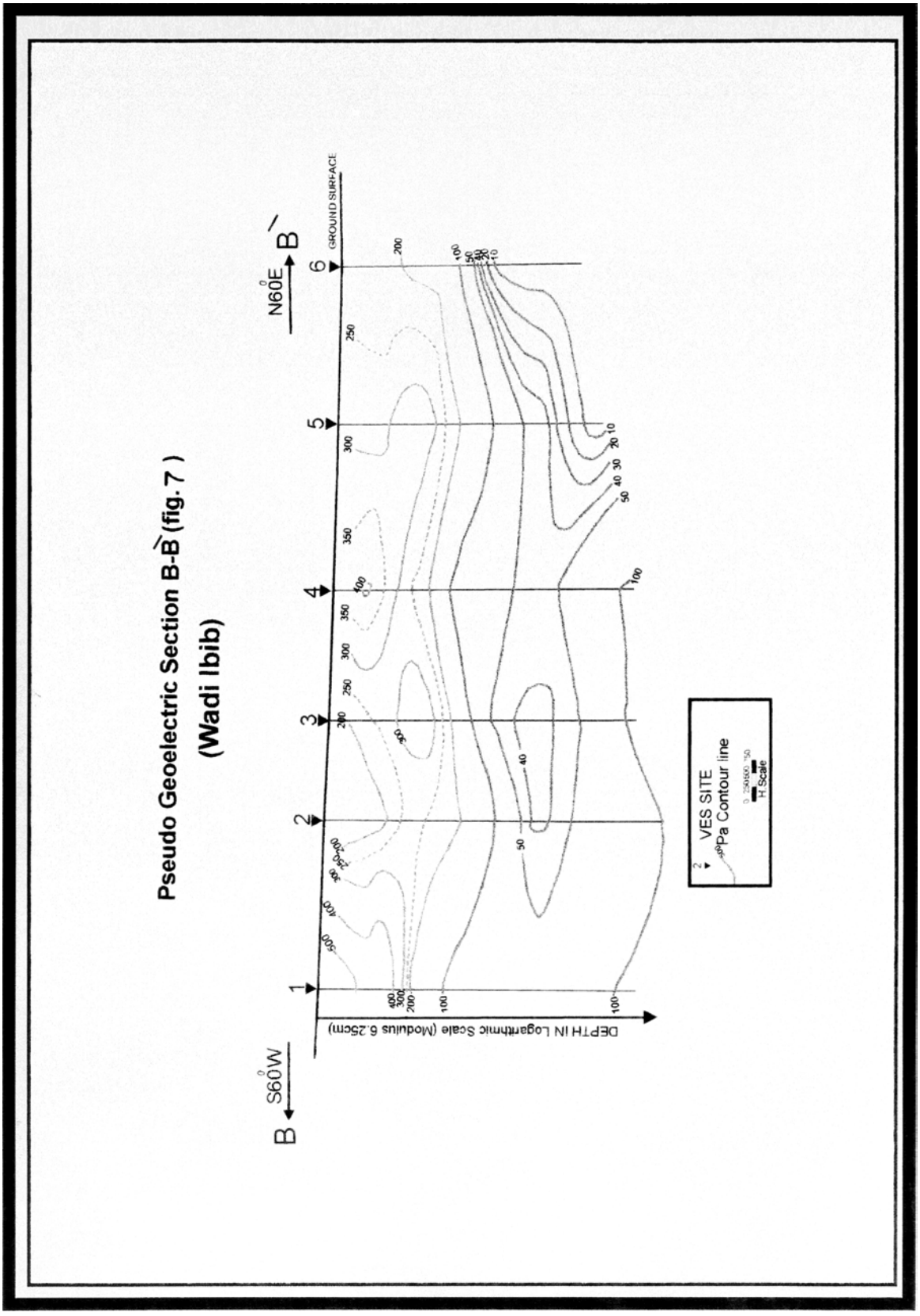
This wadi lies about 60 km south of Shalatin town. The basement rocks are dominant in this area such as granitic rocks, metavolcanics and metamorphic rocks. The floor of the wadi is covered with Quaternary sediments. Gebel Hamra Dome lies to the north of this wadi. The studied part of this wadi runs almost N 45° E following a concealed fault. Many other fault trends exist, i.e., N 80° E and N 30° W especially at the entrance of the wadi from east. No water points (Bir) exist in this wadi to a distance of about 50 km from its entrance. There was one Bir in older times as said by the local inhabitants.

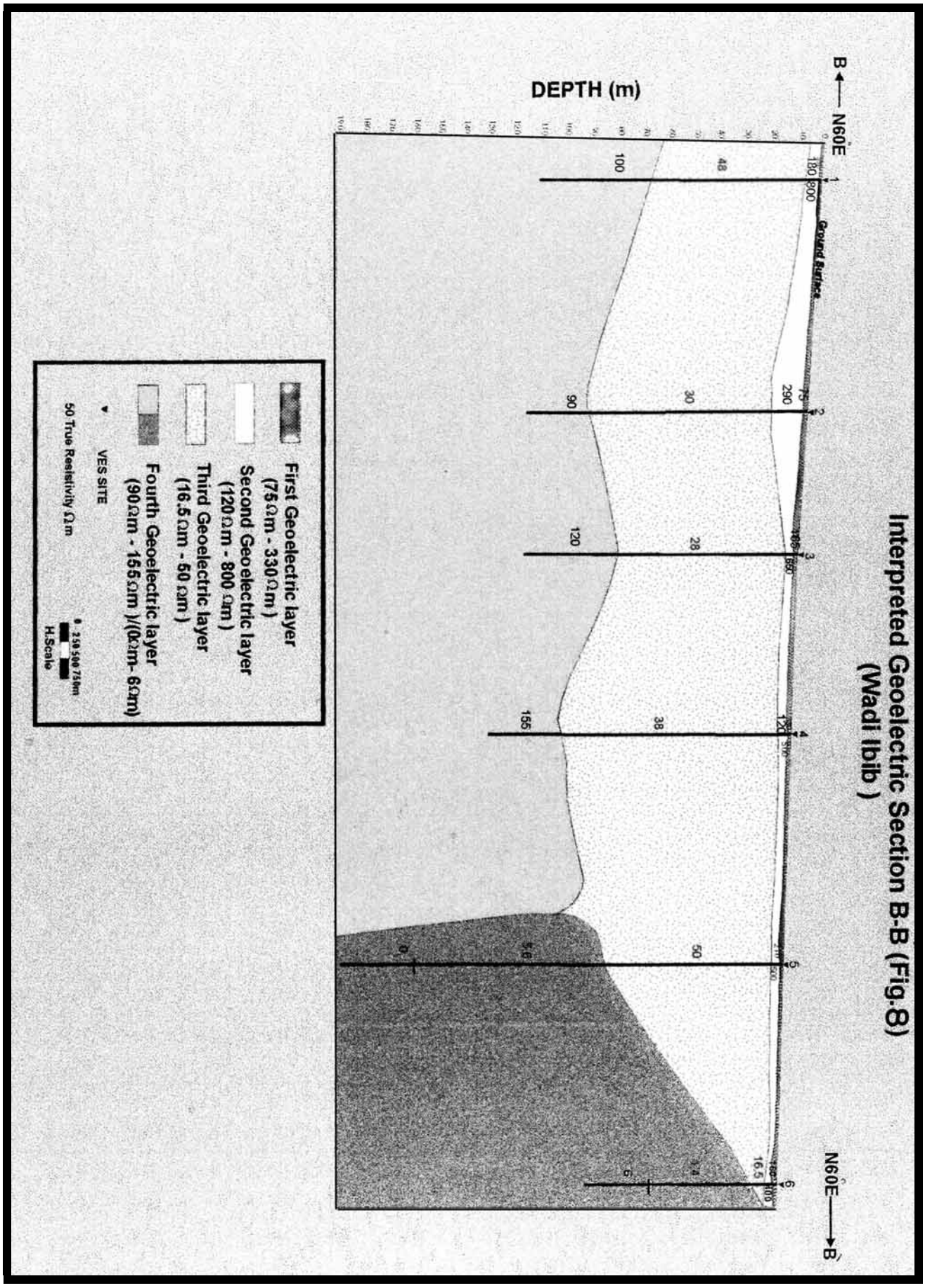
Six VES were carried out in the Wadi Ibib searching for the most suitable sites to dig for groundwater using the Shlumberger four-symmetrical electrodes array. The VES were oriented along the course of the wadi and hence as the course changes, orientation of the spreading change or to avoid obstacles if existed. The shortest spreading (AB/2) used was only 150m. for VES 6 that reached the most saturated zone with salt water content and hence the observed field curve has reached its asymptotic value at that depth, while the longest spreading used was 700m. All measured field curves has shown no effect of geological structures that would influence their shape.

To obtain the areal extension of the geoelectric layers encountered through these measurements, two geoelectric sections were constructed. The first one is the pseudo geoelectric section which shows the variations of the values of the measured apparent resistivities (⇦a Km). The second constructed section is the interpreted geoelectric section where the true resistivity values and the true thicknesses of each measured VES are used and hence the geoelectric layers with their extensions and characteristics could be revealed including any geological barriers, boundaries or structures could be located - as will be mentioned below, in addition to delineate a phenomena such as salt water intrusion as will be discussed later.

5.2.1 Description of the pseudo-geoelectrical Section B-B` (Figure 7)

This section comprises the six measured VES in this wadi. The upper most layers are very resistive where ⇦ values range between 100 and 500 Km. This is followed in depth by more conductive layer at the area between both VES 5 and 6 but for the rest of the section, another more resistive layer exist. From this situation, it is expected to obtain not less than three geoelectric layers and could be four. Salt water intrusion effect is expected at VES sites 5 and 6. Nearly horizontal layers are expected.




Interpreted Geoelectric Section B-B (Fig.8)
(Wadi Ibib)
B
N60E
N60E
B
DEPTH (m)
Ground Surface
180
800
75
290
100
48
90
30
120
28
155
38
120
500
50
5.6
0
16.5
6
First Geoelectric layer
(75Ωm - 330Ωm)
Second Geoelectric layer
(120Ωm - 800 Ωm)
Third Geoelectric layer
(16.5Ωm - 50 Ωm)
Fourth Geoelectric layer
(90Ωm - 155Ωm)/(0Ωm- 6Ωm)
VES SITE
50 True Resistivity Ωm
H.Scale

5.2.2 Description of the interpreted neoelectric section B-B (Figure 8)

Four main geoelectric layers could be distinguished in this interpreted section. From top to bottom, these layers are:

The first main geoelectric layer :
This resistive layer extends through the section with resistivity values ranges between 75 Km and 330 Km. This layer is very thin and is composed mainly of sands.

The second main geoelectric layer:
This layer is more resistive than the first one. This layer extends through the section with resistivity values ranging between 120 Km and 800 Km The lower surface of this layer is undulated specially at VES 2 in a syncline-like structure and its maximum thickness is 12.45 m. This coincide with the location and trends of the tracing of folds at the area bound by VES 3, 4 and 5 (Figure 8). It is composed mainly of the weathered products of the exposed rocks mentioned before.

The third geoelectric layer
This layer is continuous and has moderate values of the interpreted true resistivity values that range between 28 Km and 50 Km except at VES 6, where ⇦t = 16.5 Km due to the effect of salt waters. The maximum thickness of the layer is 85 m. This layer could be water-bearing as suggested from the true resistivity values encountered in this section in addition to the presence of the ancients abandoned old hand-dug well mentioned before.

5.3 Wadi Serimtai

Wadi Serimtai is one of the most important wadis that located near Gebel Elba, south of Abu Ramad town by about 12 km The wadi and its adjacent highlands and mountains are covered by natural vegetation. The main wadi is running N 45° E following a major fault trend. Many other fault trends exist in the area (Conoco, 1987). The surface geologic units surrounding this wadi are mainly composed of granitic rocks (alkaline, non tectonized granitic to alkali feldspare granitic rocks) and to a certain extent, intermediate to acid metavolcanics and meta pyroclastics. A thin layer of Quaternary wadi deposits cover the wadi bottom. The existing water supplies are far beyond the water demands at this locality as well as other parts of this region. The only water point that exist in this wadi is the hand dug well called Sararat Serimtai.

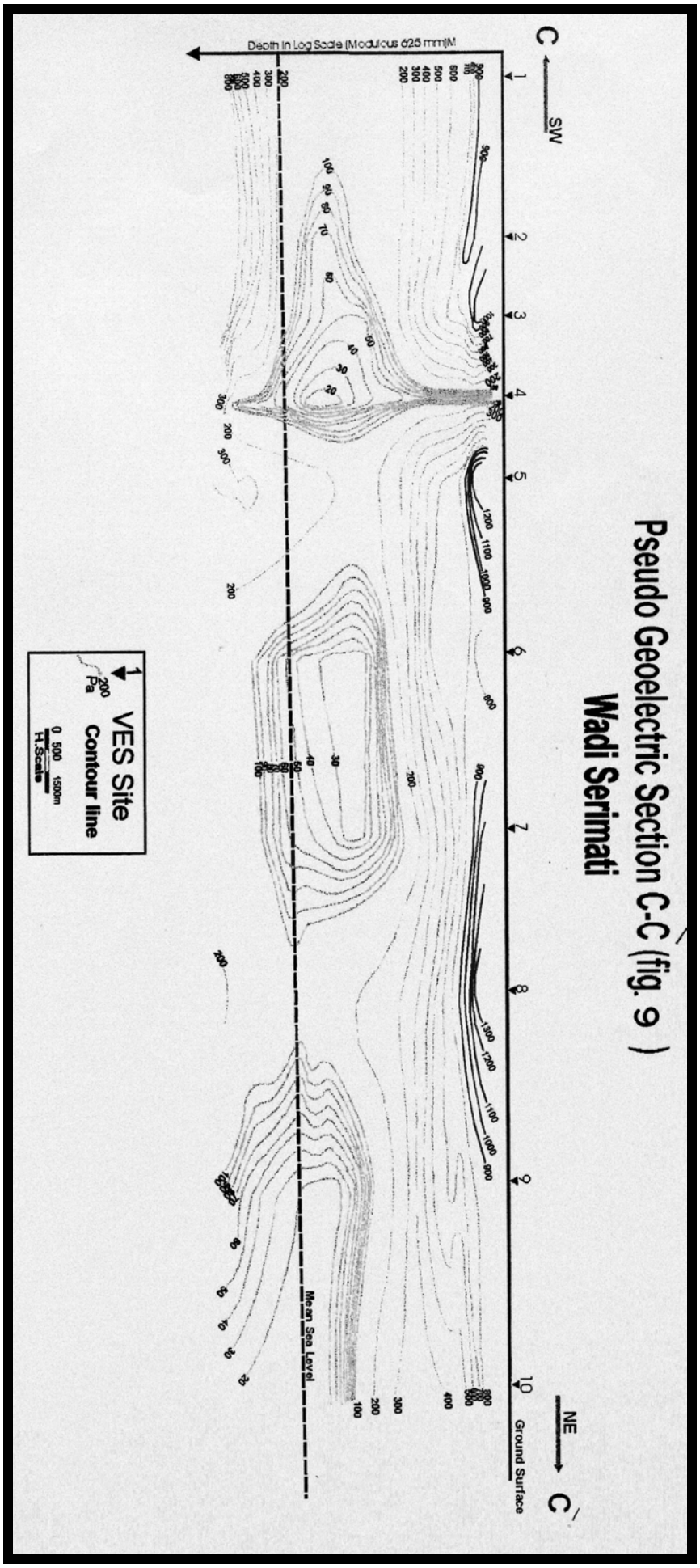
5.3.1 Field Work

Vertical Electrical Soundings (VES) were carried out through this wadi searching for suitable sites to dig for water using the Schlumberger four-symmetrical electrodes array. A total number of ten VES were executed in the field Figure(3), from which VES 4 was nearby Bir Sararat Serimtai. All VES were oriented N 45° E following the main course of the wadi except VES 1 which was oriented N 80° E. The effect of some other fault trends has already affected the measured field curves numbers 4, 8 and 10 to a very low extent at different depths. Table (5), shows the interpreted values for each measured VES. In order to delineate the subsurface geoelectric units and their both vertical and horizontal extent, two geoelectric sections were constructed. The first one is the pseudo-geoelectric section which shows the variations of the apparent measured resistivities, ⇦a, along the section against the measured depths. This section delineates the structural deformations, faults and folds, that would exist in this study area and their areal extent. The second constructed section is the interpreted geoelectic section.

5.3.2 Description of the Pseudo-Geoelectric Section C-C` (Figure 9):

The ten measured VES are encountered in this section. The section is oriented SW-NE and runs for about 20 kilometers. The shortest measured AB /2 was 250m. for VES 2, while the longest AB /2=700m. was for VES 5 to satisfy asymptotic needs. The explanation of the section is as follows:

- The highest values of ⇦a (apparent resistivity) are concentrated at the uppermost parts of the section, i.e., at very shallow depths, except at site of VES 4.
- Low to very low values of ⇦a are found at three sites of the section and having conspicuous elongated shapes of contour lines that have the values of 20 up to 100 Km. The shapes follows in depth the upper layer.
- Moderate to high values of ⇦a are found in between the three shapes of low ⇦a mentioned above and also above and below them. These values would represent the least disturbed and fractured basement rocks.


Pseudo Geoelectric Section C-C (fig. 9)
Wadi Serimati
C
SW
NE
C'
Depth in Log Scale (Modulous 625 mm)M
Ground Surface
Mean Sea Level
VES Site
Contour line
H.Scale
0 500 1500m

5.3.3 Remarks

- The conspicuous elongated shapes of a contour fines are formed as a result of the effect of faults that are dominant in the study wadi which have trends especially other than the N 45° E trend. At the location of the first shape found at the site of VES 4 and has an extension towards VES 3 and VES 2, the dominant fault trends are: N 45° E, N 20° E and N 80° W.
- The second shape that extends between VES 6 and VES 7, there are the following fault trends which are found between both sites as follows: N 45°E,N20°Wand N70°E.
- The third shape is found between VES 9 and VES 10 and extends towards VES 8, there are several faults found between VES 8 and VES 9, having the following trends: N 45° E and N 20° E. At VES 9 there are several faults having trends of N 45° E and N 20° W. The salt water intrusion affects the value and shape of this third shape at the site of VES 10.

Three shapes mentioned above represent water bodies found (or entrapped) in such faulted and dislocated basement rocks which had become ready to host waters falling seasonally on this wadi.

5.3.4 Description of the interpreted geoelectric section C-C` (Figure10):

There are three geoelectric units included in this section.

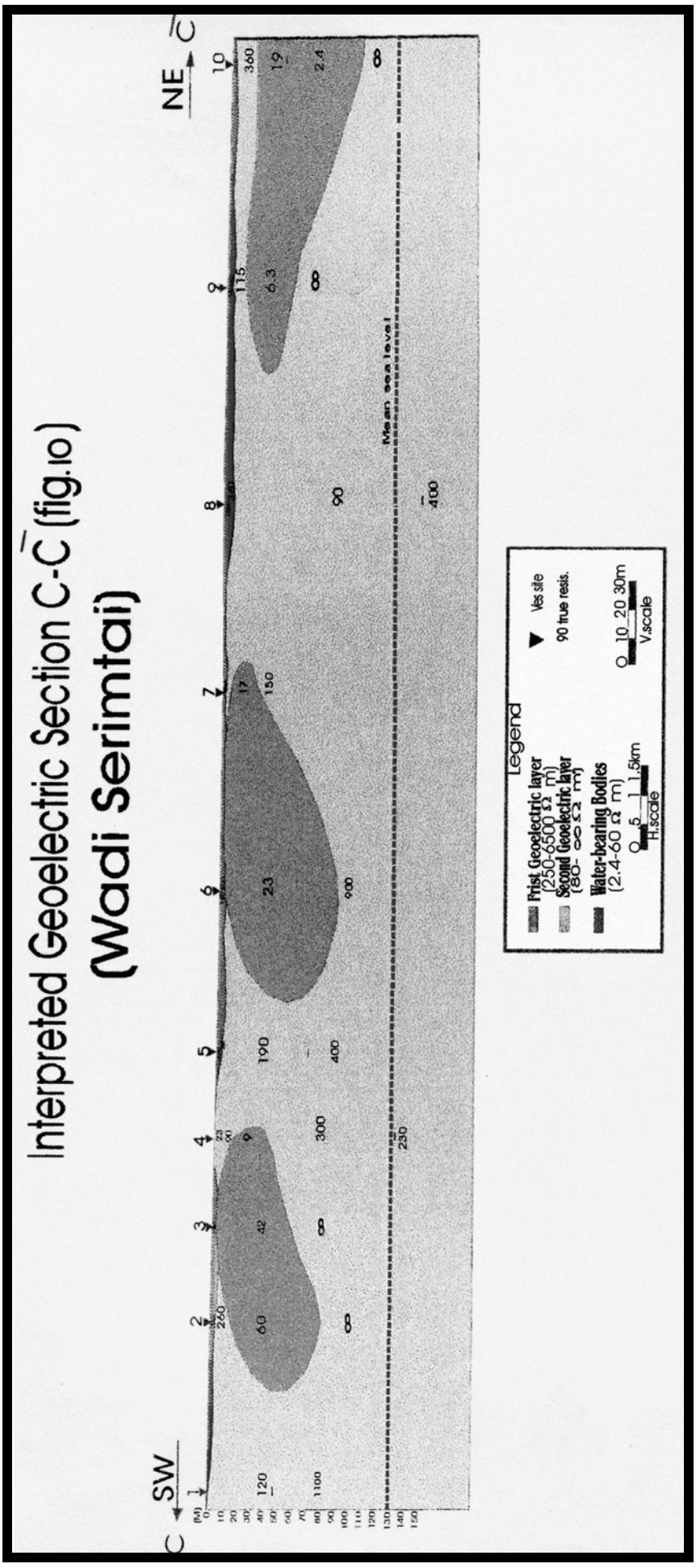
The first geoelectric unit (Red color) extends through the whole section except at VES 4 where Sararat Serimtai dug well exists. This resistive layer has ⇦ (true resistively) values ranging from 250 Km. To 6500 Km. and a maximum thickness of 7m. and represents the wadi deposits. The soil surrounding the site of the Bir is mixed with the wastes of camels and sheepes and hence an artificial soil is formed and has ⇦=23 Km. This layer is subdivided into two layers at some sites.

The second geoelectric unit or layer (pink color)follows the first one and extends through the whole section and could be subdivided into more than one at some sites such as at VES 5. This unit is resistive to highly resistive layer as ⇦ values ranges between 80 Km. and ÷ Km. except at VES 4 and hosts three, very local and limited water-bearing units-like basins, which represents the third geoelectric unit in this section. This unit comprises three water-bearing bodies. The first body is located between VES 2 and VES 4 and has a horizontal extension of about 7.5 Km. and a maximum thickness of about 70m. The true resistivity of this body ranges between 9 Km. and 60 Km. The second water-bearing body is located between VES 6 and 7, and has a horizontal extension of about 9.5 Km. attaining a maximum thickness of about 80m. at VES 6. The values of ⇦ are 17 Km. and 23 Km. and water of good quality is expected in this body. Noteworthy that the groundwater obtained from Bir Sararat Serimtai has a total dissolved solids of 4650 ppm. and the depth to water is 22m.

The third water body is located at the northeastern part of this section starting from VES 9 and extends through VES 10. The ⇦ values for this body are 2.4 Km, 19 Km, and 6.3 Km. The water possessed within this body is expected to be saline water. The main reason for such severe invasion of salt water intrusion towards this wadi is attributed to the fact of the absence of natural barriers.

The fourth main geoelectric layer:

This geoelectric layer is the base layer and could be distinguished laterally into two completely different layers facing each other nearby the site of VES 5 and there is a basement rock roots that acts like a stiff concrete geological barrier. The first layer of this fourth main geoelectric extends between the sites of VES 1 through 4 and is consisted of basement rocks with true revistivity values that range between 90 Km. and 155 Km. Its upper surface is undulating which leads to give a shape of very local syncline-like and anticline-like structures to the sedimentary section which is represented by the third main geoelectric layer mentioned above. The second layer of the fourth geoelectric layer extends from about 700 m. from the site of VES 5 from its south western direction till VES 6. The ⇦ values of this part of the section range between zero Km. and 6 Km. This part of the section represents the domain of the dominance of sedimentary section that represents the delta or fan of Wadi Ibib which is saturated at depth by saline waters resulted from salt water intrusion. This salt water intrusion was stopped by the natural barrier mentioned above from the south western direction. The fault with the trend N 30°W, that lifted the basement rocks to be exposed at the entrance of the wadi, has constructed the natural barrier that stopped the salt water invasion at the south western direction.


Interpreted Geoelectric Section C-C̄ (fig.10)
(Wadi Serimtai)
SW
NE
C
C̄
Mean sea level
Legend
First Geoelectric layer
(250-6500 Ω m)
Second Geoelectric layer
(80- ∞ Ω m)
Water-bearing Bodies
(2.4-60 Ω m)
Ves site
90 true resis.
H.scale
V.scale

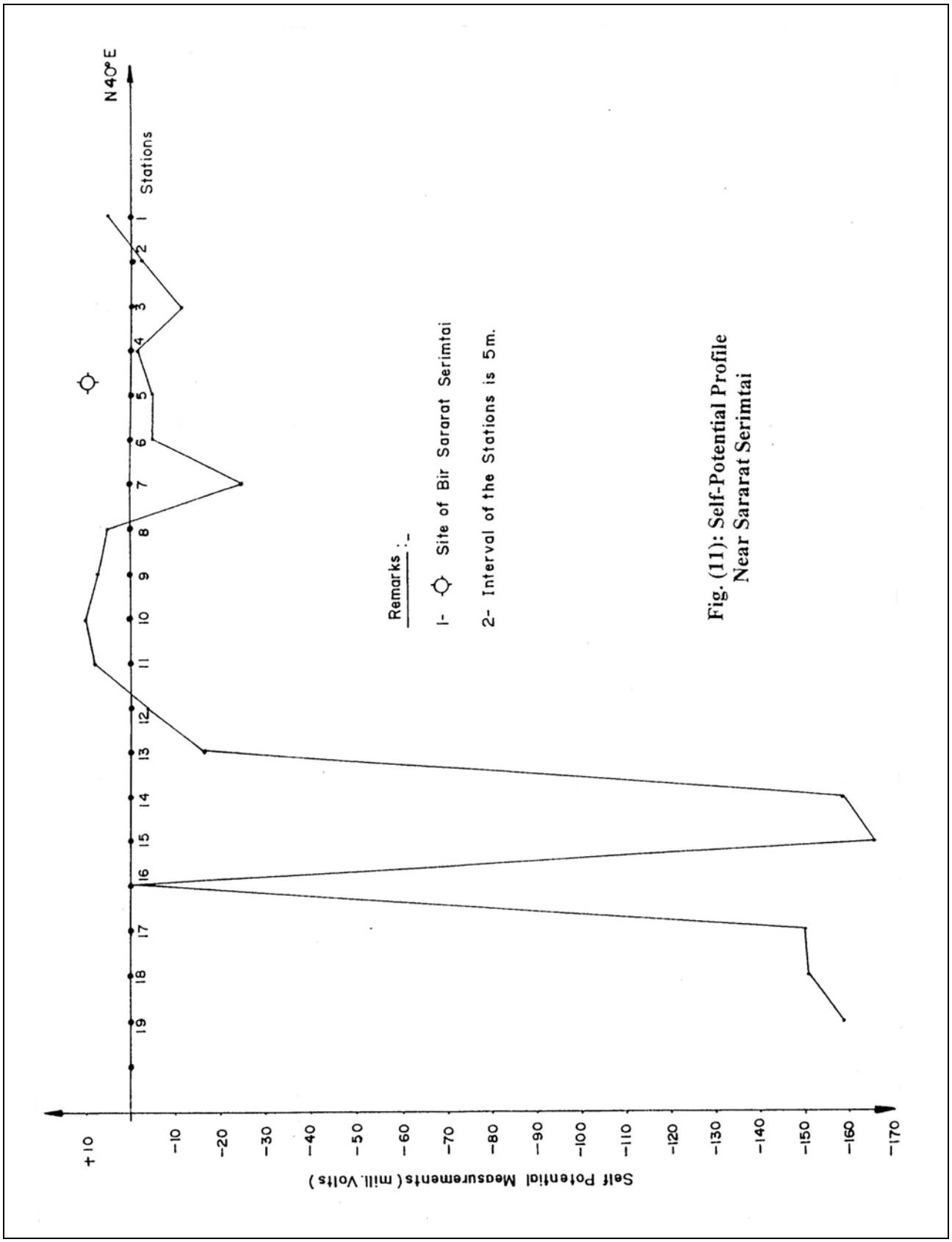


Fig. (11): Self-Potential Profile
Near Sararat Serimtai

6. Summary and conclusion

From the previous discussions, the following conclusions could be obtained:

6.1 For Wadi Abu Saafa

1. The least affected measured field curves are those oriented E-W, which leads to conclude that most of the dominant faults in the area are oriented E-W.
2. The eastern boundary of the sedimentary cover is delineated by both geoelectric work and also by drilling.
3. The sedimentary cover is composed wadi deposits, Umm Barmil Formation and Timsah Formation and is a water-bearing as proofed by drilling.
4. The salinity increases downstream.
5. The safe yield for the drilled wells is 15 m^3/ h.
6. Local geological structures are delineated.

6.2 Wadi Ibib

1. There is a fairly good sedimentary cover in the wadi that has a thickness of about 85 m. between VES 1 through 4 with intermediate ⇦ values which could be water-bearing.
2. Salt water intrusion was delineated and this invasion is stopped at the south western direction by the faulted block of basement rocks at the entrance of the wadi. This leads to the fact that the area of Wadi Ibib's delta was invaded by salt waters, but the rest of the wadi is not affected and its groundwater would be of good quality.

6.3 Wadi Serimtai:

1. The forementioned water-bearing bodies-like basins are initially originated as a direct impact of faults of different orientations at and nearby these sites which gave also the chance of recharging them seasonally.
2. The most recommended sites to dig for groundwater are at VES 3 and VES 6. as for the site of VES 4, where the hand dug well Sararat Serimtai exist, in addition to the VES carried out, there self potential measurements, Figure 11, were conducted along four lines that surround the site of the well from its four directions. It was noticed that the groundwater flows the south-southwestern direction from the well where a tributary of the main wadi exists.
3. The main recharge of the Bir (Serimtai) comes from the direction where VES 2 and VES 3 are located and for this reason the true resistivity values at VES 2 is 60 Km. and at VES 3 was 42 Km. while at VES 4 it is only 9 Km.
4. The main course of recharge, most probably comes from the tributaries of the wadi more than from the wadi itself.

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Kamel Zouari et My Ahmed Maliki

Contribution à l'évaluation et à la gestion des eaux de la nappe profonde du Sahel de Sfax par les méthodes isotopiques

(Isotope methodologies' contribution to the evaluation and management of the Sfax Sahelian Aquifer)

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Abstract

This study has been carried out on the Sfax Sahelian deep aquifer which is located in the eastern part of Tunisia. This aquifer is lodged in the sandy series of Upper Miocene (Upper Serravalian-Tortonian). Its important extension (14,000 km^2) offers considerable resources.

Groundwater flow was established by measuring the boreholes piezometric levels. The piezometric level ranges between 35 and 17 m and groundwater flow from north-west to south-east, and from the north to the south. The hydraulic gradient is very low and translates a slow flow and a sedentary groundwater state.

An isotopic study ($^{18}0$, $^{2}0$, ^{3}H, ^{13}C and ^{14}C) achieved more than four years ago, on groundwater deep aquifer has allowed to understand certain particularities of this basin's flow regime. The absence of tritium and the very low ^{14}C contents show that this groundwater is old and that aquifer recharge occurred during different climatic conditions compared to the present one (Ages superior to 10,000 years). The homogeneity of the stable isotope and ^{14}C contents suggests a slow flow, with very weak fluxes, in the system.

The hydrochemical study shows that groundwater is characterized by a chemical facies of Na-Cl type. The groundwater mineralisation varies between 3 and 10 $g.l^{-1}$. On the scale of the basin, the spatial distribution of the salinity is not progressive.

Keywords
Tunisia, Sahel of Sfax, deep aquifer, isotopes, recharge

Résumé

Une étude isotopique (^{18}O, ^{2}H, ^{3}H, ^{13}C et ^{14}C) entreprise depuis plus de quatre ans sur les eaux de la nappe profonde de Sfax (Sahel de Tunisie) a permis de comprendre certaines particularités du régime des écoulements souterrains du bassin. L'absence de tritium et les faibles activités ^{14}C montrent que les eaux de la nappe sont anciennes et que la recharge de cet aquifère a eu lieu sous des conditions climatiques très lointaines, vraisemblablement plus froides et différentes des conditions actuelles (période de l'Holocène-Pléistocène supérieur). L'homogénéité des teneurs en isotopes stables et les basses teneurs en ^{14}C suggèrent des écoulements très lents et de faibles flux à l'entrée et à la sortie du système.

Mots clés
Tunisie, Sahel de Sfax, aquifère profond, isotopes, recharge

1. Introduction – problematique

Dans la région de Sfax, l'exploitation des eaux souterraines a intéressé en grande partie et jusqu'à les années 1985 les nappes phréatiques, et notamment celles se trouvant sur la zone côtière. Actuellement, l'exploitation globale à partir des nappes de surface est estimée à 32,6 Mm^3, représentant ainsi environ 106 % des ressources exploitables (30,75 Mm^3). Par conséquent, cette exploitation actuelle est arrivée à un stade avancé se traduisant par une surexploitation dans de nombreux secteurs du bassin.

Cette surexploitation et la fluctuation des précipitations sur la région (faiblesse et variabilité dans le temps) ont conduit à une dégradation quantitative et qualitative des eaux et à un danger réel de l'avancée de l'eau de mer, phénomène déjà observé dans de nombreux secteurs au Nord (région de Djebeniana, située à 35 km de la ville de Sfax) et au Sud (région de Hajeb-Sidi Abid) du bassin (Figures 1 et 2). Compte tenu de cette situation et afin de répondre à une demande de plus en plus croissante en eau, pour satisfaire les besoins en eau surtout pour l'agriculture et l'industrie, d'une part, et pour soulager les aquifères de surface, d'autre part, le recours aux ressources profondes devient inévitable.

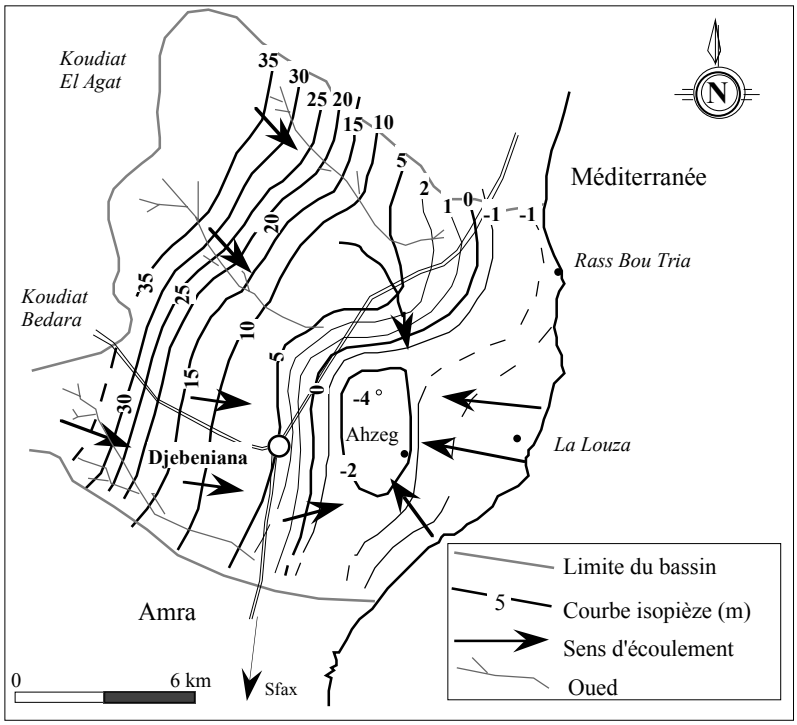


Figure 1: Etat piézométrique de la nappe phréatique de Djebeniana en 1994 (Maliki 1994)

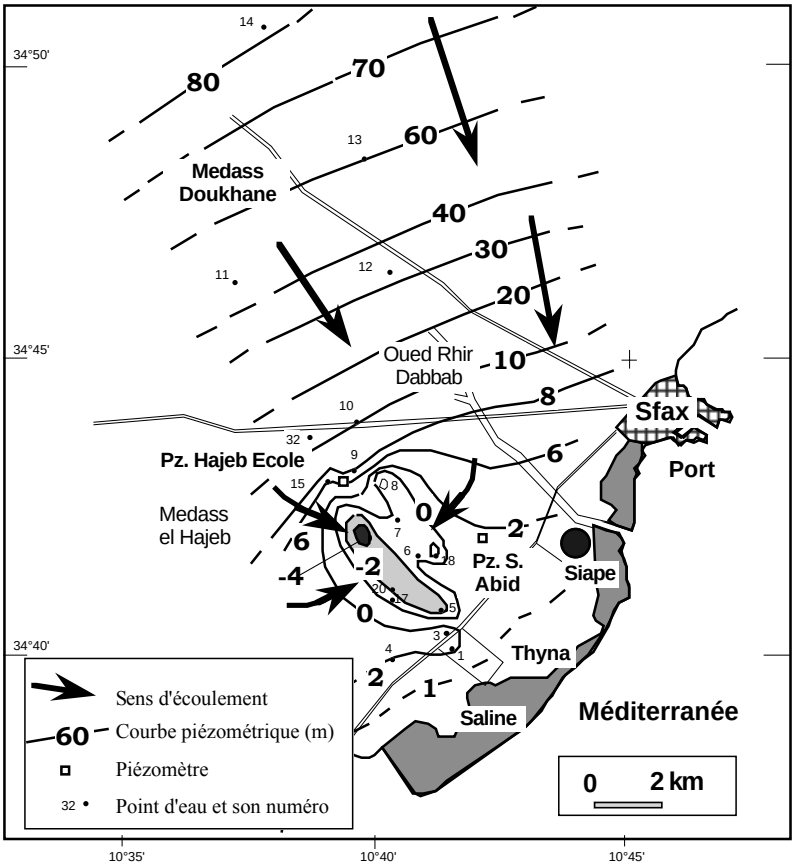


Figure 2: Piézométrie de la nappe phréatique de la région de Sidi Abid en 1997 (Fedrigoni 1998)

En effet, l'analyse de l'évolution de l'exploitation de la nappe profonde montre que les prélèvements sont passés de 9,6 Mm^3 en 1986 à 13,4 Mm^3 en 1987 puis à 17,8 Mm^3 en 1988. A partir de cette dernière année, les prélèvements restent plus au moins stables (19 Mm^3) (Figure 3).

Compte tenu de cette situation, cette étude a pour but de contribuer à une meilleure connaissance du fonctionnement hydrodynamique du système aquifère profond du Sahel de Sfax en adoptant une approche pluridisciplinaire (hydrogéologique, hydrochimique et isotopique).

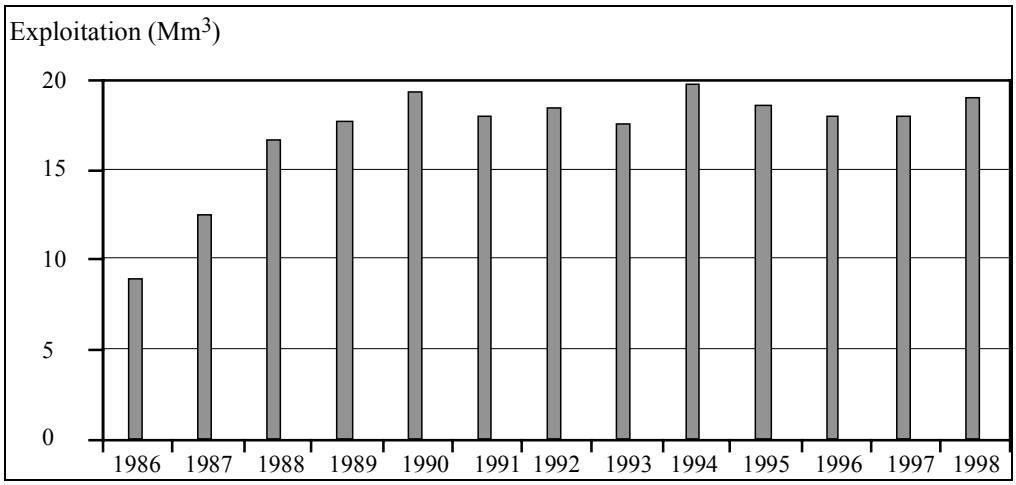


Figure 3: Exploitation annuelle des eaux de la nappe profonde de Sfax (Mm^3) (DGRE 1998)

2. Généralités sur la zone d'étude

2.1 Localisation et aperçu géologique

La zone d'étude faisant partie du Sahel de Tunisie est limitée à l'Ouest par l'axe Nord-Sud, au Nord, par le Sahel de Sousse, au Sud, par le Golfe de Gabès et à la l'Est, par la Méditerranée (Figure 4). Le bassin de Sfax, qui fait partie de la plate forme tunisienne, est constitué essentiellement de sédiments tertiaires et quaternaires. Les affleurements connus dans la région sont surtout d'âge Mio-Pliocène et Quaternaire. Quelques terrains d'âge Miocène supérieur sont rencontrés au niveau des reliefs de bordure (Djebel Krechem el Artsouma et au niveau du chaînon de Mezzouna), ainsi que dans le secteur de Zeramdine-Beni Hassen, situé au nord du secteur d'étude (Figure 4).

2.2 Aperçu climatique

La région d'étude se caractérise par un climat aride à semi-aride. Les précipitations moyennes annuelles se limitent à 252 mm (1968-93) (Station El Maou), un module sujet d'ailleurs à de grandes fluctuations. A l'échelle mensuelle, la région de Sfax se caractérise par un régime pluviométrique moyen complexe (Figure 5). La variabilité constitue une caractéristique fondamentale des pluies dans la région sfaxienne. Le coefficient de variation atteint 45 % au niveau des pluies annuelles et augmente au fur et à mesure que l'on considère les quantités saisonnières et/ou mensuelles. D'une manière générale, la variabilité est inversement proportionnelle aux modules moyens : elle est d'autant plus élevée que les quantités sont faibles.

La région de Sfax connaît un climat thermique de type méditerranéen assez chaud. La moyenne annuelle s'élève à 19°C, avec des températures moyennes de l'ordre de 11,5°C en janvier, et de 25,6°C en juillet.

En plus de la rareté des précipitations, l'évaporation élevée sur la région de Sfax, accentue davantage la sécheresse. Elle fonctionne tout le long de l'année, même en hiver où elle atteint sa valeur minimale 127 mm. Le maximum d'évaporation est enregistré en été avec 602 mm. En raison de l'irrégularité et la faiblesse des pluies, le réseau hydrographique est peu développé. Tous les oueds sont à caractère temporaire.

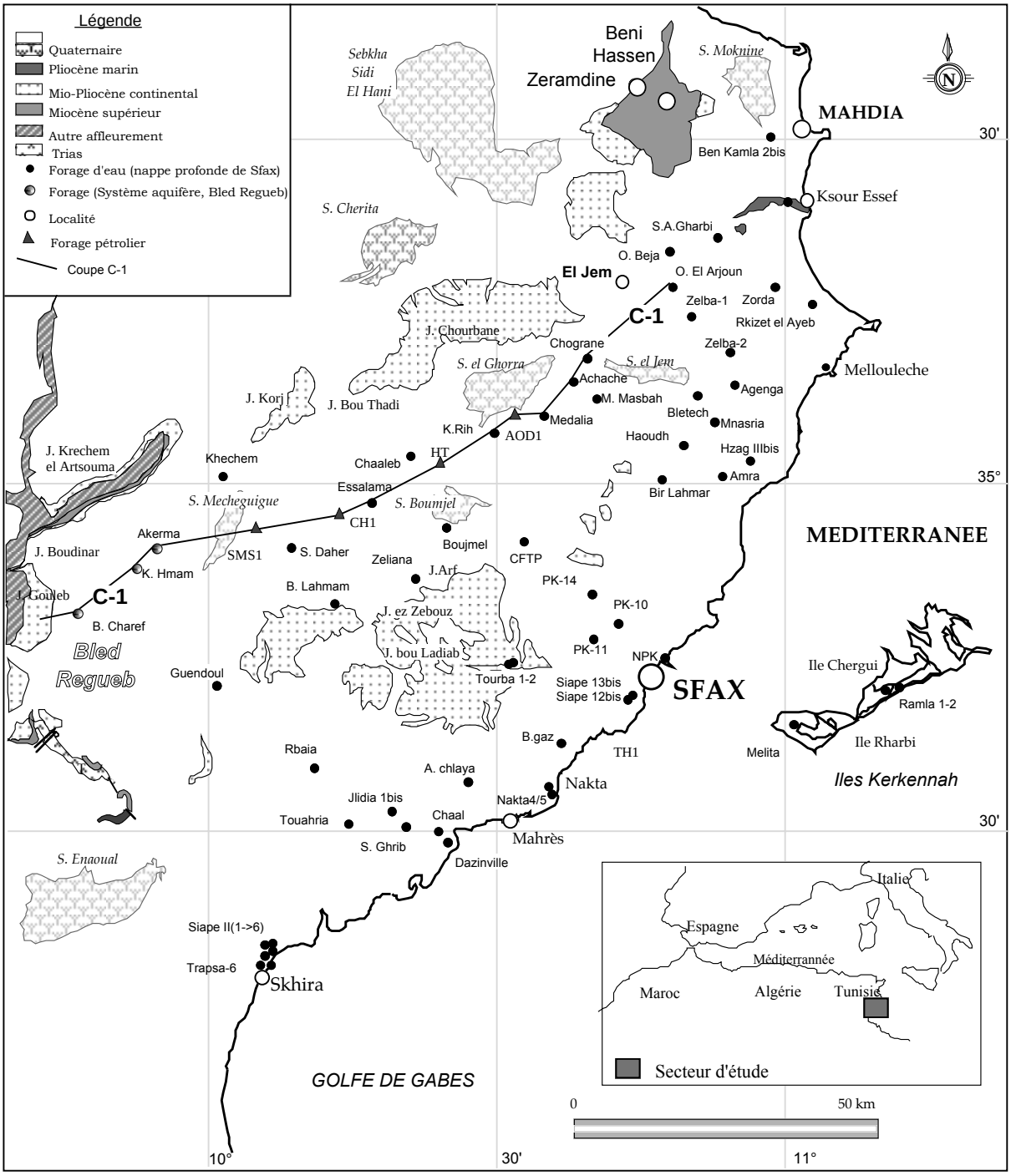


Figure 4: Carte géologique du secteur d'étude et localisation des points d'eau

2.3 Aperçu hydrogéologique

D'un point de vue hydrogéologique, la nappe profonde de Sfax est logée dans les sables du Miocène supérieur qui forment le réservoir aquifère profond le plus important dans la région. D'une puissance moyenne de l'ordre de 200 m, ce réservoir est formé essentiellement de sables et d'argiles. Affleurant au Nord, au Nord-Ouest et Sud-Ouest du bassin, il est capté à une profondeur variant de 200 à 700 m. Libre dans la partie amont du bassin, il est captif au centre et devient jaillissant le long du littoral.

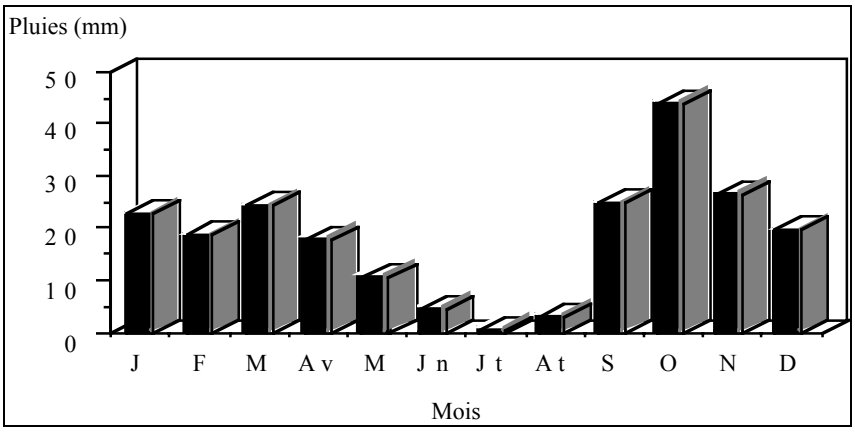


Figure 5: Régime moyen des pluies à Sfax (1901-90)

La corrélation lithostratigraphique réalisée à partir des sondages pétroliers associées aux renseignements fournis par les coupes de forages d'eau profonds, nous a permis de mieux définir la structure et la géométrie des différentes formations réservoirs existantes dans le Sahel de Sfax.

La coupe C-1 (voir Figure 4 pour l'emplacement) de direction SW-NE, débute à partir des reliefs de l'axe N-S au niveau de Djebel Gouleb et s'étend jusqu'à l'Oued el Arjoun (Figure 6). Cette coupe, à structure assez complexe, illustre la continuité de la série sableuse à travers la plaine de Sfax. Elle montre un grand développement des séries sédimentaires au niveau du forage pétrolier AOD1 où le Miocène moyen à supérieur atteint une épaisseur de l'ordre de 670 m puis une réduction de leur puissance vers les bordures. Vers le NE, la présence de forages d'eau, dont la profondeur d'investigation ne dépasse pas les 700 m (forage de Meddalia) et captant probablement la partie sommitale de l'aquifère (la plus productive), rend difficile toute tentative de caractérisation de la géométrie de l'aquifère.

La carte piézométrique établie au cours de la période juin-juillet 1995 par Maliki (en prép.) montre que les écoulements souterrains de la nappe se font du Nord et du Nord-Ouest vers Sud et le Sud-Est (Figure 7).

3. Methodes d'analyses

Les forages d'eaux échantillonnés pour des analyses chimiques (éléments majeurs) et isotopiques sont représentés sur la Figure 4. Les teneurs en isotopes stables de la molécule d'eau ont été mesurées par spectrométrie de masse au laboratoire d'Hydrologie et de Géochimie Isotopique de l'Université de Paris-Sud (Orsay, France) et à British Geological Survey (Wallingford, UK).

Les teneurs en oxygène-18 ont été mesurées sur du CO_2, préalablement équilibré avec l'eau des échantillons. La mesure est exprimée par rapport au standard international SMOW [Standard Mean Ocean Water, représentant la composition isotopique moyenne des eaux océaniques (Craig 1961)]. L'incertitude analytique est de ± 0,2 ‰. Les teneurs en deutérium ont été mesurées sur le gaz hydrogène obtenu par réduction en utilisant le zinc (Coleman *et al*. 1982). L'incertitude analytique est de ± 2‰.

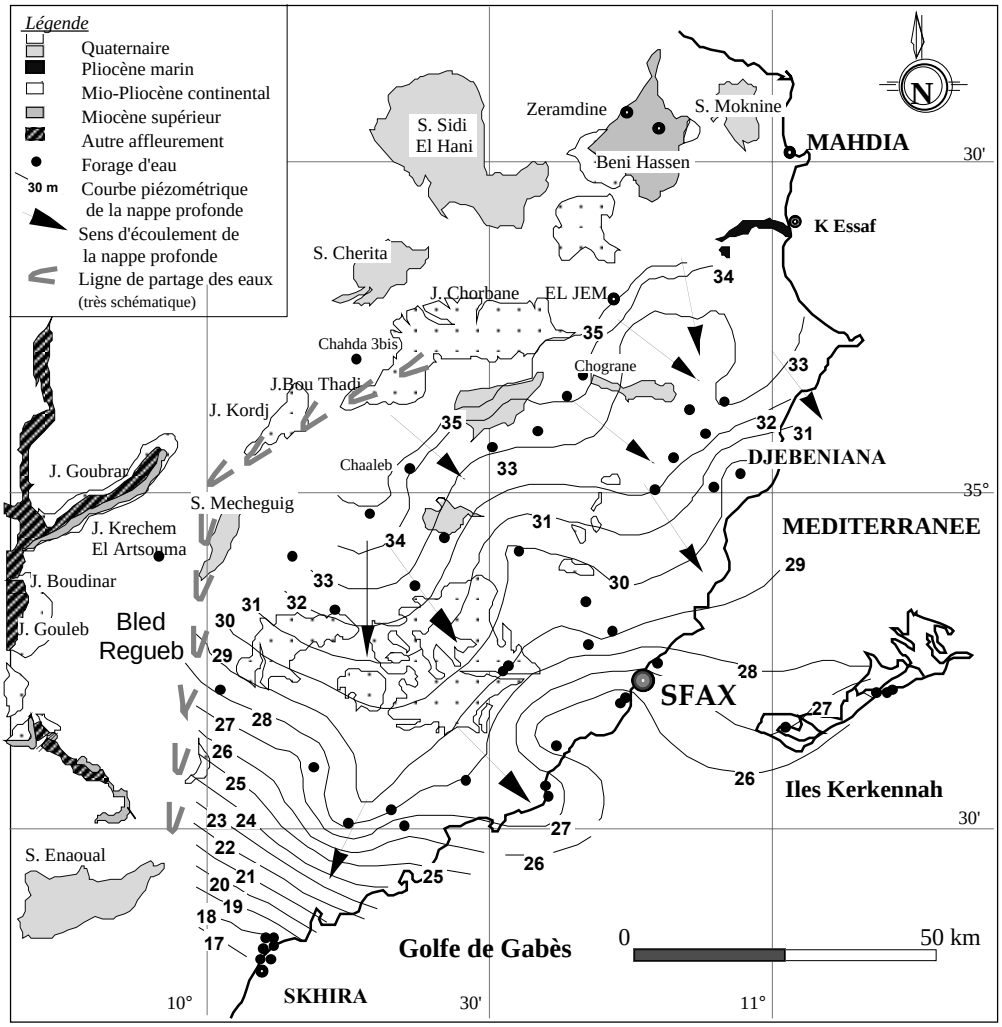


Figure 7: Carte piézométrique des eaux de la nappe profonde de Sfax (juin-juillet, 1995)

L'activité ^{14}C du Carbone Inorganique Total Dissous (CITD) a été déterminée par comptage € dans un compteur à scintillation liquide (type Beckman), au laboratoire de Géochimie Isotopique et de Paléoclimatologie de l'Ecole Nationale d'Ingénieurs de Sfax, selon la méthode décrite par Fontes (1971). Les teneurs en ^{13}C sont mesurées par spectrométrie de masse au Laboratoire d'Hydrologie et de Géochimie Isotopique à Orsay sur le CO_2 dégagé après attaque acide complète de H_3PO_4 (ultra-pur) sur le $BaCO_3$. Le tritium a été déterminé, par enrichissement au Centre de Recherches Géodynamiques de Thonon (CRGT) en France et à l'Agence Internationale de l'Energie Atomique (AIEA) à Vienne, en Autriche.

4. Resultats et discussions

4.1 Hydrochimie

Les points représentatifs des eaux de la nappe profonde de Sfax sont reportés sur le diagramme de Piper (Figure 8). Les eaux montrent une grande homogénéité du faciès chimique. Elles sont de type chloruré sodique.

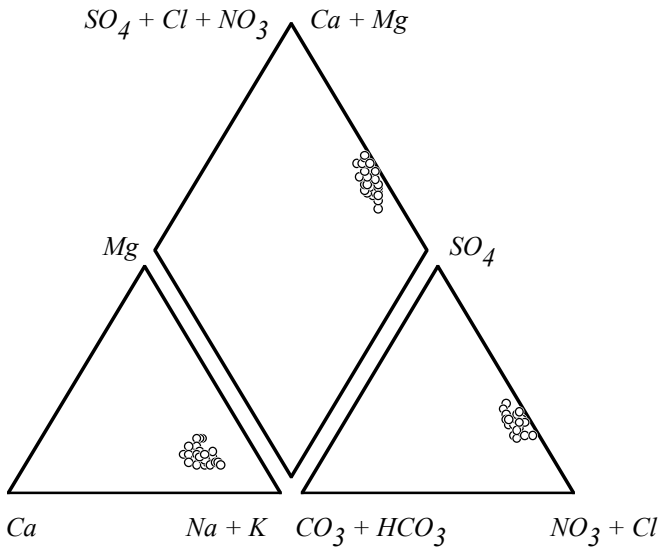


Figure 8: Diagramme de Piper des eaux de la nappe profonde de Sfax

La salinité des eaux de la nappe représentée par la Figure 9, varie entre 3 et 10 $g.l^{-1}$. Les eaux à minéralisation modérée (comprise entre 3 et 4,5 $g.l^{-1}$) sont rencontrées dans le Nord et le Centre du bassin. Dans la partie sud, les eaux se distinguent par une minéralisation nettement plus élevée (autour de 10$g.l^{-1}$).

Les teneurs élevées en sels enregistrées dans les eaux prélevées dans la partie sud du bassin sont vraisemblablement liées, en partie, à une intrusion d'eau de mer, comme en témoignent leurs rapports Br/Cl et Na/Cl proches du rapport marin, et à la mise en solution de minéraux tels que le gypse, l'anhydrite, la calcite et la dolomite vis-à-vis desquels les eaux sont saturées voire même sur-saturées. Dans le reste de la plaine, les eaux acquièrent leurs minéralisations par dissolution des évaporites (Maliki, en prép.).

4.2 Géochimie isotopique

Pour déterminer le temps de séjours des eaux et tenter de remonter aux périodes de recharges qui ont été à l'origine de la mise en eau dans ce système aquifère profond, nombreuses analyses isotopiques ont été réalisées. La détermination du tritium par enrichissement a été effectuée sur neuf échantillons. Les résultats obtenus montrent que les eaux sont très faiblement tritiées, voire non tritiées (Figure 10). Ces teneurs suggèrent des temps de séjours moyens prolongés et une infiltration antérieure à 1952, date de début des essais thermonucléaires.

Les teneurs en ^{14}C du CITD ont été mesurées sur environ 40 échantillons. Sur l'ensemble des analyses ^{14}C, environ 20 échantillons présentent des activités en carbone moderne inférieures à 5 % et 14 échantillons affichent des teneurs comprises entre 5 et 10 %, alors que 4 points d'eau montrent des activités ^{14}C variant de 10 à 15 pCm. Les activités ^{14}C comprises entre 15 et 20 % n'intéressent que 3 points d'eau. L'histogramme de fréquence (Figure 11) montre clairement la distribution des différentes analyses ^{14}C. D'une façon générale, les basses activités en ^{14}C mesurées dans les eaux de la nappe de Sfax correspondent à des âges corrigés (selon le modèle de Pearson), s'échelonnant entre 28 ka et 11 ka. Ces âges corrigés confirment déjà l'origine ancienne des eaux et l'absence de recharge récente. En termes paléoclimatiques, la nappe profonde de Sfax est rechargée sous des conditions climatiques très lointaines, vraisemblablement plus froides, et différentes des conditions actuelles (période de l'Holocène-Pléistocène supérieur).

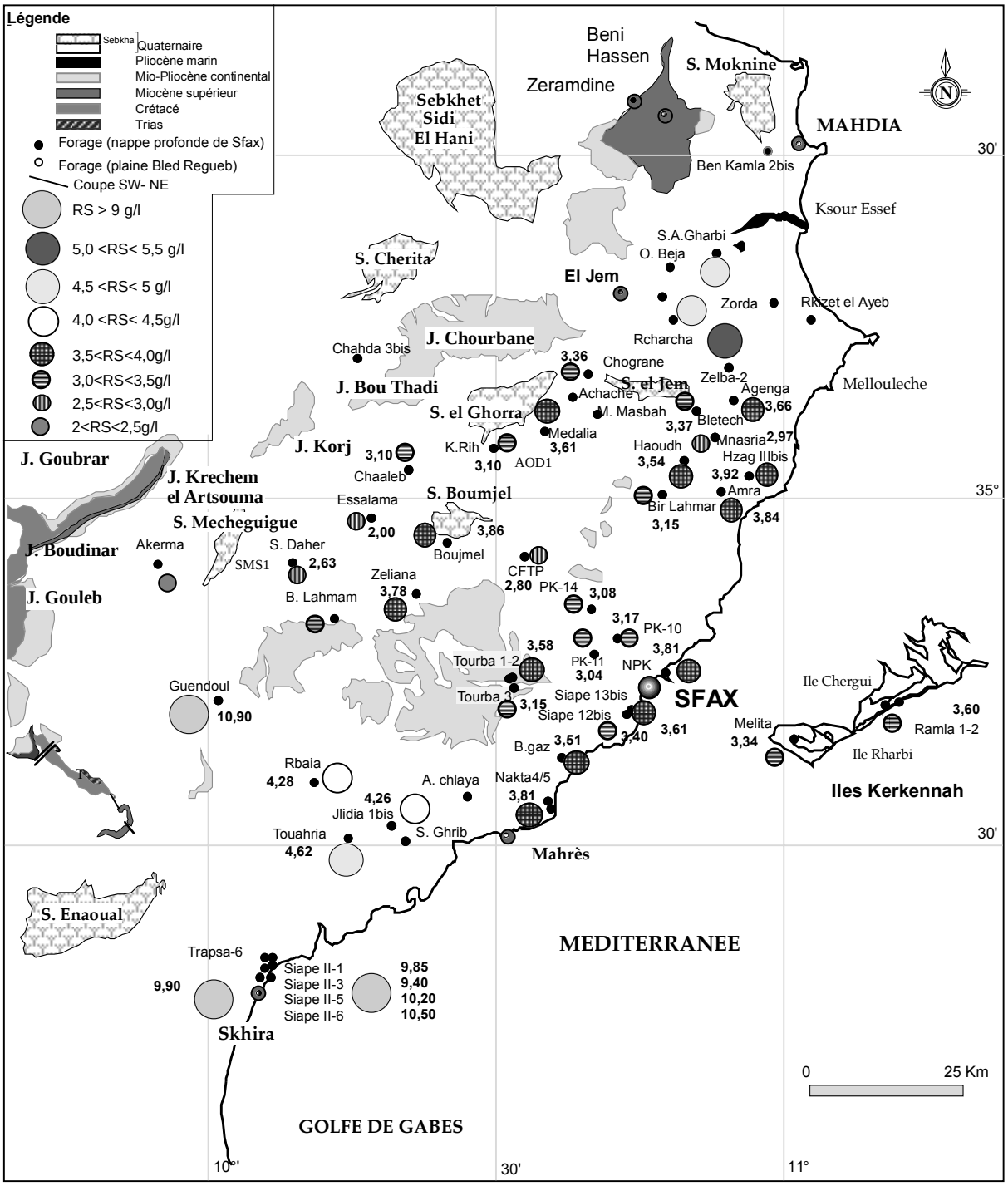


Figure 9: Carte de minéralisation des eaux de la nappe profonde de Sfax

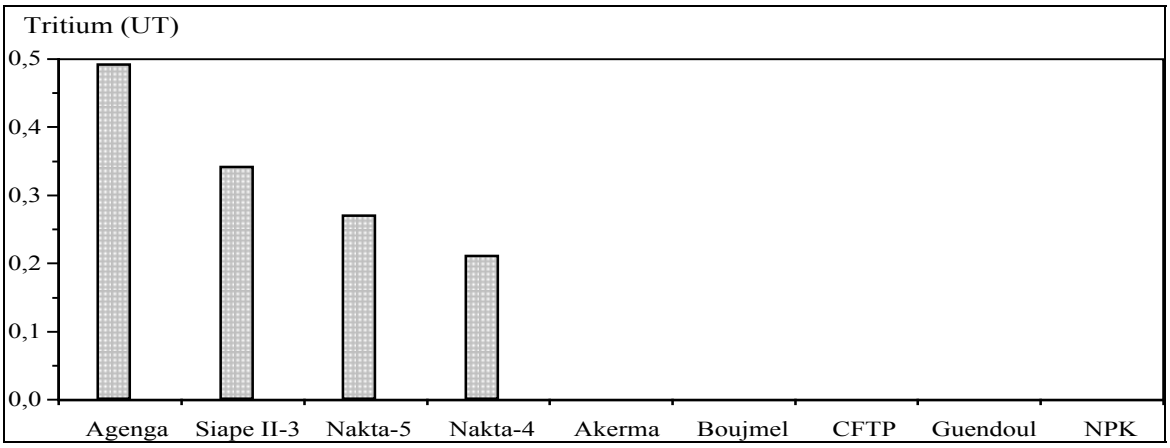


Figure 10: Teneurs en tritium dans les eaux de la nappe profonde de Sfax

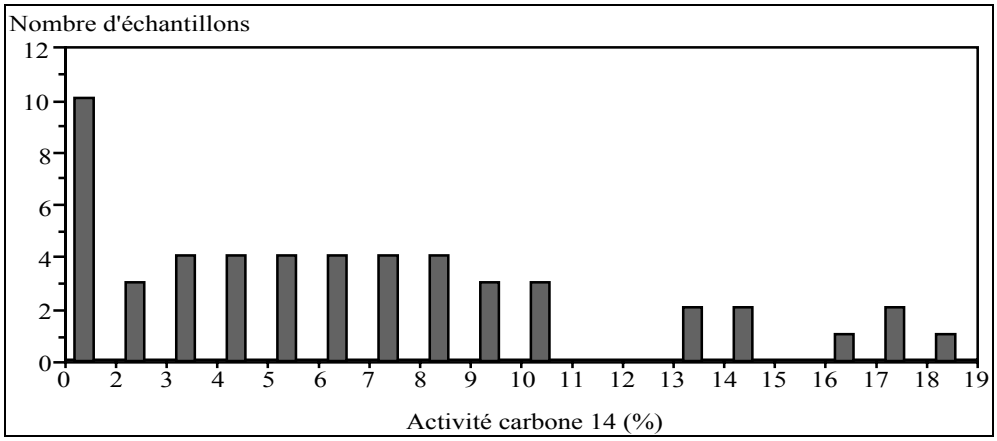


Figure 11: Histogramme de fréquence des teneurs en ^{14}C dans les eaux de la nappe (Maliki, en prép.)

Par ailleurs, les teneurs en isotopes stables (^{18}O et ^{2}H) mesurées dans les eaux de la nappe profonde sont très homogènes et sont centrées respectivement pour juin 1994 et janvier 1995 autour de -6,2 et -6,0 ‰ *vs* V-SMOW pour l'oxygène-18 et autour -40,8 et -40,7 ‰ *vs* V-SMOW pour le deutérium (Maliki *et al*., sous presse). Dans un diagramme $^{18}O/^{18}O$ (Figure 12), les teneurs isotopiques des échantillons prélevés au cours des deux périodes d'échantillonnage (juillet 1994 et janvier 1995) ne montrent pas de différences significatives à l'échelle de la saison (estivale et hivernale), puisque pour la plupart des échantillons, les légères variations que l'on observe s'inscrivent dans les marges d'incertitude analytique.

L'absence de variations marquées à l'échelle de six mois signifie que les variations saisonnières de la recharge sont effacées par un temps de résidence dans l'aquifère beaucoup plus long. Ceci est logique si l'on considère que la nappe est captive sur presque la totalité du bassin.

Dans le diagramme classique $\delta^{2}H$ en fonction de $\delta^{18}O$ (Figure 13), les points représentatifs des eaux de la nappe profonde de Sfax forment un groupe très homogène, ils sont situés pour la plupart, légèrement en dessous de la droite météorique mondiale (Craig 1961). Ces points restent dans tous les cas très en dessous de la droite météorique locale et leurs teneurs isotopiques sont très inférieures aux teneurs isotopiques moyennes pondérées des précipitations actuelles (-4,6 ‰ en ^{18}O et -23,3 ‰ en ^{2}H). Cette différence de teneurs isotopiques peut être liée, soit à un effet d'altitude de recharge, soit un effet paléoclimatique.

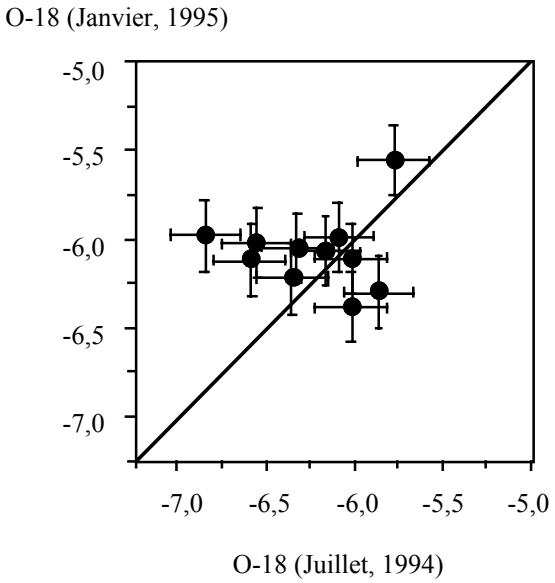


Figure 12: Relation ^{18}O (juillet, 1994)/^{18}O (janvier, 1995) des eaux de la nappe profonde de Sfax

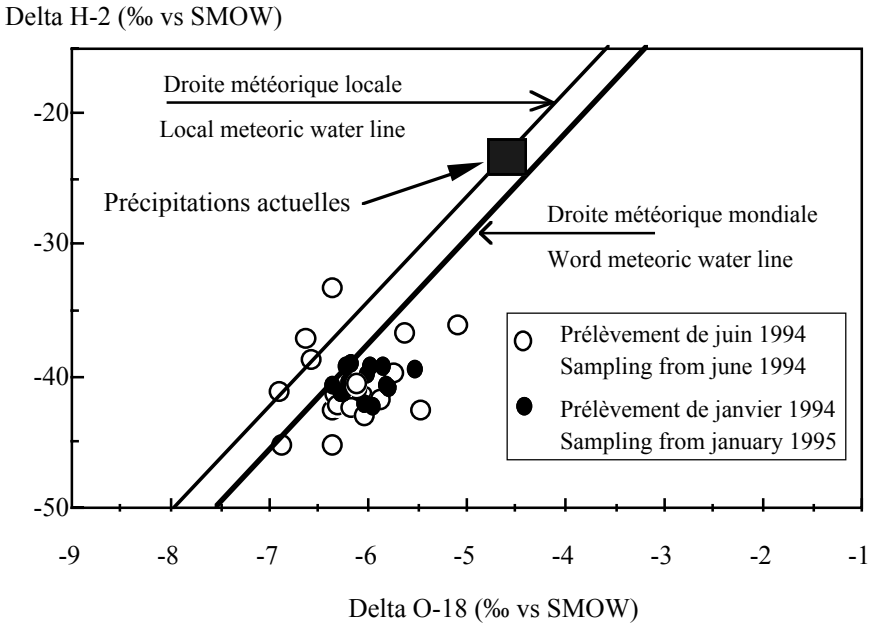


Figure 14: Relation oxygène 18 / deutérium des eaux de la nappe profonde de Sfax

Dans le premier cas, l'altitude de recharge, calculée en adoptant un gradient altitudinal moyen en ^{18}O voisin de 0,3 ‰ par 100 m d'altitude (Blavoux 1978), est de 800 m, alors que l'altitude du point culminant dans le bassin n'est que de 677 m. Donc, les différences dans les compositions isotopiques entre les eaux de la nappe et celles des précipitations actuelles seraient donc essentiellement le résultat d'un effet paléoclimatique, c'est à dire que la recharge se serait effectuée, en grande partie, sous un climat plus froid que celui qui règne actuellement sur la région.

La grande homogénéité des teneurs en isotopes stables de l'eau et des teneurs en carbone-14 suggère un écoulement très lent et de très faibles flux à l'entrée et à la sortie du système. L'état de "quasi-stagnation" de cette nappe en région côtière serait lié aux variations du niveau marin au cours du Quaternaire récent (Maliki *et al*., sous presse). En effet, les écoulements dans la nappe pourraient être en grande partie régis par la charge au niveau de son exutoire, charge qui n'a fait que croître depuis l'époque de recharge si l'on se réfère à l'élévation continue du niveau marin depuis environ 15 ka B.P., suivie de sa relative stabilisation au niveau actuel, depuis environ 7000 ans B.P. (Fairbanks 1989).

5. Conclusion

Cette première étude isotopique de la nappe profonde de Sfax a mis en évidence le caractère ancien de ses réserves. Les activités ^{14}C mesurées dans les eaux (dépourvues de tritium) sont très faibles, pour la plupart, inférieures à 10 %. Ces faibles activités correspondent à des âges corrigés allant de 28 ka à 11 ka. Ces âges confirment que les eaux de la nappe sont très anciennes et reflètent une réserve parfaitement isolée et confinée. En termes paléoclimatiques, la nappe profonde de Sfax est rechargée sous des conditions climatiques très lointaines, vraisemblablement plus froides et différentes des conditions actuelles (période de l'Holocène-Pléistocène supérieur). Ces résultats sont similaires de ceux obtenus dans d'autres systèmes aquifères du Sud tunisien (Zouari 1988) et de la Tunisie centrale (Zouari *et al*. 1999).

Ces eaux profondes anciennes doivent être bien gérées et par conséquent leur exploitation dépend beaucoup plus de certains choix économiques de développement de la région que des caractéristiques de la nappe elle même.

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THEME III: PRINCIPLES OF GROUNDWATER ABSTRACTION FROM FOSSIL AQUIFERS

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Crop response to irrigation with slightly and moderately saline water

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Abstract

This paper presents crops response and yield to different salinity levels of irrigation water (low quality water) obtained through blending of irrigation water with drainage water and through use of saline ground water at field conditions. Crop yields at ACSAD experimental farm located in Deir ezor north east of Syria, agricultural experimental farms in Tunisia and in Libya are presented. Yields functions as related to salinity of irrigation water (EC_{iw}) were obtained using non-linear programming. Threshold data obtained were comparable to EC_e values tabulated by FAO (1992), but not comparable to EC_{iw} tabulated by FAO (1986).

Data of soil moisture extraction obtained by gravimetric soil moisture measurements versus soil depth and time throughout growth period and using tensiometers at three depths: 25 – 50 – 75 m to schedule irrigation time with different quality of irrigation water were used in order to develop soil moisture extraction pattern in the form:

wx=w1(time)*w2(root zone depth)*w3(EC of irrigation water)

Where wx unit is mm/day/cm and w1, w2, and w3 are statistical experimental functions obtained by non-linear programming softwares. Validity of the model obtained was assessed by repeated integral of wx function over depth and time to give the water consumption throughout the irrigation period(Et) in mm in the form of: $Et=\Pi\, wx*dz*dt$ for each salinity level and compared to actual water consumption data. Excellent matching was obtained.

Soil solution obtained by vacuum lysimeters inserted at different soil depths in the root zone was obtained at field capacity and analyzed for cations and anions. Data obtained were correlated to salinity of irrigation water at three levels of leaching fractions, i.e., 0%, 15% and 30% for cotton.

Keywords
Modelling, crop salt tolerance, threshold, soil moisture extraction pattern

1. Introduction

There is a growing demand for fresh water for domestic, agriculture and industrial purposes. Scarcity of good quality water in several regions in the world emphasizes the need to use saline water for agriculture with good farm management.

Many situations exist where saline ground water or agricultural drainage water could be used for irrigation, if the water is readily accessible and available. However, such reuse should be taken only if long term deleterious effects on soil properties can be avoided. Various scientists Rhoades (1987) and Abdelgawad (1981-1993-1995), have concluded that the use of saline water for irrigation is feasible, especially when saline waters are blended with good quality water or alternated especially in case where annual rate rainfall is greater than 200 mm (Abdelgawad 1995) and drainage conditions of soil are adequate. In the Pecas valley, Texas water averaging 2500mg/l TDS has been used for irrigation for decades, Moore and Hefner (1976). In Iraq, pear trees have been grown with water ranging up to 4000 mg/l. In Algeria palm trees (Phoenix dacty lifer) have been grown with water ranging up to 5000 mg/l for centuries In Tunisia and Jordan olive trees (Olea curopaea) have been irrigated with water having 4200 mg/l. In Palestine cotton is grown commercially with 3000 mg/l, Keren and Shainberg (1978). This practices sustained for 15 years but in presence of 400 mm of annual rainfall.

In Sherefsh station in Tunisia, migrada river water with EC of 2.5 - 3.5 ds/m have been used for irrigating semi tolerant and tolerant crops for more than 50 years with no effects on soils in the presence of annual rainfall of 350- 450 mm, Abuaziz (1997). In India irrigation water with EC of 4 to 5 ds/m has been used

successfully over long-term periods, Paliwal (1972). In Uzbekistan cotton irrigated with drainage water having 5000 to 6000 mg/l has been used successfully for many years.

Bressler (1979), Shalhevet and Kumburov (1976) made survey of irrigation water salinity, and concluded that water with salinity as high as 6000 mg/l is acceptable for irrigation. Pillashuvy and Blaney (1966) suggested that the upper limit of the salinity of irrigation water should be up to EC of 7.5 ds/m (about 4800 mg/l). In Libya, water with 5000 mg/l has been used for centuries for irrigation of barly (Hordeum vulgare), tomato (lycopersicon Lycopersicum), alfalfa (Medicago sativa), squash (Spinacia oleracea) and palm trees in the coastal zone of Tripoli, Abdelgawad (1981).

Threshold levels of salinity often used as standards for evaluating irrigation water quality and reflect the response of crops to the average root zone salinity after the establishment of seedlings. Studies conducted in many arid regions of the world have shown that the water conventialy classified as too saline for agricultural use in one area can be used to irrigate certain crops in other area without a significant loss in yield or quality. Abdelgawad et al. (1981, 1995), provided data on such subject on the use of water with 1200 - 8000 mg/l for irrigating barley, wheat (Triticum aestivum), cotton (Gossypium hirsutum), maize (Zea mays), sugar beet (Beta vulgaris), sorghum (Sorghum bicolor), alfalfa, onion (Allium cepa), sorghum, wheat have been grown in Colorado, Arkansas valley, with water containing 1500 mg/l to 5000 mg/l Miles (1977).

This paper presents results of more than three years of field data on crops response to irrigation with saline water in Syria, Tunisia and Libya. It also focuses on water extraction pattern related to salinity of irrigation water. The ionic composition of soil solution as function of ionic component of irrigation water is also presented.

2. Materials and methods

This research was carried out at ACSAD experimental station in Deir Ezor - Syria since 1991 up to date and in Tunisia since 1993 up to date and in Libya since 1993 (1999).

In Syria The soils are torrifluvents thermic mixed, loamy in texture, with soil pH of 7.5, soil water saturation extract (EC_e) of 2 ds/m, and containing 25 percent calcium carbonate. The water used for irrigation of barely,cotton, maize, vetch (Vicia angusti folia), wheat, and alfalfa was drawn from agricultural drainage water with an average electrical conductivity of 11.4 ds/m blended with Euphrates river water from irrigation canals with average EC values of 1.5 ds/m.Appropriate ratios of blending was carried out between drainage water and Euphrates river water in concrete reservoirs to produce EC_{iw} values of 1.5, 4.4, 6.4, 8.4, 9.4 ds/m. The amount of water used in irrigation was based on gravitational measurement of soil moisture at 0.15 m intervals down to 1 m depth to this an additional water was added for each mixture with the purpose of leaching the salts, equivalent to 0, 0.15, 0.3 leaching fraction *LF*. The design of the experiments was randomized block design with leaching fraction were the blocks and salinity levels were the treatments with six replicates 50 m^2each. The experimental areas were irrigated by furrows.

In Tunisia, the soils are silty clay in texture with pH 7.8 ds/m and 35% $CaCO_3$ and classified as torrifluvents mixed xeric silty clay in texture.The design of the experiments was randomized block design with six replicates and a plot size of 1000 m^2. The treatments of water salinity were fresh water of 0.3 ds/m from a water well, migrada river water with EC 2.3 ds/m and agricultural drainage water with EC of 9 ds/m and the mixture between the two to produce EC of 3.9 and 5.4 ds/m. The amount of applied irrigation water was based on previous studies about crop water requirement and crops irrigated were tomato, melon (Citrcullus), maize, pepper (Capsicum annuum), water melon (Citrcullus lanatus), clover Berseem (T. Alexandrianum), potato (Solanum tuberosum) and broccoli (Brassica oleracea botrytis).

In Libya, saline ground waters was used for irrigating barely with EC_{iw} values of 3.9, 8.0, 11.6, 16.7 ds/m with *LF* of 0, 0.1, 0.2.The soils are xeric psamments siliceous sandy in texture, with 95% sand fraction and deep soil profile with pH of 8.0 and 5 % Ca CO_3. Soil samples were collected before irrigation at 0.15 m intervals down to 1.50 m and analyzed for moisture content and 1:5 extract was made to determine the ionic composition. Analyses of soil solution ions were carried out according to the methods of soil chemical analyses edited by Page et al. (1982).

Soil moisture tension was measured by gauge tensiometers placed at depths of 0.25 - 0.5 and 0.75 m. The irrigation water was applied when the soil moisture tension reached 50 centibar at 0.25 m depth in early stages of plant growth and 50 centibar after the mid season. Soil solutions were collected by vaccum lysimeters placed at 0.25 and 0.50 m after 48 hours of irrigation time. The soil solution and irrigation water were analyzed for pH, soluble ions including NO_3, P and Boron.

3. Results and discussions

3.1 Crops yield functions in relation to salinity of irrigation water

Data obtained on yields versus salinity of irrigation water of Syria, Tunisia and Libya were evaluated on the basis of Maas and Hoffman (1977) model in the form:

$$Y = A - B(EC-T) \quad (1)$$

Other shift functions kin to the model in the form of quadrates and exponential

$$Y = A + B\,(EC - T) + C\,(EC - T)2 \quad (2)$$

$$Y = A \exp\,(EC - T) \quad (3)$$

as suggested by Abdelgawad and Ghaibeh (1997) were also evaluated for wheat and maize. Where A is the absolute yield in ton/ha, B is the slope, EC is the mean electrical conductivity of the irrigation water throughout the season, and T is the estimated salinity threshold expressed in ds/m.

Figures 1, 2, 3 and 4 show scatter plot of field data collected in Syria for cotton, maize, wheat and for alfalfa respectively versus EC_{iw}. The response of yield to water salinity had a mode of two macro stages.The first stage with low inclination and the second stage with sharp inclination. The two stages were well defined in case of alfalfa and wheat but not well defined for cotton and maize. However, the obtained field data depict a chaotic response to salinity of irrigation water which reflects the interference of soil, climatic factors and management practices attributes of the quality of irrigation water. Fitting of the data, herewith, reverted to non-linear programming analysis using sequential quadratic programming available in statistical software. The procedure used is a doubly iterative algorithm to search for a solution of the parameters of the linear function. A common constraint was used in the analysis, that was the upper bound for A parameter to equal or less than the maximum yield values obtained. In fact this procedure can also be used to fit data to continuous functions of the kind suggested by Van Genuchten (1983).

Table 1 shows the obtained absolute functions, the thresholds values T, the relative percentage of yield reductions per unit EC of irrigation water s, with different leaching fractions *LF* and the EC of zero-yields.

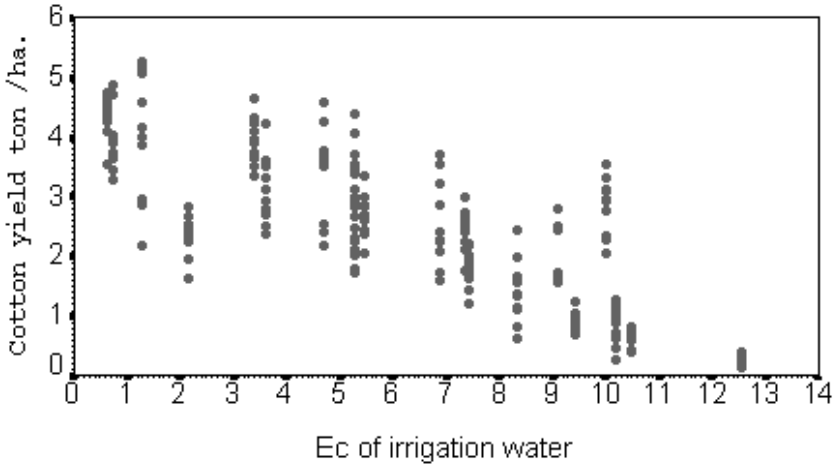


Figure 1: Scatter plot of cotton yield (Ton/ha) versus EC of irrigation water

In Syria, Cotton T values of 4.75, 4.81 and 4.72 ds/m were obtained for the three LF fractions. The corresponding slope values S expressed in percentages were 11, 9.8 and 9.1 respectively. It can be deduced that increasing LF from 0.0 to 0.15 elongated slightly the tolerant stage but further increase of LF depressed it. The S value was also depressed with the rise of LF.

For maize at the same locality, at different leaching fractions the threshold values obtained were 3.99, 4.02 and 3.83 ds/m with an overall value of slope and T were 15.5 % and 3.80 ds/m respectively The high rate of decline for maize can be reasoned that maize is grown in Syria as an intensive crop after wheat, i.e. in hot and low humidity period (July to September). Shift quadratic and exponential functions gave T values of 3.96 and 3.60 ds/m respectively with improvement in R^2. This manifest the sigmoidal response noted by Tanji (1996) for the whole range. For vetch T values obtained were 2.9, 2.99 and 2.98 ds/m and slope value of 6.1%. Data reflect the sensitivity of vetch to salinity but with a low rate of decline. For wheat T values obtained, were 3.61, 5.43 and 4.36 ds/m and the corresponding slopes were 10.2, 8.3 and 9.6% respectively at different leaching fractions. The overall T value was 4.36 ds/m and S value 9.5%. *LF* value of 0.15 increased the T value and depressed S value indicating better condition in the root zone, whereas, *LF* of 0% shortened the

tolerant stage and resulted with higher rate of decline. Shift quadrates and exponential gave T values of 3.1 and 5.4 ds/m respectively with improvement R^2.

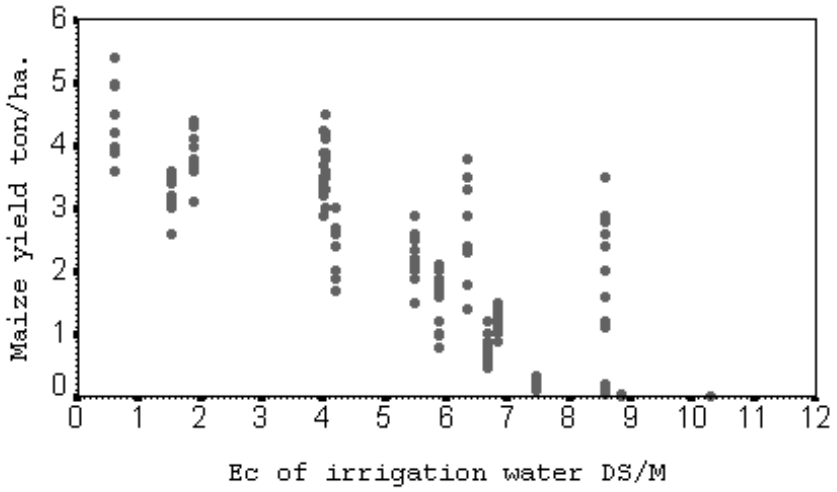


Figure 2: Scatter plot of Maize yield (grain) ton/ha versus EC of irrigation water

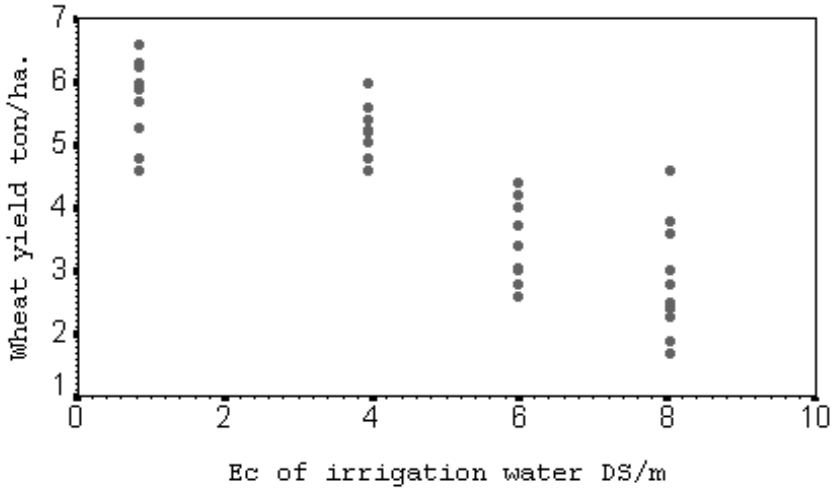


Figure 3: Scatter plot of Wheat yield (grain) ton/ha versus EC of irrigation water

Wheat-hay yield gave T values of 4.6, 7.9 and 7.0 ds/m with corresponding S values of 8.63, 9.91 and 11.6 at different leaching fractions respectively. The T values of hay were higher than the grain T values, whereas, the use of 0.3 LF value depressed T and sharpened slope indicating unfavorable conditions induced by extra water added in the root zone. Barley grain yield gave high T values of 7.1, 8.0 and 5.7 and S values of 7.5, 6.6, 6.6 at different leaching fractions respectively with an overall T value of 7.0 ds/m and S value of 7%. LF value of 0.3 depressed considerably the T value from 8.0 to 5.7. Barley hay yield gave comparable T values to grain yield but with higher rate of decline. Alfalfa dry yield acquired T values of 6.1, 6.1 and 4.4 with S values of 11.7, 11.7 and 10.2 for the three indicated LF values.The overall T and S values were 6.4 and 12.4 respectively. The sharp decrease of T values from 6.1 at LF of 0.15 to 4.4 at LF of 0.3 indicated less favorable root zone conditions with extra amount of water added for leaching. This phenomenon stands for the above discussed crops and can be attributed to the presence of water table close to the surface (1.4 m) and the aridity of the climate which favor the dominance of the upward movement of water in case of extra moisture in the unsaturated zone with high LF value and low hydraulic conductivity of these soils near saturation Ghaibeh (1989).

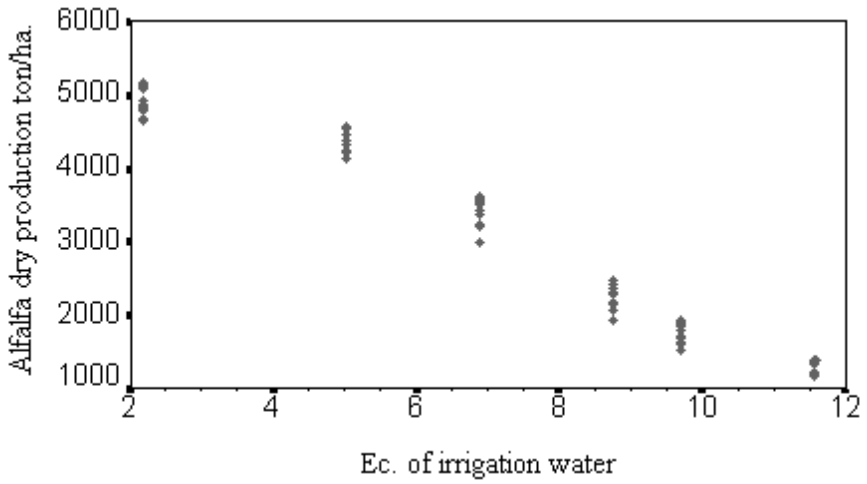


Figure 4: Scatter plot of Alfalfa yield (Ton/ha) versus EC of irrigation water

Yield functions obtained at the locality of Tunisia are shown in Table 1. However, the range of salinity of irrigation water (0.3, 2.3, 3.9, 5.5 ds/m) in general were lower than the irrigation water used in Syria.

In Libya, Tawerga with salinities of the irrigation water of 3.9, 8.0, 11.6 and 16.7 ds/m used to irrigate barley with LF value of 0.10. The T value for grain yield was 7.0 ds/m and T value for hay yield was 6.9 which are comparable to values obtained in Syria with the same variety of barely used. Other studies conducted in Libya by Sror et al. (1977) using wide range of salinity of irrigation water (1.5, 4.7, 9.4, 14.1 ds/m) on three wheat varieties (Bedri, Sedimasri, florance) got T values of 4.7, 4.9 and 4.8 ds/m respectively. Hay yields gave T values of 4.9, 4.8 and 4.5 ds/m respectively less than values obtained from field experiments.

In general it can be noted that long term field experiments gave strong evidence to higher threshold values of the salinity of irrigation water. Their magnitudes are comparable to those values reported by Hoffman et al. (1983) for the saturated soil paste extract. Linear declination of yield occurs as EC of irrigation water surpass the threshold value with mild curvature. It can also be noted that A and T parameters are inherently dependent with unit negative correlation coefficient due to the nature of shift models and actual crop response such negative correlation should be evaluated on different varieties and may have important economical consequences indicating that higher yielding varieties have low threshold values.

Table 1: The absolute yield functions, the threshold values T, the slope % and leaching fractions obtained on the use of saline irrigation water in Syria, Libya, and Tunisia

Syria: EC_{iw} range = 1.5, 4.4, 6.4, 8.4, 9.4, 11.4 ds/m

Crops	Absolute function	Threshold	Slope %	Leaching fraction	EC_{iw} of Zero yield
Cotton	Y = 2.91-0.32 (EC-4.75)	4.75	11.0	0.0	13.8
	Y=2.98 - 0.29 (EC - 4.81)	4.81	9.8	0.15	15.0
	Y=2.64 - 0.24 (EC - 4.72)	4.72	9.1	0.30	15.7
	Y=2.88 - 0.29 (EC - 4.78)	4.78	10.2	all	14.7
Maize	Y=2.76 - 0.48 (EC - 3.99)	3.99	17.5	0.0	9.7
	Y=3.00 - 0.48 (EC - 4.02)	4.02	16.1	0.15	10.3
	Y= 2.73 - 0.42 (EC - 3.83)	3.87	15.5	0.30	10.3
	Y=2.9 - 0.46 (EC - 3.88)	3.88	15.9	all	10.2
Vetch	Y=2.23 - 0.12 (EC - 2.90)	2.90	5.52	0	21.5
	Y=2.46 - 0.15 (EC - 2.99)	2.99	6.10	15	19.4
	Y = 2.4 - 0.16(EC - 2.98)	2.98	6.60	30	18.0
	Y = 2.36 - 0.14 (EC - 2.95)	2.95	6.14	all	19.8
Wheat grain	Y=4.51 - 0.46 (EC - 3.61)	3.61	10.2	0	13.4
	Y=4.23 - 0.35 (EC-5.43)	5.43	8.3	0.15	17.5
	Y=4.50 0.43 (EC - 4.36)	4.36	9.6	0.30	14.8
	Y=4.52 - 0.43 (EC - 4.36)	4.36	9.51	all	14.9
Wheat hay	Y=8.88 - 0.77 (EC - 4.6)	4.6	8.62	0	16.1
	Y=8.82 - 0.87 (EC - 7.89)	7.89	9.91	0.15	18.0
	Y = 8.22 - 0.95 (EC-6.96)	6.96	11.6	0.30	15.6
	Y = 8.24 - 0.864 (EC - 7.2)	7.2	10.4	All	16.7

Syria: EC_{iw} range = 1.5, 4.4, 6.4, 8.4, 9.4, 11.4 ds/m (continued)

Crops	Absolute function	Threshold	Slope %	Leaching fraction	EC_{iw} of Zero yield
Barley	Y = 3.49 - 0.261 (EC - 7.11)	7.14	7.5	0	20.5
grain	Y = 3.5 - 0.232 (EC - 8.02)	8.02	6.6	0.15	23.1
	Y = 3.49 - 0.236 (EC - 5.72)	5.72	6.7	0.30	20.5
	Y = 3.5 - 0.243 (EC - 6.95)	6.95	7.0	All	21.4
Barely Hay	Y = 8.6 - 0.85 (EC - 6.4)	6.4	9.9	0.0	16.5
	Y = 9.0 - 0.85 (EC - 7.33)	7.33	9.5	0.15	17.9
	Y = 8.6 - 0.81 (EC - 6.4)	6.4	9.4	0.30	17.0
	Y = 8.99 - 0.84 (EC - 7.05)	7.05	9.3	All	17.8
Alfalfa Dry Production	Y = 3.65 - 0.43 (EC - 6.1)	6.1	11.7	0.0	14.6
	Y = 3.65 - 0.43 (EC - 6.1)	6.1	11.7	0.15	14.6
	Y = 4.05 - 0.42 (EC - 4.4)	4.4	10.2	0.30	14.0
	Y = 3.41 - 0.42 (EC - 6.4)	6.4	12.4	all	14.5

Tunisia: ECiw range = 0.3, 2.3, 3.9, 5.5 ds/m

Crops	Absolute function	Threshold	Slope %	Leaching fraction	EC_{iw} of Zero yield
Tomato	Y = 50.67 - 7.43 (EC - 3.27)	3.27	14.7	0.15	10.1
Melon	Y = 18. - 1.63 (EC - 1.83)	1.83	9.1	0.15	12.8
Maize	Y = 8.31 - 0.71 (EC - 1.2)	1.2	8.6	0.15	12.9
Pepper	Y = 29.26 - 2.61 (EC - 2.12)	2.12	8.9	0.15	13.3
Water melon	Y = 9.86 - 0.82 (EC - 1.43)	1.43	8.3	0.15	13.5
Clover	Y = 79.99 - 6.07 (EC-0.33)	0.33	7.58	0.15	13.5
	Y = 13.98 - 0.97 (EC - 1.2)	1.2	6.9	0.15	15.6
Potato	Y = 41.89 - 2.3 (EC - 0.58)	0.58	5.5	0.15	18.8
Broccoli	Y = 10.74 - 0.48 (EC - 2.87)	2.87	4.5	0.15	25.2

Libya: ECiw range = 3.9, 8.0, 11.6, 16.7 ds/m

Crops	Absolute function	Threshold	Slope %	Leaching fraction
Barley	Y = 4.59 - 0.08 (EC - 6.97)	6.97	1.72	0.2
Barley hay	Y = 7.694 - 0.19 (EC - 6.89)	6.89	2.49	0.2

3.2 Moisture extraction pattern of cotton in relation to salinity of irrigation water

We present cotton data of measured soil moisture content versus depth, time and salinity of irrigation water in the presence of water table for the years 1994, 1995, 1996 and 1997 which were used to build a model for moisture extraction pattern of cotton in Syria in the form of:

$$wx = (A+B*t + C*t2) \exp (D*z + E*ECiw) \quad (4)$$

Where wx is the rate of moisture extraction by cotton roots in mm/day/depth (cm), t is the time in days, z is soil depth in cm and ECiw is Conductivity of irrigation water, ds/m. Parameter values obtained by non-linear regression analysis were: A = 0.21, B = 0.0001, C = 0.0000095, D = -0.027, E = -0.052 with R2 = 0.64 for 686 cases. Equation (4) was integrated twice over root zone depth z (0 – 1.4 m). and irrigation period of cotton (m) of135 days which is the actual period of irrigation or the weaning time to give Et in mm for each salinity level of irrigation water:

$$Et = \int_0^m \int_0^z wx \, dzdt = m/D \exp (E*EC_{iw}) (A+ B.m/2+C*m^2/3) (1-expDz) \quad (5)$$

The solution of equation (5) for the indicated ECiw range used to give Et of 1214, 1045, 943, 851, 808 mm respectively. These Figures matched closely (± 3%) with the actual average irrigation water values applied and expressed in mm. Et values obtained showed that the rise of ECiw from 1.5 to 9.4 ds/m had reduced water requirements by 33%. However, the reduction in yield amounted to 59%. This can be attributed to the poor stand of plants irrigated with saline water which gave rise to increased direct evaporation from soil surface and the early senescence of crops irrigated with saline water.This is in agreement with the conclusion made by Hamdy (1998).

Figure 5 shows the soil moisture extraction of cotton for the hole growth period (180 days) representing data of three years. Figure 6 shows the soil moisture extraction pattern for wheat obtained in the same period in Syria, differences between the two patterns depict deference between two different root

systems and different growth period (winter crop and summer crops).However the evaluation of such functions is of great importance to apply models such as the simulation model suggested by Gordan and Dutt et al 1972.

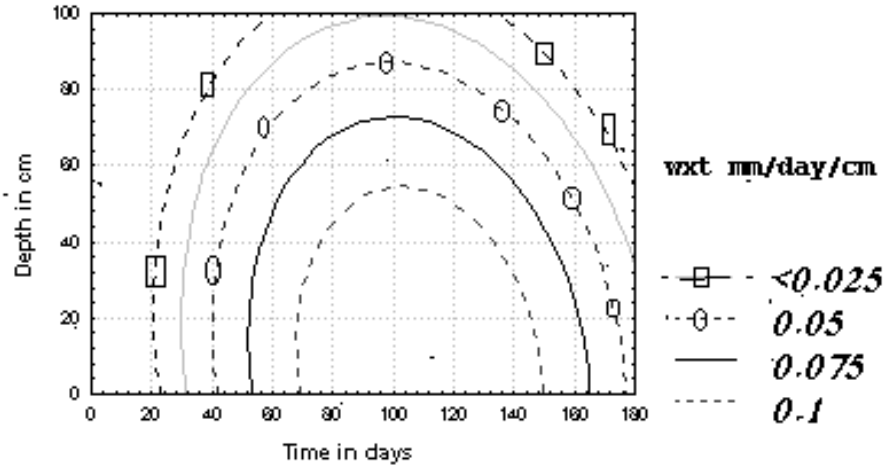


Figure 5: Water extraction of cotton in mm/day/cm versus depth and time for EC_{iw} 7.5 ds/m

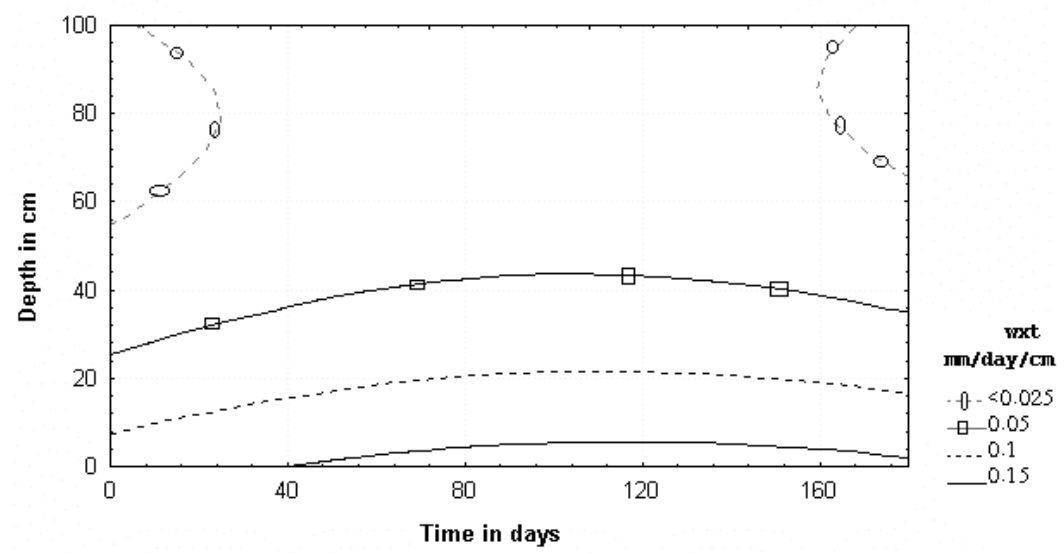


Figure 6 : Water extraction pattern of wheat versus depth and time for EC_{iw} = 7.5 ds/m.

4. Ionic composition of soil solution of cotton root zone in relation to salinity of irrigation water

Soil solution obtained by vaccum lysimeters inserted at 0.25 and 0.50 m within cotton root zone collected 48 hours after irrigation were analyzed for cations and anions. Four years data of ionic composition is presented herewith. Figure 7 depicts the regression equation between EC of soil solution obtained from 0.25 m and 0.50 m vaccum lysimeters. The convex slope of the curves, ie, the tendency of the salinity of soil solution to decline with EC_{iw} of 4 - 5 ds/m and henceforth was attributed to the decrease of moisture extraction with the increase of salinity mainly due to early senescence of crops as shown in Figure 8.

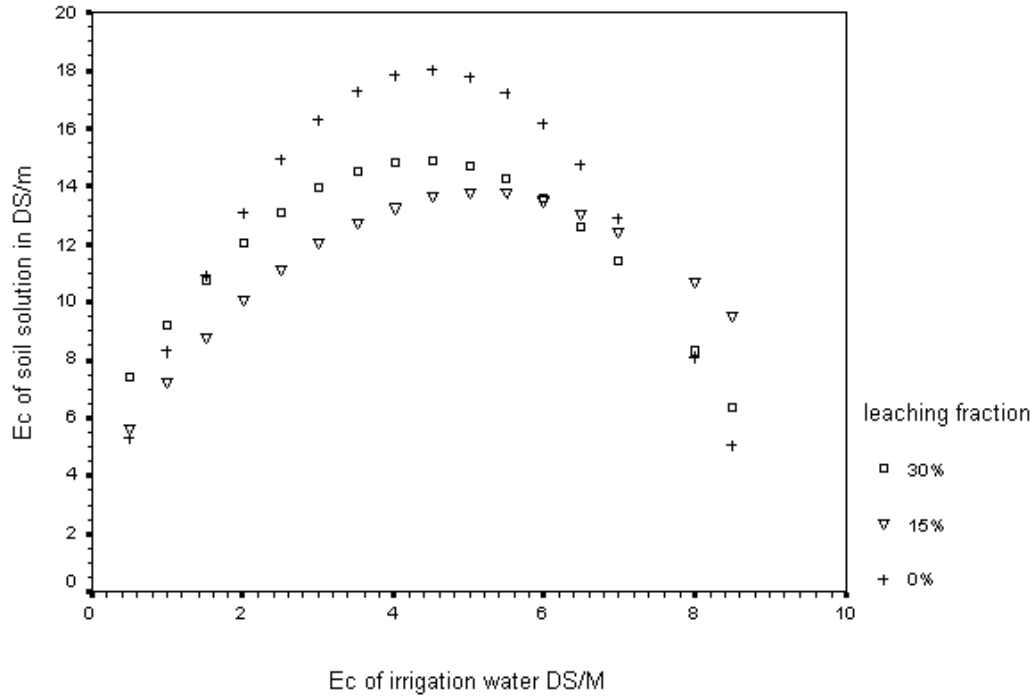


Figure 7: The effect of EC of irrigation water on the EC of Soil solution versus leaching fraction

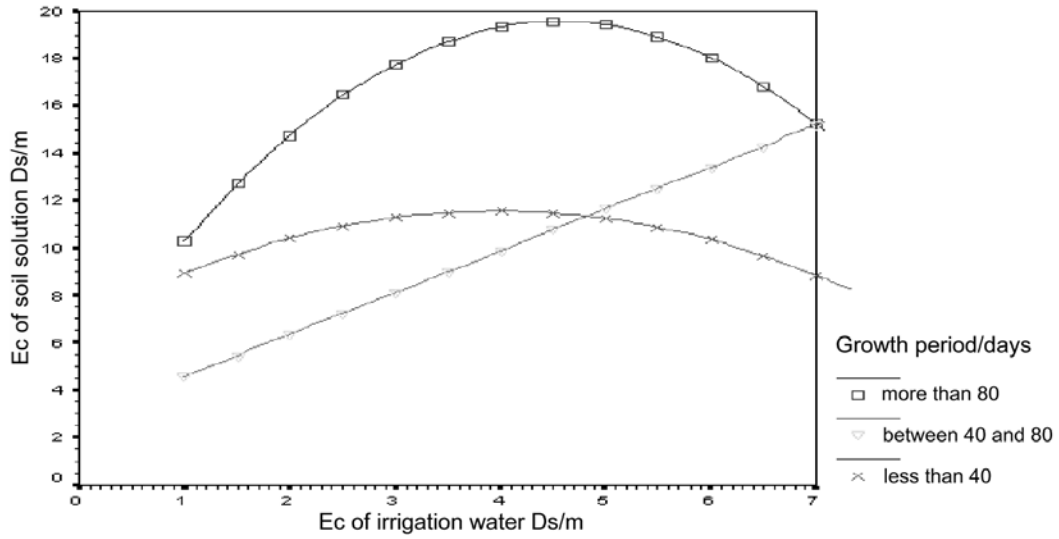


Figure 8: The relation between EC of soil solution and EC of irrigation water versus the growth period

Figure 7 also shows that increasing LF from 0 to.15 depressed the apex of the curves from 18 to 13 ds/m. However, further increase of LF had increased the apex EC_{ss} from 13 to 15 ds/m. This indicate the delicacy of management practices using saline water in arid regions, a phenomenon manifested in yield functions discussed earlier.

Figure 9 to Figure 13 show the corresponding ionic composition of soil solution versus ionic composition in irrigation water ECiw. At 0 LF, sulfate and chloride anions with sodium and calcium cations dominated the soil solution composition. However, chloride apex at 20 meq/l then tended to decline. Increasing LF to.15 had considerable effects on reducing chloride and sulfate concentrations in soil solution. With .15 and .30 LF rates, sulfate ion tended to stabilize near 40 meq/l Figure 10. Figure 12 also indicates an apex for calcium with 30% LF rate at 10 meq/l. It also indicated that the ratio of Ca/Mg in soils solutions approximated unity which might cause serious nutrient problem considering the negative charge of plant membrane and electrostatic theory of cation exchange as indicated by Cramer et al (1986).

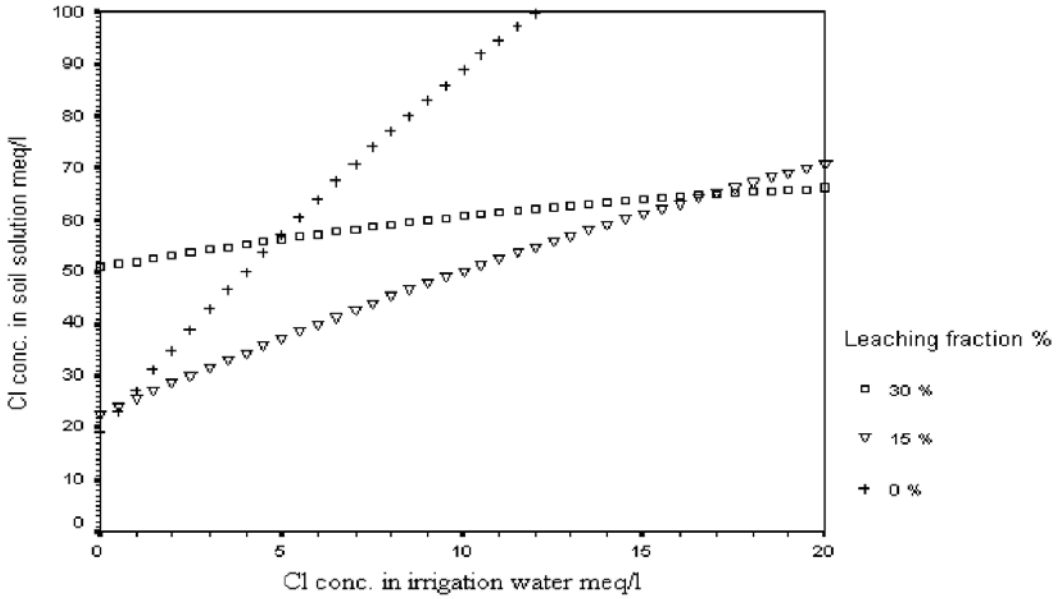


Figure 9: Cl concentration in soil solution as function of Cl concentration in irrigation water

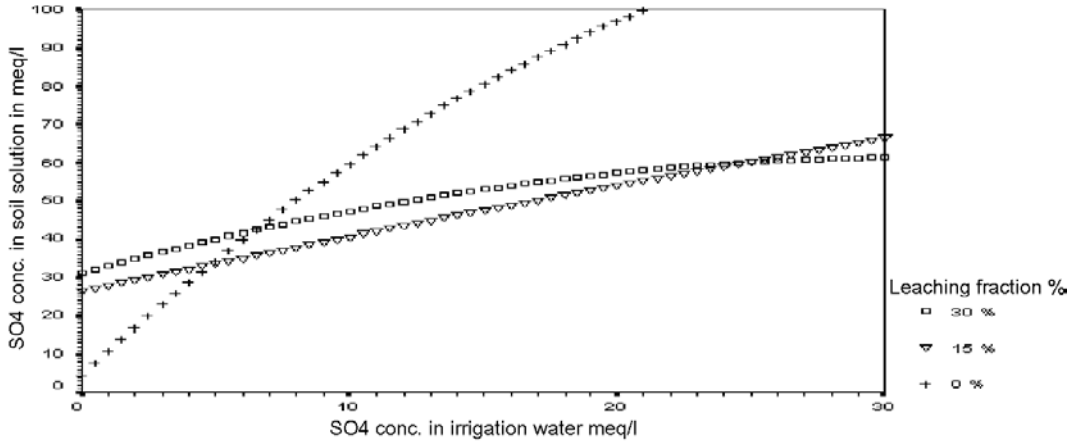


Figure 10: SO_4 concentration in soil solution as function of SO_4 concentration in irrigation water

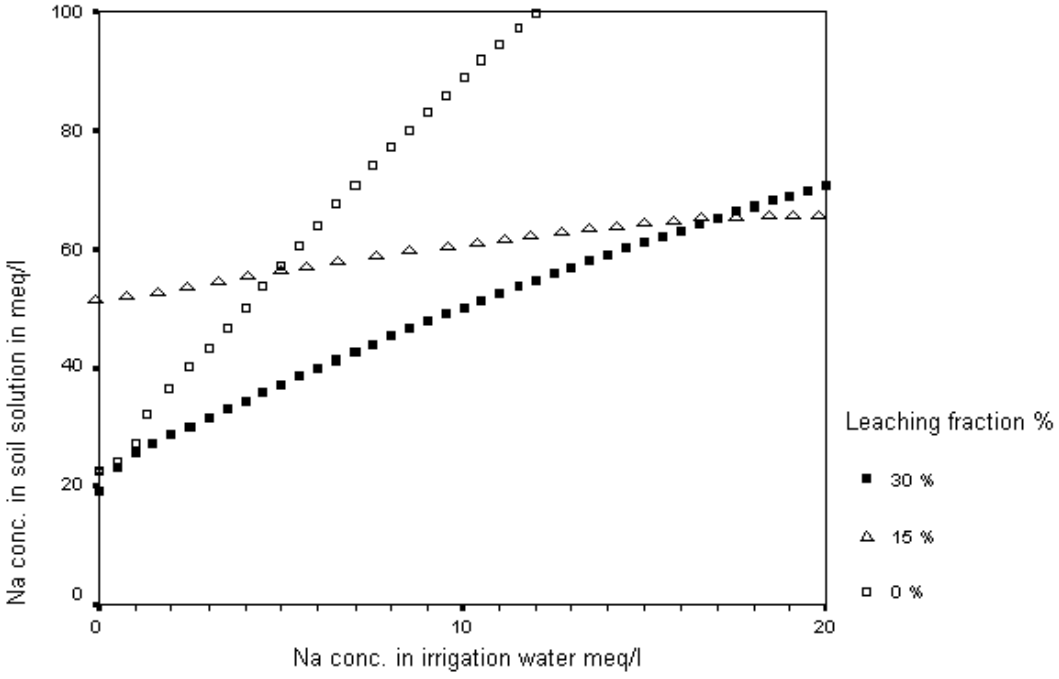


Figure 11: Na conc. in soil solution as function of Na in irrigation water

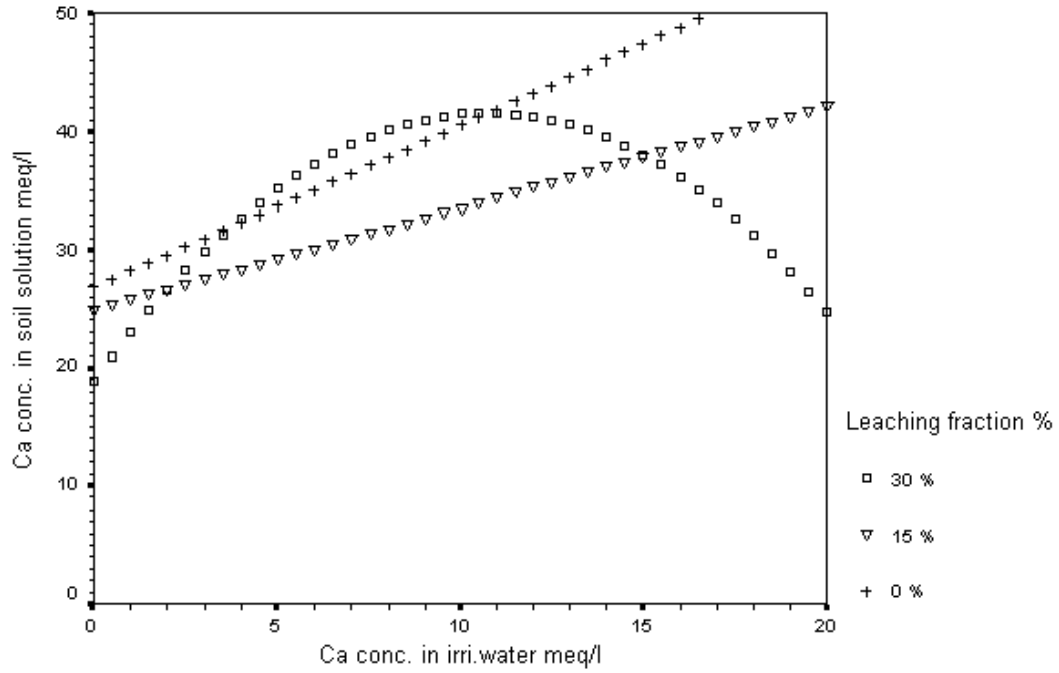


Figure 12: Ca concentration in soil solution as function of Ca in irrigation water

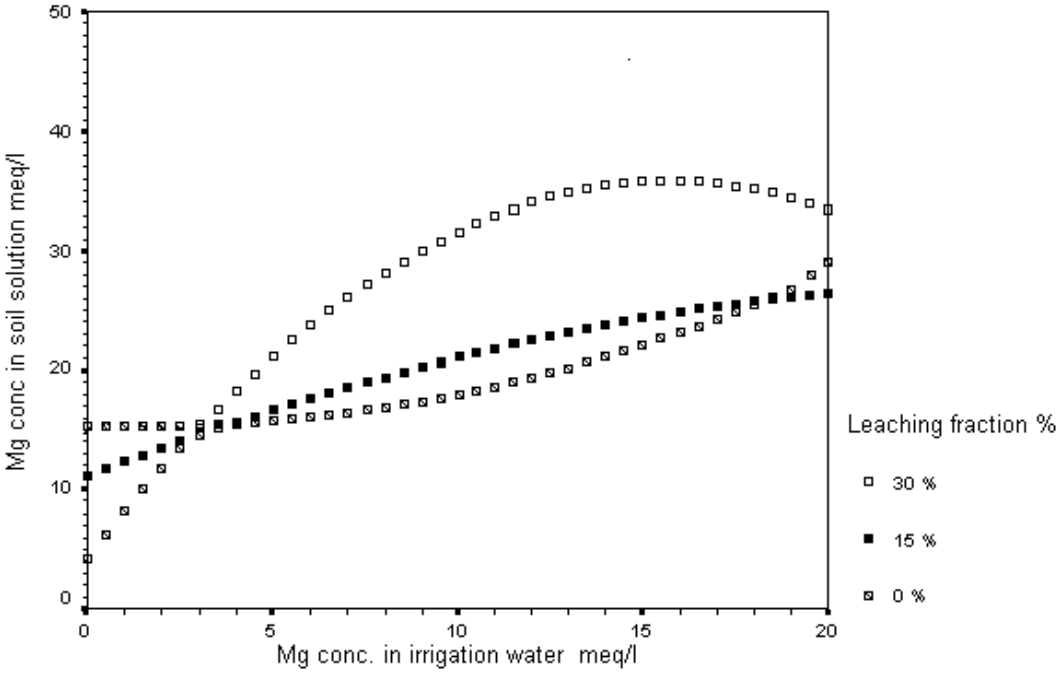


Figure 13: Mg concentration in soil solution as function of Mg in irrigation water

In General a linear relationship between EC_{ss} and EC_{iw} was not found as suggested by Rhoades (1984) a phenomenon to be considered in management practices considering early maturation of crops irrigated with such water.

5. Conclusion

Crop yield functions obtained parameters found to be dependant on leaching fractions. It was also found that a Two-piece model recommended for the relation between yield and ECe by Maas (1986) can be used to fit the model for yield and ECiw.

A models for moisture extraction patterns of cotton and wheat were suggested and were found to be dependant on the salinity of irrigation water, however the reduction in yield exceeded the reduction in moisture

extraction. The models depict a case where water table is close to the surface and under arid condition which favor surface accumulation of salts.

Non linear relationship was also found between ECss and ECiw as well as for cations and anions for different LF values. This was attributed to early senscence of crops irrigated with saline. It was found that LF value of 0.15 was more effective than 0.30 either in depressing the ionic content of soil solution and reflected on an increasing crops yield. This applies to the specific condition of the locality, i.e. water quality used, soil physical properties and drainage efficiency.

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The use of Hydrogeological Model Simulation to locate and optimize wellfield layouts of the Great Man-Made River Project Phase II, North-East and East Jabal Hasouna, Libya

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The wellfields of North-East and East Jabal Hasouna are planned to provide fresh groundwater abstractions with a rate exceeding 2.0 million cubic meters per day to be pumped to the Jefara plain, Tripoli. The wellfields were located and simulated by the use of a quasi-three dimensional numerical referred to as "GEASS" which was developed by the services company, Geomath (1989).

The hydrogeological model represents the Westem Jamahiriya Groundwater Systems (WJS). The model integrates the aquifer systems existing in both Hamadah and Murzuq basins. The model extends beyond the Libyan political boarders into the Republic of Tchad, Niger and Algeria and encompass an area of about 900,000 km^2.

The "GEASS" model represents new added interpretations in the Region of Qargaf and the northern region of the Murzuq basin. The conceptual model plan adopted contains three aquifer units with interbedded two aquitards in each of the two basins.

Steady and unsteady state calibrations were performed using the existing natural water levels before 1970 before the onset of important industrial abstractions in addition to historical water levels' variations in response to industrial exploration between the year 1970 - 1989.

Distributed groundwater abstractions amounting to 2 Mm^3/day were simulated by the model. "GEASS" cntered it five predetermined project areas (north Fezzan, West Fezzan, Sarir Quafussel, Wadi Arriyal and Meknussa). Hydrogeological and economical considerations precluded all the areas except the area of North Fezzan witch has been subsequently extended to provide the target abstractions.

In the extended area of North Fezzan, the hydrogeological model was utilized to forecast future wellfield performance for the 2.0 Mm^3/day abstraction rate between the year (1989 to 2046) from the accessible Cambro-Ordovician Aquifer. In this respect, the simulations corresponding to ten scenarios were performed to identify the most suitable layout wellfield extension for the planned abstractions.

The most promising GMRP wellfield layout has been reached in simulation number (6) for the 2 Mm^3/day rate.

The final layout of two wellfields, a North-East Jabal Hasouna wellfield is located predominantly in the confined aquifer zone and is composed of 133 wells assembled in a line pattern of 1.5 km. Spacing and each well is predetermined to produce with a rate of 45 l/sec.

The Eastern Jabal Hasouna wellfield is composed of 315 wells assembled in a line pattern of 1.5 km. Spacing and occupies the unconfined aquifer areas, each well having a flow rate predetermined as 54.49 l/sec.

Hydraulic optimization of the weilfields collector systems has been achieved by the implementation of three computer programmes in addition to the predicted head produced by the simulation program "GEASS". The programs used are the WATNET-4, the data program rnanager, Master-1 and the costing program, Cost-1. The hydraulic opimizations were run using the wellfield layout, WJS-1. Which is an improved modification of the layout corresponding to optimization No.6.

Recent piezometric distribution recorded in the North-East Jabal Hasouna wellfield exhibited very low drawdowns less than 2.51 m. And corresponding to an average abstraction rate of 250,000 m^3/day for a period of thirty months, which is in acceptable result when compared with the previous simulations.

Jean-Marc LOUVET et Jean MARGAT

Quelles ressources en eau les grands réservoirs aquifères offrent-ils ? Evaluation et stratégie d'exploitation

(Which type of water resources offer big reservoir aquifers? Evaluation and strategy of exploitation)

Observatoire du Sahara et du Sahel
Paris, France

Abstract

Considerable but non-renewable groundwater resources could be provided by the deep aquifer reservoirs of the large sedimentary basins. Those aquifers are usually confined, often initially artesian. Their reserves are voluminous and part of them may be abstracted, to depletion, for tens of years.

Many regions of the world are concerned with those resources. While they are not essential in countries with a temperate or humid tropical climate where ground and surface water are renewable, abundant and very predominant, non-renewable resources become of vital importance in arid or semi-arid zones where renewable resources, generally internal, are limited and irregular. At the present time, mining exploitation of "fossil water resources" already contributes to a large extent to the water supplies of these countries.

These resources are first characterised by a specific ratio between the huge volumes of reserves in the aquifers and the very low average present recharge flow. Another characteristic concerns the acceptable economic conditions for groundwater abstraction, without degradation of its qualities, nor negative impacts on the environment. Assessing these resources is therefore inseparable from the choice of an exploitation strategy. This implies - as for any mining exploitation - a compromise between the intensity and the duration of production, *i.e*. between a high rate of development on the short term, and a more moderate development but more "sustainable", though always and unavoidably limited in time.

Furthermore, managing these resources creates specific problems when the natural contours of the aquifers extend over borders, sharing their resources between several countries. The distribution of these resources then becomes more complex than sharing out the flow of transboundary rivers: it implies equity of influences from all parties concerned and joint co-operation in development policies and plans.

Reviewing assessment and management modalities for these non-renewable resources is the subject of the proposed paper.

Résumé

Des ressources en eau souterraines considérables mais non renouvelables sont offertes par les réservoirs aquifères profonds des grands bassins sédimentaires. Les nappes sont généralement captives et souvent initialement artésiennes, et à réserves volumineuses dont une partie peut être extraite, en régime d'épuisement, durant des décennies.

Ces ressources sont présentes dans de nombreuses régions du monde. Mais, alors qu'elles sont accessoires dans les pays à climat tempéré ou tropical humide où les ressources en eau renouvelables, superficielles et souterraines, sont abondantes et très prédominantes, les ressources non renouvelables prennent une importance relative capitale en zone aride ou semi-aride où les ressources renouvelables, surtout intérieures à chaque pays, sont rares et irrégulières. L'exploitation minière des « eaux fossiles » contribue dès à présent largement aux approvisionnements en eau dans ces pays.

Ces ressources se caractérisent d'abord par un rapport spécifique entre les volumes des réserves des aquifères, très grands, et des flux moyens de renouvellement actuels, très faibles. Puis par des conditions économiques acceptables d'extraction de l'eau, sans détérioration des qualités, ni impact dommageable pour l'environnement. Leur évaluation est donc inséparable du choix de stratégie d'exploitation qui - comme pour toute exploitation minière - implique un compromis entre l'intensité et la durée des productions, entre un développement plus rapide mais à plus court terme, et un développement plus modéré mais plus « durable », quoique toujours temporaire.

De plus, la gestion de ces ressources pose des problèmes particuliers lorsqu'il s'agit de réservoirs aquifères transfrontaliers, qui rendent les ressources communes à plusieurs pays. La répartition de celles-ci est alors plus complexe que le partage du débit de fleuves transfrontaliers : elle implique une équité des influences respectives et la concertation des politiques et des plans d'exploitation.

La revue des modalités d'évaluation et de gestion de ces ressources non renouvelables est le sujet de la communication proposée.

1. Introduction

Les ressources en eau souterraine sont le plus souvent renouvelables, tout comme les ressources en eau superficielles. Ainsi, dans les régions tempérées ou intertropicales, les réserves aquifères ont surtout une fonction régulatrice qui facilite notamment l'exploitation des ressources en eau souterraine renouvelables. Les bases de leur évaluation et l'orientation de leur gestion reposent sur l'instauration d'un régime d'équilibre dynamique moyen, sinon à court terme, entre les flux naturels d'apport d'une part, les quantités prélevées et les flux sortants à conserver d'autre part.

Dans différentes régions du monde, grâce à des conditions géologiques favorables, de grands bassins sédimentaires d'une épaisseur de plusieurs milliers de mètres de sédiments détritiques et d'une superficie de plusieurs centaines de milliers de km^2, renferment des réserves en eau souterraine profondes appréciables (de l'ordre de plusieurs milliers de milliards de m^3 à des profondeurs pouvant atteindre mille à deux mille mètres suivant les bassins). Les apports potentiels sont très faibles au regard des volumes très importants qu'ils renferment; c'est pourquoi on qualifie ces ressources de non renouvelables.

De tels réservoirs aquifères et les ressources qu'ils offrent, existent dans les régions arides et semi-arides, notamment en Afrique saharienne et sahélienne où leur importance devient naturellement primordiale et où leur extension les rende souvent communs à plusieurs pays.

EN QUOI CONSISTENT LES RESSOURCES EN EAU SOUTERRAINE NON RENOUVELABLES ?

Tout réservoir aquifère contient un certain volume d'eau, variable, dont l'ordre de grandeur moyen peut être comparé aux flux moyen qu'il reçoit et qu'il débite, en renouvelant son stock. Tant que ce volume est de l'ordre d'une à plusieurs dizaines de fois de fois celui du volume moyen annuel des apports et du débit. Dans ce cas, on parle alors de ressources renouvelables et la réserve de l'aquifère joue essentiellement un rôle régulateur d'abord vis à vis de son débit naturel, toujours plus régulier et plus continu que son alimentation, puis en permettant un certain degré de liberté du régime d'exploitation par rapport à celui des apports.

Lorsque le volume en réserve atteint des centaines ou des milliers de fois celui du flux moyen annuel l'aquifère peut offrir une ressource non renouvelable c'est à dire la possibilité d'extraire une partie du stock pendant une durée limitée mais assez longue (de l'ordre de plusieurs décennies ou siècles) en produisant annuellement des quantités d'eau sans commune mesure avec celles qui seraient fournies par le seul captage du flux moyen de l'aquifère en régime d'équilibre. De toute façon, les exploitations des ressources strictement renouvelables, visant un régime d'équilibre dynamique final, nécessiteraient aussi une certaine ponction sur la réserve pendant une phase initiale de réorganisation des écoulements vers les captages impliquant des rabattements non négligeables.

Ces réserves considérables accumulent donc des eaux dont les apports s'échelonnent sur de très longues périodes, aussi sont-elles parfois qualifiées de "fossiles". Elles sont peu sensibles aux fluctuations actuelles des conditions hydroclimatiques. Mais elles ne sont pas pour autant inertes ou passives et elles participent à la dynamique actuelle des aquifères.

Non renouvelable doit donc s'entendre non pas dans l'absolu comme le pétrole ou le charbon, mais relativement à l'échelle humaine des projets de développement (et des durées d'amortissement des investissements…).

Dans les régions arides et semi-arides où les ressources en eau renouvelables sont rares et irrégulières, ces ressources en eau non renouvelables (à l'échelle humaine), de volumes considérables et indépendantes du climat présent, sont d'une grande importance économique (développement agricole - irrigation - et l'alimentation en eau des populations) et forment souvent la principale source permanente d'approvisionnement en eau actuelle. Bien que leurs réserves exploitables n'aient pas été estimées suivant des approches comparables suivant les pays, leur mobilisation peut compenser les défaillances des ressources conventionnelles, notamment en cas de sécheresses, etc. occupant ainsi une place originale et constituant parfois un enjeu d'importance primordiale à long terme.

L'évaluation et la gestion de ces ressources particulières soulèvent donc des questions spécifiques qui se distinguent des démarches classiques de la gestion des ressources en eau renouvelables. En

particulier parce que la mobilisation de ces eaux souterraines est nécessairement limitée dans le temps et n'autorise que des options à moyen ou long terme.

Il est essentiel que cette spécificité soit bien comprise par les autorités responsables de l'aménagement et de la gestion des eaux.

L'exploitation "minière" de l'eau souterraine n'est donc pas affranchie de certaines contraintes. D'abord des contraintes économiques stricto sensu : la durée d'exploitation choisie doit être compatible avec celle d'amortissement acceptable des investissements requis, ce qui conditionne l'intensité de production requise. Mais aussi des contraintes d'économie d'eau plus large : cette exploitation ne peut coexister avec un captage séparé du seul débit renouvelé de l'aquifère considéré. La possibilité d'extraction de la réserve qui implique de grands rabattements de niveau remet nécessairement en cause la conservation ne serait-ce que partielle des captages en régime d'équilibre (notamment par des procédés gravitaires traditionnels en certaines pays ou par des puisages extensifs à faible profondeur) ou encore des débits effluents naturels (sources, etc.).

Ces contraintes sont atténuées en zone aride en raison d'abord de la valeur accrue de l'eau due à sa rareté relative et à la faiblesse des émergences permanentes.

Les ressources en eau renouvelables ou non renouvelables sont donc les termes d'une alternative plutôt que deux ressources complémentaires dont les systèmes d'exploitation pourraient coexister et les productions s'additionner :

- Ou bien on exploite les seules ressources renouvelables avec une production minime mais "durable" et suivant des coûts énergétiques stables après la phase initiale de croissance et de mise en équilibre ;
- Ou bien on exploite les ressources non renouvelables avec une production beaucoup plus forte suivant des coûts croissants (passage de l'artésianisme au pompage, etc.) et en entravant dans une certaine mesure - en tous cas en retardant beaucoup - un éventuel retour à long terme à l'exploitation des seules ressources renouvelables de l'aquifère.

QUELS SONT LES GRANDS RESERVOIRS AQUIFERES DU SAHARA ET DU SAHEL OFFRANT DES RESSOURCES EN EAU NON RENOUVELABLES ?

Pays concernés	Dénomination	Etendue en 1000 km^2	Volume en réserve estimé en 10^9 m^3	Alimentation moyenne actuelle estimée en 10^6 m^3/an	Durée de renouvellement théorique en années
Egypte, Libye Soudan et Tchad	Système aquifère Nubien	2 000	75 000	≅ 1 000	75 000
Algérie, Libye et Tunisie	Système aquifère du Sahara septentrional (Complexe terminal)	350	≅ 20 000	580	35 000
Algérie, Libye et Tunisie	Système aquifère du Sahara septentrional (Continental intercalaire)	600	≅ 40 000	270	150 000
Niger, Nigeria, Mali et Algérie	Bassin d'Iullemenden (Continental intercalaire)	≅ 500	10 à 15 000	≅ 800	10 à 20 000
Sénégal et Mauritanie	Bassin sénégalo-mauritanien (Maestrichtien)	200	≅ 1 500	130	≅ 12 000

2. Comment evaluer les ressources en eau non renouvelables ?

L'évaluation de ces ressources doit d'abord reposer sur l'estimation des réserves d'eau souterraine accumulées basée sur des données et connaissances adéquates, validées et utiles à l'échelle des systèmes de ressource (comportement hydrodynamique, voire hydrochimique, des réservoirs aquifères en régime d'exploitation, etc.). Cette estimation doit être établie non seulement en valeur absolue des réserves stockées

mais porter plus précisément sur les réserves exploitables suivant des critères techniques et économiques pertinents.

L'exploitation minière des eaux souterraines non renouvelables ne doit pas être confondue avec la surexploitation des ressources renouvelables qui correspond à une exploitation le plus souvent involontaire en régime de déséquilibre et donc à une gestion défectueuse …

La démarche d'évaluation consiste alors :

- A estimer le volume d'eau en réserve dans un aquifère et à la comparer au flux d'alimentation actuel afin d'apprécier si le taux de renouvellement est compatible avec l'offre de ressources non renouvelables. Cette estimation ne doit pas se réduire au chiffrage d'un volume d'eau global mais doit le répartir dans l'espace en fonction de la structure du réservoir aquifère, de ses variations de puissance et surtout de l'importance et des positions respectives de ses composantes dont les coefficients d'emmagasinement sont différents. L'estimation de réserve est donc inséparable de la description du réservoir.
- A identifier les contraintes et les critères d'exploitabilité : profondeurs maximales admises des niveaux abaissés (niveaux dynamiques dans les forages) liées aux coûts maximaux unitaires de production supportables au stade final ; flux à conserver éventuellement à certaines limites ; qualité d'eau à conserver lorsqu'elle peut être dégradée par mélange avec des eaux attirées par l'effet des forts rabattements ; limitations aux possibilités d'implantation des ouvrages d'exploitation (difficultés d'accès, etc.).
- A concevoir plusieurs scénarios d'exploitation contrastés en durée et en intensité de production, mais correspondant à des projets compatibles par exemple avec les potentialités agricoles, les croissances de demandes en eau ou les capacités d'investissement ; puis à éprouver leur faisabilité dans les conditions physiques de l'aquifère et à estimer les impacts respectifs pour les comparer aux contraintes.
- Enfin à évaluer les volumes d'eau exploitables suivant les différents scénarios tout en respectant les contraintes.

A l'instar des ressources en eau renouvelables, les ressources en eau non renouvelables exploitables - et non simplement les volumes stockés - ne peuvent être évaluées de façon unique mais toutefois peuvent s'exprimer :

- Soit par une fourchette de volumes d'eau productibles en référence à un horizon fixé, convertis en production moyenne annuelle au cours de la durée correspondante ;
- Soit par une fourchette de volumes d'eau totaux extractibles en référence à un abaissement régional maximal admissible et à des coûts de production supportables en stade final ; et ce, en se basant dans les deux cas sur des scénarios et des plans d'exploitation réalisables.

Les modèles de simulation hydrodynamique sont les outils les plus appropriés pour étudier la faisabilité des programmes d'exploitation, déterminer leurs impacts et opérer les nécessaires exercices de gestion prévisionnelle. De tels modèles ont déjà été réalisés à ces fins au cours des dernières décennies pour la plupart des grands systèmes aquifères du Sahara et du Sahel ou sont l'objet de projets actuels pour leur actualisation.

LES MODELES DE SIMULATION HYDRODYNAMIQUE :
OUTILS D'EVALUATION ET DE GESTION PREVISIONNELLE

Basés sur des modèles conceptuels pertinents, les modèles de simulation hydrodynamiques sont d'abord des instruments de connaissance et de compréhension du fonctionnement des systèmes aquifères en vérifiant la cohérence entre les données observées, les hypothèses et les résultats de calculs. Ce sont ensuite des simulateurs de comportement permettant de prévoir les conséquences d'actions sur le système, notamment de scénarios d'exploitation, la validité de leurs réponses étant fonction de leur représentativité.

Ces modèles - qu'ils soient monocouches ou multicouches - doivent être aptes à simuler des évolutions en régime transitoire de longue durée. La validité des coefficients d'emmagasinement adoptés est donc ici primordiale.

Ces modèles ont surtout servi jusqu'ici à fournir des éléments d'appréciation et de comparaison de différentes variantes de projets d'exploitation à des horizons définis. Ils devraient pouvoir davantage servir à estimer les réserves exploitables, à calculer les volumes extractibles correspondant à des abaissements de niveaux jugés acceptables quel que soit l'horizon défini, moyennant toujours toutefois des plans d'exploitation réalisables.

Ainsi, l'évaluation des ressources en eau non renouvelables exploitables est indissociable d'exercices de gestion prévisionnelle et du choix de stratégie d'exploitation. Il convient donc de replacer ce type d'estimation dans le contexte des plans d'exploitation et de développement à long terme envisageables tenant compte des sites et des régimes de production possibles et permettant le choix entre différents scénarios fiables et à long terme.

De tels choix appellent ainsi plusieurs remarques et questions :

- Convient-il de s'engager dans une telle politique d'exploitation minière de l'eau, créatrice de richesse appréciable à moyen et long terme, mais non durable et nécessitant de penser dès maintenant à des reconversions inévitables qui entraîneront des coûts sociaux importants ?
- Faut-il privilégier les avantages à court terme des exploitations « minières » dans un contexte économique présent ou bien dans une optique plus patrimoniale, répartir leurs bénéfices entre plusieurs générations afin notamment de reculer les échéances de reconversion, mais dans un contexte futur incertain (coût de l'énergie, valeur des productions permises par l'utilisation de l'eau, etc.) ?
- Dans quelle mesure les bénéfices tirés de l'utilisation de l'eau (indépendamment de la répartition des coûts de production) doivent-ils concourir à préparer les relais vers une économie de l'eau future compatible avec les principes du développement durable, donc basé sur les seules ressources en eau renouvelables, conventionnelles ou non ?
- Enfin, le caractère transfrontalier associé à la nature non renouvelable des réserves en eau des aquifères des grands bassins empêchent de dresser des bilans et analyses homogènes et cohérents et rend difficile une approche unitaire et concertée de leur gestion : le choix de stratégie d'exploitation, notamment des paramètres d'intensité et de durée, pose encore aujourd'hui des problèmes géopolitiques liés aux influences potentielles des exploitations entre pays partageant une même ressource.

3. Quelle stratégie d'exploitation choisir ?

L'exploitation d'aquifères profonds a débuté en différents pays de la zone aride et semi-aride dès qu'ils furent découverts et que les moyens techniques et économiques requis le permirent. Cette exploitation fut souvent facilitée par le jaillissement initial des puits - l'artésianisme - et croissante ce qui a entraîné des baisses de niveau et/ou de débits jaillissants appréciables avec le temps. Mais cette exploitation ne s'accompagnait pas de la conscience qu'il s'agissait d'une ressource non renouvelable, ni de la conception d'une stratégie à long terme. Les premières études se sont intéressées surtout à la productivité des forages et la ressource à exploiter était conçue comme un flux entretenu par l'alimentation et donc considérée comme une ressource renouvelable, alors qu'en fait on entamait déjà les réserves. L'étude du système aquifère du Sahara septentrional en Algérie et en Tunisie par l'UNESCO au début des années 70 fut l'un des premiers exercices d'évaluation de ressource et de plan de gestion basé sur des simulations hydrodynamiques de scénarios d'exploitation à long terme. Aujourd'hui, les conditions sont réunies pour qu'un nouveau projet soit mené à la suite de cette première initiative : dans le cadre de l'Observatoire du Sahara et du Sahel, il a pour objectif l'optimisation de la gestion des ressources en eau du système aquifère partagé entre l'Algérie, la Libye et la Tunisie par :

- l'actualisation de l'évaluation des ressources en eau pour permettre de prévoir l'impact des scénarios futurs de développement dans les pays eux-mêmes et potentiellement au delà des frontières ;
- la mise en place d'un mécanisme de concertation au niveau du bassin en vue d'assurer une gestion harmonieuse de ces ressources en eau communes aux trois pays.

4. Exploitation minière des ressources non renouvelables ou captage des ressources renouvelables ?

Avec la prise de conscience du caractère non renouvelable à l'échelle humaine de la ressource offerte par l'exploitation des stocks des grands réservoirs aquifères, et donc de sa limitation à long terme, la première question qui se pose est de savoir s'il est opportun ou non de s'engager dans cette exploitation et quelle place il est prudent de lui accorder dans l'économie de l'eau nationale et le plus souvent régionale. En zone aride, hors des secteurs qui disposent de ressources renouvelables abondantes - notamment grands fleuves transfrontaliers avec leurs aquifères alluviaux - il est incontestable que l'exploitation des réservoirs aquifères à réserves considérables est avantageuse et constitue un facteur de développement appréciable.

Néanmoins, deux conditions spécifiques aux zones arides favorisent la faisabilité d'une telle exploitation :

- Les critères de coût de production acceptable sont très influencés par la rareté et la faiblesse des ressources renouvelables : plus qu'ailleurs la production d'eau par extraction des réservoirs est compétitive par rapport à d'autres choix, transferts d'eau par exemple.
- Les contraintes de conservation des débits naturels d'émergence de ces aquifères sont réduites du fait qu'une grande partie est en fait évaporée et que les débits de source sont petits par rapport aux productions praticables, donc leur tarissement peut être quantitativement facilement compensé. C'est ainsi que les exploitations du Continental intercalaire en Algérie dans la région de l'oued Rhir depuis le milieu du XIX^{e} siècle ont extrait de la réserve plus de 2 milliards de m^{3} d'eau jusqu'en 1981, soit environ 10 fois plus que le préjudice subi par les sources qui débitaient initialement à peine 200 l/s. et dont le débit a été progressivement réduit des deux tiers. Ces situations peuvent toutefois appeler des problèmes sociaux à ne pas négliger dans un contexte d'exploitation traditionnelle des résurgences de ces aquifères.

Néanmoins, s'engager dans l'exploitation minière d'un réservoir aquifère doit être un choix réfléchi de politique de l'eau tenant compte non seulement des avantages immédiats et à moyen terme procurés, mais aussi des problèmes qui seront posés à long terme par l'épuisement de la ressource et auxquels il faudra nécessairement faire face.

5. Comment gérer les ressources en eau non renouvelables ?

La première question est celle du choix du couple intensité-durée de production, comme pour toute industrie minière : produire plus moins longtemps ou moins plus longtemps ?

Un premier critère est microéconomique : la durée doit être accordée au moins à celle souhaitée pour amortir les investissements - qui peuvent être eux-mêmes divisés et étalés dans le temps, notamment en fonction des choix de production (maximiser dès le début ou progresser par étapes). Ce choix n'est pas subordonné au "marché de l'eau" et aux incertitudes de son avenir, à la différence d'une production pétrolière par exemple ; néanmoins, il peut dépendre de celui du résultat de l'utilisation s'il s'agit de produits marchands (agriculture de vente, etc.). Les incertitudes à long terme des marchés peuvent s'ajouter à celles qui pèsent sur les coûts de production (coût de l'énergie, rabattements inévitables et productivités futures) pour faire préférer une stratégie maximisant les profits à court ou moyen terme. Un point de vue plus social et macroéconomique peut donner la préférence dans une optique plus patrimoniale, à une répartition de la "rente minière" entre plusieurs générations, donc à une exploitation plus modérée et prolongée, mais tout autant finie.

A défaut de gestion durable, un moyen de faire durer les exploitations pourrait consister à déplacer les champs d'exploitation et d'utilisation vers des secteurs où la nappe est moins déprimée, ce qui est généralement possible dans les aquifères très étendus où les dépressions consécutives aux exploitations n'entament qu'une partie des réserves. Cela implique toutefois que de nouvelles conditions socioéconomiques soient remplies. Cela pourrait permettre une ou plusieurs phases de développement complémentaires mais en différant seulement l'échéance finale d'épuisement.

Quoiqu'il en soit, la recherche d'un relais est inéluctable à terme et cela pose un second problème de gestion lié aux choix des objectifs d'utilisation de l'eau. Lorsque l'exploitation doit être stoppée parce que les coûts de production deviennent inacceptables dans le contexte économique ou bien que la qualité de l'eau s'est dégradée, voire que des barrières physiques sont atteintes, ce relais peut consister :

- Dans la mise en œuvre de solutions de substitution devant satisfaire les demandes en eau : transferts d'eau jusque là différés, recours à des ressources non conventionnelles, etc.
- Dans une gestion renouvelée des demandes et des utilisations d'eau pouvant impliquer des réductions, des modifications ou des suppressions d'activité.
- Dans une combinaison de ces deux voies.

Dans tous les cas, ces relais ont des coûts économiques et sociaux d'autant plus élevés que ces relais n'ont pas été préparés. La politique pratiquée par les exploitants miniers et pétroliers qui consiste à investir une part suffisante des profits dans la prospection pour découvrir de nouveaux gisements, n'est pas directement transposable à l'eau souterraine. La mobilisation de ces ressources en eau particulières étant largement assistée par une aide publique, la mise en valeur permise par l'utilisation de l'eau ne dégage guère de profit appréciable et disponible pour contribuer à des investissements en vue de préparer des relais de ressources ou d'utilisation. Ceci est d'autant plus marqué que les utilisations d'eau dans les régions arides sont largement dominées par l'irrigation des cultures dans un contexte de prix agricoles à l'échelle mondiale en baisse constante.

On pourrait pourtant se demander si l'utilisation de l'eau obtenue par l'extraction de réserves doit exclusivement ou préférentiellement servir à résoudre au moindre coût des problèmes de subsistance immédiats, voire à créer des profits à court terme pour certaines catégories d'usager, ou si les agents qui bénéficient aujourd'hui de ces avantages doivent les partager avec les générations futures en concourant aux investissements nécessaires à préparer les relais par le biais de redevances. Il peut aussi s'agir d'efforts de recherche et de développement technologique, d'équipements ou de formation visant à accompagner les changements de modes d'usage de l'eau ou de reconversion d'activité.

C'est sans doute à cette condition que l'utilisation des ressources en eau non renouvelables pourrait non pas simplement faciliter un développement temporaire en repoussant les échéances critiques, mais s'inscrire dans une perspective de développement plus durable.

Enfin, la plupart de ces grands bassins sont transfrontaliers et sont répartis entre plusieurs pays : les cadres territoriaux des systèmes de ressource s'étendent sur plusieurs pays et leurs limites naturelles recoupent les frontières ce qui pose d'autres questions liées à leur gestion. Partager ces ressources communes à plusieurs pays ne consiste pas simplement à convenir d'une répartition des écoulements transfrontaliers souterrains entre territoires, à l'instar des quotes-parts des débits des fleuves frontières, mais à concerter les plans d'aménagement des eaux et à cogérer la maîtrise, les utilisations et la conservation des eaux, et équitablement les influences réciproques potentielles résultant des exploitations. Cela requiert une véritable cogestion des réservoirs communs par une autorité communautaire dotée de moyens d'action et de contrôle adéquats.

6. Vers de nouvelles solidarités ?

L'eau sera assurément l'un des grands enjeux internationaux du XXIème siècle, tout particulièrement dans les zones arides et semi-arides. Mais le seul recours au développement de nouvelles sources d'approvisionnement suffira t-il à faire face à la croissance des demandes ?

Dans ce contexte et de par leur caractère non renouvelable, les ressources considérables d'eau dite fossile sont appelées à jouer un rôle de transition déterminant et constituent dès aujourd'hui un enjeu capital, avec trois conséquences :

- un rôle majeur de la puissance publique dans la reconnaissance et l'exploitation des ressources ;
- la nécessité d'une gestion de stock à long terme basée sur des approches homogène entre pays permettant de dresser des bilans et analyses cohérentes ;
- l'opportunité de concertation entre les pays partageant un grand réservoir transfrontalier ;
- la nécessité impérative d'un effort simultané visant une meilleure gestion des demandes.

Au delà de simples négociations, il s'agit d'établir les bases d'une connaissance et d'une gestion collectives de ces réservoirs qui seules permettront de garantir un usage plus efficace des ressources, la sécurité de l'alimentation des populations et donc la paix.

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THEME IV: ENVIRONMENTAL IMPACT OF GROUNDWATER EXPLOITATION

Waleed K. AlZubari

Impacts of groundwater over-exploitation on desertification of soils in Bahrain – A case study (1956-1992)

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Abstract

Accelerated development growth in Bahrain in the last four decades has led to excessive groundwater pumping and over-drafting of the Dammam aquifer, the principal aquifer in Bahrain, causing the lowering of its potentiometric levels and its salinization by adjacent brackish and saline waters. The deterioration of groundwater quality had a significant and strong impact on the agricultural activities in Bahrain, which depends exclusively on groundwater irrigation. As groundwater used for irrigation has become increasingly more saline, farmers have resorted to using high rates of irrigation water to leach salts from the soil top layer. This has caused more groundwater abstraction and accelerated groundwater quality degradation and further soil salinization, thus, escalating the situation, eventually leading to the abandonment of major agricultural areas due to the complete loss of their productivity and desertification. The utilization of tertiary treated wastewater in the late 1980s in the reclamation of abandoned agricultural lands have contributed significantly in stopping further losses of agricultural lands, and compensated for the loss of cultivated lands. Conservation of groundwater resources and their availability for irrigation should be considered as the main objective to combat desertification in Bahrain. Rationalized groundwater abstraction by improving irrigation methods at the national level and selecting crops of high water productivity, and the expansion in the utilization of treated wastewater, are suggested to alleviate groundwater stresses and improve their water quality, and, hence, help combat desertification in Bahrain.

Keywords
Bahrain, groundwater over-exploitation and salinization, agricultural land desertification.

1. Introduction

The State of Bahrain consists of an archipelago of 33 islands located in the Arabian Gulf, about midway between Saudi Arabia on the west and Qatar on the east (Figure 1), with a total area of about 695 km^2 and a population of more than half a million. Bahrain is considered as one of the most densely populated in the world, with a population density of about 731 inhabitant/km^2 (CSO, 1992). The climate is characterized by high temperatures, erratic, often scanty rainfall (<80 mm/y), and a high evapotranspiration rates (>1850 mm/y), which in combination create an impossible conditions for surface water bodies to exist. The country water demands, amounting to about 290 Mm^3/y, are met mainly by groundwater abstraction (76%) and desalination plants (19.5%), and to a lesser extent (4.5%) on treated wastewater (AlZubari, 1997).

Bahrain, like most of the Gulf States, has experienced an accelerated development growth since the early 1960s. This occurred as a direct result of the sudden increase in the country's oil revenues, which led to fast increase in its economic base and an improvement in the standard of living, resulting in a rapid increase in the country's population. The fast growth rate in population and the associated development processes, represented by rapid urbanization, expansion of irrigated agricultural and industrialization, in the last four decades have significantly increased groundwater abstraction rates to reach more than twice their suggested safe yield. This has caused rapid decline in aquifer potentiometric levels and a reversal of hydraulic gradients between the relatively fresh-water aquifer and adjacent brackish- and saline-water bodies. As a direct consequence, encroachment of these waters into the aquifer has occurred, causing its salinization, and the restriction of its use from the invaded parts of the aquifer, estimated at more than half the original groundwater reservoir under steady-state conditions (AlZubari et al., 1993).

The deterioration in groundwater quality in the past four decades has been accompanied by a gradual decrease in cultivated areas and loss of agricultural lands. As groundwater used for irrigation has become increasingly more saline, farmers, in an attempt to combat the salinity, have resorted to using increasingly high rates of irrigation water to leach salts from the soil, thus, further increasing the abstraction rate from groundwater and accelerating its quality deterioration; the annual hectare share of irrigation water in Bahrain has increased during the last four decades from 27.9x103 m^3/ha in 1953 to 46.5x103 m^3/ha in 1992, an increase of about 67% (Alaa El-Din, 1995).

This has aggravated the situation even further, and finally led to the loss of the productivity, or desertification, of many cultivated lands, and the abandonment of major agricultural areas in Bahrain.

Furthermore, a preliminary investigation indicated that many traditionally agricultural areas in Bahrain (e.g., east coast and north-central areas) have been subjected to urbanization after, and not before, their abandonment due to severe groundwater salinization in those areas. This might indicate that salinization of irrigation water may be the direct cause for urbanization into abandoned agricultural lands in some areas in Bahrain. Furthermore, while urban expansion causes an irreversible loss of cultivable land, which once built upon cannot be created or regained easily, remediation of soil salinization caused by groundwater quality deterioration can be achieved by implementing proper water resources management and development schemes.

This study reviews the development of groundwater in Bahrain in the period from 1956-1992, and discusses the role of water resources degradation and its impact on agricultural land desertification in the country. The spatial and temporal trends in cultivated land distribution are correlated with groundwater quality for the period from 1956 to 1992. Based on these investigations, recommendations relating to the preservation and/or increase of agricultural lands in Bahrain by proper management options of the country's water resources are presented.

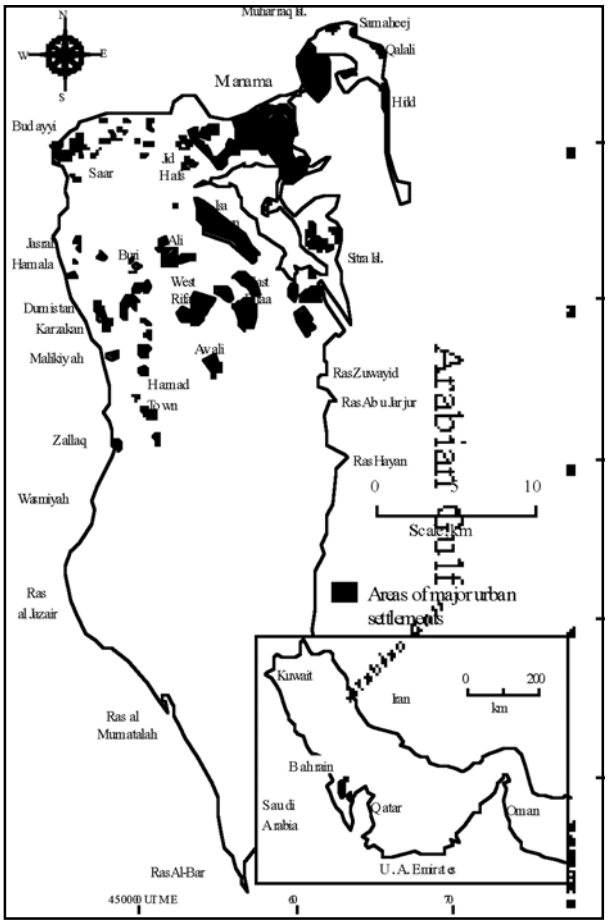


Figure 1: Location map and major urban settlements of Bahrain

2. Prevailing climatic conditions

Bahrain Islands are classified as lying within an arid to extremely arid environment (Brunsden et al., 1980). The climate is characterized by high temperature, erratic often scanty rainfall, high humidity, and high evapotranspiration rates. The year may be divided into two main climatic periods, with summer from June to September and winter from December to March. These two periods are separated by two transitional zones: April-May and October-November, respectively. Meteorological records (Normals: 1961-1994) indicate that the mean monthly temperatures in Bahrain range from 17.20° C in winter to 34.20° C in summer (Table 1). The daily sunshine hours range between 7.3 hours in winter to 11.3 hours in the summer, with total annual sunshine hours of over 3350 hours. Bahrain is characterized by high relative humidity levels due to the surrounding Arabian Gulf waters. The annual relative humidity averages about 67.2%, with mean daily maxima varying from 78 to 88% annually, and mean daily minima varying from 39 to 59%. The predominant winds in Bahrain are those blowing from the northwest, locally called "Shamal". The Shamal winds also represent the strongest surface winds over the islands, where its average speed is about 11.3 knots (20.6 km/h).

Rainfall records of annual precipitation in Bahrain during the period 1903-1998 (Figure 2) show that the amount of precipitation varies considerably from one rainfall season to another, and may become extremely scant. Averages range from 234 mm, in the 1975/76 rainfall season, to as low as 7.4 mm, in the 1945/46 season. The average annual rainfall, calculated for a 81-year period, is 77 mm, and occurs in the winter period from November to April, sufficient only to support the most drought-resistant desert vegetation. The potential evapotranspiration rate in Bahrain averages about 1,850 mm/yr, and can peak to over 10 mm a day in some of the summer months (AlZubari 1987), which poses severe stresses on the cultivated crops during the summer period. The combination of these climatic conditions has created a continuous annual deficit in the water budget, and led to the exclusive dependence of agriculture in Bahrain on irrigation by water abstracted from groundwater reservoirs.

Table 1: Summary of Climatic Data for Bahrain, 1961-1994

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air Temperature (°C)												
Mean monthly	17.2	18	21.2	25.3	30	32.6	34.1	34.2	32.5	29.3	24.5	19.3
Mean daily maxima	20	21.2	24.7	29.2	34.1	36.4	37.9	38	36.5	33.1	27.8	22.3
Mean daily minima	14.1	14.9	17.8	21.5	26	28.8	30.4	30.5	28.6	25.5	21.2	16.2
Relative Humidity (%)												
Mean daily maxima	88	88	85	82	79	78	80	83	86	88	85	87
Mean daily minima	59	55	50	44	39	40	41	44	45	46	52	57
Sunshine (h)												
Mean daily	7.3	7.9	7.7	8.5	9.9	11.3	10.7	10.7	10.4	9.8	8.7	7.3
Rainfall (mm)												
Mean monthly	14.6	16	13.9	10	1.1	0	0	0	0	0.5	3.8	13.7
Mean # of rainy days	2	1.9	1.9	1.4	0.2	0	0	0	0	0.1	0.7	1.7

Data Source: CAD (Civil Aviation Directorate), 1995.

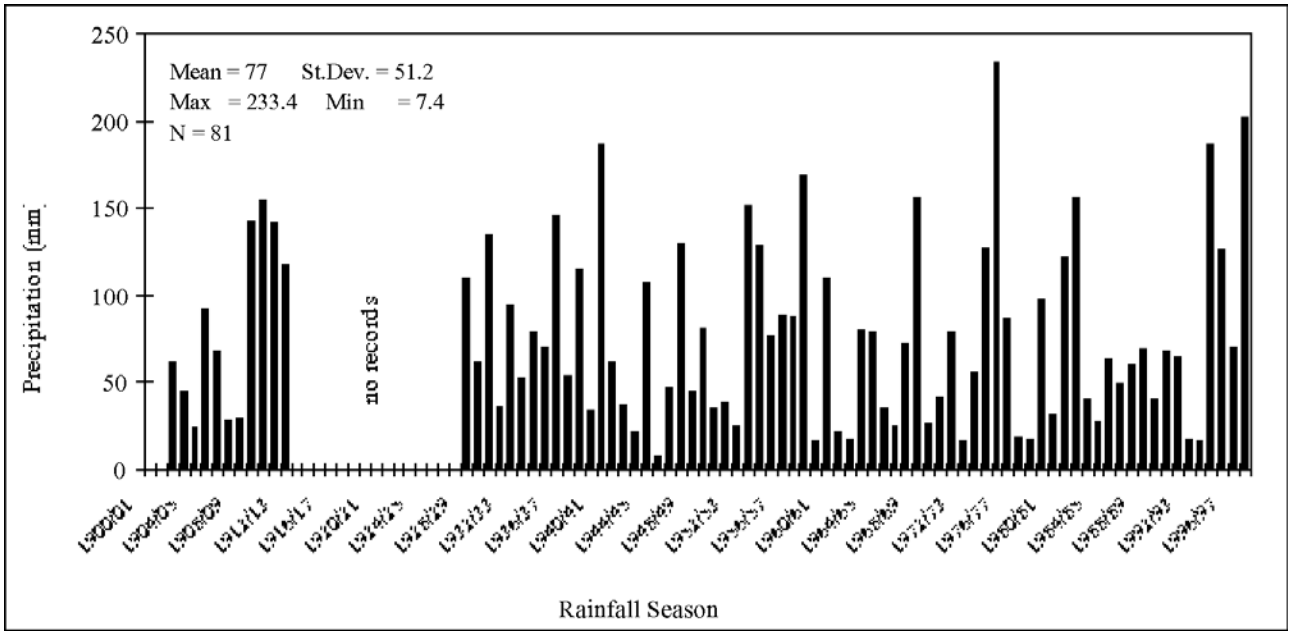


Figure 2: Recorded rainfall in Bahrain, 1903-1998.

3. Water resources and development

Bahrain depends principally on the Dammam aquifer in meeting its fresh water demands. At present, the aquifer provides more than 75% of the country's total water consumption. The Dammam aquifer forms only a small part of the extensive regional aquifer system termed the Eastern Arabian Aquifer, which extends from Central Saudi Arabia, where its main recharge area is located at about 300 meters above sea level, to Eastern Saudi Arabia and Bahrain, which are considered the aquifer discharge areas (Figure 3). It is this large aquifer that supplies the aquifer at Bahrain by lateral under-flow.

In Bahrain, the Dammam aquifer system, a confined coastal aquifer, consists of two aquifer zones: from the top, these are the 'A' and 'B' zones, developed in the Alat (15-25 m) and Khobar (40 m) members of the Dammam Limestone Formation (early to middle Eocene), respectively (Figure 4). The 'A' zone has limited hydraulic properties, where it possesses an average transmissivity of about 350 square meters per day (m^2/d). The 'B' zone, developed in highly fractured limestones and dolomites, is the principal aquifer in Bahrain, where it provides more than 75% of the total groundwater abstraction (AlZubari et al., 1993). This is due to the high transmissive properties of the aquifer; average transmissivity is about 10,000 m^2/d. The salinity of the Dammam aquifer in northeast Bahrain, where the aquifer receives its water by lateral under-flow from Saudi Arabia aquifers, is about 2.2 grams/liter (g/L). As groundwater flows in the Dammam aquifer in the east and southeast directions, its salinity gradually increases to reach over 20 g/L at the east coast due to mixing with both deep brackish water and saline seawater.

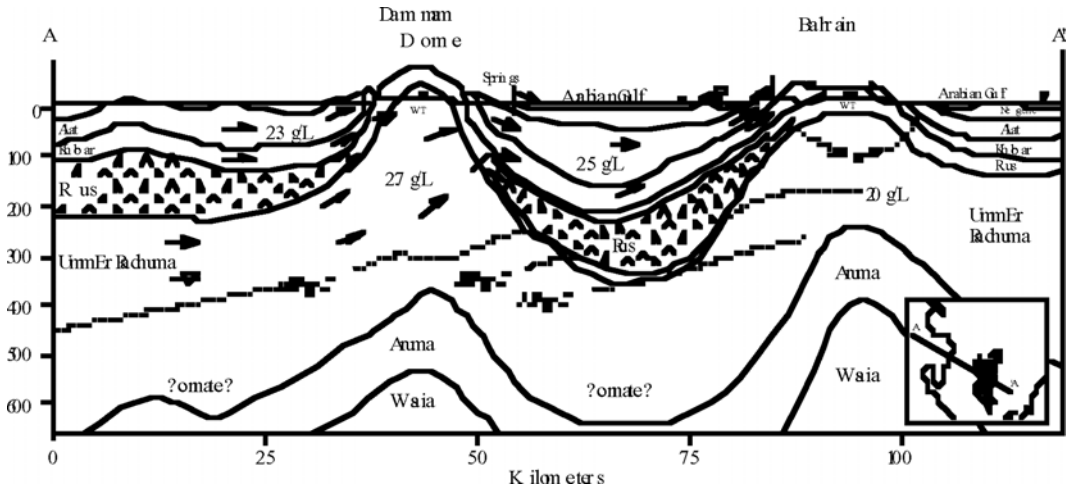


Figure 3: Generalized hydrogeological cross section of the Eastern Arabian Aquifer System, Eastern Saudi Arabia - Bahrain (GDC, 1980a).

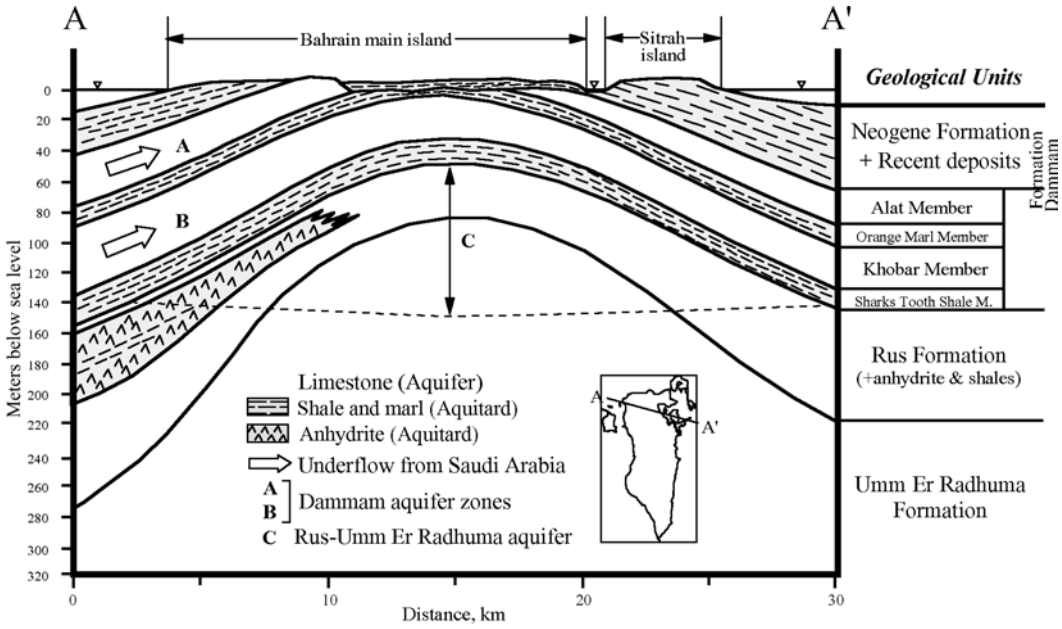


Figure 4: Hydrological section, Bahrain.

A third aquifer zone, termed 'C', is developed in the fractured chalky limestones of the Rus (early Eocene) and the upper parts of the Umm Er Radhuma (Paleocene to early Eocene) formations, and contains brackish to saline water. Typical salinity of the C aquifer is around 12 g/L, and occurs in the form of a large lens in central Bahrain Island. Due to its high salinity, 'C' aquifer utilization is restricted to industrial purposes and feeding desalination plants (AlZubari and Khater, 1995).

Prior to 1925, Bahrain's population depended entirely on the naturally flowing freshwater, land and offshore springs, to meet its domestic and agricultural needs (Figure 5). The estimated natural springs (about 15 land and 20 offshore) discharge from the aquifer was about 90 million cubic meters per year (Mm^3/yr) (Ferguson and Hill, 1953; Hill, 1953).

Mechanized well drilling and abstraction was introduced to the Bahrain Islands in 1925 along with oil exploration activities (Hamilton, 1965). The oil discovery in 1932 and particularly the sudden increase in the country's oil revenues in the early 1970s, has resulted in a rapid population growth, urban development, industrial and agricultural expansion, and was accompanied by a dramatic increase in water demands and consumption. This demand was been met mainly by abstraction from the Dammam aquifer and hence substituted the natural springs, which experienced a significant reduction in their discharge with most of them ceasing to flow.

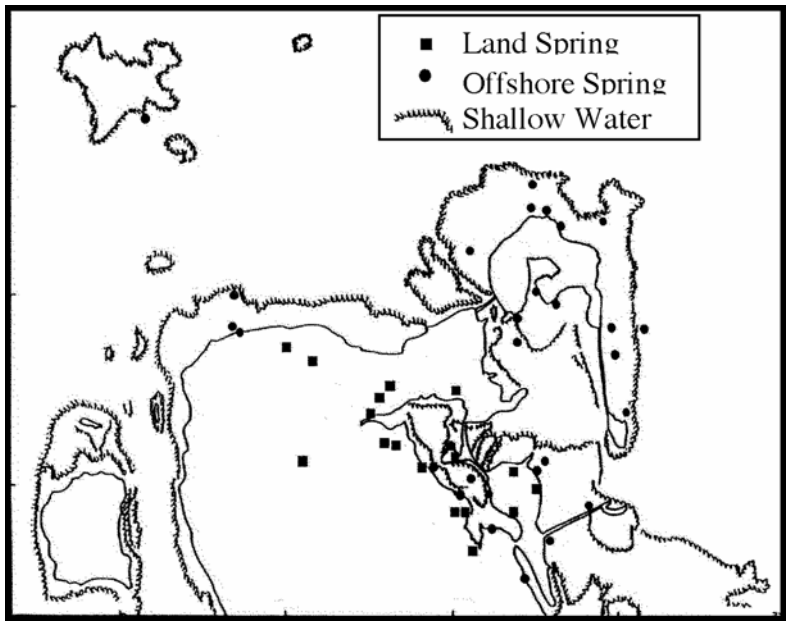


Figure 5: Natural springs locations in Bahrain.

Figure 6 displays the abstraction history from the Dammam aquifer in Bahrain. The total abstraction rate from the aquifer was about 65 Mm^3/y in the early 1950s (Porritt, 1953), increased to about 112 Mm^3/y in the mid-1960s (Sutcliff, 1966) and reached about 138 Mm^3/y in the late 1970s (GDC, 1980a). In the early 1990s, the total abstraction from the aquifer reached about 205 Mm^3/y, and at present (1998) it is estimated at about 250 Mm^3/y. Figure 6 also indicates the Dammam aquifer safe yield, estimated at about 110 Mm^3/y (Al-Noaimi, 1993), which is equal to the aquifer's recharge rate received at Bahrain by lateral under-flow from the up-gradient Saudi aquifers under steady-state conditions. Total groundwater withdrawal (abstraction + natural springs discharge) in Bahrain have exceeded the suggested safe yield of the aquifer since the early 1960s, and presently are more than twice that rate, indicating that a large proportion of the water abstracted is being taken from the aquifer's storage.

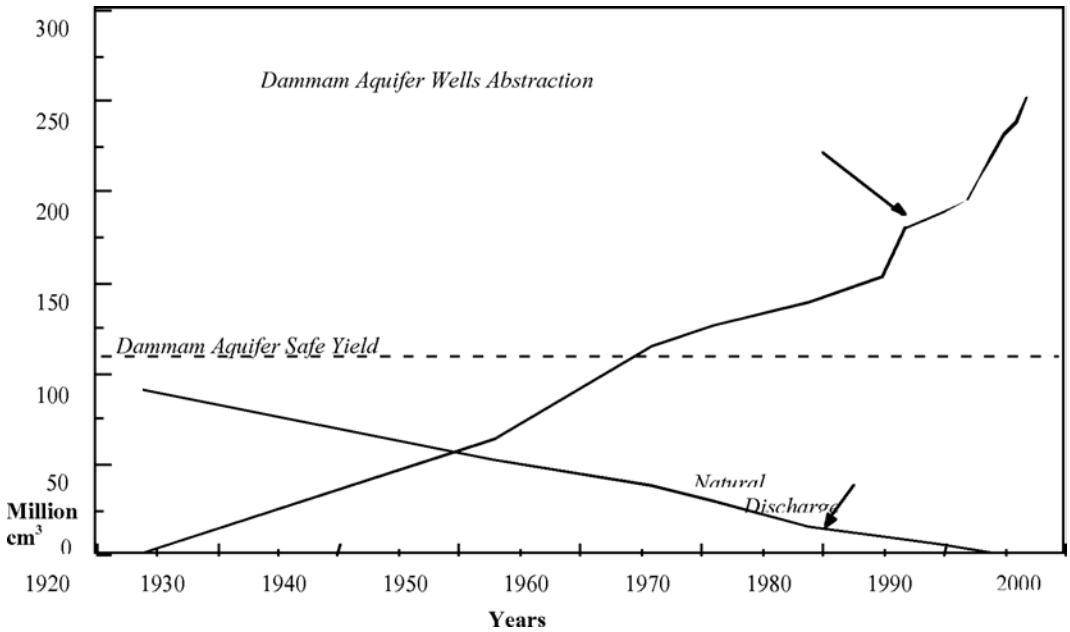


Figure 6: Dammam aquifer Discharge in Bahrain, 1924-1997.

Figure 7 displays two potentiometric contour maps for the Dammam aquifer in Bahrain: the first represents the period prior to 1925 (GDC 1980a), where the aquifer was believed to be under steady state conditions, and the second is for the year 1992 (Al-Noaimi 1993). Comparison between the two maps indicates that the Dammam aquifer potentiometric surface at Bahrain has dropped, on the average, by about 3 m. The maximum drop in the potentiometric surface is observed in the up-gradient western areas of Bahrain reaching about 4 m, whereas the minimum drop is observed at the down-gradient area of the aquifer on the

east coast reaching about 1 m, where the aquifer water is in direct contact with the seawater. In the north-central areas of Bahrain, the potentiometric levels show an anomalous increase in the potentiometric surface reaching about 2.5 m. This anomaly is attributed to the upward migration of the Rus formation water into the Dammam aquifer due to the absence of the anhydrite layer between the two at that locality (GDC 1980a).

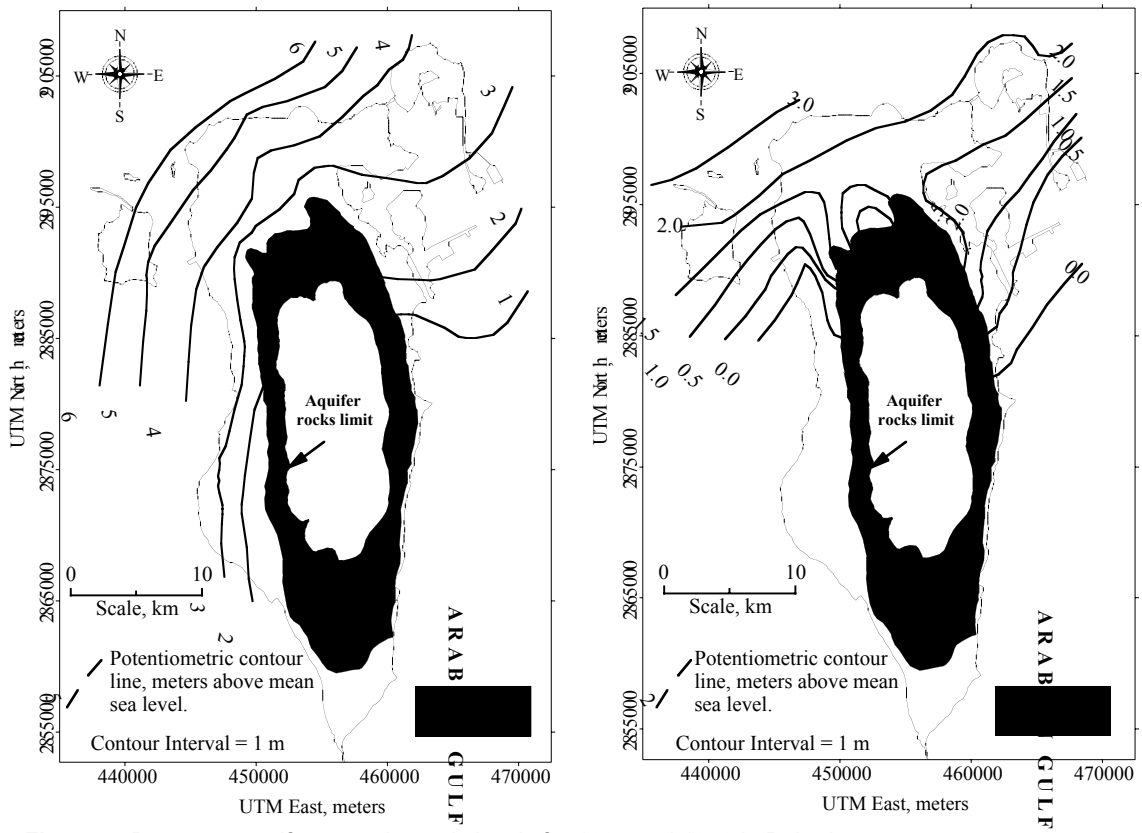


Figure 7: Dammam aquifer potentiometric levels for 1925 and 1992 in Bahrain.

The reduction of the Dammam aquifer storage and drop in its potentiometric surface have led to a marked quality deterioration and salinization of the aquifer's water. This salinization is caused by one or both of the following processes (AlZubari et al. 1993):

- Brackish water up-flow from the underlying 'C' aquifer to the 'B' aquifer zone, especially in the north central areas of Bahrain where the anhydrite layer separating the two is absent (Figure 4). The rate of upward movement of the brackish waters has increased significantly due to the increase in head differential between the 'B' aquifer zone and the 'C' aquifer zone as a result of the sharp decrease of the former.
- Seawater intrusion in the eastern and southwestern areas of Bahrain Island, where the aquifer's relatively fresh water is in direct contact with the saline seawater. Because of the continuous change in the aquifer's hydraulic gradient, the interface between the aquifer's relatively fresh water and the saline seawater in the east and the south has moved inland.

4. Land resources and agricultural activities

Apart from a narrow fertile strip of land in the north, Bahrain is low lying, rocky and bare, consisting of limestone rocks covered with varying depths of sand, which is too poor to support vegetation except for a few tough desert plants. There is little soil in Bahrain that could be described as good from the agricultural point of view. The soils common to Bahrain are the Entisols type (which are formed under arid conditions), coarse textured (mainly sandy), poor in organic matter (0.05-1.5%), and deficient in macro- and mirco-nutrients. Bahrain soils suffer from moderate to high salinity (4-12 mmhos/cm); non-cultivated abandoned sites may have higher salinities with EC values reaching 60 mmhos/cm. The dominant cation is sodium, which exceeds the dominant anion sulfate. The calcium carbonate in most soils ranges from 15 to 30%. Most of the soils contain moderate amounts of gypsum, mainly in the upper 75 cm of the soil profile. The water-holding capacity is very low and only 2-6% of the soil moisture is available to plants. Infiltration rates are generally high up to more than 120 mm/hr (UNEP 1992). In areas along the coastal strip, calcareous impermeable layers are found at varying depths between 1, 2, and 3 m, and these have caused water logging and impeded leaching. In many areas of the recently abandoned agriculture, salinity has built up to a level where cultivation is not possible without extensive leaching.

Agriculture in Bahrain is generally in an unhealthy state with tenancy problems, small holding sizes, labor shortage, and lack of financial incentives restricting investment. About 3,200 people are engaged in agricultural activities, which amounts to about 2% of the national workforce in Bahrain (CSO 1992). Agricultural activities share in the gross domestic product (GDP) is low as it is limited to about 1%. Despite government efforts towards modernizing irrigation methods in Bahrain, more than 79% of the total cultivated area in Bahrain still use the traditional irrigation methods (FAO 1997), which causes high water losses. Several studies estimated that these methods are accompanied by water losses ranging between 24 and 40% (Dastane and Ayub 1982, GDC 1980b, Italconsult 1971, Ayub 1970).

The inefficient irrigation methods (flood) as well as the cultivation of high water consuming crops (alfalfa and vegetables), and the increasing salinity of groundwater used in irrigation have led to over irrigation of cultivated crops in Bahrain, and hence, decreased the water use efficiencies by the cropping plants. Amounts of irrigation water applied in Bahrain are 37% to 123% higher than the actual water requirements of the cultivated plants (Al-Dulaimi 1994), which makes the water cost to produce agricultural commodities very high in Bahrain.

5. Groundwater quality and agricultural lands

The impact of groundwater salinity used in irrigation on the desertification of agricultural lands in Bahrain, is illustrated by using four overlay maps of the agricultural land distribution and groundwater salinity contour maps for the years 1956, 1977, 1988, and 1992 (Figure 8).

Figure 8a illustrates the agricultural land distribution in 1956 (MHME, 1988), which represents the earliest available information on agricultural activities in Bahrain. It is believed that this distribution does not differ significantly from the historical distribution of the agricultural land in the Bahrain islands. The overlaid salinity contour map of the Dammam aquifer is prepared from available well bore data for the year 1965. Similarly, this map represents the earliest available information on the aquifer salinity in Bahrain, and is believed to represent closely its undisturbed, steady-state conditions. The agricultural land area (designated agricultural areas) was estimated at about 64.6 km^2, with about 32.3 km^2 actually cultivated (water managed areas by irrigation). Agricultural activities were concentrated around the locations of the natural land springs, which were located at the eastern and north-central regions of Bahrain islands (Figure 5). In the western region, agricultural lands were depending on underground canal systems (qanat), hand-dug wells and a limited number of artesian wells waters for irrigation. Comparison between the Dammam aquifer salinity and the distribution of agricultural activity areas shows that the latter were approximately confined by a salinity level of less than 6 g/L.

Figure 8b presents the agricultural lands distribution (MHME, 1988) and the aquifer salinity (GDC, 1980a) for the year 1978/79. The total agricultural land area decreased from 64.6 km^2 in 1956 to about 41 km^2. Out of this total, only 17.5 km^2 were actually cultivated by farmers (GDC, 1980b), i.e., a reduction of about 15 km^2 in the cultivated area from 1956, or a loss of about 46% of agricultural activities. This reduction indicates the size of the abandoned agricultural lands in this period, although urbanization did not take place at many of the abandoned areas in the north-central and east coast regions. The most important feature that can be drawn from the comparison between agriculture lands and groundwater salinity is that agricultural lands depending historically on natural spring water for irrigation had disappeared and fragmented (e.g., Sitrah Island and north-central Bahrain) with deterioration of groundwater quality, represented by the retreat of usable groundwater (<6 g/L), and the appearance of high salinity waters reaching 10 g/L in the central region due to brackish water upflow, and 20 g/L south of Sitrah Island due to seawater intrusion. However, the contraction of agricultural activities and abandonment of agricultural lands in those areas were accompanied by an increase of agricultural lands in the western and northwestern regions, which indicates an agricultural activity migration and intensification from the central areas to those areas that were still, at that time, possessing relatively good quality irrigation water.

In 1980, the government initiated a 5-year major agricultural development program to conserve agricultural lands and increase the cultivated areas. The program included: 1) introduction and subsidizing of modern irrigation methods to maximize water use efficiency; 2) construction of a major irrigation drainage system in Bahrain to alleviate water-logging and salt accumulation; and 3) provision of agricultural extension services in terms of educating and advising farmers on types of crops suitable for agriculture under the prevailing climatic, soil and water conditions in Bahrain (AlZubari et al., 1993).

Figure 8c displays the agricultural land distribution (MHME, 1988) and groundwater salinity (Al-Junaid, 1990) for the year 1988. The above mentioned governmental efforts have been successful in maintaining the overall agricultural lands and activities in Bahrain; of the total agricultural land area of 41 km^2, about 30 km^2 was actually cultivated. However, despite these intensive efforts in increasing the agricultural lands, the general deterioration of the aquifer salinity continued; agricultural lands located in the

north-central regions have been lost completely with the increase in groundwater salinity (11 g/L). Furthermore, the advent of the 6 g/L salinity contour line towards the western region, where heavy abstraction centers for agricultural and domestic purposes are located, had affected agricultural activities and a shrinkage of agricultural lands had also taken place in this region.

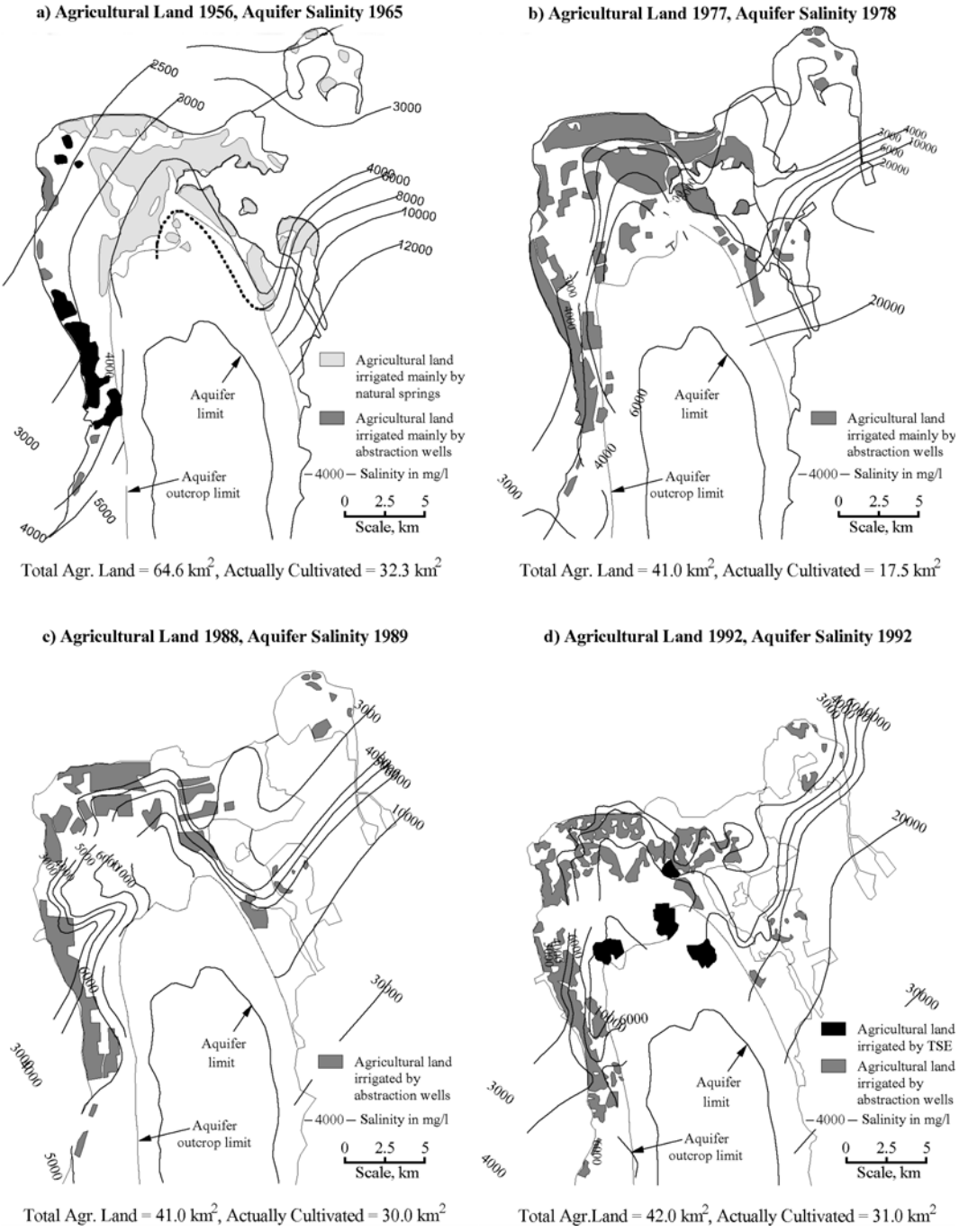


Figure 8: Changes in agricultural land vs. Dammam aquifer salinity in Bahrain, 1956-1992.

In this period, urban and industrial expansion had become an important factor in the complete and irreversible loss of some agricultural lands in Bahrain, especially in the northeastern and eastern regions. For example, the urban expansion of the capital Manama City (Figure 1) was at the expense of agricultural lands, even when the quality of groundwater in those areas was still acceptable for irrigation (3-4 g/l). In the eastern parts of Bahrain (Sitrah Island and surroundings), abandonment of agricultural lands due to deterioration of irrigation water quality led government planners and authorities to changing land use in this area to an industrial one with some urban settlements.

Figure 8d displays the agricultural land distribution (MHME, 1993) and groundwater salinity (Al-Noaimi, 1993) for the year 1992 in Bahrain. The figure indicates that the previously observed trends in the

agricultural lands have continued in most areas of Bahrain. Shrinkage and fragmentation of the agricultural lands due to both groundwater quality deterioration and urban/industrial expansion have continued. Strong urban expansion has been taking place in the northern parts where groundwater has relatively better water quality, whereas abandonment of agricultural lands has continued to take place in the western parts due to groundwater deterioration. However, as a result of extensive government efforts, agricultural land and cultivated land areas were maintained at about 42 km^2 and 31 km^2, respectively. These consisted of government reclamation of agricultural lands, which compensated for the loss of traditionally cultivated lands, and the utilization of tertiary treated wastewater in their irrigation. These efforts have led to the creation of new agricultural areas and the reclamation of agriculturally abandoned ones in north central Bahrain. These reclaimed areas are irrigated with treated wastewater and, therefore, unconstrained by groundwater quality.

It can be seen from the above that there is a strong relation between the salinity increase in groundwater used in irrigation and the salinization of agricultural lands and their desertification and eventually their abandonment in Bahrain. Figure 9 illustrates the mechanism of this relationship. The use of saline groundwater in irrigation causes soil salinization, which leads the farmers to increase irrigation periods to wash the soil in an attempt to lower the accumulation of salts in the top soil layer, which has led to more groundwater abstraction and accelerated its quality degradation. The use of primitive irrigation methods and lack of efficient drainage system exacerbate the situation even further. This cycle continues, with each cycle further increasing both groundwater and soil salinity, until the agricultural land is abandoned due to the complete loss of its productivity.

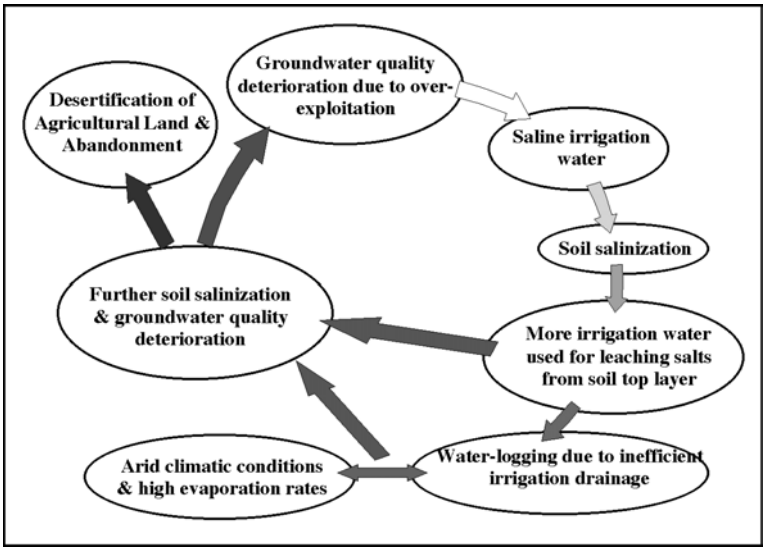


Figure 9: Mechanism of agricultural lands desertification in Bahrain.

6. Conclusions and recommendations

The study revealed a strong spatial and temporal correlation between salinity increase of groundwater used in irrigation in Bahrain and the reduction of agricultural lands. In some traditionally agricultural areas in Bahrain (eastern and north-central), urban expansion has been triggered by the abandonment of agricultural lands due to soil salinization, which is caused by the deterioration of groundwater used in irrigation. Groundwater salinity increase is attributed to aquifer abstraction by more than two-fold its suggested safe yield. The utilization of tertiary treated wastewater in irrigation has contributed significantly and successfully in stopping further losses of agricultural lands in Bahrain. Conservation of groundwater resources and their availability for irrigation should be considered as one of the main objectives to combat desertification and help in achieving sustainable development of the agricultural sector in Bahrain. This could be achieved by reducing groundwater abstraction rates to their safe yield to allow water levels to recover and, subsequently, improve water quality used in irrigation. The reduction of groundwater abstraction rates can be achieved by improving water use efficiency and by augmenting and substituting groundwater supply by other non-conventional water sources, such as treated wastewaters.

Groundwater abstraction by the agricultural sector is the highest in Bahrain compared with other sectors, as it represents more than 65% (140 Mm^3/y) of the total withdrawal from groundwater. The agricultural sector also has the highest water loss rate (24-40%) and, therefore, reduction of abstraction in this sector would have significant effects in alleviating the present groundwater stresses. This could be

achieved primarily by improving irrigation methods at the national level and selecting appropriate crops for cultivation and evaluate their success according to their water productivity.

As a substitute to the limited fresh groundwater resources, treated wastewater has an important role to play in combating the desertification of agricultural lands in Bahrain. Presently, the total available treated wastewater in Bahrain is about 55 Mm^3/y, which represents about 40% of the present groundwater over-drafting rate in Bahrain. However, reuse of treated wastewater in Bahrain is still at its early stage, as only 13 Mm^3/y are being used in irrigation, while the rest is treated secondarily and disposed off to the sea. The Water Authorities in Bahrain have ambitious plans for the expansion in the treatment and utilization of wastewater in irrigation and to substitute groundwater abstraction for agriculture. It is anticipated that tertiary treated wastewater amounts of about 36, 55, and 73 Mm^3/y would be used in irrigation by the years 2001, 2007, and 2011, respectively. These amounts, if used properly and efficiently in irrigation, would provide a significant reduction in groundwater abstraction in Bahrain, especially since that, in almost all areas in Bahrain, tertiary treated wastewater has lower salt content than groundwater. Treated wastewater substitution plans should be prioritized and concentrated in those areas where groundwater salinization is most (north-central, western, and southwestern areas), and where large-scale urbanization has not taken place yet.

Acknowledgement

This study is funded and sponsored by the Arab League Educational, Cultural and Scientific Organization (ALECSO) and the Islamic Development Bank.

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A. Boudoukha and L. Djabri***

Conséquences d'une surexploitation d'un aquifère en pays semi-aride cas de la nappe superficielle d'El Eulma (nord-est Algerien)

(Consequences of overexploitation of an aquifer in a semi-arid country – Case of the superficial aquifer of El Eulma, northeastern Algeria)

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Resume

L'aquifère superficiel du Mio-Plio-Quaternaire se trouvant dans les hautes plaines sétifiennes a été fortement sollicité des dernières années suite à la grande sécheresse qui s'est abattue sur la pays et à l'accroissement incontrôlé des puits et forages du secteur privé. Le rabattement moyen de la nappe varie entre 5 et 10 m, ce qui provoque une inversion de l'écoulement près des lacs salés. Ces derniers représentaient l'exutoire naturel principal de cet aquifère. Actuellement, ils alimentent la nappe, du moins dans la périphérie. Ceci a provoqué une augmentation de la salinité de l'eau. Par ailleurs, les besoins en eau de la région ne sont plus satisfaits.

Mots-clés :
Aquifère, mio-plio-quaternaire, eau, plaine, sécheresse, puits, forages, rabattement, inversion de l'écoulement, nappe, lac salé, salinité

1. Introduction

L'étude géologique des hautes plaines sétifiennes et celle du faciès des différentes unités stratigraphiques, laisse supposer l'existence de trois aquifères parmi lesquels l'aquifère superficiel se trouvant dans les alluvions du Mio-Plio-Quaternaire.

La faiblesse relative (10 à 15 m) de la profondeur de la nappe et la bonne qualité chimique de ses eaux, ont encouragé les habitants de la plaine, à s'installer autour des villes et des villages de la région et à multiplier les puits et les forages surtout pour l'irrigation. Cette situation a provoqué une baisse alarmante et dramatique de la surface piézométrique. Ainsi, nous allons nous intéresser à l'évolution piézométrique au cours du temps et l'impact de la baisse du niveau statique sur la qualité chimique des eaux souterraines de cet aquifère.

2. Conditions naturelles de l'aquifère

L'aquifère superficiel du Mio-Plio-quaternaire se trouve dans des alluvions à dominance argileuse caractérisée par une résistivité variant entre 20 et 40 ohm.m (Figure 1 et 2). L'épaisseur de cette formation est de l'ordre de 50 m. Elle repose soit sur des argiles rouges dont la résistivité est inférieure à 12 ohm.m, soit sur des calcaires lacustres mettant en évidence la présence d'un phénomène de drainance bien visible dans la région de Dj. Braou.

3. Etude de la piézométrie

2.1 Etat initial de l'aquifère

La région a fait l'objet de plusieurs campagnes piézométriques dont quatre en période de basses eaux. La première campagne a été réalisée en 1974 dans le cadre d'aménagement des hautes plaines sétifiennes. Puis nous avons effectué trois autres campagnes respectivement en 1985, 1994 et 1997. Ces différentes

campagnes ont montré que la nappe a conservé la màme structure pendant toute cette période (Figure 3) L'examen de la carte fait ressortir cinq sous bassins hydrogéologiques limités par des lignes de partage des eaux souterraines définissant ainsi :

- le sous bassin d'El Eulma est caractérisé par une limite àflux imposé entrant au Nord alors que le reste des limitescorrespondent à des lignes de partage des eaux souterraines. La partie Sud de l'aquifère est le siège d'un lac salé typeSebkha jouant le rôle d'un exutoire naturel du moinsjusqu'au début des années 90 ;
- le sous bassin de Braou est limité par une ligne de partagedes eaux souterraines sur tous ses côtés. Ce sous bassin estcaractérisé par la présence d'une dépression piézométrique
- due à la drainance descendante par l'aquifère des calcaireslacustres jouant le rôle de substratum à cet endroit ;
- le sous bassin de Aãn Lahdjar, limité par une ligne de par-tage des eaux souterraines au Nord-Est et une limite à flux entrant à l'Est, à l'Ouest et au Sud. On note que cettenappe est drainée par Chott El Hmiet ;
- le sous bassin d'El Fraim limité par des lignes de partagedes eaux et drainé par Chott El Fraim ;
- le sous bassin de Baida Bordj drainé par Chott El Baida etlimité au Nord comme au Sud par une limite à flux imposé entrant. Par contre à l'Est comme à l'Ouest on a des lignesde partage des eaux souterraines.

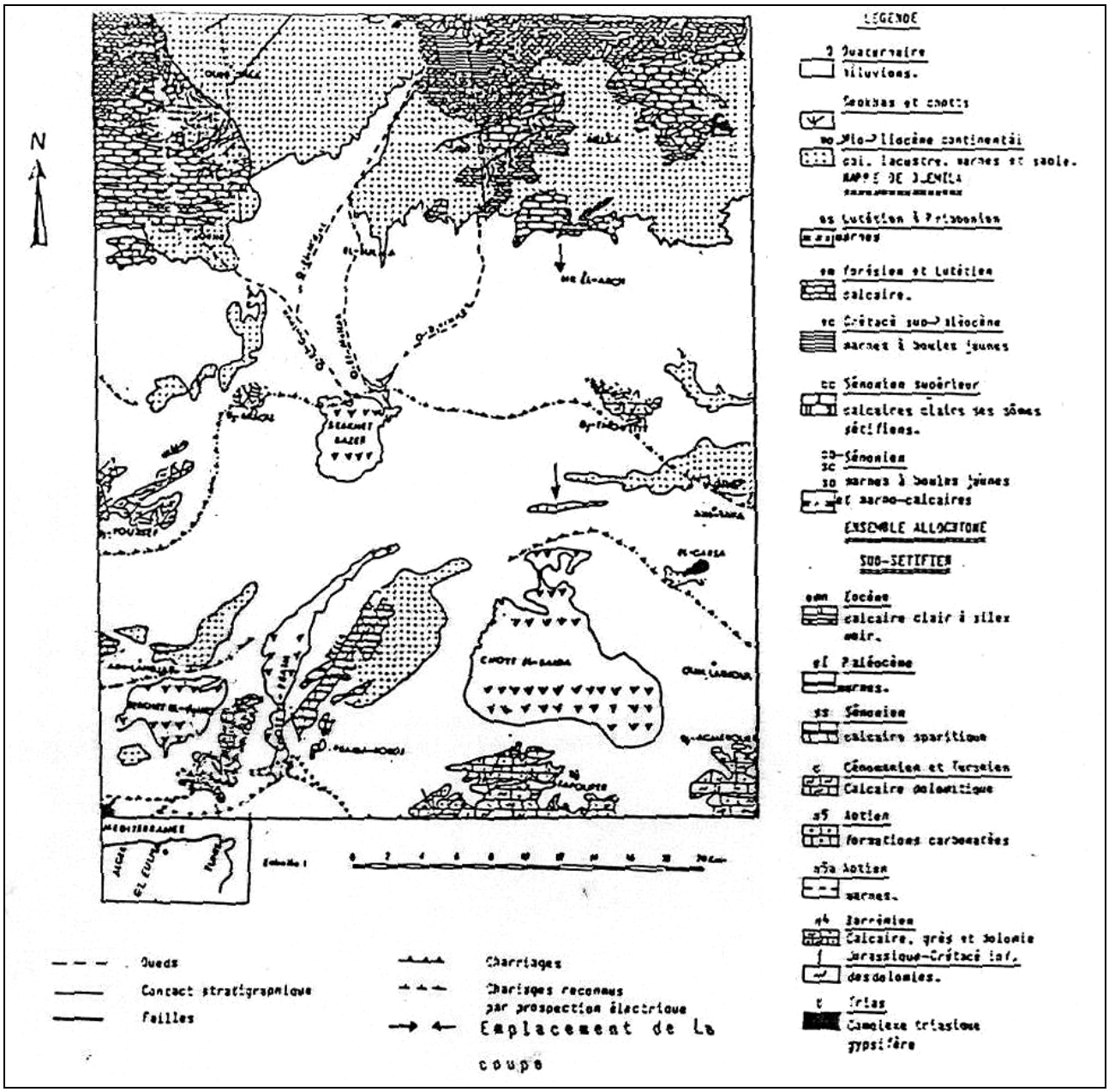


Figure 1: Carte géologique des dépressions fermées d'El-Eulma (in J. M. Vila 1980).

Quant aux paramètres hydrodynamiques, l'aquifère est caractérisé par une perméabilité qui varie entre 10^{-2} m/s près des affleurements calcaires et diminue progressivement vers les lacs salés pour atteindre une moyenne de 10^{-4} m/s. Le coefficient d'emmagasinement varie entre 10 et 20%.

2.2 Evolution de la piézométrie

2.2.1 Entre 1974 et 1985

L'étude piézométrique que nous avons mené en 1985 a montré que le niveau piézométrique dans les puits et les forages a baissé d'une manière alarmante. Les deux régions qui semblent àtre les plus affectées sont celles :

- de Aãn Lahdjar où l'assèchement du lac salé a provoqué un abaissement de la surface piézométrique de plus de 7 m ;
- d'El Eulma où le niveau piézométrique a baissé dans la partie Sud-Est de 10 m environ (Figure 4) Cette baisse est sur-tout due à l'accroissement du nombre de puits qui est passé du simple au double dans la région d'El Eulma et qui a quadruplé dans la région de Aãn Lahdjar.

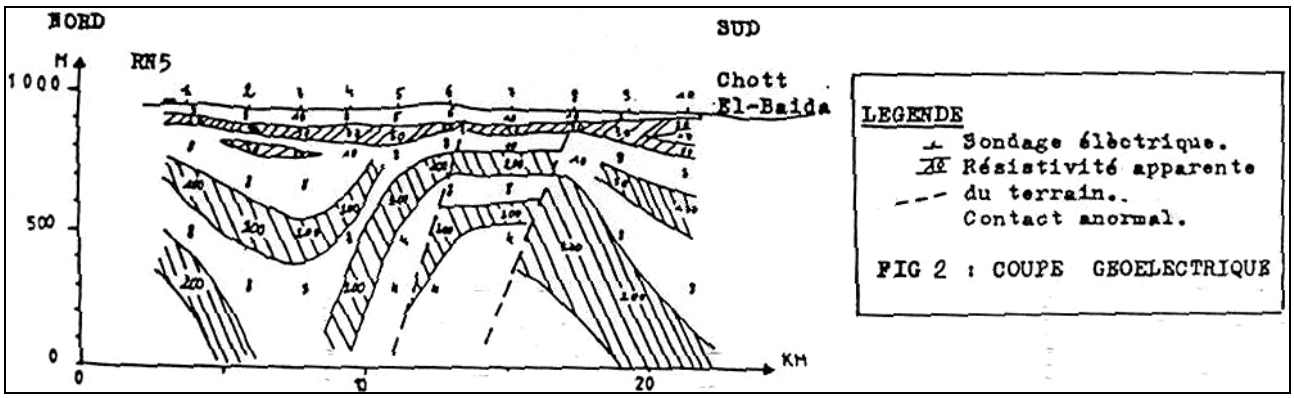


Figure 2: Coupe géologique

Actuellement, on compte plus de 9000 puits dans la région d'El Eulma pour une superficie de 150 km^2 et plus de 5000 puits pour la région de Aãn Lahdjar pour une superficie de 50 km^2. Cet accroissement a provoqué un déséquilibre dans le bilan hydrogéologique ce qui a entraîné la chute du niveau piézométrique. Les précipitations dans ces régions sont inférieures à 450 mm. Plus de 95% de ces précipitations sont repris par l'évapotranspiration et moins de 5% représentent le ruissellement et l'infiltration. On note que la température moyenne annuelle est de l'ordre de 15°C pour un maximum de 38°C et un minimum de -5°C.

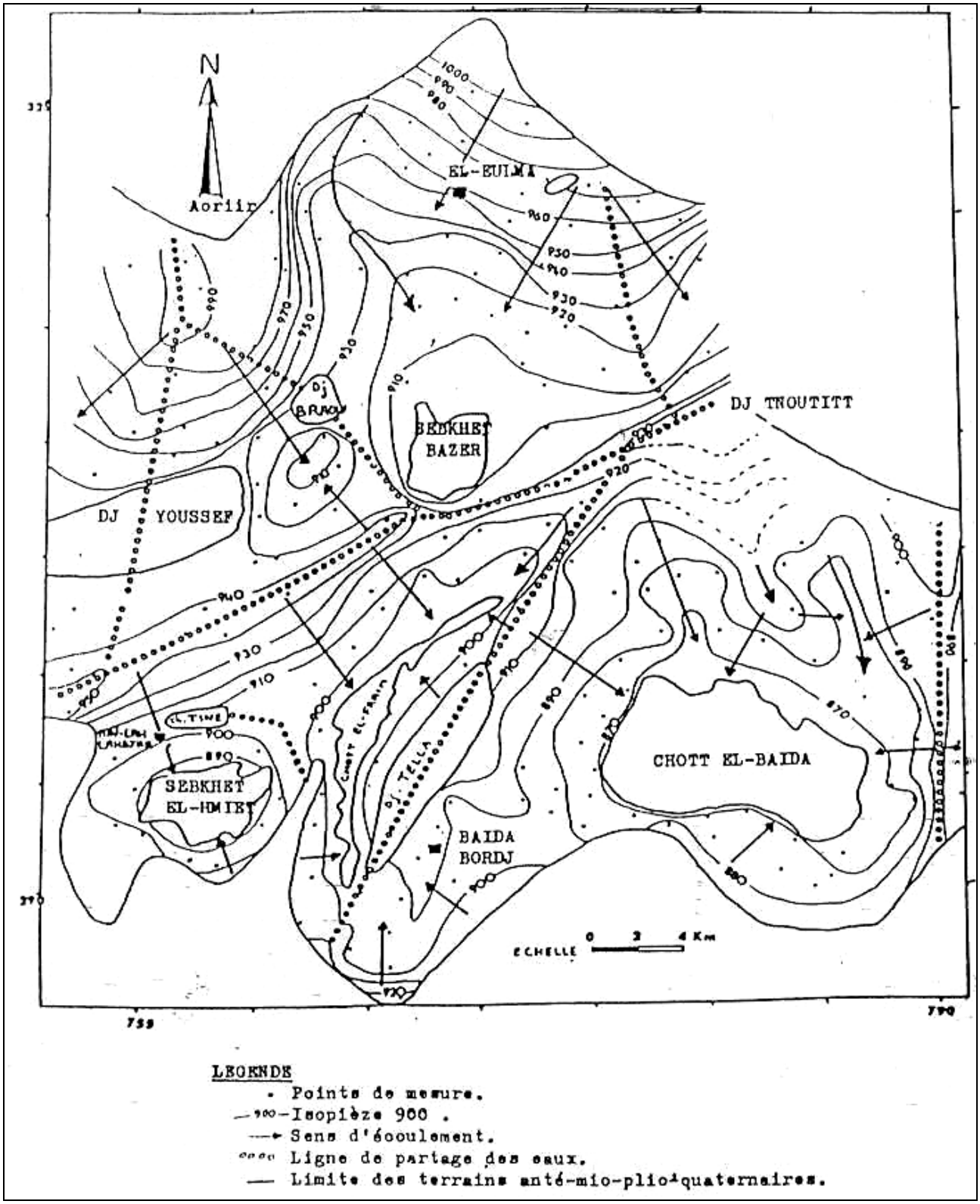


Figure 3: Carte piézométrique de basses eaux (septembre 1985)

2.2.2 Entre 1985 et 1994

Le battement moyen de la nappe pour cette période est de l'ordre de 5 m. La partie Nord du système a enregistré une baisse relativement forte pouvant atteindre un maximum de 14 m dans certains endroits. Cette zone a été fortement sollicitée à cause de la bonne qualité de ses eaux qui sont destinées à l'irrigation des cultures maraîchères. Par contre, la partie Sud de l'aquifère a enregistré une baisse du niveau piézométrique inférieure à 5 m due sans doute à la proximité des lacs salés.

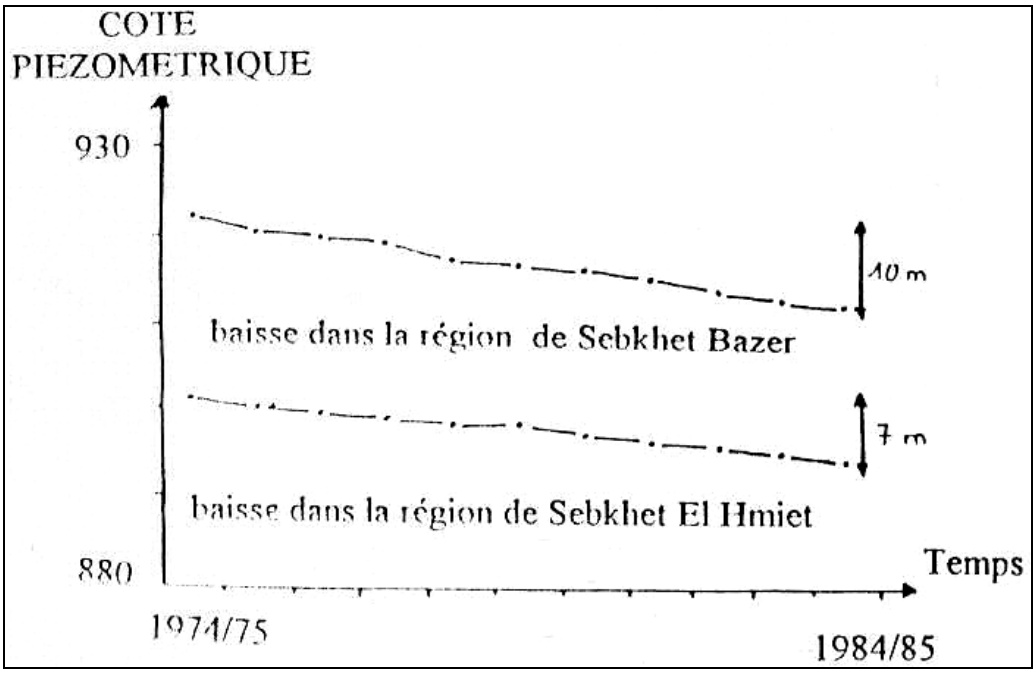


Figure 4

2.2.3 Entre 1994 et 1997

L'étude de l'état piézométrique en 1997 montre que la sur-exploitation de l'aquifère a entraîné un changement dans le sens de l'écoulement qui est bien visible près des lacs salés (Figure 5). Ainsi, Sebkhet Bazer montre une baisse du niveau piézométrique de plus de 14 m, induisant une inversion de l'écoulement de la nappe. Cette inversion a été remarquée dans l'ensemble du terrain où on a enregistré un rabattement de 4 à 10 m près des autres lacs salés.

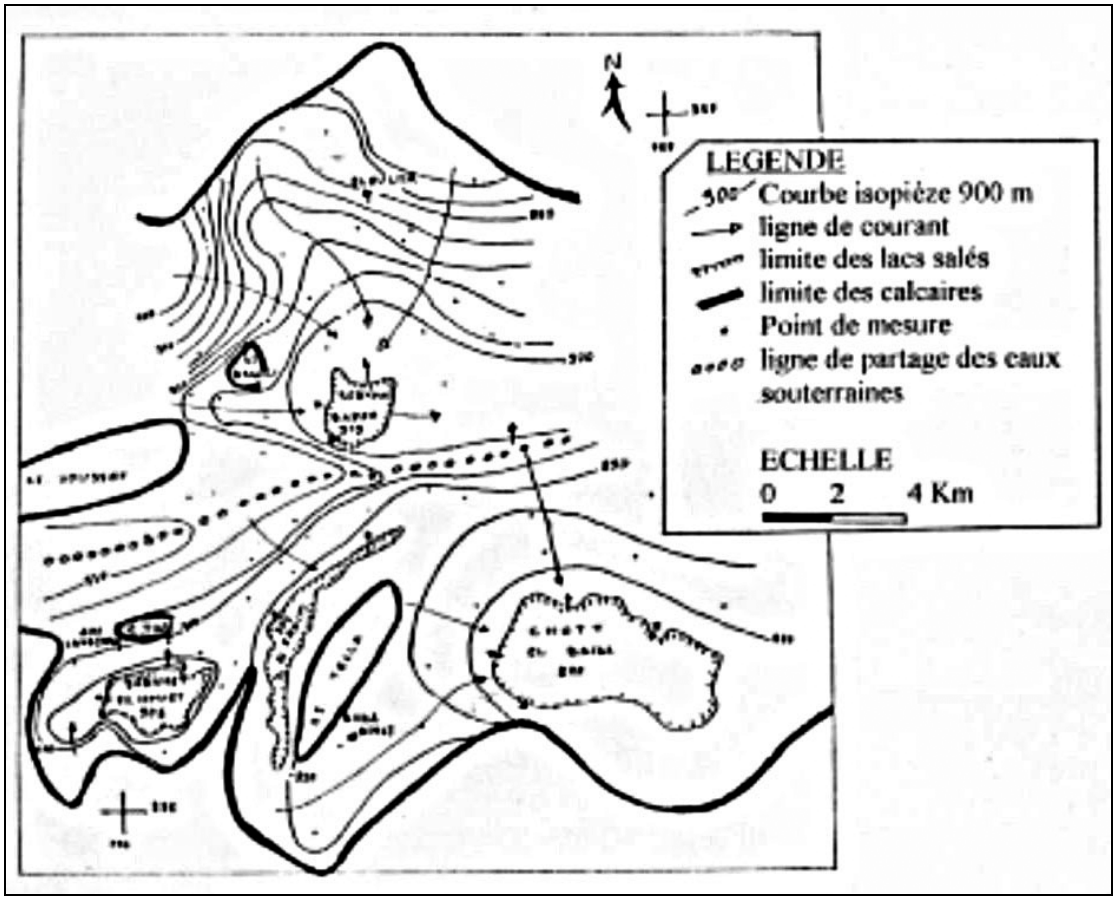


Figure 5: Carte piézométrique de basses eaux (18 au 20 septembre 1997)

Actuellement, la quasi totalité des puits on atteint le substratum et pour subvenir aux besoins domestiques, ces ouvrages fonctionnent avec des drains subhorizontaux.

4. Evolution du chimisme des eaux souterraines

L'évolution constatée montre que cet aquifère n'a aucun intérât pour les habitants de la région. C'est pourquoi, nous ne nous sommes intéressés qu'à l'évolution de la conductivité électrique de l'eau pour déterminer l'influence du biseau salé. Pour cerner ce problème, on s'est intéressé à l'évolution de la conductivité électrique le long de quatre lignes de courant convergeant vers les lacs salés entre 1986 et 1997 (Figure 6) Cette figure montre que dans les régions de Sebkhet Bazer, El Hmiet et El Fraim, la salinité a surtout augmenté près des lacs salés. ceci confirme l'alimentation de la nappe par les lacs salés provoqués par l'avance du biseau salé. Par contre, dans la région de Chott El Baida, on a une quasi stabilisation de la salinité de l'eau due au faible abaissement du niveau statique.

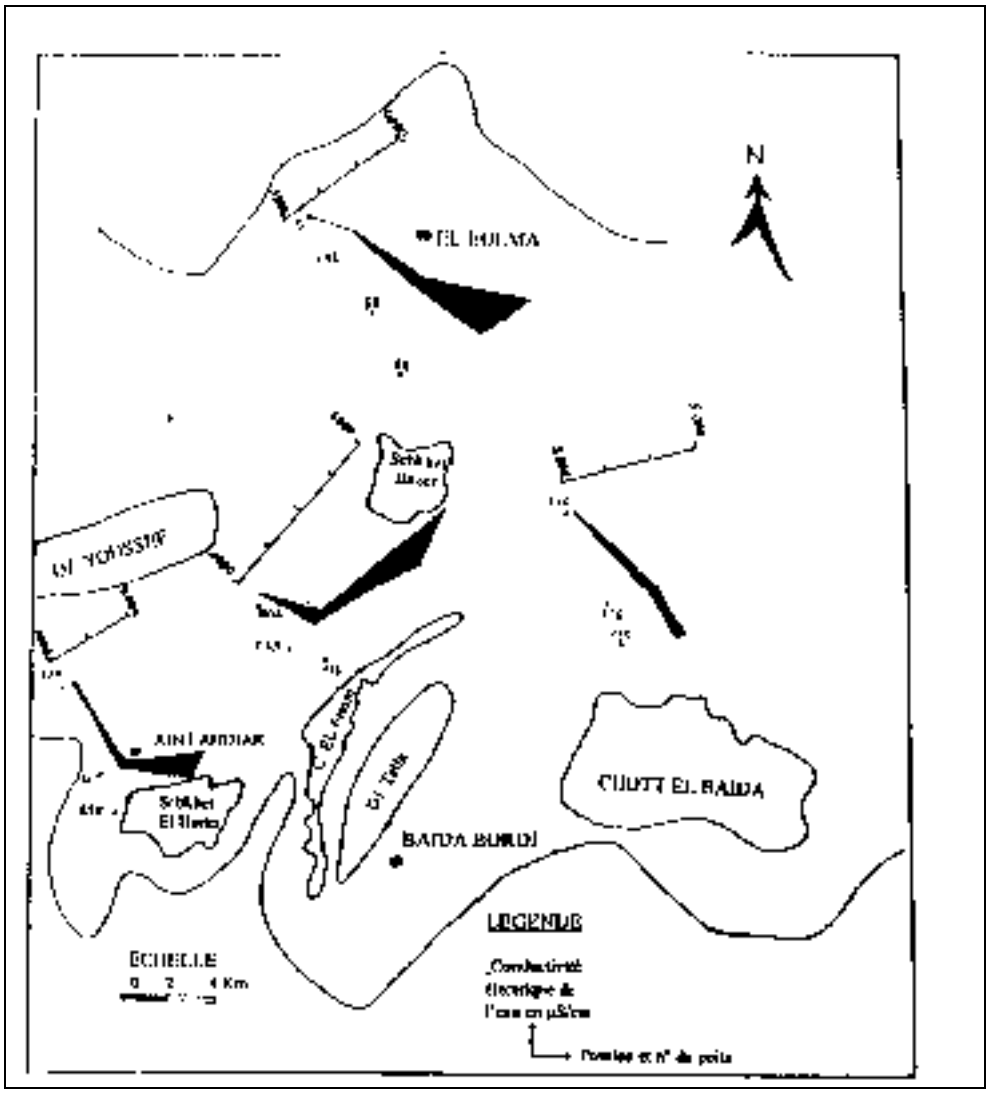


Figure 6: Evolution de la conductivité de l'eau entre septembre 1986 et septembre 1997

5. Conclusion

L'aquifère du Mio-Plio-Quaternaire est quasiment déstocké et ne répond plus aux besoins de la région surtout pour l'irrigation. Cette surexploitation a été suivie par une dégradation de qualité chimico-biologique due à l'avancé du biseau salé à partir des lacs salés et par le déversement des eaux usées des villes et des villages limitrophes. Actuellement, les besoins de la région sont satisfaits en partie par les eaux de deux autres aquifères qui sont celui des calcaires lacustres du Villafranchien et ceux de l'ensemble allochtone Sud sétifien, le reste est puisé dans les barrages des régions voisines.

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Alireza Guiti, Nasser Mashhadi and Ali Torabi

Salinization of groundwater in the north of Kashans plain (Iran) within 32 years

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Abstract

The kashan's plain is located in the center of Iran, adjacent to the borders of the Great Kavir. This region is one of the arid regions of the country. As a result of increased water uitization in recent years, the water tabel has decliand considerably.

In this study , a survey of groundwater depth and qulity is described. Groundwater depth, EC and Cl data for 1965, 1982, 1988, 1997 have been used. The data correspond to 37-83 wells. With the use of Kriging methods and Surfer computer software Iso value plans for each parameter were determined and calculated together with the averege amouns of EC and Cl for each one of the 5 above years.

Comparing the results, it is concluded that: the maximum water salinity occurs in the northern and eastern part of the region, with the minimum water salinity in the south.

1. Introduction:

In arid and semi-arid regions, due to low rainfall major pressure is exerted on groundwater basins. Gradual warming of climate in recent years and decreasing precipitation from one side and increase in population from the other side has caused excessive removal from this resources resulting in decline of water table and the equipotential head of aquifers equilibrium. With due attention to salinization of substrata below water table results in extraction of a more saline water which in itself is the cause for the increase in the salinization of soils.

In view of the fact that salinization of soil and water results in decrease of crop yield and abandoning of land its ultimate transformation into desert investigation regarding its trend of changes of ground water salinity in the course of time is of special importance. In this study with the aid of results obtained from respected measurements made from 1965 to 1997 at specific time intervals, the water table, ECw and Cl^- content of water were determined. All the curves, tables and data and statistics do not fit in the volume of this paper. Therefore, attempt is made to show the minimum amount possible

2. The study area

The extent of area under study is composed of 630 square kilometer. This area is situated in the central region of Iran and close to the central desert. The region starts from north to north-east to the salt lake and its salinized lands from west to the hilly terrain and ends in the southern plains of Kashan.

The meteorological data and statistics available for the years 1964-1984 gives the following information:

- Mean minimum and maximum temperatures in the region are 12° C and 26° C respectively. The minimum precipitation spread in the region is between 45 to 62 millimeter and maximum precipitation ranges between 285 to 305 mm and its average being 120 to 140 mm (3, 4, 5).
- The highest elevation in the region is 1020 meter and lowest being 811 meter from sea level. The surface area of the region is composed of alluvial fan of fourth ear but the nature of formation of underground region in the north and east shows formation of Miocene and in central and south-west, factors of Pliocene.(8)

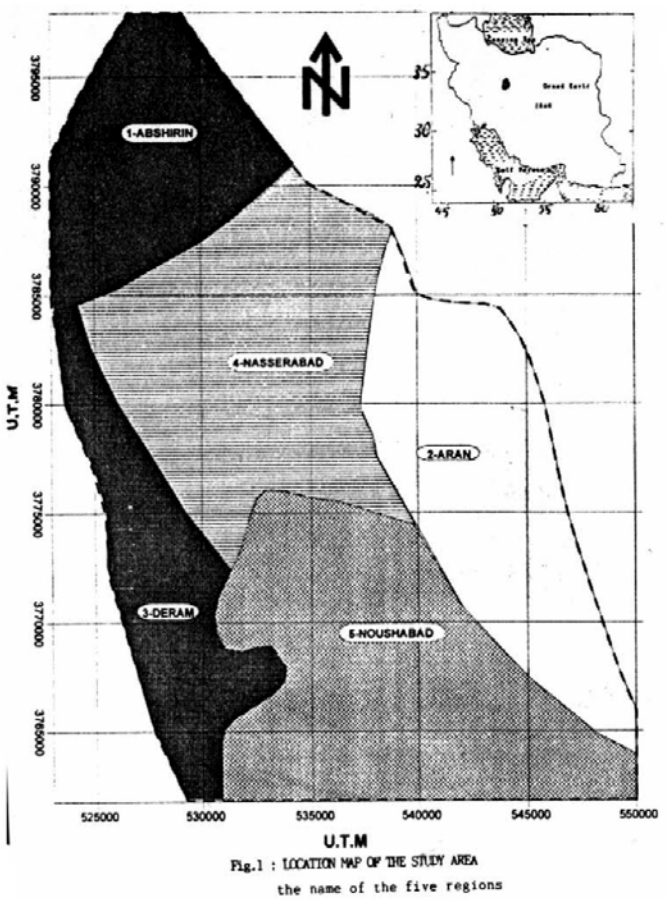
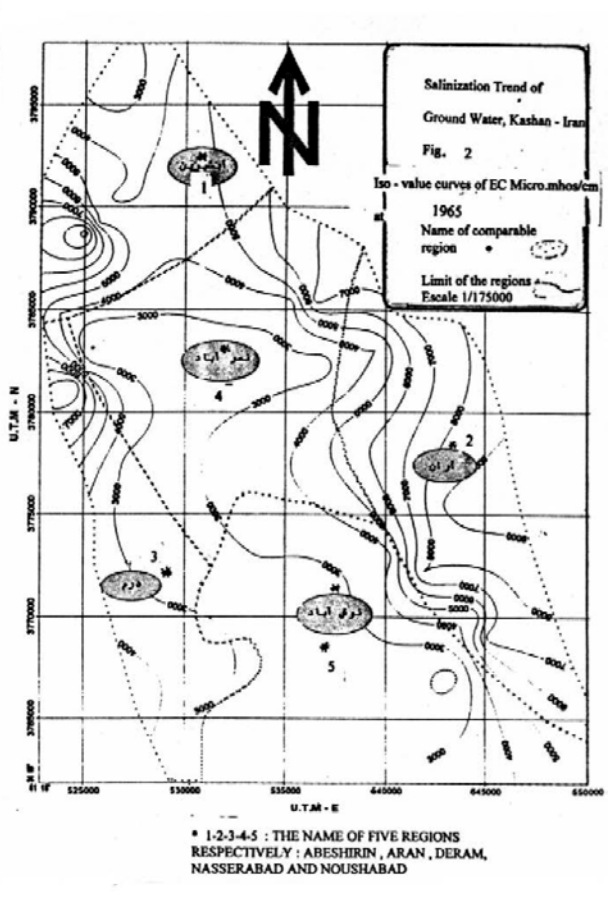


Fig.1 : LOCATION MAP OF THE STUDY AREA
the name of the five regions



* 1-2-3-4-5 : THE NAME OF FIVE REGIONS RESPECTIVELY : ABESHIRIN , ARAN , DERAM, NASSERABAD AND NOUSHABAD

Table 1 : Weighted average of ECw in the stady area expressed as µmho/cm

REGION	1965	average variation per year	1982	average variation per year	1988	average variation per year	1994	average variation per year	1997
ABSHIRIN	4702	104	6478	430	9059	393	11414	378	12546
ARAN	7035	78	8364	102	8978	196	10154	303	11062
DRAM	3696	5	3786	55	4118	22	4247	84	4500
NASSER ABAD	3720	17	4013	66	4407	130	5188	103	5499
NOUSH ABAD	2973	6	3068	9	3120	-17	3015	24	3088
TOTAL	4353	38	5004	111	5667	129	6444	162	6929

Table 2 : Weighted average of Cl in the stady area expressed as mg/L

REGION	1965	average variation per year	1982	average variation per year	1988	average variation per year	1994	average variation per year	1997
ABSHIRIN	1023	33	1584	149	2476	82	2965	66	3162
ARAN	1351	51	2226	22	2360	65	2748	10	2778
DRAM	581	3	628	11	697	16	794	5	809
NASSER ABAD	527	12	727	7	771	26	924	60	1104
NOUSH ABAD	475	1	495	8	542	-1	538	9	564
TOTAL	765	19	1092	32	1285	34	1487	30	1576

Figure 1, Tables 1 and 2

3. Materials and methods

Initially data and statistics of divers periods of data collection 1965, 1982, 1988 and 1995 were collected (6, 7, 9, 10, 11, 12 and 13). In 1997 actions were taken to collect samples and analyze it. As a result data related to 32 years was available which is explained in detail below. The present data is related to 37-83 deep wells. In 1965 the region was surveyed with geophysical methods. These studies have revealed the location of intake, discharge, total number of moist layer,… as well as and depth of water table possessing sweet water.

After collection of necessary data and statistics with due attention to the vast difference that was observed in respect to quality of ground-water and also due to the vast expanse of the region under study it was divided into five homogenous regions. This division was based on degree of salinity of water and type of regional formations (Figure 1). After the implementation of aforementioned operations due action was taken to sketch ISO-value curves. These curves were drawn by the aid of Kriging Method and use of Surfer Computer program, which is a computer program for sketching iso-value curves.

For comparing the intensity of one parameter in various years, as well as, different regions, a quantitative unit of measurement is required to denote average degree of that parameter in various years as well as different locations within a region. For this purpose by use of ISO-value maps the required parameters in the region was obtained by weighted average in such a way that after obtaining the area between the two ISO-value lines it is multiplied between the average lines. This operation is repeated in the case of all ISO-value lines present in the region and the figures obtained is divided by the total area of the region to obtain the weighted average. This method was employed for obtaining weighted average of electrical conductivity and chlorides of homogeneous regions and for different statistical years in the region. This amount has been shown in table 1 and 2. The curves representing the degree of changes in EC and chloride, in the first and final year in shown in figures 2, 3, 4 and 5.

4. Discussion and conclusion

With due attention to the prepared maps of ISO-values for specifying factors, namely, electrical conductivity and chlorides, it can be observed that on the whole the degree of salinity of ground water in the study region is in the direction of groundwater movement (Figure 6) which increases from south to north.

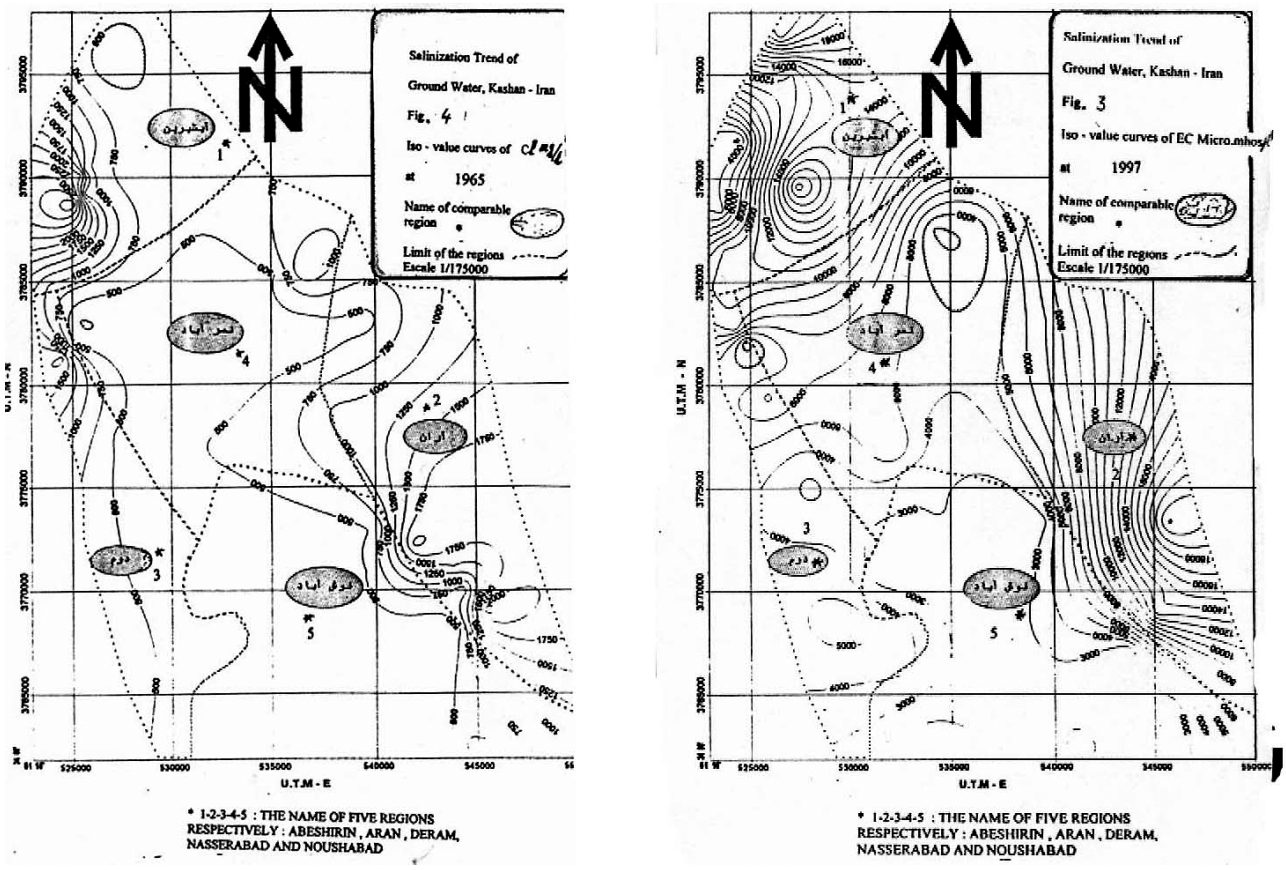
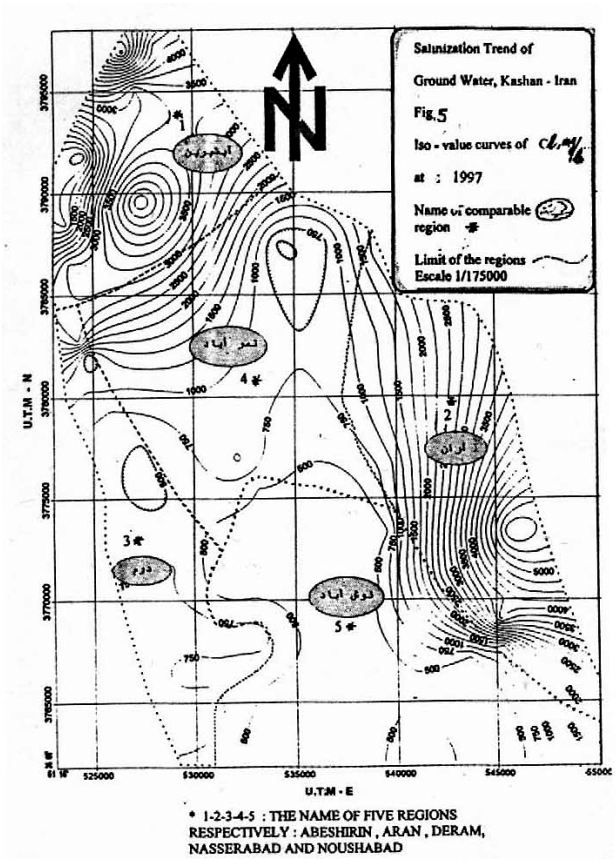


Figure 3 and Figure 4: Salinization trend of groundwater, Kashan, Iran



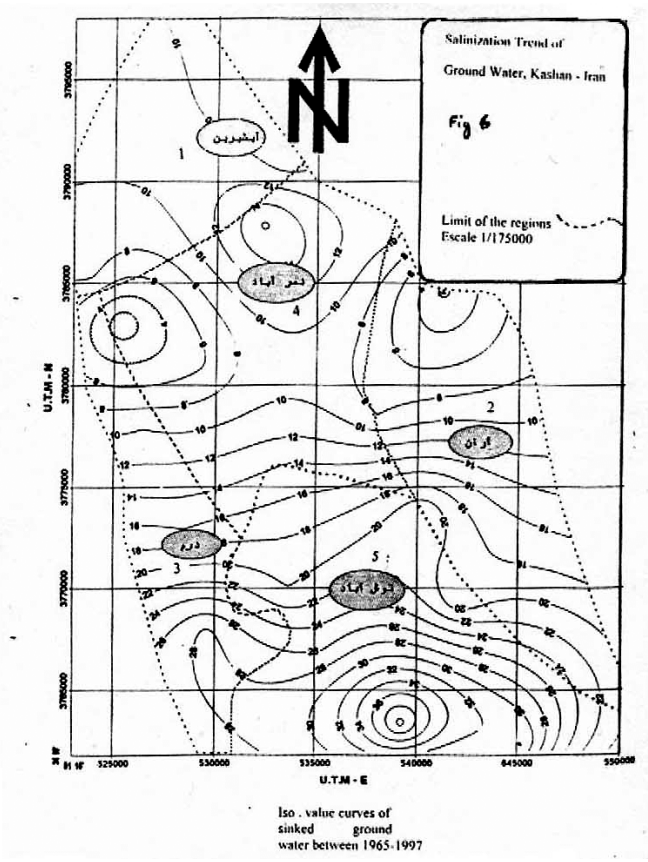


Figure 5 and Figure 6: Salinization trend of groundwater, Kashan, Iran

Moreover, the degree of salinity increases from west to east. The minimum degree of salinity is in the south and its maximum amount is in the north (groundwater exit from the plain) as well in the region of east and north of ARAN region (location of salt domes (8)). Moreover, these maps also determine the effective replensihment of acquifiers from the southern heights. From the other side, investigation and study of these maps confirms this matter too that the degree of salt concentration during these years (32 years) is on the increase in most of the regions, certainly the speed of increase in different years and regions are different from one another.

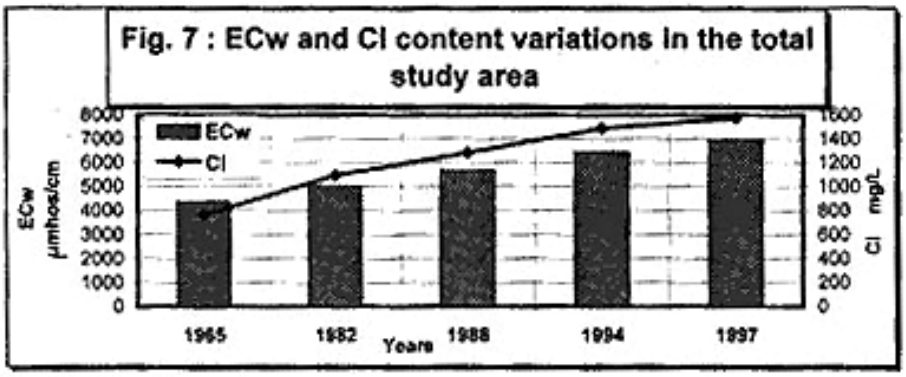


Figure 7: ECw and Cl content variations in the total study area

4.1 Abe-Shirin region

In the north of region and Abeshiring area the degree of increase in salinity whether on the basis of ECw and /or on the basis of chloride was extremely high. Average degree of Electrical conductivity in this area which is also the location for the exit of groundwater from this plain, was 4700 micromho/cm in 1965 which in the year 1997 has reached 12,546 micromho/cm.

Moreover, average concentration of chloride during the year of commencement of his study was about 1023 MgL^{-1} which after 32 years of exploitation its concentration has increased to 3163 MgL^{-1}. These

changes denote intensive increase of salinity in this region. The depth of groundwater table in this region decreased to a lower extent and was about 18.66 meter and amount of decrease is 0.37 meter per year. The reason for increase of salinity was due to extraction of saline water from lower depths.

4.2 Aran region

In the east of study region, due to existence of salt domes, the concentration of water was high from the beginning. In the first year of study period ECw in this region was 7035 micromho/cm and concentration of Cl^- was 1351 MgL^{-1}. These two parameters in the year 1997 were 11062 micromho/cm and 2778 MgL^{-1} respectively. The depth of groundwater in this region in 1997 was equal to 28.9 meter and at present shows a drop equivalent to 0.56 meter per year. The cause of increase in salinity in this region too, in addition to prevalence of salt domes, was extraction of water from more saline layers of water table (due to change of hydraulic slope (Figure 6).

4.3 Dram region

In the west and region of DRAM the degree of variation of salinity is comparatively small in such a way that from a salinity concentration of 3696 micromho/cm in year 1965 has amounted to 4500micromho/cm. The Cl- parameter related to the same year was equal to 581 and 809 MgL-1 respectively. On the other side the depth of groundwater table in the region is 63.5 meter. The rate of decrease of water table is equal to 0.88 meter/year.

4.4 Nasserabad zone

In the center and district of Nasserabad, increase of salinity was medium. Electrical Conductivity of water (ECw) and chloride (Cl-) in the years 1965 and 1977 was 3730 micromho/cm, 527 MgL-1, 5499 micromho/cm and 1104 MgL-1 . The depth of groundwater table in the region is 28 meter and amount of annual depletion at present is 0.32 meter. The cause of increase of salinity in the region is due to movement of saline water from the ARAN region.

4.5 Noosh Abad

In the south of the region and district of Nooshabad increase of salinity was relatively low and during the 32 years it has not changed much. The depth of groundwater table in this region is about 71 meter and annual decrease is equivalent to 0.9 meter.

In the total area of study region, changes of ECw and concentration of Cl- between the years 1965 to 1977 was equal4353 micromho/cm, 765 MgL-1, 6930 micromho/cm, and 1576 MgL-1.

It appears that the salinity hazard is severe in the northern region of the district and must be reduced by artificial recharge and decreasing water extraction to prevent the rapid rate of salinization. In other regions too similar recommendation is made. Moreover, by construction of underground dams, permeation of saline and sweet waters in the regions should be prevented.

The future ground water basin management must be checked, controlled and reduced to sustainable extraction rates from renewable to fossil aquifers. Revision of the administration and legislation structures related to water resources and management is required especially for proper planning of water sector.

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Barakat Hadid

Summary of study on the environmental impacts of groundwater exploitation

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Abstract (see full text in Arabic at the end of this volume)

The groundwater resources in the Arab world have special importance because of their limitations and the problem of the balance between the requirements necessary to provide the need of people and the available and limited water resources. This has led to many negative impacts in the groundwater basins both of quantity and quality deterioration. This is most clearly demonstrated in the basins which are not supplied with annual recharge (i.e. those that do not have water to compensate for the loss as a result of exploitation).

The economic dilemma is how to take advantage of non-renewable water. If it is exploited, how will storage depletion, function?

It is well known that the geological layers store groundwaters at depths and that this storage is worth economical and technical considerations. The waters in these layers are often under high pressure and sometimes are free flowing.

In some cases of exploitation, the reduction of the pressure leads to significant drawdown, the free flow ceases and as a result the exploitation may not be economical. Exploitation of this kind poses problems and requires:

– Knowledge of the geological and hydrogeological situation and recharge resources, if any. and define the layers bearing the water and its ages in order to define the renewable and the non-renewable.

– A prediction of the exploitation conditions: the method of exploitation and the amounts which have to be pumped.

It is essential that a progressive management of the resources is instituted, or it is possible that desertification would result from over-exploitation

Frequently the overexploitation can lead to saltwater intrusion which can totally negate a groundwater resource. Further, because of the inexactitude of groundwater analysis and prediction it is difficult to determine the long-term response of exploitation from deep aquifer layers. Where much layers cross international boundaries, considerable care is required.

The paper discusses:

– groundwater level decline in regional basins;

– ground salinization;

– the possibilities of saline groundwater ingress and the threat of desertification.

Jean Khouri

Impacts of intensive development on regional aquifer systems in arid zones

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Abstract

Regional aquifer systems underlie large sedimentary basins in several arid regions. In the Sahara and great deserts of North Africa, some nine large groundwater basins have been identified. The Nubian Basin, The Taoudeni- Tanezrouft Basin encompasses each an area of about 2 million km^2 in the Sahara. In southwest Asia the greater part of Arabian Peninsula is underlain by an extensive regional aquifer system discharging in the Gulf, Bahrain and Hassa Oasis of Saudi Arabia. In the most of these regional aquifer systems consist of an extensive set of aquifers and confining units which act as a single aquifer system on a regional scale.

Isotopic evidence has shown that the majority of regional aquifer systems in arid zones contain non-renewable groundwater resources. Traditionally groundwater in arid zones was utilized by local communities in situe, in oases, via springs and shallow wells. Well known oases, in this context are the Kharga, the Dakhla oases in Egypt and Hassa Oasis in Saudi Arabia. Later socio-economic development of the desert communities was based primarily on drilling deep wells. However increasing water scarcity and rapidly rising water demand driven by high population growth rates and a strategic aspiration to attain food security has lead to intensive development of non-renewable groundwater resources of arid zones.

The impacts of the intensive development of regional aquifer systems in arid regions comprise environmental impacts related to water use and impacts on the resources base resulting from “mining fossil groundwater”.

The impacts on the resource base include (a) rapid and excessive decline in water levels, (b) depletion of the reserves and (c) deterioration of groundwater quality. In Qatar and Bahrain simulation has indicated that at present extraction rates the aquifer will be completely depleted during few decades. Salt water intrusion has occurred in areas which are intensively or inappropriately developed, and near the discharge zones of regional aquifer systems. Vulnerable areas include Siwa Oasis in Egypt, Sarir Oasis in Libya and Chott Djerid of Tunisia. Up or down coning from underlying or overlying saline water bodies is a serious problem in these areas.

In order address the issue or over-development in arid zones, an approach should be developed that gives future generations the ability to meet their own needs. The fundamental issue is that mining of non-renewable resources will inevitably come to an end sooner or later. Thus the main issue has two indissociable aspects, namely “the choice of a long term strategy of exploitation and the choice of a replacement solution which will take over at a later date.

1. Introduction

Water resources development results in some modification of the environment. Since surface water is scarce in arid and semi-arid zones, groundwater becomes the principal source of water supply. As water demand increases stresses on groundwater systems increase. The withdrawal of water through wells from aquifers intially results in removal of groundwater from storage, with an associated lowering of water levels. As water levels decline, new hydraulic gradients are established in the aquifer system, which may either reduce discharge or induce groundwater recharge. When recharge is negligible, sustained withdrawal from aquifer storage and continued lowering of water levels occur. The result is eventually a depletion of the groundwater resources.

The discussion about scarcity of water is usually intimately bound up with the concept of water as a renewable or non-renewable resource. In some regions such as the Sahara in North Africa and the Arabian Peninsula in Southwest Asia, large basins, underlain by regional aquifer system occur almost entirely in arid and hyper-arid regions. In other continents such as Australia and North America large basins do occur in arid zones, but many of the underlying aquifer systems extend to semi-arid or even semi-humid areas and the regional aquifers receive important recharge at the peripheries of the basins. Regional flow is driven by

hydraulic gradients which extend over long distances in arid zones. Intra-platform basins are characterized, by gentle gradients and low flow velocity. Groundwater needs, therefore, several hundred thousands years to pass through the system.

In North Africa and Southwest Asia development of groundwater primarily for oases irrigation began in the first half of the 19th century. However, extensive development of the regional aquifer systems started by mid 20th century and increased rapidly. Water transfers for urban water supply (e.g. water supply of Riyadh before conveyance of distilled sea water from the Gulf) or for blending (Doha, Kuwait) with desalinated sea water took place in the last few decades, and the largest scheme "The Great Manmade River" has been implemented in Eastern Libya in 1991 and has been followed by a second phase involving long distance water transfer to Tripoli in western Libya. More and more wells increased in each basin, resulting in several places in aquifer depletion, deterioration of groundwater quality and certain environmental impacts connected with water use in irrigation. Impacts from existing and anticipated developments have had both local and regional effects. Therefore continued development of some of the more intensively developed basins requires new methods for managing groundwater resources.

Regional aquifer systems studies are required to provide an areal perspective so that the effects of intensive development can be evaluated and improved management approaches are developed. The present paper address the issue of intensive development and aquifer response to such development The approach taken has been to examine first the impacts of pumpage and water use and then certain actions and measures are proposed to minimize negative effects.

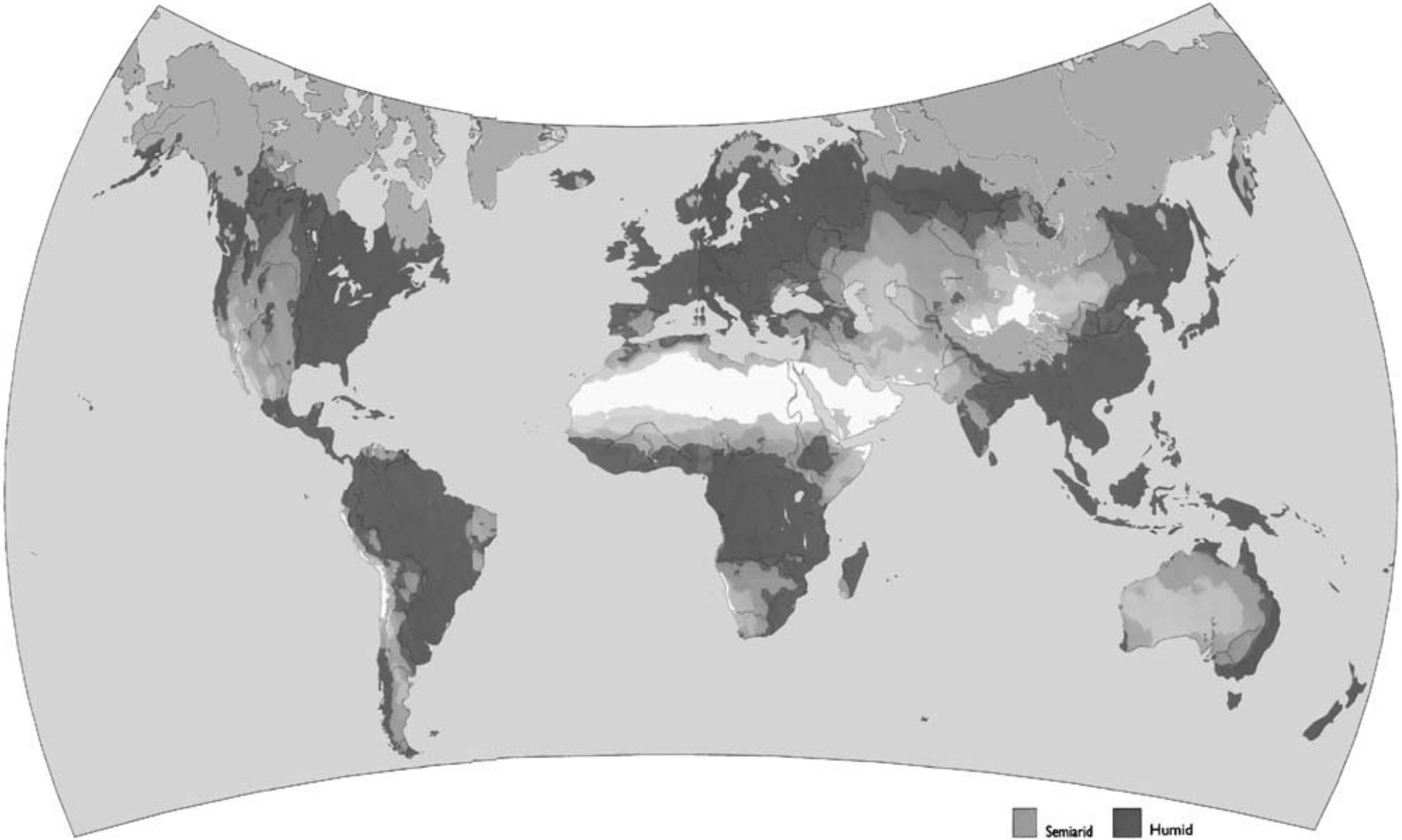
2. General characteristics of non-renewable water resources

2.1 Occurrence of Groundwater in Arid Zones

Large sedimentary basins occurring in different continents are of primary importance for the satisfaction of water demand of man in arid zones. In the vast arid and hyperarid regions, which extend from the Atlantic ocean in North Africa to the Indean Ocean in Southwest Asia (Figure 1), several regional aquifer systems underlying intra-platform basins have been recognized. These extensive aquifer systems store huge quantities of groundwater which were formed in former pluvial periods and are considered now, to a large extent, non-renewable resources.

In temperate regions unconsolidated deposits such as sand and gravel rank among the most important water yielding formations. In the United states about 90% of groundwater withdrawn come from unconsolidated detrital aquifers (Walton 1970). In arid zones wadi aquifers, consisting of gravel and sand constitute an important source of freshwater, but storage is small and recharge is variable. By contrast in humid zones sand and gravel deposits of stream valleys are relatively small in volume but form often highly productive aquifers with considerable recharge by induced infiltration from streamflow. The storage of aquifers occurring in intermontane and submontane basins is large compared to annual recharge in arid and semi-arid zones. In these basins, bordered by mountain ranges, occur large volumes of unconsolidated deposits, mainly sand and gravel. They are recharged by seepage from wadi flow and flood into alluvial fans lying at the base of mountains.

In the Arabian Peninsula, aquifers underlying arid sub-montane basins, flanking the Oman and Red Sea highlands are intensively developed for groundwater irrigation. Spate irrigation used in Yemen and Saudi Arabia ensures the integrated use of surface and groundwater resources. In the United States, the aquifers of arid basins are almost exclusively the unconsolidated sediments of wadi fill underlying intermontane or sub-montane basins. Sustainable development is possible to achieve in alluvial basins, in arid or semi-arid zones. Spate irrigation practiced in Yemen and Saudi Arabia in the Red Sea (Tihama) sub-montane basins have minimized the negative effects of intensive development, by playing the role of aquifer recharge through spreading in spate irrigated fields.



Source : UNEP 1997

Fig 1. Aridity Zones

In southern arid Central Arizona, use of modern irrigation technology in some 72 alluvial basin have resulted in water-level decline. Water levels in the intensively developed inter-montane basins have declined more than 120 m (Sun 1986).

The hydrogeological setting and the impacts of development is often more complex in platform type basins. Such basins are particularly important in North Africa and Australia. Regional aquifer systems underlying these basins are extensive covering vast desert areas and encompassing important parts of several countries. In North Africa large arid basins occupy about 5 million km^2 (Figure 2). About 1.8 million km^2 of desertlands is underlain by extensive aquifer systems in Southwest Asia. In Australia about 75% of the continent is occupied by arid basins.

2.2 General Characteristics of Non-Renewable Groundwater Resources

In the Northern Sahara of Africa delineated regional aquifer systems, rank among the largest systems in the world (Table 1).

Table 1: General Characteristic of Selected Regional Aquifer Systems in Arid Zones

Regional Aquifer System	Countries	Area km^2	Reserve BCM	Recharge MCM/Y	Withdra-wal MCM/Y	Depletion	
						BCM	Period
Nubian Regional Aquifer System	Chad, Sudan, Egypt, Libya	2 000 000	150 000	1 000	1 200	-	-
North Sahara Aquifer System	Libya, Tunisia, Algeria	780 000	60 000	580	1 100	14.500	1970-1992
East Arabian Aquifer System	Saudi Arabia, Kuwait, Bahrain, Qatar, UAE	1 400 000	35 000	1 050	17 000	2546	1980-1995
Great Artesian Basin Aquifer Systems	Australia	1 700 000	20 000	1 100	1 500 (1991)	25	1880-1973
High Plain Aquifer System	United States	450 000	15 000	7 000	22 (1980)	196	1940-1980
Alluvial Basin aquifer systems	United States (Arizona)	212 000	-	370	6 000	180	1950-1980

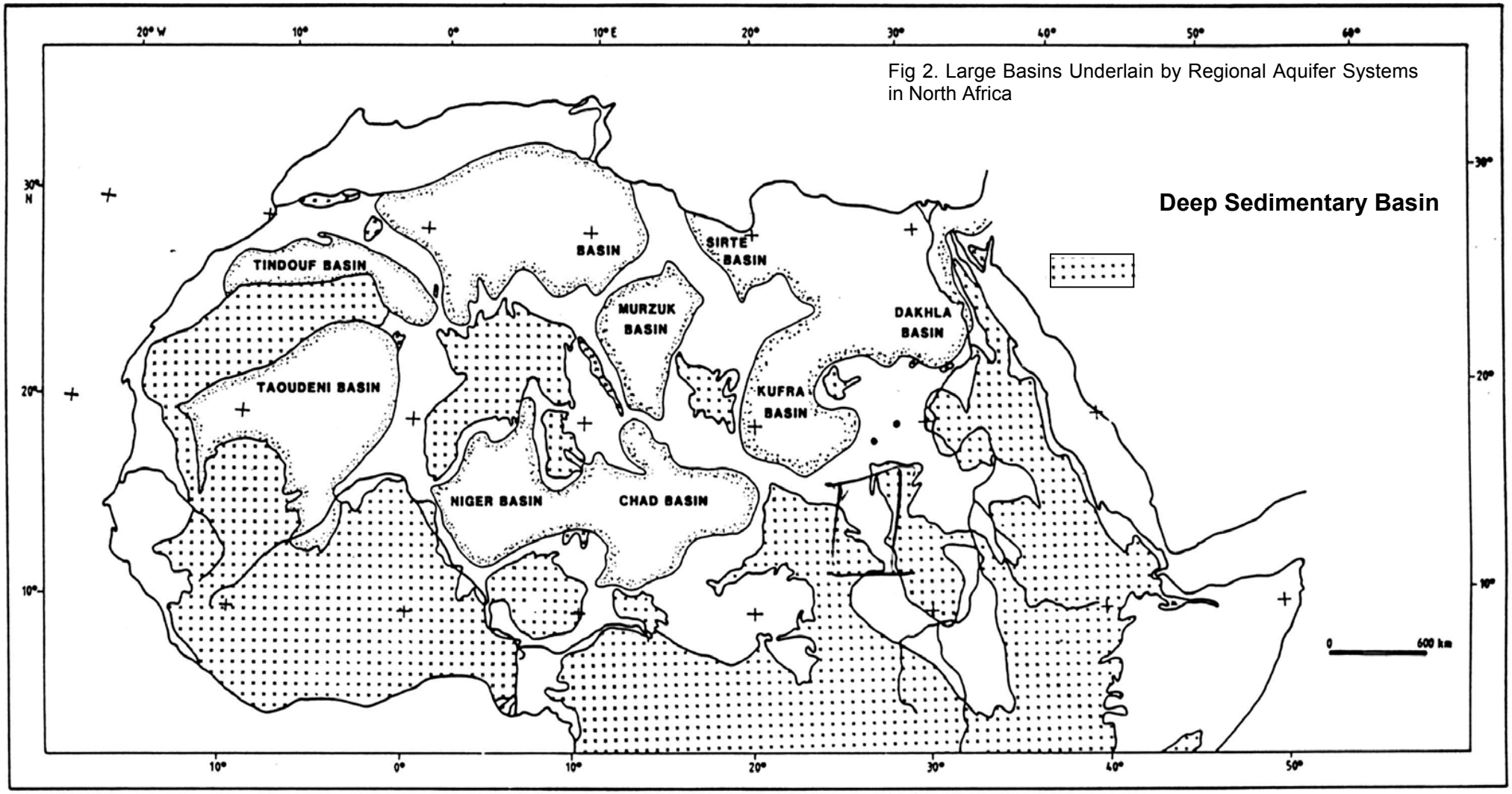


Fig 2. Large Basins Underlain by Regional Aquifer Systems in North Africa

Source: Thorweihe and Heinl 1998

There are certain characteristics of flow in this region that deserve to be highlighted. In general, throughout the northern Sahara, the regional flow is directed northward towards the Mediterranean (Figure 3). Geological structure, particularly the configuration of the basement may cause flow, locally to be directed northeastward (in Egypt, Tunisia) or rarely southward (in Sudan, Algeria). Groundwater emerges in oases or sabkhas that are located at some distance from the Mediterranean. It is possible that the northernmost discharge areas lie along a "Sabkha line" similar to that identified in the Arabian peninsula, but since several structural highs, exist near the Mediterranean the line of discharge would be an intermittent one. As yet, no evidence exist that such a discharge pattern was controlled by Pleistocene sea level.

The head distribution has shown only regional trends, and rarely reflects local influences. This is probably due to the localized nature of the investigations (Lloyd 1990). An important feature of the Nubian Regional Aquifer System is the occurrence of a sequence of oases within the extensive confined area. This discharge pattern is known as the "New Valley" and is believed to be controlled by fracture zones associated with structurally high areas (Lloyd 1990). To the west in Libya the Nubian system contributes to the groundwater flow in the Tertiary Sirte Basin (Figure 4) and eventually discharge takes place in low-lying zones of sabkhas extending along the Gulf of Sirte (Wright et al. 1982).

A regional model developed for the Nubian aquifer system, showed that the groundwater body, estimated at about 150,000 km^3 formed in earlier "pluvial periods occurring in late Pleistocene (older than 20,000 years and in the Holocene between 14000 and 4000 BP)" (Thorweihe & Heinl, 1996). Simulation showed that groundwater was primarily formed by local paleo-recharge, and natural discharge decreased from 2400 million m^3/year during the last pluvial to 500 million m^3/year today. The model has also demonstrated that recent aquifer recharge is negligible and withdrawal from the system is "mining of a non-renewable resources" (Thorweihe & Heinl 1996).

The great sedimentary basin of the Northern Sahara encompasses about 700,000 km^2 in parts of Algeria, Tunisia and Libya. It is underlain by a regional aquifer system comprising two major aquifers (Figure 2);

1. The lower Continental Intercalaire (CI) aquifer composed mainly of continental sandstones.
2. The upper Complex Terminal (CT) aquifer consisting of sandstones and carbonates.

The Lower (CI) and Upper (CT) aquifers are almost independent in west in Algeria, towards the coast they are interconnected or merge to form one aquifer system. The head is always higher in the lower continental Intercalaire aquifer, and consequently upward leakage increases eastward.

Aquifer recharge is low compared to the volume of water in storage. However it is believed to occur through runoff from wadis heading into the Sahara Atlas, or by direct infiltration from precipitation on the Grand Erg Accidental or Tademait Plateau. Groundwater flows southward and northeastward towards major discharge areas. Discharge occurs via foggaras in Tonal-Gourara-Tidikelt, by pumpage from deep wells, or Naturally by evaporation in Chotts of Medenine and Melrhir in the northeast.

The regional aquifer system of Saudi Arabia was conceived by Italconsult (1969). According to this concept the Great Basin of Eastern Arabia is underlain by two major aquifer systems (Figure 5): A "recharging-depleting" and "non-depleting" system. The first regional aquifer system comprises several aquifers, mainly carbonates of Post-Jurassic age, whereas the second aquifer system include the Saq, Wajid, Tabuk and Minjur- Dhruma aquifers, consisting mainly of Nubian-type sandstones of Paleozoic and Lower Mesozoic age. The most significant feature of the Carbonate Aquifer System in the discharge via Sabkhas arranged along a line "The sabkha Line" (Figure 6) which extend from Kuwait through the coastal gulf region of Saudi Arabia. Where the groundwater is not covered by sands, the sabkhas seem to be accompanied by a fringe of karstic features. These features are believed to be discharge zones which were operative in periods of higher aquifer head. It is possible that the sabkha line represents an ancient shore line (FAO 1979). It is worth noting that apart from this distinctive regional discharge feature running approximately along the 150 m topographic contour, discharge is completely absent from the vast desert areas of the Peninsula.

Aridity is the most significant factor in the management of groundwater resources in much of the Australian continents. Of the total area of Australia, about 8 million km^2, arid basins occupy some 6 million km^2 (Figure 7). Deep sedimentary basins include the Amadeus and Officer basins in central Australia, covering 160,000 km^2 and 275,000 km^2 respectively. The Canning Basin underlies the Great Sandy Desert in the northwest of the continent and has an area of about 430,000 km^2 of southwest Australia (DPIE 1987, Jacobson et al. 1983).

An area of relative uplift composed of pre-cambrian and proterozoic rocks outcroping in the arid regions of central Australia separate area of relative subsidence represented by Amedens and Canning basins in the north from the officer and Eucla basin in the south. Major aquifers systems, therefore consist mainly of Paleozoic sandstone in the Amadeus and Officer and Canning basins being adjacent to the Pre-cambrian uplifted areas. On the other hand Mesozoic sandstones are followed by Tertiary limestone in the Eucla Basin.

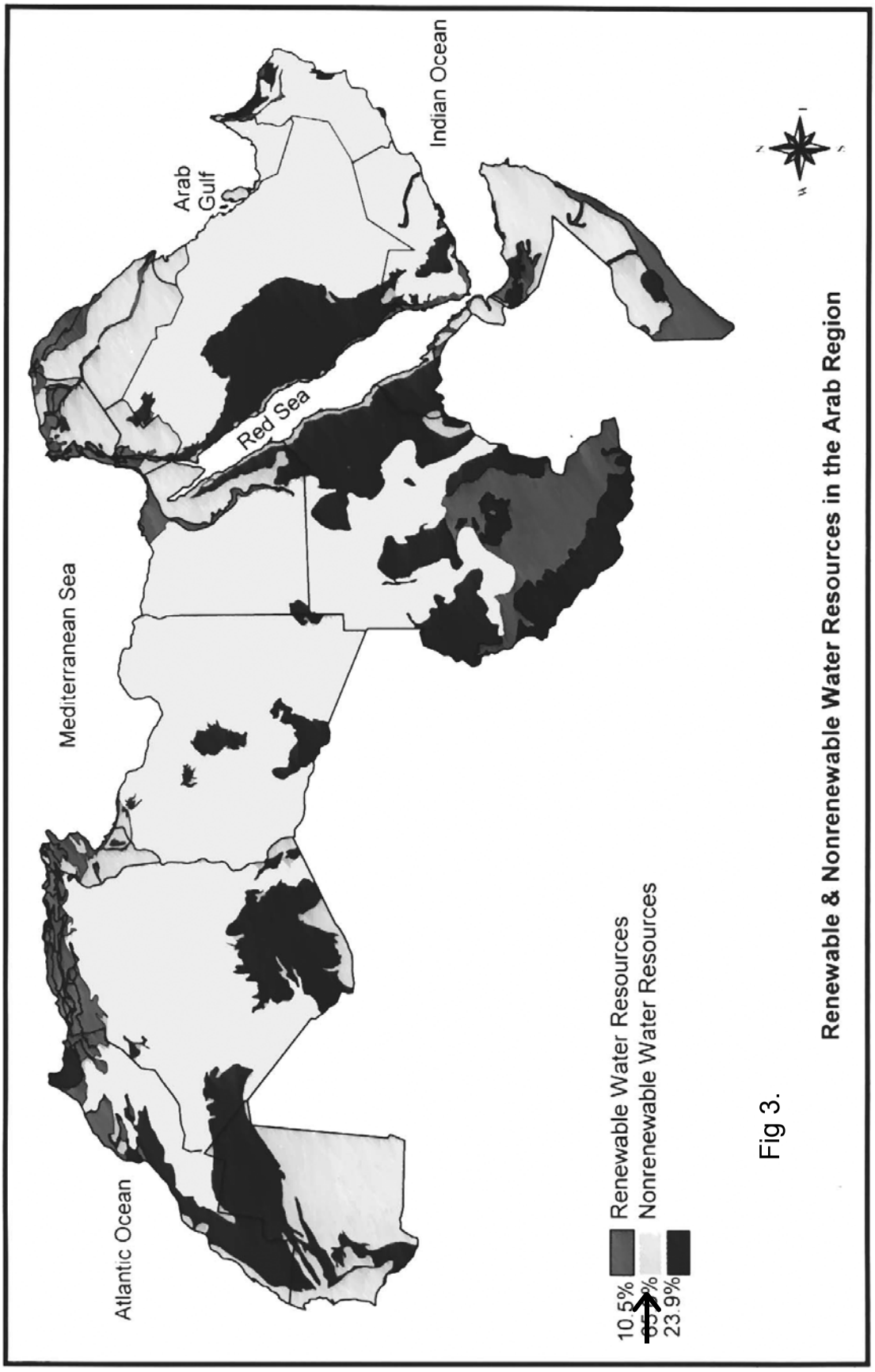


Figure 3: Renewable and non-renewable water resources in the Arab region

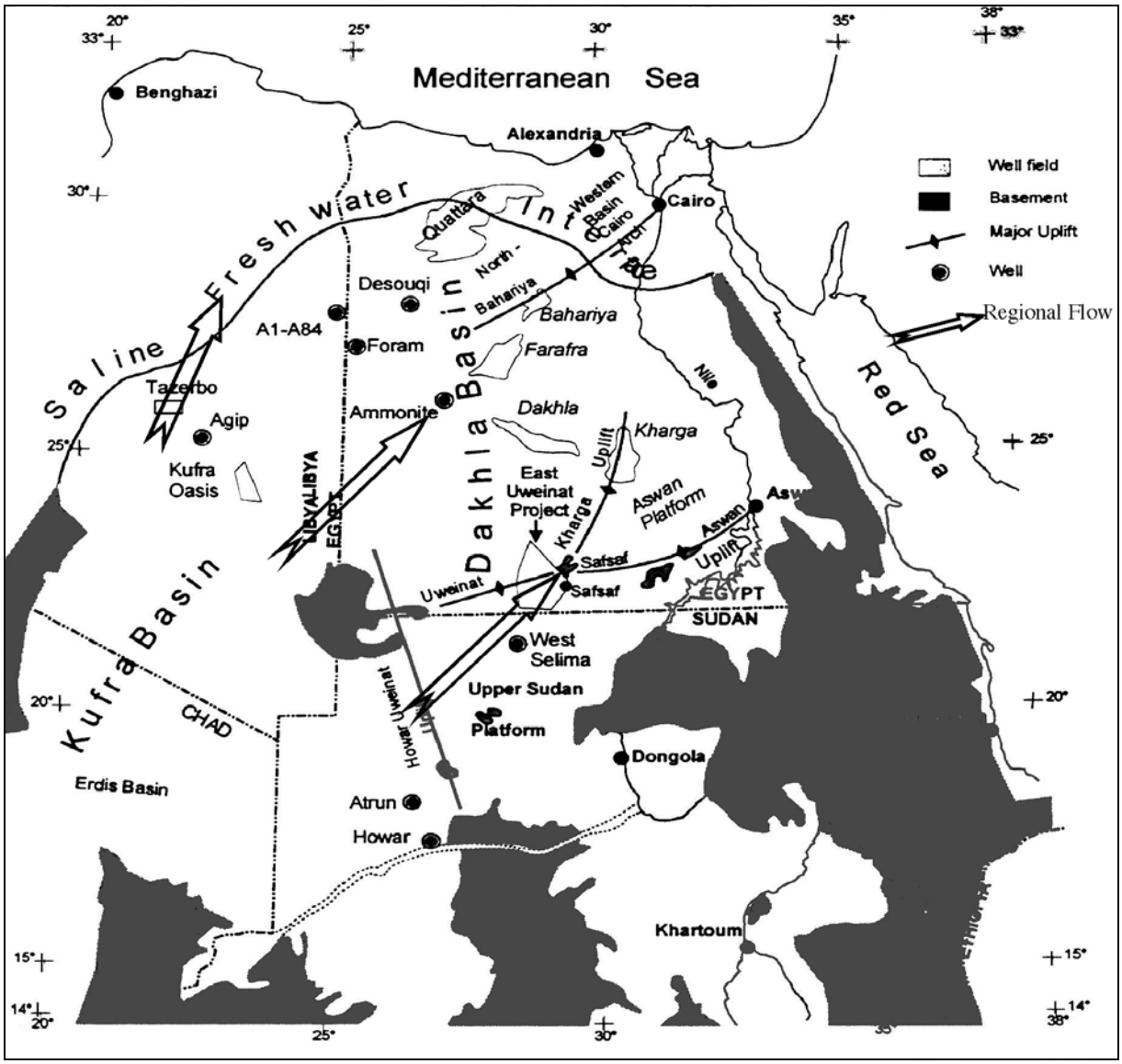


Figure 4: General map of the Nubian Aquifer System area. (Source: Thorweihe & Heinl 1996)

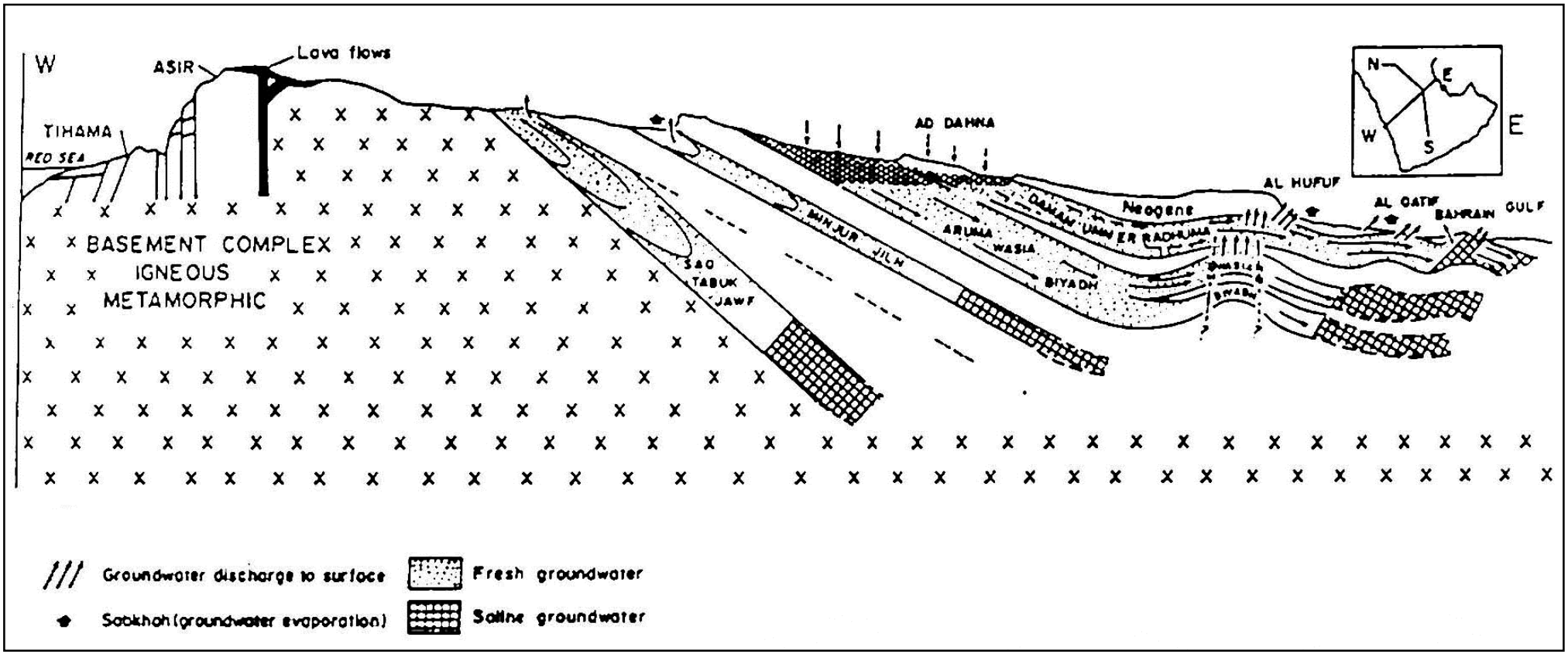


Figure 5: Cross-section of regional aquifer systems in the Arabian Peninsula (Source: ESCWA 1999)

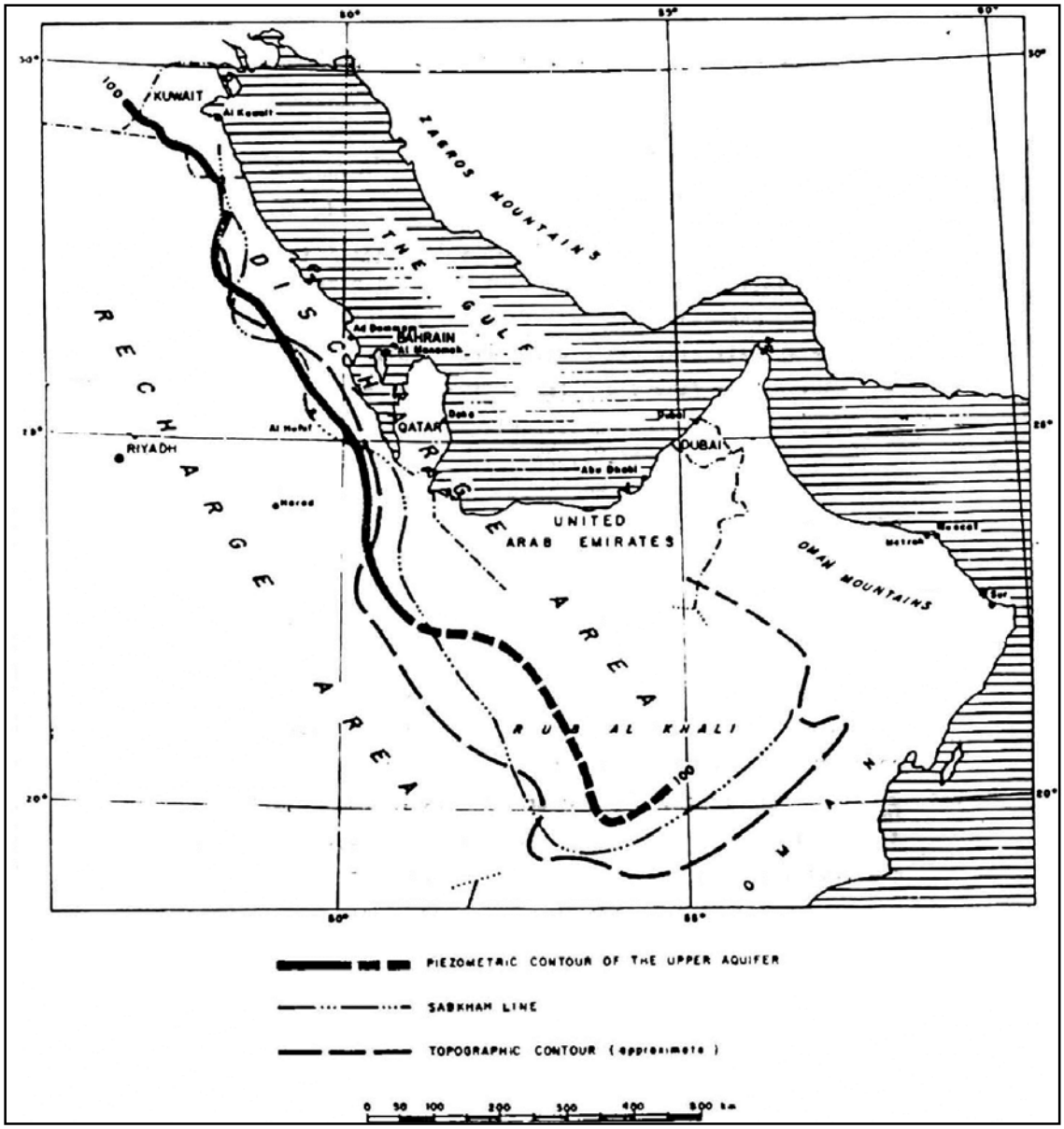


Figure 6: Paleo-discharge zone in the Arabian Peninsula (Source: FAO 1979)

Modeling of the multi-layered groundwater system in the Amadeus Basin has indicated that flow time along a section 250 km long and 6000 m deep to be several million years (Brown et al. 1990), and the system may reflect paleorecharge conditions in the early Tertiary. The results of Chlorine 36 confirm the great antiquity of some groundwaters (Jacobson et al., 1994). Another important characteristic of the Australian arid basin is the development central Australian Groundwater Discharge zones in the south of Amadeus Basin, which consists of a chain of salt lakes 500 Km long. In this discharge zone hypersaline brines containing more than 100,000 mg/l of TDS are concentrated by groundwater discharge. The groundwater discharge which is still active under present dimatic conditions is similar to a certain extent to the paleo-discharge sabkha zone in the Arabian Peninsula.

Any review of arid basins of Australia cannot overlook the importance of the “Great Artesian Basin” encompassing some 1.7 million km^2. The multilayered Mesosoic sandstone aquifer system underlying the basin extends from the arid interior to the semi-humid eastern coast where it receives recharge from rainfall. Groundwater ages up to 2 million years have been estimated using Chlorine 36 (Airey et al. 1983). These ages are comparable with calculated groundwater flow times. This result is similar to that obtained from the study of the Nubian Basin, thus in the certain parts of the great basins, that are far away from sources of recharge, groundwater development is a mining process at a human time scale.

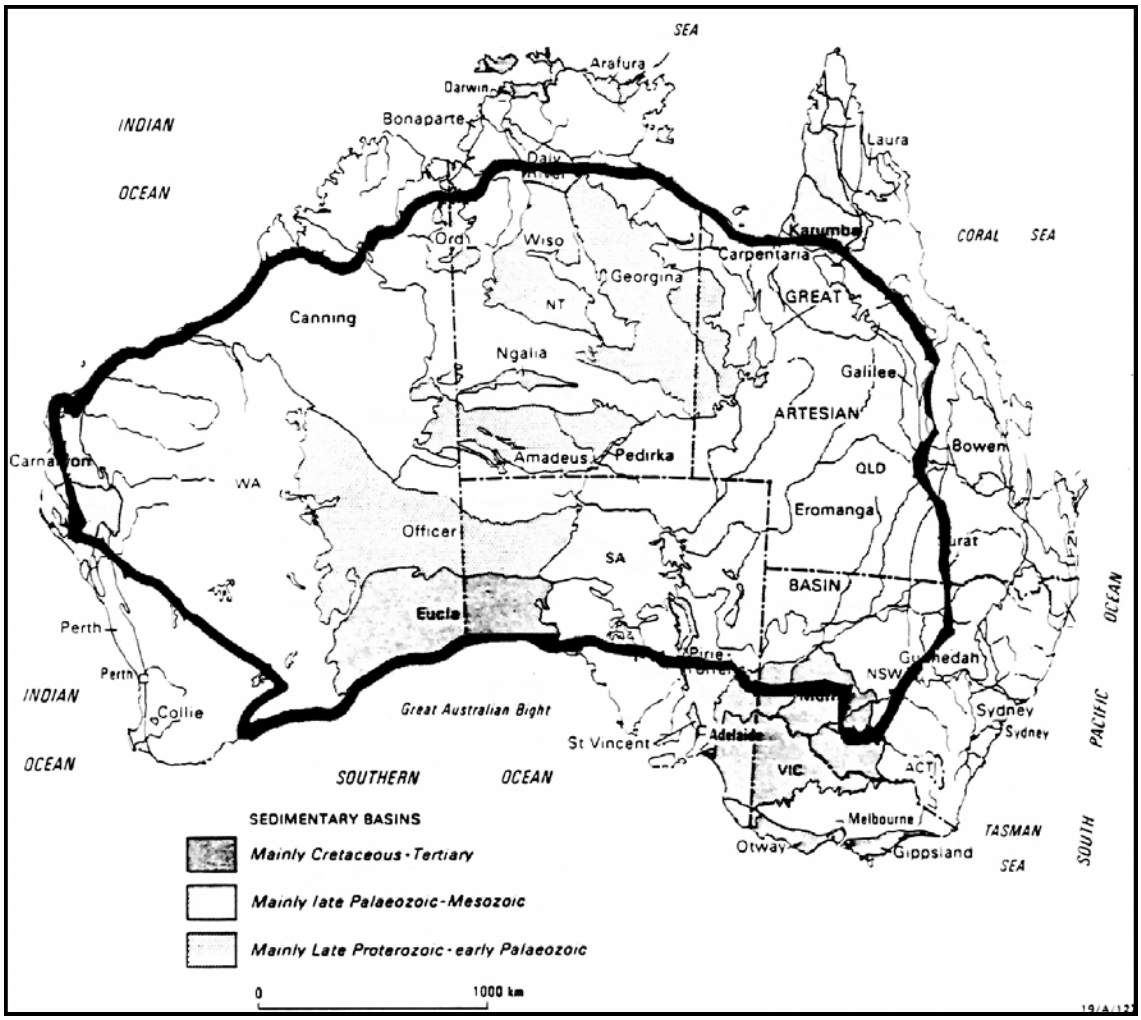


Figure 7: Arid basins in Australia (Source: Jacobson & Brown 1999)

2.3 System approach

For several decades “aquifers” have been proposed as basic units for groundwater studies and evaluation (Todd 1959, Waltan 1970) Adoption of a “system approach” has introduced new concepts regarding the “natural groundwater unit”, thus the ideal delineation of a groundwater flow system involves locating the **recharge and discharge zone and linking these parts by identifying the zone of lateral flow** and establishing boundaries of the system. Unfortunately reliable flow system delineation is difficult in some areas due to paucity of fluid potential information, and because areas of recharge cannot be directly proven in arid and semi-arid zones. Investigations regarding the “natural groundwater unit” which is most suitable for groundwater resources assessment has lead to the definition of “groundwater flow system” as a region within saturated earth material where there is dynamic movement of groundwater from source to sink (Mifflin 1968, Freeze & Witherspoon 1967, Engelen 1984). Toth (1963) modeled hypotentical systems and concluded that given certain boundary conditions it is possible to recognize local, intermediate and regional systems. The so-called zone of lateral flow between recharge and discharge zones is commonly extensive in arid and semi-arid zones.

The concept of “regional aquifer system” has a world-wide recognition at the present time. In North Africa, the groundwater resources of the Nubian basin have been evaluated by developing a numerical model of groundwater flow (Thorweihe & Heinl 1996). **The Nubian aquifer system** has been considered the basic unit instead of the conventional unit, the “Nubian Sandstone Aquifer”. In United States 25 regional aquifer systems were delineated. Using computer based numerical models. Regional groundwater budgets were assessed, and the groundwater development effects were evaluated. In Southwest Asia 18 regional aquifer systems were recognized (ESCWA 1999). As seen by Engelen (1984), a groundwater system has input, throughput and output of energy in various forms, and usually evolves passing through stages of growth in time and space. This advanced concept is applicable to groundwater systems in arid zones: Paleo-

recharge and paleo-discharge are indicative of the system's evolution "The stages of growth" of the Nubian Aquifer System have been described by Thorweihe and Heinl (1996).

Application of the system approach yields a wealth of information which could be used more effectively if regional aquifer systems are defined and delineated, and their resources are evaluated as natural hydrodynamic units.

3. Evolution of concepts for the development of non-renewable groundwater resources

3.1 Intensive Development of Regional Aquifer Systems

Groundwater, being the main or the sole water resource in arid zones have been extensively and intensively developed in several arid region in the past decades. Rapid population growth, improvement of the standard of living, and expansion of irrigation has led to a sharp increase of demand for water in the Arabian Peninsula to meet rising demand. Both shallow and deep fossil groundwater have been mined and depleted at an accelerating rate.

In North Africa, Two major projects the "New Valley" in Egypt and the "Great Man-Made River" in Libya has brought about intensive development of the regional aquifer systems. In some regions long-distance conveyance of water has decreased pressure on heavily developed aquifers. Water has been conveyed between different areas or basins within the same country. In Saudi Arabia withdrawal from groundwater, mainly non-renewable increased from about 3 BCM in 1986 to about 17 BCM in 1996 (El-Turbak 1999). Total withdrawal from aquifer systems in the eastern hyper-arid region of the Peninsula was estimated at 19.9 BCM in 1998 (Zubari 1998).

In contrast to intensive groundwater development in the Northern Sahara, only small proportion of the large groundwater reservoirs has been developed in the Sahelian countries south of the Sahara. Future groundwater development in this region, needs, however, improved knowledge and better understanding of the groundwater systems in order to evaluate their potentialities and define their limitations.

The Arid basins of the United States include the heavily populated part of southern California and the Great Basin in Nevada, Arizona and parts of other states. Withdrawal from the alluvial basin aquifer systems in southern and central Arizona increased from 2.1 BCM in 1942 to about 5 BCM in 1980. A total amount of about 226 BCM was pumped mainly from aquifer storage during 1920-1980 (Sun 1986). One of the most heavily developed aquifer systems in the United States is the High Plain regional aquifer system. Pumpages from this aquifer system increased from about 4 BCM in 1950 to about 22 BCM in 1980. Over-development has led to declines in water levels in about 29% of the area underlain by the aquifer system. Maximum water level decline was nearly 60 m (200 ft).

Australia's most productive aquifers are phreatic alluvial aquifers underlying the Eastern and southern regions. A large part of western and central Australia is, however, arid with mean annual rainfall below 250 mm. Some 12 MCM is abstracted from the Mereenie aquifer system underlying about 26000 km^2 of the Amadeus Basin in Central Australia. The water is derived from regional storage (Jolly & Chin 1992). Groundwater withdrawal from Great Artesian Basin is estimated at about 550 MCM/yr.

Non-renewable resources by definition are natural groundwater resources and their development or "mining" is "intensive" (OSS 1995). It is not because the aquifer contains very "old water" that is considered a non-renewable resources. It is above all on account of a relationship between its discharge and storage, which is such that any historically significant pumpage necessarily represent much more a withdrawal from aquifer storage than simply drawing off water from throughflow (Margat & Saad 1984). This is a system of exploitation on a basis of hydraulic imbalance not only during an initial transitional period but also for the intire duration of the exploitation. The lowering of the water table will continue even under steady abstraction conditions.

According to several authors regional aquifer systems underlying arid basins could be in disequilibrium even under natural conditions (Burdon 1977, Pallas 1980). Lloyd and Farag (1978) have examined the hypothesis that present day groundwater gradients in arid regional sedimentary basins are a decay feature of old recharge mounds, and demonstrated, using a modeling approach, that a head decay could have occurred over the past 10,000 years to produce the present day gradient. By applying this concept to the Nubian regional aquifer system Thorweihe and Heinl (1996) has shown, (using a numerical model of groundwater flow), that groundwater was primarily formed by local paleorecharge, and that the natural discharge of the whole system decreased from 2400 million m^3/year 800 years ago to 500 million m^3/year today.

In many arid basins little water is withdrawn in comparison with their large aquifer storage. Groundwater in the Canning, the Officer and Eucla basin are as yet untapped or poorly developed although they offer important groundwater resources.

3.2 The concept of permissive mining yield

Development of groundwater resources has economic, social and environmental consequence, some beneficial and others adverse. According to the traditional concept of groundwater management recharge must balance discharge to maintain the resource. In order to attain this objective the notion of “Safe Yield” was introduced and has been adopted as basic criteria for groundwater management. According to this concept groundwater withdrawn annually should not exceed long-term mean annual recharge (Walton 1970). Since this concept cannot be applied to the development non-renewable water resources, Walton proposed the term “maximum mining yield” which he defined as the total quantity of non-renewable water stored in the groundwater reservoir. “The permissive mining yield” was defined as that part of the maximum mining yield obtainable through economic pumping patterns.

Several authors has recently discussed the “Safe Yield” concept and its application for the sustainable development of renewable groundwater resources, and recommended the use of appropriate methodology. To assess possible effects of exploitation such as groundwater quality changes and other impacts on the environment (ESCWA 1999). For applying the concept on non-renewable water resources, a “Safe Yield” cannot be assessed indefinitely but can be computed under certain socio-economic conditions for a given usually limited period of time (25, 50, 100 years). Groundwater is “mined” or depleted during this period.

A resource could therefore be defined as “the water available or capable of being available for use in sufficient quantity or quality at a location and over of a **period of time** appropriate for identifiable demand”.

Simulation could be utilized to plan future development and examine the aquifer response to different management strategies. Since regional aquifer systems underlie very large basins, and is often shared by several countries, a regional model need to be developed. The regional simulation s intended primarily to improve understanding of regional flow patterns and to provide boundary conditions for sub-regional or local simulations studies. These studies are implemented for investigating site-specific groundwater problems.

Operational models are useful for setting up the groundwater development plan. Using these models withdrawal can be managed to prevent, if possible, pumping water levels in wells from declining to depths near the bottom of wells. Water managers need to consider areal distribution of wells, pumping rates and period, so that the water level declines will not cause wells to go dry. Calibrated local or “well field” models are used to project future decline of the potentiometric surface, probable wells yields and changes in saturated thickness that would result from various management strategies. Such information is necessary for planning or refining and adjusting future development plans.

4. Assessment of groundwater development effects

Planners and managers are now aware of the fact that development of non-renewable groundwater resources amounts to drawing water from the reserve and that the volume of water abstracted is the practical equivalent of the depletion of the reserve of the aquifer. Sustained withdrawal from aquifer storage will result in a continued lowering of water levels. Such lowering will, in turn lead to internal or external effects that may considered impacts. The primary task facing managers is to maximize positive impacts and minimize the negative ones. In order to address the adverse impacts it is necessary to analyses, describe and assess consequences of development and use of “mined” water including estimates, if possible, of damages incurred to the resources base or to the environment.

The most heavily developed aquifer systems are the regional aquifer systems underlying the eastern deserts of the Arabian Peninsula. They extend from the Arabian shield in the west of the Peninsula to the gulf, where discharge via springs and sabkhas takes place. Major aquifer systems include:

- The Paleozoic sandstone aquifer system encompassing parts of Jordan and Saudi Arabia;
- The Tertiary Carbonate aquifer system encompassing significant parts of Saudi Arabia, Kuwait, Bahrain, Qatar and the United Arab Emirates.

Current abstraction is estimated at 20 BCM of which some 17 BCM comes from aquifer storage. Intensively developed aquifers in North Africa include:

- The Nubian Regional Aquifer System;
- The North Sahara Regional Aquifer System.

Abstraction from these aquifer systems is of the order of 3 BCM. Planned withdrawal will increase to about 4 BCM (Hany 1991, Salem 1991) from Nubian Aquifer System and about 2.5 BCM from Sahara Aquifer system (Zitoun & Droubi 1992).

In the United States the most intensively developed aquifer system for irrigation in arid regions is High Plain regional aquifer system. The Ogalla Formation which underlies 80 percent of the High Plains is the principal aquifer.

A review and assessment of the consequences of intensive development of these aquifer system occurring under arid or hyper-arid conditions and subjected to different degrees of stress, demonstrate not only the negative or adverse impacts of intensive pumping, but also the positive impacts represented by the economic and social benefits derived from their development. In most cases development was not based on reliable and accurate assessments of water resources and their response to stress. Strategies have been developed at later stages in order to rectify and minimize negative effects.

Regional models were developed to provide quantitative understanding of regional flow and to provide boundary conditions or subregional or local simulations. Sub-regional and local model were developed to address site-specific issues and provide more detailed information to planner and managers at a local level (Sun 1986). Regional programmes have been developed in the United States (RASA 1978-1992). 25 regional aquifer systems including the most heavily pumped aquifers were intensively studied to provide information and characteristics of aquifers and to support better management of regional aquifers and to resolve development associated problems (Sun and Johansten 1994).

In North Africa regional programme are now being implemented for improving the knowledge base and re-calibrating the regional models of the Nubian Aquifer System and North Sahara Aquifer System (Khouri 1992).

The objective is to arrive at an improved management of regional aquifer systems shared by several countries.

The impacts of intensive development of regional aquifer systems include:

- Impacts on the resource base;
- Impacts on the environment.

4.1 Impacts on the Resource Base

4.1.1 Decline of Water Levels and Depletion of the Reserves

The sandstones aquifers belonging to the Paleozoic regional aquifer system have been extensively developed in both Jordan and Saudi Arabia. Extraction of water in Jordan increased from 15 MCM/Yr in 1983 to 80 MCM/Yr in 1989. It is generally accepted that the Paleozoic (Disi-Saq) aquifers does not receive major replenishment, and consequently groundwater is drawn mainly from storage. The total pumpage of about 300 MCM during the period 1983-89 has caused a decline in water levels amounting to more than 9 metres in some areas (Figure 8).

In Eastern Saudi Arabia extraction rates from Tertiary regional aquifer system increased in the Gulf coastal area from 250 MCM in 1976 to about 750 MCM in late 1980s (Rasheedudeen 1989). It was estimated that some 10 000 MCM were extracted from the aquifer system by 1990. If extraction trends of 1980s continue in the 1990s, simulation shows that water levels will continue to decline uniformly, and a large cone of depression will develop. Maximum drawdown will range from 14 m to 43 m by the year 2000. This will cause a dewatering of the aquifer in individual wells (Rasheeduddin, 1989).

About 67% of the non-renewable groundwater reserves of Saudi Arabia is stored in major aquifers (Al-Turbak 1999). During the period 1980 -1995 pumpage from groundwater amounted to 254 BCM (Al-Qunaibet 1997). About 35 % of proven groundwater reserves in major and minor aquifers has been used by 1995 (Al-Turbak 1999).

Development of the Dammam regional aquifer system in Bahrain has significantly increased since 1950. Abstraction from the aquifer systems increased from about 63 MCM in 1932 to about 220 MCM in 1990 (Alnaimy 1992). The potentiametric surface dropped by about 4 m on the average. The decline at the sea coast is about 2 m, resulting in sea water intrusion. It has estimated that about 50% of the groundwater resources have been polluted (Zubari et al. 1993).

Qatar is another area where intensive development of the Dammam Carbonate regional aquifer system produced serious adverse effects. Total extraction from the carbonate aquifers in 1980 was estimated at about 80 MCM. Withdrawal increased to 244 MCM in 1997 (Al-Sulaiti 1999) computations indicate an average depletion of aquifer storage at a rate of 20 MCM/Yr. At such abstraction rate, it was

estimated that the aquifer storage will be depleted in 20-30 years (Al Hajry 1992). The prsent rate of sea-water intrusion was estimated at 1 km/yr.

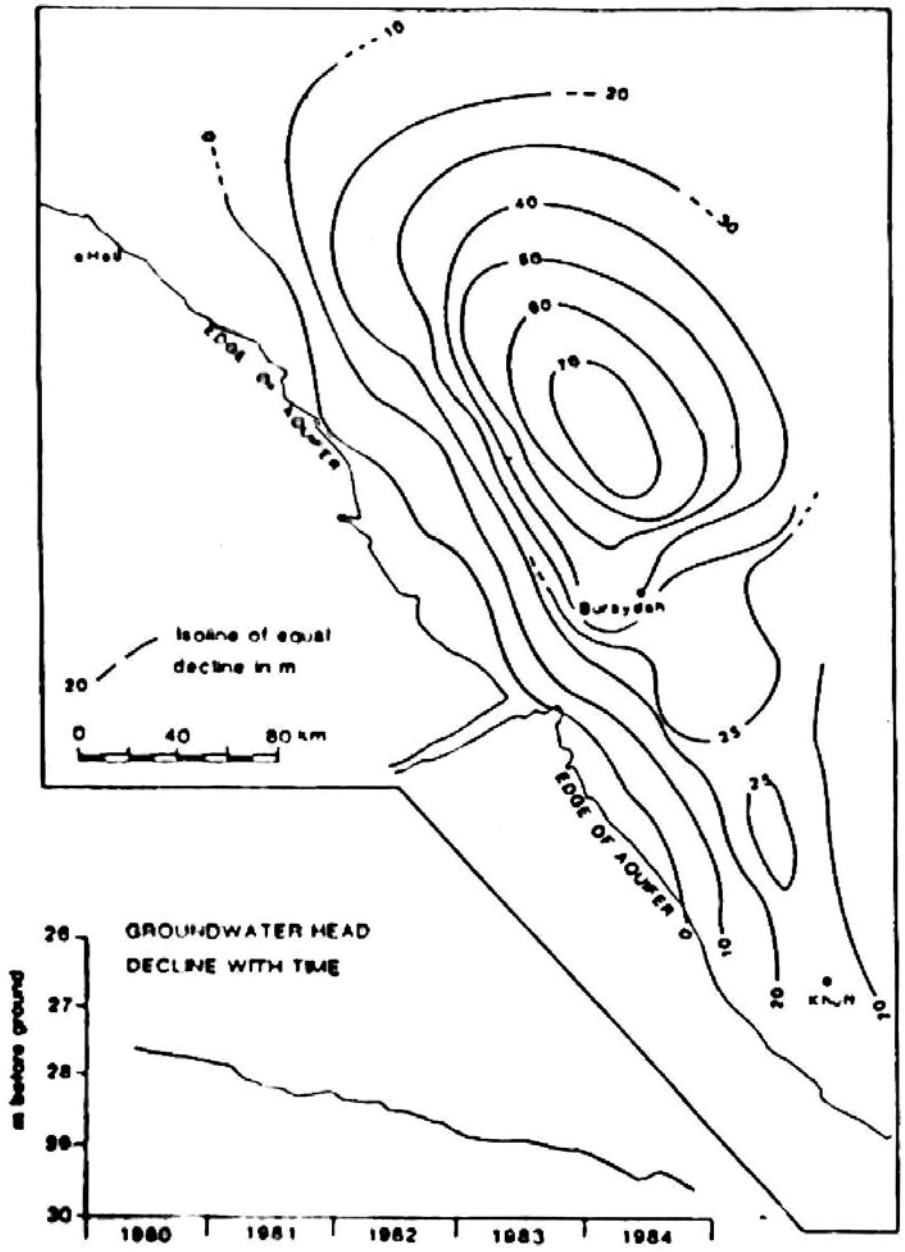


Figure 8: Development of a cone of depression in the Saq (Disi) aquifer in northern Saudi Arabia (Source:BRGM)

In North Africa, large scale groundwater developments took place mainly in the Northern Sahara. In the past decades major groundwater basins have been heavily developed, mainly in oases and desert depressions where relatively good soils and found. During the 1980s, however, well fields were sited in other areas where the aquifer system is characterized by high productivity and good water quality.

The exploitation of the Nubian regional aquifer system has taken place in Egypt, mainly in the “New Valley”, in a series of oases which extend from latitude 25°N to latitude 30°N.

Appreciable withdrawal from the deep Nubian sandstone aquifer in the Kharga Oasis started in 1956. Since most of extracted groundwater comes from storage a substantial decline in groundwater head occurred.

A continued lowering of groundwater head also occurred in the Dakhla oasis as a result of sustained withdrawal from aquifer storage as can be seen from the following figures (DRI, 1989) (Table 2).

In the United States, intensive pumping for irrigation has resulted in a significant water level decline and reduction of the saturated thickness in the High Plain aquifer system. The consequence of this reduction of the saturated thickness has been a significant reduction of the areas irrigated by wells tapping this aquifer system.

Table 2: Head Decline in the Dakhla Oasis

Area	Period	Head Decline M	Rate of head decline M/yr
Eastern zone	1962-1975	8-18	0.6-1.4
Western zone	1963-1968	17	3.4

A comparison of pre-development conditions (1940) with 1980 pumping conditions indicates that the saturated thickness has been reduced by more than 10% over an area of about 114000 km^2 which is about 25 percent of the areal extent of the aquifer and more than 25% reduction in saturated thickness occurred over an area of 36000 km^2 (Sun & Johnston 1994).

From 1980 top 1989 water levels declined more than 4.5 m (14 ft) in areas of intensive irrigation in Kansas, New Mexico, Oklahoma, Colorado and Texas (Figure 9). In turn this has caused a reduction in well yields, and increased pumping costs, and locally many wells have gone dry.

4.1.2 Deterioration of Groundwater Quality

Groundwater withdrawal can cause directly or indirectly changes in groundwater quality. Impact on groundwater quality may be gradual and allow to take corrective measures or may be rapid and could lead to serious consequences that eventually results in the destruction of resource.

Saline intrusion into freshwater aquifers is the common phenomenon that leads to degradation of groundwater quality. In addition to the usual contamination sources such as sea water and saline water bodies in sabkhas (Playas) gypsum and evaporite deposits may cause serious quality problems. The deeper parts of regional aquifer systems may contain brackish or saline water. Intensive exploitation from the aquifer system has the potential to lower the quality of the groundwater by drawing in lower quality waters from surrounding zones and from lower formations.

Changes of groundwater quality resulting from the intensive development of Palmyrian regional aquifer system in the Syrian Desert (Badiet El-Sham) has been demonstrated. New agricultural development based on the intensive exploitation of upper aquifer caused the intrusion of saline sabkha water into the freshwater aquifer, resulting in substantial increase groundwater salinity (Figure 10) and deterioration of agriculture. Several farms were abandoned and other productive farms deteriorated. In order to address this problem a mathematical model was developed and scenarios were proposed to plan future development in a more sustainable manner.

The regional carbonate aquifer system of the Arabian Peninsula extends into Qatar where it has been subjected to intensive development. Intensive pumping which has reached 224 MCM/Yr (Al-Sulaiti 1999), has resulted in an unbalanced hydraulic setting between freshwater and saltwater which underlies and surrounds the aquifer system in this peninsula. It was estimated that saltwater advances about 800 m/yr (FAO 1981). Accumulated saltwater intrusion was approximately 29000 m in 1994. The process of deterioration under the pressure of increasing withdrawal results from both sea water intrusion and upconing from lower saline aquifer. The rate groundwater quality deterioration was estimated at 6% per year.

A similar hydrogeological and hydrochemical setup exists in Bahrain. The regional carbonate aquifer system (the Dammam aquifer system) extends from Saudi Arabia to Bahrain. Upconing of saline water from deeper aquifers (Rus-Umm Radhuma aquifer) and intrusion of sea water resulting from excessive lowering of the potentiometric surface has caused substantial deterioration of water quality (Figure 11). The sea water brackish water interfaces advance at a rate of about 100 m/yr (Zubari et al. 1993).

The Saq regional aquifer system is one of most heavily developed aquifer systems in the Arabian Peninsula. The Saq aquifer comprise coarse and fine grained sandstones of Paleozoic age resting directly on the crystalline basement in the Qassim arid area. A comparison of chemical data in 1985 with data of 1996 has revealed that the total soluble salts have increased by 21% on the average (Al-Sagaby & Moallim 1999).

The deterioration of the water of Saq aquifer with time is attributed to heavy pumpage during the past decade. Groundwater of good quality is available in an extensive area underlain by the Nubian aquifer system in Sudan, Chad, Egypt and Libya. The relatively low concentration of dissolved solids from the upper and deep aquifers have minimized adverse effects related to groundwater development. Available data indicate that the salinity of groundwater in the Nubian Sandstone aquifer in the Kharga oasis ranges from 300 to 450 mg/l. In the Dakhla Oasis the concentration of dissolved solids is still lower ranging from 176 to 252 mg/l and decrease with depth.

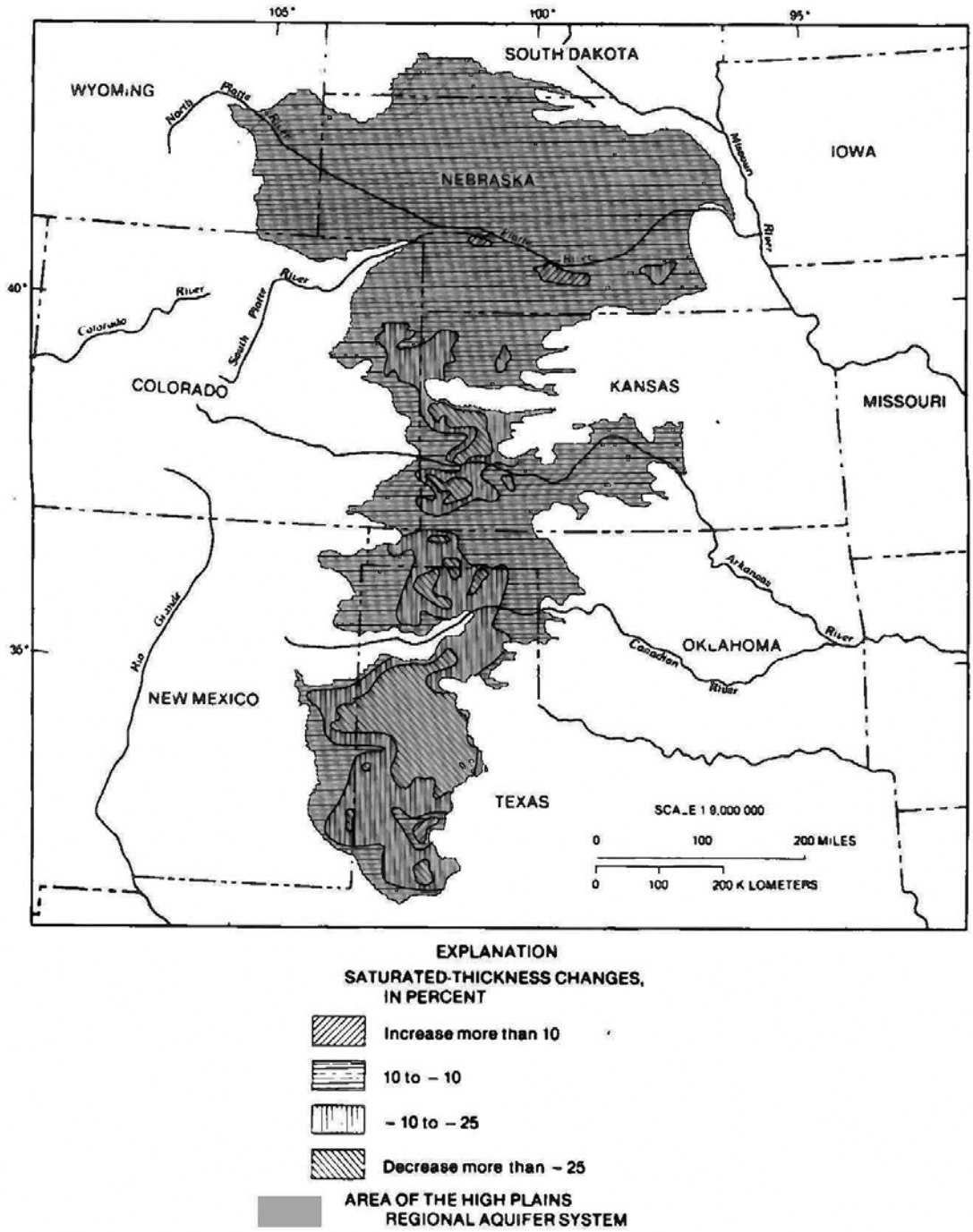


Figure 9: Saturated thickness changes, from predevelopment to 1980, in the High Plains Regional Aquifer System

Downstream upon approaching the principal discharge zone of the Nubian regional aquifer system, the concentration of dissolved solids increase northeastwards and reaches about 550 mg/l in the upper aquifer in Bahriya oasis. In the Siwa oasis the deeper aquifers become highly mineralized and parts of upper aquifer contain brackish water. The balance between the various members of the aquifer system, in this area is delicate and although present development concentrates on the upper aquifer, future development should be based on the concept that the upper and lower aquifers act as a single hydraulically connected aquifer system.

By contrast, the North Sahara regional aquifer system is a multi-layered aquifer system with several aquifers containing brackish or saline water. In Tunisia degradation of water quality occurred in Zeuss-Kouhine area. Measures were taken to reduce withdrawal to minimize further deterioration. Similarly degradation of water quality of the complex Terminal aquifer occurs in Algeria (Latrech 1992). The potential for such impacts exists in most areas because the vulnerability of the aquifers system to salinization is high.

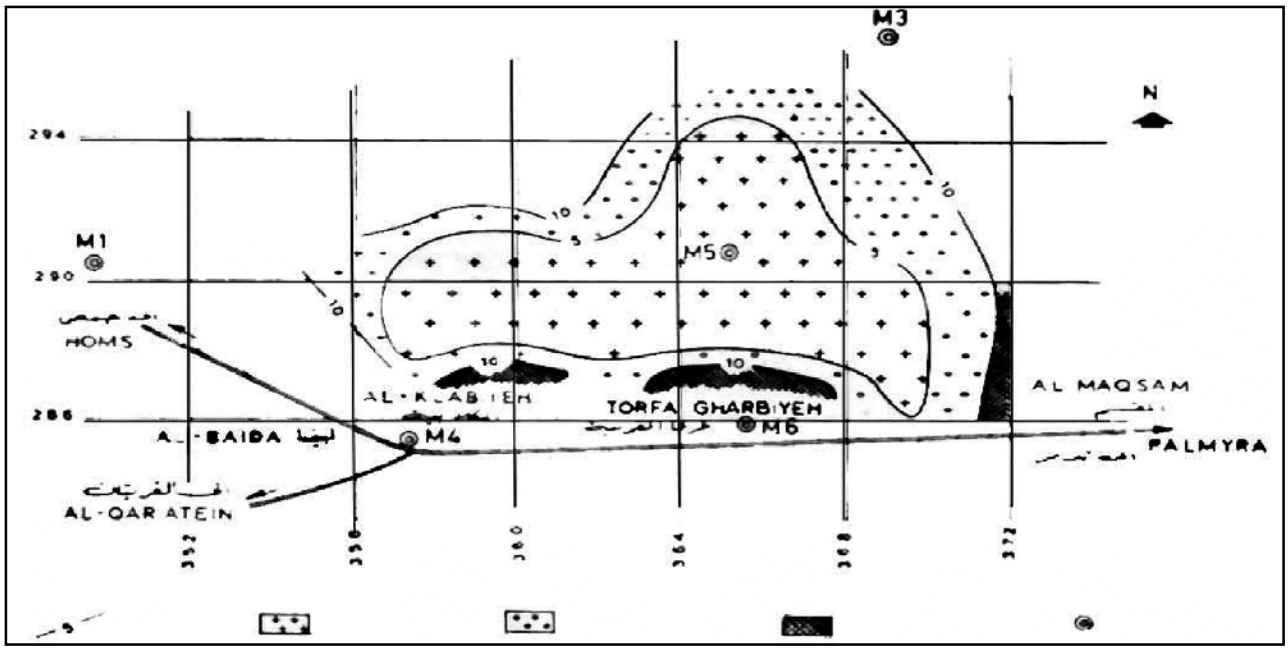


Figure 10: Intrudsion of Saline Sabkha Water into the freshwater Aquifer in the Palmyra basin, Syria (Source: ACSAD)

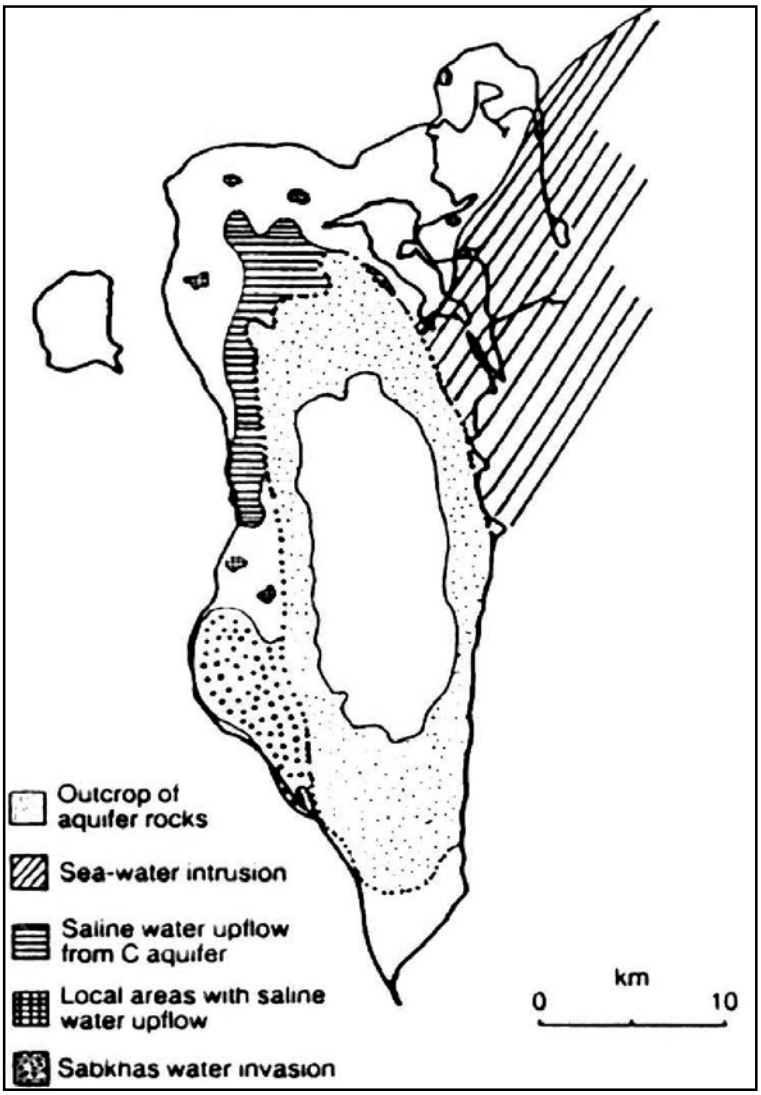


Figure 11: Extent of pollution in Dammam Aquifer, Bahrain

4.1.3 Decrease of spring discharge

When an aquifer system is developed, the cone of depression is formed around the pumping well. As pumping continues the cone of depression expands outward from the pumping center and water is removed from storage until it reaches a recharge or a discharge boundary. In arid and semi-arid areas, reduction of groundwater discharge will occur, when the cone of depression reaches a discharge boundary, and depending on the degree of stress the flow of springs will decrease. In highly stressed aquifers the spring or sabkha will dry up.

Springs in arid zones are rare, but when they exist, they are intensively used and such water occurrence in the arid environment has formerly controlled or influenced the traditional social environment. Many of the rural settlements established around major springs in the hyper-arid zones of Arabian Peninsula have formed the nuclii of modern urban centers.

This is exemplified in Bahrain, Oman and the Hassa area of Saudi Arabia. Some of the “Aflaj” (canat) systems of the United Arab Emirate and Oman are originally springs (Ayn) and have been developed to form traditional “falaj” systems.

The impacts of extensive and intensive development on springs in arid zones have been demonstrated in several regions. A well known examples are the evolution of the springs issuing from the Dammam regional aquifer system in Bahrain as shown in the following table (3) and (Figure 12);

Table 3: Springs discharge in Bahrain in MCM/Yr.

Spring Issuing	1924	1953	1966	1971	1979	1990
On the island	70	42	28	23	8.1	1.5
Submarine springs	13	9.6	9.6	6	6.6	3.5

Source: Al-Nuaimi 1999.

The decrease of flow from coastal springs has, not only affected the users but also has lead to a reversal of flow along the aquifer boundaries and caused further degradation of groundwater quality (OSS 1995).

In south Tunisia, intensive development of “Complex Terminal” aquifer system was exclusively through artisan (flowing) wells until 1950. Withdrawal increased gradually from 3 m^3/s in 1990 to 6 m^3/s in 1997 and water production became entirely through pumping. The impact of development of the North Sahara regional aquifer system is also reflected in the gradual decrease of major springs. The flow of Djerid and Nefzaoua springs dropped from about 2.5 m^3/s in 1900 to almost nil today .

5. Assessment of impacts on the environment

Use of water have always economic, social and environmental consequences, some beneficial and other adverse. Groundwater irrigation in arid zones may create serious impacts unless it is managed in an environmentally sound manner. Salinization is undoubtedly one of the major environmental impacts of irrigation. The problem is more acute if groundwater is used extensively for irrigation in an arid environment. Another effect, on the environment, of groundwater development is subsidence of the land surface due to decline of groundwater levels. The principal cause of subsidence is compaction of the fine-grained aquifer materials such as argillaceous sediments. Compaction results from an increase of overburden pressure when the potentiometric surface of an aquifer is lowered by intensive pumping. In this regard, few examples have been reported or described in North Africa.

There has been a growing concern about the impact of the intensive development of Nubian regional aquifer system on the soil stability in the Kufra and Sarir basins in Libya. Land subsidence has occurred in several areas in the United States, especially in the Central valley of California and in Houston, Texas. Land subsidence occurs when the water level declines below a critical value, termed a “pre-consolidation level”. Under such conditions the compaction is inelastic and subsidence is non-recoverable.

Groundwater development and use in oases, desert depression and closed basins may cause serious environmental impacts. The salinity of the aquifer systems may increase steadily when irrigation water is abstracted from the some aquifer that receives the return flow (Llamas et al. 1992).

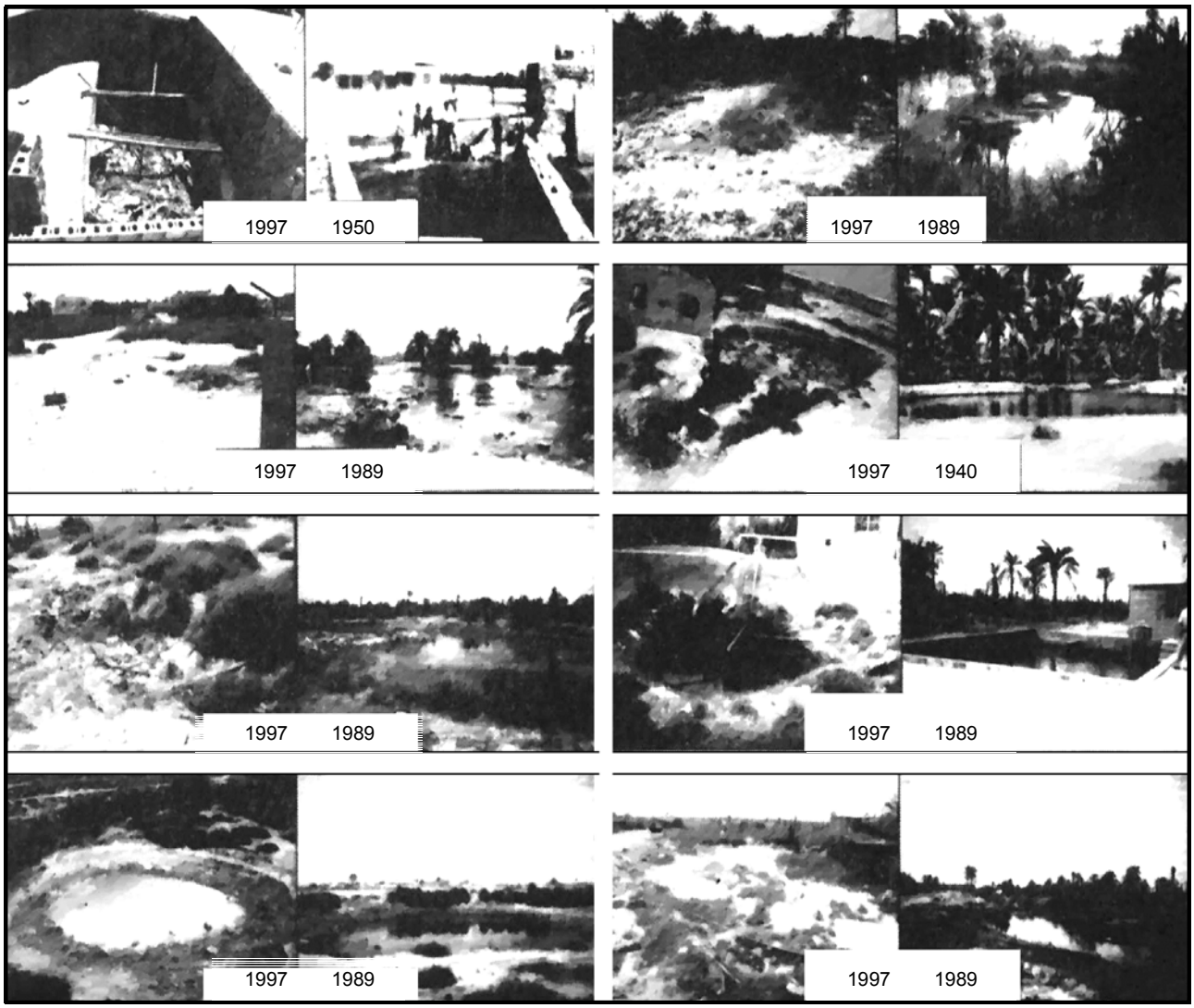


Figure 12: Impacts on springs in Bahrain

The long-term effects of irrigation on the soils depends on the composition of groundwater, soil properties, climatic conditions and adequacy of drainage facilities. Without adequate drainage the water table will rise to cause a water-logged saline soil. Such a critical problems has developed in the Ouwargela Oases in Algeria to a serious proportion and addressing it requires an appropriate method for disposal of drainage water. The results of soil studies in the New Valley indicate that the soils of the Dakhla and Kharga Oases are affected by salinity and alkalinity (Figure 13). For more than 2000 years the farmers of the New Valley have utilized groundwater for irrigation of sandy soils without causing much salinization. In contrast, the use of good quality water on heavy soils in the Oases was inductive to secondary salinization after a relatively short period of irrigation (El-Gabaly 1980).

6. Planning and management of groundwater development in arid zones

Future strategies and plans for groundwater development in arid regions should draw lessons from the implementation of different developments in arid basins and their impacts on the resources, the environment and socio-economic system. Planning future development need to consider different approaches, strategic choices and measures to mitigate adverse impacts:

6.1 A diagnostic approach

The "side-effects" of over-exploitation of renewable groundwater i.e. the impacts of developing non-renewable resources are normally diagnosed a posteriori, chiefly because reliable assessment of groundwater resources can be best achieved when the aquifer is developed or even stressed.

Methods of assessment of vulnerability of an aquifer systems to contamination and susceptibility to exploitation side-effects has been proposed as an important tool for planning and management of groundwater resources (Vrba & Zaporozec 1994, Adams & MacDonald 1995). Assessment of groundwater vulnerability addresses mainly groundwater quality problems, whereas groundwater susceptibility deals mainly with aquifer sensitivity in term of quantity, such as decline of water levels and land subsidence. Groundwater susceptibility was presented as a potential adjunct to aquifer vulnerability in order to provide resource managers and planners with an additional method of evaluating potential aquifer degradation resulting from intensive development (Adams & MacDonald 1995).

Evaluation of groundwater vulnerability is based on the assessment of natural factors or attributes such as recharge, soil unsaturated zone and aquifer properties. In arid regions the rate of natural recharge is very low, but in irrigated areas, return flow of irrigated water constitutes a significant fraction of the recharge. Such areas are therefore highly vulnerable to contamination, when they are underlain by unconfined aquifers. The high water levels and the soil characteristics are factors that increases their vulnerability to contamination and salinization (Khouri and Miller, 1994).

Aquifer susceptibility to depletion and subsidence, can be evaluated by estimating susceptibility factors such as hydraulic deffusivity, volume of aquifer, lithology and aquitard compressibility. Attributes are usually assigned different weight and ratings, according to their considered importance for vulnerability or susceptibility assessment. The computed index of susceptibility indicates high or low susceptibility to depletion or subsidence, whereas vulnerability index (Such as DRASTIC index) refers to the relative vulnerability degree.

Using a diagnostic approach helps to identify vulnerable areas that have the greatest risk to groundwater development, and supports the efforts to address present exploitation problems and plan new development in less vulnerable areas. A diagnostic approach is an effective tool for planning future development when aquifer systems are untapped or subjected to a low degree of stress.

6.2 Strategic choice

The most important issue that need to be examined and addressed is a choice between a strategy based on intensive and large-scale development or "mining" of the resource, or a long-term strategy based on a development plan which spans a longer period and offers opportunities for development for future generations. In arid zone it is not possible to maintain groundwater resources indefinitely. However in several large arid basins the reserve is huge. For instance the groundwater mass in the Nubian Aquifer system, in Northeast Africa, was estimated at 150 000 km^3 (Thorweihe & Heinl, 1995). Simulation has shown that it is possible to plan development in the sub-basins (The regional aquifer system encompasses some 2 million square kilometers) for at least 50 years, without causing excessive drawdowns or interference between major development projects such as the New Valley Development schemes in Egypt and the Great Manmade River Project in Libya. The former abstracts some 540 MCM from the Dakhla sub-basin and the latter abstracts about 750 MCM from Kufra sub-basin. Planned withdrawal may not exceed 2000 MCM from Nubian Regional Aquifer System. Such as small percentage of withdrawal/total reserve (200/150,000) in 100 years certainly justifies groundwater development based on mining of the resource.

Arid regions are underlain by aquifer systems in almost every state of development from those practically unused and capable of considerable development to those capable of very little sustained perennial use and seriously over-developed. Measures to mitigate impacts of development on parts or the entire aquifer system is a fundamental need in some regions. Actions required may include substantial reduction of current withdrawal or at least "freezing" of abstraction at current rates. Certain measures, however, could be implemented to minimize negative effects independly of the development strategy. They could address major issues:

6.3 Specific measures

Groundwater quality deterioration is normally caused by salt-water intrusion (from sabkhas or from the sea) or may result from up-down coning of underlying or overlying saline water.

Retroactive effects on water quality can be predicted and reduced by implementing or adjusting development plans, using simulation techniques. Development options could be generated and by developing local or well field models. Withdrawal could be regulated to minimize head decline and thereby

reducing the chances of water quality delerioration. If limitations has to be placed on withdrawal from certain parts of the aquifer system or even on the overall production a choice has to be made between quantity and quality of water withdrawn.

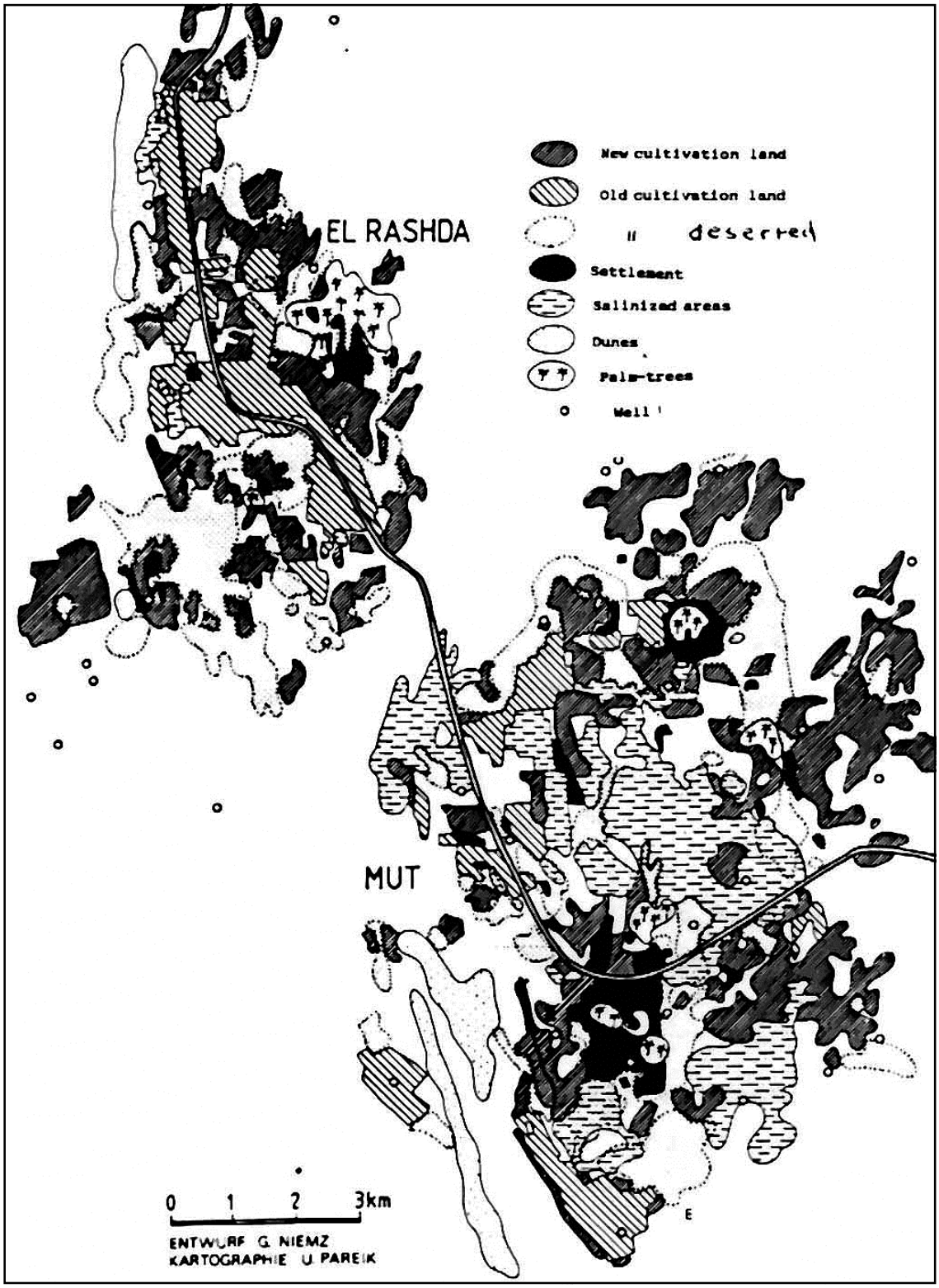


Figure 13: The extent of soil salinization in Dakhla (Source: Niemz 1986)

In irrigated areas where return flow from the irrigation water recharge the aquifer, constituents salts leached from the soil or applied pesticides and fertilizers may enter the aquifer, thus degrading water quality. Management of groundwater quality in oases in arid zones need to reconcile two necessary actions.

Leaching of salts from the soil profile and minimizing the movement of return flow into the aquifer system. In certain parts of aquifer systems and in even in major basins underlain by multi-layered aquifers (the continental Intercalair-Complex Terminal in North Sahara Basin, the East Arabian Aquifer system, the Gezira Region aquifer systems in Syria and Iraq…), the major constraint on future development is degradation of water quality rather than limitation of water quantity.

Excessive water level decline and depletion of the reserve can be resolved by reducing abstraction. The choice is between maximizing production for the benefit of the present generation, in order to socio-economic development or minimizing withdrawal to ensure availability of water resources over a longer period. A relationship between annual abstraction and periods of water production has been worked out in Saudi Arabia for each major aquifer and for the total resource (Figure14).

Extensive versus intensive groundwater development for irrigation, leads to different degrees and patterns of water level decline. Certain management strategies taking into account hydrologic social and economic factors can be examined without significant control of pumpage.

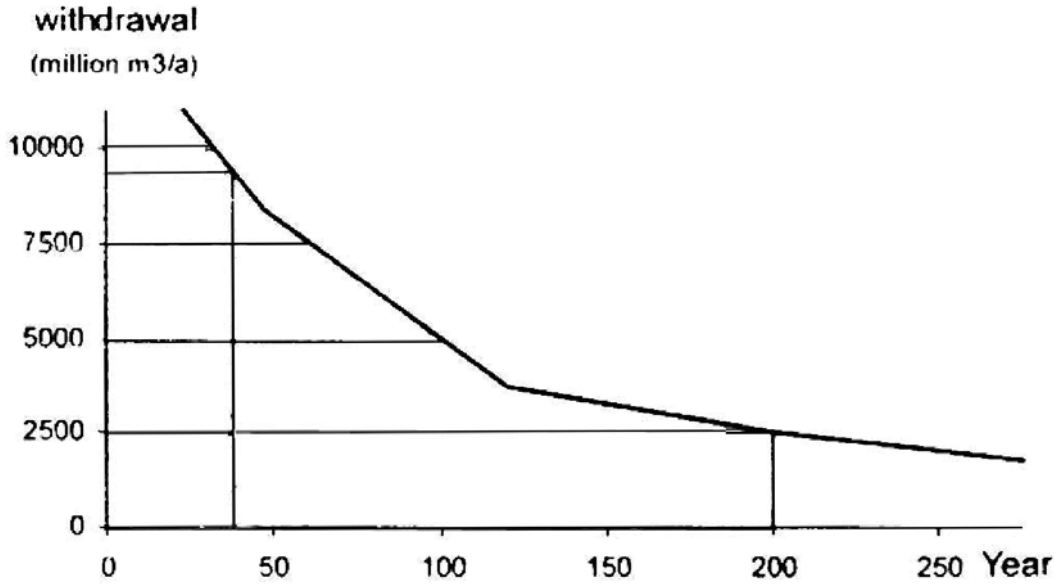


Figure 14: Relationship between total withdrawal and projected periods of water production (line – time of groundwater) in Saudi Arabia (Source: H. Neuland 1988)

The first approach is the traditional intensive cultivation in oases which requires heavy groundwater withdrawal. This type of management strategy is socially acceptable but normally results in serious hydrogeological and environmental problems, such as water logging, salinization and excessive lowering of water levels, and such impact will lead, to a decrease in well yields which, in turn, results in substantial increase in production cost.

The second approach entails expanding the area of water production. Plans of extensive cultivation could be implemented by setting up small-scale farming systems. Such a system has been proposed for future development in the New Valley in Egypt. The small scale farming systems can minimize water level decline and maintain the water lifts at economical level and reduce environmental issues. It may, however, create socio-economic problems such as health care. Education and transportation (Hefny 1991).

The third alternative is to design well fields and control drawdown by using well field models (simulation) and transporting water to irrigate collection cultivation. Another option is the long-distance water transfer, such as the Great Manmade River which conveyed water from the Kufra-Sarir basin to coastal zone of northern Libya. The project is socially acceptable and environmentally sound, and is considered, under the present conditions of increasing scarcity, the most economically viable option (Salem 1991).

Impacts on the environment in arid regions result mainly from water use under extreme climatic conditions, especially high temperature and high evaporation. Certain impacts could result from heavy pumpage. These include land subsidence and ecological impacts on aquatic ecosystems.

Susceptible areas are usually underlain by multi-layered aquifer systems containing fine-grained derital sediments. Inelastic compaction of these argillaceous formations will not occur until water levels are lowered below a critical value. The continental Intercalaire and complex terminal are susceptible to land subsidence in the North Sahara basins and certain parts of Nubian Aquifer Systems are also vulnerable in

terms of land subsidences. In areas where the "pure" Quartz-sandstones pass northwards into mixed mairne-continental facies. Extensive land subsidence occurred in the central Valley of California.

In vulnerable areas land subsidence causes engineering problems and failure of well casing. In regional carbonate aquifer systems intensive development caused collapse of sinkhole, triggered by lowering of water levels. Several example were reported in the western and northeastern parts of Syria during the 1950s and 1960s. A spectacular collapse has also been reported in 1981 in Florida (Sun & Johnston 1994). To address these problems, a diagnostic approach could identify the degree of groundwater susceptibility, and a well field design can mitigate possible impacts, nevertheless a strategic choice becomes necessary in extreme cases.

Impacts resulting from water use in arid zones can be minimized by improved management at the farm-level. The most difficult problem in arid zones is disposal of drainage water in oases irrigated from groundwater. These depressed areas are usually cultivated because they offer more favorable water and land resources for agricultural development. Impacts resulting from intensive cultivation can only be mitigated if an appropriate plan for the disposal of drainage water and wastewater is implemented. In Ouorgla Oases in Algeria and Bahrya and well as Siwa Oases in northern Egypt complex groundwater development and use problems have risen due to natural factors, and uncontrolled development and inadequate management practices. In order to address these environmental issues in the New Valley the proposed groundwater development plan envisages limiting irrigation to relatively higher areas. The sabkhas and depressions could then be used as a discharge zone for drainage water, especially, when the act under natural conditions as discharge area to unconfined aquifer systems.

7. Conclusions

Groundwater development like any other type of resource development have both positive and negative effects. In arid areas the magnitude of negative effects is relatively high, especially when the aquifers are heavily developed.

Extensive deserts and Sahara are often underlain by regional aquifer systems containing large volumes of non-renewable resources. The assessment and management of such aquifer systems need special approaches and strategy formulations. Mining of groundwater will inevitably come to an end. The ethical question with regard to groundwater mining has been considered by several authors.

Same consider development of a non-renewable resource an "ecologic sin" because it contradics the principle of sustainable developments. Many others contend that groundwater mining could be a viable option under certain circumstences and these exist in many areas or regions underlain by non-renewable aquifers.

In practice a commitment has already been made in many countries to the mining option. Non-renewable resources in arid regions are almost in every state of development from those practically unused to those that are seriously developed.

The deep groundwater basin in the arid parts of Australia (Canning, Eucla Officer basins…) south of the Sahara (Chad, Niger, Taudeni basins) are almost untapped. The regional aquifer system underlying large basins in the Sahara and deserts of northeast Africa and southwest Asia has been intensively developed. These comprise deep basins of large areal extent such as Nubian Basin (over 2 million km^2 encompassing 4 countries) and the Gulf sedimentary basin (about 1 million km^2, encompassing 6 countries). Development of several parts of these aquifer systems has resulted in serious consequences.

Depletion of the aquifer storage ranges from about 25% in Saudi Arabia to approximately 50% in Bahrain and Qatar. The question that now arises is one of choosing between maintaining the present trend or modifying development plans with the objective of prolonging aquifer development, by considerably reducing withdrawal. Unfortunately most adopted solutions envisage freezing production at present levels.

Impacts of intensive groundwater development in arid zones can summarized as follows:

7.1 Impacts on the resource base

- Excessive decline of water levels;
- Depletion of aquifer storage;
- Decrease of spring discharge;
- Deterioration of groundwater quality.

7.2 Impacts on the environment

7.2.1 Impacts resulting from groundwater development

- Land subsidence;
- Collapse of land surface and sinkhole formation (in basins underlain by carbonate aquifer systems).

7.2.2 Impacts resulting from water use

- Water logging;
- Salinization;
- Aquifer contamination;
- Creating artificial ecosystems.

These impacts could be considered “primary impacts” and they could lead to other “secondary impacts”. Thus excessive and continued lowering of water levels increases pumping lifts. The result is an increase in pumping costs decrease in well yields and extension of well fields. The most important consequences, however are socio-economic and socio-cultural impacts such as re-settlement or immigration.

While considering negative impacts positive impacts such as economic benefit and social progress should not be ignored. More water, food and other commodities are urgently required to meet the basic needs of growing population in arid regions.

Addressing water problems that arise from groundwater development in arid zones aims to avoid environmental degradation and the partial or complete destruction of the resource base on which socio-economic development depends.

Actions required to address and seek a solution to existing groundwater development problems may include:

1. A decision at the national policy level to choose a strategy for groundwater mining, either to maximize production in order to enhance socio-economic development and implement a replacement solution to take over, or adopt a plan of exploitation that prolongs the period of water production to ensure water availability for future generations.

   The solution could be a middle way because “Malthusian underdevelopment” of groundwater could be as damaging to the socio-economic system as over-development” (Llamas 1999). It is conceivable that a technological breakthrough in the foreseeable future will render some replacement solutions a viable option.
2. Several negative impacts such as deterioration of groundwater quality are manageable to a certain extent by improving understanding of the regional flow patterns, and planning development using simulation and other relevant techniques.

   Certain impacts such as decrease of artesian flow and decrease or disappearance of flow of springs is often inevitable. In large basins, however, drawdown could be regulated in certain instances to protect natural spring discharge. For instance, in south Australia large withdrawal (4x106 m^3/y) from the Great Artesian Basin was controlled using a numerical simulation model to protect spring discharge and wetlands.
3. Environmental impacts are not inevitable and in most cases they are manageable. In irrigated lowlands and oases, water management should consider not only improvement of efficiency but also the leaching requirements under the desert climatic conditions.

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A. Mamou

Gestion des ressources en eau du système aquifère du Sahara septentrional

(Management of the water resources of the Northern Sahara Aquifer)

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Abstract

In the three contries of Algeria, Tunisia and Libya, the common Saharian groundwaters are located in the major basin of North-Western Sahara Aquifer System (NSAS). The author presents geologic and hydrogeologic characteristics of this aquifer system and describes structure of the both aquifers: Continental Intercalaire (CI) and Complexe Terminal (CT). Massively mobilisated, these groudwaters, have generated the development of this Saharian area. The author analyses the impacts of this massive abstraction on the piezometry and quality of water.

The hydrodynamic of these aquifers is commanded by decompression and the effects are observed in a large area arround the extraction zones. Since the 80's, the water extractions have been increasing in the three countries concerned causing the lowering of the piezometric levels, the drying of many sources and the pumping of wells more and more frequent. The decrease of the pression in the aquifers favours the hydrodynamic changes between layers and the leakage from deeper horizons, is intensificated.

The solute changes are more active near outcrops and where the aquifer is free. In confined aquifer, these changes are commanded by variation in pression and temperature. After a long time, the quality of water should be more homogenous in the same aquifer, but more bad. The contamination of aquifers from salt water should be more important in extraction area where the deep aquifer is connected with the phreatic water table.

The management of these water resources needs a good monitoring system to control the abstraction, piezometry and water quality. The transit from artesian to pomping extraction introduces changes in quality and distrubution of wells. It affects storage of springs and reverses of movement water in non-saturated zone.

The approach used for assessment of water resources, is the modeling method. It gives some evaluation of volume able to be extracted from those aquifers and piezometric changes introduced by the intensification of exploitation. The futures simulations have to consider natural boundaries of all the aquifer system including the libyan part, the intensification of abstraction and the change in quality of water. They should give the environmental impact of this exploitation and how to optimize the use of these resources.

Résumé

Après avoir passé en revue les caractéristiques géologiques et hydrogéologiques des deux principaux systèmes aquifères du Sahara septentrional (Continental intercalaire et Complexe terminal), l'auteur analyse l'impact de leur exploitation sur l'évolution de leurs piézométrie et hydrochimie. Il aboutit aux conclusions suivantes:

Le fonctionnement hydrodynamique de ces systèmes se fait par décompression dont l'effet se propage loin des champs captants et la baisse piézométriques finit par intéresser l'ensemble de la nappe. D'autre part, la pression piézométrique régit au sein du même système, les échanges hydrodynamiques entre ses différents niveaux aquifères ce qui se traduit par des drainances s'exerçant des niveaux les plus captifs et souvent les plus profonds, vers les autres à travers des aquicludes semi-perméables ou des failles drainantes.

Les échanges de sels dissous dans l'eau et les mélanges entre « eau ancienne » et « eau moderne » s'effectuent suivant des mécanismes qui traduisent davantage l'écoulement physique de l'eau vers les champs captants ou les exutoires de la nappe que l'influence de la décompression. De ce fait, les échanges chimiques aboutissent à long terme, à une homogénéisation des salinités au sein du même système aquifère. D'autre part, la salinisation résultant d'une contamination suite à une exploitation

intensive, n'intéresse souvent que des zones localisées centrées sur les aires de prélèvement. Elle évolue dans le temps, en fonction de l'ampleur de la salinité de la source de pollution, des échanges avec les niveaux aquifères adjacents et de la perméabilité des épontes.

Sur la base de cette analyse, l'auteur propose afin d'assurer une gestion rationnelle des ressources en eau de ces systèmes aquifères, de mettre en place un mécanisme de suivi interessant les prélèvements, la piézométrie et l'hydrochimie de ces nappes. Une attention particulière doit être accordée au passage de la phase d'exploitation de l'artésianisme vers le pompage, ainsi qu'au tarissement des sources. Il y a lieu de distinguer également les réactions induites par les champs captants situés dans la partie captive de la nappe de ceux de la nappe libre.

L'évaluation des ressources exploitables à partir de ces systèmes aquifères doit prendre en considération le fait qu'elles sont peu ou pas renouvelables, les particularités de leur fonctionnement hydrodynamique et géochimique et son évolution dans le temps. La simulation du fonctionnement de ces systèmes permet d'établir le bilan de leurs échanges, de vérifier les hypothèses relatives à ces échanges et de faire des simulations prévisionnelles dans l'objectif d'optimiser la gestion de leurs ressources en eau. Comme ces systèmes interessent plusieurs pays riverains, la gestion de leurs ressources doit faire l'objet d'une concertation qui permet de minimiser lse impacts des prélèvement et d'assurer un développement durable.

1. Introduction

Le Système Aquifère du Sahara Septentrional (SASS) occupe une superficie dépassant le million de km^2 dans la partie occidentale du Sahara de l'Afrique du Nord : environ 700 000 km^2 en Algérie, 80 000 km^2 en Tunisie et 250 000 km^2 en Libye (figure 1). Le SASS consiste essentiellement en dépôts continentaux dans lesquels on distingue de bas en haut, deux niveaux aquifères: le Continental Intercalaire (équivalent des Grès de Nubie) et le Complexe Terminal.

La mise en place des réserves aquifères de ce système s'est éffectuée durant les périodes humides du Quaternaire (ERESS 1970, Aranyossy J.F & Mamou A. 1985). Depuis, ce système fonctionne avec un écoulement souterrain vers les dépressions (sebkhas et chotts) situées le long de la bordure septentrionale du Sahara et vers les sources dont le débit n'a cessé de décroître à mesure que s'intensifie l'exploitation et que et diminue la pression de la nappe. Ces exutoires naturels traduisent la lente vidange du réservoir aquifère (quelques millimètres par an) et expliquent l'écoulement souterrain actuel essentiellement orienté Sud - Nord.

Des écoulements de surface épisodiques le long du piémont atlasique et sur le versant du Dahar, contribuent à l'alimentation actuelle des nappes, mais de façon très limitée. Comparée aux prélèvements actuels ces réserves géologiques donnent l'impression de ressources illimitées, mais en fait, une partie seulement du volume total stocké dans ce système aquifère est physiquement et économiquement accessible à l'exploitation. La clé d'une utilisation optimale de cette ressource souterraine doit être recherchée dans l'élaboration et la mise en oeuvre de stratégies de développement, maximisant les bénéfices attendus et minimisant les effets négatifs.

2. Caractéristiques hydrodynamiques et chimiques

D'une extension saharienne sur l'ensemble des deux bassins du Grand Erg oriental et de l'Erg occidental, le Système Aquifère du Sahara Septentrional (SASS) s'étend en Algérie, en Tunisie et en Libye (ERESS 1970, BRL 1996). Il correspond à plusieurs niveaux aquifères regroupés dans deux principales nappes qui sont le Continental intercalaire (CI) et le Complexe Terminal (CT). Ce système est logé dans des formations détritiques et carbonatées du Mésozoïque dont l'âge varie d'un endroit à l'autre du bassin. La nappe du CI est logée dans les séries détritiques du Jurassique supérieur et du Crétacé inférieur et celle du Complexe terminal, dans les formations carbonatées du Crétacé supérieur et les sables du Mio-Pliocène (figure 2).

Les formations aquifères atteignant des épaisseurs de quelques dizaines à quelquede mètres, subissent des variations verticales et latérales de faciès, ce qui se traduit par des différences dans la charge piézométrique et des variations dans les faciès chimiques de l'eau. Les deux nappes du SASS sont fortement captives au centre du bassin et tendent à devenir faiblement en charge puis libres sur les bordures où affleurent les formations aquifères. La structure en cuvette à grande extension de ce bassin, a largement favorisé l'apparition des sources en plusieurs points. Elles sont souvent liées à des accidents tectoniques (seuil d'el Hamma) ou à la configuration structurale (ligne de falaise).

Si les entrées de ce système sont principalement l'infiltration sur les bordures, ses sorties sont par contre, plus diffuses et correspondent aux points d'exploitation (sources, foggaras, forages, puits, etc.) et aux pertes par évaporation (chotts et sebkhas). La présence de zones captives et d'autres libres sur l'aire d'extension des deux nappes du CI et du CT, fait que la réaction du système vis à vis de l'exploitation, diffère d'une zone à l'autre. Ainsi, sur le plan piézométrique, la décompression se fait sentir avec un grand rayon d'influence dans la partie captive de la nappe, alors qu'elle est localisée dans la partie libre de la nappe. La drainance s'exerce à travers des aquicludes semi-perméables ou des failles drainantes, à partir des niveaux captifs et souvent les plus profonds, vers les niveaux superficiels.

La piézométrie, la température de l'eau et sa composition chimique plaident en faveur d'un écoulement des bordures vers les exutoires naturels du système (chotts et mer Méditerranée) avec passage de la partie libre vers la zone de mise en charge puis la partie confinée des nappes (Mamou, A. 1990). Les échanges de sels et les mélanges entre « eau ancienne » et « eau moderne » s'effectuent essentiellement dans la partie libre de la nappe suivant des mécanismes qui traduisent l'écoulement physique de l'eau (piston flow et infiltration gravitaire) vers les champs ou les exutoires de la nappe (Mamou, A. & Zouari, K. 1995). Dans la partie captive, les réactions d'échanges chimiques sont de loin plus atténuées et allégées par les variations de pression et de température. Elles dénotent des échanges entre l'eau et les formations encaissantes et se traduisent par une concentration suivant les directions d'écoulement.

3. Gestion des ressources en eau

3.1 Historique de l'exploitation

La gestion des ressources en eau du SASS se faisait dans une optique d'exploitation sur place pour répondre aux besoins en eau de la population et du développement économique de la région. L'usage agricole de l'eau mobiliose plus de 90% des prélèvements. Dernièrement, est apparue l'option d'exporter une partie de cette eau en dehors du bassin afin de répondre aux besoins des zones limitrophes (Cas d'el hamada el hamra en Libye). Cette situation se traduit par des prélèvements sans cess croissants avec un coût de mobilisation de plus en plus élevé (Salem, O. 1992).

L'exploitation des ressources en eau du SASS se faisait jusqu'à la fin du siècle dernier, dans la limite des oasis existantes et au gré de la répartition naturelle des sources et des foggaras. Avec le développement des techniques de forage, la création de sondages hydrauliques a largement contribué à changer la localisation des zones de prélèvement sur les ressources aquifères du CT et du CI. Cette situation est restait maîtrisable jusqu'à l'apparition des premiers signes d'affaiblissement du débit jaillissants (forages, sources et foggaras) au début des années cinquantes.

Depuis, le recours au pompage pour le remplacement de l'affaiblissement de l'artésianisme, est devenu de règle; ce qui a largement contribué à étendre les champs d'exploitation aux zones situées en dehors des oasis traditionnelles. C'est à cette étape que s'est imposée la nécessité d'une connaissance approfondie du fonctionnement hydrodynamique du système. Depuis 1970, la simulation numérique du fonctionnement hydrodynamique de ce système s'est avérée le meilleur moyen pour l'établissement de son bilan aquifère et pour la prévision de la réaction des nappes à court et moyen termes, vis à vis de l'augmentation des prélèvements.

3.2 Impacts hydrodynamiques et chimiques

L'alimentation actuelle des nappes du SASS est limitée aux zones de la bordure septentrionale (Atlas saharien et Dahar) collectant les eaux de ruissellement pour une pluviométrie souvent inférieure à 200 mm/an. Cette alimentation est estimée pour l'ensemble des nappes à **575 millions de m^3/an** (575 Mm^3/an). D'autre part, l'exploitation de ces nappes est estimée en 1992, à 1000 Mm^3/an (Pallas, Ph. 1992). Actuellement, elle est de l'ordre de **1500 Mm^3/an** (250 Mm^3/an en Libye, 535 Mm^3/an en Tunisie et 750 Mm^3/an en Algérie). A ceci s'ajoutent les autres sorties des nappes représentées par l'évaporation au niveau des exutoires (Chotts) et l'écoulement en mer.

Cette situation fait que le système aquifère du Sahara septentrional est déjà nettement déséquilibré et une partie non négligeable de ses prélèvements provient de ses réserves géologiques. Ceci le place dans un type de gestion dite souvent « minière ». Cette gestion conduit à accepter les conséquences hydrodynamiques et hydrochimiques qui en résulteraient. Parmi ces effets, il y a lieu de s'attendre à :

- la diminution de l'artésianisme et au tarissement des sources ;
- la baisse continue du niveau piézométrique et l'augmentation des hauteurs de pompage ;
- l'altération de la qualité chimique de l'eau suite à la drainance entre les niveaux aquifères adjacents.

Une telle gestion exige la possibilité de prévoir les différents effets engendrés par la politique de gestion adoptée ce qui nécessite des outils de simulation et de prévision suffisamment performants pour assurer la pérennité de la ressource ou du mois son exploitation à long terme sans risques de dévaluation.

3.3 Diminution de l'artésianisme et tarissement des sources

La diminution de l'artésianisme des deux principales nappes du SASS s'est produit en fonction de l'augmentation des prélèvements et de la multiplication des sondages qui les exploitent. Cette baisse tributaire au niveau des ouvrages d'exploitation des caractéristiques hydrodynamiques (pertes de charge) se traduisent par des cônes de dépression dont l'extension ne cesse de s'élargir avec le temps. Ainsi, les groupes d'exploitation (oasis et groupes d'oasis) constituent les points focaux de cette baisse du fait qu'ils matérialisent les points de dépression extrême de la surface piézométrique de la nappe.

Dans une première phase durant laquelle l'exploitation des nappes du SASS se faisait essentiellement par artésianisme (sources et forages jaillissants), l'espacement des forages et leur éloignement des sources étaient de règle. Ceci contribuait à maintenir l'artésianisme un peu plus longtemps et à réduire les frais d'exploitation. Avec la baisse excessive de l'artésianisme, le recours au pompage n'a fait qu'accélérer le tarissement des sources et la baisse généralisée de la surface piézométrique (Figure n°3). De toutes les manières, la disparition de l'artésianisme se traduit sur le plan hydrodynamique, dans les zones à faible charge piézométrique, par un échange de flux de haut vers le bas ce qui est à l'opposé de la disposition précédente. Cette nouvelle situation finit à la longue, par entraîner des échanges de solutés les différents niveaux aquifères dsystème. Ceci se traduit par une altération de la qualité chimique de l'eau, plus particulièrement dans les zones sensibles à la salinisation (proximité des chotts et des failles drainantes).

3.4 Baisse piézométrique et augmentation des hauteurs de pompage

La baisse piézométrique est à l'origine de l'augmentation du coût d'exploitation des eaux du SASS du fait que cette baisse est continue et croissante avec l'augmentation des prélèvements. C'est le cas plus particulièrement de la nappe du Complexe terminal qui est plus accessible à l'exploitation que le Continental intercalaire (moins profonde). Cette baisse piézométrique linéaire au départ, ne cesse de s'accélérer avec le temps au point que paffichent déjà des niveaux piézométriques au-dessous de la surface du sol (figure 4).

Dans certaines de ces zones proches des aires d'affleurement des couches abritant les deux nappes du complexe terminal et du Continental intercalaire, la nappe étant libre, elle affiche une nette réponse à l'alimentation actuelle (variations piézométriques et géochimie d'eaux modernes). C'est dans ces zones où la nappe est libre ou à faible charge captive, que les changements de qualité sont autant plus à craindre que le coût du pompage soit appelé à augmenter avec l'accroissement des prélèvements.

3.5 Altération de la qualité chimique de l'eau

L'altération de la qualité chimique de l'eau du SASS résulte des deux phénomènes suivants :

1. la communication entre le niveau aquifère exploité et ses épontes suite à l'accroissement des prélèvements et de la drainance,
2. l'infiltration des eaux de surface particulièrement celles du drainage dans les zones d'exploitation où la dépression piézométrique est la plus intensive.

Ces deux phénomènes sont appelés à devenir de plus en plus sensibles à mesure que l'exploitation des aquifères augmente. Du premier phénomène résulterait une homogénéisation de la qualité de l'eau au sein des aquifères englobant plusieurs niveaux aquifères et du deuxième phénomène qui sera le plus sensible, une nette dégradation de la qualité de l'eau. Cest le cas du CT dans la région du Bas-Sahara: Oued Rhir en Algérie et Nefzaoua en Tunisie (figure 5).

Les approches de modélisation adoptées traduisent-elles mêmes, l'évolution scientifique et technique enregistrée dans ce domaine. Ainsi, les deux modèles mathématiques de l'ERESS représentant le CT et le CI étaient à mailles carrées bidimentionnels et ne représentaient que les écoulements horizontaux. Ces modèles ont été largement limités par la configuration figée de leurs mailles (à taille unique) et l'absence de données en dehors des zones d'exploitation. Les aux limites sur les échanges du système (entrées et sorties naturelles) ont fait l'objet d'hypothèses dont la vérification par mesures sur terrains, s'avère encore difficile. Les améliorations introduites par la suite dans les techniques de modélisation (mailles variables et liaisons verticales) ont contribué à mieux tirer profit de la masse de données accumulées et à vérifier la représentativité du fonctionnement naturel du système par ces modèles.

Un modèle d'ensemble englobant la totalité du bassin du Sahara septentrional n'a pas encore été élaboré. Pourtant, il est fort indiqué d'y inclure la partie libyenne correspondant à El Hamada el Hamra afin

de lever l'incertitude sur l'alimentation du système, associée à la coupure imposée au modèle ERESS le long de la frontière algéro-libyenne.

Avec l'accroissement des prélèvements à partir des ressources des nappes du SASS, les échanges verticaux entre les différents niveaux aquifères, sont devenus plus sensibles et peuvent conditionner à long terme, le devenir de la ressource (dégradation de la qualité chimique de l'eau). Ainsi, la nappe phréatique du Bas-Sahara (Oued Rhir et Chott Djérid) présente un sérieux danger pour la nappe du CT dans cette zone où l'affaiblissement de l'artésianisme est manifeste.

3.6 Problématique de la gestion

Les critères permettant de mettre en place une stratégie d'exploitation des ressources aquifères d'un système comme le SASS, doivent être à la fois, des critères économiques (coûts de mobilisation et d'exploitation comparés aux revenus) et de durabilité (limite d'altération de la ressource comparée au coût des solution de rechange); d'où la nécessité de veiller aux impacts de cette exploitation sur la ressouce elle même et sur son environnement (destruction des écosystèmes). Souvent les critères adoptés pour la gestion des ressources non renouvelables accordent plus d'intérêt à ceux qui répondent aux objectifs de la planification visée (minimisation du coût de développement). Cette politique si elle se conçoit à court et moyen termes, finit par afficher ses limites pour une exploitation conçus à l'échelle de deux ou trois générations.

Dans le cas de la mobilisation des ressources en eau du SASS, la politique des pays concernés vise le développement économique et social de la région. Cette politique s'est fixée un premier objectif principal qui celui de maintenir la population en place dans la mesure où elle est déjà présente. Récemment, le transfert de l'eau est apparu comme un choix qui valorise ces ressources et permet à la politique de développement de sétebdre aux zones limitrophes.

Les modèles numériques ont été utilisés comme outil de simulation du comportement des aquifères à court et moyen termes (20 à 30 ans) en vue de s'assurer de leurs réactions principalement sur le plan hydrodynamique. Les critères adoptés lors de l'étude ERESS (1970) et reconduits lors de la réactualisation de cette étude (RAB 80/011, 1983) pour juger de l'acceptabilité des résultats des simulations sont les suivants :

1. conservation en l'an 2010 de l'artésianisme de la nappe profonde (CI) dans toute la zone centrale à fort artésianisme ;
2. limitation des hauteurs réelles de pompage dans les autres zones et pour la nappe du CT, à 60 m, hormis le cas de Ghardaia où cette limite était déjà atteinte en 1981 ;
3. réciprocité des effets des prélèvements additionnels d'un pays sur l'autre (Algérie et Tunisie) ;
4. limitation dans la Nefzaoua (Tunisie) en 2010, du niveau piézométrique à l'altitude du Chott Djérid (22m /NGM) afin d'éviter un renversement de l'écoulement vertical en traînant la contamination de la nappe du CT par les eaux salées de la nappe phréatique.

Un des problèmes soulevés dès les premières simulations du comportement hydrodynamique du SASS, est son bilan en eau. Toutes les simulations faites se basent sur un bilan qui équilibre les entrées du système avec ces sorties. En réalité, cette conception qui s'applique aux systèmes ouverts, demande à être modelée du fait que le SASS fonctionne comme système en phase de vidange avec très peu d'alimentation actuelle sur ses bordures. Il est indiqué que des nouvelles conceptions de fonctionnement de ce système, prennent en considération sa lente vidange qui ne cesse de s'accélérer. Même si le résultat final sur le plan hydrodynamique ne modifie pas le bilan du système, du fait du déséquilibre flagrant qui caractérise les échanges volumiques de ce système avec l'extérieur, ses fonctions de transfert et les réactions affichées le plan qualitatif, demandent à être analysées en détail en vue de prévoir les changements qui en découleraient.

Dans ces conditions, l'effort d'évaluation doit porter également sur la « réserve en eau » et plus particulièrement « la réserve géologique » tant sur le plan quantitatif que qualitatif. Il s'agit d'évaluer des ressources non renouvelables dont la mobilisation est de nature à altérer la qualité et d'augmenter le coût d'exploitation. Il n'est plus question d'une simple estimation des volumes d'eau stockés dans ces aquifères, mais une évaluation des volumes exploitables et une optimisation des conditions et du coût de l'exploitation.

En effet, avec une structure aussi complexe que celles des aquifers du CI et du CT (systèmes multicouches) dont la lithologie est très variable d'une zone à l'autre, les épaisseurs et les paramètres hydrodynamiques adoptés dans les modèles, sont assez des valeurs moyennes répondantà un souci de schématisation beaucoup plus qu'à une simulation réelle de la structure de la formation aquifère. Les précédentes tentatives d'évaluation ont toujours été orientées vers l'aspect quantitatif. Avec le déséquilibre qu'accuse le système, les échanges qualitatifs gagnent de l'ampleur et sont de nature à conditionner les domaines d'utilisation de l'eau exploitée.

La démarche d'évaluation consiste alors à passer par les étapes suivantes (Margat J., 1992) :

1. évaluation de la réserve en eau bien répartie dans l'espace en fonction de la structure de l'aquifère et de ses caractéristiques (épaisseurs, paramètres hydrodynamiques, zones d'échanges, etc.),
2. identification des contraintes et des critères d'exploitabilité (profondemadmissibles des niveaux dynamiques, nombres d'ouvrages et répartition, etc.) liées aux coûts maximaux unitaires de production.
3. Conception de plusieurs scénarios d'exploitation contrastés en durée et en intensité de production correspondant à des projets dont la faisabilité pratique est prouvée, puis comparaison des impacts aux contraintes.

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Application of transient electromagnetic soundings in water prospecting

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Abstract

In the past decade due to the growing demand for water the use of geophysical methods in the scope of geological exploration has gained an important role. In consequence of efficient advance in electronics and computer technology, electric methods, particularly, electromagnetic methods have been improved to great extent. From aspects of economics and claim for immediate interpretation of data accessed, in certain exploration tasks electromagnetic method has become preferred than the more sophisticated seismic systems that require large investments.

The paper represents some merits of transient electromagnetic method to possible users who may intend to apply it in desert conditions, also in Libya. Two case histories of EM surveys will be introduced. The first one was carried out in the Hungarian Great Plain to map water bearing structures up to the depth of 700 m. In this project a shallow application of EM soundings for alluvial deposits up to 80 m depth was also used. The second case history is on the results of monitoring fresh water-saline water interface in the coastal range of Cuba in the depth of 50-200 m.

1. Briefly on the principles of the transient sounding method

The transient method applies a controlled electric source to investigate subsurface structures. A low frequency (2-25 Hz), pulsed, electromagnetic field generated in a large loop (about 300 m side) which is laid on the surface. The resultant secondary electromagnetic field response in the ground, according to the electrical properties (resistivity) and geometrical features of the target (size, and type, such as being confined conductor or layered structure etc.) is observed by a small multiturn loop. By means of the system a resistivity sounding with depth is carried out. Since the generating field disappears after a certain period of time thus the induced secondary field also tends to collapse.

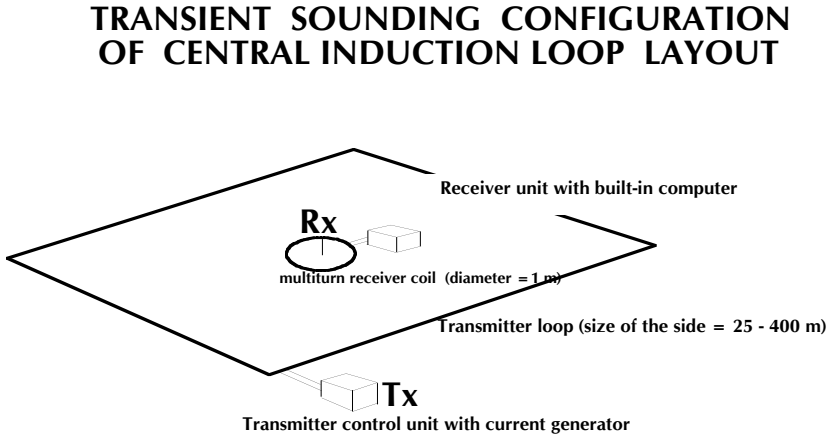


Figure 1: Transient sounding configuration of Central Induction Loop layout

This method called time-domain technique because the decay of the magnetic field induced by a single frequency is observed in time.

In general, one decay curve is observed in the time interval of a few microsec (10-6 sec) up to a few seconds (1-2 sec). The magnitude of the induced magnetic field to be monitored covers about two ranges of

Voltage, as small as a few mV. This feature reflects the high sensibility, precision, and quality what the system must fulfil.

The magnetic response curve is measured during the current source is switched off, so the secondary field is not disturbed due to the absence of the primary field.

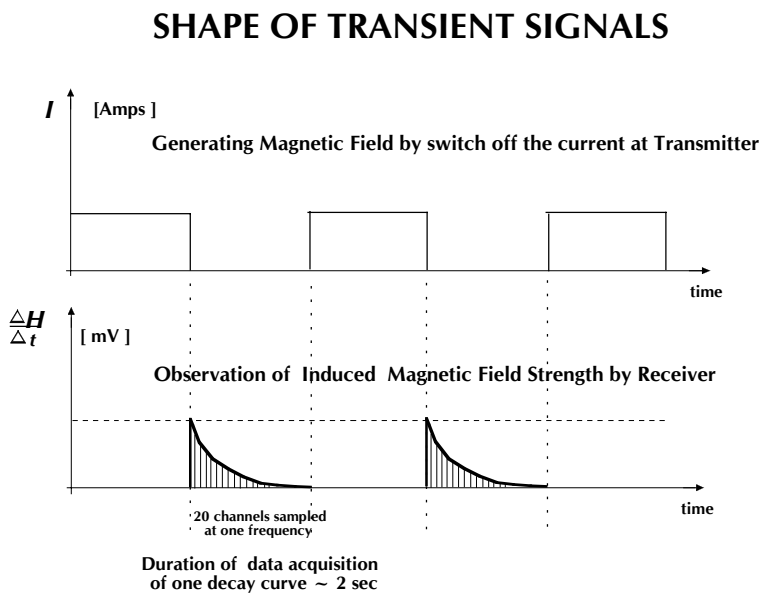


Figure 2: The shape of transient signal

Synchronisation between transmitter and receiver is provided by high precision quartz crystals. In order to detect very small magnitudes, great amount of signal gain and signal-to-noise ratio enhancement must be applied by summing the repetitive signals even up to a few thousand times (2^{12}). This means one sounding curve is measured at the same place so many times, consecutively. The shape of the recorded magnetic field versus time decay curve holds all information on the structure below the receiver. As the time passes, the later time channels correspond to greater depth. In case of high resistive medium the time decay is faster than in more conductive one.

The depth of investigation attainable by the system is determined by the electrical parameters of the area (mean resistivity, layering conditions). Electromagnetic waves propagate faster in consolidated (more resistive) medium, where the energy dissipation is small, consequently *in hard rocks greater penetration can be achieved*.

From technical point of view the penetration depth is governed by the size of the transmitter loop; in general, *the depth of penetration is 1.5-2 times the length of the side of the rectangular loop*. The larger the configuration, the deeper is the penetration.

1.1 Some advantages of the transient method

- No conductive coupling needed with ground, thus applicable in arid (desert) conditions.
- Depth of investigation capabilities up to 1500 m.
- The method is very sensitive to conductive, of low resistivity targets (high inductive response), such as water, and saline water in porous, shales, marls, clay beds, metallic objects, confined ore bodies, disseminated ores, faults and structural elements associated with clayey fractured zones etc.
- High vertical resolution. Relatively small configuration is necessary compared to depth of investigation.
- High productivity, low exploration costs compared to DC methods.
- Completely computerised data acquisition system in field, immediate data processing and representation of data at site for quality control.
- Effective for investigation below resistive overburdens (such as lava flows, thick limestone and dolomite series).
- Applicable also in rugged terrain.

1.2 Data processing

All data observed, completed with configuration parameters, system settings, and additional identifiers on the survey (location, date, coordinates, operator etc.) are recorded in solid state memory of the receiver unit, and allowed to dump out directly to the pre-processing computer.

The processing of data implies normalising data by configuration parameters and system settings (eliminating any geometrical effects on data), editing database with additional survey parameters, and transformation of data, calculation of models. First the recorded magnetic field versus time data are converted to resistivity versus time curve. The calculation is based on the assumption that the actual secondary magnetic field strength detected in each time channel corresponds to a resistivity value of a homogenous half space. At the final step the model parameters (resistivity, layer thickness) are calculated by comparison of theoretical model curve to observed resistivity versus time curve. The resistivity - depth model is calculated by finding the best fitting between theoretical curve and observed curve according to predefined numbers of iteration using least square method in Marquardt's algorithm. (The software was developed in ELGI, Hungary, by Pracser et. al.).

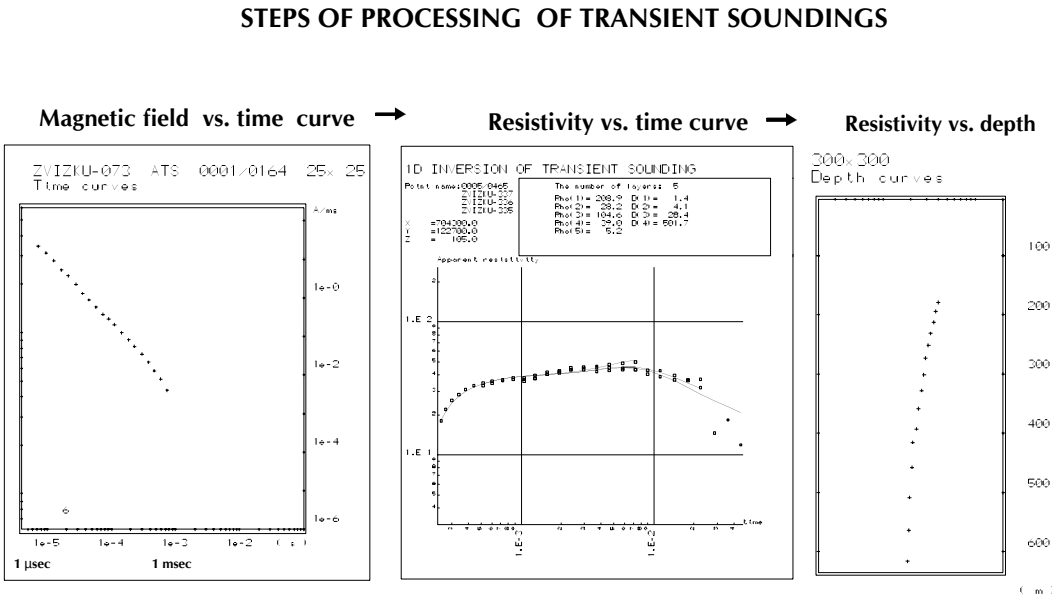


Figure 3: Steps of processing transient soundings

2. Case histories

2.1 Regional reconnaissance survey for water bearing structures by transient soundings in the Great Plain, Hungary

The survey carried out in Hungary covers up an area of about 2500 km^2. The Great Plain between the rivers Danube and Tisza is a highly cultivated agricultural area.

Here the Neogen basin is built up by Quaternary sequence of varying thickness, which exceeds 1500 meter. The section is characterised by windblown loess, alluvial deposits (gravels), and other water-bearing layers, like sand and sandstone being considered most important to provide water for consume and irrigation. In deeper position series of marls and clayey marls confine the aquifer. The geoelectrical model is characterised by a downward decreasing resistivity distribution.

The task of the reconnaissance survey was to map the structure of layers and qualify them from hydrogeological point of view. The uppermost few hundred-meter section of the basin is considered to be an aquifer from which irregularly situated group of wells produce water. These wells are considerably dense in the vicinity of settlements.

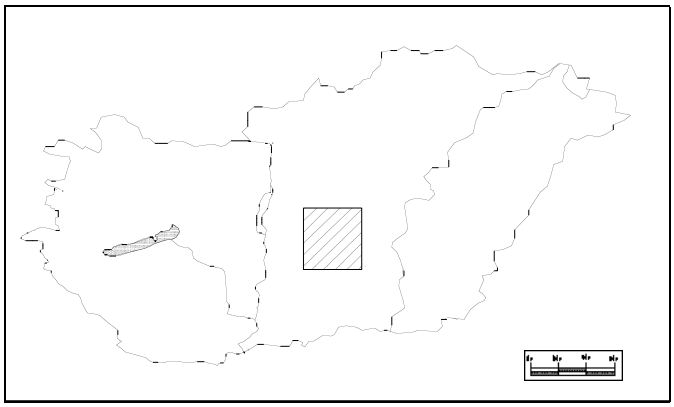


Figure 4: Map of Hungary

An electric survey including transient soundings combined with induced polarisation method was applied in a quasi-regular grid of 15 km^2/point. The transient method proved to be useful to determine the thickness of low resistive layers, while the induced polarisation (IP) measurements could qualify the inner structure of the aquifer. The IP method is capable to distinguish a sequence of highly alternating, fine layering from the one, roughly regarded homogeneous. The alternating layering (multi-layered 'sandwich-type') gives high induced polarisation response, against the homogeneous type. From this project, two applications of transient soundings of different penetration are introduced here: a conventional with depth of investigation up to 700 m, and a shallow one, with penetration up to 100 m depth.

Geological model **Geoelectrical model** **Geoelectrical model by logging data**

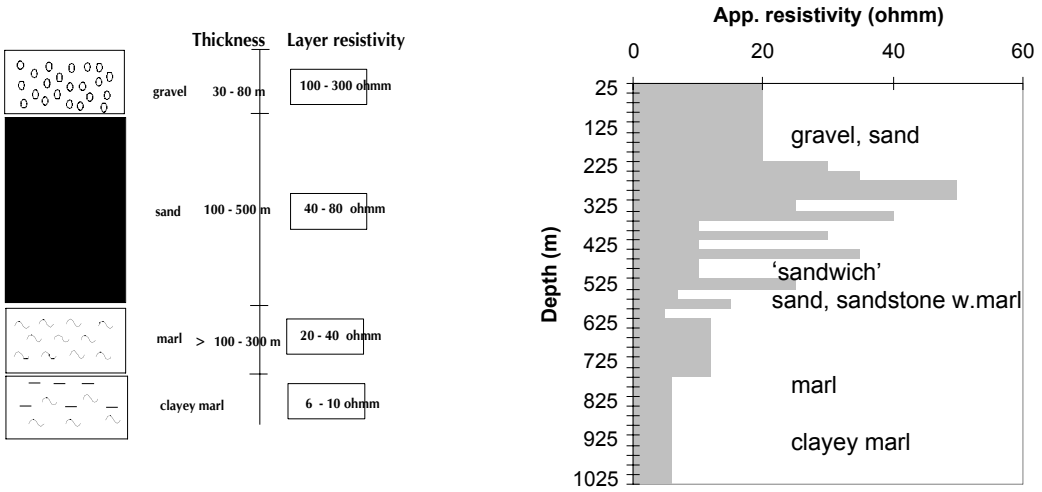


Figure 5a: Geological model **Figure 5b:** Geoelectrical model **Figure 5c:** Geoelectrical model by logging data

2.1.1 Conventional application of EM soundings depth range: 0 - 600 m

As a result of the transient soundings distributed in a quasi-regular grid of a few kilometres in the area a set of apparent resistivity maps has been constructed selecting different time channels which correspond to different horizons. This way choosing arbitrary channels a kind of slicing in depth can be achieved showing the resistivity distribution in space.

In the contour map presented in the figure below which refers approximately to the depth of 300 m, the area delineated by the contour level of 40 ohmm corresponds to sand and sandstone series, while the anomalies showing lower resistivity attributed to sandy to clayey marls. After evaluating each sounding by 2D inversion a resistivity-depth model is calculated.

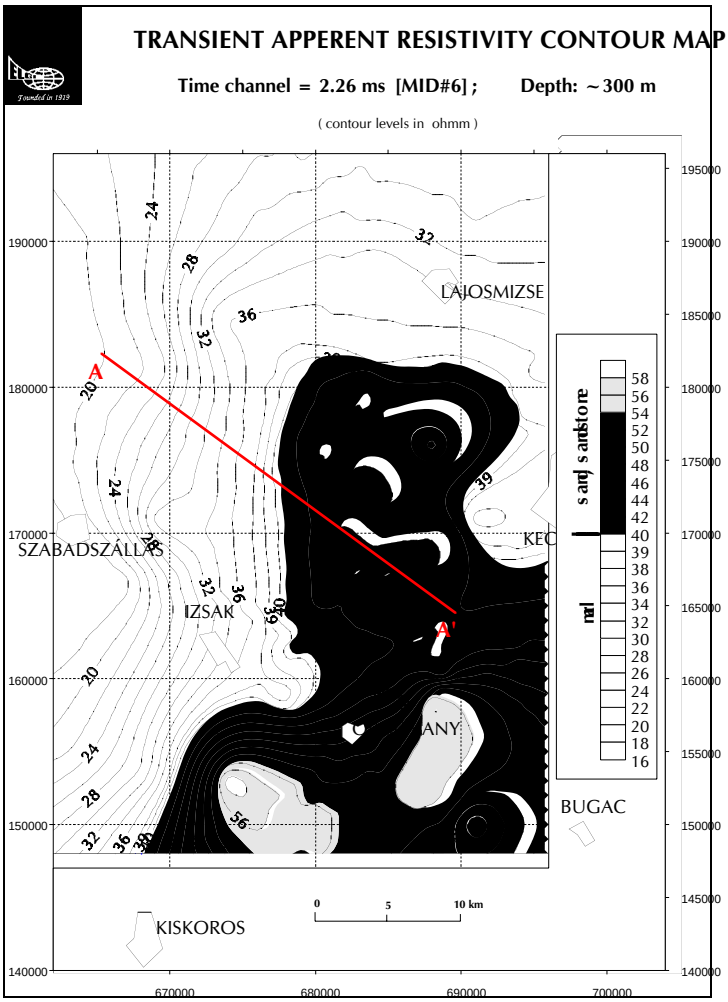


Figure 6: Transient apparent resistivity contour map

A geologic-geoelectric cross section compiled from soundings along the profile A-A' marked in the previous map is shown in the next figure.

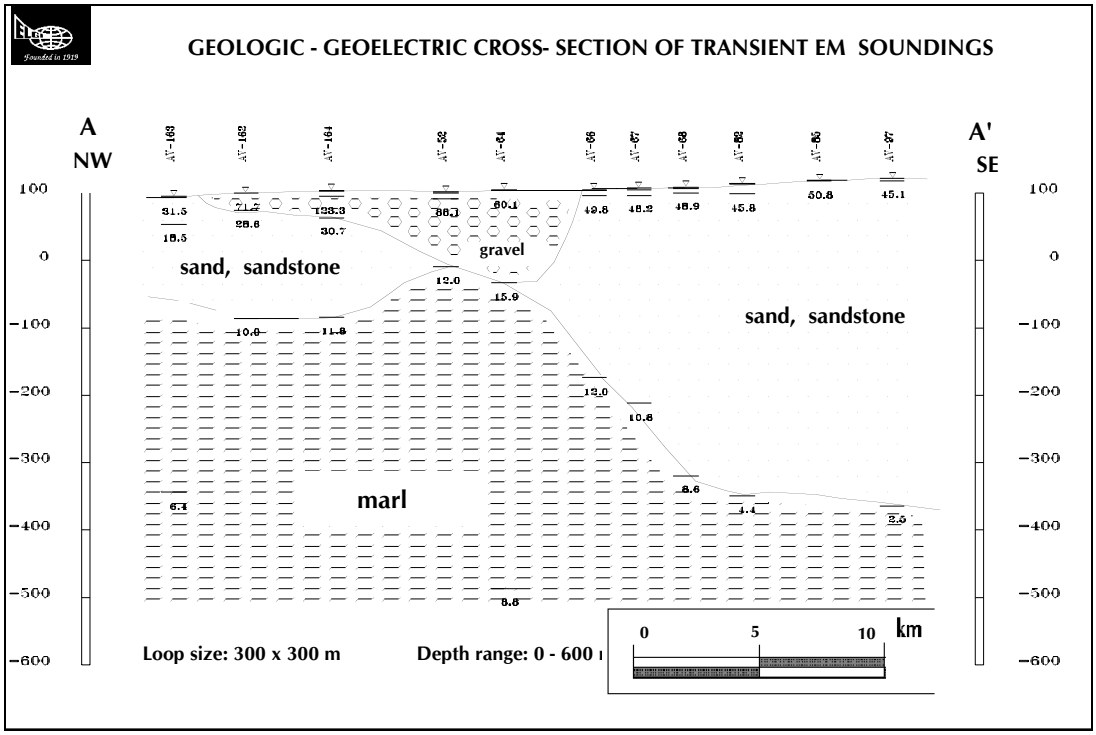


Figure 7: Geologic-geoelectric cross-section of transient EM soundings

The section indicates the interpreted interfaces between intervals having the same range of real resistivity. The identification of resistivity ranges to geology was based on core sampling and borehole logging data. Close to the surface alluvial deposits of gravel can be traced. Towards SE the thickness of the sandstone aquifer increases to great extent. The horizon of marls of the resistivity range of 5-10 ohmm deepens from 200 to 500 m depth. For this depth of investigation (about 600 m) 300x300 m size loop was applied, as configuration for the Geonics EM-37 transient system. It must be noted that for a conventional transient system the uppermost 50m is an unavailable blind zone due to the fact that its earliest sampling time is around 80 µsec.

2.2.2 Shallow application of transient soundings depth range: 0 - 80 m alluvial deposits of the ancient Danube river

Next a shallow application of transient sounding of the same project is presented. Shallow survey needs a separate system from conventional, having more sophisticated control unit working on higher frequencies, and the sampling times have to be shifted to earlier start. This early channel in Geonics PROTEM shallow system is set to about 6 µsec. From technical point of view the shallow system is more portable; it is powered by 12V car batteries, and uses 10-25 m side small-size generating loops. By this configuration over high resistive medium, like gravel and dry loess, even 80-100 m depth of penetration can be attained.

In the next figure the layer resistivity contour map compiled for 30 m depth indicates an elongated anomaly of exceeding 70 ohmm which corresponds to gravel deposits originated from a branch of the ancient Danube river.

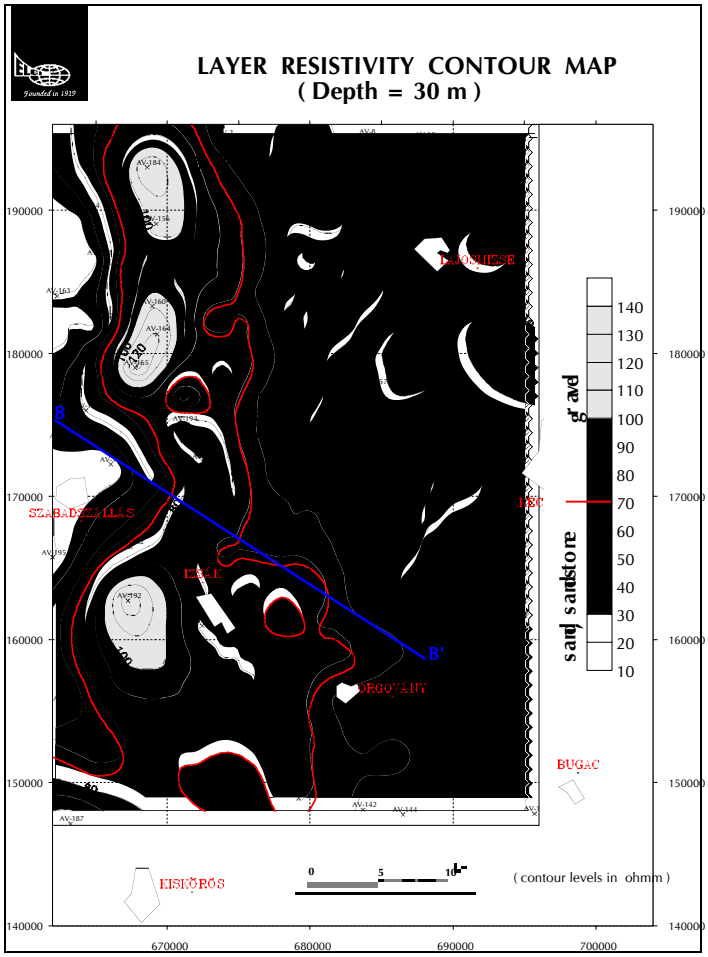


Figure 8: Layer resistivity contour map

A geological section crossing this anomaly along the line B-B' details the resistivity distribution at this shallow range. The gravel banks with varying thickness of 20-60 m are identified with those layers close to the surface, which recently produce the most amount of water for agricultural use.

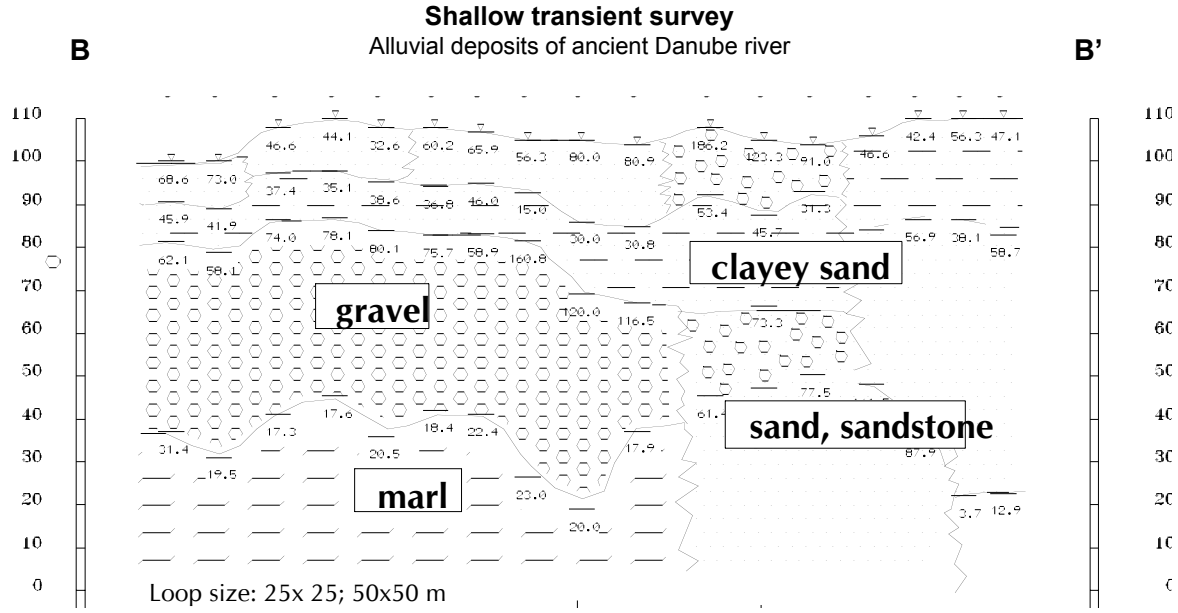


Figure 9: Shallow transient survey (alluvial deposits of ancient Danube river)

2.2 Monitoring fresh water - saline water interface by transient soundings near Batabano, at the coastline of Cuba

Another application to solve hydrogeological tasks by using transient survey is the monitoring fresh water-salt water interface. Such survey was carried out in Cuba in the southern coastline at Batabano.

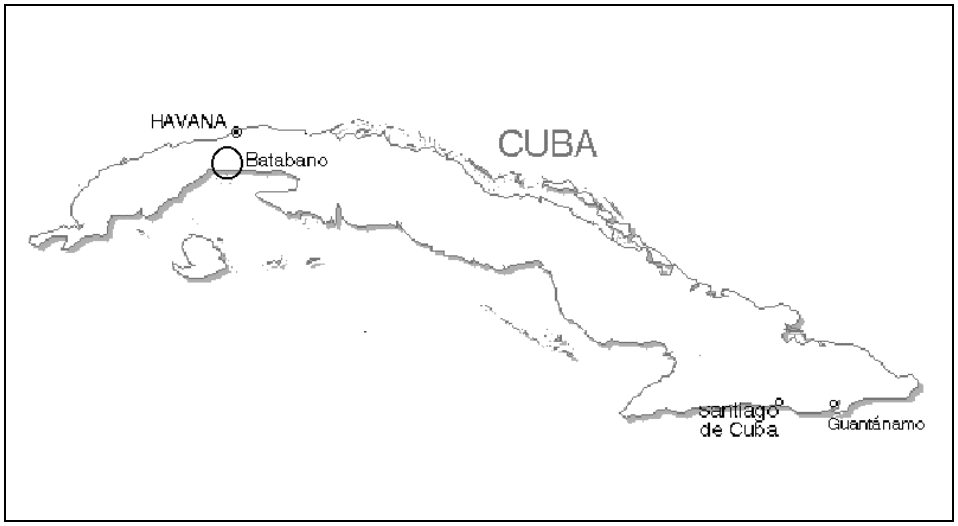


Figure 9: Map of Cuba

Havana, the capital with around 2 million inhabitants is continuously facing up to water supply problems since some of the monitoring wells had indicated intrusion of salt water into the sandstone-limestone aquifer producing water for communal use. This task is probably very common to cities all over the world situated along the seaside.

The sketch of geological-hydrogeological model indicates the principals of behaving waterfronts under subtraction from the aquifer near the shoreline.

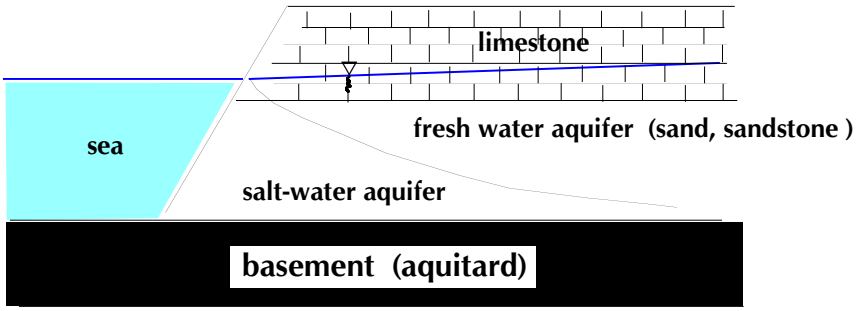


Figure 10: Geological - hydrogeological model

This case history also proves how the method is capable to investigate sections in depth range of 50-200 m, covered by resistive layers (such as limestone).

Since transient method is very sensitive to detect the response of low resistive target, the encountered resistivity range of 1 - 20 ohmm suits the best to cope with to distinguish salt water and brackish water from fresh water in porous.

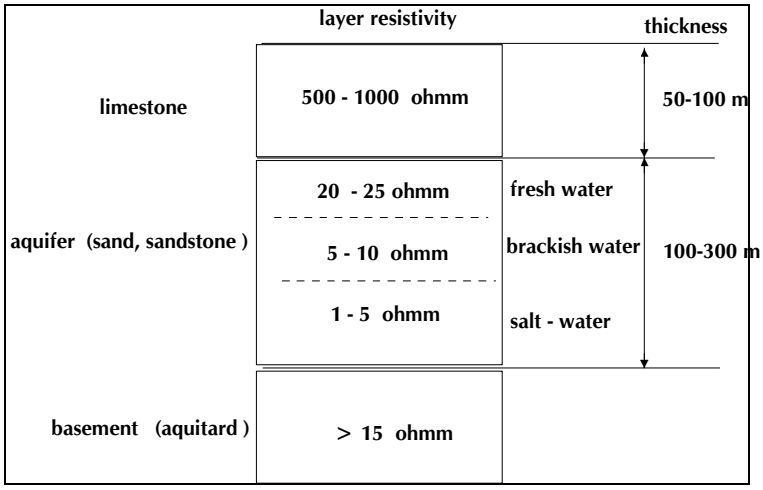


Figure 11: Geoelectrical model at coastline

Analysing the inclination patterns at the intersection of the branches of the apparent resistivity depth curves derived after 2D inversion, the layer boundaries of different transmissivity values can be delimited (upper part of the figure below. However the location of faults which particularly determine the places where water is forced to migrate upwards due to pumping is also possible.

According to the hydrogeological interpretation of the transient soundings as presented in the lower part of the figure below, the saline water invades up into the fresh water aquifer along faults, and becomes mixed. A fault in the northern part confines a block of marls with aquitard features.

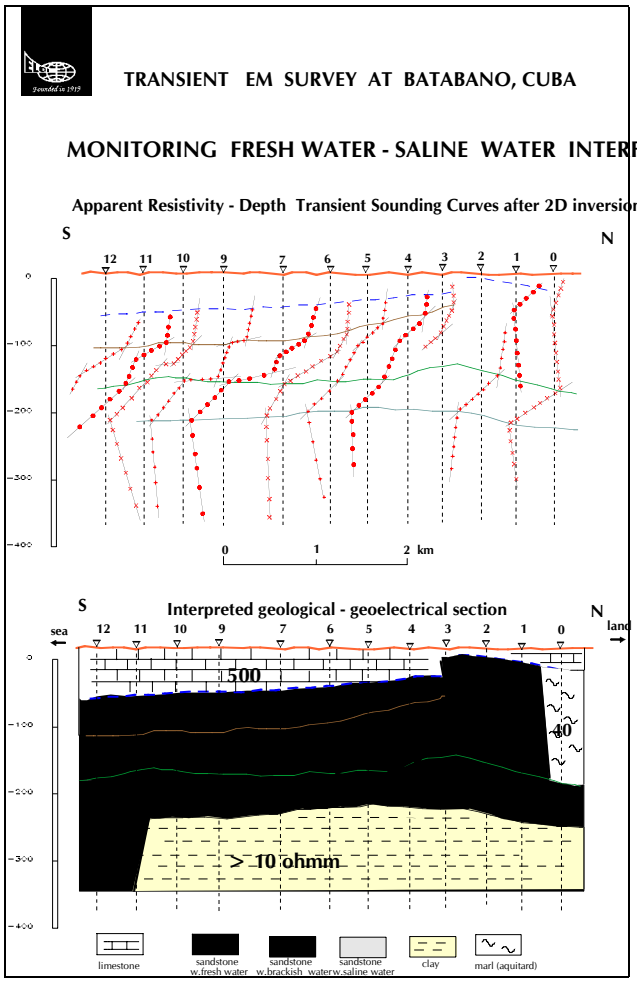


Figure 12: Transient EM survey at Batabano, Cuba

It is admitted that for monitoring, the progress of a low resistive anomaly interface attributed to saline waterfront might rather be investigated in time, preferably by mapping. However, this is only another example to show the inherent opportunity of the application of transient sounding in water prospecting.

Salaheddin Al-Koudmani

Water management of non-renewable groundwater systems in eastern part of the Arab Region

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Abstract (see full text in Arabic at the end of this volume)

This paper deals with basics and fundamentals of investment's planned of water resources in arid regions, as east Arab countries, which the non-renewable water are the main available resources. For increasing water demand in these regions in different human, industrial and agricultural used.

This study contains the non-renewable groundwater aquifers in the arid region, which extended from east of Mediterranean sea through Syrian and Jordan lands and partially of Iraq and north of Saudi Arabia north of latitude 30° N.

Water bearing aquifers in the east Arab region limit extended, although quantity of water storage limited, if we compared with wide extended bassins at North Africa.

Eastern aquifer systems can be classified by minimal water recharged because most of this water recharged from the rain period of Paleocene.

Fault plates and tectonic features influence the acceleration or retardation upon the water movement in these areas.

Available resources under hydrologic and climatic conditions do not allow the heavy investment, for that reason the arid region countries oriented for applied advanced technology as mathematical models for arrangement the non-renewable water resources investment, for understanding the water system and estimating the water availability from the main basins.

THEME V: MONITORING GROUNDWATER ABSTRACTION AND ENVIRONMENTAL IMPACTS

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Evaluation of water quantity and quality of several wells at Ghaduwa area in "Murzuk Basin"

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Abstract (see full text in Arabic at the end of this volume)

This study has been conducted in Ghaduwa area which is located 70 km south of sebha between 26°-27° latitude north of the equator and 14°-15° longitude east of Greenwich during the period of August 1995 – October 1996.

To evaluate the area's status as far as the water quantity and quality are concerned, the productivity of several wells was studied and the water discharged during the period estimated to be 562,014,478 m^3 from the surface and deep layers. The annual drawdown was also calculated to be 10.77 cm/year. The total porosity in the sandstone layer containing the water was estimated to be 17%. The average transmisivity for several deep wells was calculated to $4.1x10^{-2}$ m^2/sec, however the storage coefficient was not calculated. The water use efficiency in agriculture was found to be 61.3% during the first ten years; 70% at the beginning of the project and decreasing to 57% during the last period.

The chemical analysis of the water samples taken from 10 deep wells showed that that the average TDS was 345 ppm and suitable both for drinking and irrigation. However, the TDS obtained from 10 shallow wells ranged from 609 to 5590 ppm and is considered unsuitable for drinking. According to FAO water quality criteria, these waters are classified into increasing and severe problem classes.

Henny A. J. van Lanen

Monitoring for groundwater development in arid regions

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Abstract

In arid regions with a high water demand and where the hydrological processes typically show a high temporal and spatial variability, an adequate monitoring network is a prerequisite. Before a groundwater-monitoring network can be designed, the water use policy must clearly be stated. When using non-renewable resources, the optimal yield strategy must be defined, leading to measurable targets. Two different types of groundwater monitoring activities are distinguished; namely background monitoring and specific monitoring. A background-monitoring network (BMN) is urgently needed in all arid regions with groundwater potentials, which might be exploited. It identifies the actual state of the regional aquifer system and it helps to understand the aquifer characteristics and relevant processes (e.g. stored fossil groundwater, present day recharge) before significant exploitation starts. A specific monitoring network (SMN) need to be designed for each well field and it follow what happens in the underground in the abstraction phase. SMNs are restricted to smaller areas and they are characterised by higher network densities and sampling frequencies. The design of a monitoring network is a multi-step approach and it should be combined with groundwater modelling. Especially, if a mining strategy is adopted, it is likely that the SMN need to be adapted several times because the well field response (space and time) does not function as originally modelled or perceived. This is to be expected because of the increased understanding of the geological setting, storage properties, conductivity's, indirect recharge, leakage, and hydrochemistry during the aquifer dewatering.

The different aspects of a groundwater monitoring program, such as network density and sampling frequency are explained. Some (geo)statistical methods are dealt with which can be used to optimise density and frequency, if sufficient data prevail. A list of variables of a comprehensive monitoring program is given. This list includes hydrological (e.g. recharge, heads, stages of oases, spring flow, abstraction rates), hydrochemical (e.g. macro-components) and some environmental features (e.g. subsidence). Furthermore, general observation devices to measure some of the major variables are presented. An information system should be an integrated part of a groundwater-monitoring program. The various aspects of such a information system are described, e.g. data transmission, storage, data quality control, processing and dissemination

Keywords

Monitoring, background monitoring, specific monitoring, variables, density, frequency, modeling, observation methods, information system, (semi-)arid regions, non-renewable resources

1. Introduction

A groundwater monitoring network is an organised system for the continuous or frequent measurement and observation of the actual, dynamic state of the underground environment, often used for warning and control (adapted from UNESCO 1992). Monitoring of groundwater networks is essential to characterize regional aquifer systems and its response to abstractions. This is required to define an appropriate groundwater development strategy (e.g. sustainable safe yield or mining concept). Especially in arid regions, where the water demand can be extremely high exceeding present day groundwater recharge (e.g. Abderrahman et al., 1995; El-Baruni, 1995; Cresswell et al., 1999), an adequate monitoring network is a prerequisite. The need for such network is strengthened there because of the very high temporal and spatial variability of the hydrological processes. Data collection over all scales is difficult and expensive. However, a regional aquifer system and its response can only be understood if ample hydrological data in space and time have been collected. Physical, chemical and exploitation data need to be systematically collected to understand the governing system in a region. Groundwater should not substantially be used as a resource (e.g. for drinking water, irrigation, industrial development) unless its exploitation is based on a sound groundwater management plan, which is supported by a continuous effort of collecting hydrologic data from networks. Then, the exploitation of a non-renewable resource can be checked against the specific targets set at different stages stated in the groundwater management plan. These targets might include extension of the drawdown field, drawdown depth distribution, groundwater quality, drying up of springs or groundwater

discharge playas. In this way, deviations from the targets can be recognised in an early stage of the groundwater development. More than in other areas, in arid regions an early identification of these deviations is crucial for long-term sustainability, i.e. continuing socio-economic development and minimising environmental degradation.

Unfortunately in many arid regions, extensive groundwater network data are woefully lacking due to, for instance, the extension and accessibility of the area, and the large depth of the aquifer. Groundwater development under these circumstances can easily lead to an undesired situation (e.g. socio-economic development not adapted to the long-term water availability). Therefore UNESCO promotes the establishment of groundwater monitoring networks, including procedures for the design and analysis of networks and the description of observation methods (UNESCO 1990)

Langbein (1954) proposed the first operational procedures for hydrological data collection in networks. Over the years many good reviews of groundwater monitoring networks and observation methods were published (e.g. WMO 1994). It is not the intention of this paper to cover all the basic aspects in full extent that are already well documented elsewhere. A summary and an update are presented here, which is mainly based upon a recent UNESCO publication (Van Lanen 1998). First, the two basic types of groundwater monitoring networks are dealt with. Furthermore, the essential variables to be monitored, the network density and sampling frequency, and groundwater database development are described.

2. Type of groundwater monitoring networks

Two different types of groundwater monitoring networks should be implemented in case groundwater exploitation is foreseen. These are background monitoring networks and specific monitoring networks.

2.1 Background monitoring networks

Background monitoring or primary networks (BMN) need to be started before significant exploitation of groundwater resources occurs, which affects the natural or zero situation. BMN typically involves large areas with no significant human interference yet (low technology level). It is a governmental responsibility to establish a BMN. If transboundary effects of aquifer exploitation are expected the establishment of a network even is a supra-governmental responsibility. The objective of this monitoring is to identify the natural state of the aquifer system. It provides the initial conditions for large-scale groundwater development. This gives the people in arid regions the necessary background data to determine the change in the aquifer system in a later phase when a non-renewable resource is exploited.

Before any groundwater monitoring can start the (supra-)national land and water use policy and associated objectives must be identified (pre-monitoring phase). In the upper part of Figure 1 the main steps of the pre-monitoring investigations are presented (see also Melloul, 1995). If groundwater development is foreseen and therefore monitoring is required, basic aspects of the area, such as the geological setting and the hydrodynamic properties, need to be collected. Before monitoring begins the regional groundwater flow system must be understood and described as far as existing data allow (identification of regional aquifer system(s)). These activities start with the collection of mainly time-independent data, e.g. about geology, hydraulic properties, boundary conditions, land use, topography and soils.

The identification of the geological setting in three dimensions (3D) is a basic activity to be carried out. Special reference should be made to geological phenomena that dominate groundwater flow and storage, and groundwater quality. It is essential to consider the relevance of each geological unit involved, or even a part of a unit.

Ideally, the description of the strata should comprise:

- horizontal distribution and variation of thickness;
- aquifers: lithology (granular, fractured, granular and fractured, dissolution cavities), flow condition (confined, unconfined, semi-confined) and mineralogy;
- confining units: lithology, mineralogy and consolidation properties, and
- hydrogeological basement: buried topography, mineralogy.

The geological structure (tectonic evolution) of an area must also be carefully investigated, because it could affect groundwater flow and storage. Special considerations must be given to both local and regional effects of:

- fractures: size (length, aperture), distribution and units affected;
- faults: size (length, aperture), distribution and units affected, and
- anticlines/synclines: axes (strike of axes, dip), strike and true dip of strata, and associated tectonic structures

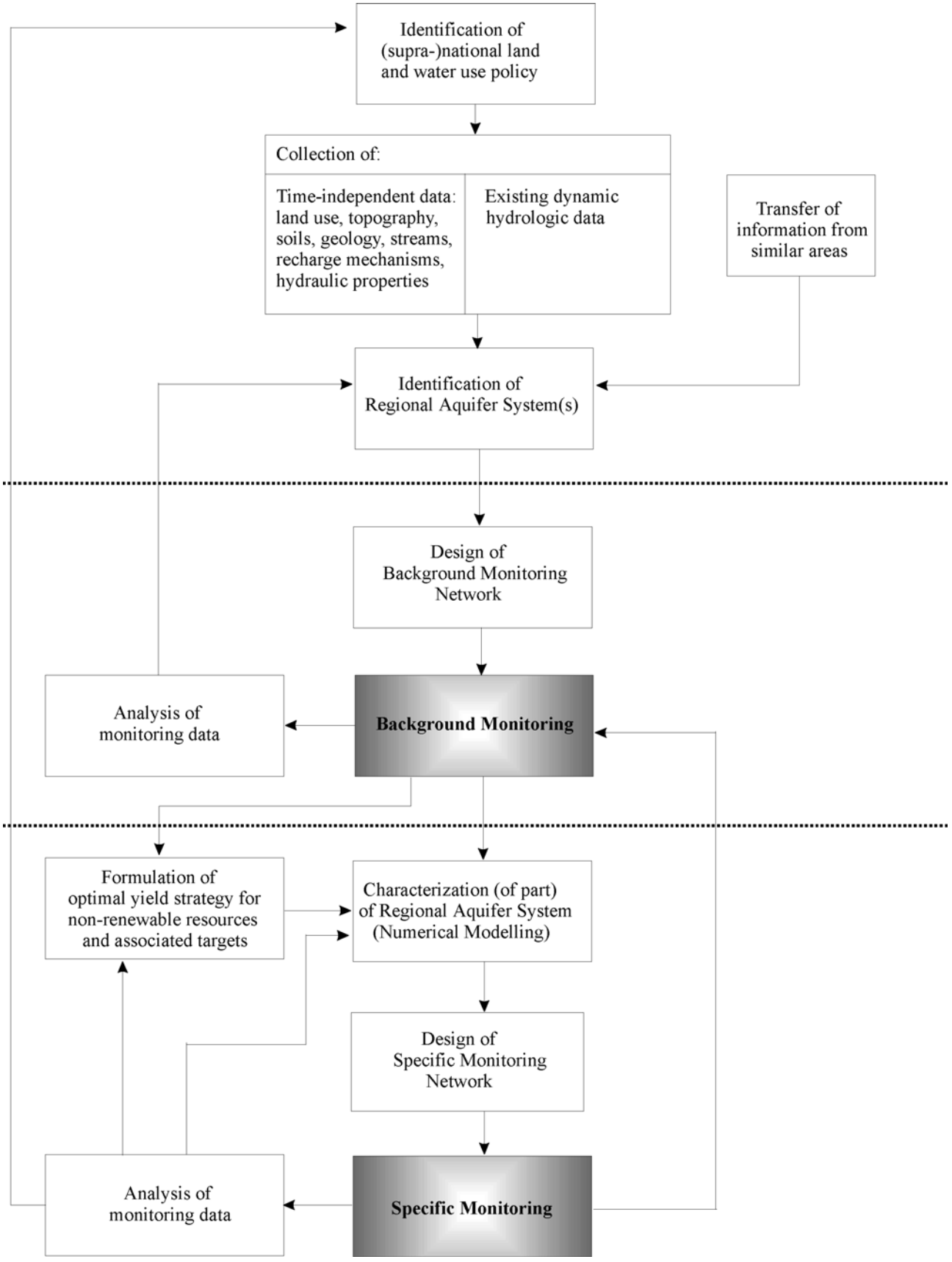


Figure 1: General outline of groundwater monitoring (adapted from Van Lanen and Carillo-Riviera 1998)

The earlier-mentioned geological data need to be converted into hydrogeological data. The following variables should be preferably available after the pre-monitoring research:

- aquifers: thickness, horizontal and vertical hydraulic conductivity and its variation in x,y, and the vertical and horizontal distribution of the storage properties;
- confining units: thickness, vertical hydraulic conductivity and its variation in x,y, and
- semi-confining units: thickness, vertical hydraulic conductivity, consolidation properties and their variation in x,y, and the vertical and horizontal distribution of the storage properties.

Except physical information, data about the chemical composition of groundwater and surface water, if present, have to be gathered. An essential activity in the pre-monitoring phase is the identification of the recharge mechanisms to determine the origin and age of groundwater at different places in the aquifer. Isotope concentrations from different locations and depths can give very valuable information about the (paleo)recharge mechanisms. Additionally to the collection and interpretation of time-independent information, dynamic data need to be gathered. These include already available or readily to collect dynamic data, such as groundwater heads in both existing wells and abandoned wells. It is also highly recommended to define the relation between groundwater-surface water, e.g. spring flow and groundwater discharge to oasis, playas or streams. Data of existing meteorological networks need to be gathered as well. Classical and more advanced methods can be used to interpret the available data. Melloul (1995) shows for the Nubian Sandstone aquifer in Egypt and Israel that Principal Component Analysis can be a suitable tool to analyse a (deep) aquifer system with scarce data. This statistical tool (factor-analysis technique) combines various multi-disciplinary data to identify physical and chemical groundwater types, which can be used to define groundwater flow paths.

It is likely that at the start of the background-monitoring phase, insufficient knowledge exits, because one of the objectives of this monitoring is to improve the understanding about the prevailing regional aquifer system. Even limited data based upon a small number of observation wells and measurements of a large number of variables in existing wells can contribute significantly to this understanding. Probably, other similar regions, which have been already investigated, might allow transfer of knowledge to the region to be monitored (Figure 1). During the system identification phase, a conceptual model needs to be developed. Such conceptual model should describe flow paths, rate and type of recharge, possible leakage from adjacent aquifers, and the evolution of the groundwater quality from the recharge area to the discharge area. When an acceptable conceptual model exists, a first version of the groundwater monitoring network is designed (middle part Figure 1). Systematic measurements of heads and chemical composition of groundwater in existing and abandoned wells should start then. This groundwater monitoring should be supported by the additional collection of data on meteorology, vadose zone, and groundwater discharge to springs, oases, playas and streams. After some years of systematic data collection, the initial version of the BMN should be thoroughly analysed. It is probable that the analysis based on the improved knowledge of local hydrological phenomena of the region itself will lead to an adaptation of the first network version, which better represents the specific characteristics of the regional groundwater system in the area (Figure 1). The refinement of the BMN should be a more or less continuous process of analysing incoming data, refinement of the description of the regional groundwater system and subsequent network adaptation (loop middle part Figure 1). Commonly the network need to be adapted more than once, especially in regions with extreme meteorological conditions, such as the arid regions. Background monitoring in these areas might be a long-term effort. If recharge prevails, the inter-annual variation of the recharge is extremely high, which implies that the background monitoring should last several years before a proper description of the natural situation can be made.

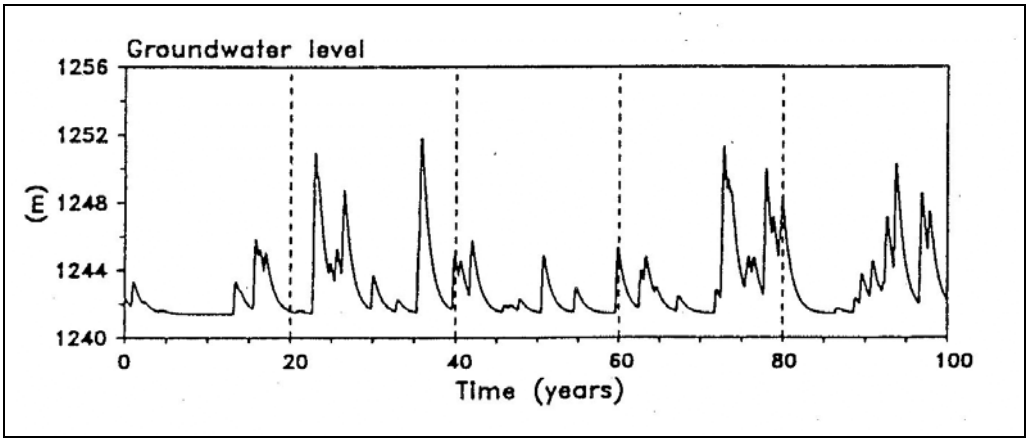


Figure 2: Simulated groundwater levels for a bore hole in the Nnywane Basin, eastern Botswana using stochastic simulated rainfall pattern (Gieske 1992).

Usually time-series of observed groundwater heads in arid regions are too short to account for the inter-annual variability. Stochastic modeling can be applied to extend the existing time-series (Figure 2). In this example for Botswana, particular wet periods occurred over a period of century (e.g. after 20-40 years).

In some arid regions, i.e. the hyper-arid regions, hardly any present day recharge events occurs. The aquifer has been replenished in the past (e.g. Issar et al. 1972; Jacobson et al. 1989; Cresswell et al. 1999). Then conceptual climate records from the Holocene and sometimes the Late-Pleistocene (e.g. last interglacial) need to be used (Lloyd and Bradford 1992) to understand the groundwater system, including its paleorecharge mechanisms and related chemical groundwater types. In this case, except data about the current state of the regional aquifer system, the BMN should also give general information about the groundwater stored in the aquifer and the slow depletion process related to recharge mechanism over the centuries. In some aquifers with hardly any recharge, e.g. the Nubian Sandstone beneath the Sinai Peninsula (in Egypt) and the Negev Desert (in Israel), billions of cubic meters are stored (Issar et al. 1972). BMNs in regions with hyper-arid conditions should mainly focus on the amount of groundwater stored in the aquifer.

2.2 Specific monitoring networks

Specific or secondary monitoring networks (SMN) follow what happens in the underground environment when a regional aquifer is substantially exploited for particular purposes. Typical for a SMN as compared to a BMN are higher sampling density, higher sampling frequency and more monitoring variables. A SMN is also established for a smaller area, although the large-scale abstraction of a non-renewable still has impact on a relatively wide area (usually hundreds of km^2). The SMN characterises the transient state of the aquifer and acts as an early warning for over-exploitation or groundwater quality degradation. In case of the exploitation of a non-renewable groundwater resource, this implies the comparisons of the spatially-distributed state variables (e.g. groundwater heads, chemical composition, stages of streams and oases), which are monitored, with the specific targets as formulated in the groundwater management plan for different exploitation phases. The monitoring is restricted to those areas and aquifer(s) where effects are expected.

A specific monitoring network should be set up after people have decided to develop groundwater resources in a particular arid region. The decision should be based on a comprehensive analysis of background monitoring data. A first estimate of the response of the regional aquifer system when it is put under severe stress, needs to be made. A management pan for the regional aquifer system has to be compiled. This plan should also include the way groundwater is withdrawn, e.g. large numbers of clustered wells in closely spaced well fields or less-dense spaced wells and well fields (e.g. Abderrahman et al. 1995). Furthermore the feasibility of aquifer exploitation need to be addressed, such as well depth related to aquifer thickness, acceptable lift and specific capacity. For a non-renewable resource the objectives, i.e. optimal yield strategy (Lloyd and Bradford 1992) and associated projected abstraction rates from the well field have to be stated. These rates govern socio-economic development. Moreover the expected effects of the abstractions need to be determined at different times. In large regional aquifer systems, e.g. Northern Africa, North China Plain, Central Australia, Middle East, the time scales for a SMN are decades to centuries. These effects learn if the abstractions are feasible within the hydrogeological and technical framework. The conceptual model of the regional groundwater flow system of the BMN phase is replaced in the SMN by a comprehensive numerical one (Figure 1, lower block) to simulate hydrological effects. The transient groundwater simulation model must specify the consequences of different abstraction scenarios in terms of groundwater heads, groundwater flow lines, residence times, changes in recharge conditions (e.g. indirect recharge), chemical composition, discharge to oases and playas, spring flow and streamflow. At least the modelling should produce results, which can be compared with the targets set in the groundwater management plan. After the modelling phase specific monitoring features can be formulated, such as the boundary of the affected area, type of hydrologic variables to be monitored, and sampling density and frequency.

A specific groundwater-monitoring network is likely to require adaptation after collated data show that the response of the groundwater flow system is more or less different from the simulated one. A hypothetical example is presented in Figure 3, where a low-permeability zone causes discrepancies between the monitoring data and the earlier simulated drawdown (see also Lloyd, 1998). Similar to background monitoring, specific monitoring needs continuous efforts in terms of collecting data, analysing them, and refinement or incidentally redefinition of the transient regional aquifer model and the monitoring network.

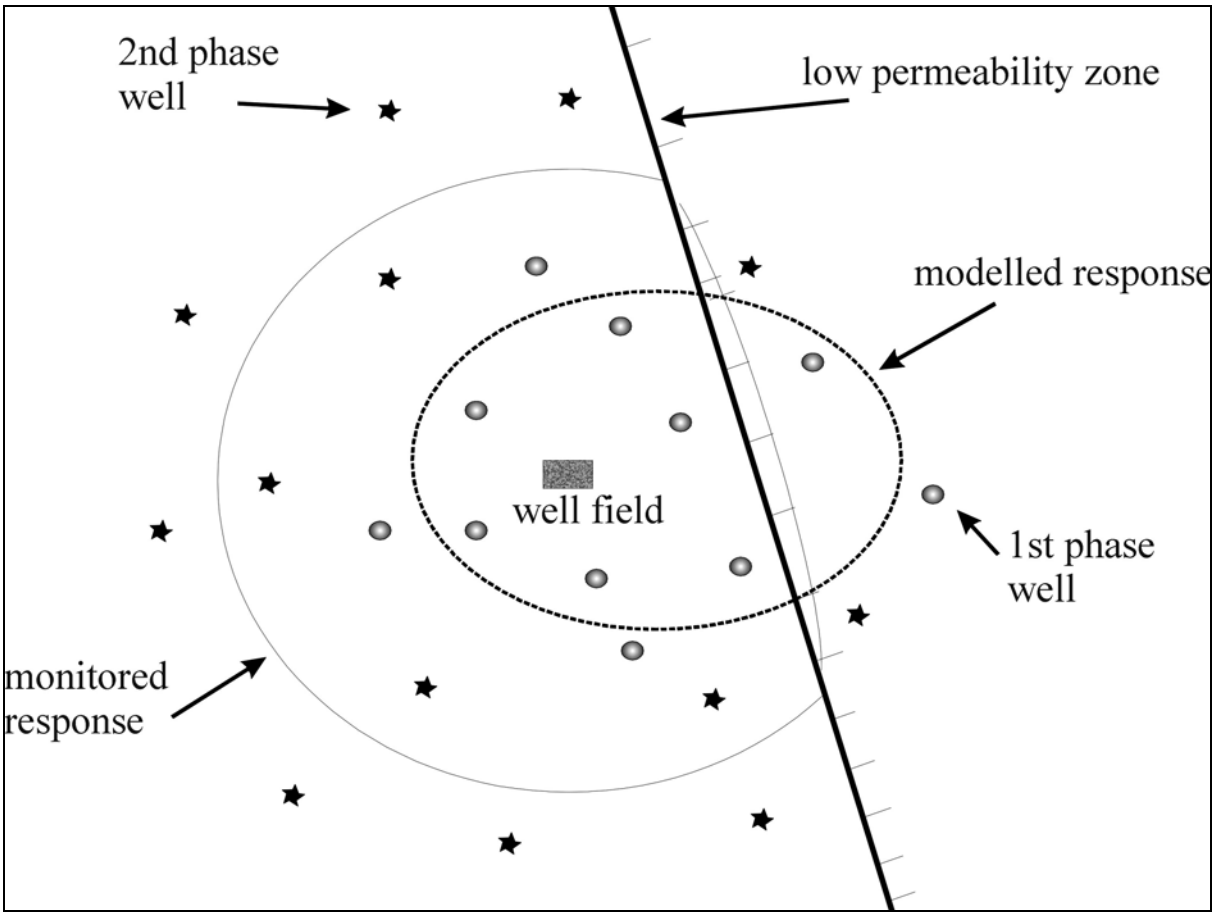


Figure 3: Deviation from the monitored response of an aquifer and the simulated one after some time, including the location of observation wells in different phases.

The specific monitoring should be integrated into the background monitoring efforts (Figure 1). Eventually the ideal situation in a country (or more countries, if it is a large aquifer with transboundary effects) is to have a background monitoring network that covers the whole regional aquifer and specific monitoring networks in regions where groundwater resources are significantly exploited (nested monitoring networks).

3. Monitoring variables and methods

Groundwater monitoring includes more than observing the state variables from the regional aquifer system itself, e.g. groundwater heads and chemical composition. A groundwater system can only be understood adequately if the recharge and discharge of the groundwater system are monitored as part of an integrated monitoring effort. This implies that meteorological, vadose zone and groundwater variables must be observed. Spring flow, discharge to oases, playas and stream flow must be observed as well (Figure 4). The meteorological, vadose zone, groundwater and streamflow networks to collect the different type of data should be integrated from the beginning (Moss 1986). Commonly, more than one organisation is responsible for the acquisition of the data, which requires a good co-ordination. For example, locations, monitoring frequency, accuracy, data processing, data transfer and publication, in the different networks need to be tuned.

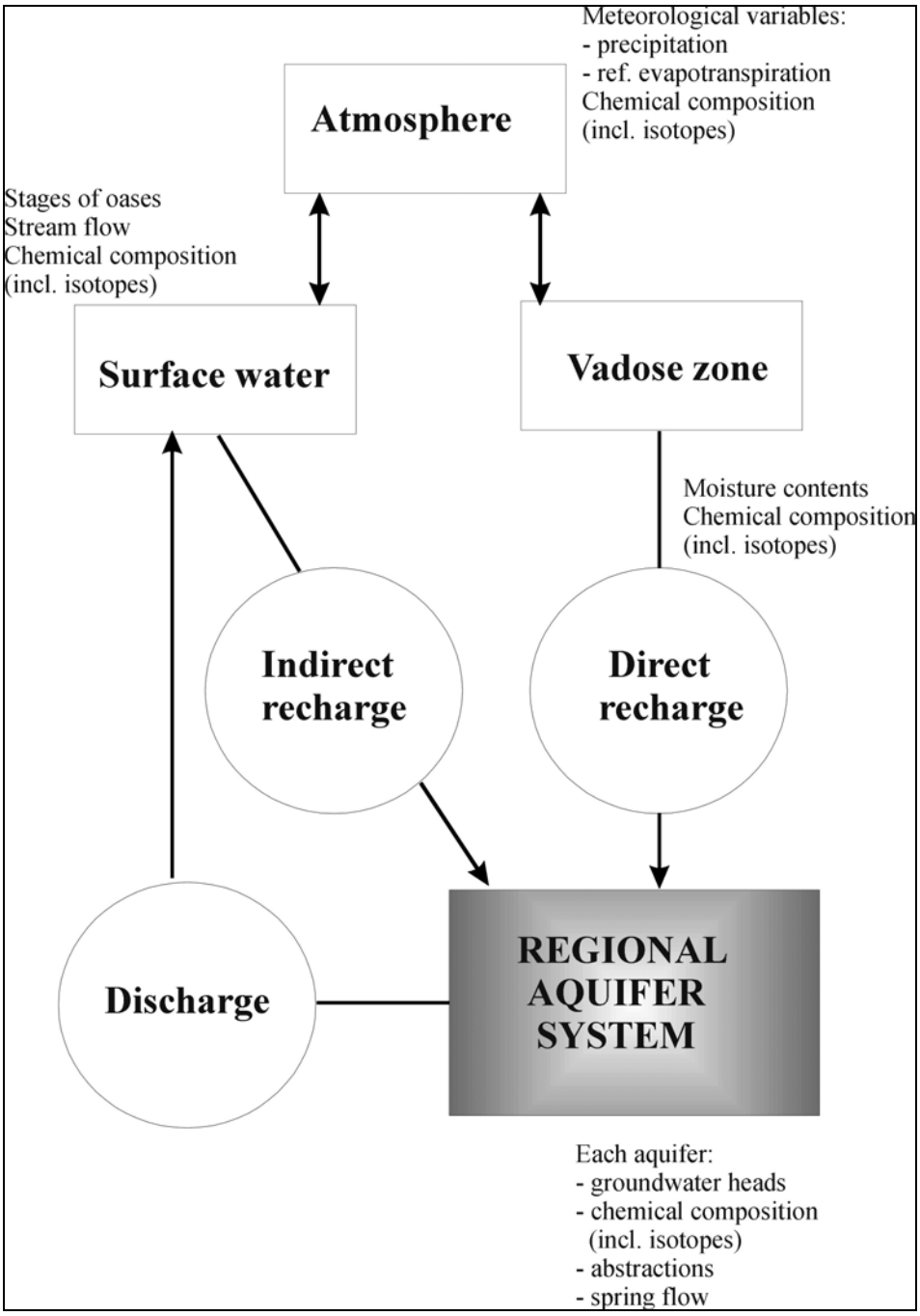


Figure 4: Monitoring variables (adapted from Van Lanen and Carillo-Riviera 1998)

3.1 Recharge

The estimated average annual recharge of aquifers in arid regions is 20-100 mm.yr^{-1} (Issar et al. 1972). Usually, in arid regions most of the groundwater stored in the aquifer systems is not from present day precipitation recharge. Paleo-recharge created groundwater storage in these regions. Most of the modern recharge is from wadi flows (indirect or surface water recharge). Commonly a relative thin layer of groundwater from recent precipitation recharge water (active layer) is superimposed on paleo-groundwater. In the vicinity of a wadi this active layer may be thicker. In the pre-monitoring phase these different groundwater types need to be identified (groundwater system identification, Figure 1). In case of exploiting a non-renewable groundwater resource, this knowledge is essential for a reasonable assessment of the optimal yield, because the extracted water consists of present day recharge, recently stored groundwater (active layer) and paleo-groundwater (Figure 5). For example, in central Australia 10% of extracted groundwater is present day recharge, the remainder is paleo-groundwater (Cresswell et al. 1999).

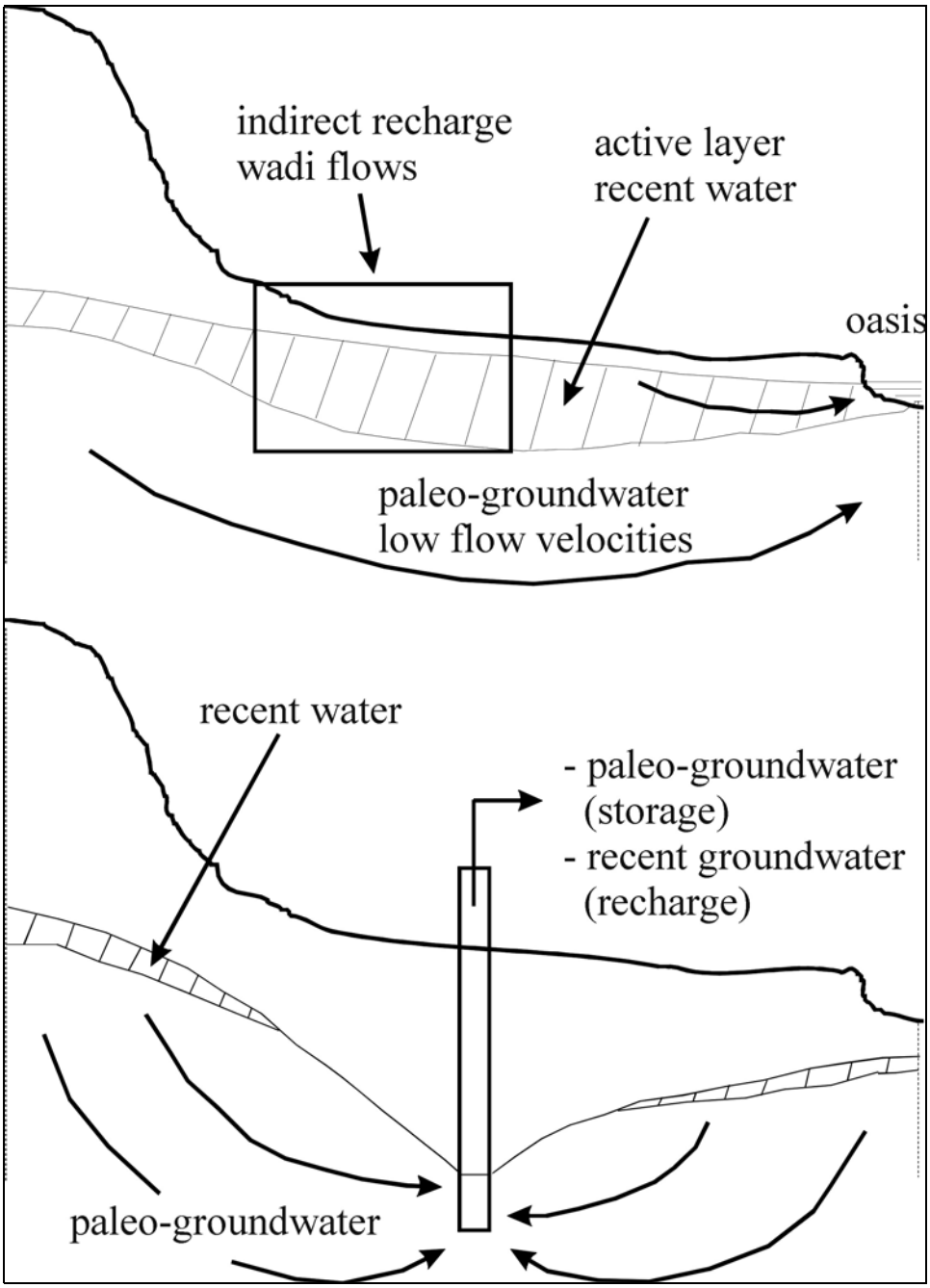


Figure 5: Schematic cross-sections in an arid region with different types of groundwater for the situation without (upper) and with abstraction (lower).

Although present day recharge is low in arid regions, it should be monitored as accurately as possible because it the renewable part of the abstracted groundwater. This might be a relevant amount of water due tothe immense depression cone, which normally develops when a non-renewable resource is exploited. For instance, if the recharge amounts 25 mm/year, about 8 Mm^3 groundwater can be extracted per year from an area with a depression cone with a radius of 10 km (Figure 6).

WMO (1994) systematically presents acquisition and analysis techniques for precipitation, evapotranspiration and soil moisture to determine groundwater recharge. Lerner et. al (1990) and Simmers (1997) give extensive reviews of recharge estimation techniques and associated collection of hydrological data for different types of recharge (e.g. precipitation recharge, surface water recharge) in (semi-)arid regions. Hendrickx and Walker (1997) state that the estimation of *precipitation recharge* is an iterative process using combined methods which is very often fraught with uncertainties due to lack of data and insufficient knowledge about the recharge processes. However, they give guidelines to reach a best estimate. As a first step daily rainfall data have to collected, as well as daily meteorological data to compute the potential evapotranspiration. Furthermore (step 2) data on soils, geology and vegetation have to be

available (Figure 1, pre-monitoring phase). Subsequently, tracer methods and computer models have to be applied in combination with easily obtainable field data (step 3). Chloride as an environmental tracer is often used. If land use has not been changed over the last century, steady-state analysis methods can be applied to determine recharge, otherwise transient methods need to be used (e.g. SODICS, Rose et. al. 1979). Hendrickx and Walker (1997 do not recommend artificial traces (e.g. tritium or bromide) because these tracers are only suited in environments with quick recharge processes, such as humid climates or irrigated conditions. The choice of the soil water model depends on the recharge process and the environment. Where surface water runoff-runon (localised recharge) plays an important role models such as developed by Boers (1994) can be applied. If surface water runoff is negligible, process-oriented flow models, e.g. SWAP (Van Dam et. al. 1997), can be used for unconsolidated rocks, whereas for hard rock areas parametric hydrologic models, such as EARTH (Van der Lee and Gehrels 1997) can be employed. In step 3 some additional fieldwork can be done, such as collection of soil texture data, soil water content and soil water chloride profiles. Usually after some years of the use of combined methods, either the tracer method or the model can solely be adopted as the method to estimate recharge. If sufficient resources are available, Hendrickx and Walker (1997) suggest installing some lysimeters. Lysimeters provide the only direct physical method to measure recharge fluxes. Direct measurements using lysimeters, however, can only be carried out under experimental conditions, which is generally impractical in arid regions. The above-mentioned procedure gives an estimate of the recharge at particular spots. Remote sensing can help to scale up the point estimates to the regional scale (e.g. Owe and Van de Griend 1998). The regular monitoring activities to determine precipitation recharge comprise collection of daily meteorological data and at a lower time resolution moisture contents or tracer concentrations dependent on the selected calculation procedure.

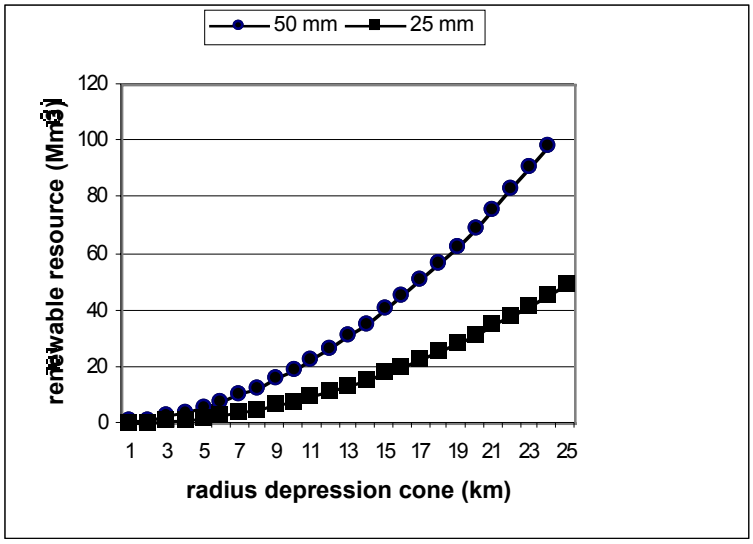


Figure 6: Amount of renewable groundwater from present day recharge (25 and 50 mm) for different areas of the depression cone.

Percolation from usually intermittent streams (*indirect recharge*) is often a more important source of groundwater recharge in arid regions than precipitation recharge. In irrigated areas the return flow also can substantially contribute to groundwater recharge (Rushton 1997). Lerner et al. (1990) give data of some case studies, which show that the indirect recharge can vary from 15-100% of the runoff. The indirect recharge is even more difficult to estimate than precipitation recharge. Kruseman (1997) lists some surface recharge estimation techniques. Direct measurements consist of applying lysimeters, which are impractical for conventional monitoring. Water budget methods, e.g. water table response and surface water budget, are more frequently used. The water table response method is based upon the assessment of the percolation volume from the sudden rise of the water table in piezometers, the specific yield and the area involved. Piezometers along and perpendicular to an intermittent stream are required for this method. Water table fluctuations over longer time periods can be further analysed with a numerical groundwater model, thereby including the Darcian approach. With the surface water budget method people compute the recharge over a river stretch from the difference between the stream discharge at two locations. Well-calibrated gauging stations are required for this method, and the recharge must be large compared to measurement errors. Furthermore Kruseman (1997) mentions tracers and empirical formulae to assess indirect recharge.

In the context of the management of non-renewable resources, the monitoring of hydrological variables to quantify recharge need only to be considered if the present day recharge is a substantial part of the abstracted amounts (Figure 5).

3.2 Groundwater

The essence of a groundwater-monitoring network is the measurement of the state variables of the different units of the groundwater body itself. The dynamic state of regional aquifer system can be monitored through observing:

- water-table depth (x,y,t)[1];
- chemical composition (incl. isotopes) of phreatic groundwater (x,y,z,t);
- piezometric heads (x,y,z,t) of each aquifer unit;
- chemical composition (incl. isotopes) of deep groundwater (x,y,z,t) in each aquifer unit;
- well yields (x,y,z,t), and
- chemical composition (incl. isotopes) of abstracted groundwater (x,y,t).

In thick aquifers from which vast amounts of groundwater are abstracted, an adequate monitoring plan should also pay attention to vertical differences in groundwater heads and chemical composition inside the groundwater body itself. The vertical flow component cannot always be neglected, especially for a correct understanding of possible changes in the chemical composition of the groundwater. At the long-term these changes may threaten the exploitation of the well field or pollute the aquifer, which could create environmental problems. In coastal areas salt water intrusion may take place (e.g. El-Baruni 1995), and in regions where the aquifer is overlying marine deposits, upconing of mineral rich connate groundwater may occur. Furthermore monitoring in a multiple aquifer system attention should also be paid to aquitard and aquifer compaction. Large-scale abstraction can lead to the development of major soil cracks (e.g. El-Baruni, 1994) or to severe damage to buildings and roads (Carrillo-Rivera 1998). The latter author shows that subsidence of unconsolidated aquitards in Mexico City because of groundwater abstraction cannot be adequately understood unless the vertical differences are monitored. When subsidence is expected extensometers need to be installed and compaction characteristics of the aquifer and aquitard material should be determined in the pre-monitoring phase.

In a region where a non-renewable resource is exploited, the establishment of a network to monitor the effects on groundwater often demands high financial efforts. The bottom of the regional aquifer system may reach substantial depths. An expensive drilling program has to be carried out to install the monitoring wells with screens at different depth. Nevertheless this effort is worthwhile, because is the only way to evaluate at regular times if the abstractions can be continued according to the formulated optimal yield, or that the optimal yield has to be adapted. The long-term sustainability depends on this information. The monitored response of the regional aquifer system in terms of heads and chemical composition can learn a lot about the regional characteristics of this system under stress. We should realise that the optimal yield and the associated monitoring network design will never be right at the beginning (Figure 2 lower part).

Measured groundwater heads at different distances from the well field over the years will tell a lot about aquifer response and its characteristics. Some simulation model experiments were done to show this. A hypothetical, unconfined regional aquifer was modelled (about 100*50 km) using ASMW (Chiang et. al. 1998). The longitudinal axis stretches east west. In the north and south impermeable units (no-flux boundary) bound the aquifer. In the west and east a discharge zone occurs with a fixed head. The aquifer was supposed to be 500 m thick and has a hydraulic conductivity of 2 $m.d^{-1}$. From a well field in the centre 25 Mm^3 was withdrawn. The *storage properties* of an aquifer, i.e. the specific yield (S_y) of an unconfined aquifer, are extremely important when exploiting a new-renewable groundwater resource (e.g. Lloyd 1998). This exploitation means mainly depleting stored “old” groundwater. The specific yield is usually derived from short-term pumping tests, which easily can lead to an underestimation. Moreover, during large-scale abstraction a semi-confined aquifer system can turn into an unconfined system starting at the well field. If the specific yield is underestimated, the monitored groundwater drawdowns will be lower than initially foreseen (Figure 7, upper row). Of course, this deviation can be noticed first in the observation wells near the well field. The specific yield also has large impact on the groundwater heads at far distance from the well field. For instance, after half a century the drawdown at 30 km is almost negligible for S_y=0.15, whereas for S_y=0.075 it already amounts more than 1 m. This graph also shows the wide area and the long time scale which need to be considered when a non-renewable resource is utilised. For a reliable, long-term estimate of aquifer response, the geological setting of an extended area (hundreds of km^2) need to be known. Of course, uncertainties exist, because this setting is derived from interpolation between drillings, geophysical data and common geological sense. For example, a *discontinuity in the hydraulic conductivity field* is hard to detect from the groundwater gradients prior to pumping. These gradients are mostly very small if groundwater head decay is only governed by the slow depletion of the dessertic aquifer, which have been recharged long ago (e.g. Lloyd and Miles 1986). In the model a low conductivity zone (k=0.1 $m.d^{-1}$) was introduced at 7-8 km west of the well field. This zone stretches south north. After some time, such discontinuity clearly shows up in

1 x, y, z, t denotes position in space and time

the aquifer response (Figure 7, middle row). East of the zone, where groundwater is drawn, the drawdowns will be larger and west of the zone the opposite occurs. Of course, east of the well field the deviation in the response is smaller than in the area west of the abstractions. This model experiment also shows that important hydrogeological features of the aquifer system do not show up in the early phase response. Another aspect of the geological setting is the boundaries of the aquifer system. From large regional aquifer systems the location of all these boundaries is not exactly known. In the early phase response of a large-scale abstraction, the effect of these boundaries cannot be seen. In some aquifer systems it will last decades before it can be detected from the monitored groundwater heads. In the model the impermeable units in the south and north are assumed to occur a little bit closer to the well field. Moreover the boundary is supposed to be irregular in stead of straight as it was in the previous simulations. So, the aquifer is less wide. This implies that the drawdowns will be larger (Figure 7, lower row). In this case the response will not be seen earlier than after two decades. So, specific monitoring need to be a continuous effort, because there are many reasons that the monitored response will deviate from the expected one.

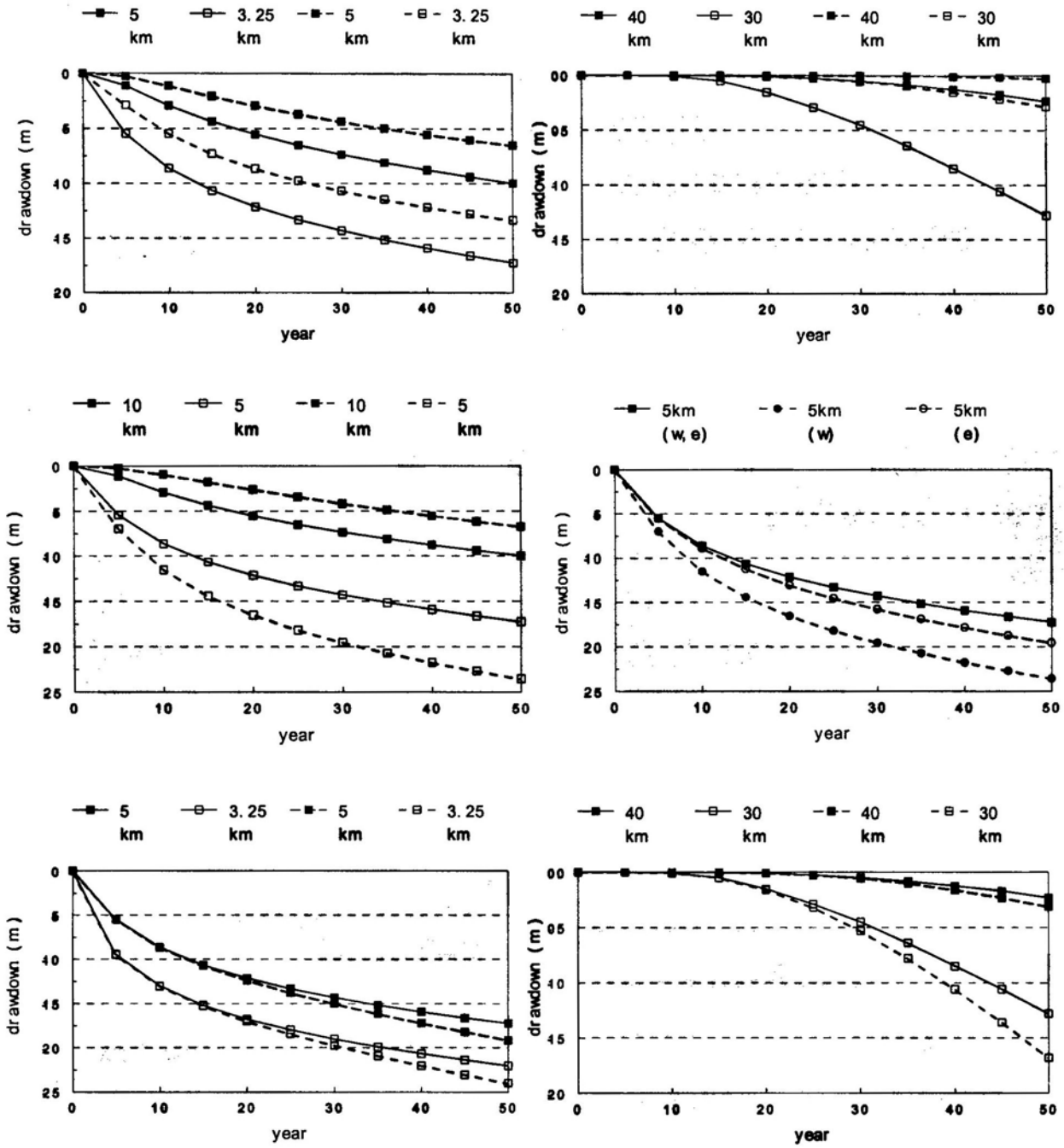


Figure 7: Simulated drawdown; upper row: effect of the specific yield (S_y=0.075: solid line, S_y=0.15: dashed line), middle row: effect of low conductivity zone 6-7 km west of the well field (without zone: solid line, with zone: dashed line; w and e: denote: west and east), and lower row: effect of irregular aquifer boundaries (regular boundaries: solid line, irregular boundaries: dashed line).

3.3 Surface water

In arid regions where a non-renewable resource is exploited, perennial surface water is usually absent. Oases, seepage faces and springs may occur in deep depressions, along fault systems or at the edge of the regional aquifer system. Even if these surface water features are intermittent, it is worthwhile to monitor stages, fluxes and chemical composition (Figure 4). In a groundwater management plan, for instance, minimum stages of oases, playas or minimum spring flow might be prescribed to monitor the environmental impact of the large-scale groundwater exploitation. Furthermore surface water reveals information about groundwater system behaviour, including its response on abstractions. Using flow velocity methods or tracer methods can monitor stream or spring flow incidentally. Non-equidistant time series are obtained in this way, which are likely to miss important events typically for arid zones. More expensive measurement structures, e.g. weirs and continuous water stage recorders, are preferred. These tools provide a continuous record of discharge. Extreme fluctuations in stream flow and high sediment loads, however, severely hamper continuous discharge measurements in arid regions.

3.4 Observation methods

Extensive reviews of methods to monitor the groundwater variables exist (e.g. WMO 1994; Otto 1996). Data on groundwater heads and the chemical composition are obtained at observation wells or piezometers. These wells or piezometers must be well installed, developed and regularly maintained. Multi-piezometer devices (cluster in a single borehole or in different boreholes in one place) need to be used when the head or chemical composition has to be measured at different depths. Manual-operated and automated-recording instruments are available to measure groundwater heads in observation wells or piezometers (Table 1). Automatic recording of groundwater heads can be necessary to monitor at remote places, or at locations where a quick response is expected (e.g. determination of indirect recharge using the water-table response method). For proper groundwater management each well within a well field should be instrumented to monitor abstraction amounts and well performance. Mechanic flow meters record the total water abstraction and an observer from the meter reads the data at periodic intervals. Electronic totalling flow meters are used in case the data can be stored on a logger. Boiten (1993) and WMO (1994) present an extensive review of methods to measure stream flow.

When sampling aquifers for the monitoring of the chemical composition, a distinction should be made between non-point and point sampling. Non-point samples obtained by pumping from open bore holes or fully screened observation wells provide information on the overall changes in the chemical composition at a location. Actually it might be a mixture of different groundwater types. Such a sampling program monitors broad changes in the chemical composition of groundwater in an aquifer at a relatively low cost. Non-point sampling, however, is inadequate for monitoring groundwater quality changes at a local and three-dimensional scale. Therefore a different sampling design than non-point is required to monitor site-specific groundwater changes such as mixing of young and old groundwater, salt water intrusion or upconing of connate water. To ascertain a representative sample of groundwater, the standing water in the well casing has to be purged by bailing or pumping. The representativity can be checked in the field by examining readily to measure physical-chemical components (e.g. temperature, pH, EC) of the purged groundwater that should reach a constant value. Otto (1996) lists the characteristics (e.g. well and device diameter, sampling depth, sample volume, chemical alteration, relative costs) of some standard sampling devices, such as the cheap bailers and the more expensive submergible pumps.

At least three problems may seriously affect the chemical composition of a groundwater sample, namely:

1. effects of well construction and contamination with drilling fluid;
2. sample deterioration; chemistry of samples can change due to variations in temperature and gas pressure. Cool and dark storage of samples is necessary. Prompt transportation to the laboratory can improve data quality. In-situ analysis should preferably be done in the field. Standard measurements that characterise the physical-chemical composition of groundwater in the field are temperature, dissolved oxygen (DO), redox potential (Eh), hydrogen concentration (pH) and electrical conductivity (EC), and
3. careless field and laboratory practices; sample contamination caused by improper bottle washing and filtering is a main concern. Submitting blanks and duplicates should check quality of laboratory analyses.

4. Network density and sampling frequency

Ideally the design of network density and sampling frequency would be based on an optimisation of cost of monitoring and accuracy of collected and derived data related to the objectives of the network as stated in the groundwater management plan. Without a thorough understanding of the hydrogeological setting of a region, there is little chance that a network would produce adequate information (Figure 1 lower and middle part). At the start of monitoring in a region, however, a classical problem in the design of a monitoring network is insufficient hydrogeological knowledge and therefore an unknown spatial and temporal variability for each variable to be monitored, although we know that groundwater heads and chemical components possess a spatial and temporal correlation structure. However, lack of prior hydrogeological knowledge how to interpolate (in space and time) between measurements points should not hamper the beginning of monitoring. If hardly any data are available, background monitoring should start anyway by designing a network based on few existing data and expert knowledge from similar regions. After some years of data collection and if sufficient data are available, (geo-)statistical techniques can be applied to explore the spatio-temporal structure of each hydrologic variable in the region of interest (Figure 8). Eventually, under ideal condition optimisation theory and socio-economic analysis can be used in decision-making procedures to propose optimal networks to the policy makers (WMO 1994). The rest of the section is restricted to groundwater data, because they are the core of monitoring network.

Table 1: Summary of commonly used instruments to measure groundwater heads (from WMO 1994; Otto 1996)

Method	Readout device	Advantages	Disadvantages	Costs, skills
Manual				
wetted-tape or flexible steel	tape markings, sometimes with steel rule	accurate if depth is not too large	several measurements needed to find approximate depth	Low price and easy to produce and to use
Dipper	tape markings, sometimes with steel rule	accuracy within 0.01 m, fast	not-applicable in noisy environ-ments	Low price and easy to produce and to use
inertial devices	tape markings	accuracy within 0.01 m, fast and simple, to use in polluted ground-water	calibration	Moderately priced, easy to operate
two-electrode devices	tape markings	fast and simple, accuracy decreases with depth	calibration, regular maintenance, batteries	Moderately to high priced dependent on cable length, easy to operate
Automatic recording				
mechanical float recorder system	drum chart or data logger	widely applied	float lag, mechanical failure, large well diameter	High priced, regular maintenance and checking
pressure transducer	data logger	less components than float systems	temperature effect, connection with the open air, calibration	High priced, regular checking
ultrasonic sensors	data logger	less components than float systems	temperature and humidity effects; for under-water types effects of pressure, solute concentrations and air bubbles	High priced, regular checking

4.1 Network density

In arid regions the density (horizontally and vertically) of a background monitoring network probably is never dense enough to apply a comprehensive geo-statistical analysis as proposed by Van Bracht and Romijn (1985) or Stein (1998). The same is likely to apply to the specific monitoring network of a well field exploiting a non-renewable resource. Because of the vast area of the depression cone it is nearly impossible to establish an optimal network density as follows from the geo-statistical procedures. Maybe such an optimal density can only be reached at and near the well field. Under these conditions expert knowledge should be used to refine the preliminary design (Figure 8, option I), despite of its subjective nature.

For those subregions where sufficient data exist (Figure 8, option II), the effectiveness of a groundwater network in terms of network density is often defined as the accuracy of the spatial interpolation, i.e. the standard deviation of the spatial interpolation error (Van Bracht and Romijn 1985; Stein 1998). Therefore a spatial interpolation technique is required that provides not only estimates of the groundwater variables, but also of the standard deviation of the estimation error. Kriging is a well-known and suitable technique for such a purpose. Kriging is a method for estimating the value of a regionalised random variable (e.g. groundwater head or chemical component) at any point that has not been measured from a set of measurements at different locations. The semi-variogram plays a key role in the kriging procedure. The semi-variogram describes the spatial correlation structure of the regionalised variable, i.e. it shows that observations closer to each other are likely to be more similar than observation at larger distance. If the semi-variogram is known, it is only a simple routine to compute the hydrological variable on the nodes of a specified network, including the standard deviation of the interpolation error (*SDIE*), from the locations with measurements. Subsequently, a network density graph is calculated. This graph specifies the relation between the *SDIE* and the number of observation wells per unit area (e.g. 10 km^2) and is derived from the calculation of the hydrological variable on the nodes of a specified network from a decreasing number of locations with measurements. Finally, the optimal density is calculated from the network density graph and the acceptable *SDIE*. The acceptable *SDIE* need to be derived from the objectives mentioned in the groundwater management plan.

4.2 Sampling frequency

Besides a spatial variability, groundwater heads and chemical components in arid regions often show a temporal variability, which introduces the question how often a variable has to be monitored. The hydrologic variables in hyper-arid form an exception. Inter-annual variability of groundwater heads in most arid regions is large because of the irregular recharge events (Figure 2). Therefore long time series are required to understand the temporal variability. Groundwater hydrographs might show trends, periodic fluctuations, which are caused by seasonal recharge and abstractions, and stochastic components. Time-series analysis procedures can be applied to analyse these trends, periodic fluctuations and stochastic components (Figure8, option II). Detection of trends is relevant for monitoring the impact of groundwater abstraction or the deterioration of the groundwater quality. Furthermore, time series analysis is applied to determine the sampling frequency (Zhou 1992). The use of time series analysis is frequently hampered by frequently missing data, irregularities in sampling intervals, and shortness of the time series. In this situation expert knowledge is extremely valuable to estimate the sampling frequency and to refine the preliminary network design (Figure 8, option I). Although subjective, such an expert analysis already can reveal relevant information about the monitoring frequency. For example, a bore hole in Central Spain (Figure 9) shows a clear downward trend due to abstraction for irrigation and some periodic patterns, which are caused by the seasonal abstractions and recharge. In this case, a relatively low frequency is sufficient, e.g. 4 times per year with a sampling interval length dependent on the seasonal features. Rusthon (1998) illustrates a similar approach for Gujurat, Western India.

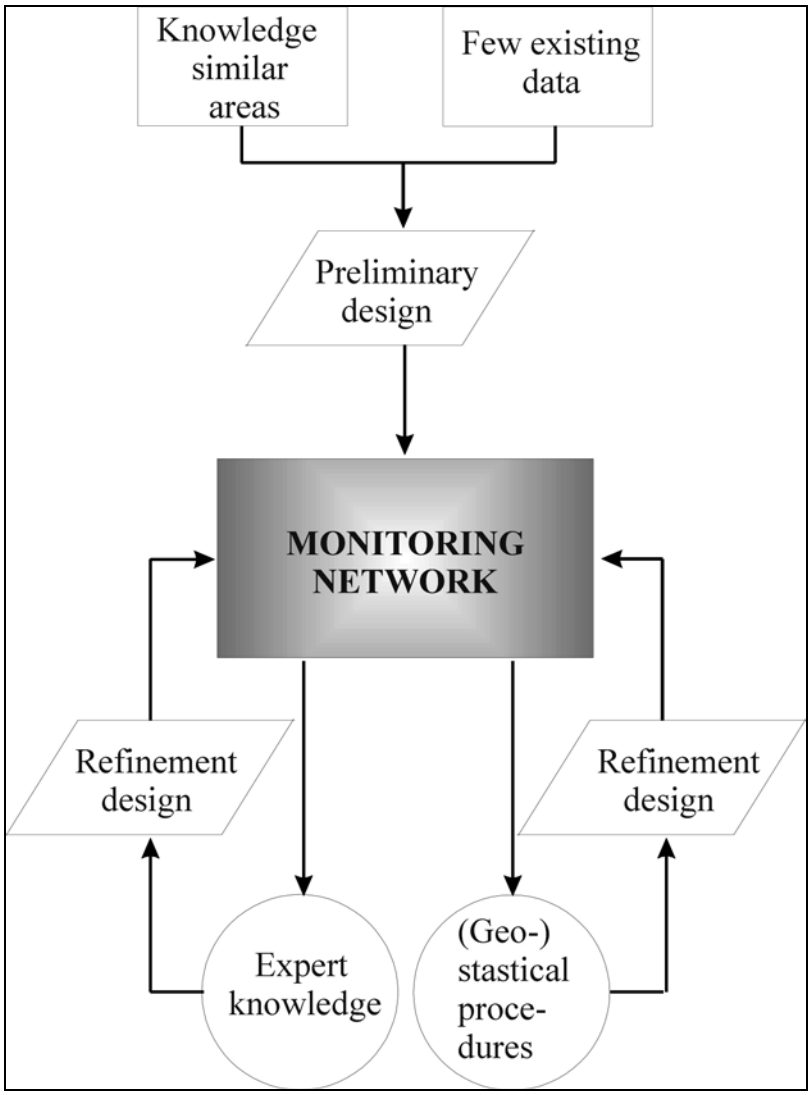


Figure 8: Determination of network density and sampling frequency (adapted from Van Lanen and Carillo-Riviera 1998).

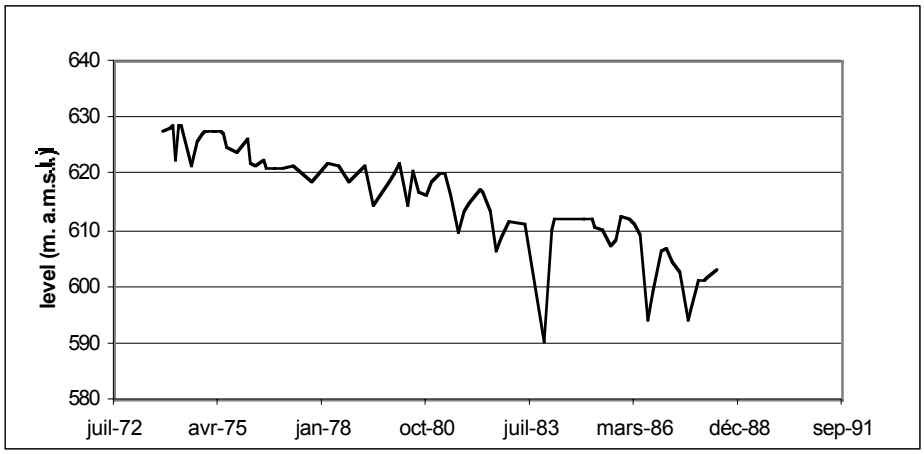


Figure 9: Groundwater hydrograph of well 2030-3002 (Upper-Guadiana basin, Spain)

In case sufficient data exits, time series analysis can be applied to optimise monitoring frequency (Figure 8, option II). The analysis of groundwater time series is confronted with some special properties of a groundwater system, i.e. the groundwater head or chemical composition at time *t* is dependent on previous values at time *t-1* (autocorrelation), and non-stationarity due to trends and periodic fluctuations. If these features are recognised the appropriate time series analysis techniques can be applied to evaluate the time series and subsequently to design the sampling frequency (e.g. Zhou 1992). First the trend (e.g. a linear or

step trend) has to be detected and removed from the time series. Then possible periodic fluctuations have to be investigated by using, for instance, spectral analysis. When the trend and the periodic fluctuations have been subtracted from the original time series, a time series of residuals remains. The latter is analysed on stochastic components. The trend, the periodic fluctuation and the stochastic component have their own sampling frequency. It depends on the objectives of the monitoring which of these frequencies is relevant.

5. Groundwater information system

Data collection from a monitoring network is useless, unless an information system is available that organises the data flow from observation or measurement to dissemination. Although most steps are obvious, many mistakes are made in this context. The following steps can be distinguished (see also WMO 1994).

5.1 Recording and transmission

At specified times the value of a hydrologic variable is recorded either in a field notebook or it is stored automatically into a data logger. Recording by skilled observers offers the possibility for an initial quality control. It is essential, in maintaining good quality observations, that the observation point itself regularly is inspected on possible malfunctioning of observation devices.

At specified times the observed data go to a data-processing centre. Copies of field notebooks are mailed, or the observer calls the centre. Automatically stored data are retrieved on site with a portable PC. In the field a first quality check can be done, by plotting the observed data in a graph, and some simple statistics (e.g. determination of minimum and maximum) can be performed. Fully automated stations can transmit the recorded data instantaneously to the centre, or observations can be held in the storage for some time (usually several months). This relative expensive option is attractive for far-off locations, but skilled staff is needed. Moreover, regular inspection of the observation point in the field is still needed. Generally, several observers do the recording and transmission of data. Therefore it should be adequately organised and well supervised, i.e. clear, concise notebooks with obvious instructions on coding, required accuracy and initial quality control, and a proper manual for each observation instrument, data logger and PC used for data retrieval.

5.2 Central data storage and quality control

After receiving the data in various forms and storage media, the initial processing can start. For instance, correction of data for zero-shift, detection of missing values and replacement with an appropriate code, conversion of stage levels into discharges and transfer of water tables or piezometric levels to meters above datum.

After having stored the raw data and some initial processing, a quality control must be carried out. Several methods are available, e.g. visual control by plotting in a graph, detection of outliners, comparison with similar time series, comparison with data of an allied hydrologic variable. Information associated to the data element, such as the date and station code, need to be checked as well. Data can be stored in data books and quality control can be done by hand, but usually it is more efficient to store the data in a computer system. Then, quality control is more feasible because it can be done automatically. Staff members with a hydrologic training can only do an appropriate quality control. Computer skills are not enough.

5.3 Processing and dissemination

After the data have been checked, descriptive statistics can be applied, such as the calculation of totals over different periods, mean, median, minimum en maximum and variation. Probability distributions can be computed giving probability of occurrence of certain events or return periods. In this stage, missing data also can be replaced by a predicted value by using statistical techniques, such as regression.

Monitored data need to be readily accessible to people dealing with the groundwater exploitation. If the data are not stored on a computer system, data books should be published. In general not all-basic data can be published, then only some processed data are provided. On request, basic data can be supplied then. If the data are available in a computer system, an on-line connection with the database is preferred. Such a connection offers the possibility to retrieve and to analyse only those data relevant for the user. Of course, the database should be well organised, described and protected.

6. Concluding remarks

- Background monitoring of a regional aquifer system should be immediately started if the exploitation of a non-renewable resource is foreseen or even earlier.
- In the pre-monitoring phase the regional aquifer system must be identified as far as possible. In case of exploitation of a non-renewable resource special attention should be paid to the recharge mechanisms, especially paleo-recharge. In hyper-arid regions with no present-day recharge the assessment of the amount of groundwater storage is extremely important.
- Groundwater systems and impact of abstraction can only be adequately identified if both physical and chemical groundwater data are collected. Furthermore vertical differences in the aquifer should not be neglected, especially in thick aquifers.
- Specific monitoring, which is characterised by a smaller area, more hydrologic variables, higher sampling frequency and density, should be introduced if the groundwater exploitation starts.
- The magnitude of the optimal yield of a non-renewable resource, which is the key factor for socio-economic development and therefore long-term sustainability, need to be continuously be supported by monitoring results.
- Groundwater monitoring networks should be supported by other networks, which collect data on direct and indirect groundwater recharge, groundwater discharge to oases, playas and intermittent streams, and subsidence.
- Redesign and redefinition of monitoring networks is a continuous process. The monitored response of a groundwater system learns a lot about the properties and hydrogeological setting of a regional aquifer system.
- An adequate monitoring plan includes groundwater modelling, which is regularly updated, to simulate aquifer response in the next abstraction phase.
- Network density and sampling frequency are usually hard to define for monitoring of non-renewable resources in arid regions. Expert knowledge based upon the limited amount of data and also obtained in similar areas, is very valuable and should be used. If sufficient data exist, (geo-) statistical techniques can successfully be applied.
- Groundwater information systems, which organise the flow of monitoring data from observation to dissemination, are a prerequisite for an adequate use of the monitoring network.
- Several methods are available to monitor groundwater quantity data. Required frequency (continuous or non-continuous), accuracy and skills, and available budget determine the best selection. Similar criteria apply to methods for quality monitoring. Additionally, diameters of wells and devices, required sample volume, and chemical alternation should be considered.
- Groundwater quality monitoring should consider the frequent occurrence of vertical concentration gradients, especially in a thick aquifer. Sampling discrete parts of the underground environment in stead of taking a mixed sample over the entire depth is a necessity for some purposes.

Acknowledgements

The research was carried out as part of the program of the Wageningen Institute for Environment and Climate Research (WIMEK-SENSE) and was in part supported by the EC Climate programme ARIDE contract EVN4-CT97-0553, Climate and Water resources**.** Some of the groundwater data were kindly provided by Centro de Estudios Hidrograficos, CEDEX (Madrid).

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THEME VI: NATIONAL AND REGIONAL POLICIES CONCERNING SUSTAINABLE USE OF WATER

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The North African aquifer system: a reason for cooperation and a trigger for conflict

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Abstract

The North African countries are experiencing severe water shortages that increase with time. Surface water supplies are insufficient to meet the escalating water demands. Nonvonventional water resources, such as seawater desalination, are technically difficult and economically expensive to develop. The need to provide for the exploding population in the region and their socio-economic development has led to increasing dependence on groundwater resources of a limided recharche. The huge and extensive North African aquifer system offers an alternative water resource to alleviate present shortages, at least for the foreseeable future. Large parts of this system, however, are shared by more than two countries. The sustainability of this precious resource depends on the peaceful cooperation among the countries involved. Several issues related to exploiting shared groundwater resources must be tackled in a mutual cooperative spirit; They include problems of common pool resources, hydrogeological uncertainties and a paradigm shift from the fragmentary conception of separately isolated aquifer subsystems to a holistic “megawatershed” approach covering the whole region. Certain strategic and managerial guidelines must be formulated. Alternative water saving development models may be considered. Regional socioeconomic integration should be encouraged. Failure to achieve these objectives enhances competition and speeds up the exhaustion and deterioration of this valuable resource. The ensuing economic problems can lead to sociopolitical strife and trigger conflicts that will potentially endanger the peace and stability in the whole region.

1. Introduction

The relation between man and his environment in North Africa (Figure 1 [not available]) had been stabilised throughout the centuries by the establishment of production systems and sociopolitical structures based on subsistence economies and a simple way of life. The introduction of misguided modern technologies and mutilated production systems imported from the highly developed economies of the humid western countries has shattered the intricate balance between the subsistence economies and the meager natural resources of the region including water. Conventionally available water resources on renewable basis are simply insufficient to meet the insatiable water demands of the present modes of economic activities and resource exploitation. Nonconventional water resources are limited in quantity and highly expensive to develop and maintain. Thus the whole region is becoming increasingly dependent on unsustainable mining of local groundwater presently threatened by depletion and pollution. Rising water demands and uncontrolled population growth compelled some countries in the region to extend groundwater resources development and exploitation to the huge southern aquifers that are mostly shared by more than two countries of the region. Proper management and rational utilization of these aquifers offer the coriparian countries a very good reason for regional cooperation and socioeconomic integration. Uncontrolled competition and individualistic approaches, however, may trigger unnecessary conflicts that can potentially disturb the peace and stability of the whole region and hamper its progress. This article is intended to clarify certain aspects of the North African aquifer system that may furnish the grounds for cooperation and eliminate misconceptions and pitfalls leading to conflict.

2. The present water resources situation

The population of North Africa increased from 49.5 millions in 1955 to 118.1 millions in 1990 and it is expected to reach more than 188 millions by the year 2025 (UNPD 1994)? The total annual renewable fresh water supplies available in the region has been estimated at the fixed rate of 113.1 Km^3/yr (PAI 1995). According to these figures, the regional annual average per capita water availability has been reduced from

2285 m^3 in 1955 to 958 m^3 in 1990 and is expected to reach 602 m^3 by the year 2025. Thus the whole region is already experiencing water scarcity that is getting severer with time.

As indicated in Tables 1 and 2, however, these regional averages mask the spatial variability of the severity of water scarcity on a country by county basis. Even within the same country water availability varies widely from one location to another. But since almost all surface water supplies have been already developed to their full potential, the above fact implies increasing dependence on groundwater resources wherever they are technically and economically feasible to develop and exploit. Most of the significant groundwater resources, however, are located in the southern Saharan and Sub-Saharan regions far away from dense population centers and important socio-economic activities. This situation posed the question of whether to move people and economic activities to where groundwater can be explored and economically exploited or to pump water and mass transfer it to where it is most urgently needed. The countries of the region are responding to both alternatives in varying degrees with more emphasis on one alternative than the other. Libya, for example, has emphasized huge mass water transfer schemes through its Great Man-made River project (Alghariami 1997). Egypt is contemplating large scale agricultural settlement projects and industrial centers in the western and south-western desert with the objective of reducing population pressure in the Nile valley and exploiting the waters of the Nubian sandstone aquifer. The other countries may start similar projects when they feel the need and get the means. But before heating up the race several issues concerning the sustainability of the North African aquifer system and its role in the future development of the region must be raised and satisfactorily settled. These include the basis for sharing a most likely non-renewable common resource, the need for its cooperative regional study and management, conflict avoidance and risk aversion, and socioeconomic integration among the countries involved.

Table 1: Total renewable available water supplies and population distribution in the North African countries.

Country	**Water supply (km^3/year)**	**Population (millions)**		
		1955	1990	2025
Egypt	58.9	24.7	56.3	87.1
Morocco	28.0	10.1	24.3	36.3
Algeria	17.2	9.7	24.9	40.4
Tunisia	4.4	3.9	8.1	11.8
Libya	4.6	1.1	4.5	12.4
Total	113.1	49.5	118.1	188.0

Source: UNDP (1994)

Table 2: Per capita renewable water availability in the North African countries.

Country	**Per capita water availability (m^3/year)**		
	1955	1990	2025
Egypt	2385	1046	676
Morocco	2764	1151	770
Algeria	1770	690	426
Tunisia	1130	540	369
Libya	4103	1017	332
Regional average	2285	958	602

Source: PAI (1995)

3. The North African aquifer system

The North African aquifer system is composed of numerous groundwater subsystems ranging in areal extent and storage volume from the several localised groundwater basins scattered along the Mediterranean coast in the north to the huge and extensive Saharan and Sub-Saharan aquifers in the south. Time and space do not allow a comprehensive hydrogeological description of these aquifers and the discussion in this article is limited to certain aspects of the major shared groundwater basins and their prospective potential as means for fostering peaceful cooperation towards sustainable development or as triggers for igniting regional conflicts and environmental disasters. These major groundwater basins, which are briefly described below, include the Dakhla-Kufra-Sarir Nubian sandstone aquifer complex shared by Egypt, Sudan, Chad and Libya,

the Murzuk-Hamada-Ghadames aquifer complex shared by Libya, Tunisia, Algeria and Niger and the Great Erg aquifer complex shared by Tunisia, Algeria and Libya.

3.1 The Dakhla-Kufra-Sarir complex

This Nubian sandstone aquifer covers an area of two million square kilometers in Egypt, Libya, Chad and Sudan. It is considered the most important groundwater system in North Africa in terms of its large storage volume, high productivity and good water quality. Its thickness may reach up to 5000 meters in Egypt and 3000 metres in Libya and Sudan. The volume of stored groundwater in the whole complex has been estimated at 75,000 km^3 of which 50,000 km^3 are located in Egypt (Hesse et al. 1987). Isotopic investigations in the same study revealed that the age of stored groundwater ranges between 10,000 and 33,000 years. In the Dakhla region of Egypt water quality changes from less than 100 ppm in the Southwest to 10,000 ppm near Siwa and Quattara depression. In the Kufra region inside Libya water quality does not exceed 300 ppm. Average transmissivity ranges between 10^{-5} and 10^{-4} m/s. Water moves in response to a hydraulic gradient towards the north and Northeast (Figure 1 [not available]) where the aquifer system discharges into the salt marshes and depression surrounding the Gulf of Sirte in Libya and the Quattara depression in Egypt. Present abstraction is estimated at 700 million m^3/yr. will soon be extracted after the final completion of phase one and phase two of the Great Man-made River project in Libya. Ahmad (1993) proposed the construction of 2000 wells distributed in the western desert to pump more than 4.7 billion m^3/yr. for future agricultural development in Egypt. The long range impacts of present abstractions and proposed future exploitation are difficult to assess at the present time. This issue will be discussed in further detail later in this article.

3.2 The Murzuk-Hamada-Ghadames complex

This regional groundwater aquifer system extends over an area of 900,000 km^2. It is surrounded by the Algerian Meguid Al-Biod fault system in the west, the Atlas flexure and the Gafsa-Madnine - Khoms Fault in the north, the Abu-Nujem-Hum Graben in the east and the basement complex outcrops in the south. This extensive aquifer system (Figure 2 [not available]) is hydrogeologically divided into two groundwater basins by the east-west axis of the Qarqaf uplift in Libya. The northern basin includes the subbasins of Al-Hamada Alhamra in Libya and Fort Polignac in the Great Erq Oriental between Algeria and Tunisia. A third sub-system including parts of western Hamada and eastern Polignac has been recently designated as the Ghadames sub-basin. The southern basin is mainly composed of the Murzuk aquifer system in Libya and Algeria and parts of the Chad basin in Algeria, Niger, and Chad. The hydrogeological formations of this complex aquifer system range from the Paleozoic to the Quaternary and are laying on a displaced impervious crystalline basement.

The Paleozoic and Nubian sandstone formations are the major water-bearing strata in this aquifer system complex. In the Murzuk basin groundwater moves in response to a Piezometric head that ranges from 700 meters in the Southwest to 250 meters near the Hun Graben in the Northeast. Transmissivity values are within 10^{-2} and 10^{-3} m^2/s and water quality is within 150 and 1000 ppm of total soluble salts. The lower confined Cambro-Ordovician sandstone aquifer outcrops at the Jabal Fezzan region where it becomes unconfined and empties in the Hamada subbasin. This aquifer will provide the abstraction of more than 800 million m^3/yr. that are planned to feed phase two of the Great Man-made River project in Libya.

In the northern Hamada-Ghadames basin the Paleozoic formations become deeper and their water quality deteriorates. The most important aquifer in this basin is the lower Cretaceous sandstone which is vertically recharged by upward flow from the Paleozoic and downward rainwater infiltration in the north-western Hamada. It may even receive some long distance recharge from the Desert. Atlas mountains in Algeria. Water movement in this aquifer is from Southwest to Northeast and water quality ranges between 1000-2000 ppm.

3.3 The Great Erg Aquifer complex

This extensive aquifer system is composed of two basic sedimentary groups; The lower group is known as the Continental Intercalcaire and extends over an area of 500,000 km^2 covering all the northern Sahara in Algeria and Tunisia. This group is generally homogeneous and represents a single continuous aquifer ranging in thickness from 250 meters to 1000 meters in the center of the basin. The water bearing strata had been filled during the Quaternary pluvials and continue to receive significant amounts of recharge by rainfall infiltration at the Erg Occidental, estimated as 8 m^3/s, by run-off seepage from the Desert Atlas estimated as 12 m^3/s and by floods from the Tadamit plateau estimated as 3 m^3/s. This significant recharge contributes to groundwater movement in two directions according to a hydrodynamic system that discharges in a large extended areas of the basin. One direction is from the north to the south and Southwest where the aquifer discharges through a large number of foggaras and wells. The other direction is towards the Tunisian coast

in the east and Northeast where water is discharged into the scattered salt depressions west of the Gulf of Quabes.

The upper group is known as the Continental Terminal and represents water bearing formations ranging between the upper Cretaceous and the Tertiary. The group extends over 350,000 km^2 to form a nonhomogeneous confined aquifer in the center of the basin. Both the upper and lower groups are hydraulically connected and unconfined at the basin boundaries. Water quality changes from less than 500 ppm near the Erg Occidental to more than 2000 ppm in the eastern region. Both groups can sustainably provide up to 2.2 billion m^3/yr in Algeria and 656 million m^3/yr in Tunisia (UNESCO 1972).

4. The reasons for cooperation

4.1 Common pool problems

The increasing dependence on these shared aquifer will soon bring about several problems that are usually related to the exploitation of common pool resources (Gardner et al., 1990). The basic characteristics of a common pool resource are its subtractability and the costly exclusion of users from exploiting the resource. Subtractability means that a unit volume of groundwater withdrawn and utilised by one country is not available for use to the other countries sharing the same resource. The high exclusion cost is self-evident since it is almost impossible to convince one or more countries to stop exploiting a shared resource without compensations in excess of, or at least equal to, their lost benefits. The only other alternative is to resort to force and, hence, armed conflicts that are politically damaging and financially expensive.

Common pool problems arise in shared water resources when a rationally optimal water use by one country leads to undesirable result as viewed by the countries sharing the same water resource as a group. There is always an institutionally feasible better strategy to collectively manage a common pool resource such as shared groundwater aquifers. The realisation of the most appropriate strategy, however, is usually hampered by the inadequate economic and institutional framework within which the resource is exploited. This inadequacy was discussed in detail by Qashu (1993)

Common pool resources have been used according to a rule of capture in an open access framework. When no single country owns the resource the sharing countries have no incentive to raise water use efficiencies and conserve for the future. Thus mere self-interest of single countries leads them to overexploiting the resource. Where the shared aquifers are non-renewable or the renewal rate is much less then that of the withdrawal, the increased competition among coriparians will eventually lead to aquifer exhaustion and water quality deterioration. To effectively manage this unsustainable situation and to avoid the development of potentially possible future conflicts, the sharing countries must cooperatively formulate a long term rational plan for exploiting their shared resource on sustainable basis. But before such a plan can be formulated on sound basis a large amount of detailed hydrogeological and socioeconomic information must be accurately collected and analysed within a regional holistic framework that encourages further cooperation and confidence building among prospective users.

4.2 Hydrogeological uncertainties

The most important uncertainties surrounding the North African aquifer system are related to regional recharge, aquifer branching and hydrogeological interconnections. Several intensive hydrogeological investigations and mathematical modelling have been made in many countries of the region with the purpose of well field designs for localised groundwater exploitation and mass water transfers. The accumulating information, however, has not been interpreted and integrated to give a comprehensive picture of the whole regional aquifer system and its ramifications, especially with respect to sources and rates of recharge.

Available information confirms that significant annual recharge is limited to the small size groundwater basins scattered along the Mediterranean coastal regions where annual precipitation exceeds 100 mm per year. Most of these subunits of the North African aquifer system may be considered as localised within-country subsystems of limited extent and transboundary mobility. These aquifers are not expected to exhibit the common problems normally related to shared resources, despite the fact that they have been severely exploited and mismanaged as a common pool resource by the local beneficiaries in each country.

As to the more significant and extensive Sub-Saharan and Saharan aquifers, it is believed that the Great Erg aquifer complex receives a significant annual recharge of no less than 700 million cubic meters per year, mostly by rainfall infiltration in the western parts and annual floods from the Desert Atlas (UNESCO, 1972). Recharge of the other significant aquifers of Murzuk-Hamada-Ghadames and Dakhla-Kufra-Sarir basin complexes is still uncertain, however. But since these aquifers are acquiring increased importance as basic water resources for mega-sized development projects such as the Great Man-made

River project in Libya (Alghariani 1997) and the other proposed and planned settlement projects in Egypt (Ahmad 1993), the question of their recharge and renewal must be satisfactorily answered before any appropriate management plan can be successfully implemented.

Conflicting conclusions have been reached by different investigators. Ball (1927) was convinced that the Nubian sandstone aquifer of Dakhla-Kufra-Sarir complex is significantly recharged by direct rainfall infiltration and run-off seepage in the high altitude regions of the Erdi-Ennedi and Tibesti mountains where precipitation ranges from 328 up to 920 mm per year. In 1934, for example, the outpost village of Aozou near Tibesti received 370 mm of rainfall that produced great floods during three days (Walton 1969). In another investigation, Sandford (1935) came to the conclusion that the Nubian aquifer receives at least 4.6 million cubic meters per day of subsurface flow from wadi Howar south of the Erdi region in Chad an Sudan. On the other hand, Hellstrom (1940) and Murray (1952) indicated that this aquifer is made up of fossil water and does not receive any recharge at the present time. The present hydraulic gradients towards the north and north-east that are responsible for the movement of large volumes of water through the Kufra-Sarir basin complex have been attributed to a variety of mechanisms. Pallas (1980) attributed them to the slow emptying of this huge area that was filled up by rainfall during the Quaternary pluvial periods. Burdon (1977) related these gradients to residual heads, basin tilting, aquifer compaction and evaporation in the discharge zones of coastal depressions. To ensure the sustainability and sound management of these aquifers the question of recharge must be decisively answered by further investigations that take into consideration all the regional variables of climate, hydrology, geomorphology, hydrogeology and socioeconomic activities. Different approaches and techniques must be used for this purpose.

4.2 The need for a new paradigm

The North African aquifer system has been traditionally divided into more than 17 separate, localised, groundwater units that are geographically distributed allover the North African region. They have been frequently investigated and conceptualised according to vertical logging data and hydrodynamic tests obtained from a few scattered boreholes that seldom represent the actual geological formations and accurately reflect their complexities. This simplistic approach normally leads to a highly idealised layered-cake model of confined or unconfined water-bearing strata rarely describe their actual hydrogeological properties. Technically speaking, however, groundwater basins can be defined as complex hydrogeological systems that are spatio-temporally open to both vertical and horizontal interactive exchanges of hydrological variables with their environments. These exchanges occur across any arbitrarily selected boundaries that are based on geography, geomorphology, hydrogeology, or administrative and political frontiers.

While the above simplified approach to groundwater basins facilitates their investigation, data collection and modelling their behavior for rational management, it should not, however, mask the fact that they are an integral part of an overall regional or continental, if not a global, hydrological cycle dominating the whole North African region. Recent realisation of this fact has led to the development of the integrated systems approach as exemplified by the « megawatershed » concept for groundwater development and management (Bisson 1995). Recent advances in satellite imagery and data acquisition technology by remote sensing have opened the way for the establishment of a highly sophisticated computer-based Geographical Information Systems (GIS) that can be efficiently used for large scale monitoring and evaluation of all the regional components of the hydrological cycle as related to the climatology and geomorphology of North Africa. A megawatershed of the North African aquifer system could be synthesised and used for the optimisation of both exploration and management of the different aquifers within the systems, especially those that are shared among the countries of the region such as the Nubian sandstone and the Ghadames aquifers. The collected data can also provide important information on the sources and amounts of local and regional recharges as well as the most productive locations for prospective future well fields. A closer look at Figure 1 [not available] emphasises the need for the regional cooperation in the detailed investigation ofthese shared aquifers.

5. Perspectives of exploitation

It is expected that the most intensively exploited regions of the North African megawatershed will be in the Nubian sandstone aquifer in Libya and Egypt. Libya has been exploiting this resource out of necessity. The coastal aquifers in the most populated north-western and north-eastern parts of the country has been overdrafted and are presently exposed to severe pollution by seawater intrusion. Surface water supplies are almost negligible compared to demand. Sociopolitical considerations necessitate the development of the strategic coastal areas surrounding the Gulf of Sirte which represents a demographic and geopolitical vacuum that separates the most economically and sociopolically important parts of the country. Comparative studies indicated that mass water transfers from the southern Kufra-Sarir and Murzuk-Hamada aquifers to

the coastal areas offer the best available option. Hence, the Great Man-made River project was conceived and implemented (Alghariani 1997). After its completion the project will abstract 1.2 billion m^3/yr from the Kufra-Sarir basin and 0.8 billion m^3/yr from the Murzuk-Hamada basin.

The problems in Egypt are of a different nature, however. The major objective is to relieve the pressure of high population density in the Nile delta and valley through creating new comprehensive development projects such as the New Valley, the Southern Wadi and the Al Ouenat in the western desert. These projects are planned to resettle millions of people in newly developed agricultural and industrial communities that will require huge amounts of water under the extremely arid desert climate (Abu-Zeid & El-Shibini 1997). Ahmad (1993) proposed the construction of 2000 wells arranged in 5 well fields that are distributed along the Libyan-Egyptian border and designed to abstract 4.7 billion m^3/yr from the Kufra-Sarir-Dakhla aquifer complex.

The increasing groundwater abstractions on both sides of the Nubian sandstone aquifer raise some questions about the sustainability of the implemented and proposed development projects and their environmental impacts, especially when the previously discussed hydrogeological uncertainties are considered. Planning for an optimum exploitation and regulating the abstracted flow is not possible at the present level of knowledge base. However, general guidelines and indicators may be followed until further comprehensive information becomes available. These guidelines and indicators which apply to both water transfers and in situ water use, must include the following strategic considerations:

1. Water transfers from this aquifer system should represent a surplus after including all the present and projected needs of the local human and natural ecosystem activities in the reasonably foreseeable future.
2. The water requirements for different uses must be reduced to the minimum possible amount that does not impair economic production efficiency and threaten environmental Integrity. All alternate water resources should be evaluated before exploiting the aquifer system. These alternate resources may prove to be more economically feasible and environmentally sound in the long run than mining a most likely non-renewable fossil water.
3. It has not been proven yet that the Nubian sandstone aquifer system is hydraulically connected with any sources of recharge in the region. Long distance secondary porosities and scanty occasional rainfall infiltration are suspected to contribute some recharge but this has not been conclusively confirmed. Thus it should be considered that pumped water from this aquifer system will not be replaced once it is withdrawn. Therefore, its development and exploitation should be undertaken with the full understanding that it will be depleted within a limited period of time depending on the aquifer storage volume that can be economically pumped and utilised. Within this period, the implemented and proposed development projects should generate economic returns sufficient to develop other water resources, such as desalination, to replace the exhausted supplies.
4. It must be recognised that a water resources development project, once made becomes essential to the welfare, if not the existence, of the people it serves. Thus the project must be continued in service or replaced by another source of water. Otherwise, all the socioeconomic activities based on the project cannot be sustained in the future. The developed water resource is a new element added to the physical environment and it certainly enhances economic development and population growth. If the developed water supply were to be discontinued due to aquifer exhaustion or any other reason, human activities based on this resource would experience catastrophic curtailment unless other alternate supplies are secured.
5. It must be realised that the development projects based on this resource will have profound economic, hydrological and environmental impacts, both during their construction and throughout their operating lifetimes. The resulting socioeconomic and environmental costs of these impacts must be born by the national or regional authorities in the countries concerned. Such costs should be recognised and mitigated in advance. They must be partially or fully compensated for by users through an efficient and effective water pricing system.

6. Water management issues

6.1 Sustainability considerations

Sustainable water resources management imply the three basic principles of achieving equity, economic efficiency and environmental integrity. To realise these objectives in the face of increasing water scarcity and rising demand for water use, the North African countries must establish water management strategies oriented towards doing more with less through the development and adoption of new innovative water saving

technologies and development policies that increase water use efficiencies with minimum environmental hazards.

As to the question of the sustainability of the water supply in these aquifers there is no clear and definite answer yet. All the present studies are based on the assumption of 50 years of continuous operation. The results obtained from simulation models and pumping tests of operating well fields in Libya and Egypt indicate that maximum regional drawdown after 50 years of continuous pumping at the design discharge for the proposed projects do not exceed 100 m in the center of well fields (Ahmad 1993). Radial influences of the predicted drawdowns are not expected to extend to more than 300 km radius. Pallas (1980) estimated that the saturated aquifers of the Kufra-Sarir basin alone can provide up to 40,000 million m^3/yr with a 1 m per year lowering of the water table over the whole reservoir extent of more than 500,000 km^2. Thus the question of sustainability seems to depend on water production costs and managerial skills rather than on available water supplies which are apparently sustainable for hundreds of years even in the absence of natural recharge of the aquifers. Sustainability can be assured if the exploited water is utilised in such a way as to provide the national economies of the countries concerned with the means and strength that enable them to develop alternate water supplies when the groundwater resources of the aquifers become uneconomical to pump or are exhausted altogether.

6.2 Environmental impacts

It must be realised that any attempt towards satisfying, even partially, the increasing food demands of an ever exploding population growth through expanding irrigated agriculture can be achieved only on the expense of the non-renewable water storage in the local aquifers. But since irrigated agriculture in the mostly arid climates of the region is essentially a high intensity evaporator, the accumulation rates of salts and other pollutants in the production environment are relatively high and must be contained within tolerable limits if sustainable irrigation in particular and the development process in general are to be maintained.

Assuming equilibrium salt precipitation and dissolution by chemical processes and negligible salt uptake and removal by biological activities, the general salt balance equation for an agricultural production environment can be expressed in its simplest form as

$$(I)\,(Ci) - (O)\,(Co) = O\,SS \qquad (1)$$

Where; (Ci) is the average salt concentration of the total annual water inputs (I) entering the production environment, (Co) is the average salt concentration of the annual outflows (O) leaving the production environment, and (O SS) is the change in salt storage within the physical boundaries of the production environment.

Equation (1) is presented here to illustrate two points upon which management strategies may be based. First, salts and other pollutants will continue to accumulate in the production environments as long as the outflow rates leaving these environments are insufficient to remove the added salts accumulating through the process of evopatranspiration. With highly mineralised groundwater this fact will eventually leads to an environmentally destructive unsustainable situation that is technically difficult and economically expensive to ameliorate. Secondly, to achieve development sustainability within production environments at any level of acceptable salt content and pollution load equation (1) becomes

$$(I)\,(Ci) = (O)\,(Co) \qquad (2)$$

Implying that a certain percentage of the water inputs utilised within the production environments must leave them with drainage outflows. This percentage can be estimated as

$$(O)/(I) = (Ci)/(Co) \qquad (3)$$

This concept has been widely used to manage salinity in irrigated agriculture.

6.3 Increasing Water Use Efficiency (WUE)

The concept of WUE is highly controversial and can be clarified only according to one's perspective within the context of several interrelated factors. When generally defined as the total benefits (material goods, services, or financial returns, etc.) produced by each unit of water used, it can be directly linked to demand water management, opportunity cost of water uses, comparative production advantages and other economic manipulations. In irrigated agriculture, however, its use has been directly related to irrigation efficiency when water is the only factor limiting crop production. Under this condition any water management practice that improves irrigation efficiency tends to increase WUE. But in all cases, both WUE and irrigation efficiency should be optimised within the constraints of achieving the maximum potential yields of crop plants and maintaining the minimum basin outflows that are required by the environmentally acceptable salt balance as

indicated by equation (3). Precautionary measures should be taken against deficit irrigation with its correlates of crop water deficiencies and soil salinization.

The highest priority has to be given to realising potential crop yields by removing any production constraints other than water. Present crop yields in the region are depressingly low. The WUE of cereal crops in Egypt, for example, is close to 0.5 kg per cubic meter of water (Higgins et al. 1988). Similar figures are expected throughout the North African countries. In modern high-input systems of irrigated agriculture, it is hoped to obtain WUE values for cereal crops approaching 1.5 kg per cubic meter. Here lies the potential for getting more with less.

6.4 Economic integration and socio-political manipulations

In view of the present and expected future water scarcities in the region, irrigated agriculture cannot grow and expand in parallel lines with the demand for food by an increasing population. When the other projected rising water demands of urbanisation and industrialisation are considered, irrigated agriculture cannot be sustained even at its present level of production if new water resources by importation or desalting are not developed.

The future concerns with water management will be most likely related to allocation problems of the limited water supplies. The economic and socio-political challenges are enormous but not insurmountable. The opportunity cost of water in the competing sectors for water use should be one of the guiding criteria for water allocation. Subsidies must be limited to the minimum equity requirements for the poor and unprivileged. Water pricing and water rights systems should change the conception of water supplies from water as a free common pool resource to water as an economic commodity in the market place. Irrigated agriculture will certainly be a looser under these institutional arrangements. But irrigation does not have to be necessarily expanded, or even maintained at its present level, as long as the reallocated water supplies from the agricultural sector to the other sectors produce economic activities for the population and sufficient financial returns for food importation from the international markets. Agriculture may be restricted to crops of relatively high and competitive comparative production advantages at the regional and global levels.

The present trends of pursuing the mirage of food security and self sufficiency through the government and donor sponsored irrigation projects of the green revolution and the lavish provision of subsidies to the private sector are major contributors to the present crisis. These trends must be reversed by reorienting the present socio-economic systems towards privatisation and the introduction and encouragement of other development models such as light industries, commerce and tourism that use less water with more economic returns. The geographical location and the favorable climate of the region are highly conducive to these activities. Linking this region with the rest of the African continent by modern transportation and communication systems will enhance this transformation. Sustainable development is a holistic approach that can be realised through several options and alternatives. It should not be restricted, however, to a single economic activity on the expense of the socio-economic system as a whole.

7. Conclusions and future prospects

The North African region is facing an increasing water scarcity that imposes severe constraints on its future development; the huge and extensive groundwater aquifer system in the Saharan and Sub-Saharan areas offers the promise of alleviating a large part of these constraints, at least until other more favorable water supply options become available. The exploitation of this shared megawatershed has already started on the basis of an incomplete and, in some cases, erroneous knowledge base. The countries involved should develop cooperative strategies and managerial policies that ensure the sustainability of this precious resource. Regional cooperation eliminates the negative hydrological and environmental impacts that may trigger conflicts and socio-political strife. Fortunately, all the countries of the region are ethnically, religiously and culturally homogeneous, a fact that fosters understanding and cooperation, if not economic and sociopolitical integration. The continuation of the presently misguided policies and incompatible paradigms of resource utilization are highly unsustainable and should be completely reconsidered and reoriented towards other development models that are more adaptable to the local conditions of meager resources and environmental aridity.

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The impact of plausible climate warming on evapotranspiration and groundwater demands

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Abstract (see full text in Arabic at the end of this volume)

The effects of plausible climate warming on potential evapotranspiration and agricultural demands (crop water requirements) are investigated. There are numerous methods for estimating potential evapotranspiration in the literature. However, in this paper it was decided to use the "Penman method" which was adopted by the Food and Agriculture Organization of the United Nations (FAO); and for the purpose of comparison the "Thornthwaite method" has also been used. The agriculture project of phase II of the Great Man-made River Project has been chosen as case study in Libya.

The amount of water needed for agriculture with and without global warming is estimated and discussed. To compare results of the different models, two climate change scenarios were used in the analysis. The results show that the effects of climate warming on evapotranspiration will increase agricultural water demands from northern to southern projects, as a result technical measures for groundwater management will be suggested.

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Integrated water policy water allocation and water use pricing critical review of national and regional options

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Abstract

As countries and regions attempt to cope with rapidly growing water problems, pressures on national governments and regional authorities for policy intervention and water sector reform grow. Societies are forced to build capacity for water management to meet social welfare and development expectations and sustain the life-supporting eco-systems. Normally this requires a wider approach with water policy as an integrated part of macro- and sector, social and economic policy. The review and reform of water policy is a multidisciplinary process involving economists, hydrologists and technicians and layers.

Supply management is costly and limited and economic management of the demand for efficient utilisation, limiting waste and bringing water into sustainable use is becoming increasingly important. The options for economic management include pricing and market approaches and also water allocation for non-economic criteria. The institutional alternatives range from market allocation, quasi-markets with public management and regulated prices to government controlled management.

The principles for water pricing are being debated between economists. Economic management requires assured legal property rights and regulation of the markets. At the base is society's position on basic economic principles on water as a public, common or as a private economic good. It is particularly important to recognise long-established cultural and ethical positions, which may support, or conflict with full-market water pricing and trade in water. *Neo-classical* economics aims at pricing for social opportunity costs, however actual practice is generally cost-based pricing. Most economic and ethic approaches and paradigms, even in different cultural economic settings support the two social and economic principles of access to water for all and efficiency-in-use for competitive agricultural and other production.

Management of groundwater comprises specific issues and problems. Groundwater is however an area where economic water allocation to use sectors and end-users is commonly practised especially at the local level.

Economic management of transboundary waters between sovereign states differs from allocation at the national and local level. In this case there is no central authority to regulate markets and secure and enforce ownership rights. Allocation and international cooperation is therefore based on voluntary action with negotiated and non-enforceable decisions between sovereign states. The management capacity at the national level remains however the critical factor for implementation of international water agreements.

The paper presents a summary of economic, and non-economic water pricing options and provides proposals for integrated economic water management also at regional level. Current trends of hydro-economics and economic options for water resources management, including ethical values and interdependencies of the society, the economy and the life-supporting eco-systems are discussed. In conclusion suggestions for an integrated policy framework linked to national level policy is put forward. As regionalisation is raising in profile and it is expected that regional economic bodies could provide a strong alternative to basin commissions. The proposed option is to build on established political and economic regional forums and draw from the financial and economic authority of regional economic communities for integrated management of both transboundary and national water resources.

Keywords

Economic water management, conflict resolution, environment, groundwater management, economic integration, regionalisation, transboundary watercourses, water allocation, markets, policy, pricing, scarcity.

1. Introduction

1.1 Adapting to water scarcity, the new dimension

Rio-UNCED, 1992 stated that: integrated water resources management based on the perception of water as an integral part of the ecosystem, a natural resource and a social and economic good", also emphasising "the implementation of allocation decisions through demand management, pricing mechanisms and regulatory measures". The principles endorsed in the 1992 Dublin and Rio-UNCED conferences that have been the subject of critical review still remain by and large to be implemented. They represented a turning point and global acknowledgement that water issues fall in the social and economic sphere rather than in a narrow water sector. The conferences also painted an uncomfortable perspective of water scarcity and underlined the need for integrated management to mitigate potential water problems and conflicts in the society.

Over recent years the scope of the water sector has widened and the multidisciplinary dimension of is generally acknowledged. With growing water stress it has become increasingly important to move from technical and administrative solutions and water resources policy to integrate water in the economy. The ultimate goal of water management, (Lundquist, et al, 1999.) is to safeguard the two basic social and environmental values:

- Ecosystem productivity and diversity, and
- Welfare and development expectations.

Society's adaptation to limited water resources involves a sequence of management interventions, normally in the three stages as presented in Figure 1:

- engineering efforts attempting to "get more water,
- end-use efficiency, to "produce more with less", through demand management measures, and finally
- allocative efficiency, for higher economic water values.

As societies enter extreme water scarcity policy intervention for efficient allocation becomes a necessity. Linkages and integration with the economy and the resulting impacts on the entire society become more critical. Countries might therefore not have the necessary capacities to adapt to water scarcity and integrate the water sector in the economy (Lundquist, et al. 1999).

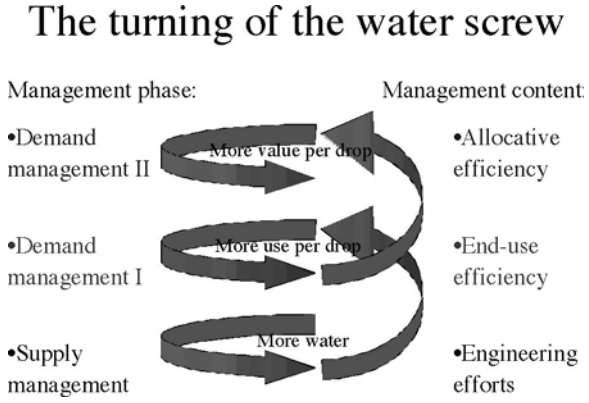


Figure 1: The different phases of water management are envisaged as the increasingly harder "turning of a screw". At each stage of social adaptation to water scarcity the social consequences and the need for input of social resources are higher. (from Lundquist, et al. 1999).

1.2 Frameworks for water policy

There is a distinction between water policy imperatives, often with far-reaching implications, such as precautionary principles in water pollution control, and policy-implementing strategies, such as regulation, institutions, planning and integration within the economy through appropriate socio-economic strategic interventions. Policy positions are not always adapted to political realities or made an integrated part of the social and economic political agendas. National policy reforms are therefore often restricted to adjustment of the institutional frameworks with only limited impact.

Water policy reflects social, political, economic and technical perspectives and is at the same time responsive to emerging issues, whilst providing a basis for planning and regulation of public and private development. For effectiveness water policy needs to be integrated with macro- and micro-economic policy and in particular agricultural policy. The evolution of efficient drilling technology also forms a threat to

sustainable allocation and use of groundwater and only recently has the need for deep aquifer management and protection been acknowledged. Deep groundwater exploitation is therefore an area where integrated policy responses are required.

Water policy must be stable with each component well founded and non-conflicting with other aspects. The risk for controversy reduces with a clear policy structure, which requires:

- a basic position of allocation, balancing for equity and efficiency, with legal provisions for ownership and right of use,
- guidelines for demand management; water pricing and water values, water entitlements, conservation agreements and education and awareness building; and as the minimum for policy implementation, and
- institutional and legal arrangements with well defined management responsibilities, authorities and with access to resources.

Water policy reforms are normally issue driven in response to critical region- and country-specific issues. Implementation of the reform requires effective and practical frameworks to ensure comprehensiveness, consistency and participation. The FAO water policy guide (FAO 1995) practised in many countries in different regions provides methods and suggestions for the water policy approaches and processes.

- *Political economy of policy making.* In any system politicians have the incentive to balance allocation of budgets in a way that preserves political support. The distributional goals make important parts of political agendas and distribution is often given higher priority than efficiency. It is also likely that a politically unacceptable distribution will be blocked. Efficiency losses to the society and the price imposed on the public could therefore be substantial, but are often disregarded as they carry only limited political currency. The affected groups might lobby for or against different policy alternatives and make policy makers aware of who are involved and what are the related potential political benefits and cost in the process. In the political environment therefore policy is often made to respond to shorter-term concerns more than to the ultimate consequences to the society. The objective of policy selection clearly differs from maximising efficiency, as dictated from rent-seeking behaviour. One practical consequence is that policy analysis and formulation, to be effective need to be adapted to the preferences of the policymakers (Just, Netanyahu et al. 1998).

1.3 Specifics of groundwater management

Effective groundwater management policy needs to focus on specific problems and to support society's ability to respond to them, such as expansion in well numbers, uncontrolled pumping for irrigation, unregulated disposal of pollutants, etc. (UN-DDSMS/ISE, 1997). Such considerations include:

- the common pool nature of the resource base,
- great variation in problems, opportunities and conditions,
- under-valuation or no pricing of groundwater,
- different objectives for use between different social and economic sections of society,
- limited scientific information, which makes monitoring difficult and costly,
- difficulty to control free riders[2],
- insufficient management capacity in relation to large and rapidly growing numbers of individual users. Economic approaches for local "water markets", have proven to be effective for efficiency, equity and resource conservation, and
- low level of public awareness.

2. Economic options for water management

Economic water management (Keith 1998) is based on the two aspects of: (a) the resources; and (b) the concept for scarcity. Water resources are available as flows and stocks. The use of flows, differently from the use of water stock in a groundwater reservoir, does not affect the availability of the resource in a future period. Flow resources can be transferred into stocks, at a capital cost, as in the case of water storage facilities, with possible gain, or loss, depending on whether the stock is efficiently, or wastefully, appropriated into flows. Economic management of flows, based on marginal costs and values, is quite straightforward,

[2] A direct reduction in wasteful use is often essential, however it is difficult to ensure compliance by users, who act as individuals. As the wells are located on private lands there is no tradition to control free riders (see footnote 3).

while optimal use of stocks, representing a physical capital, requires that impacts of current decisions on future values be taken into consideration. Water is frequently a combination resource, with linkages between flow and stock. This conjunctive aspect makes economic water management more complex.

Water scarcity that is well understood at least intuitively has specific economic attributes. The resource is not scarce, when there is enough to satisfy all consumers at a zero opportunity cost and with every individual demander satisfied. On the other hand resources for which the use by one person limits the availability for another are termed scarce and the value of the resource is the opportunity cost, or the value foregone in the allocation of the resource. For the *neo-classical* paradigm the water management objective is to maximise the value of the water resources to the society, on short and longer term.

Water may be scarce: (a) in one location, (b) at one time of year or day, (c) with respect to adequate quality and therefore its suitability for use, and (d) become more scarce over time as competing uses expand or stock is used up. The relative scarcity of water is determined by the opportunity cost, when water is used in a specific way and investments or other resources are made and traded to redistribute water from a location and/or time of "non-scarcity" to a location and/or time of "scarcity".

- *Iran: Economic groundwater scarcity management by restriction.* Rapidly increasing groundwater use in Iran that has grown from 15 to 50 million m3 between 1965-90, is resulting in lowering of water tables and water quality degradation. Agricultural uses, representing about 98%, are inefficient and an estimated 25 million m3 is wasted compared to the requirements for optimal irrigation. Quantity restrictions to efficient irrigation requirements based on set cropping patterns and resulting water availability constraints have increased the scarcity value of water at the scheme level. As a result water waste has reduced and the efficiency of use improved considerably. Individual water savings from allocated volumes belong to users for transfers at a value in local water markets, while the overall water savings are available for allocation by the government (FAO, 1997).

As demand for water grows, with resulting competition and conflict, efficient allocation of the scarce resource becomes a crucial issue for the society. The costs are long-run[3] marginal costs to meet increments in demand. In the case of water mining of aquifers, present consumption, and pollution, will put forward the date of depletion. The depletion factor of the cost of water, as the avoided future cost of supply substitution discounted to present value, should then be included in the water price. The marginal externalities as costs arising from various uses should be as low as possible. The demands for water with higher values are then served so long as water is available, and lower value uses are not.

Scarcity management of groundwater refers to basic issues, such as the ownership of the water in wells, which is linked with the common and therefore not so clearly appropriated. Customary views, in contrast to administrated created or appropriated resources, often conflict with economic management approaches, even in market economies. A *neo-classical* economic approach with private rights to support market transfers to the highest value uses might be in conflict with social traditions in a society. The argument that water is an economic good that should be allocated to the highest value uses is being increasingly challenged. Others see water as a common heritage to which all people, including the natural environment have basic and inalienable rights. Such conflicting claims appear more sharply, when there is competition for water between regions and nations with management left to collective and voluntary, negotiated decisions. It is increasingly argued that water transfers by free markets out of agriculture to urban areas could undermine the future economic possibilities of the areas of origin.

The debate is often referred to as an institutional problem. Given that water is ultimately considered as "publicly owned", the issue is how the state as the public owner can assure itself of getting the greatest benefit from its asset while, at the same time, assuring its conservation and efficient use. In fact there are few, if any, societies in which water is treated as a purely private good with the full management authority resting with private individuals. Water is with few exceptions recognised as being the property of the state. But how clear is this public aspect of water? A pure public good is both *non-exclusive*, with no capacity to control access of use and *non-rival*, where consumption by one person does not preclude somebody else to consume the same unit. *Non-rivalry* is often discussed as a "zero marginal cost", including costs of provision as well as opportunity costs.

- *Flood control - a true public good?* Flood control is often given as an example of a true public good, which will be under-provided by private markets due to the free rider4 aspect of the good. However,

[3] With unused capacity and priority to increase take-up a supply system is likely to apply limited short-term marginal costs. However as new capacity is likely to be required in the future, short term pricing will conflict with longer-term needs.

[4] Control of free riders is essential for effective management. Free riders, who benefit from management initiatives, such as improved land values from flood control or surplus supply from efficient end-use by other users, are unwilling or not explicitly required to contribute to them.

flood control related investments provide multiple other services, such as redistributing flows to more "scarce" periods and/or recreation, sometimes also transferring flooding problems to other users in other areas. The flood control aspect of water pricing is therefore far from clear. If flood control is the only service of the investment, pricing at marginal cost yields efficiently no price and therefore costs have to be recovered as lump sums. These costs are normally included in land taxes and not in water charges as a reflection of benefits to reduced flood hazards. The costs are allocated and make part of a "core" of subsidy free and incentive compatible solutions.

A public good can be scarce since there is a cost to furnishing it. Water may be non-exclusive but in most cases non-rivalry does not apply since for consumptive use the water is lost to the system and is not available to others. Water is therefore not a typical pure public good. What is then the base for the claim to water made by governments, that all waters belong to and be managed for the benefit of the society as the responsibility of the state? The argument is that water is too important to be left to individuals, and has by tradition and in practice a public common character emerging from its attributes:

- It is a fugitive resource, which has the aspects of a *common* (non-exclusive but rival) property,
- It is essential for health and life, and for the security of the society, and
- Water management is costly with declining average cost over large ranges of investment sizes and requires large and long term capital investments.

There is therefore clearly the need for policy intervention by governments to correct these market problems.

- *Economic and property aspects:* Economic aspects of water resources have since Roman times been included in public or private ownership in Western legislation. Economic principles differ in societies with other (e.g. Muslim, Hindu etc.) backgrounds, however in general the law, in reaction to the economic aspects of scarcity, supports the property and right of use aspects. Legal systems also recognise and balance social and environmental needs to protect third parties including the environment and the resource base. There is the general intent to prevent speculation and waste of the resource, with the universal legal requirement of effective and beneficial use of water rights, both at national and regional level. To this discussion could be added that, while water markets may support economically optimal use, water marketing is bound to the many peculiarities of the resource and related social, economic and environmental considerations (Solanes, Villareal 1996).

Water economic includes pricing of the resource for social opportunity costs, as direct costs and foregone present and future opportunities and externalities, applied as long-run marginal costs and sectoral water values, which define the willingness to pay for individual uses. The value-in-use stays independent of the sources and their costs. There are basic differences in the social and economic costs and the pricing of water for a flow resource as renewable surface or annually recharged shallow aquifers and a stock resource as represented by non-renewable groundwater resources. In practice water pricing is generally restricted to cost-recovery that is often limited to recurrent operation and maintenance costs.

2.1 Alternative economic paradigms

The principles for water allocation and pricing are being debated between the different competing schools of economy to which economist identify themselves. *Neo-classical* economy, for application in free markets of capitalistic firms, stands in contrast to Marxian, planned economy in countries with centralised administrations. The school of *evolutionary political economy* is increasingly challenging the *neo-classical*[5] paradigm. The evolutionary paradigm is based on fundamental social processes in contemporary time in providing goods and services to the society and is consistent with the concept of *the hydro-social cycle* (Merret, 1997). The approach is building on:

- An evolutionary, non-static approach,
- The acknowledgement of contemporary institutional realities and positions,
- A sound scientific knowledge base,
- The consideration of the interdependencies of economy and environment, and
- Open-mindedness and recognition of ethical values.

The evolutionary political economic approach is adapted to social and societal behaviour and also, as argued in the present paper, to voluntary action and collective decision-making such as in transboundary water resources management. Evolutionary political economic analysis is based on institutional realities and

[5] The static assumption that demands, as willingness to pay, does not consider the fact that the users as sectors, communities and institutions react to scarcity and increased costs through enhanced willingness to pay.

solutions and, while not in conflict with *neo-classical* theory, builds on flexible and tolerant positions on water pricing, water markets and pollution control, emphasising evolution with time, institutions and planning:

- The water price is an administered price that is not necessarily market clear. Prices are based on short-term costs projection with additional mark-ups for long-term market considerations,
- The market is still reflected through water utilities as private companies, state regulation, no cross-subsidy between user groups, metered consumption and with turnover generated by average cost tariffs. Even private water utilities with a goal of capital accumulation might abstain from pricing to expand sale volumes,
- The control of pollution requires intervention and wastewater treatment driven by regulations is costly. Therefore pollution management is often linked to enhanced environmental awareness of the general public, which will oppose to pollution-related costs to the society, and
- Strategic policy options of supplies and uses are identified in a planned water balance rather than to leave water management to the "invisible hand" of the market.

3. Water management options

Provision of water at no charge has several shortcomings, since there is no incentive to the users to conserve water and efficiency improvements depend entirely on the government. One related example is on-farm irrigation efficiency improvements, which may not always result in "wet" water savings (Seckler, 1996). The opportunity costs of water, in other uses, are in general not considered and the resource is often provided in response to political or sectoral objectives rather than for the optimal societal good. As a result of non-economic management many government water systems are in decline. There are therefore economic pressures to explore market-based options and privatisation for water management that are often driven by the need for savings and retrenchment in government.

In economic theory the most efficient allocation, maximising the welfare of both producers and consumers, is represented by the intersection of the demand, as the willingness of consumers to pay for the resource and the supply, as the marginal cost of production. Efficient allocation generates market-cleared prices, which reflect the marginal cost of production and at the same time the opportunity cost, or willingness to pay foregone.

There are two different types of economic approaches to water management. The first is to provide a basis for true market-driven allocation and prices and the second is pricing by a central authority to recover the costs of services, manage the demands and limit wasteful water use. The options for economic public management of water by the government fall in two categories: (a) private rights and water markets, and (b) public management with administered prices.

3.1 Water markets

Market allocation is a viable option for, and only for, situations where: (a) secure property rights are in place or can be established; and (b) where transaction costs are low. The state as the ultimate owner of the water gives legal entitlement to individuals or groups as usufructory rights to use water. These rights could be tradable in some form. The owners/holders of the rights will trade as long as they bring higher returns in a sale than in use. Whether the state is able to collect revenues as water fees from the rights is then of secondary importance.

Water use rights are sometimes subject to conditions of beneficial use by the holders. To protect third parties, including the environment from harm from the transaction, transfers often require government's approval. Surface- and groundwater are treated similarly, although groundwater use rights are in some cases subject to a "safe yield" determination, to consider stock extraction/recharge of the aquifer and the conjunctive use of surface and groundwater. The stochastic nature of water availability is recognised by attaching a priority, with higher value to the owner, for accessing water in periods of drought. Many countries apply water rights assignments to individuals or groups, but full property rights with free transfers and markets are rare.

The allocation and property rights in international transboundary waters are traditionally built on riparian principles developed in areas with good supply and no water scarcity. Water is getting increasingly scarce also at regional level and effective management for timely development and utilisation of transboundary watercourses is a major challenge in many regions. It can be argued that when regional water security is threatened this is a common concern where there is justification for regional guidance and policy intervention.

With secure use rights, markets can develop. If however the transactions costs exceed the gains from trade no trades will occur and markets will not exist. Those who value water more will purchase from those who value it less and as long as trades are not restricted, water will be traded until the marginal value is equal among all users. The markets will therefore assure that:

- water is used in the most beneficial (e.g. allocation from use in agriculture to industry) and best use,
- the value of water resource is maximised,
- flexibility and adaptation to change relative to these values are ensured independently if the private entity is an individual or a jointly-owned company, and
- water efficiency (e.g. allocation from consumptive irrigation-uses to non-consumptive water diversions or in-stream uses).

In many countries incentives have been provided as capital resources to farmers to invest in improved on-farm irrigation efficiency and less diversions. In this perspective however the market supports policy implementation and provides alternatives to subsidies by the state. The role of governments, in addition to securing rights and assuring low transactions costs is to provide mechanisms, through established administrative and judicial structures for the resolution of conflicts.

- *Government Agencies and Water Pricing.* Water markets are rarely seen as appropriate and there is the tendency, and also the justification, in governments to try to keep out of market based scarcity pricing. Governments favour to augment supplies before allocating the existing supplies more efficiently. Efficient allocation is more complicated at political and administrative levels and would conflict with constitutional prerogatives or cultural principles. Supply augmentation is also reasonable so long as costs do not exceed the benefits and there are market incentives to invest. In most cases however the costs outweigh the benefits and new water supplies have to be subsidised. In this case scarce capital resources have to be allocated to provide water at less than cost. Many new water schemes are done to expand or stabilise the economic conditions in the nation, both in constructing the facilities and in providing water to the ultimate users. The economic issue is whether the often-scarce capital resources invested in water could bring better returns in other alternatives. For water quantity management, from the economic perspective, the day-to-day allocation and pricing questions could stay out of Government, which could focus on the provision of public services. Where natural monopolies already exist, some regulation may be necessary, but securing access of potential market entrants to contest the market may be sufficient.

Economists often argue that economic approaches are fit to assure efficient use of the water resource and maximum economic surpluses. But the related problems are also easy to identify. Trading water withdrawals requires control and measurement of the water, of flows and volumes and in terms of both space and time. The control is costly and the investments frequently have the characteristics of natural monopolies. Water markets are also exposed to external uncontrollable effects related to e.g. commodity trade. Finally, as indicated above governments tend not to want to relinquish control over water resources, which are closely related to common values and cultural perceptions that often carry high political currency. Water is a power for economic development and distribution of income and wealth. Re-allocating water over time, in space, and between users is a significant policy instrument, which often makes part of governments' regulatory role. It also requires technical and administrative capacities that do not easily transfer to private individuals.

3.2 Quasi-market management: public management with administered prices

This category, with options that differ from a full market mechanism for water management, stretches over a wide range, from regulated private utilities selling water on a restricted market basis to full governmental allocation and pricing of water resources. The common to the approach is the use of a pricing mechanism in conjunction with water allocations.

3.3 Natural monopolies and public utilities

Often the investments required to deliver water are large with declining average costs. In this case private regulated private companies, as public utilities or government entities, often accomplish management of water. The responsibility is assigned to quasi-private entities with the management of a private company, but with characteristics of public agencies, subsidised by public funds and with public powers, such as taxing. The entities are granted the water rights by the authorities and the prices to charge are regulated. Pricing regulations, normally subject to review by regulators at the political level, provide in general for cost-based pricing. The price is the cost to supply the water and not necessarily the opportunity cost of the water or including a return to future earnings of the water itself. Prices are regulated also to include a "normal" average return on the investments made. The prices represent the marginal costs or supply based on the

assumption that pricing at the cost of provision results in an economically efficient allocation[6]. Monopoly pricing is generally less of a problem when subject to political accountability or with the market left open and contestable to other companies. Failure to examine the stock value of the investment and operation subsidies has however made cost-based pricing less than efficient. The tendency is toward prices that are too low, resulting in over-utilisation of water.

3.4 Non-economic, government allocation and pricing

When the government vends water to users, water is priced to generate revenue and to provide resources for operation and maintenance and replacement of the facilities. Governments are limited to cost-based pricing mechanisms, although marginal cost pricing approaches are used. Governments often subsidise water provision and fail to recover even the costs of the facilities and, much less any stock value of the resource. Further instances of "over-interference" of government agencies in water allocation have been fixing maximum prices and preventing trades of water in the name of equity[7], with the objective to prevent windfall gains from public investment. In the perspective of growing demands and increasing water values this is likely to cause large losses to society exceeding many times the gain accrued to original purchasers.

Governments may also revert to restrictions and legal sanctions or ration scarce water by fixed quotas and norms, monitoring compliance or charging penal charges for consumption exceeding these norms.

3.5 Water quality management and environmental allocation

Water scarcity is clearly linked also to water quality. Polluted water is unsuitable and at best temporarily not available, but toxic pollution may permanently blot out the entire resource. Unpolluted groundwater is suitable for drinking water supplies, however economic approaches do not always result in efficient allocation and protection of these valuable resources.

Economist would argue that water pollution is a result of the use of the under-priced public good of waste disposal. As water consumption and waste disposal are left free the development of water-consuming and water-polluting sectors is encouraged. Water-polluting sectors are also hard to control once powerful industries, including chemical and food processing sectors and intensive irrigated agriculture have been established (Winpenny, 1994).

With growing demands and dwindling supplies environmental economic water values-in-use are generally high. For example the opportunity cost of economic services provided annually by wetlands and lakes and rivers is estimated to $US 15 000/ha and $US 8 500/ha respectively (UNEP, 1999), corresponding 0.5 – 1.3 $US/m^3 at an annual evaporation of 1.5 m, compared to about 0.05 $US/m^3 for intensive food crops irrigation and 0.10 $US/m^3 for inland fisheries production (FAO, 1999.).

Effective economic management of water quality is not easy to achieve. The "polluter-pays" principle, while clear-cut and fair, is difficult to manage. Degradation of water quality is certain with most water uses, directly through new polluting constituents and indirectly with consumptive use. Pollution causes harm to downstream users in the form of reduced productivity, increased treatment costs, health hazards and is a threat to the sustainability of the resource.

Since there is no market in which consumers can purchase non-pollution and environmental quality and demonstrate their willingness to pay, the issues will not be addressed by the market and are therefore managed by a social authority. A principle of "victim-pays" is non-ethic and rarely applied. Even if one can draw implications about the willingness to pay (by hedonic pricing), there is no market for the quality parameter alone. Environmental quality is non-exclusive in nature, which tells against the rights to water quality (as opposed to quantity), and limits determination of what is the efficient optimal amount of quality or its opposite, pollution.

The options for water quality management are therefore normally limited to:

- a governmental entity responsible to determine optimal amounts of pollution (recipient standards) at any point in time or space, a difficult (if not impossible) task, and

[6] Based on both equation of marginal cost with supply and a "normal" return as the standard criteria for the entire economy.

[7] Nourishing the equity debate on distribution of who will benefit from added values of originally distributed water and water use rights.

- governments use mandated technology such as, emissions incentives and disincentives, marketable permits, and other tools to achieve the most effective and least-cost approach to achieving pollution control[8]. Economic tools as non-market valuation techniques are generally open to criticisms.

3.6 Review of water prices

Water price levels vary in different kinds of organisations. This variable price, see Table 1, affects the extent (in quantity or quality) of the water use. The tabled data indicate a higher price charged by private providers, and to less extent, the ease of transfer from irrigation to M&I uses with higher prices representing higher values.

While low water prices do not provide the signals to save water and use water efficiently, the policy failure from under-pricing is even more evident when comparing water costs and returns from one unit of water. Table 2 presents the costs and values of water for high value crops in water scarce countries in the NE-region. With under-priced water and lucrative but vulnerable and short-lived local and export markets for the produces, the society pays dearly for non-sustainable groundwater mining, resulting in both local, and international water conflict and environmental degradation and loss of the scarce resources. As long as the resource is under-priced farmers will however continue to collect high rents through maximum water use and with little incentive to save water.

3.7 Non-economic allocations

Non-economic and non-pricing approaches form the reference to compare and assess economic management options. Quantity allocation of water to users without charges forms a common feature in centralised government systems and planned economies. Water is allocated to meet central needs, based on a variety of societal objectives. The end-user applies what is provided but with limited incentive to conserve water. Some governments allocate water at no price to meet development targets, for production and self-sufficiency in food, to boost national employment or other social schemes. Use efficiency is the government's responsibility, however implementation by the users of more efficient technologies is not automatically encouraged. In non-economic management approaches, the opportunity cost of water in other uses, except as centrally perceived, planned and applied, has limited impact. It is critical to get shadow values right and the use of the resources is often linked with high transaction costs for administration of the systems. The focus is on production at scheme level often ignoring other dimensions of the water systems.

Table 1: Variable water prices (in US$/m^3)

Category/country	Irrigation	Munic./Ind.
PRIVATE WATER MARKETS		
Chile	0.25-1.00	0.25-1.00
France (SCP)	0.07-0.18	0.10-0.50
U.S. (Calif)	0.04-0.11	
U.S. (Utah)		0.60-0.80
Palestine		0.70-1.12
Pakistan	0.05-0.10	
Yemen	0.02-1.45	0.10-13.79
QUASI-PUBLIC/PUBLIC PRICING		
Jordan	0.01-0.04	0.12-0.35
Pakistan (canal)	0.001	
Tunisia	0.02-0.08	0.10-0.58
U.S. (Utah)	0.01-0.025	0.17-0,24
U.S. (BurRec)	0.015	
PUBLIC-NO PRICING		
Egypt	0	0.12-0.59
Saudi Arabia	0	0.04-1.07

[8] Industries, sectors or individual firms, are "point-source" polluters that often turn to pollution prevention. The available options for action, when arranged from most to least environmentally preferable often but not always go from highest to lowest cost. There are however also examples where investments to change inefficient and polluting technology have resulted in water and energy savings and improved long term competitiveness of industries.

Table 2: Near East Region: water cost and values for high value crops (US$/m^3)

Country	Water Value (1)	Water Cost (2)
Egypt	0.280	0.025
Jordan	3.40	0.10
Palestine (Jordan valley)	3.00	0.10
Syria	0.12	0.005
Yemen (Highlands)	0.22	0.035

Source: Ahmad, 1996

4. Economic aspects of water management

Economic issues critical to water management are summarised below.

4.1 Value of water

- The objective of water management is to maximise the value generated by water in the society; the value of water is therefore of main concern to water allocations,
- Water is only one input of many limiting resources to production processes (agriculture, municipal, industrial, recreational, aesthetic, etc.). Society's total benefit to all inputs should be the objective of public activities,
- Environmental values of water are problematic as non-market values of water, which are often high relative to their market values. Environmental values are often ignored in making allocations, even in markets,
- Opportunity costs of water allocation and water development must be considered. Often the costs considered by governments fro planning and pricing relative to water development are investment and O&M costs. The benefit/cost analyses seldom reflect alternative allocations of water, as well as the values of other resources (land, capital, human…). However where water is scarce, the foregone benefit from alternative uses is an economic loss paid by the society.

4.2 Water pricing

- Markets for water rights could theoretically do water pricing. However direct market approaches for water are rarely socially viable and need to be adapted to local conditions. Market-cleared pricing for water quality is problematic. Only in cases when quality can be a part of the market will the relative values to users of non-pollution be expressed.
- Water pricing could consider more than the repayment of direct costs. As this becomes controversial in some economic cultures a allocation is based on often cost-based pricing and competitiveness of (agricultural) production based on the water use,
- For natural monopolies a combination of regulation and contestability allowing competitive entry will yield efficient pricing,
- It is the government's responsibility to manage the institutional system of rights, dispute resolution, and transfers of those rights.

4.3 Water development

Economics of development of water facilities is a complicated issue for the following reasons:

- Local investments are usually not a problem and cities can often develop small storage facilities for flood protection and water supply,
- Large storage facilities, on the other hand, in which central governments are involved are usually out of the reach of private or local public resources. Under what circumstances should these developments take place and is benefit/cost analysis[9] a sufficiently convincing test for large-scale

[9] Project economists argue that financial, economic and distributional analyses used in investment planning, can provide a strong basis for evaluating projects and alternatives. The financial base reflects project viability for private investors and economic analysis assesses project-related changes in the social welfare of a region or a country. Distributional analysis complements these tests by evaluating how costs and benefits are apportioned between different groups of the population. However project analysis approaches for large water resources projects are debated issues, with the

public investment? Why are then Environmental Impact Studies (EIA) required to provide supplementary and ultimate safeguarding tests for public investment?

- In developing countries, where capital resources are scarce and interest rates are high, water developments should be viewed critically with respect to the opportunity cost of allocating the scarce capital. B/C analyses for water developments, which ignore the real interest rates could imperil development.

4.4 Social aspects

Government interventions in water rights and water markets, normally based in equity and distributional aspects, often form rationales for the government control of the resources. Governments, in many cases allocate and subsidise water to poor groups. Economics has however shown, time and again, that equity is best served by re-distributions of the income and wealth that result from efficient use[10] of the resource, and not the resource itselves. Moreover, efficient use of resources, as well as effective approach to equity is achieved through individual and not governmental choice. In summary the government role in water management should be focused on:

- market regulation to assure competitiveness and access to information,
- addressing public aspects of water such as pollution and flood control,
- as water ultimately belongs to the state, allocation of water rights, and
- equity considerations for re-distribution of income or wealth, through protection and direct social support targeted to poor and vulnerable groups.

Market mechanisms will ensure that society gains most from the use of water rights. Insistent government involvement at the implementing level would on the other hand make the resource less valuable and add uncertainty to the system. From a perspective of *neo-classical* economics, government impediments to freely negotiated transfers of rights in the name of equity are even contradictory to the objective itself.

4.5 Societal transition costs

There are clear costs as societies change from central authority to market structures. Inequity and loss of social safety for vulnerable groups are often evident. Providing for orderly transitions to and restitution of property rights to water, land, and other resources has sometimes been problematic. There are however also positive aspects. Those economies, which have moved further toward market mechanisms and privatisation are progressing more rapidly. Yields and incomes increased in Egypt, as farmers were given the choice of cropping patterns and were freed from government marketing, and China has seen rapid economic growth due at least in part to privatisation of farms.

5. Management of regional water resources

The management of transboundary waters has become an important priority to ensure water security and development in many regions. Approaches to the management of international water resources build on principles in customary and written international environmental law. The 1997 Convention (UN-ILC, 1997) accommodates two partly conflicting principles of equitable utilisation and no harm. The Convention is disputed and often seen as a compromise among legal scholars (see, Bourne, 1998), especially the substantial sections on the above principles, together with the environmental provision on protection of ecosystems and pollution control. From an economic point of view the issues are identical to those at the national level, that is how legal property rights can be assured, water markets can be regulated and how the market can consider economic and environmental values.

While hydro-politics is a rapidly emerging sector, the risk for conflict from growing water scarcity is higher within the countries than between them (Ohlsson, 1998). This observation is based on the following evolution, and turns of the “water screw”, as presented in Figure 2:

- attempts to increase supplies is the cause of international water conflict,
- these pressures can be relaxed through demand management at the local country level,

criticisms focused on limitations of the economic evaluation methods, in particular the incompatibility of discounting and sustainability and a weak introduction of the distributional considerations into decision-making.

[10] As in the case where water is made available and efficiency then assured through competition in production. In this case the principle of efficiency for water management seem to be accepted in most cultures. In-efficiency is therefore un-ethic.

- attempts to increase supply result in internal competition and water conflicts within countries, however
- the ultimate policy aspect of water conflict is to address secondary water conflict emerging from demand management practices enforced within countries.

These steps are consistent with the first and the last stage of society's adaptation to water scarcity mentioned in the introduction:

- engineering efforts attempting to "get more water",
- allocative efficiency, for higher economic water values.

It has sometimes been argued that economic approaches are also applicable for management of shared water resources. The supporting argument, to care for and efficiently use a good is non-disputable but does not consider the requirements for implementation. Without a central authority or written international law to secure and enforce property rights and regulate regional markets the management[11] approaches continue to depend on voluntary action, limited agreements and "loose" institutional arrangements for co-operation and conflict resolution between riparian states.

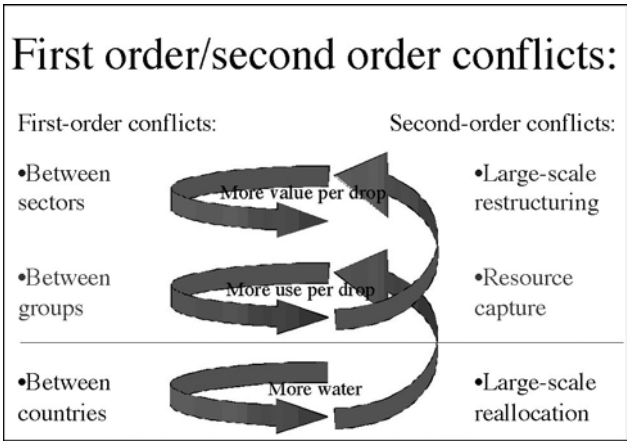


Figure 2: Allocation and or re-allocation of common and shared waters *between countries* - at the first "turning of the water screw" – carries the risk of international *first-order conflict over water*. Subsequent stages of adaptation to water scarcity, as well as to internationally agreed water sharing schemes, could trigger first-order conflicts over water between groups and sectors **within** countries. *Second-order social water conflicts, **within** countries* are caused by national policy intervention to adapt to water scarcity often related to distributional aspects. (from Lundquist et al. 1999)

In this relation it should be emphasised that *neo-classical* economic theory, which builds on legal systems to enforce contracts in markets between individuals conflicts with the fact that many exchanges also at local level are in fact informal. In transboundary water issues in particular, where decision are collective or negotiated, regional markets might not exist[12] and property rights could be contested and are not easy to establish. And even if rights are allocated, efficiency might not be the outcome of decisions by collective actions. (Just, Netanyahu et al. 1998). In this complex situation the evolutionary political economy paradigm appears as the better fit to accommodate the uncertainties related to the negotiated and collective character of the decision-making.

- *Changing scope of economic analysis:* Individual governments and the economies in a region do not form single entities but are collective in nature, and decisions represent balanced negotiated outcomes acceptable to sectors and executive, legislative and judicial powers. These facts call for introduction of alternative approaches to economic analysis in international water management, to maximise the positions of individual states and then use the agglomerated result for well-informed negotiations (see Sunding; Just, Netanyahu et al. 1998).

Similar to national policy, there are regional declarations of agreed and even binding frameworks and principles, reflecting economic and cultural conditions for management of shared surface and underground

[11] Without any superior federal authority using its fiscal and economic powers, such as in Australia (see Bjornlund, McKay, Just, Netanyahu et al. 1998), and in India (FAO, 1995b), to coerce states to overcome differences in state water policy. Establishment of "super water ministries" at regional level, such as River Basin Authorities should be carefully reconsidered as they might add to the collective structures of national governments and create additional potential interfaces of conflict.

[12] In the Nile Basin, intra-regional trade is extremely limited and virtual water in the form of grain is mainly imported from trading partners outside of the basin (FAO, 1999).

waters in a region. The provisions in 1995 SADC protocol (SADC, 1995) were initially focused on the institutional arrangements and the economic and regulatory aspects will be negotiated later. The Berlin Recommendations, (EF/DSE, 1998), recognised the challenge of efficient water use with the focus on pollution control and environmental sustainability. The priority water-sharing issue between developing economies in water scarce regions is often efficient economic allocation of quantity for agricultural production.

The Cairo Declaration of Arab Co-operation Principles Regarding Use, Development and Protection of Arab Water Resources, in 1997 (AOAD, 1997), considered water as a factor of production and a free, non-marketable natural resource that should be priced for cost-recovery. Water is made available to farmers to meet social and economic development demand of each country and guarantee the competitiveness of agricultural products. Establishment of banks for buying and selling of water contradict with the principles of a social and traditional Arab community.

In contrast, the Lesotho Highlands Water Project represents a case of international economic water allocation. Lesotho will sell water to RSA over 50 years with water royalties at a quasi-economic price level, estimated as the cost of the second most favourable supply option in RSA. In spite of the high transaction costs the scheme is seen as one of the few cases of economically efficient regional water allocation.

Regional economic efficiency has however often been attempted by linking allocation of shared waters to opportunities of mutual benefits, such as hydropower trade. In Nepal and India (Upadhyaya, 1999), where negations on the common waters have been on-going over several decades, recent initiatives for deregulation of the national energy sectors and bi-lateral power-trade have offered an opportunity for water-sharing within the context of regional economic efficiency.

As a wider example of integrated regional water management beyond the water sector a balanced mix of reciprocal flows of water and capital investment and human resources to optimise agricultural production and energy investments and support priority water conservation and environmental protection in the Nile Basin has recently been suggested for consideration by the Nile countries (FAO, 1999).

Allocative capacity at national level is critical for implementation of internationally agreed principles within the national jurisdictions[13]. Participation represents important strategy for implementation of national water policy. One dilemma is therefore the barriers to local users to penetrate international layers and provide for consultation and participation of the ultimate local private sector water users. Another critical area is to protect the poor and the environment as the most vulnerable water users at the local level.

5.1 The opportunity of regionalisation

From the neo-classical economic perspective an ideal situation would be to identify a central regional authority with powers to secure property rights, regulate markets and provide integrated economic options for efficient allocation. This represents a wider scope than the existing international RBO and commissions14 that are often lacking in political power and involvement of national governments.

5.2 Regionalization

The profile of regional governance is raising and is focusing on "good" aspects like development, economic security and stability. There are new problems emerging that can only be solved collectively drawing on common cultural backgrounds of the countries in a region. Also the perceptions of international management are enhanced and new thinking is emerging on how to approach global issues. There are also gaps, such as: (a) the jurisdictional gap; (b) the participation gap; and (c) the incentive gap. (ODI, 1999).

Regional economic commissions, markets and communities, some supported by regional parliaments[15] are growing in profile in a political environment and subject to the conditions of political economy. Regional economic frameworks are involved in all the economic and social sectors including water and natural resources management. Regional economic bodies are:

[13] In view of the delays and constraints experienced in international water allocation, the option of regional water use rights administrations, to allocate water, even for limited timeframes and subject to agreed regional economic development policies could be considered as an administrative option.

[14] The two neighbouring River Basin Organizations OMVS (Senegal) and OMVG (Gambia) that evolved from regional cooperative frameworks in the 1960s are presently re-thinking to re-enter the path of integration into regional socio-ecnomic co-operation in the West African Region.

[15] ASEAN, COMESA, East African Commission, EU, OECD and SADC; Central American Parliament and European Parliament are examples of regional economic commissions and communities some with established executive and legislative bodies.

- based on political processes and, in some cases, subject to legislative accountability,
- mandated over the entire economy including macro-aspects and social and economic sectors and therefore with the authority to handle water issues from a broader economic position,
- involved in intra-regional economic distribution, including social equity and access as well as efficient allocation of regional resources,
- involved in environmental management with policy and guidelines established in political processes,
- responsible for: regional legislation with directives, e.g. EU Water Framework Directive[16], regulations and codes of practice related to water management of national and transboundary waters of the region. Regional policy and legal provision as regional requirement for full cost-recovery in agricultural use and safety provision for compliance by members will facilitate management of transboundary waters. The regional economic bodies have the capacity to mitigate and compensate for negative impacts of regional water policy, and
- financially sustainable, with established budget allocation from regional administrative tax revenues in member countries and with overhead and management costs supported by economic sectors and activities.

To summarise, the regional economic frameworks and communities are mandated and have the capacity to:

- act from the authority of political economy,
- set policy and guidelines for water management in the region,
- integrate water and economic issues into the regional economy,
- mitigate and compensate for externalities and negative impacts of regional policy on individual member states as well as the environment, and
- monitor effectiveness and compliance with water management and environmental standards at regional and national level.

6. Conclusions

Water management needs to secure the basic values of welfare and development expectations and sustainable ecosystem productivity and diversity. The critical aspect of water management is related to water allocation and the capacity of the society to adapt to water scarcity.

Water management policy should be formulated as part of the political economy, which give importance to contemporary distributional concerns rather than economic efficiency and ultimate societal benefits. The institutions for effective policy implementation and integration of macro- and micro-economic aspects become critical for water policy reform.

Analysis of economic options for water resources management follows the schools of *neo-classical* or alternatively of *evolutionary political* economy. The basic requirement for economic management of secure property rights and market regulation are however not always in place, especially for groundwater and in transboundary shared waters.

The basic merit of economic approaches lies in consistent assessment of water costs and values at regional level (OMVS, 1999) for management with pricing and cost-sharing between sectors and countries and as basis for well-informed decisions.

Water pricing is often characterized by policy failure with under-pricing of water leading to wasteful use, collection of high rents and high externality costs to the society, the environment and to other present and future users.

Management intervention for shared transboundary resources and water conflict could ultimately trigger secondary conflict at country level. A critical factor to international water management is often limitations in allocative capacity at national level, which includes political lobbying for distribution at country level. As a result the common international waters are often left behind without being developed for the benefit of the states and the region as a whole. The hard question in situations of regional water scarcity where countries need to develop and benefit from the international water resources is therefore whether critical international water issues including water allocation can continue to be delayed and left to insecure and lengthy processes of negotiation, voluntary actions and collective decisions.

It is suggested that, with the rapid raise of regionalisation and the establishment of regional economic frameworks, the regional economic communities on the basis of growing regional economic power

[16] The framework directives address both water quantity and quality

could offer an opportunity for integrated regional water policy and management of transboundary waters. The suggestions is based at one hand on the growing awareness of the importance to integrate and manage waters as part of the entire economy, including the social and environmental aspects and on the other on the slow progress and the insufficiency and limited impact of many international basin frameworks.

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National and regional policies concerning sustainable water use

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1. Issues of groundwater sustainable use in arid zones

1.1 General

Sustainable development is generally a function of the availability of the natural resource base over time. To attain such a development, management and conservation of natural resources and orientation of technological and institutional change should be planned in such a manner as to ensure the attainment of continued satisfaction of human needs for present and future generations. Scarcity and misuse of fresh water pose a serious and growing threat to sustainable development and protection of the environment.

Identification of aspects that make development unsustainable has been more successful than the development of remedial measures that reduce or eliminate those undesirable effects. For example, if sustainable groundwater resources development is considered, it is known that excessive use of fertilizer and pesticide in agriculture may impair the use of groundwater for drinking purposes. However, responses to eliminate such a threat are usually very slow.

1.2 Definition of arid zones

A precise definition of arid zones is not straightforward. For hydrologists, arid zones are those regions characterized by low average rainfall and the absence of perennial rivers. Generally, these basic criteria are correlated with high mean annual temperatures and low atmospheric humidities giving rise to a high rate of potential evapotranspiration. Water resources in arid zones are mainly limited to groundwater, which may be derived from annual, ephemeral or fossil replenishment.

The variability of groundwater recharge in arid zones is very large. Replenishable groundwater resources may be available in regions where present day recharge is potentially very low or nil (e.g. Nubian Sandstone in North Africa). In such regions, it may not be possible to correlate directly the presence of higher rainfall belts in certain areas in recent years with the size of the local groundwater storage.

1.3 Issues of sustainable groundwater use in arid zones

The main aim of groundwater development and management is to ensure the sustainability of the resource and developments based on it. This requires, among others, a good knowledge of the system configuration and its present state which are the bases for predicting the system response to future stresses.

Geophysical investigations, which are generally considered cheap tools in defining the configuration of aquifer systems, meet several limitations in arid zones. Main reasons are: (i) the relatively dry medium in the shallow horizons which make them very resistant resulting in false resistivity; and (ii) existence of saline water in the deep horizons making the penetration of the signal difficult and its discrimination low.

A good understanding of the present state of the system is generally based on clear identification of boundaries, flow rates, and hydraulic characteristics. In arid zones, recharge is very limited and recovery time of pumping (in aquifer tests) is very long which result in a poor estimation of flow (water balance) and hydraulic properties.

2. The Nubian Sandstone Regional Aquifer System

The main concern in this paper is on regional aquifer systems that are shared by more than one country. Such aquifer systems contain generally deep-seated groundwater that is slightly renewable or even non-renewable. An example is the Nubian Sandstone Aquifer System (NSAS).

2.1 Hydrogeology of the Nubian Sandstone Aquifer System

The Nubian sandstone aquifer system (NSAS) covers SE Libya, Egypt, NE Chad, and North Sudan, with a total area of about two million square km (Figure 1). To the east, the border is formed by basement outcrops of the Nubian Plate; to the south and west by the basement outcrops of the Kordofan Block and the Ennedi or Tibesti Mountains. The northern boundary is formed by the saline-fresh water zone which is either due to recent sea water intrusion or old marine water that has not been flushed from the system.

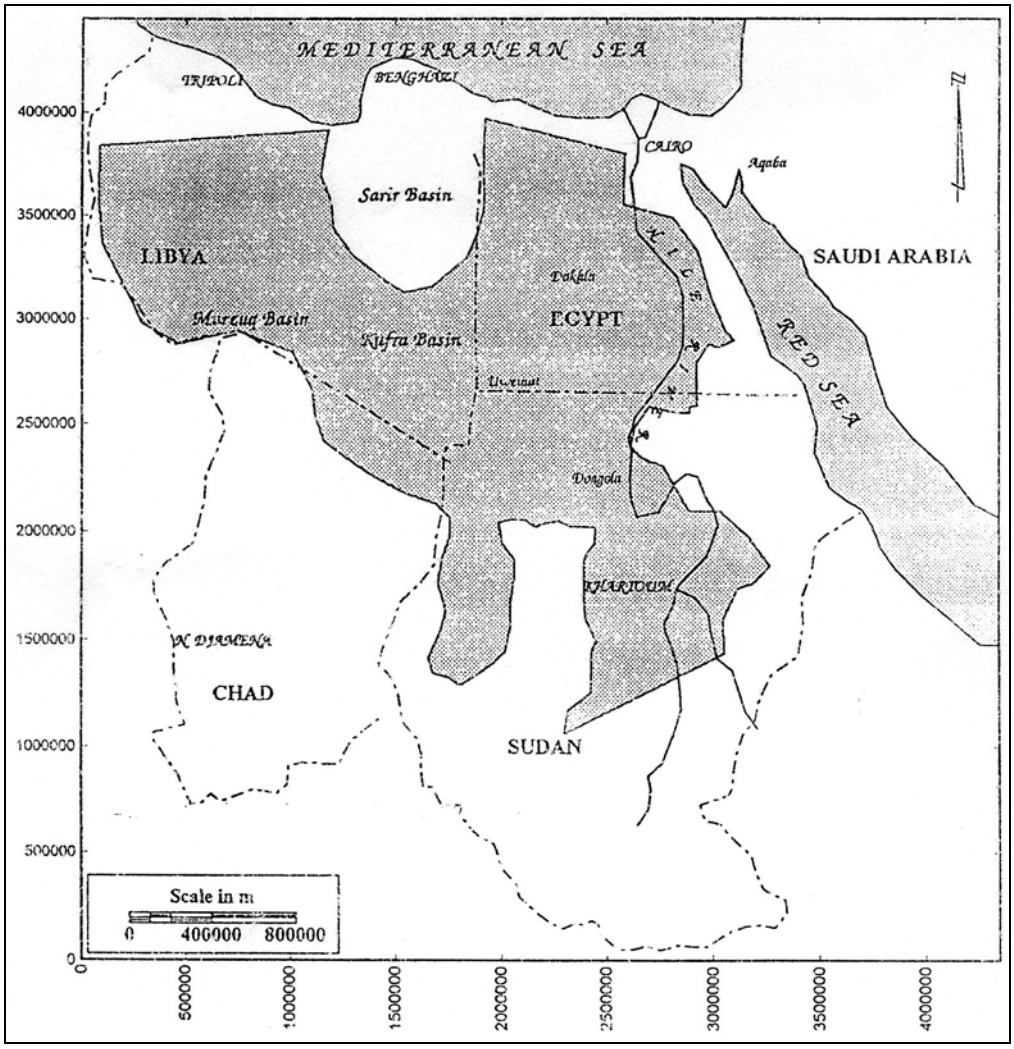


Figure 1: Extension of the Nubian Sandstone Aquifer System (Note: Northern boundary is tentative)

The NSAS is subdivided by uplifts into sub-basins, Kofra and Dakhla. These two main basins have undergone different geological developments. Based on available subsurface information, the aquifer thickness and its hydraulic conductivity are estimated to vary from 500 to 3,500 m, and from 10^{-4} to 10^{-8} m/sec, respectively (Klitzsch, 1987). The groundwater volume in storage is estimated at about 150,000 km^3.

Attempts made to estimate possible recharge to the NSAS (Based on available hydrologic and isotopic analyses), indicated that:

1. There has always been a change between humid and arid phases, each lasting for several thousand years. After an arid depletion of the aquifer, groundwater is replenished over large areas in the entire unconfined part as soon as humid climatic conditions prevail allowing for a hydrodynamic balance, as shown in Figure 2. Recent recharge and discharge can be neglected, being very limited.
2. The natural discharge does not directly depend on climatic conditions, but on the distribution of groundwaterheads. After the groundwater heads decline, natural discharge starts to diminish, approaching actual recharge.
3. The regional flow within the system is very small (Figure 3) compared with flow occurring within sub-regions due to the small magnitude of transmissivity.

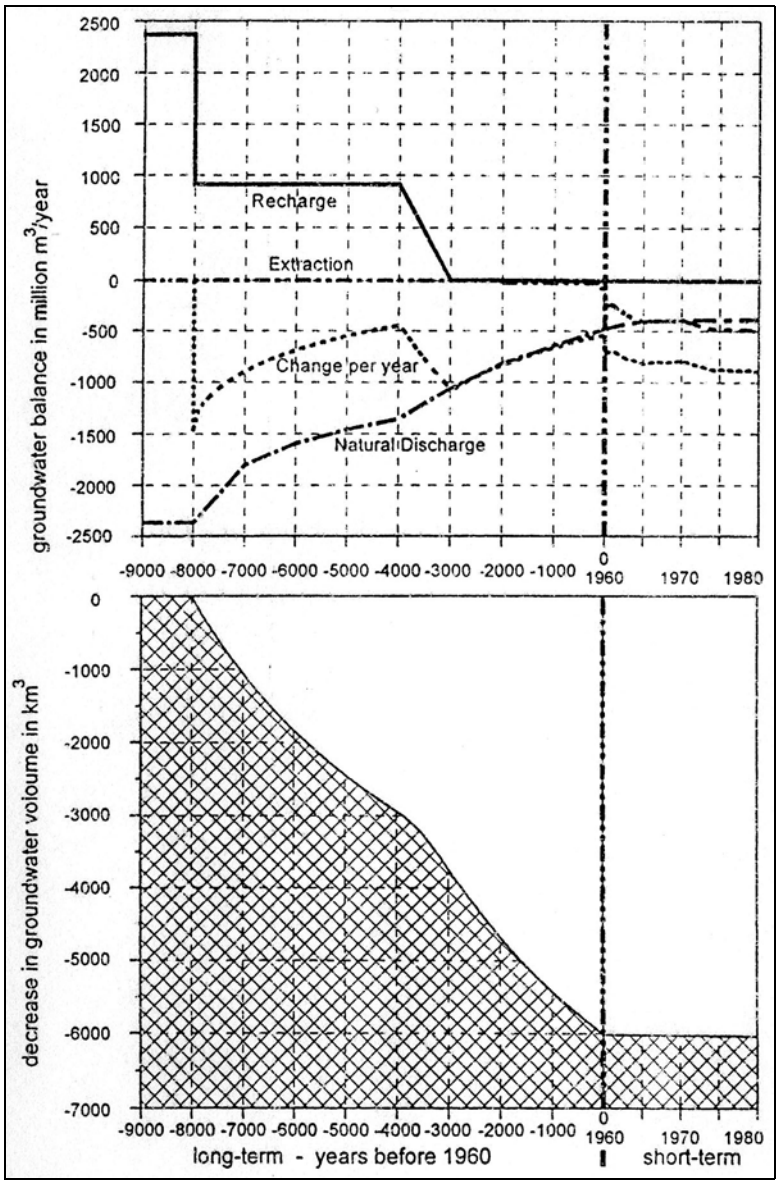


Figure 2: Groundwater Balance for the NSAS

3. A possible regional water use policy

3.1 Sustainable water use

For non-renewable water resources, the definition of sustainability is not a straightforward one. Non-renewable (fossil) water can not be treated like minerals and petrol. Water is life. This does not mean that fossil groundwater should be left under the ground.

A possible definition could be: "*the rate of withdrawal that ensures the availability of the resource for present and future generations at an economical cost*", taking into consideration poverty alleviation and protection of the environment. The time horizon is a major factor that should be determined prior to any development. Regional and national groundwater use policies are major governing factors. For example, since such aquifer systems are generally located in desert remote areas, the question to be answered first is whether people would move and settle in such areas or water be transferred to people. When the policy is to move people, other factors of importance include: (i) the period needed to settle people and start initial developmental activities, namely agricultural; (ii) the period needed to introduce other types of economic developments (e.g. agro-industries, mining, tourism, etc.); and the period needed for full production and recovery of investments.

Normally, the early stages would involve higher rates of groundwater withdrawal, which are expected to reduce after other types of development are introduced. Another factor that can be considered is the possible climatic change, or in other words, the possibility for a returned pluvial cycle.

3.2 The need for a Regional Policy

Water use policies are generally based on prevailing issues and driving forces. The policy should also consider all components of the environment. The dynamic interrelation among water resources system components impose the integrated approach on policy makers. Accordingly, a multidisciplinary approach has to be adopted in the policy formulation process. Because policies cover long term horizons and have wide spatial coverage, many uncertainties can be expected. Therefore, uncertainties have to be explicitly considered in the policy formulation rather than just being ignored. Transparency of the policy formulation process and general public approval are the key elements to achieve the policy objectives.

3.3 Driving forces

The main driving forces in the region underlain by the NSAS include:

1. Rapid population growth, rapid urbanization, internal immigration and uneven settlement patterns.
2. Aridity and continuous decline of percapita water share.
3. Decline in food share and increasing dependance on imported food.
4. Environment degradation, including depletion of natural resources.
5. Inefficient water use, including irrational use of fossil groundwater, poor water recycling practices, poor irrigation systems and practices.
6. Deteriorating rural environment.

3.4 Policy objectives

Reflecting the driving forces summarized in the precedent section, the objectives of a regional sustainable water use policy would be to:

1. Protect water resources from degradation.
2. Control water demand.
3. Enhance life style and environmental conditions, especially in the rural areas.
4. Raise water use efficiency.
5. Increase water use effectiveness by establishing appropriate dynamic plans, promoting public awareness, encouraging participation and cost recovery/sharing, enforcing legislation and mobilizing women.

3.5 The Regional Policy

For the specific case of the NSAS, studies indicated that sub-regional/local developments have very little or no effect on the dynamics of the regional system. Accordingly, the proposed regional policy would depend to a large extent on the mechanism of exchange of experiences among the countries sharing the aquifer system and the dissemination of best practices (networking). Monitoring on local as well as national scales along with stage development practices and evaluation are the best procedures to ensure proper utilization of available groundwater.

4. A possible national sustainable water use policy – Egypt case

4.1 Physical setting

The Egyptian territory is almost rectangular, with a North-South length of approximately 1,073 km and a West-East width of approximately 1,270 km (Figure 4). It covers an area of about one million square kilometers.

Geographically, Egypt is divided into four regions with the following percentage coverage of the country's area: (i) the Nile Valley and Delta, including Cairo, El Fayum and Lake Nasser (3.6%); (ii) the Western Desert, including the Mediterranean littoral zone and the New Valley (68%); (iii) the Eastern Desert, including the Red Sea littoral zone and the high mountains (22%); and (iv) Sinai Peninsula, including the littoral zones of the Mediterranean, the Gulf of Suez and the Gulf of Aqaba (6.4%).

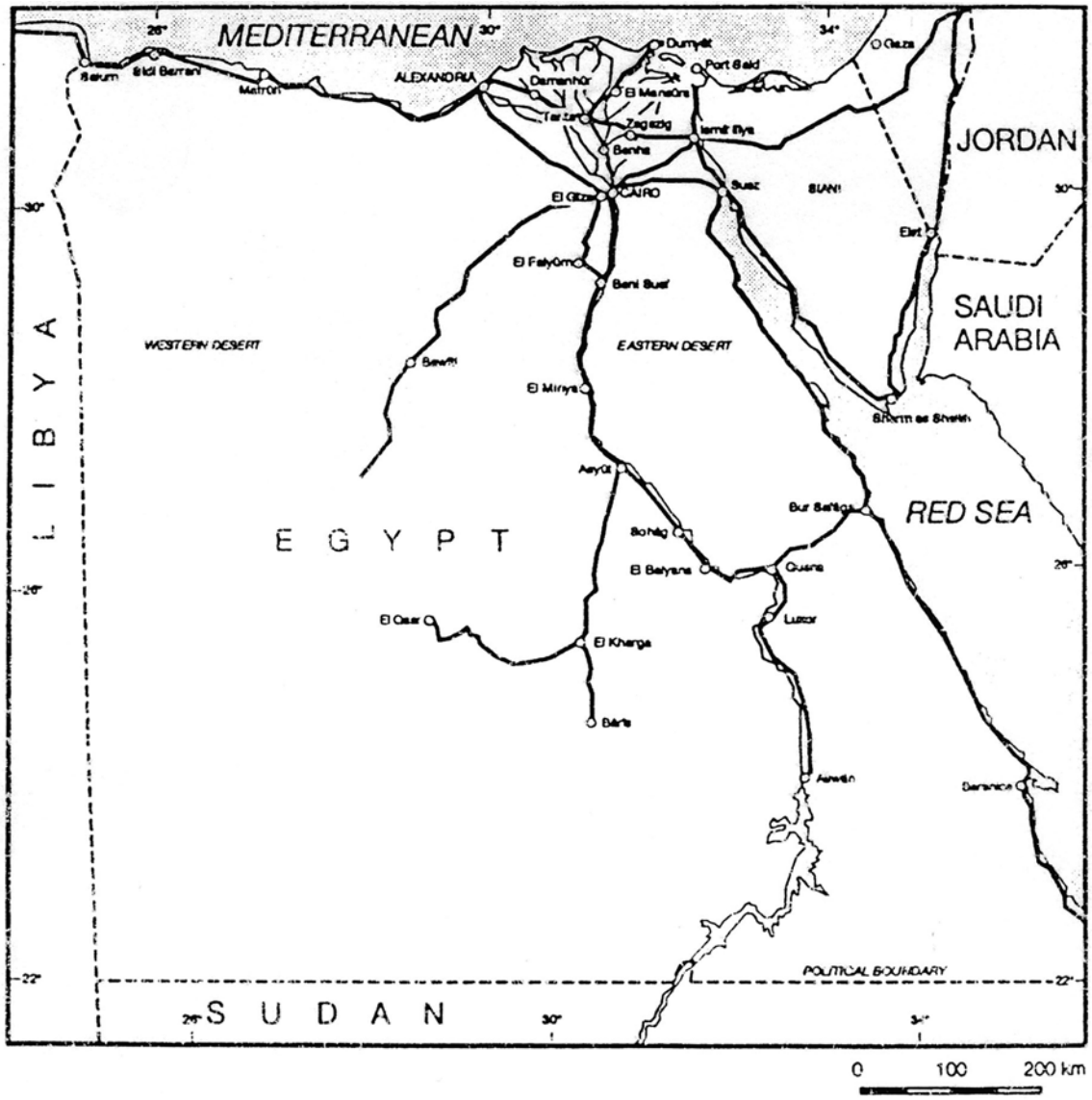


Figure 4:. General Map of Egypt

The country lies for the most part within the temperate zone. The climate varies from arid to extremely arid. The air temperature frequently rises to over 40^0 C in daytime during summer, and seldom falls to zero in winter. The average rainfall over Egypt as a whole is only 10 mm/year. Along the Mediterranean, where most of the winter rain occurs, the annual average rainfall is about 150 mm/year, decreasing rapidly inland.

4.2 Population distribution

Egypt's population is estimated at about 63 million (1998). About 11.3% of the population is concentrated in Cairo, 8.9% in the coastal governorates (including the northern portion of the Western Desert), 40% in the Delta governorates, 34.4% in the Nile valley (Upper Egypt) governorates, and the rest distributed among the remaining area of the country (Figure 5). This has resulted in an uneven population density varying from as high as 20,000 persons/km^2, in Cairo, to as low as 0.04 person/km^2, in the desert. Thus creating stresses on available facilities and on the whole environment.

4.3 Hydrogeology

The hydrogeological framework of Egypt comprises six aquifer systems (RIGW, 1993), as shown in Figure 6:

1. The Nile aquifer system, assigned to the Quaternary and Late Tertiary, occupies the Nile flood plain region (including Cairo) and the desert fringes.
2. The Nubian Sandstone aquifer system, assigned to the Paleozoic-Mesozoic, occupies mainly the Western Desert.

3. The Moghra aquifer system, assigned to the Lower Miocene, occupies mainly the western edge of the Delta.
4. The Coastal aquifer systems, assigned to the Quaternary and Late Tertiary, occupy the northern and western coasts.
5. The karstified Carbonate aquifer system, assigned to the Eocene and to the Upper Cretaceous, outcrops in the northern part of the Western Desert and along the Nile system.
6. The Fissured and Weathered hard rock aquifer system, assigned to the Pre-Cambrian, outcrops in the Eastern Desert and Sinai.

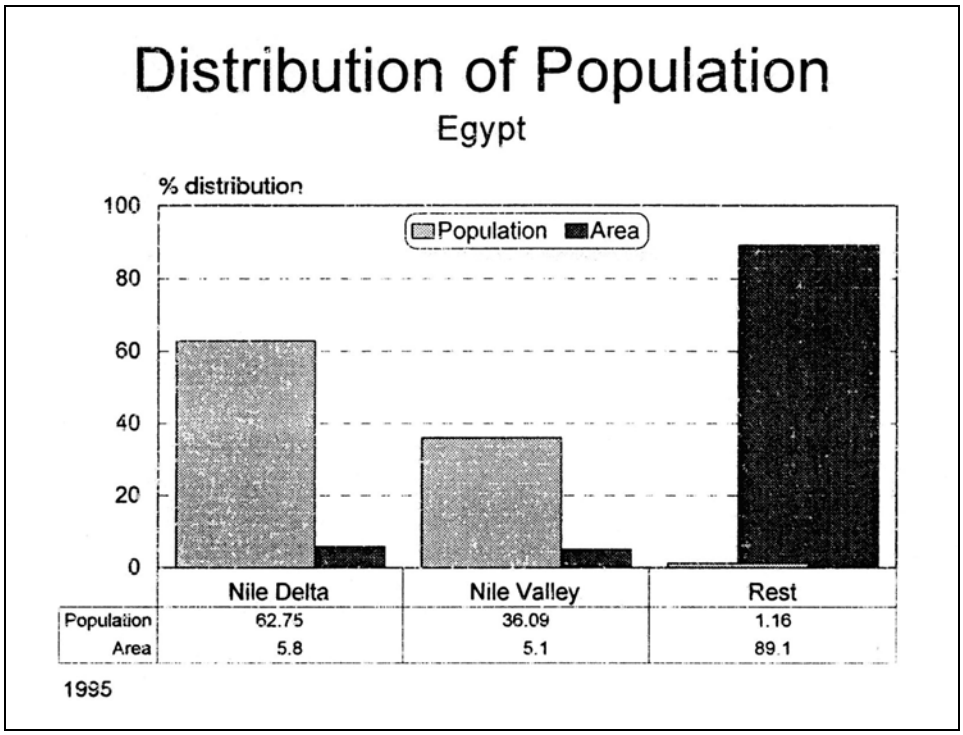


Figure 5: Egypt Population Distribution

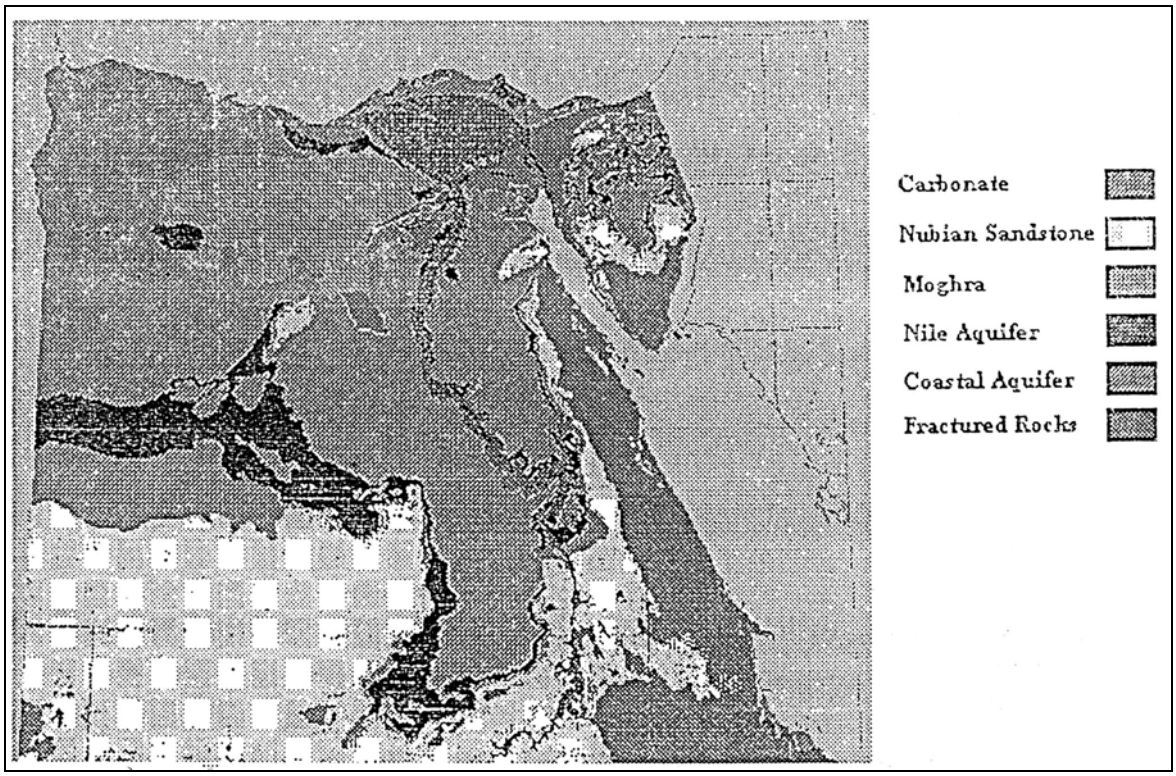


Figure 6: Surface Distribution of Main Aquifer Systems

4.4 Water resources

Egypt is an arid country with rainfall occurring only in winter in the form of scattered showers. The total amount of rainfall may reach 1.5 bcm/year; and may not be considered a reliable source of water due to its spatial and temporal variability. The main source of fresh water in Egypt is the Nile. Egypt's share from the Nile is 55.5 bcm/year. This amount is secured by the multi-year regulatory capacity provided by the Aswan High Dam and treaties made with riparian countries.

Groundwater is distinguished into two main categories, Nile and non-Nile originating. The most potential non-Nile aquifer system is the Nubian sandstone which contains non-renewable groundwater. The current total extraction amounts about 0.6 bcm/year. The only Nile-originating system is the Nile alluvium. Groundwater in the system cannot be considered a separate source of water as the aquifer is mainly recharged as a result of activities based on the Nile water, including seepage from canals and deep percolation from irrigation application (subsurface drainage). The aquifer, however, can be utilized as a regulatory/storage reservoir.

Egypt is also reusing an important portion of the effluent generated from irrigation and domestic water uses, thus increasing the overall water use efficiency, but also approaching a closed system with all possible environmental problems.

4.5 The National policy

The development of a National policy for the sustainable use of groundwater of the NSAS in Egypt derives from the General Policy of the Government (see Figure 7). The major constraint facing the implementation of the national policy is the water availability and its geographic distribution. In this respect, the Nubian aquifer system which extends over a large area of Egypt (more than 60%) can play an important role in the alleviation of pressures and population redistribution.

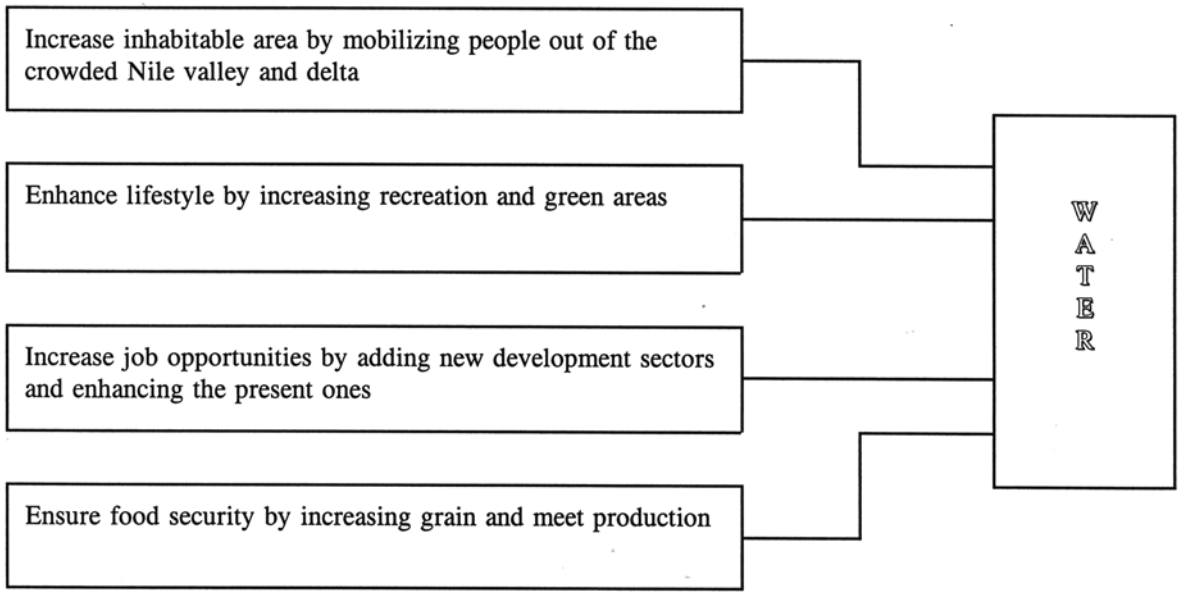


Figure 7: General National Policy of Egypt

4.6 Characteristics of the NSAS in the western desert of Egypt

The Nubian Sandstone basin in Egypt is a multilayered basin, behaving as one hydrogeologic system in hydraulic continuity with other systems located in Libya and Sudan. It is underlain by fractured basement rocks and is overlain, essentially in the area to the north of Lat. 25^{o} N, by a thick blanket of clay and carbonated rocks. The sandstone succession shows conspicuous lateral change of facies and is interbedded with some clay horizons in addition to local and thin carbonates rocks (Figure 8). The aquifer thickness varies from few meters in the south-east to more than 2,000 m in the middle (Farafra). Transmissivity, on the other hand, varies from 200 to more than 1,000 m^2/day.

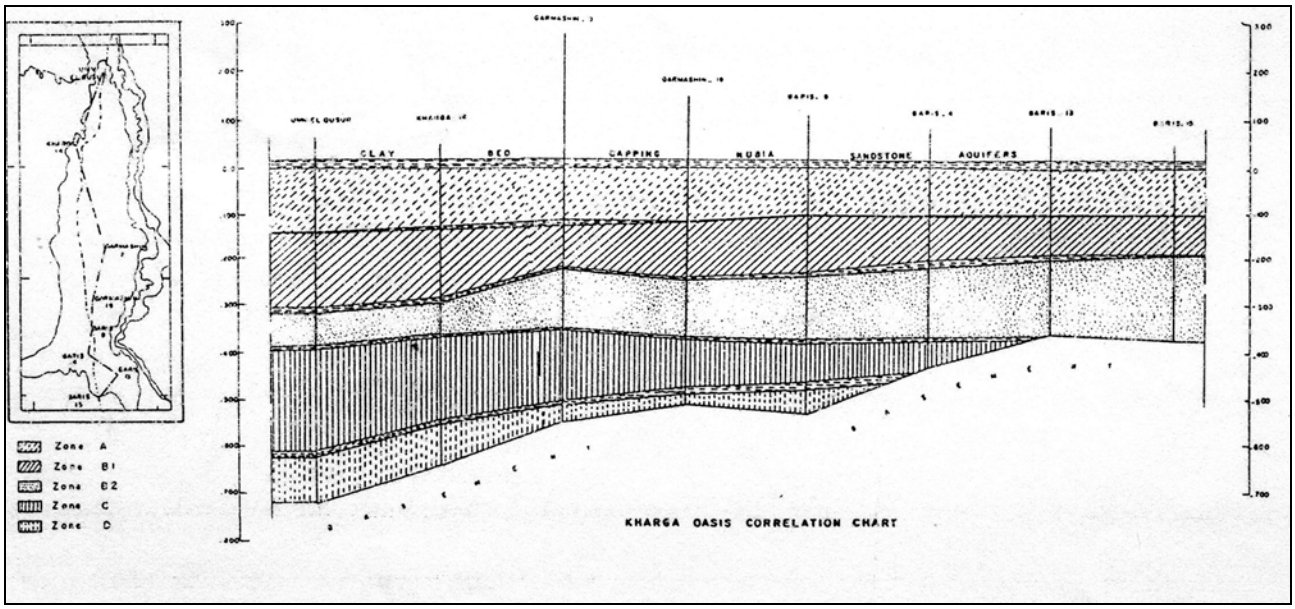


Figure 8:. A Lithological Section in The NSAS in Kharga

4.7 Present state of groundwater development and management

Historically, the population of the Western desert has consisted of nomads who depended on water driven from natural springs and shallow hand-dug wells. In the early sixties, the Government started large developments by digging deep wells. The availability of groundwater encouraged landless farmers from Upper Egypt to move to the oases. Since then, the Government took full responsibility of drilling, operating, and maintaining wells. The natives' traditions forced the continuity of old water allocation and distribution policy(ies). This situation has resulted in the abandonment of shallow wells (see examples in Figures 9 and 10), and continuous increase in the cost of water due to increased dynamic heads.

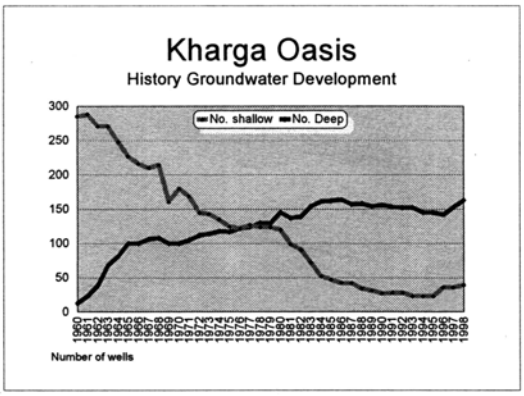


Figure 9: Change in wells number

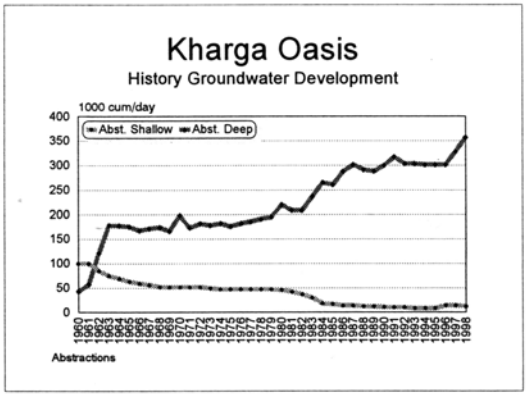


Figure 10: Change in groundwater withdrawals

4.8 Summary of water management issues

The main management issues for deep groundwater, based on previous studies and field observations, are summarized below.

1. Historic allocation of water among the natives and present remedial measures/strategies.
2. Problems facing new settlers bringing different cultures to the area (oases).
3. Poor knowledge with respect to the hydrodynamics of the system and impacts of new developments on existing schemes.
4. Lack of water user participation and lack of public awareness with respect to groundwater conservation.
5. High investment and operation costs.
6. High technologies in wells operation/control.
7. Poor land consolidation and large wastage.

Saturated Thickness of Nubian Aquifer
30 30
25 30
25 00
24 30
Legend
Main Road
Depression Boundary
200 - 300 m
300 - 400 m
400 - 500 m
500 - 600 m
600 - 700 m
Less than 200 m
Productivity of Pumping Wells from Nubian Aquifer
Main Road
Depression Boundary
Very Low (Less than 2 Cu. m /day/m drawdown)
Low (- 4 Cu. m /day/m drawdown)
Medium (4 -6 Cu. m /day/m drawdon)
High (6 - 8 Cu. m /day/m drawdown)
Very High (More than 8 Cu. m .day/m drawdown)
Groundwater Potential
Main Road
Depression Boundary
Medium
Low
None
N
8 0 8 16 Kilometers

4.9 Policy objectives

The broad policy objectives are to:

1. Ensure the sustainability of present developments and introduce new economic developments to absorb new settlers and create job opportunities.
2. Provide food security and enhance life style of natives and settlers.
3. Improve environmental conditions.
4. Alleviate poverty, and ensure equity in income distribution and regional development.

4.10 Possible strategies

The achievement of the policy objectives is not an easy task. It is generally much easier to deal with the hardware (technologies) than it is with respect to the software (people). However, a proper understanding and analysis of people perceptions is a major factor to ensure sustainable development. It is not intended here to tackle all prevailing issues. Some possible strategies/actions are summarized in the following paragraphs. With respect to water, the strategies should satisfy the long term water requirements of the community (natives and settlers, and investors) at an acceptable cost.

1. *Selection of promising areas for development*: The criteria used for the selection of promising developmental sites include: (i) relative groundwater potential (see example for Kharga Oasis in box no. 1); (ii) accessibility; (iii) land suitability; (iv) cost of water withdrawal; and (v) access to markets. Identification of groundwater potential is relative, based on various factors, namely saturated thickness and productivity.

2. *Types of development and water users*: The early development is usually agricultural as it is the main activity that ensures the mobilization of a large number of people. This also include cattle and poultry raising. The next stage would include agro-industry and water industry (bottling), tourism and mining. Other types of small scale developments include hand crafts and household productions. Each type of development involves a different category of water users ranging from small land holders (10 acres) to large investors (private and public).

3. *Acceptance of people to settle*: Small land holders are the target group because they form the largest porion of the community. They come from a category of landless farmers who are still occupied in agriculture. Those normally accept to settle if incentives are offered at the early stages of development.

4. *Appropriate practices for the increase of water use efficiency*: Various measures are needed to increase water use efficiency, including: (i) control of flowing wells; (ii) minimizing agro-chemicals and recycling of agricultural drainage water; (iii) treatment and reuse of domestic sewage; and (iv) internal treatment and recycling of industrial effluent.

5. *Wells and Well fields design*: Due to the complexity of the NSAS, the design of wells and well fields is a complicated process. It needs a proper understanding of the stratification and productivity of the various water-bearing horizons. Consolidation of wells is generally more feasible with respect to land consolidation, marketing, etc. A compromise is made to reach the most feasible set up to minimize interference between wells. This is made by scattering pumping horizons and keeping appropriate distances between wells (Figure 11).

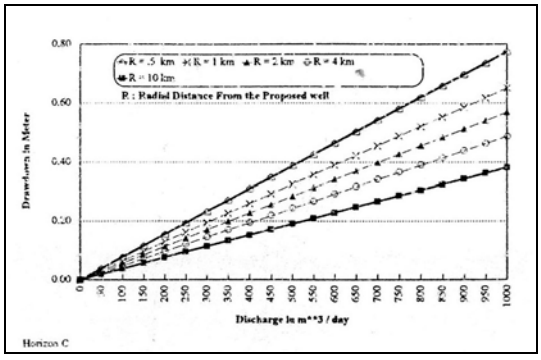


Figure 11: Estimation of distance between wells

6. *Wells operation and control*: Control of flowing wells is one of the major issues that adversely affect the water use efficiency and the environment. The introduction of new technologies should be preceded by an understanding of the hydrodynamics of the systems and the capabilities and acceptance of the operators/controllers. Since the Government plans to handle operation and control to water users, simple low-cost technologies are of high importance.

7. *Land consolidation and water shifting*: One of the main issues in the NSAS is the continuous drop in heads, and accordingly free discharge. Proper designs may help minimize this problem. Moreover, changes in water requirements along with the poor control of discharges may result in water shortages in one place and wastage in others. Strategies for shifting between agricultural spots and between users is one of the solutions to such problems.

5. Conclusions and recommendations

- Sustainable development is generally a function of the availability of the natural resource base over time.
  Management and conservation of natural resources and orientation of technological and institutional change should be planned in such a manner as to ensure the attainment of continued satisfaction of human needs for present and future generations.
- Scarcity and misuse of fresh water pose a serious and growing threat to sustainable development and protection of the environment. Problems related to sustainable water use are generally more serious in arid zones due to the hydrogeologic complexity of water systems in such zones.
  Water use policies should be based on prevailing issues and driving forces. The policy should also consider all components of the environment. Transparency of the policy formulation process and general public approval are the key elements to achieve the policy objectives.
  Sustainable water use from non-renewable aquifer systems need to be further investigated, based on the system characteristics, stage of development, and socio-economic considerations, taking into consideration poverty alleviation.
- In the case of shared water resources systems any strategy/action in one country may directly or indirectly affect the other countries. However, in the case of shared aquifers, regional flows are generally negligible compared to local flows.
  To avoid any adverse impact and conflicts that may arise, national strategies should be well investigated on their long-term impact on strategies of riparian countries. Moreover, Regional policies should benefit from national experiences and best practices.
- A National water use policy derives from the overall national policy of the country. In the case of Egypt, the main aim is population redistribution, poverty alleviation, creation of job opportunities, and food security.
  The water use policy should thus concentrate on the long-term availability of the resource, appropriate settlement of people in harmony with natives and the new environment, social welfare and sustainability of developments.

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Legal aspects of shared groundwater systems management

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Abstract

The international law of groundwater resources is dominated at present by a preoccupation with groundwaters which are connected to surface water systems, constituting a "unitary whole" and flowing into a "common terminus". Groundwaters which are un-connected to a surface water system - also known as "confined" groundwater or as "fossil water" - are however ripe for attracting rules of customary international law as authoritative as, and analoguous to, those which regulate the behaviour of States in relation to all other manifestations of groundwater. Harmonized domestic groundwater legislation adopted in response to treaty obligations or to customary obligations plays a vital concurrent role insofar as it translates the obligations of States into rights and obligations of the citizens of those same States.

Keywords
international water law, water legislation, harmonization of legislation, groundwater ownership, regulation of well-drilling, regulation of groundwater extraction, groundwater mining, groundwater pollution control, water planning, users' participation

1. Introduction

Managing groundwater resources which are "shared" by two or more States, i.e., which are bisected by an international boundary line, calls for standards of self-restraint by the States sharing such resources, and for standards of restraint by the citizens of such States. The former are set by *international law*, and consist of obligations stemming from treaties and agreements addressing groundwater resources. In the absence of treaties and agreements, loose obligations of a customary nature can be derived from the practice of States, from the limited case law available, and from the pronouncements of authoritative inter-governmental and non-governmental organizations. In addition and as a complement to international law, the *domestic legislation* of States sharing a particular groundwater resource also plays a very significant role insofar as the obligations of States stemming from international law become binding on the citizens of those same States through the instrument of domestic legislation. In particular, *harmonized legislation* can be an effective instrument of cooperation among the States sharing a particular aquifer inasmuch as such legislation will reflect criteria and parameters which are the same for all concerned States, and will thus facilitate the pursuit of a shared purpose and vision. An overview of current trends in domestic groundwater legislation is thus relevant and useful as a source of inspiration in the pursuit of harmonization goals .

2. International agreements

The practice of States, as reflected in the treaties and in the few judicial awards available on international groundwaters, reflects a preoccupation with groundwaters which are physically connected to a surface water system and which form with it a “unitary whole” “flowing into a common terminus”, being located in the territory of two or more States. Of the different manifestations of groundwater and of the circumstances under which they attract the rules of international law, virtually all are canvassed by the prevailing preoccupation with the interconnection between groundwater and surface waters.

Compared to surface systems, groundwater has often been ignored in State treaty practice concerning international fresh water resources. Still, a survey of such practice[17] uncovered treaties addressing a variety of concerns in relation to groundwater, namely, (a) the use of wells and springs in border areas, (b) frontier agreements indirectly protecting grounwaters, (c) comprehensive agreements specifically including groundwaters within their scope, and (d) agreements addressing the effects of surface water development on groundwaters, and viceversa.

[17] L.Teclaff and A.Utton, eds., *International Groundwater Law* (Oceana, New York, 1981).

Aside from the treaties concluded between or among States in relation to specific water bodies or in response to specific concerns, as categorized above, a few regional and sub-regional treaties also address groundwater. Most notable among them are the 1995 *Protocol on Shared Watercourse Systems in the Southern African Development Community (SADC) Region*, which attracts within its scope groundwaters which meet the "common terminus"standard found in the 1966 *Helsinki Rules*; and the 1992 *Convention on the Protection and Use of Transboundary Watercourses and International Lakes*, concluded by European countries under the aegis of the United Nations Economic Commission for Europe (ECE). The relevant language of this Convention, however, does not appear to emphasize so much the interconnectedness between groundwater and surface water systems as the fact of being bisected by a state boundary, as a prerequisite for attracting groundwater within its scope. Of relevance is also the 1968 *African Convention on the Conservation of Nature and Natural Resources*, insofar as it recognizes the importance of common groundwater resources in stating the obligation of the Parties to consult and, if the need arises, to set up inter-state commissions to address issues arising from the use and development of these resources shared by two or more Parties.

2.1 In particular: the 1997 United Nations Convention on the Law of the Non-navigational Uses of International Watercourses

Although it has not yet come into force, the United Nations *Convention on the Law of the Non-navigational Uses of International Watercoruses*, adopted by the U.N. General Assembly on 25 May 1997 by a majority vote, carries particular weight in any analysis of the norms of international law applicable to shared water resources. In a sense, the Convention can be viewed as a distillation of prevailing State practice, and carries the strength that accrues to it from the fact of emanating from the world community, embodied in the United Nations International Law Commission which first drafted the Convention, and in the U.N. General Assembly which subsequently adopted it. The compass of the Convention's definition of "international watercourse" and, as a result, of the scope of its provisions, in relation to, in particular, groundwater, reflects the prevailing precoccupation with the interconnection between surface and underground waters highlighted earlier. The compass is such that it is not necessary for a particular aquifer to be intersected by an international border to qualify as an international water body: it is enough for an aquifer located wholly in one State to be "related" to a river that crosses or forms an international boundary for that aquifer to attract the rules of international law reflected in those two instruments. A recharge zone in one State that feeds an aquifer in another would presumably qualify as "international" also. However, of the possible manifestations of groundwater, the so-called "confined aquifers" would not be covered by the Convention.

The principles of equitable utilization, prevention of significant harm, prior notification concerning planned measures, and protection of aquatic ecosystems, in addition to all other provisions of the Convention, apply equally to surface and underground waters "constituting by virtue of their physical relationship a unitary whole and normally flowing into a common terminus"[18]. The application of one and the same set of rules to both kinds of water resources, however, gives pause. As an authoritative commentator[19] has observed, on the one hand, the application of the above rules to aquifers may be more difficult in practice, given that the impacts of human activities on groundwater are more subtle and take longer to manifest themselves compared to surface water. Still, difficulty of practical implementation does not detract *per se* from the validity and applicability of the principles enshrined in the Convention. On the other hand, the same commentator has argued that the fact that water moves slowly underground and thus, once contaminated, it may take exceedingly long to purify itself, calls for a heightened standard of due diligence than reflected in the Convention. A standard approaching "strict liability" or "objective responsibility" for harm in one State from activities in another State affecting international groundwaters has been advocated in this connection. Also, the primacy of the equitable utilization rule over the prevention of harm rule, embedded in the Convention, has been questioned by the same commentator in the case of groundwater. Inasmuch as the former rule is capable of accommodating some harm and this is at odds with groundwater's unique vulnerability, "an exception should be made to the normal priority given to equitable utilization…over prevention of harm…"[20].

[18] Article 2(a).

[19] By Prof. S.McCaffrey, in *International Groundwater Law*, paper presented at the World Bank Seminar on "Groundwater: Legal and Policy Perspectives", Washington, D.C., 19 April 1999.

[20] *Idem*.

3. Judicial decisions

Two judicial decisions, one very old (1927) the other very recent (1997), have addressed groundwater from the standpoint of its interconnection to a surface water system. In 1927, the German Supreme Court decided a case in which two German states sued another German state and sought relief from the phenomenon of the "sinking of the Danube", or *Donauversinkung*. Even though this is a domestic case involving the states of a federation, it is relevant to the analysis here as the Court decided to apply rules of international law. The complex hydraulics of the case revolved around the fact that, at one point along its course, the Danube sinks underground and disappears. Its underground flow feeds in part the sources of another river belonging to another river basin, that of the Rhine, resulting in a net loss of water to the further course of the river, when it re-emerges to the surface. The suing states, located downstream of the point of re-emergence of the Danube to the surface, wanted the state they were suing ordered by the court to take steps with a view to correcting the sinking phenomenon and halting the loss of surface flows they suffered. The court held that, barring an agreement among the Parties providing otherwise, a State is under no duty to interfere with the natural flow of the water in favour of another State and, conversely, must refrain from altering the flow of a river to the detriment of its neighbours. The court also said, however, that the principle will not excuse a State from failing to take river-regulating measures if, as a result of its negligence, another State is injuriously affected.

In the *Gabcikovo-Nagymaros* case, decided in 1997 by the International Court of Justice and also involving the Danube river, Hungary contended, among other grounds for terminating the *Gabcikovo-Nagymaros* project and the relevant treaty it had concluded in 1977 with what was then Czechoslovakia, that the project posed ecological dangers, some of these relating to groundwaters fed by the Danube's natural course. The Court ruled that the evidence mustered by Hungary was not cogent enough to support the claim. While hinging on the legal technicality of there existing – or not – a "state of ecological necessity" which would excuse Hungary's unilateral walking out of the 1977 treaty and the obligations it entailed, the case is useful as an illustration of the difficulties a State would confront in proving prospective harm to groundwater resources, or also to surface water resources as a result of contamination of, or abstraction of groundwater in, another State.

4. The work of the international law association (ILA)

The International Law Assocation, which is an international non-governmental organization of jurists, restated in 1966 the customary rules of international water law in the widely known *Helsinki Rules on the Uses of the Waters of International Rivers*. While the *Helsinki Rules*, and those which emanated subsequently from the Association on international watercourses, are not binding on States, they carry nonetheless considerable weight accruing from the prestige and fame of the ILA and the members who drafted and adopted them. In keeping with the prevailing preoccupation highlighted earlier, the *Helsinki Rules* attract groundwater to the extent that this is connected to a surface water system. As a result, "confined aquifers" would be outside the scope of the *Rules*. Exactly twenty years later, however, the ILA adopted a set of *Rules on International Groundwaters* (also known as "Seoul Rules") , dealing specifically with all aquifers which are bisected by an international boundary and extending the *Helsinki Rules* to them. In practice, by virtue of the *Seoul Rules*, all groundwaters come within the scope of these *Rules* and of the *Helsinki Rules*, regardless of whether they are connected to a surface water system. "Confined aquifers" – or, in the language of the drafters of the *Seoul Rules*, "the structures containing deep, so-called 'fossil waters'" – are attracted as a result within the purview of the two sets of Rules. The net result is that the principles of equitable utilization, prevention of significant harm, prior notification of planned measures, protection of groundwater from pollution, and other provisions of the *Helsinki* and the *Seoul Rules* are equally applicable to groundwaters which are connected to a surface water system and to un-connected or "confined" aquifers.

4.1 In particular: the law of "confined" aquifers shared by two or more countries

It is readily apparent from the analysis made earlier of the relevant provisions of the United Nations *Convention* and of those contained in ILA's *Helsinki Rules* and *Seoul Rules*, that the two (UN Convention and ILA Rules, respectively) are at sharp variance over the treatment of groundwaters which are unconnected to a surface water system, also known as "confined aquifers" or "fossil water". Whereas the combined *Helsinki* and *Seoul Rules* do attract these within the scope of their provisions, the United Nations Convention leaves them outside its scope.

The question of "confined groundwater" was the subject of debate within the United Nations International Law Commission (ILC) during the last year of its work on the codification of the law relating to international watercourses. The then Special Rapporteur had argued in favour of including confined transboundary aquifers within the scope of the future Convention. In the end, however, the ILC rejected the Special Rapporteur's recommendation and adopted instead a *Resolution on Confined Transboundary Groundwater* which "Commends States to be guided by the principles contained in the draft articles on the law of the non-navigational uses of international watercourses, where appropriate, in regulating transboundary groundwater…". In sum, the ILC refrained from going so far as clearly stating that the principles of international water law as codified in what later became the United Nations *Convention* cover "confined groundwater". Does this imply that there is no law restraining the behaviour of States in this matter, and that each State can "mine" the resource as its policies and resources permit, regardless of the impacts these may have on neighbouring States sharing the same aquifer? The answer is surely no, as this would constitute an unreasonable reading of the ILC's reluctance to include "confined groundwater" in the scope of the future U.N. *Convention*. It has been observed[21] that, after all, it was only in the last year of the ILC's work on what later became the U.N. *Convention* that the Commission decided to include groundwater of any kind within the scope of the draft; and that extending the scope further to cover a form of groundwater that was totally un-related to surface water was more than the ILC drafters were prepared to accept. Being apparently aware of the anomaly, however, the same drafters felt compelled to go as far as implying that the rules enshrined in what later became the U.N. *Convention* offer, by apparent analogy, a solid bedrock for the guidance of States in the use of "confined" aquifers. The ILA's combined *Seoul Rules* and *Helsinki Rules* provide compelling evidence of such analogy. In contrast to the ILC drafters, however, the drafters of the *Seoul Rules* felt at liberty to carry the analogy to its logical conclusions.

As a result, it is incorrect to conclude that "confined" shared aquifers fall at present in a total legal vacuum. International law in this particular respect may have not crystallized yet to the same degree of authoritativeness as the international law of the non-navigational uses of international watercourses – i.e., the surface/groundwater "unitary whole". Significantly, at its 1998 session the ILC decided to retain "confined groundwater" as one of the topics on its agenda of work towards the codification of the rules of international law. As a result, it is to be expected that the Commission will take up this new topic once it has completed work on some other topic on its current agenda – and that, in addressing it, it will not depart significantly from the substantive direction taken in its *Resolution* mentioned earlier.

5. The role of domestic legislation and overview of relevant trends

As intimated in the Introduction, the obligations of States stemming from international treaties and agreements or from custom and expounded in the preceding sections of this paper become binding on individuals through the domestic legislation of States. As a result, ultimately this plays a critical role in the management of shared water resources in general, and of shared groundwater resources in particular. In particular, inter-State cooperation goals can be effectively pursued through harmonized legislation, i.e., legislation separately enacted by each concerned State in response to the same criteria and parameters, in pursuit of shared goals. Harmonization can be pursued as a matter of treaty obligation, with the treaty or agreement providing the criteria and parameters which the States Party must adhere to; or it can be pursued in response to the loose obligations deriving from international customary law, and result from the unilateral action independently taken by each State as it perceives a common goal and a shared purpose.

Current trends in the domestic groundwater legislation of States suggest that harmonization could be pursued along the following substantive lines:

5.1 Ownership status of groundwater

Traditionally groundwater has been regarded at law as the property of the owner of the land above. Countries following the Napoleonic Code tradition, as well as countries following the Anglo-Saxon Common law tradition, equally subscribe to the same principle. The Moslem tradition, instead, regards water as a public or communal commodity, a gift of God which cannot be owned. Only wells can be owned, whereby exclusive or priority user rights in the water accrue to the well-owners. Furthermore, the ownership of wells entails ownership of an area around the well in which new wells cannot be dug (known as *harim*, or forbidden area).

The trend nowadays is for groundwater to attract the status of public property, as a result of legislation vesting the resource in the public domain of the State (this is the approach reflected in the

[21] By Prof. McCaffrey, *ibidem*.

legislation adopted in *Spain* and in *Italy*, respectively, in 1985 and in 1994); or as a result of legislation vesting in the State superior user rights (this is the approach followed by the state of Victoria (*Australia*) as reflected in the Water Act of 1989); or as a result of legislation vesting in the State a public trust in the resources on behalf of the people, as reflected in *South Africa*'s 1998 National Water Act.

5.2 Regulation of well-drilling and of groundwater extraction

Consistent with the public property status groundwater has attracted in most countries, the legal systems have brought the digging and drilling of boreholes, the construction of wells and the extraction and use of groundwater resources under the direct control of the Government. As a result, if one wants to dig or drill bores to prospect under one's own land, or under somebody else's land, for groundwater, the Government must be first approached and a permit or authorization obtained from it, subject to terms and conditions. Equally if, following successful tests, one wants to construct a well and put it into production and start extracting and using groundwater, the Government must be first approached and a permit, licence, concession or the like instrument obtained from it, subject to terms and conditions. As a result, *user rights* accrue to the owners of the land above, or to the developers of the resource.

For ease of administration, regulatory restrictions and requirements tend to be relaxed in relation to the digging of bores and wells by hand and/or up to a maximum depth, and to the extraction and use of groundwater not exceeding certain volumes and/or for the abstractor's domestic and other household needs. For example, under the legislation of *England and Wales*, abstractors of groundwater for domestic purposes who extract up to 20 cubic meters daily are exempted from licencing requirements, with thought being given to extending the exemption to groundwater extractions for any purpose. Under the legislation of *Niger*, the extraction of groundwater for any purpose attracts simple declaration requirements, as opposed to permit requirements, if the volumes extracted do not exceed 40 cubic meters daily.

5.3 Regulation of groundwater "mining"

Where the circumstances of groundwater extraction and use result in the accelerated depletion of the resource, known also as groundwater "mining", the legal systems tend to respond through legislation providing for the establishment of control areas or districts where stricter regulatory restrictions become applicable. In Texas (United States), for instance, permitting, well spacing and setting extraction limits, become available inside areas which have been declared Groundwater Conservation Districts. Restrictions, however, are not mandatory as most of the districts which have been established have worked to get landowners to implement conservation measures voluntarily through educational programmes and by providing data on available supply, annual withdrawals, recharge, soil conditions, and waste. In Wyoming (United States), where groundwater extraction and use are governed by prior appropriation, "control areas" can be established where new applications for new groundwater extraction permits are no longer granted as a matter of course, but may be approved only after surviving a string of tests, hearings and reviews. The control area mechanism is provided for by the legislation in force in the majority of the Western states of the United States. In Spain, among several other amendments to the 1985 Water Act the Government is contemplating, one in particular provides for the declaration by the competent River Basin Authority of groundwater mining areas wherein (a) the Authority may restrict groundwater extractions until (b) a plan for the recovery of the aquifer is made and adopted. The plan will regulate groundwater extraction, including the replacement of individual extractions and of the relevant rights for a "communal" extraction and right.

5.4 Regulation of the well drilling trade

In addition and as a complement to the digging and/or drilling of bores, the construction of wells and the extraction and use of groundwater, also the exercise of the trade of well-driller tend to attract regulatory restrictions meant to scrutinize the professional competency of the individuals performing well drilling operations. This is so in most Western states of the *United States*, in *Kenya*, in *The Philippines*, in *Oman*, in *Jamaica*. With a view to strengthening the provisions laying down professional licensing requirements for well drillers, New Mexico (*United States*) legislation requires one to contract with duly licensed drillers only.

5.5 Controlling pollution of groundwater

Historically, private remedies have been utilized to address water pollution in general, and groundwater pollution in particular. Tort concepts involving negligence, nuisance and strict liability have been resorted to by injured plaintiffs, in Common law and Civil law countries alike, to seek compensation for the damages suffered as a result of groundwater contamination. These remedies continue to play a role in providing redress for groundwater pollution. However, they are available only *after* pollution has occurred, and their

successful fruition by injured plaintiffs is not without difficulty. Furthermore, it is very difficult to clean up an aquifer once it is polluted. Because of this and also of the proliferation of the sources of pollution and of their heightened pollutive potential, the legal systems virtually everywhere have been emphasizing the *prevention* of new pollution and the gradual *abatement* of existing pollution through the enactment of water pollution control legislation. With specific regard to groundwater pollution, the available legislation tends to reflect any one or any combination of the following approaches: (a) regulation, i.e., licencing or permitting, of the discharging of wastewater and other wastes on and under the ground, (b) charging for these same activities and/or (c) regulation of land use, i.e., permitting of underground storage facilities and of above-ground waste dumps and landfills, and zoning of cultivation areas sensitive to pollution from nitrates.

5.6 Planning

In response to the growing concern for the long-term viability of available water resources, countries around the globe have been resorting to planning as a preferred mechanism for informed, forward-looking and participatory decisionmaking in regard to the management and development of water resources in general, including their protection from pollution. While the legislation regulating the water resources planning process does not provide separately for groundwater planning, the aquifer can be singled out as the basic ambit of groundwater planning, on a par with the hydrographic basin. This is so in *France*, for instance, where the 1992 Water Act introduced and regulated a complex water resources planning system based on General Water Plans (S*chémas directeurs d'aménagement et de gestion des eaux: SDAGE*) covering one or more basins, and on Detailed Water Plans (*Schémas d'aménagement et de gestion des eaux: SAGE*) covering one or more sub-basins or an aquifer. With specific regard to the latter, a number of *SAGE*s are under preparation, covering designated aquifers. The aim of these instruments in preparation is, in general, the reservation of good-quality groundwater to the satisfaction of the drinking water needs of the population, or the apportionment of the available groundwater to the competing user groups on a quota basis. A distinctive feature of the French water planning system is the *participation of civil society* in the formation and adoption of the plans. Another salient feature is the *binding effect* of planning determinations on governmental water abstraction and groundwater extraction permitting. In other words, if a groundwater extraction permit is granted by Government which is at variance with the determinations of a *SAGE* or also of a *SDAGE*, it can be challenged in the courts of law and quashed. This has actually been done in connection with the grant of a permit for the extraction of groundwater for industrial use from an aquifer which the relevant *SDAGE* (for the Seine-Normandie region) had reserved for drinking water use. The decision was quashed by the court and the permit withdrawn. As a French commentator has put it, the planning instruments available under the French legislation constitute the "best tool for the conservation and protection of aquifers which is available under French law". Also in Texas (*United States*), legislation passed in 1997 instituted a complex water planning system at regional and at the state level and gave the planning determinations a binding effect which they did not use to have under previous legislation. As a result, actions by, among others, the Groundwater Conservation Districts must conform to the adopted plans.

5.7 Users' participation in decisionmaking

The participation of concerned water users in the making of decisions which affect them is widely seen and practised as an effective vehicle to build support for, and eventual compliance with, unpopular decisions. The water resources planning mechanisms and processes briefly recalled above all provide ample opportunities for water users' participation in the formation and adoption of plans, directly and through their elected representatives to the committees tasked accordingly. Under the 1997 Texas (*United States*) legislation, Regional Water Planning Groups consisting of, among others, representatives of a wide variety of water users' categories, are to prepare and submit to the state Government a Regional Water Plan for their area. In the *French* water planning system, the *SAGE*s are formed and adopted by an *ad hoc* Local Water Commission one-fourth of whose members consist of representatives of water users. Water users participate also in the adoption of the *SDAGE*s through their one-third share in the membership structure of the Basin Committees (*Comités de bassin*).

Users' participation is further fostered by legislation governing the direct involvement of water users in the management of groundwater resources in areas which experience particular problems, notably, accelerated groundwater depletion (also known as groundwater mining) and/or severe groundwater pollution. In Texas (*United States*), Groundwater Conservation Districts, traditionally formed on petition and vote by affected property owners, tend now to be formed also at Government's instigation of a property owners' election to create a district in so-called "critical areas", i.e., areas experiencing overdraft, insufficient supply, or contamination, based on studies conducted by Government. In *Spain*, the proposed amendments to the 1985 Water Act mentioned earlier provide, among others, for the compulsory formation of Water Users' Groups from among the users of an aquifer, in particular when the aquifer is, or is at risk of becoming,

overexploited. These groups are to share in the groundwater management responsibilities of the River Basin Authorities and, in particular, in the management and policing of groundwater extraction rights.

6. Conclusions

International law in relation to groundwaters which are unconnected to a surface water system, also known as “confined aquifers” or “fossil water”, is in an evolutionary state. A sharp variance exists in this regard between the United Nations *Convention* and the ILA’s *Helsinki Rules* and *Seoul Rules*, with the latter attracting "confined aquifers" within the scope of their provisions and with the United Nations Convention leaving the same outside its scope. However, it would be premature to conclude that there is no law restraining the behaviour of States in this matter, and that each State can “mine” the resource as its policies and resources permit, regardless of the impacts these may have on neighbouring States sharing the same aquifer. The law on this specific subject is probably ripe for its enunciation by the ILC, along lines which will not depart significantly from the United Nations *Convention*.

The domestic legislation of States sharing an aquifer plays a vital role in translating the international obligations of States under international law into the domestic rights and obligations of their citizens. Harmonized legislation, in particular, is an effective instrument of inter-State cooperation in pursuit of common goals and a shared vision, whether these be mandated by a treaty or agreement, or by the loose obligations stemming from customary international law. The comparative analysis of contemporary domestic groundwater legislation suggests that groundwater is fast losing the intense private property connotation it has traditionally had and that user rights in it accrue from a grant of the Government. The public domain status of groundwater underpins the usufructuary nature of individual groundwater rights and the authority of the Government to grant such rights. Control of wastewater discharging on or under the ground, and control of land use practices are the keys to preserving the quality of groundwater from degradation – and the available stocks from irreversible total loss. Groundwater planning mechanisms and users’ participation in decisionmaking play a key role in the success of legislation and, in particular, in reconciling the diversity of circumstances in the field with the uniformity of legislative provisions.

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Pour une gestion durable des ressources en eau en Tunisie : questions insitutionnelles

(Sustainable development of the water resources in Tunisia: national policies)

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Abstract

Of all the natural resources necessary to ensure human health and civilisation, water is one of the most important. The management strategy of water resources in Tunisia has been conceived on the basis of the mobilisation of this resource. It used to be an appropriate strategy when the water supply was plentiful. However, this has become inappropriate since supplies appear to fall short of meeting the increasing demands due to the growth of population and the economic development, particularly in agricultural activities. The water demand will exceed the possibilities of the traditional offer extension and this requires the use of non-conventional sources (the reuse of used waters, the treatment of salt water and of sea water).

It seems, then, that a change in the policy of the traditional water supply has to be urged in order to avoid the negative consequence on the economy of a generalized and a chronic deficit of the hydric resources. The growing scarcity of water in front of a need of expansion which threatens the quality of life will cause a recession of the economic development and of the vital ecosystems. It is fundamental that public powers review their approach and conceive a move from a politic of supply management to a balanced management strategy of supply and demand. This transition towards a common management of supply and demand has to be completed by an institutional reform, for the success of any policy depends on the institutional components. For instance, the weakness of institutions is at the heart of most problems of hydric resources management.

The mentioned problems and drawbacks show the urgency to highlight the improvement of water resources management supported by a rational policy and by the reinforcement of institutions. The new approach that one should adopt consists in conceiving a balanced way of political and of institutional reforms in a way to exploit the efficiency of marketing powers and enforce the government means to fulfil its role.

This means essentially that a legislative frame treating water as an economic good, should be adopted. This will be accompanied by a decentralization of management structures, by more participation of the concerned parties and by recourse to the price

Résumé

La stratégie de gestion des ressources en eau en Tunisie était conçue sur la base de la mobilisation de la ressource, stratégie qui était appropriée quand l'offre était facilement accessible et la demande encore limitée, mais qui devient de plus en plus insuffisante au fur et à mesure que les nouvelles sources d'approvisionnement en eau se font rares et la demande se développant rapidement, en particulier celle de l'irrigation, va dépasser les possibilités d'extension de l'offre traditionnelle et nécessitera le recours aux ressources non conventionnelles (réutilisation des eaux usées, traitement des eaux saumâtres et des eaux de mer).

Il apparaît donc qu'une mutation de la politique traditionnelle de l'offre d'eau doit être amorcée afin d'éviter les conséquences graves sur l'économie d'un déficit chronique généralisé des ressources hydriques. La rareté grandissante de l'eau face à une demande en expansion, menaçant de compromettre la qualité de vie, de restreindre le potentiel de développement économique et de mettre en danger les écosystèmes vitaux, il est primordial que les pouvoirs publics entreprennent de redéfinir leur approche, et de concevoir un passage d'une politique de gestion de l'offre à une stratégie équilibrée de gestion à la fois de l'offre et de la demande. Cette transition vers une stratégie de gestion commune de l'offre et de la demande doit être

complétée par une réforme institutionnelle, car c'est de la composante institutionnelle que dépend en large partie le succès de toute politique. En effet, la faiblesse des institutions est au cœur de la plupart des problèmes de gestion des ressources hydriques. Il est donc question de faire évoluer les institutions pour assurer l'exécution efficace d'une politique.

Les problèmes et les faiblesses mentionnés montrent qu'il est urgent de mettre l'accent sur une amélioration de la gestion des ressources en eau appuyée par des politiques rationnelles et le renforcement des institutions. L'approche nouvelle qu'il est envisagé d'adopter consiste à mettre en place un ensemble équilibré de politiques et de réformes institutionnelles de manière à exploiter l'efficacité des forces du marché et à renforcer les moyens dont disposent le gouvernement pour remplir son rôle.

Il s'agit essentiellement d'adopter un cadre législatif et réglementaire traitant l'eau comme une denrée économique, ceci s'accompagnant d'une décentralisation des structures de gestion et prestation, d'une participation plus grande de toutes les parties prenantes, et du recours au mécanisme des prix.

1. Introduction

La Tunisie possède trois principales zones climatiques : semi-aride en bordure de la Méditerranée, aride en Tunisie centrale et désertique sur tout le Sud.

La Tunisie demeure donc aride à semi-aride sur les trois quarts de son territoire. Cette aridité conjuguée aux caprices du climat méditerranéen (les moyennes pluviométriques variant entre 600 mm et 1500 mm par an dans la frange côtière de l'extrême nord, 150 mm et 300 mm par an dans le Centre et restent en deçà de 150 mm par an dans le Sud), font de l'eau une ressource rare et mal répartie aussi bien dans le temps que dans l'espace(1).

Force est par ailleurs de constater que les surexploitations des nappes phréatiques et profondes sont importantes et préoccupantes. En effet, « l'Etude sur la stratégie des ressources naturelles » a révélé que le Ministère de l'agriculture a peu de maîtrise sur l'exploitation des nappes phréatiques compte tenu des puits appartenant à des agriculteurs privés, et dont le nombre a presque doublé, et le volume mobilisé a augmenté de 80%.

Les nappes profondes (ressources renouvelables et non renouvelables), connaissent elles aussi le phénomène de surexploitation du aux pompages réalisés par des privés. On recense environ 2400 forages qui ont mobilisé 930 Mm^3, soit plus de 79% du plafond d'exploitation fixé.

Cette surexploitation des nappes qui concerne en quasi-totalité les nappes phréatiques, mais touche de plus en plus les nappes profondes avec la progression des besoins (comme c'est le cas dans le sud du pays pour les nappes aux ressources non renouvelables)(2), pose par son ampleur, les problèmes de dégradation de la qualité des eaux souterraines(3) et des difficultés qu'a l'administration à enrayer le phénomène et à faire respecter la réglementation, et risque de conduire à terme à un abaissement des niveaux piézométriques et un tarissement des puits ou des forages.

Cet état de fait témoigne de la nécessité d'une stratégie adéquate de gestion des ressources en eau. Cette gestion des ressources en eau devient encore plus impérieuse si l'on prend en compte l'accroissement notable des besoins compte tenu du développement à la fois démographique et socio-économique du pays(4).

En effet l'accroissement démographique, l'élévation du niveau de vie et l'expansion économique du pays risquent d'entraîner, d'ici l'horizon 2010, l'épuisement des ressources en eaux conventionnelles qui ne pourraient plus satisfaire les besoins en eau potable et la demande en eau des divers secteurs d'activités économiques du pays (secteurs agricole, industriel et de service dont notamment le tourisme). En effet, suite à l'étude « Eau 2000 »(5), il a été possible d'établir un bilan hydrique en Tunisie. Une comparaison de la

(1) Un diagnostic de la situation actuelle des ressources en eau est fourni

(2) 27% des ressources des nappes phréatiques et 14% des nappes fossiles en particulier dans les gouverneras de Nabeul, Ben Arous, Bizerte, Siliana, le Kef, Sidi Bouzid, Mednine, Gafsa, Tozeur et Kebili.

(3) notamment la salinisation des eaux due à des intrusions marines pour les aquifères côtiers ou au déplacement du front salin à proximité des Chotts.

(4) D'après le rapport statistique de la SONED de 1996, 6851 milliers d'habitants sont desservis en eau potable sur un total de 9169,9 milliers, soit un taux de desserte global de 74,7% environ.

(5) L'étude « Eau 2000 » est exécutée par le ministère de l'agriculture avec l'aide du gouvernement allemand ; elle établit une analyse des options permettant au pays de satisfaire sa demande d'eau jusqu'au 2010. Cette stratégie envisage la mobilisation de la totalité des eaux souterraines et de 85% environ des eaux de surface potentielles. Les projections établies de la demande et des bilans hydriques indiquent que la Tunisie pourrait avoir un bilan positif en 2010 (157 mm^3 d'eau), en régime hydrologique moyen, sous l'hypothèse de la mobilisation de toutes les ressources et de leur

situation hydrique de la Tunisie par rapport à la région MENA(6) montre qu'elle est la première, à côté de l'Algérie, à être menacée par le phénomène de rareté relative de l'eau à l'horizon 2020, et permet de constater que l'agriculture irriguée constitue un élément principal contribuant à la rareté relative de l'eau. Depuis des millénaires, la civilisation au Moyen Orient et en Afrique du Nord reste tributaire des cultures irriguées et les pouvoirs publics ont systématiquement privilégié l'irrigation pour subvenir aux besoins alimentaires des populations en rapide expansion. A l'exception de quelques Etats et zones désertiques riches en pétrole, l'irrigation est de loin le principal utilisateur de plus de 80 % des prélèvements hydriques.

On remarque que l'irrigation occupe une part importante dans la consommation totale de l'eau en Tunisie. Cette consommation totale a connu une croissance très rapide au cours des deux dernières décennies qui est due essentiellement au doublement en 15 ans de la consommation pour l'agriculture. En outre, l'activité agricole est un facteur qui participe à la rareté relative de l'eau à cause de l'accroissement de la population synonyme d'une augmentation des besoins agricoles nécessaires à la subsistance, reflétant par conséquent l'élévation des besoins d'irrigation ce qui diminue davantage les disponibilités en eau.

Selon les responsables de la mobilisation des ressources hydriques, « une amélioration de l'efficience dans l'utilisation de l'eau de 10% seulement permettra de reculer l'échéance du recours au dessalement de l'eau de mer de 10 ans » (Horchani A., 1990).

La gestion des ressources en eau et la rationalisation de leur usage constituent donc une nécessité vitale afin de retarder cette échéance de disponibilité des ressources potentielles en eau, assurer la sécurité en eau du pays, et éviter que ces ressources ne constituent un facteur de blocage du développement économique du pays. Les volets de cette stratégie sont les suivants:

1.1 Accroître et régulariser l'offre d'eau

Accroître et régulariser l'offre d'eau pour faire face à l'expansion rapide des besoins par :

- une meilleure mobilisation des ressources en eau du pays actuellement identifiées, via le développement de l'infrastructure hydraulique, de manière à répondre à la demande en eau de tous les secteurs usagers. Ce volet s'est révélé insuffisant compte tenu des limites d'exploitation des ressources.
- la prospection de nouvelles ressources à travers les recherches classiques de nouvelles nappes souterraines et également au moyen de la mise en œuvre de programmes de recherche pour le développement de la ressource en matière notamment de :
  - dessalement des eaux saumâtres,
  - recharge induite des nappes,
  - réutilisation des eaux usées et des eaux de drainage.

Il va sans dire qu'un tel recours aux ressources non conventionnelles, ne fait qu'augmenter le coût du m^3 mis à la disposition des différents secteurs usagers. En effet, une estimation du coût global de la stratégie de développement des ressources en eau au cours de la décennie 1991-2000, a révélé que celui-ci s'élèvera à 1939 MD, répartis comme suit :

Tableau 1 : Coût de la stratégie de développement des ressources en eau (1991-2000)

Ressources	Mobilisation (MD)	Prospection (MD)	Total (MD)
Eaux de surface	1529	25	1554
Eaux souterraines	100	285	385
Total	1629	310	1939

Source : Direction Générale des Ressources en eau (DGRE), Ministère de l'Agriculture.

Ainsi 87% du montant alloué pour l'exécution de cette stratégie sont consacrés à la mobilisation de la totalité des ressources actuellement identifiées au moyen de l'édification des ouvrages hydrauliques (construction de grands barrages, réalisation de lacs collinaires, ouvrages d'épandage de crues, travaux de conservation des eaux et des sols et travaux de forage). Ces ouvrages, en permettant une meilleure régularisation inter-annuelle de la ressource en eau, pourront entre autres réduire les effets néfastes induits par les années de sécheresse, sur la balance commerciale, qui reste largement tributaire des caprices et aléas climatiques.

très bonne gestion. Les résultats de la projection varient cependant selon les régions et les mois en démontrant que le sud souffrira en permanence de pénurie, le centre manquera d'eau tous les mois (sauf en octobre, décembre et janvier). Pendant les années de sécheresse, les pénuries d'eau nécessitent la rationalisation de sa distribution.

(6) La région MENA de la Banque mondiale englobe les pays suivants : Maroc, Algérie, Tunisie, Malte, Libye, Egypte, Arabie Saoudite, Bahreïn, Emirats arabes unis, Iraq, Jordanie, Koweït, Liban, Oman, Qatar, République du Yémen et Syrie.

D'un autre côté, 16% sont réservés à la mise en œuvre d'un important programme de prospection pour l'identification de nouvelles ressources naturelles, et aussi non conventionnelles.

1.2 La réorientation de la stratégie vers une meilleure gestion de la demande en eau

Un diagnostic de la situation actuelle révèle l'importance des déperditions entre la production de la ressource et son utilisation. Ces déperditions estimées à environ 30% environ, se conjuguent avec les divers gaspillages imputables à une sous-utilisation ou une mauvaise utilisation de la ressource. On estime actuellement que le taux de pertes dans les réseaux d'irrigation s'élève à 45%. L'ensemble de ces déperditions a été estimé à 40% environ du volume global de la ressource, soit 1400 Mm^3/an.

Ainsi, si on estime à 29% de la ressource le total des pertes et gaspillages irréductibles, les quantités d'eau susceptibles d'être économisées s'élèveront globalement à 700 Mm^3.

Toutefois, les efforts déployés pour enrayer le gaspillage et favoriser l'utilisation judicieuse de la ressource demeurent encore timides. Il est donc impérieux et urgent de mettre en œuvre une stratégie, dont l'objectif est la conservation de la ressource et la rationalisation de son usage, et dont les volets sont :

1.3 Un volet socio-économique

Les actions sur la tarification de l'eau sont considérées comme les mesures les plus efficientes à la valorisation de la ressource. En effet le prix de vente de l'eau reste largement inférieur à son coût de mobilisation. Etant pratiquement subventionnée pour tous les usagers, l'eau est en voie d'atteindre un prix difficilement justifiable sur un plan économique. Les actions à mener doivent porter essentiellement sur l'attribution de quotas aux différents secteurs demandeurs, action souvent difficile et infructueuse notamment pour les secteurs fortement demandeurs de la ressource (Agriculture et tourisme), et sur la révision de la tarification des eaux (taux progressif en fonction du volume consommé, taux modulé en fonction de la quantité des eaux rejetées, etc ...), qui garantirait une répartition équitable des coûts de mobilisation entre les usagers. Ce volet économique permettrait la diminution des gaspillages, des pollueurs et des gaspilleurs-pollueurs.

L'aspect social de ce volet doit porter sur une meilleure sensibilisation des utilisateurs notamment ceux fortement consommateurs au moyen des mass-média, des collectivités et associations, des institutions d'enseignement etc ...

1.4 Un volet législatif ou institutionnel

Les composantes institutionnelles et environnementales doivent être incorporées explicitement dans la conception de cette stratégie(7) afin que cette dernière puisse être durable, économiquement efficiente, et répondant à des considérations d'équité sociale, de préservation de la qualité de l'environnement et du bien-être social.

La question fondamentale qui se pose est alors la suivante : faut-il continuer à confier le soin de développer, d'exploiter, d'entretenir et de distribuer la totalité des ressources à des agences publiques qui, faut-il le rappeler, sont généralement insensibles au souci de rentabilité ou d'efficacité qui motive les entreprises privées, ou faut-il concevoir une gestion décentralisée qui accorderait aux mécanismes de marché un rôle entreprenant notamment dans la lutte contre le gaspillage et les doubles emplois ?

Un axe de cette stratégie porterait donc sur la définition d'un cadre législatif adéquat qui incite tous les usagers à une utilisation rationnelle de la ressource en eau dont la rareté grandissante menace de compromettre la qualité de vie, de restreindre le potentiel de développement économique et de mettre en péril les écosystèmes vitaux, ainsi qu'à une contribution efficace à la maintenance et la durabilité du système de distribution.

Compte tenu de tous les développements qui précèdent, nous essayerons tout au long de ce travail de recherche de mettre l'accent sur la réforme institutionnelle qui nous semble constituer la charpente d'une stratégie efficace de la gestion d'une ressource risquant de constituer un goulot d'étranglement au développement socio-économique en Tunisie et dans la plupart des PVD.

(7) Dans ce cadre, le "Programme National d'Economie d'Eau" envisage la réalisation d'un certain nombre d'actions

2. Défaillances du marché et de la politique publique dans le secteur de l'eau

L'eau possède des caractéristiques qui entraînent un dysfonctionnement du marché. L'eau pose en effet les problèmes que l'on rencontre habituellement dans la gestion des ressources naturelles et des biens et services environnementaux(8) .

La fourniture et une partie de la production des biens collectifs purs sont essentiellement la responsabilité de l'état, les biens privés purs peuvent être fournis efficacement par les marchés. Cependant, la plupart des activités intéressant l'eau ne sont ni entièrement des biens collectifs purs, ni des biens privés purs, et ce en tenant compte des deux critères – **possibilité de soustraction** et **possibilité d'exclusion** – qui font qu'un bien ou service est « **privé** » ou « **collectif** » (Samuelson P., 1954).

Tableau 2 : Catégories de biens

Catégories de biens	Possibilité d'exclusion	Possibilité de soustraction
Biens collectifs exemple : prévention des inondations, barrages...	Faible	faible
Biens privés	Forte	Forte
Biens tarifiés exemple: réseaux d'égouts, aménagements de la navigation	Forte	Faible
Biens d'accès libre Exemple : ressources telles que les nappes aquifères	Faible	Forte

Dans le cas de biens collectifs, il n'y a pas de possibilité de soustraction ou non rivalité des consommateurs ; les biens peuvent continuer à offrir les mêmes avantages à chaque consommateur tant qu'ils ne sont pas endommagés ou qu'il n'y a pas encombrement. Si l'utilisation accrue du bien n'entraîne pas de dégradation des avantages retirés par les autres consommateurs ou d'augmentation de coût pour la société, elle augmente le bien-être économique total. Le coût marginal du service d'un consommateur supplémentaire est nul.

Or, une utilisation efficace des ressources exige une tarification au coût marginal. Comme le coût marginal est nul, le prix serait donc nul. En outre, les individus ne révèlent pas leurs préférences pour les biens publics, chaque individu pouvant tirer profit du bien collectif dés qu'il est produit, aura intérêt à avoir un comportement de resquilleur ou « cavalier libre » (Musgrave R., 1959). On ne peut donc définir de demande effective pour la catégorie des biens collectifs. Certaines activités de mise en valeur des ressources en eau telles que les réseaux d'égouts, les canalisations d'eau et les voies de navigation sont caractérisées par une faible possibilité de soustraction, tant qu'ils ne sont pas utilisés à pleine capacité. La faible possibilité de soustraction, rend nécessaire un investissement ou une subvention sur fonds publics, les forces du marché ne pouvant produire un volume optimal de production.

Par ailleurs, la deuxième caractéristique des biens collectifs, est qu'il n'y a pas de possibilité d'exclusion (tableau 2). De nombreuses activités relatives à l'eau sont caractérisées par l'impossibilité ou la difficulté d'empêcher leur utilisation à certains usagers. Tel est le cas par exemple des grands périmètres d'irrigation, les puits de village, les barrages construits pour la lutte contre les inondations. Les activités caractérisées par une faible possibilité d'exclusion ne peuvent être l'objet des entreprises privées car il est difficile d'obtenir un paiement du consommateur, à moins que les pouvoirs publics assurent le financement de ces activités. En outre, une réglementation publique devient nécessaire si la faible possibilité d'exclusion entraîne une utilisation excessive de la ressource.

Par conséquent, dans le cas de biens collectifs, la non rivalité des consommateurs et la faible possibilité d'exclusion constituent les deux causes de l'échec du marché à garantir une allocation optimale des ressources(9), et rendent nécessaire l'investissement public, avec toutefois la possibilité de confier la gestion de la ressource au secteur privé ou à des groupes d'usagers. Les investissements sont en effet en règle générale importants et assurent des rendements d'échelle. Or des activités économiques entraînant des économies d'échelle (coût fixe important par rapport aux coûts variables), ou des économies de gamme (abaissement du coût unitaire de la production de plusieurs produits en combinaison plutôt que séparément, par exemple les projets hydrauliques polyvalents), constituent des **monopoles naturels** où les forces du marché sont incapables de réaliser une allocation optimale des ressources. En effet, dans ce cas l'incitation

(8) La théorie des finances publiques et l'économie du bien-être offrent un cadre analytique permettant d'examiner les caractéristiques des biens collectifs et privés des différentes activités relatives aux ressources en eau (Kessides CH, 1992).

(9) Les forces du marché ne donnent naissance à une affectation efficace des ressources que s'il y'a concurrence.

à innover et le dynamisme sont limités car le risque d'entrée de concurrents potentiels est réduit, les entités monopolistes ont tendance à produire moins et à demander plus pour un bien et service, qu'en situation de concurrence. Les grands barrages, les réseaux d'égouts, les canaux d'irrigation à grande échelle et les réseaux d'alimentation en eau des villes constituent des exemples de monopoles naturels. Dans le secteur de l'eau, les installations entraînent souvent des coûts fixes initiaux importants. Toutefois, les activités d'exploitation et l'entretien ne génèrent pas ensuite des coûts fixes élevés, peuvent donc être confiées à de petites entreprises privées, et sont donc caractérisées par un fort degré de « **contestabilité** »(10). Par ailleurs, l'eau est liée à des effets externes multiformes(11) . Les activités liées à l'eau sont physiquement en rapport avec le reste de l'écosystème et avec d'autres activités économiques ; elles sont donc difficiles à gérer et s'inscrivent dans des structures institutionnelles complexes, compte tenu de la complexité de l'écosystème, du caractère fluctuant de l'offre d'eau, et de la complexité du cycle de l'eau. Aussi, les prix du marché ne peuvent refléter toutes ces corrélations.

La théorie néo-classique des externalitès préconise l'utilisation des mécanismes du marché au moyen des « instruments économiques » (taxes, redevances, permis négociables). Une autre **approche réglementaire** s'appuyant sur une tradition régalienne, propose que les politiques de l'environnement reposent sur des réglementations de type administratif (permis, normes, interdictions ...), s'inscrivant dans un cadre législatif et réglementaire qui fixe les objectifs, les principes généraux, les procédures et instruments d'application.

C'est donc cette diversité des défaillances du marché dans les activités de gestion de l'eau qui justifie l'action des pouvoirs publics afin que des normes rationnelles d'efficacité soient observées, de limiter la formation et la captation excessive d'une rente dite de monopole, et d'éviter les pratiques discriminatoires. C'est en fait la raison pour laquelle la puissance publique toujours dans les situations de monopole pour imposer certains principes notamment en matière de détermination des tarifs. Une distinction entre les deux fonctions de fourniture de l'équipement et sa production permet de déterminer le rôle de l'état(12). La fourniture d'installations en forme de réseaux au niveau primaire « canal principal », la planification de l'investissement, ont le caractère de bien collectif, et constituent des monopoles naturels. Par contre, la production des services à partir de ces réseaux et leur entretien peuvent être soumis à la concurrence, et donc peuvent être effectués avec possibilité d'exclusion et avec un degré de « contestabilité ».

Par ailleurs, un grand nombre des effets externes liés à l'extraction et l'utilisation de l'eau peuvent être «internalisés» soit par le recours à des instruments économiques, soit par la pratique des instruments réglementaires avec l'exercice de la fonction de contrôle et de régulation des monopoles(13).

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(10) Le terme «contestabilité» désigne le risque pratique de concurrence résultant de l'entrée sur le marché de nouveaux concurrents. Lorsque le degré de contestabilité est élevé, l'entrée et la sortie sont peu coûteuses. Dans le cas où l'accés au marché nécessite des dépenses d'investissement élevées qui risquent d'être perdues en cas d'échec, le degré de contestabilité est faible.

(11) L'eau est liée à des effets externes positifs et des effets externes négatifs. Les effets externes négatifs entraînent une surproduction de l'activité concernée, alors que les effets externes positifs impliquent une sous-production.

Exemple d'effet externe positif : les avantages sanitaires découlant pour l'ensemble de la population, du raccordement des domiciles individuels au tout-à-l'égout.

Exemple d'effet externe négatif : la contamination des eaux de surface et des eaux souterraines par les eaux usées et par des produits chimiques ou par l'eau salée dans l'irrigation, la dégradation des zones marécageuses due au détournement d'un cours d'eau et l'abaissement de la nappe phréatique par le pompage dans une nappe aquifère commune.

(12) La production est l'acte consistant à réaliser l'investissement et à produire les services, comme la construction d'un barrage par une entreprise privée ou la gestion d'une usine d'épuration. La fourniture de l'équipement suppose un ensemble de décisions et d'actions qui rendent possible la fourniture des installations et des services, exemple : l'investissement public direct dans la construction de systèmes d'adduction d'eau.

(13) La recherche du profit maximal par un monopole peut conduire à une forme d'inefficacité dans le fonctionnement des marchés, d'où la nécessité de contrôle et de régulation des monopoles. En effet, le prix étant supérieur au coût marginal, le bien être collectif n'est pas optimal. Les premiers débats théoriques sur les monopoles naturels et leur régulation remontent aux écrits de L Walras, A Cournot, J Dupuit,...). Par la suite plusieurs théories de la régulation « public utility reglation » ont été développées afin d'exploiter la rationalité sous-jacente à la régulation des monopoles dont :

- la théorie de la régulation dite de l'intérêt public : la régulation y est un substitut institutionnel à la concurrence et un moyen d'atteindre l'optimum collectif (Posner, 1974) ;
- la théorie de la régulation dite de l'équité et de la stabilité : l'objectif de l'intervention de la puissance publique n'est pas de corriger les imperfections du marché mais d'assurer la protection des sociétés, des conséquences du libre fonctionnement des forces du marché. Cette approche traduit la volonté des régulateurs de remplacer les marchés par des dispositions institutionnelles de type administratif et juridique considérées les mieux adaptées à promouvoir les objectifs sociaux, d'équité et de justice, au détriment, si besoin est, des objectifs d'efficience économique. Pour une discussion plus large sur cette question cf (Mitnick, 1980).

La régulation d'un monopole naturel concerne le contrôle de l'entrée et des prix, et a été proposée comme un moyen de reprendre tous les avantages d'efficacité de la structure de monopole. Cette régulation fait par conséquent appel à l'incontournable intervention de la puissance publique sous plusieurs formes : le régime de concession (avec cahier de charges) qui accorde un monopole légal sur un territoire donné, la régulation (monopole privé régulé), la nationalisation (monopole public)..., l'objectif étant de réglementer l'entrée de nouveaux «prédateurs» intéressés par les seuls segments rentables et susceptibles de réduire les économies d'échelle et de protéger les consommateurs des abus du monopole par un contrôle au niveau des tarifs(14).

3. Organisation du secteur de l'eau en Tunisie : questions institutionnelles

3.1 Cadre institutionnel

La législation tunisienne stipule que toutes les ressources en eau appartiennent à l'Etat.

La propriété étatique de l'eau est un droit original subordonné à la reconnaissance à des degrés divers de l'appropriation par la communauté, les droits des entreprises et des particuliers sont supplétifs. Il faut un permis de l'Etat pour se livrer à une exploitation privée, et l'Etat a la responsabilité, soit directement soit sous forme de concessions, du traitement et de distribution de l'eau et de grands travaux publics.

Conformément aux dispositions du Code de l'eau(15) , promulgué au début d'une période d'expansion substantielle d'adduction d'eau dans le pays, l'Etat réserve la quantité d'eau potable nécessaire aux besoins de la population et confie la gestion du reste de la ressource au Ministère de l'Agriculture. Ce code est orienté vers la réglementation des problèmes de stockage, de distribution et d'offre d'eau et permet aux particuliers d'effectuer sans autorisation préalable des sondages ou des forages de puits jusqu'à une profondeur de 50 mètres, à condition que ceux-ci ne se situent pas dans un périmètre de préservation ou d'interdiction. Le Ministère de l'Agriculture intervient pour désigner « les périmètres d'utilisation » où les ressources en eau sont jugées insuffisantes pour répondre aux besoins actuels et aux priorités(16) .

En outre, le Ministère de l'Agriculture peut désigner des périmètres de «préservation» ou d' « interdiction » dans lesquels, toute nouvelle exploitation de l'eau risque de compromettre sa qualité ou sa conservation. Il y interdit d'effectuer de nouveaux sondages ou puits.

Le Ministère de l'Agriculture contrôle toute la production publique d'eau à partir des eaux de surface par le système de barrages et grands canaux. La SONEDE est responsable de l'exploitation et du transport de l'eau à partir de deux réservoirs dont la finalité est exclusivement non agricole (Beni M'tir et Kasseb), et des nappes souterraines profondes produisant une eau potable.

En situation de pénurie d'eau, le Code de l'eau ne prévoit de confier à aucune entité la responsabilité d'ensemble de l'allocation des ressources en eau.

Récemment, on assiste à l'émergence des Associations d'intérêt Collectif (AIC). Il s'agit de regroupement des usagers de l'eau d'irrigation qui visent l'exploitation de certaines nappes et l'entretien de leurs puits et forages dont l'investissement initial est réalisé par l'Etat. Ces AIC, dont l'action est principalement développée dans les Oasis du sud, mobilisent et fournissent environ un cinquième de l'eau utilisée obtenue essentiellement par des forages.

3.2 Gestion traditionnelle et carence institutionnelles

En vue de garantir une amélioration de la gestion des ressources en eau, le Ministère de l'agriculture a conçu sa stratégie hydraulique sur la base de la mobilisation de la ressource, stratégie qui était appropriée quand l'offre était facilement accessible et la demande encore limitée, mais qui devient de plus en plus insuffisante au fur et à mesure que les nouvelles sources d'approvisionnement en eau se font rares, et la demande se développant rapidement, en particulier celle de l'irrigation, va dépasser les possibilités

(14) Pour la distribution aux particuliers, par exemple, l'importance des frais fixes relatifs aux conduites de raccordement des ménages explique la tendance au monopole naturel auquel cas, les prix risquent d'être excessifs s'ils sont livrés à eux-mêmes. Si l'on fait intervenir les entreprises privées, il est recommandé de réglementer les prix ou d'introduire des mécanismes qui maintiennent la pression de la concurrence et protègent les écosystèmes.

(15) Le Code de l'eau a été promulgué par la loi n° 75-16 du 31 mars 1975.

(16) Tout propriétaire ou exploitant de l'eau dans ces périmètres est dans l'obligation de déclarer ses installations à l'administration. Ailleurs, les exploitants sont autonomes puisqu'ils doivent financer tous les investissements et coûts d'exploitation.

d'extension de l'offre traditionnelle et nécessitera le recours aux ressources non conventionnelles (réutilisation des eaux usées, traitement des eaux saumâtres et des eaux de mer).

Les volets de cette stratégie de gestion traditionnelle de l'offre sont les suivants :

- **accroître ou régulariser l'offre d'eau** par des investissements lourds (barrages, transferts d'un bassin versant à un autre), et étendre de nombreux réseaux urbains pour faire face à l'expansion rapide des besoins des villes. Parallèlement, d'autres formes non conventionnelles d'approvisionnement ont été développées comme le dessalement des eaux saumâtres ou de mer, et le pompage des nappes fossiles. Or malgré le fait qu'une telle politique de gestion traditionnelle permet d'augmenter l'offre d'eau par la localisation et l'exploitation de nouvelles ressources, et en dépit de sa capacité à éviter les risques de pénurie d'eau à moyen terme par l'installation des moyens matériels de captage, d'emmagasinage et d'acheminement de l'eau au lieu de son traitement et de sa consommation, elle enregistre actuellement un recul sur le plan pratique dû essentiellement à deux facteurs, l'un économique et l'autre est naturel :
  - Sur le plan économique la gestion traditionnelle de l'offre se heurte à plusieurs problèmes dont les principaux sont ceux du coût élevé de la réalisation des projets hydrauliques. Selon le Ministère de l'Agriculture, la stratégie de mobilisation des ressources en eau a un coût estimé à 2 milliards de dinars.
  - En outre cette méthode trouve son meilleur champ d'application dans une circonstance d'abondance de l'eau, alors qu'il est maintenant établi que la Tunisie connaîtra un déficit structurel entre les ressources mobilisables en eau et les besoins potentiels à l'horizon 2010.
- **une surveillance en temps réel d'offre d'eau** (flux et stocks d'eau dans les réservoirs). Cette surveillance est assurée à l'aide d'un système moderne de collecte et de transmission des données ;
- **l'extension du contrôle de toutes les réserves d'eau souterraines** et en particulier des nappes aquifères de surface qui sont actuellement exploitées sans grand contrôle par les propriétaires terriens. En effet, on relève une grande prudence de la part des responsables à pratiquer une gestion rigoureuse de l'offre, souvent à cause de contraintes politiques ou institutionnelles, notamment dans le secteur agricole qui absorbe prés de 80% des ressources et qui demeure régi par des règles traditionnelles de répartition de l'eau, qui rencontrent de vives résistances pour toute tentative d'amélioration(17) .
- **la sous, tarification de l'eau :** souvent pour des raisons culturelles ou religieuses, le
  - prix de l'eau est inférieur à sa valeur économique. L'eau est vendue à un prix qui ne reflète pas sa rareté aux habitants des villes, aux industriels, et encore moins aux paysans. Les paysans paient souvent fort peu l'eau d'irrigation fournie par les services publics et ils ne sont guère incités à l'économiser ou à renoncer aux cultures fortement consommatrices d'eau. La tarification de l'eau sur les périmètres irrigués publics n'incite pas les utilisateurs à faire des économies. Ainsi sur ces périmètres (en particulier ceux du Sud), on constate des remontées de la piezométrie des nappes sous-jascentes qui entraînent une salination des terres, un gaspillage et une utilisation inefficace des ressources, notamment dans ces secteurs hydro-agricoles publics qui prennent la part du lion pour des usages peu rentables par rapport aux usages domestiques et industriels. Une autre conséquence, est que les investissements réalisés, souvent trop coûteux pour la mobilisation des ressources hydriques (20), ne sont presque jamais rentables. Le bas tarif de l'eau ne permet pas d'assurer la récupération des coûts d'exploitation et d'entretien. La gestion s'écarte ainsi de l'optimum.

Il apparaît donc qu'une mutation de la politique traditionnelle de l'offre d'eau doit être amorcée afin d'éviter les conséquences graves sur l'économie d'un déficit chronique généralisé des ressources hydriques. La rareté grandissante de l'eau face à une demande en expansion, menaçant de compromettre la qualité de vie, de restreindre le potentiel de développement économique et de mettre en danger les écosystèmes vitaux, il est primordial que les pouvoirs publics entreprennent de redéfinir leur approche, et de concevoir un passage d'une politique de gestion de l'offre à une stratégie équilibrée de gestion à la fois de l'offre et de la demande. En effet, si augmenter l'offre par le développement des ressources encore mobilisables est une solution coûteuse (les ressources non encore mobilisées sont d'accès difficile et nécessitent des investissements lourds et coûteux) et surtout non durable (car ces développements pourraient conduire dans certaines situations telles que le recours aux nappes fossiles et phréatiques à recharges limitées, à la

(17) D'après le droit islamique, l'eau est un don de Dieu, elle appartient donc à la communauté ce qui crée un droit primaire d'utilisation. La valeur ajoutée résultant des investissements dans les systèmes de distribution ou de conservation donne toutefois un certain droit à la propriété permettant l'appropriation et la commercialisation locale de l'eau. En situation de pénurie, le partage varie selon l'usage local mais le droit d'appropriation préalable reste valable, combiné aux coutumes locales concernant la distribution de tout excédent.

surexploitation et surtout à la dégradation des ressources), maîtriser la demande serait la solution la moins coûteuse et surtout la plus durable. Etant donné les pertes et gaspillages au niveau de la consommation en Tunisie, une gestion appropriée pourrait réaliser des économies considérables. Le taux des pertes dans les réseaux d'irrigation estimé à 45% s'explique par plusieurs raisons dont les principales sont : la mauvaise maintenance du réseau de distribution et l'utilisation inefficiente par l'agriculteur lui même vu les prix largement subventionnés en vigueur. Les techniques qui permettent de conserver l'eau existent actuellement (l'aspersion, le goutte-à-goutte, etc...), cependant elles sont relativement peu utilisées étant donné qu'elles ne sont pas rentables comparées aux prix de l'eau pratiqués actuellement.

Cette transition vers une stratégie de gestion commune de l'offre et de la demande doit être complétée par une réforme institutionnelle, car c'est de la composante institutionnelle que dépend en large partie le succès de toute politique. En effet la faiblesse des institutions est au cœur de la plupart des problèmes de gestion des ressources hydriques. Il est donc question de faire évoluer les institutions pour assurer l'exécution efficace d'une stratégie équilibrée des ressources en eau.

4. Vers une nouvelle stratégie équilibrée de gestion a la fois de l'offre et de la demande : reformes institutionnelles

Les problèmes et les faiblesses mentionnés montrent qu'il est urgent de mettre l'accent sur une amélioration de la gestion des ressources en eau appuyée par des politiques rationnelles et le renforcement des institutions. L'approche nouvelle qu'il est envisagé d'adopter consiste à mettre en place un ensemble équilibré de politiques et de réformes institutionnelles de manière à exploiter l'efficacité des forces du marché et à renforcer les moyens dont disposent le gouvernement pour remplir son rôle. Il s'agit essentiellement d'adopter un cadre législatif et réglementaire traitant l'eau comme une denrée économique, ceci s'accompagnant d'une décentralisation des structures de gestion et prestation, d'une participation plus grande de toutes les parties prenantes, et du recours au mécanisme des prix(18) .

Par suite des défaillances du marché, les pouvoirs publics ont pris en charge la gestion d'ensemble de la ressource en eau. Or, les actions qu'ils engagent quand elles ne sont pas bien formulées ou bien mises en œuvre, sont souvent cause d'erreurs de répartition et de gaspillage des ressources en eau. Quatre types de problèmes se posent :

- *une gestion fragmentaire du secteur public qui a négligé les interdépendances entre organismes publics, juridictions et secteurs.* Or, les stratégies et activités de gestion des ressources en eau doivent être formulées dans le cadre d'une analyse globale qui prend en compte l'interdépendance entre secteurs et protège les écosystèmes. Un tel cadre permettra une meilleure coordination entre institutions, une réglementation plus homogène, des politiques plus cohérentes, et des actions gouvernementales mieux ciblées.
- *une gestion centralisée qui s'est désintéressée de ce qui a trait à la participation des utilisateurs et à la responsabilité financière.* Il faut rationaliser la gestion de l'eau en jouant davantage sur la décentralisation, la participation des usagers, la privatisation et l'autonomie financière de manière à responsabiliser les parties concernées et améliorer le système d'incitations.
- *une sous-tarification et un non-recouvrement des coûts* : il est question de mettre en place un système de tarification de l'eau qui incite à utiliser judicieusement cette ressource, élément clé d'une gestion rationnelle des ressources en eau.
- *des investissements publics et des réglementations oublieux de la qualité de l'eau, de la santé et de l'environnement.*

4.1 Gestion fragmentaire du secteur public et structures de coordination

Vu le caractère fragmentaire qu'a souvent revêtu la gestion des ressources en eau par le passé, la nouvelle approche consiste à établir un cadre global pour la formulation de décisions publiques qui tiennent compte des interdépendances caractéristiques des ressources en eau et de leurs répercussions sur les écosystèmes naturels, et de la santé des populations.

En Tunisie, comme dans la plupart des pays, une pléthore d'organismes publics et commissions font parfois la même chose dans le domaine de la gestion des ressources en eau. Or, les organismes publics s'occupent généralement d'un seul type d'utilisation de l'eau, et les décisions ont tendance à se prendre de

(18) Cette nouvelle approche est conforme à la Déclaration de Dublin (1992), de la Conférence internationale sur l'eau et l'environnement, ainsi qu'à l'Action 21 (1992) de la Conférence des Nations Unies sur l'environnement et le développement.

manière fragmentaire. Les activités gouvernementales sont en général organisées de telle sorte que chaque type d'utilisation de l'eau est géré par un ministère ou un organisme différent (par exemple pour l'irrigation, l'approvisionnement municipal, l'électricité et le transport), chacun étant responsable de ses propres opérations et indépendant des autres. Les questions relatives à la quantité et la qualité de l'eau, à la santé et à l'environnement sont également examinées séparément, de même que les questions se rapportant à l'eau de surface et l'eau souterraine.

Par conséquent, les plans proposés par différents organismes peuvent être en conflit les uns avec les autres, ce qui entraîne souvent une mauvaise affectation des ressources en eau. La solution consiste donc à mettre en place des dispositifs institutionnels destinés à encourager les administrations chargées de l'eau à se concerter et à s'entendre sur leurs priorités et politiques d'investissement, de réglementation et d'affectation des ressources. Une autre solution consisterait à créer des comités de coordination constitués des représentants des principaux organismes chargés des ressources en eau. Leurs fonctions seraient d'étudier et de recommander les changements souhaités dans les investissements et la gestion, de manière à promouvoir une stratégie globale et coordonner les différentes interventions.

Afin de pourvoir au besoin de coordination et de cohérence dans la formulation des règles et réglementations pour l'application d'une approche analytique globale, la Tunisie a déjà entamé une coordination des activités à l'échelon national, par la création des comités au sein des ministères du Plan ou des Finances, et leur attribution des pouvoirs suffisants pour suivre ce qui se fait dans le domaine des ressources en eau, et veiller à en assurer la conformité avec les stratégies nationales(19). Le principe à suivre concernant l'attribution des fonctions consiste à séparer, à chaque niveau d'administration, celles d'orientation, de planification et de réglementation, de celles d'exécution.

Il est donc vital de poursuivre ces réformes et de soutenir l'adaptation des structures institutionnelles au niveau national, mais également régional, chargées de coordonner la formulation et l'application des politiques tendant à améliorer les programmes de gestion de l'eau afin de résoudre les problèmes liés au manque de coordination et au morcellement du processus de prise de décision.

4.2 Rôle du secteur public, décentralisation, privatisation et participation

La diversité des défaillances du marché dans les activités de gestion de l'eau examinés plus haut, justifie l'action du secteur public(20) , considéré comme le mandataire chargé de la gestion des ressources en eau. Dans beaucoup de cas, les pouvoirs publics ont tendance à répartir l'eau en fonction de critères politiques et sociaux, plutôt que purement économiques. De plus, craignant les échecs éventuels d'un recours exclusif à des marchés non réglementés, beaucoup de pays dont la Tunisie, font appel à des administrations centralisant la direction et le contrôle de l'aménagement et de la gestion des ressources en eau, et confient à des organismes gouvernementaux la tâche d'aménager, d'exploiter et d'entretenir les réseaux d'eau.

Les organes gouvernementaux sont alors surchargés sur les plans administratif et financier, et il arrive souvent que les procédures à suivre pour la réaffectation des ressources en eau à des usages prioritaires soient vagues et ne soient pas expressément stipulées ; les réaffectations n'ont donc pas lieu, ou elles sont le fait de décisions ponctuelles coûteuses.

Or, la gestion des ressources en eau n'impose pas que la prestation des services soit centralisée. Bien au contraire, la décentralisation modifie et facilite la nature du travail des pouvoirs publics. Des programmes prévoyant le transfert de distribution d'eau gérés par l'Etat à des entreprises privées, des sociétés de distribution financièrement autonomes et des associations d'usagers de l'eau doivent être établis(21).

(19) Le Mexique a également entrepris une réforme de son système de gestion de l'eau dans le sens sus-mentionné. Certains pays industrialisés, tel que la France, ont adopté des plans de coordination plus ambitieux. Un aspect important du système français est que la gestion des ressources en eau se fait au niveau du bassin fluvial. Il y'a 6 comités de gestion des bassins fluviaux (CGBF) et 6 organismes de financement des bassins fluviaux (OFBF), qui correspondent aux principaux bassins fluviaux de la France. Ces OFBF sont chargés depuis 25 ans de la planification et macrogestion des ressources en eau. Les CGBF se composent de 60 à 110 membres qui représentent les parties concernées (l'administration nationale, les régions et les collectivités locales, les groupes industriels et agricoles et les particuliers), et facilitent la coordination entre toutes les parties concernées pour la gestion des ressources en eau.

(20) La taille considérable de certains investissements, le temps de gestation extrêmement long qu'ils demandent, les possibilités d'économies d'échelle dans les infrastructures tendent à créer des monopoles naturels qui nécessitent une réglementation pour éviter une tarification abusive.

(21) De telles associations sont actuellement mis en place en Amérique Latine (Argentine, Colombie et Mexique), en Asie (Bangladesh, Indonésie, Népal, Pakistan, Philippines et SriLanka), en Europe de l'Est (Hongrie) et en Afrique (Côte d'Ivoire, Madagascar, Maroc, Niger, Sénégal). Les leçons d'expériences récentes de certains pays montrent que la décentralisation des moyens de distribution permet de parvenir à une utilisation plus rationnelle de l'eau.

En Tunisie, les Associations d'Usagers de l'Eau (AUE ou AIC) existent depuis le début du siècle, légalisées en 1913 par le gouvernement colonial français. Le statut juridique des AUE a été ensuite réaffirmé par le gouvernement tunisien par des lois promulguées en 1975 et en 1987. Depuis, l'Etat s'est employé à la création des AUE et à l'encouragement de celles qui existent, et à permettre le concours progressif du secteur privé notamment dans le secteur de l'irrigation(22). Les planificateurs des ressources hydro-agricoles réalisent en effet de plus en plus que ces AUE permettent des gains substantiels, dans la mesure où le coût de mobilisation de l'eau n'est plus totalement supporté par des organismes publics subventionnés, mais supporté au moins partiellement par les bénéficiaires.

Les AUE ont connu le succès le plus important dans le sud du pays où elles contrôlent pratiquement tous les réseaux d'irrigation à partir de forages couvrant chacun 50 à 200 hectares. Les exploitants agricoles y sont responsables de l'exploitation et de l'entretien, et peuvent assurer certaines réparations de routine avec toutefois l'aide du gouvernement pour les grands travaux de réparation en contrepartie d'une contribution des AUE.

Force est de constater que le concours des AUE allège la charge financière de l'état et donne surtout aux exploitants le sentiment qu'ils sont propriétaires des installations. Ils réagissent désormais avec beaucoup de souplesse à l'évolution de la demande des différentes cultures sur le marché, alors qu'auparavant une telle souplesse était impossible du fait de la forte centralisation et du contrôle exercé par les pouvoirs publics. La participation des usagers est en effet un processus qui amène les parties prenantes à établir un sens de « propriété » et à influer ainsi sur les choix des investissements et les décisions de gestion affectant leur communauté. Ainsi, avec la participation des usagers à la gestion des ressources en eau, la sélection des projets, les prestations des services et le recouvrement des coûts s'amélioreront indubitablement. La participation des usagers est donc un processus à encourager et à généraliser.

Une démarche qui suscite également un intérêt grandissant consiste à avoir plus largement recours au secteur privé au moyen de contrats de concession et de gestion. La participation du secteur privé peut prendre différentes formes. La forme la plus courante est la concession attribuée par voie d'appel d'offres dans laquelle les équipements sont loués à un opérateur privé qui apporte des capitaux et exploite les installations durant une période donnée(23). Une autre forme de privatisation est l'investissement public assorti d'un contrat de gestion privé pour une durée donnée(24).

Un autre volet serait de créer et promouvoir des institutions d'assurance dont les rôles seraient de récompenser et garantir un service adéquat aux usagers qui participent activement à la gestion et la maintenance, s'acquittent convenablement de leurs redevances, mais aussi de pénaliser les « Free-rider ». C'est là un moyen de responsabilisation des usagers et d'amélioration du recouvrement des coûts. Ce problème du non-paiement et du non-recouvrement des redevances d'eau est lié à l'insuffisance des incitations au recouvrement, et à la réticence à payer en raison de la mauvaise qualité des services. Le non-recouvrement des coûts engendre l'impossibilité de réinvestir dans les réseaux de distribution et créent un cercle vicieux, la qualité du service se dégradant davantage faute de fonds, et la réticence des usagers à payer pour des services de qualité médiocre augmentant. En revanche, un fort taux de recouvrement est synonyme de services d'eau financièrement autonomes et responsables, fournissant un service de qualité pour lequel les usagers n'éprouvent pas de réticence à payer(25).

La décentralisation, le recours au secteur privé au moyen des contrats de concession et de gestion et aux sociétés d'assurance, la participation des usagers et des collectivités locales à la gestion des ressources en eau, sont un moyen d'introduire des incitations appropriées qui contribuent à renforcer la responsabilisation des usagers et donc à accroître leur efficacité au plan de la gestion et de l'utilisation rationnelles de l'eau. C'est également un moyen de mieux tenir compte des besoins des usagers, de fonctionner librement sans ingérences politiques, d'accroître la souplesse et l'efficacité, d'améliorer le recouvrement, et d'alléger le poids de la charge financière qui pèse sur les pouvoirs publics.

(22) La Banque Mondiale a appuyé cette évolution par le financement de 3 projets d'irrigation et 2 prêts à l'ajustement du secteur agricole.

(23) Cette formule de privatisation est déjà répandue dans certains pays comme la Côte d'Ivoire, l'Espagne, la France, la Guinée, le Macao, le Portugal et récemment l'Argentine. Mais la formule de privatisation la plus développée a été observée en Angleterre et au pays de Galles en 1990, où des sociétés publiques de distribution de l'eau ont été vendues au public et leurs actions cotées en Bourse.

(24) Cette forme de privatisation où le contrat est en général de plus courte durée, est prédominante dans les réseaux d'assainissement où les accords de concession sont rares.

(25) A ce titre, la Guinée offre l'exemple le plus frappant. La privatisation de la distribution de l'eau municipale y a permis de briser rapidement ce cercle vicieux. En effet, le service d'eau s'était considérablement amélioré et le taux de recouvrement était passé de 15 à 70%, 18 mois après la privatisation (Banque Mondiale, 1994).

4.3 Système de tarification et incitations

L'une des principales faiblesses de l'approche traditionnelle qui a été suivie dans le secteur de l'eau, a été de trop s'en remettre, pour la gestion des ressources en eau à des organismes publics surchargés. Un volet de la réforme consiste à réviser leur organisation et à tenter de rationaliser le système en décentralisant et en jouant davantage sur la politique des prix et les incitations.

Une gestion décentralisée ne donnera en effet de bons résultats que si elle est appuyée par des actions sur la tarification de l'eau qui sont considérées comme les mesures les plus efficientes à la valorisation de la ressource. Ces actions sont généralement motivées par la hausse des coûts de transfert et de traitement de l'eau, l'importance des investissements pour la recharge des nappes et le recyclage de l'eau, et l'accroissement des coûts de pompage. Un prix de l'eau qui reste inférieur à sa valeur économique, entraîne une mauvaise allocation et une utilisation inefficace des ressources(26) .

En vue de repousser l'échéance d'une pénurie structurelle des ressources en eau et le recours au dessalement, le gouvernement tunisien a entamé la mise en œuvre d'un programme de hausse progressive du prix de l'eau et le lancement de campagnes de sensibilisation du public visant à aboutir à des modifications dans les comportements humains à l'égard de la conservation et de l'usage de l'eau. Les appels lancés au public dans le cadre des campagnes de sensibilisation, de programmes éducatifs et d'initiatives analogues peuvent également aboutir à de profondes modifications dans les comportements humains à l'égard de la conservation et de l'utilisation de l'eau. Cette méthode relativement peu coûteuse, peut de toute évidence apporter une réelle contribution et devrait être systématiquement privilégiée et assortie d'autres programmes visant à renforcer le rendement et conserver les ressources. La réduction des pertes joue également un rôle crucial dans le programme de gestion de la demande et reste de première priorité compte tenu des taux élevés enregistrés dans les réseaux urbains de distribution. Les programmes de détection des fuites et de réparation, la détection des branchements illégaux et la réduction de la pression dans les réseaux sont autant d'interventions techniques permettant de réaliser des baisses des taux de déperdition dans les réseaux urbains de redistribution, et offrent des possibilités particulières dans le domaine de l'irrigation. Le secteur agricole est en effet amené en tant que consommateur dominant, à recevoir plusieurs mesures incitatives à la conservation de la ressource. Parmi ces mesures, on relève une amélioration des techniques d'irrigation et une hausse progressive du prix de l'eau d'irrigation.

Au niveau des techniques d'exploitation, l'irrigation de surface peut être améliorée en nivelant le terrain, ou remplacée par l'irrigation par aspersion ou par la micro-irrigation (par exemple le goutte-à-goutte), qui offre des possibilités réelles d'économies, de l'ordre de 30 à 50% par rapport à l'irrigation de surface(27).

La hausse progressive du prix de l'eau d'irrigation permettrait une récupération rapide des coûts d'exploitation et d'entretien(28). Elle est en outre susceptible d'affecter la demande d'eau d'irrigation et des différents facteurs de production agricoles, mais également peut contribuer à orienter l'allocation des superficies agricoles aux différentes cultures développées. La différence des besoins en eau de cultures, pourrait en effet inciter les exploitants agricoles à renoncer aux cultures gourmandes en eau et à réallouer les superficies vers les productions les moins consommatrices d'eau.

Pour l'usage urbain et industriel de l'eau, la tarification s'exprime par le calcul des redevances. Il s'agit de mesurer la consommation d'eau et de facturer en fonction du volume d'eau consommé et de la régularité de l'approvisionnement. L'efficacité économique pourrait être atteinte si les redevances étaient alignées sur le coût d'opportunité de l'eau. En effet, tant que les coûts d'extraction restaient raisonnablement constants et les effets externes étaient limités, les prix arrêtés pour assurer le recouvrement des coûts pouvaient s'approcher des prix liés aux coûts marginaux. Cependant, l'augmentation considérable des coûts

(26) Dans beaucoup de pays, pour des raisons politiques, culturelles ou religieuses, il est plus rentable d'accroître l'offre que de relever les prix, et on se préoccupait peu de la gestion des prix et de la demande. Toutefois, les limites d'exploitation des ressources ont poussé les gouvernements de certains pays à réorienter leur stratégie vers une meilleure gestion de la demande. La conservation de la ressource et la rationalisation de son usage sont assurées par l'attribution de quotas aux différents secteurs demandeurs, ou par la hausse de son prix.

(27) Cette micro-irrigation, bien que revenant relativement coûteuse pour l'exploitant et nécessitant une source d'alimentation très fiable, permet d'augmenter fortement la productivité, notamment si elle est assortie d'utilisation des engrais ou d'autres produits chimiques.

(28) Le gouvernement s'est en effet engagé à relever le tarif de l'eau d'irrigation de 9% par an en termes réels. Cette hausse sera accompagnée par la restructuration de la tarification de manière à tenir compte des différences régionales de coûts. La nouvelle tarification repose sur les trois principes suivants :

- un terme fixe obligatoire proportionnel à la superficie exploitée de l'exploitation, calculé sur la base de la consommation minimale souhaitable et donnant droit à un volume de franchise correspondant ;
- un terme proportionnel à la consommation observée au dessus du volume en franchise ;
- une indexation automatique de tous les périmètres de la tarification fixe et proportionnelle, sur la base d'une formule incorporant les prix de produits agricoles, les salaires, le coût de l'énergie...

et le renforcement des effets externes, ont fait que le prix économique ou le prix lié au coût d'opportunité, grimpe pour dépasser le niveau nécessaire à la réalisation des objectifs fixés pour le recouvrement du coût. Le prix d'équilibre qui égalise les coûts réels de l'extraction de l'eau et sa valeur dans le cadre de son utilisation marginale, n'est plus alors possible ; l'utilisateur demeure non conscient de la valeur économique de l'eau, et n'est nullement incité à sa conservation et à son utilisation rationnelle.

Toutefois, dans la pratique, l'adoption immédiate d'une tarification fondée sur le coût d'opportunité pourrait être politiquement difficile ; les redevances d'eau restent bien en dessous du niveau nécessaire pour récupérer les coûts financiers, et encore plus pour relever les coûts marginaux et les effets externes dans la mesure où elles sont fixées à des niveaux qui n'indiquent en rien la véritable valeur économique de l'eau. Le public n'en est pas conscient, il n'est pas incité à la conserver, et on ne peut pas donc s'attendre à ce qu'il assume la responsabilité de sa protection et de sa conservation.

De ce fait, étant donné l'ampleur de la sous-valorisation des tarifs de l'eau et le faible niveau de recouvrement actuel des coûts et son importance pour la viabilité des opérations(29), la SONEDE devrait mettre en place et promouvoir une tarification de nature à lui assurer son autonomie financière. Il est question d'envisager le relèvement des tarifs par tranche, pouvant à la fois répondre aux besoins essentiels de l'ensemble de la population et être comptabilisé avec les principes du coût d'opportunité à la marge, de nature à allier à la fois critère économique et prise en considération des objectifs sociaux (Rogers, 1986).

Le principe consiste à établir des tarifs de telle sorte que les usagers reçoivent une certaine quantité d'eau pour un coût peu élevé, toute consommation supplémentaire leur étant facturée à un tarif supérieur. Il serait ainsi possible d'obtenir des prix économiques pour toute consommation supplémentaire tout en offrant des taux de base qui sont à la portée des classes sociales défavorisées, et en veillant en même temps à ce qu'au total, le barème assure le recouvrement total des coûts.

Une autre forme de subvention aux pauvres pourrait consister au recours à la formule de « redevances sociales », c'est à dire faire subventionner les pauvres par les catégories plus favorisées, et à celle des transferts budgétaires pour subventionner les branchements, en faisant toutefois garde de ne pas compromettre et de ne pas mettre en péril ni la viabilité, ni l'autonomie financière des services des eaux.

Toutes ces mesures peuvent donner l'impulsion nécessaire à une gestion décentralisée, rationnelle, économiquement viable, et socialement équitable.

4.4 Négligence de la qualité de l'eau, de la santé, et de l'environnement

A l'évidence des ressources en eau de qualité sont indispensables au progrès économique et à la sauvegarde du milieu naturel, gage même du progrès économique. En effet, une grande partie du patrimoine naturel, des écosystèmes du littoral aux marécages, dépend de l'eau. En réduire donc la qualité peut avoir des effets désastreux sur la santé, l'environnement et la biodiversité(30). Ce faisant, la protection, l'amélioration ou le rétablissement de la qualité de l'eau et la lutte contre la pollution de l'eau doivent faire l'objet d'opérations soutenues du secteur public et privé.

Or, beaucoup de pays en développement accordent peu d'attention à la qualité de l'eau et à la lutte contre la pollution ; la qualité des approvisionnements en eau y est médiocre, et l'eau est souvent impropre à la consommation. L'emploi d'eaux polluées pour la consommation humaine est à l'origine de nombreux problèmes sanitaires. La pollution des eaux a également des conséquences économiques et écologiques catastrophiques. La pollution de l'eau est examinée comme un problème d'externalité (Stigler, 1952). Elle représente une commodité indésirée pour un consommateur ou un input non désiré dans le processus de

(29) Les redevances d'eau restent inférieures au niveau nécessaire pour récupérer les coûts financiers malgré le léger relèvement du tarif de l'eau.

(30) Des efforts étaient déployés pour développer un indice total de la qualité de l'eau capable d'intégrer les indicateurs physiques, chimiques, bioligiques et micro-biologiques. Cet indicateur composite, désigné par l'indice de qualité de l'eau ou « Water Quality Index » (WQI), développé par la Fondation Nationale du Système Sanitaire (Brown et al, 1970), est défini comme suit : WQI = φ Wti qi, où WQI est une valeur numérique entre 0 et 100 ; qi est la qualité du ième paramètre défini par une valeur numérique entre 0 et 100, Wti est le poids du ième paramètre défini par une valeur numérique entre 0 et 100 et N est le nombre des paramètres. Les paramètres qi et Wti sont déterminés par un groupe de professionnels dans la gestion de la qualité de l'eau et choisis à partir d'une liste d'indicateirs, parmi lesquels on peut citer l'oxygène dissolu, le nitrate, le phosphate, la radioactivité, la température... Un risque majeur pour la santé est la formation possible dans une eau contaminée d'une nitrosamine carcinogénique (Williams et Culp, 1986). La couleur de l'eau est un paramètre qui est lié à l'acceptation du consommateur plutôt qu'à sa sécurité. La couleur d'un échantillon d'eau est mesurée par sa compraison avec un extrait standard de chlropulatinate de potassium (Sawyer et Mc Carty, 1967).

production d'une firme lorsque l'output est diminué par la pollution(31). Pour l'économiste c'est la « gratuité » des ressources qui est la cause première de la détérioration de l'environnement. Le Principe Pollueur Payeur (PPP) consiste en un abandon de cette gratuité en faisant de sorte que le pollueur prenne en compte les coûts d'utilisation ou de la détérioration des ressources environnementales (principe d'internalisation des coûts). L'objectif est alors de donner un « signal-prix » de façon à ce que l'environnement se trouve pleinement intégré dans la sphère marchande de l'économie. En tant que principe d'internalisation des coûts (la taxation des coûts ou déséconomies externes), le PPP, pur produit des « Economics of Welfare » (A.C. Pigou, 1920), peut être considéré comme un principe d'efficacité économique. L'internalisation des coûts d'environnement se fait en affectant un prix aux ressources environnementales. Puisque le marché ne fixe pas « spontanément » un tel prix, on impose un prix administré, sous forme de taxe. L'intensité d'utilisation de l'environnement sera fonction du niveau de ce prix. J.P. Barde définit la taxe ou redevance de pollution comme »un paiement effectué sur chaque unité de pollution déversée(32).

La décharge des déchets industriels non traités, l'exploitation minière, les écoulements de produits chimiques synthétiques non dégradables et agricoles, et les mauvaises pratiques d'utilisation des terres dans l'agriculture causent la dégradation massive des ressources de l'eau et des terres. Les projets d'assainissement manquent également faute de fonds(33) .

La solution consiste donc à développer des technologies peu coûteuses et mieux adaptées pour réduire les coûts élevés des systèmes classiques d'assainissement et d'évacuation des eaux d'égout.

L'intervention des secteurs privé et public doit aboutir à l'adoption d'un programme d'actions coordonnées en vue de mettre au point des techniques financières et institutionnelles permettant de réduire les coûts unitaires, de rendre efficace la fourniture et la gestion des services, et d'appliquer dans de bonnes conditions de coût-efficacité, des technologies permettant d'améliorer l'approvisionnement en eau, la protection contre les inondations, la surveillance et la réduction de la pollution, ainsi que le traitement des déchets(34).

Conjuguées à une politique de tarification basée sur le recouvrement des coûts, ces réformes de gestion des systèmes d'assainissement dégageront des fonds pour financer l'infrastructure sanitaire.

Dans le cas des déchets industriels, des écoulements miniers et des évacuations d'eaux usées, il serait recommandé de développer une stratégie équilibrée faite d'incitations économiques et de dispositions législatives et réglementaires efficaces pour maîtriser la pollution et dissuader les émissions d'effluents à la source, et en particulier les substances toxiques, et en stimuler la réutilisation.

Il est alors question de promouvoir l'application d'un système de prix économiques et l'imposition de taxes de pollution fondées sur le principe du pollueur-payeur pour encourager la conservation de l'eau et réduire la pollution.

5. Conclusion

La réforme institutionnelle, la décentralisation de la prestation des services d'eau, la privatisation, la participation des usagers et leur responsabilisation, et l'adoption d'un système de prix qui incite à utiliser judicieusement cette ressource, sont des éléments clés d'une gestion rationnelle des ressources en eau.

Pour qu'elle puisse parvenir à de bons résultats, une gestion décentralisée doit s'appuyer sur un cadre juridique approprié ainsi que sur une capacité réglementaire adéquate, compte tenu des considérations sociales, des externalités environnementales, et la tendance au monopole naturel qui font des systèmes de réglementation veillant à l'application des lois, accords, règles et normes en vigueur, une condition préalable d'une gestion décentralisée.

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(31) Ainsi comme il a été confirmé par Pearce et Turner (1990), un coût externe existe lorsque (i) une activité d'un agent cause une perte de bien-être pour un autre agent et (ii) la perte de bien être n'esst pas compensée. non potable, etc... (Coase,1960).

(32) Par exemple, 100 dinars par tonne de SO_2 dans le cas de la pollution de l'air, ou 200 dinars/kg de DBO (demande biochimique en oxygène) pour les déversements dans les eaux . Le taux de la taxe représente en quelque sorte le prix à payer pour l'utilisation de l'environnement (utilisation de l'air et de l'eau comme moyen d'évacuation des rejets polluants). (J.P.BARDE , 1991)

(33) En effet les conclusions d'une étude de l'expérience de la Banque Mondiale relative à 120 projets d'approvisionnement en eau et d'assainissement, montrent que 104 projets étaient destinés au financement de l'approvisionnement en eau et que 58 projets seulement comportaient un volet assainissement. En outre, à cause des dépassements de coûts, les volets assainissement de plusieurs projets furent éliminés.

(34) Dans ce cadre, l'utilisation des équipements d'assainissement municipaux par les entreprises doit être soumise au paiement de redevances calculées sur la base du volume et de la charge polluante des effluents industriels et doit obéir à des normes établis de traitement préalable.

Une gestion conforme aux principes de l'analyse globale, d'une tarification utilisant les coûts estimatifs d'opportunité comme guide, de la décentralisation, de la participation et de la protection de l'environnement, favorisera la conservation et améliorera l'efficacité de la distribution de l'eau, donnera plus de cohésion aux politiques et investissements entre secteurs, et répondra à une évaluation multi-critères incorporant des considérations d'équité, de développement durable, de préservation de la qualité de l'environnement et du bien-être social.

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Considerations on ethical issues in relation to groundwater development and/or mining

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Abstract

Large engineering structures have been constructed since early civilizations to develop irrigation and urban water supply. These hydraulic structures and their operation contributed significantly to the building of the civil society: cooperation and not confrontation was necessary for the common benefit. These are the so called hydraulic civilizations, like those developed in Egypt and Mesopotamia more than forty centuries ago. Development of groundwater through wells and/or infiltration galleries was at a smaller scale and usually did not require important societal cooperation.

During the first two thirds of this century most of the large water developments were based on surface water structures (dams and canals). Most of them were designed, constructed and operated by government agencies and heavily subsidised with public money. Nevertheless the second half of this century might be characterized by a strong development of groundwater mainly in arid and semiarid regions. Usually, this development has been performed by many individual users with little or no government planning and control. The growth in groundwater use has contributed significantly to provide food and potable water in arid and semiarid regions. Nevertheless, mainly because of the lack of knowledge and planning, this "wildcat" groundwater development has caused significant problems in a few regions. Such problems are often exaggerated or unknown because the lack of hydrogeological experience among many water planners who are often surface water-engineers.

One usual false paradigm or "hydromyth" among water resource planners is that groundwater is an unreliable or fragile resource; for them: "almost always every water well becomes dry of brackish after a few years". Another hydromyth is that groundwater mining (or development of non-renewable groundwater resources) is always an unethical attitude because it is unsustainable and damages future generations. It will be shown that this general statement is wrong because it only presents a simplistic perspective of a rather complicated problem. Each case is site-specific and all the factors (technological, economic, social, and ecological) should be assessed as accurately as possible, in order to make a scientifically sound and politically feasible decision. In summary, long-term groundwater mining may be ethical or unethical depending on the circumstances.

Keywords
Over-exploitation, overdraft, groundwater mining, sustainable yield, conflict resolution, freshwater ethics.

1. Introduction

Groundwater development has significantly increased during the second half of this century in most semiarid or arid countries. This development has been mainly undertaken by a large number of small (private or public) developers and often the scientific or technological control of this development by the responsible Water Administration has been weak. In contrast, the surface water projects developed during the same period are usually of larger dimension and have been designed, financed and constructed by Government Agencies which normally manage or control the operation of such irrigation or urban public water supply systems. This historical situation has often produced two effects: 1) most Water Administrations have limited understanding and poor data on the groundwater situation and value; 2) in some cases the lack of control on groundwater development has caused problems such as depletion of the water level in wells, decrease of well yield, degradation of water quality, land subsidence or collapse, interference with streams and/or surface water bodies, ecological impact on wetlands or gallery forests.

These problems have been frequently magnified or exaggerated by groups with lack of hydrogeological know-how, professional bias or vested interests. Because of this in recent decades groundwater over-exploitation has become a kind of "hydromyth" that has pervaded water resources literature. A usual axiom derived from this pervasive "hydromyth" is that groundwater is an unreliable and

fragile resource that should only be developed if it is not possible to implement the conventional large surface water projects.

Another usual "hydromyth" is to consider that groundwater mining – i.e. the development of non-renewable groundwater resources – is always an "overexploitation". The implication of this word is that groundwater mining goes against basic ecological and ethical principles. In this paper, which is an updated version of another paper (Llamas, 1998), it will be shown that such "hydromyth" may not be correct under certain circumstances.

2. Scope and aim

The aim of this article is to present a summary of: 1) the many meanings of the term over-exploitation and the main factors of the possible adverse effects of groundwater development; 2) the criteria to diagnose aquifers prone to situations of over-use; 3) the strategies to prevent or correct the unwanted effects of groundwater development in "stressed aquifers".

An emphasis will be put on the ethical issues in relation to the use of non-renewable groundwater. Nevertheless, groundwater mining is only an end case in the Ethics of water resources use. Therefore, the general framework of this paper will be the technical and ethical issues related to the management of "stressed aquifers".

But what is a stressed aquifer? During the last decade the expression "water stressed regions" has become pervasive in the water resources literature. Usually this expression means that those regions are prone to suffer now or in the near future serious social and economic problems because of water scarcity. Some authors insist in the probable outbreak of violent conflicts, that is**,** water wars among water stressed regions. The usual threshold to consider a region under water stress is 1000 m^3/person/year, but some authors almost double this figure. If this ratio is only 500 m^3/person/year the country is considered in a situation of absolute water stress or water scarcity (Seckler et al., 1998).

This simplistic approach of considering only the ratio between water resources and population has little practical application and is misleading. First of all most water problems are related to its quality and not its relative abundance. As a matter of fact, a good number of regions – such Israel or several watersheds in Spain – with a ratio lower than 500 m^3/year/person are regions with a high economic and social standard of life.

United Nations (1997) in its last Assessment of Global Water Resources has done a more realistic classification of countries according to their water stress. This assessment considers not only the ratio water/population but also the Gross National Product per capita. Other experts are beginning to use other more sophisticated indices in order to diagnose the current of future regions with water problems. The result of these analyses will probably show that a certain "water-stress" may be an incentive to promote the development of the region. In this case, it could be defined as a "eu-stress", i.e. a good stress. For example, during the last decades in a good number of semi-arid or arid regions tourist's activities or high value crops agriculture have been very intensive. The scarcity of precipitations has been fully compensated by the great amount of sun hours and the high radiation energy. The examples of these developments are the "sunny belt" in the USA and most of the European Mediterranean coast. The necessary water for these activities may have different origins. Groundwater is probably the greater and more frequent resource but also may be imported, recycled or desalinated water.

3. The manifold concept of over-exploitation

The term over-exploitation has been frequently used during the last three decades. Nevertheless, most authors agree in considering that the concept of aquifer over-exploitation is one that is poorly defined and resists a useful and practical definition (Adams and MacDonald, 1995; Collin and Margat, 1993; Custodio, 1992 and 1993; Foster, 1992; Llamas, 1992 a and b; Sophocleous, 1997).

A number of terms related to over-exploitation can be found in the water resources literature. Some examples are: safe yield, sustained yield, perennial yield, overdraft, groundwater mining, exploitation of fossil groundwater, optimal yield and others (Adams and MacDonald, 1995; Fetter, 1994). In general, these terms have in common the idea of avoiding “undesirable effects” as a result of groundwater development. However, this “undesirability” depends mainly on the social perception of the issue. This social perception is more related to the legal, cultural and economic background of the region than to hydrogeological facts.

For example, in a recent research study on over-exploitation financed by the European Union, called GRAPES, three pilot catchments were analysed; the Pang in the UK, the Upper Guadiana in Spain and the Messara in Greece. The main social value in the Pang has been to preserve the amenity of the river, related

to the conservation of its natural low flows. In the Messara the development of irrigation is the main objective and the disappearance of relevant wetlands has not been a social issue. In the Upper Guadiana the degradation of some important wetlands caused by groundwater abstraction for irrigation has caused a serious conflict between farmers and conservationists (Llamas et al., 1996; Cruces et al., 1997).

The Spanish Water Code of 1985 does not mention specifically the concept of sustainability in water resources development but frequently indicates that this development has to be respectful with nature. Nevertheless, it basically considers an aquifer "overexploited" when the pumpage is close or larger than the natural recharge. In other words, the Spanish regulations follow the common misconception of considering that the "safe yield" or "sustainable yield" is practically equal to the natural recharge.

This misconception, already shown by Theiss (1940), has been voiced by other American and Spanish hydrogeologists such as Bredehoeft et al. (1982), Llamas (1986), Shophocleous (1997) and Bredehoeft (1997). Bredehoeft et al. (1982, pag. 53, 54 and 56) describe the issue in the following way:

"Water withdraw artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction of the previous discharge from the aquifer, an increases in the recharge, or a combination of these changes. The decrease in the discharge plus the increase in recharge is termed capture. Capture may occur in the form of decreases in the groundwater discharge into streams, lakes, and the ocean, or from decreases in that component of evapotranspiration derived from the saturated zone. After a new artificial withdrawal from the aquifer has begun, the head of the aquifer will continue to decline until the new withdrawal is balanced by capture". "In many circumstances the dynamics of the groundwater system are such that long periods of time are necessary before any kind of an equilibrium conditions can develop".

As an example of the change in the social perception of water values it is interesting to remark that for Theiss (1940, pag. 280) the water "was gained" by lowering the water table in areas of rejected recharge or where the recharge was "lost" through transpiration from "non-beneficial vegetation" (phreatophytes). At Theiss' times "wetlands were wastelands".

Bredehoeft et al. (1982) present some theoretical examples to show that the time necessary to reach a new equilibrium or steady state between groundwater extraction and capture may take decades or centuries. Custodio (1992) has also presented a graph to show the relationship between the size of the aquifer, its difussivity and the time necessary to reach a new steady state after the beginning of a groundwater withdrawal and obtains similar values than Bredehoeft et al. (ibid).

On occasion of the preparation of new Spanish Water Law of 1985 these misconceptions were also discussed before the Law was enacted (Llamas et al., 1985) and afterwards (Pulido et al., 1989). Also two international Conferences on "overexploitation" were organized by Spanish hydrologists (cf. Simmers et al., 1992; Custodio and Dijon, 1992) in order to contribute to dispel these misconceptions. Nevertheless, up to now the success of these activities has been limited.

As was previously discussed, certain authors consider that "groundwater mining" is clearly against sustainable development and that this kind of "ecological sin" should be socially rejected and/or legally prohibited. Nevertheless, a good number of authors (Freeze and Cherry, 1979; Issar and Nativ, 1988; Llamas, 1992 a; Collin and Margat, 1993; Margat, 1994; Lloyd, 1997) indicate that, under certain circumstances, groundwater mining may be a reasonable option. As a matter of fact, groundwater mining is today practised in a good number of regions (Bemblidia et al., 1996; Custodio, 1993; Issar and Nativ, 1988; Zwingle, 1993). Fossil groundwater has no intrinsic value if left in the ground except as a potential resource for future generations, but are such future generations going to need it more than present ones?

4. Diagnostics of real or pretended over-used aquifers

4.1 Introduction

Adams and MacDonald (1995) noted that, in general, over-exploitation is only diagnosed "a posteriori". They have tried in their report and in other subsequent papers to present a method to analyse "a priori" the susceptibility of an aquifer to become stressed (or over-exploited). They consider three main effects or indicators: a) decline in waterlevels, b) deterioration of water quality and c) land subsidence. In this paper two other relevant effects are considered: d) the hydrological interference with streams and lakes; e) the ecological impact on aquatic ecosystems fed by groundwater.

Before describing these five indicators, it is relevant to mention that these indicators are sometimes wrongly used. This is either because of lack of hydrogeological knowledge or because certain lobbies may have an interest in expanding the "hydromyth" of the unreliability of groundwater development in order to promote the construction of large hydraulic works.

4.2 Groundwater-level depletion

It has not been unusual -like in the Spanish 1985 Water Law- to define over-exploitation as the situation when the groundwater withdrawal exceeds or is close to the natural recharge of an aquifer. The observation of a trend of continuous significant decline of the levels in water wells during one or two decades is frequently considered as a clear indication of imbalance between abstraction and recharge. This is a simplistic approach that might be a long way from the real situation as it has been shown previously, with reference to the papers of several authors, mainly Bredehoeft et al. (1982) and Custodio (1992).

When a well field is operated, even if the general input is much greater than pumping, a transient state will always occur before the water levels in wells stabilise. The duration of the transient state depends mainly on aquifer characteristics such as size and hydraulic diffussivity, degree of stratification and heterogeneity. On the other hand, the natural recharge of an aquifer in semiarid and arid climates does not have a linear relationship with precipitation. In dry years recharge might be negligible or even negative due to evapotranspiration or evaporation from the watertable. Significant recharge may only occur once every one or more decades. Therefore the water table depletion trend during a long dry spell -when the recharge is almost nil and the pumpage is high- might not be representative of a long-term situation.

4.3 Degradation of groundwater quality

Groundwater abstraction can cause, directly or indirectly, changes in groundwater quality. The intrusion into a freshwater aquifer of low quality surface or groundwater because of the change in the hydraulic gradient due to groundwater abstraction is a frequent cause of quality degradation. Saline intrusion may be an important concern for the development of aquifers adjacent saline water bodies. This is a typical problem in many coastal regions of semiarid or arid regions. The relevance of the saline water intrusion not only depends on the amount of the abstraction, in relation to the natural groundwater recharge, but also on the well field location and design, and on the geometry and hydrogeological parameters of the pumped aquifer. In many cases the existing problems are due to uncontrolled and unplanned groundwater development and not to excessive pumpage (cf. Custodio and Bruggeman, 1982).

The degradation of groundwater quality may not be related at all to excessive abstraction of groundwater in relation to average natural recharge. Other causes may be responsible, such as return flow from surface water irrigation, leakage from urban sewers, infiltration ponds for wastewaters, septic tanks, urban solid waste landfills, abandoned wells, mine tailings and many other activities not related to groundwater development (Foster et al., 1998; Barraqué, 1997). Also a temporary situation, such as a serious drought, can contribute to the degradation of groundwater quality (Lambrakis et al., 1997).

According to the European Commission, groundwater pollution is the most serious problem of the EU water resources policy. The Programme for the Integrated Management and Protection of Groundwater (Official Journal of the EU, 25 November 1996) has been designed to deal with this problem, although it is still too early to assess the practical effectiveness of this EU Programme.

Only in a few countries there exists an awareness of the crucial importance of preventing groundwater pollution in order to avoid a future water crisis. The old proverb: “out of sight out of mind” is very apt in this case. A strong educational effort is necessary in order not to bequeath next generations some of our better aquifers almost irreversibly polluted (Llamas, 1991). This is the real problem in most countries, humid, arid and semiarid. The depletion of groundwater storage (classical misconception of over-exploitation) is not generally a problem as serious as groundwater quality degradation and may often be solved without great difficulty, e.g. if water-use efficiency is improved.

One might think that the problem of groundwater quality degradation is mainly an issue in humid and industrialised regions. This does not seem to be the general situation. For instance, Salameh (1996) in his study of Jordan water resources says: “It is not water quantity, but its worsening quality that will bring us to our knees”. And Jordan is one of the countries with least amount of renewable water resources per capita (about 160 m^3/year and person) (Gleick, 1993, pag. 131; Bemblidia et al., 1996).

It is significant that the book Groundwater Protection published by the Conservation Foundation (1987) shows no significant concern about groundwater overdraft or overexploitation in the USA. The main interest is to mitigate groundwater pollution.

4.4 Susceptibility to subsidence and/or collapse of land surface

Sedimentary formations are deposited at low density and large porosity. As subsequent layers are deposited the overburden compresses the underlying strata. The overburden is in static equilibrium with the intergranular stress and the pore water pressure. This equilibrium is quickly reached in coarse-granular

layers, but in fine-grained layers with low permeability, it may take a long time. The effect of this process is the natural progressive consolidation of sediments.

When an aquifer is pumped the water pore pressure is decreased and the aquifer solid matrix undergoes a greater mechanical stress. This greater stress may produce compaction of the existing fine-grained sediments (aquitards) if the stress due to the decrease in water pore pressure is greater than the so-called “preconsolidation” stress. This situation has occurred in some aquifers formed by young sediments, such as those in Mexico City, Venice, Bangkok and others (Poland, 1985).

Caves and other types of empty spaces may exist under the watertable in karstic aquifers. When the watertable is naturally depleted the mechanical stability of the “roof” of such empty spaces may be lost and the roof of the cave collapses. This is a natural process that gives rise to the classical “dolines and poljes” in the karstic landscape. When the water table depletion or oscillation is increased by groundwater abstraction the frequency of karstic collapses can be also increased. The accurate prediction of such collapses is not easy (LaMoreaux and Newton, 1992).

In both cases the amount of subsidence or the probability of collapses is related to the decrease in pore water pressure which is related to the amount of groundwater withdrawal. Nevertheless the influence of other geotechnical factors may be more relevant that the amount of water abstracted in relation to the renewable groundwater resources of the aquifer.

4.5 Interference with surface water bodies and streams

Some anthropogenic activities may have a significant impact on the catchment hydrologic cycle, as was already stated by Theiss (1940) and Bredehoeft et al. (1982). For example in the Upper Guadiana catchment in Spain (Cruces et al, 1997), a serious water table depletion (about 30-40 m) has decreased the evapotranspiration from the watertable and wetlands between 100 and 200 Mm^3/year. This depletion has degraded several important wetlands but has increased significantly the renewable water resources that can be used for irrigation, which were estimated between 300 and 400 Mm^3/year under non-disturbed situation. The artificial depletion of the water table can also change dramatically aquifer-streams relationship. “Gaining rivers” fed by aquifers may become dry except during storms or humid periods when they may become “losing rivers”, an important source of recharge to the aquifer. Nevertheless, this "new water budget" may present legal problems if the downstream water users have previous water rights. This is also the case in the Upper Guadiana river in Spain.

4.6 Ecological impacts

Ecological, real or pretended impacts are becoming an important new constraint in groundwater development in some countries (Llamas, 1992 b; Acreman and Adams, 1998). These impacts are mainly caused by water table depletion. This can induce different effects such as: 1) decreasing or drying up of springs or low flow of streams; 2) diminution of soil humidity to an extent in which phreatophitic vegetation cannot survive; 3) changes in microclimates because of the decrease in evapotranspiration. In some cases, the ecological impact of such changes is obvious. For instance, if the water table that was previously at land surface and it is lowered by more than 10 meters during more than twenty years it is obvious that the peatland or riparian forests that might exist on that aquifer are not going to survive. But if the water table is depleted only during one or two years and not more than one or two meters probably it cannot be assured that the ecological impact will be irreversible. Quantitative and detailed studies on this type of problems are still rather scarce.

5. Strategies or criteria to solve the problems of “stressed” aquifers

5.1 Introduction

In this section seven criteria or strategies are presented in order to solve the potential impacts or problems that groundwater development can induce. One aim of this paper is to analyse the Ethics of groundwater mining but such analysis demands a more general framework. Perhaps the main moral of this paper is that an "stressed aquifer system" can become an "eu-stressed aquifer system" if the criteria described hereafter are applied.

5.2 Diagnostic method of aquifer susceptibility to excessive abstraction

As previously mentioned, Adams and MacDonald (1995) proposed a method to make an “a priori” diagnosis of aquifer susceptibility to over-exploitation effects. The method established three levels of susceptibility

which relate to groundwater level decline, saline intrusion and subsidence. The ecological impacts and the influence of groundwater abstraction in surface water hydrology are not graded. The technique involves assigning numerical values to the contributing factors and then summing them up to give an overall grade or susceptibility to the particular impact under consideration. Only relative values are used in the final designation (high, medium, low) due to the high parameter variability at individual locations. According to these authors, as only relative values are used in the grading, this diagnostic method should only be used with great caution for inter-regional comparisons.

5.3 Management of uncertainties

A generally accepted principle is that “prevention is better than cure”. But this version of the precautionary principle should be applied with considerable prudence. In general, groundwater development should not be rejected or seriously constrained if it is well planned and controlled. During recent decades, notable socio-economic benefits have derived from groundwater withdrawal**,** particularly in developing countries. It has provided affordable potable and irrigation water**,** thus improving public health and significantly contributing to alleviate malnutrition and famine.

An important first step when trying to manage a resource in the face of uncertainties**,** is to assess the seriousness and type of the assumed problem. Often the adverse effects of “over-exploitation” may be misunderstood or exaggerated. This is often the case in relation to the interpretation of a long (e.g. 10 years) water level decline as an indication of a groundwater abstraction higher than the average renewable resources. As previously explained, such a decline may be due to: a) a dry spell, 2) a transient situation, or 3) scarce or incorrect data about streamflow, groundwater levels, climatic conditions, groundwater abstractions and natural recharge. The two last factors are usually difficult to determine in arid and semiarid countries.

Frequently it will be necessary to ask for more funds in order to obtain more and/or better data. Nevertheless, the natural recharge in semiarid regions will only be accurately known after a good number of years of good climatic and hydrological data have been collected. One should avoid transferring to the public a sense of accuracy that is really only illusory.

The use of numerical models to analyse groundwater flow and management might be useful. Such models should employed to perform sensitivity analysis of the plausible variations of the stochastic and deterministic parameters, including those related to social sciences, such as the possible future scenarios of the irrigated agriculture in the next decades.

Uncertainty about water resources is usually not higher in when dealing with groundwater as compared with surface water or other water policy**-**related problems. A good example of such uncertainties is related to the general exaggeration that is associated with the prediction of future water demands. Gleick (1998) has analysed the progressive decline in estimates of future water demands, according to different authors. These have decreased from 7,000 km^3/year about 20 years ago, to less than 4,000 km^3/year in one of the latest predictions issued by United Nations (Shiklomanov, 1997). Even this last prediction is probably exaggerated. For example, it estimates a 20% growth in North America´s water demand. However**,** the U.S. Geological Survey (Solley, 1997) has indicated a steady decline in total water uses in the USA over the past two decades, while during that same period population and standard of life have continued to grow during. Wood (1999) considers that this decline may be due to the pressure of conservation groups that have demanded a more efficient use of water.

In summary, professional hydrogeologists should transfer the awareness of these uncertainties to decision makers and the general public. This transfer must be done with prudence and honesty in order to avoid loss of credibility of the scientific community either in the short term (by giving the impression of lack of knowledge) or in the medium term (because of the failure of the predictions to be realised). The frequent and widely voiced "gloom and doom" pessimistic predictions done by certain individuals and/or institutions about the depletion of natural resources or the population explosion have usually not been realised. For example, Dyson (1996) shows how the predictions done along the last three decades by the "pessimistic neo-malthusians" have not been realised. On the other hand, quite recently, according to Pearce (1999), it seems that the focus about population explosion is misplaced and next century may have to worry about falling birth rates, not rising ones.

5.4 Is it ethical to abstract non-renewable (fossil) groundwater?

In most countries it is considered that groundwater abstraction should not exceed the renewable resources. In other countries -mainly in the most arid ones- it might be considered that groundwater mining is an acceptable policy, as long as available data assure that the groundwater development can be economically maintained for a long time, for example, more than fifty years and that the potential ecological costs and

socio-economic benefits have been adequately evaluated (Llamas et al., 1992). Nevertheless, some authors consider this option as unsustainable development or a dishonest attitude with respect to future generations. What Lazarus (1997, pag. 22) proposes for South Africa could also be the policy in many other countries: "In essence, current thinking in the sector is that strategies need to be developed to ensure that groundwater resources are utilised within their capacity of renewal. It is recognised however that quantification of sustainable use levels requires extensive research".

In contrast, few authors speak of the frequent unsustainability of most dams in arid regions. Bemblidia et al. (1996, pag. 20) consider that the "useful life" of most dams in the North African Mediterranean countries use to be between 40 and 200 years because of their silting.

Lloyd (1997) states that the frequently encountered view that the water policy of arid zone countries should be developed in relation to renewable water resources is unrealistic and fallacious. Ethics of long-term water resources sustainability must be considered with ever improving technology. With careful management many arid countries will be able to utilise resources beyond the foreseeable future without major restructuring.

In Saudi Arabia, according to Dabbagh and Abderrahman (1997), the main aquifers (within the first 300 m of depth) contain huge amount of fresh fossil water -a minimum of 2,000 km^3- that is 10,000 to 30,000 years old. It is considered that these fossil aquifers can supply useful water for a minimum period of 150 years. Current abstraction seems to be around 15-20 km^3/year. Another example is the situation of the Nubian sandstone aquifer located below the Western desert of Egypt. According to Idriss and Nour (1990), the fresh groundwater reserves are higher than 200 km^3 and the maximum pumping projected is lower than 1 km^3/year. Probably similar situations do exist in Libia and Algeria.

It is not easy to achieve a virtuous middle way. As Collin and Margat (1993) state: "we move rapidly from one extreme to the other, and the tempting solutions put forward by zealots calling for *Malthusian underexploitation of groundwater* could prove just as damaging to the development of society as certain types of excessive "pumping".

5.5 Apportioning the available groundwater resources in an equitable manner

The distribution of the estimated available groundwater renewable resources or fossil groundwater among the potential or actual users may be a source of conflict between persons, institutions or regions. There is no universal solution. Each case may be different according to the cultural, political and legal background of the region. Nevertheless, it may be useful to try to achieve some kind of universal agreement on the ethical principles that should rule water distribution and management. The recent initiative of the International Association of Hydrologists to create a Working Group to analyse the problems in internationally shared aquifers may become a positive step forward.

5.6 Mitigating ecological impacts

The ecological cost of groundwater development should be compared with the socio-economic benefits produced (Barbier et al., 1997). The evaluation of the ecological impacts is highly dependent on the social perception of ecological values in the corresponding region. This social perception is changing rapidly in most countries. For example, the new Framework Directive on Water of the European Union (in preparation) pays great attention to monitoring and conservation of aquatic ecosystems and especially to wetlands. In arid and semiarid regions wetlands or oases are usually rare and related to groundwater discharge zones. The development of groundwater for irrigation or other uses may often have a significant negative impact on the hydrological functioning of wetlands or oases. These impacts should be properly evaluated by decision-makers.

The social relevance of the conflict between nature conservation and groundwater development and its solution will be different from country to country and also changes with time.

5.7 Socio-economic issues

Groundwater development has produced great economic benefits in many respects during the last half of this century. For example, the intensive use of groundwater for irrigation has contributed significantly to alleviate the problem of hunger or famines and of potable water supply to cities and rural areas. Although in some cases this groundwater development has induced some of the problems previously described (depletion of water levels, degradation of water quality, subsidence, deterioration of aquatic ecosystems and land subsidence), this author is not aware of any case of a large aquifer (e.g. with a surface greater than 1,000 km^2) in which intensive groundwater development has caused social disturbances. In contrast, serious social problems are well known because of the construction of dams (e.g. Narmada Valley in India), soil

water logging and salinisation (e.g. S. Joaquin Valley in California and Punjab plain in Pakistan) or water diversions (e.g. Aral Sea disaster).

Economic studies analysing in detail stressed aquifer cases are still rare. In his economic analysis of over-exploitation, Young (1992) defined it as a "failure to achieve maximum economic returns of the resource". Nevertheless, the estimation of the real economic cost of the different factors is a difficult and controversial matter. Therefore the final solution of conflicts related to overexploitation will not probably be only dictated by economic rules; socio-political motivations may play the leading role.

Different scenarios can be presented in relation to the economy of over-used aquifers. Among them, two extreme situations are unrestricted (free) development against controlled development (Custodio and Gurgui, 1989, and Foster, 1992). More recently an attempt to guide the economic valuation of wetlands has been published (Barbier et al., 1997).

Another issue to be considered is the almost universal policy of public "perverse subsidies" for water supply, mainly for irrigation. According to Myers and Kent (1998) these subsidies are those which are noxious both for the economy and the environment. In most cases, the water users only pay a small fraction of the real cost of the water supplied. This is especially true in surface water for irrigation. Water policy all over the world has, during the past decades, focussed on the management of the supply and not to on the management of the demand. This has induced an almost universal wasteful use of water.

In most groundwater developments the situation may be quite different. The owners of the water wells usually pay for the wells' construction, maintenance and operation. But they do not usually pay the external costs caused by the impacts of the groundwater abstraction.

The great socio-economic benefits produced by groundwater developments are rarely documented. According to Dhawan (1995), research in India indicates that yields in areas irrigated with groundwater are one third to one half higher than those in areas irrigated with surface resources. In a previous report Dains and Power (1987) estimated that as much as 70-80% of India's agricultural output may be groundwater dependent. More recently, the Indian Water Resources Association (1999) has published, among others, the following significant data:

- Groundwater is contributing at present 50 percent of irrigation water, 80 percent of water for domestic use in rural areas, and 50 percent of water in urban and industrial areas;
- Groundwater abstraction structures have increased from 4 million in 1951 to nearly 17 million in 1997;
- In the same period groundwater irrigated area has increased from 6 to 36 million ha;
- It is estimated that this rapid pace of development is likely to continue and will reach 64 million ha in the year 2007.

Corominas (1999) has recently published an assessment of irrigated agriculture in Andalusia (Spain). It is a well documented analysis. Some significant data from this study are:

- Out of 800,000 ha currently under irrigation, 75% use surface water and 25% groundwater;
- Average water applied per ha is 4000 m3/ year in groundwater irrigation and 7500 m3/year in surface water;
- The average economic yield per ha is more than three times greater in groundwater irrigated areas than in surface water irrigated areas;
- The economic yield by cubic meter used is five times higher in groundwater than in surface water.

The main explanation for these striking differences is probably that: 1) surface water cost for farmers is almost nil and water is wasted; 2) groundwater is more reliable against drought than surface water; therefore, most high value crops use groundwater.

5.8 Stakeholders participation and education

There exists a general consensus that, in order to avoid conflicts and to move from confrontation to cooperation, water development projects require the participation of the social groups affected by the project, the stakeholders. The participation should begin in the early stages of the project and should be, as much as possible, bottom-up and not top-down. The first question is to define who the stakeholders are; the second, how, when and where they should intervene in the decision making processes.

The Spanish experience, in trying to implement groundwater management as a public dominion, indicates clearly that the active collaboration of Groundwater Users Associations is a key element (Aragonés et al., 1996).

Recently the Spanish Ministry for the Environment (MIMAM, 1998) has proposed a programme to inventory, diagnose and manage the "overexploited and/or salinazed aquifers of Spain". In this author's

opinion, this is an interesting attempt but it seems designed from a top-down central Government technocratic perspective to be implemented through consulting firms. This will not solve the real problems because two important factors are not even mentioned in the programme: a) the participation of the stakeholders (mainly farmers and conservation groups); and b) the crucial need of educational programmes to implement the theoretically good technical solutions.

Obviously, there is not a universal solution. For example, in some arid and semiarid developing countries, when dealing with correction of ecological impacts of overexploitation, the influence of conservationists groups will probably be weak compared to the influence of farmers associations or urban water supply companies.

The necessary participation of the stakeholders demands that they are aware of the way the issue at hand will affect them directly or indirectly**,** and also a basic knowledge of the hydrogeological concepts involved in aquifer development. Probably in most countries there exist a good number of "hydromyths" (wrong ideas) about the origin, movement and potential for pollution of groundwater. In any stressed aquifer it is essential to organise different types of educational activities aimed at different groups: from school students and teachers to officials of Water Administrations.

6. Conclusions

6.1 Various factors that have made possible the significant increase of groundwater development

Various factors have made possible the significant increase of groundwater development over the second half of this century, particularly in arid and semi-arid regions:

1. Technological: invention of the multistage pump, improvements in drilling methods and in the advance of the scientific knowledge on occurrence, movement and exploration of groundwater.
2. Economic: the real cost of groundwater is usually low in relation to the economic benefits obtained from its use.
3. Sociological: groundwater development can easily be carried out by farmers, industries or small municipalities, without financial or technical assistance from Water Authorities. It does not require significant financial investments or public subsidies like surface water projects typically do.

6.2 Significant socio-economic benefits of groundwater development

The socio-economic benefits of groundwater development have been significant.

Groundwater is an important source of potable drinking water. World-wide 50 per cent of municipal water supplies come from groundwater. In some regions the proportion is much higher. In general, groundwater is particularly important as a source of drinking water for rural and dispersed population.

Seventy percent of all groundwater withdrawals world-wide are used for irrigation, particularly in arid or semi-arid regions. In India, for instance, 50 per cent of all water used for irrigation comes from groundwater sources. Irrigation with groundwater has been crucial to increase food production at a greater rate than population growth.

Irrigated agriculture using groundwater is often more efficient than irrigation using surface water. This is mainly because groundwater irrigation farmers typically assume all abstraction costs (financial, maintenance and operation).

6.3 Groundwater administration

In most countries, groundwater development has not been adequately planned, financed, or controlled by existing Water Authorities. Historically, officers of these agencies have been trained to manage surface water systems and lack adequate hydrogeological training. The result use to be a bias toward surface water management and the frequent mismanagement of groundwater sources.

Groundwater management presents particular challenges given the great number of users on a single aquifer system. Coordination among the thousands of stakeholders that generally exist on an aquifer of medium or large size uses to be scarce. Various reasons can account for this: 1) the coordination was not really necessary at the beginning of the development; 2) the usual tendency among farmers to individualism; and 3) the lack of willingness to promote such coordination by the Water Authorities.

6.4 Emerging problems in groundwater developments

In certain regions unplanned and uncontrolled development has caused certain problems, which can be classified in five groups:

- Excessive drawdown of the water level in wells, which increases costs by requiring more pumping energy. Some shallow wells may become dry. Nevertheless, there is no documented case of a medium or large aquifer which has been physically emptied.
- Degradation of water quality because of different factors such as point pollution coming from the surface or from saline groundwater intrusion from adjacent aquifers. Pollution coming from the surface is generally not caused by groundwater use but by inadequate land use planning. In most countries, groundwater pollution or degradation is the main threat to achieve a sustainable water resources management.
- Land subsidence or collapse may be induced by groundwater abstraction but it is more related to the geotechnical properties of the terrain and to the location of the well fields than to the amount of groundwater withdrawal.
- *Impact on surface water bodies and in the water cycle of the whole basin.*
  In some rivers intensive groundwater pumping has caused significant changes in their hydrological regime with the consequent legal problems when the water of such river was previously allocated to other users. Nevertheless, the total renewable water resources in the basin can be significantly increased because of the augmentation of the natural recharge.
- *Impact on wetlands and other aquatic ecosystems.*
  Relatively small (e.g. 2 m) but long-term (e.g. 10 years) depletion of the water table often causes dramatic changes in wetlands, springs and riparian forests. These impacts have only been a cause of concern during the last three of four decades.

6.5 Five ethical issues in groundwater use

Five ethical issues are considered relevant in trying to achieve sustainable or reasonable groundwater use.

1. *Perverse subsidies to surface water projects*
   The hidden or open subsidies that have traditionally been a part of large hydraulic works projects for surface water irrigation, are probably the main cause of the pervasive neglect of groundwater problems among water managers and decision makers. Surface water for irrigation is usually given almost free to the farmers; and its wasteful use is the general rule.
   Progressive application of the “user pays” or “full cost recovery” principle would probably make most of the large hydraulic projects economically unsound. As a result a more comprehensive look at water planning and management would be necessary and adequate attention to groundwater planning, control and management would probably follow.
2. *Public, private or common groundwater ownership*
   Some authors consider that the legal declaration of groundwater as a public domain is a “conditio sine qua non” to perform a sustainable or acceptable groundwater management. This assumption is far from evident. For many decades groundwater has been a public domain in a good number of countries. Nevertheless, sustainable groundwater management continues to be a significant challenge in many of those countries. Highly centralized management of groundwater resources is not the solution but to promote solidarity in the use of groundwater as a “common good”. Groundwater management should be in the hands of the stakeholders of the aquifer, under the supervision of the corresponding Water Authority. The stakeholders’ participation has to be promoted bottom-up and not top-down.
3. *Lack of hydrogeological knowledge and/or education*
   Adequate information is a prerequisite to succeed in groundwater management. It has to be a continuous process in which technology and education improve solidarity and participation to the stakeholders and a more efficient use of the resource.
4. *Transparency in groundwater related data*
   Good and reliable information is crucial to facilitate cooperation among aquifer stakeholders. All stakeholders should have easy access to good, reliable data on abstractions, water quality, aquifer water levels. Current information technology allows information to be made available to an unlimited number of users easily and economically. Nevertheless, in a good number of countries it will be necessary to change the traditional attitude of water agencies of not facilitating the easy access to water data to the general public.

5. *The ethics of pumping non-renewable groundwater resources (groundwater mining)*
   Some arid regions have very small amounts of renewable water resources but huge amounts of fresh groundwater reserves, like for example the existing reserves under most of the Sahara desert. In such situations, groundwater mining may be a reasonable action if various conditions are met: 1) the amount of groundwater reserves can be estimated with acceptable accuracy; 2) the rate of reserves depletion can be guaranteed for a long period, e.g. from fifty to one hundred years; and 3) the environmental impacts of such groundwater withdrawals are properly assessed and considered clearly less significant that the socio-economic benefits from groundwater mining.

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The Rum-Saq aquifer resource – risk assessment for long term resource reliability

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Abstract

The Rum-Saq aquifer is a part of the Arabian Nafud basin fossil aquifer system. It represents one of the last major fresh water resources for the Region, which can alleviate shortages that will become critical within the next five to ten years. A significant study has been carried out to evaluate the resource yield and reliability of supply, in advance of plans to extract upto 250 Mm^3 for a minimum of 30 years, at an investment of over $630M. A substantial quantity of this water will be transmitted 350 km to the north of the proposed wellfields, to satisfy the deficits in north Jordan.

Field investigations (1992-1993) included a drilling programme of 18,800 m linear metres, with some holes drilled to 1,500m depth, comprehensive geophysical logging, over 6,000 hours of pump testing at 12 sites and a comprehensive synthesis of the data by means of a 3D mathematical model, extending over the 70,000 km^2 of aquifer area. Additional lumped parameter modelling, hydrochemical modelling, laboratory analysis of formation cores for hydraulic parameters, was also carried out.

A key factor in the reliability of the resource for beneficial use by Jordan could be the impact of production from the aquifer outside its territory, in Saudi Arabia. Resource production there (650 Mm^3/a) is approximately ten fold the current production in Jordan. A risk assessment procedure was adopted to gain an insight into the critical issue, of long term reliability and how investments should be managed.

The risk model included all the hydrogeological parameters, i.e. formation characteristics, inter formation relationships of leakage of poor quality water, wellfield infrastructure problems, variation of the annual (very limited) recharge, etc. In addition the risk derived from actions on the Saudi side were analysed; water resources there until recently were destined for wheat production but current trends suggest that wheat production is to drop, with a consequent supposed drop in aquifer production. However, the risk of continued high production for alternative crops (fruit or barley, etc.) or other activities (mining or other manufacturing industry) needed to be incorporated into the hydrogeological risk assessment. The presentation will highlight these issues and describe the conclusions of the risk assessment, concluding that the best option for the beneficial development of this transboundary resource might be through a joint treaty, managed and developed through an International Rum-Saq Aquifer Commission (IRSAQ). The issues in developing such an approach will be explored in the paper.

1. Introduction

The Rum-Saq aquifer is a part of the Arabian Nafud basin fossil aquifer system being one of several that are present in the whole of North Africa and the Middle East. The region as a whole is characterised by arid conditions and large expanses of uninhabited land. Majorities of the populations live either along the major rivers river systems or in the coastal regions. The region is underlain by these relatively large aquifers which are receive very limited contemporary recharge due to natural climatic changes over the last several tens of thousands of years. In developing these resources the key issues that need to be addressed by scientists and decision makers are concerned with sustainability and reliability in the longer term, as defined for planning purposes. This paper describes a project, which reviewed a very extensive range of issues in the development of the Rum-Saq aquifer as far as it contributes to resources for Jordan.

The Rum Saq aquifer represents the last major fresh water resource that Jordan can develop, to alleviate shortages which will become critical within the next five to ten years. A significant resource study has been carried out to evaluate the resource yield and reliability of supply, in advance of plans to extract upto 250Mm^3 for a minimum of 30 years, at an investment of over $630M. A substantial quantity of this water will be transmitted 350 km to the north of the proposed wellfields, to satisfy the deficits in the capital city, Amman (Harza Group 1997).

2. Hydrogeology & explorations

Field investigations (1992, 1993) included a drilling programme of 18,800 m linear metres. Some holes were drilled to 1,500 m depth with comprehensive geophysical logging, over 6,000 hours of pump testing at 12 sites and a comprehensive synthesis of the data by means of a 3D mathematical model, extending over the 70,000 km^2 of aquifer area were completed. Additional lumped parameter modelling, hydrochemical modelling, laboratory analysis of formation cores for hydraulic parameters, was also carried out.

2.1 Exploration design approach

Drilling investigations have been carried out in the southern desert since the mid 1960's. Therefore the first stage of the project was to identify areas where new deep wells could be drilled with sufficient monitoring boreholes to conduct long term test pumping. The overall aim was to identify areas where additional abstraction would be feasible to supply the major demand centre of North Jordan including Greater Amman via a 350 km pipeline whilst also ensuring current production for irrigation is sustained.

Using flownet analysis the exploration area was split into aquifer blocks and for each block the most appropriate analysis was carried out. In blocks currently in production, the existing wells were evaluated to assess the impact of continued long term production, while in the remaining blocks, exploration holes of appropriate design were drilled in locations defined on the basis of expected hydrogeology (Table 1). The main constraint was the capacity of the drilling rigs available. The only rigs available when the project commenced were water well rigs with a maximum capacity to drill and install casing to depths of around 600m. Fortunately oil standard drilling rigs were provided later, increasing depth capacity and consequently a more appropriate data set was obtained giving a more detailed description of the aquifer.

Table 1: Exploration design approach for Qa Disi Aquifer Study

Block	Characteristics	Assessment need	Exploration needs
A	Unconfined outcrop area. Aquifer thickness 400m. Currently in use for irrigation. Water quality remains good. Drawdowns increasing at about 1m/year	Review well logs, production data, devise improved wellfield operational management	None required except minor rehabilitation of monitoring wells
B	Confined area. Aquifer thickness ca. 400m, below 100m of aquitard. Currently in use for irrigation. Quality apparently good. Drawdown decline rate approx. 1.5 m/year	As above, with construction of monitoring wells into the overlying formations for detection of leakage of poorer quality water into the Rum Aquifer	As above, with new monitoring wells
C	Confined area. Aquifer thickness ca.800m, below 400m of aquitard. Area not in use. Aquifer geometry conjectural. Water quality conjectural Potential yield unknown	Review available sparse geophysics data and reinterpret physical geology	Design a detailed exploration programme with drilling and testing to establish missing data, for use in 3-D, regional mathematical model

Previously knowledge of the regional aquifer geometry and water yield was conjectural because the focus of interest was limited to the vicinity of wellfields. Earlier modelling studies had isolated portions of the Rum Aquifer, ignoring the regional system for which little or no data were available. In this study, aimed at a long term planning strategy of 200 years, it was very clear that the whole flow system, as shown in Figure 1, must be included in the assessment in order to incorporate the long term impacts of any future development in neighbouring Saudi Arabia.

2.2 Definition of the aquifer system

The Rum Aquifer underlies southern Jordan and a large part of northern Saudi Arabia, where it is called the Saq Aquifer, with groundwater in this huge aquifer flowing generally from the southern and south-western outcrops to the north, and discharging westwards to the Dead Sea. The aquifer comprises a sequence of Cambro-Ordovician (ca. 600 to 450 million years old) sandstones with an average thickness of about 1000 metres and a maximum of over 2000 metres. It is one component of the Aquifer System defined by the recent Qa Disi Aquifer Study in southern Jordan (Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995):

Table 2

System Component	Geological Unit	General Characteristics
Leaky layer	Khreim Group	heterogeneous unit of sandstones, bearing moderate/poor quality groundwater, mudstones, shales & claystones
Confining layer	Hiswa Shale	a low permeability shale unit, consistently about 50 m thick
Rum Aquifer	Rum Group	a thick sequence of permeable sandstones, bearing good quality groundwater
Aquifer base	Basement rocks	low permeability granitic sequence intruded by numerous dykes

2.3 Aquifer properties

The Qa Disi Aquifer Study demonstrated that the Rum Group sandstones have excellent aquifer properties in this region. Specifically, they have high transmissivities (1000 to 1500 m^2/day) which facilitate groundwater flow, and high storage coefficients (1x10-3 to 5x10-3) which result in large volumes of water being stored in the aquifer. In addition, the water is of good quality having a total dissolved solids (TDS) of about 250 milligrams per litre (mg/l) in the unconfined aquifer, while the confined aquifer, even at depths of 1200 metres has a TDS of about 435 mg/l. (El Naser 1997a, 1997b). Both concentrations comply with the national drinking water upper limit, set as a range of 500 to 1500 mg/l (Jordanian Industry and Trade Ministry, 1990).

3. Development of resources

The groundwater currently being abstracted is used mainly for large scale local irrigation, but also for supply of urban and rural communities in the surrounding area including Aqaba. During the Qa Disi Aquifer Study, collation of available abstraction records, coupled with interpretation of satellite imagery of crop pivots in terms of water usage (Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995), allowed the estimation of 1982 to 1993 abstraction rates from the Rum-Saq Aquifer. These together with population, agricultural and industrial growth figures have been used to predict future abstractions. The scenario placing the greatest demand on the aquifer system resulted in the following estimates and predictions:

Table 3: Groundwater abstraction rates

	Groundwater Abstraction Rates (MCM/year)		
	1993	***2000***	***2014***
Jordan	75		87 then remaining constant
Saudi Arabia	650	977 then remaining constant	

3.1 Modelling demand scenarios

By implementing a range of modelling techniques (e.g. a three-dimensional mathematical model and a simpler lumped parameter model), the past and current behaviour of the aquifer in response to natural water level recession and increasing abstraction has been simulated, and the impact of future abstractions predicted. Based on the model investigations, and a complementary risk assessment, the Qa Disi Aquifer Study established that abstractions of new abstraction could be developed in southern Jordan, in addition to the above abstractions. These could be maintained over the period 2000 to 2040, taking account of both declining water levels and potential deterioration in water quality.

A key factor in the reliability of the resource for beneficial use by Jordan could be the impact of production from the aquifer outside its territory, in Saudi Arabia. Resource production there (650 Mm^3/a) is approximately ten fold the current production in Jordan. A risk assessment procedure was adopted to gain an insight into the critical issue, of long term reliability and how investments should be managed.

3.2 Risk assessment model

The risk model included all the hydrogeological parameters, i.e. formation characteristics, inter formation relationships of leakage of poor quality water, wellfield infrastructure problems, variation of the annual (very limited) recharge, etc. In addition the risk derived from actions on the Saudi side were analysed; water resources there are currently destined for wheat production but recent trends suggested that wheat production is to drop, with a consequent supposed drop in aquifer production. However, the risk of continued high production for alternative crops (fruit or barley, etc.) or other activities (mining or other manufacturing industry) needed to be incorporated into the hydrogeological risk assessment.

4. Meeting future demand

It has been predicted that Jordan will have a 1200 MCM water deficit for 2015. Resources that should become available from the Jordan-Israel Peace Treaty, plus the new resources from the Rum Aquifer only balance about 30% of this deficit. Further development of the Rum Aquifer may be possible as knowledge of the resource increases, but embodied within the recommendations of the Study is the risk-based recognition, that uncertainties in Saudi Arabian abstractions could have measurable impact on Jordanian groundwater resource management planning. Specifically, this is related to:

- the magnitude of Saudi Arabian abstractions, and
- the development of new Saudi wellfields closer to the border with Jordan.

As a result of the importance of these uncertainties, the increased utilisation of groundwater resources from the Rum Aquifer in Jordan cannot be contemplated without addressing international groundwater issues (Puri & Jones 1997). Such issues make it essential to establish a management framework for further development of the Rum-Saq Aquifer groundwater "capital" and to assist in long term strategic decision making, in particular the identification and development of an alternative, sustainable water resource. This step should be complemented by the drafting of an international groundwater treaty (e.g. Hayton & Utton 1989) between Jordan and Saudi Arabia, culminating in the institutionalisation of collaboration between the two countries in the form of a Rum-Saq groundwater basin resource management commission.

Acknowledgement

The authors are indebted to Scott Wilson and the Ministry of Water & Irrigation in allowing the authors time to prepare this paper. They would also like to acknowledge the work of their colleague Dr M Jones, for the risk analysis conducted for the study.

The views expressed in this paper do not necessarily reflect the views of the Ministry of Water & Irrigation, Jordan and are those of the authors alone.

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Deep non-renewable groundwater in Syria and future strategic options for the management of water resources

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Abstract (see full text in Arabic at the end of this volume)

As water supplies continue to decrease sharply in arid and semi arid zones, exploring and harnessing new resources in different parts of the world becomes a fundamental need, to meet growing demand.

The Arab Countries, situated in the heart of arid zones of the world explore different technological options that are adaptable to prevailing economic and environmental conditions. The goal is always to balance the resource-demand equation.

The present paper aims to consider possible technological options in Syria to meet future water demand und examines the role of deep groundwater as one of the most important options. The viability of developing deep nonrenewable groundwater is investigated on the basis of geophysical, hydrogeological and deep drilling within the framework of oil and water exploration activities.

The paper deals with the main deep groundwater reservoirs in Syria, taking into consideration different views and concepts regarding the accurence and potential of deep groundwater resources. The relative importance of different boundary conditions and limitations such as quality, renewability, productivity and other parameters influencing the exploitability of the aquifer systems have been carefully analysed.

The study in this context hopes to arrive at a criteria and concepts for rationalizing development and future management of deep aquifers in Syria based on a better understanding of the hydrogeological framework and the regional flow systems.

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ANNONCE – ANNOUNCEMENT

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Une version digitale expérimentale du Glossaire International d'Hydrologie

L'UNESCO et l'OMM ont publié en 1992 la seconde édition du Glossaire International d'Hydrologie. Cet ouvrage rassemble des définitions en quatre langues (Anglais, Espagnol, Français e Russe) de 1418 termes d'utilisation courante en hydrologie. Malgré son grand intérêt et sa reconnaissance internationale, cet ouvrage fondamental pour tous ceux qui travaillent dans le domaine de l'hydrologie (ingénieurs, chercheurs, enseignants, étudiants, etc…) souffre d'une diffusion limitée. Pour tenter de remédier à cet état de choses, à l'initiative du Comité National Français d'Hydrologie (PHI-PHO) et avec le concours de nombreux organismes et personnalités de plusieurs pays, une version digitale expérimentale du Glossaire, qui pourrait être accessible sur la Toile et/ou sur CD-Rom, a été élaborée. Elle comprend huit langues (l'Allemand, l'Arabe, le Chinois et le Roumain ont d'ores et déjà été ajoutés aux quatre langues de l'édition imprimée) et d'autres (l'Italien, le Japonais, le Portugais et le Turc en particulier, sans que cette liste soit limitative) y trouveront bientôt leur place. De nombreuses illustrations (photos, diagrammes, portraits et même vidéos) enrichissent les définitions textuelles. Par son contenu et par les liens qu'elle permet d'établir, une telle version digitale du Glossaire International d'Hydrologie pourrait être le noyau d'un vaste système d'information multilingue sur l'hydrologie et la gestion des eaux, et le vecteur d'une fructueuse coopération internationale dans le cadre des programmes hydrologiques de l'UNESCO et de l'OMM.

An experimental digital version of the International Glossary of Hydrology

UNESCO and WMO have published in 1992 the second edition of the International Glossary of Hydrology. This book gathers the definitions in for languages (English, French, Russian and Spanish) of 1418 terms commonly used in Hydrology. In spite of its outstanding interest an international recognition, this fundamental book for all those who are involved in the field of Hydrology (engineers, researchers, teachers, students, etc…) lacks of sufficient dissemination. In order to try to remedy to that matter of fact, an experimental digital version of the Glossary, that could be easily available on the WEB and/or on a CD-Rom, has been elaborated, starting from an initiative of the French National Hydrological Committee (IHP-OHP) with the active collaboration of numerous individuals and organisms from several countries. Height languages are present in this version (Arabic, Chinese, German and Romanian have already been added to the for original languages of the printed edition) and others will follow soon (Italian, Japanese, Portuguese and Turkish in particular, this list being a non-limitative one). A great number of pictures (photographs, diagrams, portraits and even videos) are enriching textual definitions. From its content, and by the links it enables, such a digital version of the International Glossary of Hydrology could be the core of a large multilingual information system about Hydrology and Water Management and the vector of a valuable international cooperation within UNESCO and WMO hydrological programs.

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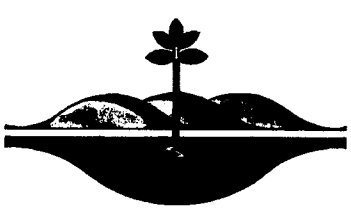
البرنامج الهيدرولوجي الدولي



منظمة الأمم المتحدة
للتربية والعلوم والثقافة

الأوراق العلمية :

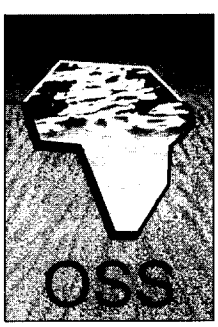
المؤتمر الدولي
حول الأحواض المائية الجوفية الكبرى
بالمناطق الجافة
إدارة الموارد غير المتجددة



الهيئة العامة للمياه
بالجماهيرية العربية الليبية
الشعبية الإشتراكية العظمى

IHP-V | Technical Documents in Hydrology |N°. 42
UNESCO, Paris, 2001

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الكفلاء

تم تحضير هذا المطبوع بدعم مرصد الصحراء والساحل OSS

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محتويات الكتاب

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تقديم

يشكل المؤتمر الدولى حول الأحواض المائية الجوفية الكبرى فى المناطق الجافة - إدارة الموارد غير المتجددة ، الذى عقد فى طرابلس فى الفترة من 21-25 نوفمبر 1999 ، حدث هام فى مراجعة ومناقشة وتحليل المفاهيم المنبثقه لتخطيط الإستثمار الإستنزافى للمياه الجوفية ، وقد ساهم المؤتمر كحلقة إتصال لتوطيد التعاون وتبادل الخبرات بين الدول المشاركه وكذلك الإستخدام المستدام لمصادر المياه الجوفية المشتركة .

وقد تم عقد المؤتمر بالإشتراك مع قسميّ علوم المياه وعلوم الأرض بمنظمة اليونسكو والهيئة العامة للمياه بالجماهيرية العربية الليبية الشعبية الإشتراكية العظمى. وقد ساهم فى دعم المؤتمر وتمويله العديد من الهيئات والمنظمات والمؤسسات العربية والدولية وهى : منظمة الأغذيه والزراعه (FAO) ، مرصد الصحراء والساحل (OSS)، الهيئة الدولية للهيدرولوجيا (IAH)، الإتحاد الدولى للعلوم الجيولوجية (IUGS)، الهيئة الدولية للموارد المائية (IWRA)، المركز العربى لدراسات المناطق الجافة والأراضى القاحلة (ACSAD)، المنظمة العربية للتربية والثقافة والعلوم (ALECSO) ، مركز التنمية والبيئة للمنطقة العربية وأوروبا (CEDARE) والبنك الدولى للتنمية (IDB).

وقد إنطلق المؤتمر من القرار 12-8 والذى تم إقراره بواسطة المجلس الحكومى المشترك للبرنامج الهيدرولوجى الدولى (IHP) فى اليونسكو والمنعقد بتاريخ 23-28 سبتمبر 1996. وقد إعتبر هذا المجلس أن أنظمة الخزانات الجوفية غالبا ما تمثل المصدر الرئيسى للمياه العذبه فى المناطق الجافه وشبه الجافه. وقد أوصى المؤتمر بتعميق المعرفة عن «المياه الجوفية الأحفوريه غير المتجددة» فى المناطق الصحراوية وشبه الصحراوية بأفريقيا.

وفى مناطق عديدة ، يتم تخزين الموارد المائية فى الخزانات العميقة والتى لايتم تغذيتها بصفة سنويه. وهذا يعنى أن السحب من مثل هذه الخزانات يشكل إستنزافا لها.

والعديد من هذه الخزانات له صفة إقليمية من حيث أنه كبير جدا ويغطى مساحات واسعة تشارك فيها عدة دول متجاورة. وهنا تثار بعض الأسئلة مثل كيف يجب تقييم مصادر المياه فى هذه الخزانات؟ وكيف يمكن إدارة هذه المصادر غير المتجددة لتغطى متطلبات الزيادة المضطردة للسكان؟

ويمثل هذا المؤتمر خطوة مهمه على الطريق لإعطاء إجابات مناسبه للرد على كل هذه التساؤلات.

وقد شارك فى هذا المؤتمر أكثر من 600 باحث من أكثر من عشرين بلداً وكذلك ممثلون لهيئات ومؤسسات ومنظمات إقليمية ودولية. وتم عرض ثمانية وأربعون بحثا تغطى الموضوعات التالية :

1) الخصائص الجيولوجية لنظم الخزانات الإقليمية فى المناطق الجافة.
2) طرق التقييم والمحددات للمصادر المائية غير المتجددة.
3) أسس إستغلال المياه الجوفية من الخزانات الأحفوريه.
4) التأثيرات البيئية لإستغلال المياه الجوفية والتصحر.
5) مراقبة سحب المياه الجوفية والآثار البيئية المترتبه على ذلك.
6) السياسات الوطنيه والإقليمية الخاصة بالإستخدام المستدام للمياه.

ويمثل بيان طرابلس إحدى الإنجازات المباشرة لهذا المؤتمر حيث أنه يشجع البلدان للدخول فى مفاوضات بهدف الوصول الى إتفاقيات لتنمية وإدارة وحماية مصادر المياه الجوفية المشتركة.

عمر سالم
الهيئة العامة للمياه
الجماهيرية العربية الليبية الشعبية الإشتراكية العظمى

المحور الثاني : طرق تقييم المصادر المائية غير المتجددة والصعوبات التي تعترضها

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م. محمد سعيد زهراء
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النموذج الرياضي لحوض سبخة الموح (الجمهورية العربية السورية) تجربة رائدة في تقويم وادارة الموارد المائية الجوفية في المناطق العربية الجافة

* معاون مدير المركز العربي لدراسات المناطق الجافة والأراضي القاحلة - دمشق - سوريا

الخلاصـــة

ان الهدف الاساسي لاعداد النموذج الرياضي لحوض سبخة الموح هو التمثيل الكامل لحركة المياه الجوفية المحدودة في منطقة البادية السورية في اطار الظروف الهيدروجيولوجية الحدية ، وضرورة تخطيط استثمارها على أسس علمية ، واجراء المعايرات اللازمة من اجل تحديد المعاملات الهيدروجيولوجية وتوزعها ضمن حدود الحوض ، وبالتالي تحديد عناصر الموازنة المائية للحوض ، ومن ثم تحديد الافاق المستقبلية لمناطق الاستثمار الكثيف الحالية منها والمخطط لها مستقبلاً وتقدير المناسيب والتأثير المتبادل فيما بين هذه المناطق وتغير هذا التأثير بمرور الزمن .

استخدم في اعداد هذا النموذج وتشغيله نظام MODFLOW المطور من قبل هيئة USGS الامريكية . والمستخدم على نطاق عالمي في نمذجة الاحواض المائية الجوفية ودراسة الأنظمة المائية فيها ، كما استخدم نظام المعلومات الجغرافية PC-ARC/INFO في اعداد الشرائح المعلوماتية التي استخدمت كمدخلات للنموذج وتم تحميلها في شبكة النموذج .

بني هذا النموذج اعتمادا على قاعدة المعلومات التي توفرت من خلال الدراسات السابقة والتحريات الهيدروجيولوجية التي نفذت ضمن اطار هذا المشروع من قبل الشركة العامة للدراسات المائية في الجمهورية العربية السورية . وتم بنتيجتها وضع صيغة النموذج الهيدروجيولوجي الاعتباري واعداد المخططات الاساسية التي تصف الظروف الحدية للخزان الجوفي ونظام حركة المياه الجوفية فيه والتي استخدمت كمدخلات للنموذج الرياضي ، وتم تحديد المؤثرات الخارجية عليه الحالية والمتوقعة مستقبلاً والتي تم على اساسها تشغيل النموذج ومعايرته والتنبؤ بالتبدلات التي ستطرأ على النظام المائي الجوفي نتيجة تطبيق سيناريوهات مختلفة تنطلق من الخطط المقترحة واخرى قابلة للتطبيق مع اخضاع النظام لمؤثرات خارجية حدية لمراقبة واستقراء التأثيرات السلبية الممكنة .

وقد توصل هذا النموذج إلى تحديد نوع المعاملات الهيدروجيولوجية التي تحقق نظام حركة المياه الجوفية في الحوض وتحديد مركبات الموازنة المائية وتأثيرات تطبيق خطط الاستثمار المطلوبة التي أشارت إلى حدوث هبوطات مركزة في مناطق الاستثمار وصلت في حدها الأعظمي إلى حوالي 20 متر ، وهبوطات عامة في الحوض لم تتجاوز 1 متر .

كما طبقت خطط استثمارية تعادل ضعف الخطة المطلوبة وثلاثة أضعافها ، ودرست المنعكسات السلبية على النظام المائي في الحوض وتبين أن زيادة معدلات الضخ ستؤدي إلى هبوطات كبيرة نسبياً في مناطق الضخ المركز ، إضافة إلى حدوث تداخلات هيدروليكية فيها ، وسوف يزداد اتساع الهبوطات المساحية ليصل إلى الحدود الهيدروليكية المعتبرة للحوض دون الوصول إلى حالة الاستقرار ، وقد بين النموذج أنه بالامكان تطبيق الخطة المطلوبة دون التعرض لمشكلات بيئية هامة مع ضرورة استمرار المراقبة وتحديث المعطيات وإعادة المعايرة بشكل مستمر ، كما يجب الانتباه إلى عدم المبالغة في زيادة الاستثمارات عن الحدود المعتمدة في الخطة تجنباً لاستنزاف الموارد المائية المتاحة في الحوض وتدهور نوعيتها .

المقدمـــة

تعتبر تقانة النمذجة الرياضية من التقانات الحديثة التي تطورت مع تطور الحاسبات الالكترونية وأنظمة المعلومات والبرمجيات وأصبحت تشكل اداة هامة وفعالة في محاكاة وتحليل الأنظمة البيئية والاجتماعية والاقتصادية ، وربما من أهم تطبيقات هذه التقانة في محاكاة وتحليل الأنظمة البيئية هي نمذجة النظام المائي الجوفي الذي يمثل التأثير الهيدروليكي على الخزان الجوفي الناجم عن ظروف طبيعية أو أنشطة اجتماعية اقتصادية مختلفة معبراً عنه بتبدلات مناسيب المياه الجوفية مع الزمن وتغير في نظام الجريان الجوفي الافقي والشاقولي في الخزان الجوفي وفي الحدود الهيدروجيولوجية له .

وانطلاقاً من أهمية هذه التقانة فقد أعطى المركز العربي اهتماماً خاصاً لها منذ تأسيسه وقام باعداد أول نموذج رياضي في أواخر السبعينات ، وكان آخر النماذج الهامة التي نفذها المركز مؤخراً على المستوى الاقليمي هو النموذج الرياضي لحوض سبخة الموح في سورية الذي يقع في البادية السورية الجافة وتتعرض مياهه إلى استثمارات متزايدة نتيجة تطبيق خطط تنموية طموحة الأمر الذي دفع الحكومة السورية ممثلة بوزارة الري إلى التعاون مع المركز العربي لاعداد نموذج رياضي لهذا الحوض والذي نعرض في هذه الورقة أسلوب اعداد هذا النموذج وأهم النتائج التي تم التوصل اليها كمثال تطبيقي لما يمكن اجراءه في كثير من الاحواض العربية الجافة التي تتعرض مياهها إلى الاستنزاف والتدهور .

الموقع والمورفولوجيا

يقع حوض سبخة الموح في المنطقة الوسطى من سورية ويشكل جزءا هاما من حوض البادية وتصل مساحته الاجمالية حسب التحديد الهيدروجيولوجي الذي اعتبر في النموذج إلى حوالي 16 ألف كيلو مترمربع (شكل 1)، وتعتبر هذه المنطقة جافة إلى شديدة الجفاف ، حيث يتراوح المعدل السنوي للهطول المطري فيها 100-120 ملم ويتصف هذا الهطول بالتوزع غير المنتظم وشدة الهطول غير المنتظمة أيضاً حيث تهطل معظم الكمية المذكورة آنفاً خلال بضعة هطولات قد يصل سماكة الهطول الواحد منها الى أكثر من 30-40 ملم ، هنالك بعض السدود السطحية المنتشرة في المنطقة يتراوح حجوم تخزينها بين 0.7-5 مليون متر مكعب ، وهي مستخدمة لأغراض الشرب وسقاية الماشية والري. أما الهطولات الضعيفة المتفرقة فغالباً ما تتبخر مياهها بمجرد وصولها إلى سطح الأرض بسبب ارتفاع قيمة التبخر ، وتنتشر في المنطقة مجموعة من الوديان الكبيرة التي تشكل مصارفاً رئيسية للمياه السطحية في المنطقة تصب في منخفض سبخة الموح التي تصل مساحته المسطحة إلى ما يقارب 170 كيلو متر مربع .

الوضع الهيدروجيولوجي العام

يتكون الحوض من مجموعة من التشكيلات الجيولوجية يصل أقدمها إلى عمر الجوراسي، وتتكشف صخوره في الحوض في محدبات جبال السلسلة التدمرية الجنوبية بمساحات محدودة وصغيرة وتتكون صخوره من الدولوميت والحجر الكلسي والمارل والغضار والجص ، وتتوضع فوقها صخور الكريتاسي وتختلف سماكاتها من منطقة لأخرى ولكنها لاتقل عن 150 متر (المنطقة الشرقية) وتزداد لتصل إلى أكثر من 700 متر (المنطقة الانهدامية)، وتتكون من مجموعات متمايزة ليثولوجياً وهيدروجيولوجيا ، الأمر الذي سمح بتصنيفها كمجموعات حاملة للماء وأخرى غير حاملة ، وهي تتكشف في مساحات محدودة تمتد على طول المرتفعات الجبلية المكونة للسلسلة التدمرية الجنوبية .

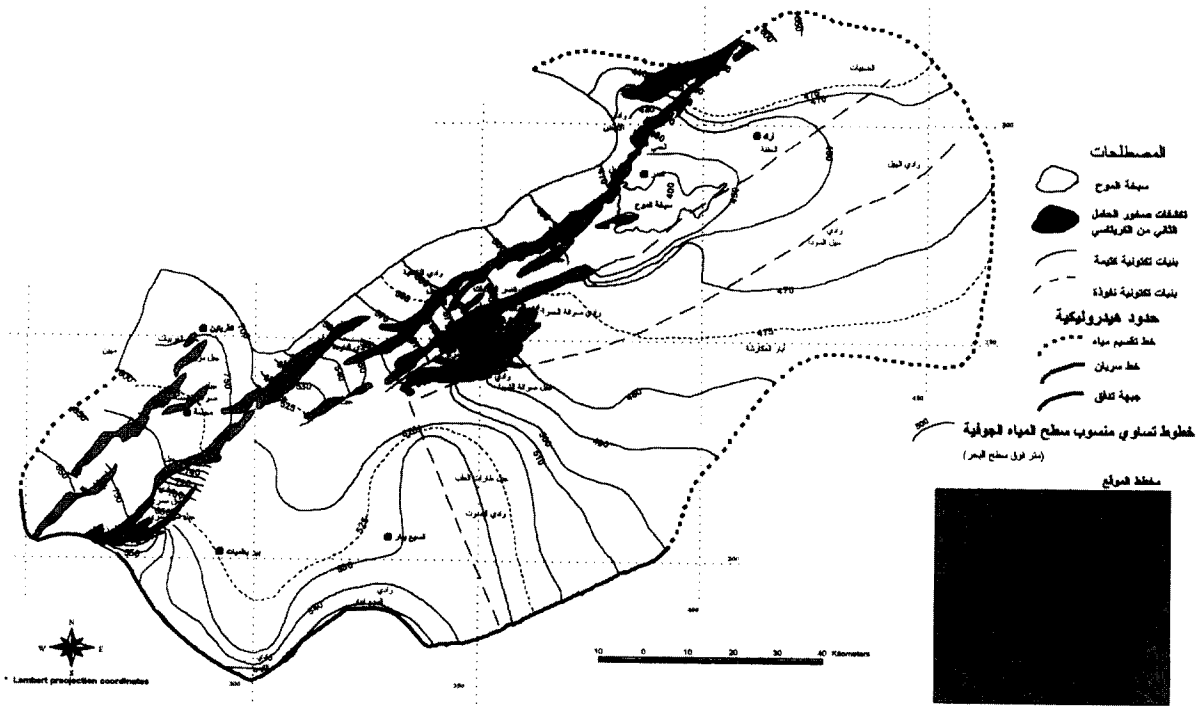
تتكون صخور الكريتاسي الأسفل من توضعات رملية غضارية وغضار، وقد اعتبرت بمثابة تشكيلة كتيمة غير حاملة للماء بشكل عام، بينما تتكون صخور الكريتاسي الأعلى من حجر كلسي ودولوميت ومارل وحجر رملي ، مع آفاق بينية من الصوان والمارل، وقد اعتبرت التشكيلة سالفة الذكر العائدة للكريتاسي الأعلى بمثابة معقد جيولوجي حامل للماء ومتصل هيدروليكياً على المستوى الاقليمي للحوض، وهو الحامل الرئيسي الذي تمت دراسته في النموذج الرياضي.

أما صخور أعلى الكريتاسي العلوي العائدة لعمر الماستريخت - دانيان فتتكون من الحجر الكلسي الغضاري وتهيمن عليها السحنة المارلية وقد اعتبرت هذه التشكيلة بمثابة الطبقة شبه الكتيمة المغلفة للمعقد الحامل للماء من الكريتاسي الأعلى والتي تفصله عن التوضعات الحديثة نسبياً .

تعتبر تشكيلات صخور الأيوسين الأوسط والأعلى ، وطبقات التورتون والبليوسين، وأخيراً طبقات التوضعات الرباعية ، جميعها بمثابة معقد جيولوجي متصل هيدروليكياً يشكل نظاماً مستقلاً حاملاً للمياه الجوفية يعلو النظام السابق المكون من التشكيلات العائدة للكريتاسي الأعلى الحاملة للماء ولكنه لا يوازيه في أهميته كحامل مائي حيث يتصف بنفاذيته الضعيفة نسبياً التي تنخفض إلى قيم دنيا توازي الطبقات شبه الكتيمة العائدة للباليوسين وأسفل الأيوسين التي تتوضع تحتها أحياناً.

تؤثر في المنطقة مجموعة كبيرة من الفوالق ترافق اتجاه الطيات العنيفة التي تشكل السلسلة التدمرية الجنوبية وتأخذ الاتجاه جنوب غرب-شمال شرق أهمها فالق الأبتر الذي يتشكل على المنحدر الجنوبي لسلسلة جبال الأبتر ويمتد باتجاه الشمال الشرقي وبرميه هابطة نحو الجنوب تزداد من بضعة عشرات الأمتار في منطقة الأبتر إلى بضعة مئات الأمتار في الطرف الشرقي للحوض مشكلاً حداً هيدروليكياً مؤثراً في نظام حركة المياه الجوفية في منطقة السبخة الواقعة شمال هذا الفالق والمنطقة الجنوبية للسبخة الواقعة جنوبه حيث تكون مستويات الحامل المائي العائد للكريتاسي الأعلى ذات أعماق كبيرة وبالتالي واقعة تحت ضغط عالٍ (حبيسة) وتبين الابار المحفورة في تلك المنطقة أن المياه تدفقية وذات درجة حرارة مرتفعة تزيد عن 50 درجة مئوية .

أما حركة المياه الجوفية فتتجه من الطرف الجنوبي الغربي للحوض نحو الشمال لتنصرف عن طريق البنية الفالقية المشققة لوادي غدير الحمل باتجاه الشرق نحو سبخة الموح ، كما تتحرك أيضاً باتجاه الشرق محاذية لخط توزع المياه الذي يحد الحوض من جهة الجنوب حتى سبخة الموح ، وتشكل السبخة منطقة صرف لكامل نظام المياه الجوفية في الحوض . وفي مناطق النهوض المشكل للسلسة التدمرية تتوزع حركة المياه خلال الحواجز البنيوية الكتيمة لتنصرف في النهاية أيضاً في سبخة الموح(شكل1) . وتكون المياه ارتوازية في المنطقة التي تقع إلى الجنوب و الشرق من سبخة الموح .



شكل (1) مخطط تسوية سطح المياه الجوفية للحامل الثاني

النموذج الهيدروجيولوجي الاعتباري

تم تشكيل النموذج الهيدروجيولوجي الاعتباري الذي يمثل جميع الظروف الهيدروجيولوجية للطبقات الحاملة ، وكذلك الاتصال الهيدروليكي بين هذه الطبقات على ضوء البنية الجيولوجية والتكتونية والوضع الهيدروجيولوجي العام وقد تم اعداد هذا النموذج وتمثيل الطبقات فيه كمايلي :

الاعتبارات الطبقية

الطبقة الاولى تشكل الحامل المائي الأعلى والتي تضم مجمل التشكيلات الجيولوجية التابعة للرباعي والنيوجين والقسم العلوي من الباليوجين.

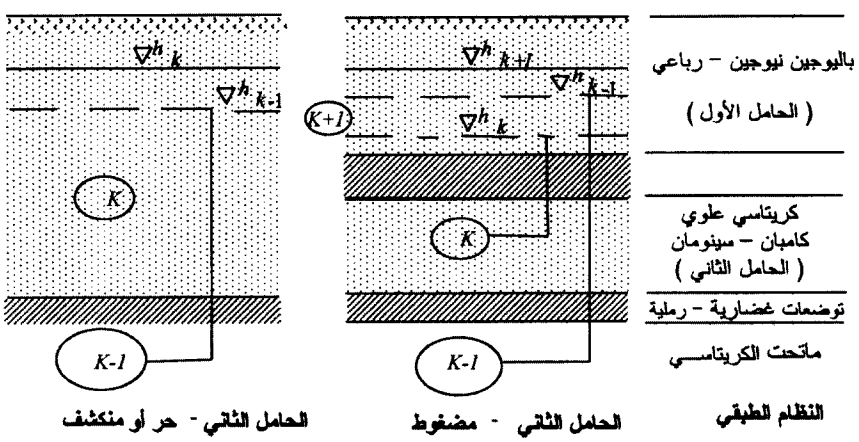
الطبقة الثانية تشكل الطبقة شبه الكتيمة الفاصلة بين الحاملين الأول (العلوي) والثاني (السفلي) وتتكون من الطبقات الغضارية المارلية العائدة لأسفل الباليوجين وأعلى الكريتاسي العلوي (الماستريخت- دانيان).

الطبقة الثالثة تشكل الحامل المائي الأسفل الذي يضم مجمل التشكيلات الجيولوجية العائدة للكريتاسي الأعلى والتي تضم السينومان- تورون- كونياس أساساً مضاف إليها السانتون-كامبان والتي تشكل بمجملها الحامل الثاني الرئيسي في الحوض وتشكل وحدة هيدروليكية متصلة ذات نفاذية عالية نسبيا ومتأثرة بنظام تكتوني معقد يلعب دوراً هاماً في تغير نفاذيتها الأفقية والشاقولية.

تغلف هذا الحامل من الأسفل طبقة كتيمة تعود إلى عمر الكريتاسي الأسفل أو الجوراسي وقد تكون هذه الطبقة كتيمة في مناطق ونفوذة في مناطق أخرى وبالتالي فقد تم لحظها في النموذج حيث يمكن تفعيلها مستقبلاً على ضوء ما يستجد من معطيات.

الاعتبارات الهيدروليكية

- تم اعتبار الحامل الأول بمثابة حامل حر (غير حبيس) اقليمياً وذو نفاذية منخفضة ومن المفيد التعامل معه كحامل ذو طاقة محدودة يتغذى من مياه الامطار بشكل رئيسي ومن تسرب رأسي من الحامل الثاني وتستثمر مياهه عن طريق آبار ضحلة العمق لأغراض سقاية الماشية واستخدامات محدودة.
- تم اعتبار وجود تغذية للحامل الثاني من المياه السطحية (أمطار- سيول) في مناطق تكشفات هذا الحامل على امتداد السلسلة التدمرية الجنوبية وجزء من الشمالية .
- تم اعتبار الحامل الثاني بمثابة حامل حر (غير حبيس) في بعض المناطق ومضغوط (حبيس) في مناطق أخرى (خاصة المنطقة الوسطى والشرقية) وتدفقيه في بعض المناطق (جنوب سبخة الموح).
- تم لحظ إمكانية وجود تسرب من الحامل الثاني إلى الحامل الأول في المناطق الحبيسة التي يكون فيها منسوب المياه الجوفية للحامل الثاني أعلى من منسوب المياه الجوفية للحامل الأول.
- تم اعتبار وجود تبخر لمياه الحامل الثاني في سبخة الموح ذو قيمة محددة .
- تم لحظ الاستثمارات المائية الجوفية القائمة في الحوض .



شكل (2) النموذج الاعتباري

والشكل (2) يمثل النموذج الاعتباري ويوضح وضع الحامل الثاني في حال سريان حر أو مضغوط والاتصال الهيدروليكي بين الحامل الأول والحامل الثاني

الشروط الحدية للنموذج

تم تمثيل النموذج الهيدروجيولوجي الاعتباري ضمن مجموعة الشروط الحدية الجيولوجية- البنيوية واخرى هيدروليكية حيث قسمت الحدود المغلقة تكتونياً إلى حدود خارجية واخرى داخلية (شكل 1) ، تحد الخارجية منها الحوض من جهة الشمال وتتمثل هذه الحدود بالمنطقة الانتقالية بين الحد التكتوني للسلسلة التدمرية الجنوبية والانحدار شديد الميل للطرف الشمالي لها نحو منخفض الدو ، أما الحدود الداخلية المغلقة تكتونياً ، فقد تم تحديدها على امتداد تكشفات الحامل الثاني وما يليه من توضعات كتيمة على امتداد جبال السلسلة التدمرية الجنوبية والتي تشكل حاجزاً كتيماً ، وتلعب دور الفاصل الهيدروليكي الذي يتحكم في توزع سريان المياه الجوفية .

أما بالنسبة للحدود الهيدروليكية ، فقد تم تحديدها على أساس هيدروجيولوجي انطلاقاً من النظام شبه المستقر لحركة المياه الجوفية في الحامل الثاني حيث اعتبر خط تقسيم المياه الذي يفصل النظام الهيدروجيولوجي للحامل الثاني كحوض مستقل عن الأحواض المجاورة من ناحية الشرق والجنوب الشرقي والجنوب بمثابة حدود هيدروليكية محكمة واعتبرت جبهة السريان المحددة على امتداد خط التسوية الذي يحد الحوض من الجهة الغربية والجنوبية الغربية بمثابة حدود هيدروليكية محكمة أيضاً .

شبكة النموذج

تم تحديد شبكة النموذج باستخدام نظام (MODFLOW) وبما يتوافق مع كثافة المعطيات المتاحة وضرورة تمثيل التفاصيل الهيدروجيولوجية البنيوية بشكل مقبول ودقة كافية ضمن إطار مقياس الدراسة واتساع مساحة المنطقة.

وقد شكل هذا التقسيم مجموعات من الخلايا (المضلعات) بلغ عددها الاجمالي 1509 خلية ، حددت ابعادها لمحاكاة الشروط الحدية الخارجية والداخلية للحوض وتمثيل النموذج الاعتباري بدقة مقبولة ، وقد مكن هذا التقسيم من تمثيل التفاصيل البنيوية والحدية للحوض وتغطية كامل مساحته بامتداد 18560 كم^2 .

أسلوب تنفيذ النموذج الرياضي

تم ربط نظام المعلومات الجغرافية PC-ARC/INFO بنظام MODFLOW المستخدم لهذا النموذج من أجل تحميل مدخلات النموذج النقطية والمساحية عن طريق نظام المعلومات الجغرافية على شكل مخططات مرتبطة بقاعدة المعلومات النقطية وتم استخدام نظام الجدولة الالكترونية EXEL لمعالجة المعطيات الرقمية وتبادلها بين النظامين ARC/INFO و MODFLOW وذلك حفاظاً على دقة المعلومة ومعالجتها بسهولة في نظام مترابط يسهّل عملية التصحيح والتحديث حيث تم تحديد التناقضات الممكن حدوثها عند التعامل مع المجموعة الكبيرة من الشرائح المعلوماتية التي استخدمت في نظام النمذجة وبالتالي تم تصحيحها.

ومن الجدير بالذكر أنه تم اعداد برامج تحويلية يتم بمقتضاها تحويل المعطيات ثنائية الأبعاد (Two Dimensional) إلى ثلاثية الأبعاد (Three Dimensional) حتى يتسنى اسقاط هذه البيانات على شبكة النموذج ، كما أعدت برامج تحويلية عكسية للاستفادة من نتائج النموذج وتحويلها إلى الشكل الذي يتقبله النظام الجغرافي من أجل اعداد المخططات الخاصة بتمثيل النتائج.

مدخلات النموذج

تضم المدخلات جميع المعطيات الممثلة للنموذج الاعتباري والشروط الحدية وسطح المياه الجوفية والمعاملات الهيدروليكية والمؤثرات الخارجية ، ومن أجل اتمام ذلك تم اعداد الشرائح المعلوماتية بشكل يتوافق مع شبكة النموذج وهي كمايلي :

مدخلات الابعاد الجيوهندسية للنموذج الاعتباري

تم تمثيل الابعاد الجيولوجية الهندسية للنموذج الهيدروجيولوجي الاعتباري من خلال الخرائط التالية :

- سطح الأرض
- السطح السفلي للحامل الأول (السطح العلوي للطبقة شبه الكتيمة الفاصلة بين الحاملين الأول والثاني) .
- السطح العلوي للحامل الثاني (السطح السفلي للطبقة شبه الكتيمة الفاصلة بين الحاملين الأول والثاني) .
- السطح السفلي للحامل الثاني (السطح العلوي للطبقة شبه الكتيمة تحت الحامل الثاني).

المدخلات الهيدروجيولوجية الأولية

تم ادخال المعطيات الممثلة لنظام حركة المياه الجوفية والثوابت الهيدروليكية في النموذج من خلال الخرائط التالية :

- منسوب سطح المياه الجوفية للحامل الاول وللحامل الثاني .
- معامل النفوذية الاولي للحامل الاول وللحامل الثاني .
- معامل التخزين الاولي للحامل الاول وللحامل الثاني .
- معامل التسرب للطبقة شبه الصماء بين الحامل الأول والحامل الثاني .

هذا مع العلم بان جميع المعاملات الهيدروليكية التي تم الحصول عليها من نتائج تحليل تجارب الضخ المنفذة في المنطقة ، اعتبرت قيم أولية تحتاج الى معايرة .

التأثيرات الخارجية (External Stresses)

هناك عوامل اخرى اخذت في الاعتبار وتم ادخالها في بنية النموذج وهي :

أ - **التبخر** : قدرت قيمته بحوالي 62.4 مليون متر مكعب في السنة من مساحة تقارب 140 كيلو متر مربع في منطقة مسطح السبخة ، وقد تم

تمثيل هذه القيمة من الطبقة المائية الاولى.

ب - **التغذية من الامطار** : أوضحت الدراسات الهيدروجيولوجية التي أعدتها شركة الدراسات المائية بان قيمة التغذية تقدر بحوالي 15٪ من قيمة الهاطل المطري السنوي الذي يقدر وسطيا بحوالي 120 ملليمتر/السنة ، وبالتالي فان قيمة التغذية لسطح المياه الجوفية تقدر بحوالي 18 ملليمتر/السنة ، وقد تم تمثيل هذه الكمية في النموذج للطبقة الثانية على امتداد تكشفات هذه الطبقة .

ج - **الاستثمارات القائمة في المنطقة** : اعتمدت كميات الضخ التي استثمرت في عام 1992 والتي بلغ مجموعها حوالي 15.4 مليون متر مكعب من الطابق الثاني ، كاساس وتم توزيع هذه الكميات على الخلايا المقابلة في مناطق الاستثمار الكثيف .

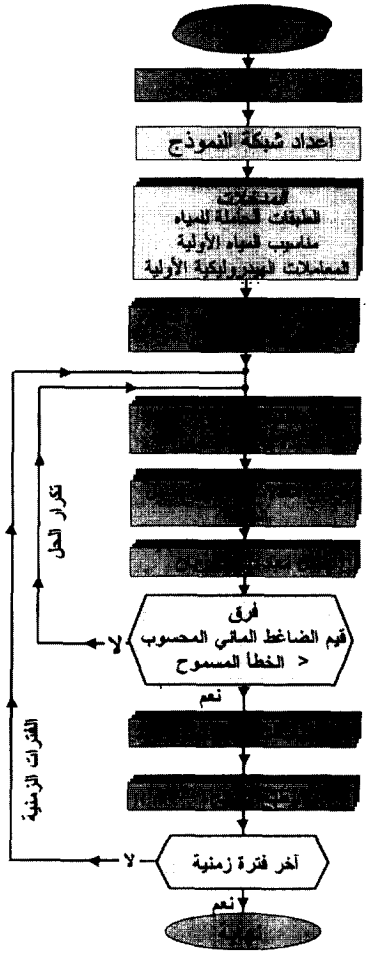
د - **جبهة السريان في الحدود الهيدروليكية المحكمة**: تم حساب قيمة السريان الافقي الداخل للحامل الثاني على امتداد خط الكمون المائي (550 متر) في المنطقة الجنوبية الغربية للنموذج واعتبرت كتصريف ثابت الى الحوض في تلك المنطقة قدرت قيمته بـ 4,6 مليون متر مكعب في السنة ، كما أعتبرت مناطق ذات قيمة ثابتة للضاغط المائي على امتداد حدود الحوض الهيدروليكية ومساوية لقيمة منسوب المياه فيها ، وان قيم الضاغط المائي في هذه الخلايا الحدية تحدد قيمة السريان سواء الداخل الى الحوض أو الخارج منه اعتماداً على تغيرات منسوب المياه الجوفية في المناطق المجاورة داخل الحوض .

تشغيل النموذج

بعد أن استكمل تحميل مختلف المعطيات المطلوبة لبناء النموذج الاعتباري والتي تتضمن شرائح المعطيات سالفة الذكر ، تم اختيار أسلوب الحل الرياضي (SIR) وتحديد الضاغط البيزومتري البدئي وشروط التشغيل المتعلقة بفترات التأثير (Stress Periods) والفواصل الزمنية (Steps Time) وقيمة (Relaxation) ودقة الحساب وغيرها من الثوابت الرياضية وطرق المعالجة الرقمية التي يتطلبها تشغيل النموذج، كما تم تفعيل جميع الشروط الحدية المدخلة في النموذج والقيم البدئية للمعاملات الهيدروليكية.

ويوضح المخطط البياني للنموذج الرياضي (شكل 3) الخطوات التي اجريت لتشغيل النموذج حيث بوشر بوضع الظروف الحدية الهيدروجيولوجية متضمنة التأثيرات التكتونية والجيولوجية المختلفة ومن ثم تحديد الحدود الهيدروليكية المختلفة سواء النفوذة أو الكتيمة. وقد بوشر بتشغيل النموذج بوضع قيم أولية لجميع الخلايا للضاغط المائي والمعاملات الهيدروليكية التي تم الحصول عليها نتيجة تحليل تجارب الضخ والاستعاضة . وقد اجرى حل للمعادلات التفاضلية الجزئية (Partial differential equations) لكل خلية مع ارتباطها بجميع الخلايا المجاورة في اتجاه المحاور (z,y,x) ، وقد استخدمت طريقة الفروق الضمنية (Implicit finite differences) والحل الرياضي الذي تم تطبيقه هو الحل الضمني المتكامل (Strongly implicit SIP Procedure).

تم تشغيل النموذج لكل طبقة على حده لحالة الثبات ودراسة التجاوب في الحل الرياضي وإجراء تجارب الحساسية للحل العددي حتى تم التحقق من عمل النظام المائي في النموذج بشكل سليم. كما تم التأكد من استمرار عمل النموذج لجميع فترات التأثير والفواصل الزمنية ، حيث تم الحصول على نظام الجريان الممثل للشروط البدئية التي تم تشغيل النموذج وفقها.



شكل (3) المخطط البياني لتشغيل النموذج الرياضي

معايرة النموذج

تم حساب الضاغط المائي لكل خلية ، حيث جرى مضاهاه قيمته مع القيمة الاولية ، فإذا تعدى الفرق بين هاتين القيمتين قيمة الخطأ المسموح ، فيتم تكرار تشغيل النموذج وتكرار الحساب على اساس اعتبار القيمة التي تم حسابها للضاغط المائي قيمة أولية وتحدد القيمة الجديدة للضاغط المائي وتستمر هذه العملية لحين تلاقي القيمة الاولية مع القيمة المحسوبة ولايتعدى الفرق بينهما قيمة الخطأ المسموح به ، وبذلك يمكن اعتبار هذا التلاقي بانه تم الوصول الى الحل السليم وان التمثيل الرياضي يعتبر تمثيلاً كاملاً لحركة المياه الجوفية، ومن ثم يتم حساب الموازنة المائية بناء على قيمة الضاغط المائي النهائي ،ويكرر أسلوب الحل هذا لكل خطوة من الخطوات الزمنية التي تم تشغيل النموذج وفقها .

آ -**المرحلة الاولى (معايرة النموذج لحالة الثبات)**

تم في هذه المرحلة تمثيل حركة المياه الجوفية والوصول الى الشكل العام لسطح المياه الجوفية تبعا للظروف الهيدروجيولوجية والظروف الحديه لمنطقة الدراسة .

وبناءا عليه تم تمثيل مخطط سطح المياه الجوفية وتحديد المعاملات الهيدروليكية لكل حامل ومعاملات التسرب الرأسي للطبقة شبه الكتيمة التي تفصل الحامل الاول عن الحامل الثاني ، والموازنة المائية لكامل الحوض حسب استثمارات عام 1992 لحالة الثبات .

ب -المرحلة الثانية (معايرة النموذج لحالة عدم الثبات)

كان هدف المرحلة الثانية من التشغيل هي المعايرة لحالة عدم الثبات حيث اعتبر عام 1992 كعام أساس ، وتم تشغيل البرنامج تبعا للاستثمارات التي سجلت حتى عام 1996 . وبناءاً عليه تم تشغيل النموذج لحالة عدم الثبات ومعايرة المعاملات الهيدروليكية المختلفة ، وقد تم الحصول على قيم معامل التخزين للحامل المائي وتغيره على كامل الحوض .

التنبؤ بتغيرات نظام المياه الجوفية نتيجة لخطة الاستثمار المقترحة

بعد معايرة النموذج لحالة الثبات ومن ثم لحالة عدم الثبات تم تشغيل النموذج لدراسة تاثير الاستثمارت المقترحة ضمن اطار خطة التنمية المطلوبة ، حتى عام 2026 على النظام المائي لكامل الحوض والتنبؤ بمناسيب المياه الجوفية والهبوطات .

اعتبرت قيم المعاملات الهيدروليكية التي تم الحصول عليها من خلال المعايرة في المرحلة الاولى والمرحلة الثانية قيم أولية(Initial) لتشغيل النموذج للفترة من 1996حتى 2026.

كما اعتبرت قيمة الاستثمار وفق الخطة لعام 2026 ثابتة بعد عام 2026 ولغاية عام 2046 وبناء عليه تم تشغيل النموذج وتم ايجاد الهبوطات في مناسيب المياه المتوقعة حتى عام 2046 ، وبذلك تم تقييم الخطة اذا مااستمر الاستثمار الاعظمي المتوقع لمدة عشرين عاما تالية .

تقييم حساسية النظام المائي الجوفي للاستثمار المكثف

تم تشغيل النموذج لعدة مشاهد (سيناريوهات) مختلفة ، وقد تم وضع هذه المشاهد بحيث توضح التأثير المحتمل على نظام الماء الجوفي في حال اجراء استثمار مكثف بدرجات مختلفة .

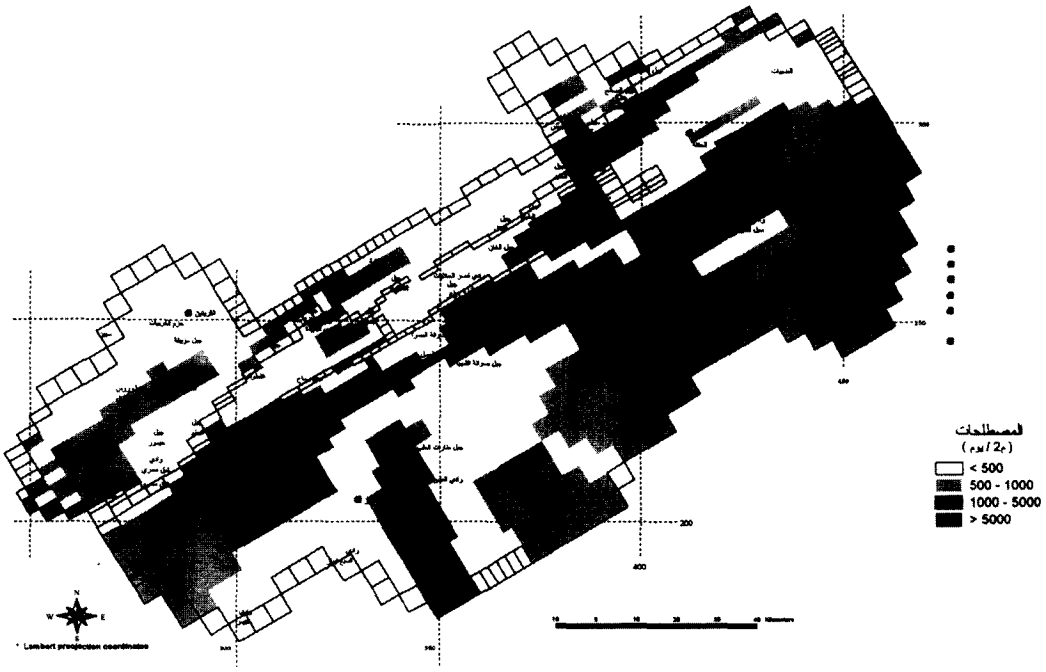
نتائج المعايرة

-تم التوصل الى محاكاة نظام حركة المياه الجوفية الطبيعي الممثل بمخطط التسوية لمناسيب المياه الجوفية .

-تحديد قيم المعاملات الهيدروليكية لكل من الحامل الأول والحامل الثاني ، حيث تراوحت قيم النفوذية في الحامل الثاني مابين أقل من 2.5 متر/يوم الى اكثر من 75 متر/يوم، في بعض المناطق التكتونية ، وحددت قيم معامل التخزين في مناطق المياه الجوفية الحرة بـ 3×10^{-2} وفي المناطق الحبيسة بـ 2×10^{-5} ، أما معامل النفوذية الشاقولية للطبقة شبه الكتيمة فقد حدد بـ1×10^{-4} متر/يوم .

-استنتاج توزع معامل الناقلية (T) ، (شكل 4) اعتمادا على توزع قيم المعاملات الهيدروليكية للحامل الثاني نتيجة المعايرة حيث تراوحت قيمته في الحامل الثاني مابين أقل من 100 متر مربع/يوم في مناطق محدودة بنفوذية ضعيفة وسماكة ضعيفة ووصلت قيمته الى أكثر من 10000 مترمربع/يوم في المناطق ذات النفوذية المرتفعة والسماكات الكبيرة ، كما تم استنتاج معامل الانتشار (∝) الذي يمثل الطاقة الانتاجية الكامنة لهذا الحامل ، حيث حددت على اساسه التوزع النسبي للمناطق المأمولة .

- تم حساب مركبات الموازنة المائية وفق معطيات عام 1992 حيث اوضحت هذه الحسابات أن مجمل عناصر التصريف الداخل الى الحوض ضمن اطار النظام الطبيعي المستقر القائم يقدر بحوالي 92 مليون متر مكعب/سنة ، موزعة ضمن مركبات موجبة للسريان الأفقي والتسرب الرأسي والتغذية يقابلها حجم مساوي موزع ضمن مركبات سالبة للسريان الأفقي والتسرب الرأسي والاستثمار، أما عنصر التبخر فيظهر ضمن عناصر التصريف الخارج من الحامل الأول فقط ، ومن الجدير بالذكر بان هناك ارتباط هيدروليكي بين الحامل الأول والحامل الثاني وهذا بالتالي يؤدي الى الترابط الكامل لحساب عناصر الموازنة في كلا الحاملين (جدول 1) .



شكل (4) توزع معامل الناقلية الهيدروليكية (نتيجة المعايرة)

جدول (1) الموازنة المائية لكامل الحوض (عام 1992)
(حسب الاستثمار الحالي - حالة الثبات)

الموازنة المائية للحامل الأول :

ألف متر مكعب/سنة

عناصر الموازنة	التصريف الداخل	التصريف الخارج	محصلة التصريف
السريان الأفقي	31012	68668	-37656
التسرب الرأسي	67908	4491	63418
التغذية	38181	0	38181
التبخر	0	62357	-62357
الاستثمار	0	1578	-1578
المجموع	137102	137095	7

الموازنة المائية للحامل الثاني :

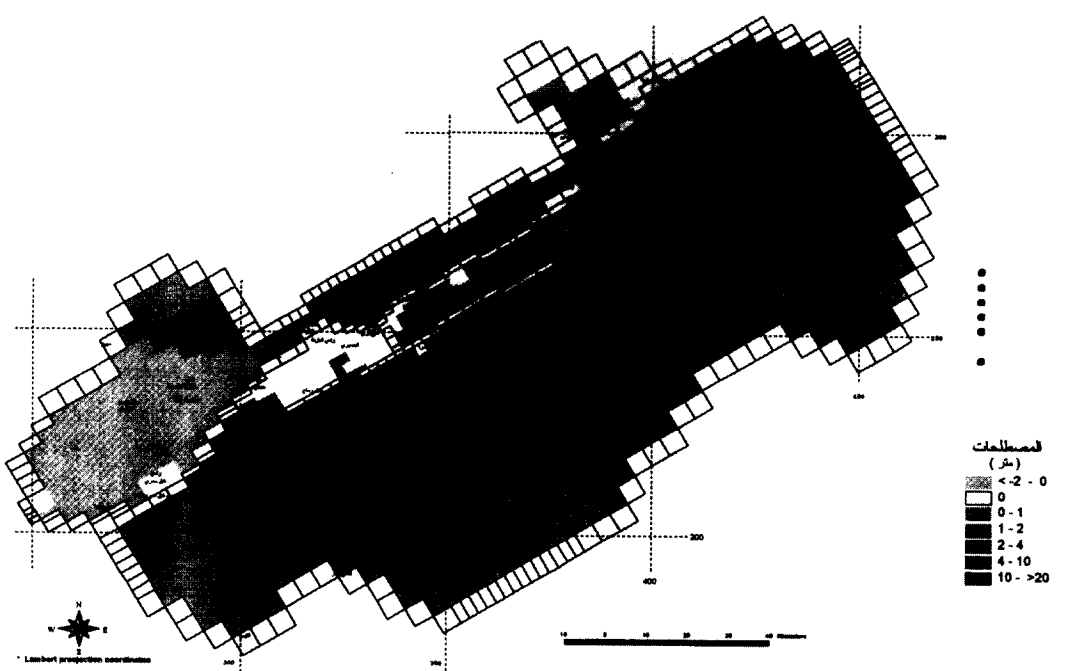
ألف متر مكعب/سنة

عناصر الموازنة	التصريف الداخل	التصريف الخارج	محصلة التصريف
السريان الأفقي	66060	9169	56891
التسرب الرأسي	4512	67907	-63396
التغذية	21646	0	21646
الاستثمار	0	15389	-15389
المجموع	92218	92466	-248

نتائج تشغيل النموذج :

آ - وفق الخطة الاستثمارية المقترحة

- حددت قيم الاستثمارات المطلوبة في المناطق المقترحة لتطوير المياه الجوفية في الحامل الثاني ، اعتبارا من عام 1992 بحوالي 15 مليون متر مكعب/سنة وحتى أفق 2026 حيث بلغ مجموعها حوالي 33 مليون متر مكعب/سنة ووزعت قيم هذه الاستثمارات على هذه الفترة بمعدلات متغيرة خطياً وتم اعتبار مجموع الاستثمارات ثابتا في الفترة الواقعة بعد 2026, ولفترة عشرين سنة أخرى .
- تم تشغيل النموذج لفترات تأثير (Stress Periods) موزعة على مدى 30 سنة حتى عام 2026 وفق التزايد المقترح في استثمار المياه الجوفية وعلى مدى 20 سنة اخرى وفق استثمار ثابت بالقيمة التي وصل اليها عام 2026 ، وتم تحديد الموازنة المائية ، كما تم رسم خرائط توزع الهبوطات المقابلة لتلك الاستثمارات .
- بحساب الموازنة لعام 2026 مع الآخذ بعين الاعتبار خطة الاستثمار المقترحة التي تعبر عن زيادة حجم الاستثمار من 15 مليون متر مكعب/سنة لعام 1992 الى مايقارب 33 مليون متر مكعب/سنة لعام 2026 تبعا للخطة المقترحة ، تبين حدوث تغيرات واضحة في عناصر الموازنة بالنسبة للتصريف الخارج من منطقة الدراسة حيث وصل الى حوالي 107 مليون متر مكعب/سنة، وهذا أدى الى فاقد في المخزون الجوفي بقيمة تقارب 13 مليون متر مكعب/سنة . وهذا يتضح من قيم الهبوط التي توقعها النموذج لنفس العام 2026 لمناسيب المياه الجوفية والتي لم تتجاوز 1 متر في معظم منطقة الدراسة إلاّ في بعض مناطق الاستثمار الكثيف حيث وصل الهبوط الى حد أعظمي يقارب 20.0 متر (شكل 5).
- قامت الدراسة بتحديد الموازنة المائية لكل منطقة من مناطق الاستثمار المقترحة وهي 11 منطقة ، وقد تبين أن نظام حركة المياه الجوفية في حالة اتزان في تلك المناطق في عام 1992 ، وبمقارنة نتائج تشغيل النموذج للعام 2026 مع الوضع القائم عام 1992 تبين انه في بعض المناطق كان تأثير الاستثمار فيها ضعيف جدا ولم يتعدى الهبوط فيها نصف متر، حيث أن قيمة الاستثمارات المقترحة في هذه المنطقة تضمنت ارتفاع في الاستثمار من 1 مليون متر مكعب/سنة لعام 1992 الى أكثر من 3 ملايين عام 2026 ، وقد أظهرت الموازنة توازن تام في عناصرها ولم يلاحظ اي تغير واضح فيها، وهذا يتوافق تماما مع ارتفاع قيم معامل الانتشار في تلك المنطقة التي تم الحصول عليها من معايرة النموذج.



شكل (5) توزع هبوط منسوب سطح المياه الجوفية للحامل الثاني
(تنبؤ النموذج لعام 2026 وفق استثمارات الخطة المقترحة)

ب - وفق مشاهد لخطط استثمار مكثف افتراضية

- تم وضع مشاهد (سيناريوهات) مختلفة لخطة الاستثمار المقترحة التي اعتبرت بمثابة السيناريو I والتي بلغ مجمل الاستثمارات فيها حسب الخطة المقترحة 33 مليون متر مكعب/سنة ، واصبحت في السيناريو الثاني 67 مليون متر مكعب/سنة (ضعف الاستثمارات) والسيناريو الثالث حوالي 100 مليون متر مكعب/سنة (ثلاثة أضعاف الخطة) وذلك من أجل دراسة المنعكسات السلبية والتغيرات المحتملة في الموازنة المائية والهبوطات والتبدلات في نظام حركة المياه الجوفية في الحامل الثاني .

- وبدراسة الموازنة المائية للحامل الثاني في كامل الحوض حسب هذه السيناريوهات المختلفة لعام 2026 تبين ان الفاقد في المخزون الجوفي في عام 2026 سيزداد من 12.7 مليون متر مكعب/سنة للسيناريو الأول الى 35 مليون متر مكعب/سنة للسيناريو الثاني ويصل الى مايقارب 57 مليون متر مكعب/سنة للسيناريو الثالث ، وهذا أدى الى زيادة الهبوط الأعظمي في الحوض بنسب متباينة وفقاً لتوزع الخواص الهيدروليكية في الحوض .

- بدراسة هذه السيناريوهات تفصيليا للمناطق المختلفة المقترحة لفترة خمسين عاما اي حتى عام 2046 حيث ثبتت قيمة الاستثمار خلال الفترة 2026 الى 2046 ، اتضح أن المناسيب تأخذ بالاستقرار خلال الفترة المذكورة للسيناريو الأول (الخطة المقترحة) أما بالنسبة للسيناريوهات الاخرى فان المنسوب بقي آخذا في الهبوط ولم يستقر حتى عام 2046 .

أمكن الاستخلاص بأن الخطة المقترحة خطة مقبولة وتتوافق مع امكانيات منطقة الدراسة حيث أن قيمة الفاقد في المخزون الجوفي في عام 2026 تعادل حوالي 12.7 مليون متر مكعب/سنة وتمثل 38٪ من قيمة الاستثمار المقترح كما تمثل حوالي 13٪ من قيمة مجموع عناصر الموازنة الداخلة للمنطقة ، وتمثل مايقارب 12٪ من مجموع عناصر الموازنة الخارجة منها. في حين أن السيناريو الثاني الذي أظهر أن فاقد المخزون الجوفي يقدر بحوالي 35 مليون متر مكعب/سنة، وهذا يمثل 35٪ من قيمة مجموع عناصر الموازنة للحامل الثاني الداخل لكامل المنطقة و26٪ من مجموع عناصر الموازنة للتصريف الخارج من المنطقة . وقد ارتفعت هذه النسبة للسيناريو الثالث حيث وصلت قيمة الفاقد في المخزون الجوفي الى حوالي 57 مليون متر مكعب/سنة وهذه القيمة تمثل حوالي 53٪ من قيمة مجموع عناصر الموازنة للتصريف الداخل الى الحوض والى 35٪ من مجموع عناصر الموازنة للتصريف الخارج من الحوض .

والخطة المقترحة تنسجم مع امكانات الحوض المائية وان زيادة الاستثمارات سوف تؤدي الى تأثيرات سلبية تتمثل باستنزاف سريع لموارد الحوض المتاحة وهبوطات مساحية كبيرة ومتداخلة تمتد لتصل إلى حدود الحوض ، علما بأن الهبوطات المحسوبة في النموذج هي هبوطات مساحية تمثل المضلعات المختارة للمراقبة ولاتمثل نقاط الآبار وبالتالي فان الهبوطات المتوقعة في الآبار نتيجة الهبوطات المساحية سوف تكون متزايدة وفق علاقة غير خطية الأمر الذي يؤكد أهمية الالتزام بالخطة الأولى المقترحة ووضع نظام مدروس لتوقيع الآبار وادارتها .

التوصيات

اعتماداً على ماتم التوصل إليه من نتائج تبين أن منطقة الدراسة تعتبر منطقة ذات موارد مائية محدودة وان الاستثمارات المقترحة فيها تنسجم مع إمكانياتها المائية ولا يوجد مبالغة فيها ضمن إطار الموازنة العامة للحوض، ولكن هذه النتائج تعتبر بمثابة تقويم حُسِبَ اعتماداً على المعطيات المتاحة والدراسات المنفذة، وبشكل عام يعتبر التمثيل تمثيلاً جيداً للنظام المائي في المنطقة وان نتائج النموذج ذات دقة عالية، إلا أن هذه الدقة لا تتعدى دقة البيانات الخاصة بمدخلات النموذج التي اعتمدت على الدراسات الهيدروجيولوجية المتاحة ، لذا لزم التنويه بأنه في حال القيام بوضع خطط الاستثمار التنفيذية فإنه من الأهمية تحديد مواقع الأبار وبرنامج الاستثمار النقطي لها، لاجراء دراسات تفصيلية خاصة بها.

ومن الجدير بالذكر بأن المنطقة تتصف بالتعقيد البنيوي الذي يؤثر في نظام المياه الجوفية وهذا يحتاج إلى تقويم مستمر وإجراء مزيد من التحري والمراقبة للوصول إلى الصورة الأكثر تمثيلاً للواقع وبالتالي فإن نتائج النموذج يجب أخذها بمثابة توجيه عام لتقييم موارد الحوض وحدود إمكانياته الاستثمارية للتعامل مع الخطط الاستثمارية ضمن هذا الإطار.

إن جميع الاستنتاجات وحسابات الموازنة قابلة للتطوير والتعديل على ضوء المستجدات في حالة المعرفة. وبما أن المعايرة تمت على أساس استثمارات محدودة ولم تمكن القياسات الدورية خلال فترة الدراسة من تسجيل تبدلات هامة في المنسوب فقد تمت المعايرة ضمن هذا الإطار وبالتالي فإنه من الضروري إعادة المعايرة بعد فترة الاستثمار المكثف من المناطق المقترحة وإعادة تشغيل النموذج وحساب الموازنة في كل منطقة وذلك لتدقيق النتائج التي تم الحصول عليها وتحديثها على ضوء المراقبة الدورية الدائمة التي يجب أن تتوفر ويوضع لها برامج واضحة ومتابعة من قبل الجهات المختصة المسؤولة عن استثمار الحوض.

ولابد من التأكيد على بعض النقاط الهامة في هذا المجال نلخصها فيمايلي:

آ -اعادة المعايـرة

لم تسجل خلال الفترة التي اجريت وفقها المعايرة والواقعة مابين 1992 -1996 تبدلات واضحة في قيم الاستثمارات والمناسيب وتم على اساسها تشغيل النموذج وفق خطة الاستثمار المقترحة والتنبؤ بهبوط المناسيب وتبدلات عناصر الموازنة المائية في كامل الحوض وفي مناطق الاستثمارت المختلفة وبالتالي فانه من الهام تتبع تبدلات منسوب المياه الجوفية بعد فترة كافية من بدء زيادة الاستثمارات وفق الخطة المقترحة ومطابقة تلك التبدلات (المقاسة) مع التبدلات المحسوبة في النموذج الرياضي وبالتالي فانه من الضروري اعادة المعايرة من اجل ضمان التطابق بين الحساب الرياضي والقياس الحقلي لمناسيب المياه ويتم ذلك باجراء التعديلات اللازمة في توزع قيم معامل النفوذية ومعامل التخزين.

ب -دعم وتطوير شبكة الأرصاد

هناك حاجة ماسة لدعم شبكة الأرصاد الحالية وتطويرها، وذلك بإجراء تجارب تقييم لكفاءة أداء آبار المراقبة الحالية وصيانة تلك الآبار حين اللزوم ، وكذلك متابعة تبدلات قيم الضخ من الآبار ، وتركيب مسجلات آلية على بعض البيزومترات التي تمثل الحركة العامة للمياه الجوفية في منطقة الدراسة ، بالاضافة إلى أنه من الهام حفر بعض آبار بيزومترية في المناطق الحدودية من أجل رصد التأثيرات الحدودية على منطقة الدراسة ، وأخيراً لابد من التنويه على ضرورة دراسة احتمال وجود اتصال بين الخزان الجوفي مع الطبقات المائية التي تليها (الجوراسي وغيرها)، لتحديد طبيعة هذا الاتصال وتأثيره على الطبقة الحاملة ان وجد وأخذه بالاعتبار في تشغيل النموذج ومعايرته المستقبلية .

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واقع المياه الجوفية في منطقة شمال غرب الجماهيرية

كلية الهندسة بصبراته/جامعة السابع من ابريل
صبراته/ ليبيا

الخلاصة

تعتبر مكامن المياه الجوفية في الجماهيرية مصدر ديمومة الحياة في هذه المساحة الشاسعة. وتكوين سهل الجفارة واحد من أهم هذه المكامن حيث يحتوي على خزانات مائية مهمة يأتي في مقدمتها الخزان الأول (البليوسين والميوسني العلوي). ولغرض الوقوف على ما وصلت إليه حالة المياه الجوفية في تلك المنطقة فقد تم في هذا البحث إجراء دراسة ميدانية وأخرى تحليلية نظرية.

تضمنت التجارب الحقلية اختبار مجموعة من الآبار الرئيسية في منطقة العقربية والمغذية لمدينة زوارة ذات الكثافة السكانية العالية. تم قياس المناسيب المختلفة للمياه داخل تلك الابار إضافة إلى قياس التصاريف الخارجة منها خلال فترات إيقاف وتشغيل دورية ولعدة اشهر من السنة. وتم جمع البيانات الميترولوجية الخاصة بالمنطقة.

في حين اشتمل الجانب التحليلي على معالجة تلك البيانات لغرض التعرف على كيفية تغير مناسيب المياه الجوفية مع عدة عوامل وتحت عدة ظروف.

لقد تبين وجود هبوط مستمرفي منسوب المياه الجوفية حيث بلغ 120 cm خلال فترة قصيرة (يناير 1998 ولغاية ابريل 1998). في حين لم يبلغ مقداره 62 cm خلال الفترة (1992 ولغاية 1997). كما وجد ايضاً عدم وجود علاقة واضحة بين السقيط المطري وتغير مناسيب المياه الجوفية بالمنطقة.

اما انتاجية الآبار فقد انخفضت هي الاخرى عن قيمتها التصميمية حيث بلغ اقصى انخفاض 31,5٪. واتضح أيضاً وجود تداخل بين بعض الآبار مما يتطلب الالتزام بنظام حفر الآبار.

المقدمة (INTRODUCTION)

يمكن تعريف المياه الجوفية على أنها ذلك الجزء من المياه تحت السطحية والموجودة في تكوينات ارضية مختلفة ويمكن استخراجها بوسائل متعددة كالآبار والخنادق وغيرها الى سطح الأرض[1]، وتعتبر المياه الجوفية مصدراً رئيسياً للامداد في كثير من بلدان العالم وخاصة الجافة وشبه الجافة منها. والمياه الجوفية كأي ثروة طبيعية ليست لا نهائية ولذلك يجب ان تستغل وتدار بحكمة وعلى أسس علمية صحيحة ويجب ان تُسن القوانين الصارمة لحمايتها من التلوث او الاستهلاك غير المشروع.

إن نسبة المياه الجوفية كبيرة بالمقارنة بمثيلتها السطحية حيث تمثل الأولى حوالي 30٪ من الماء العذب فيما تمثل المياه السطحية نسبة 0,27٪ من المياه العذبة[2] فاذا أخذنا سكان الوطن العربي والذي سيبلغ 160 مليون نسمة واحتياجاتهم المائية لمختلف الأغراض يحتم علينا توفير 32×10^8 m^3/d من المياه العذبة وهذا المقدار لا توفره المياه السطحية مجتمعة ولهذا يجب ادخال المفاهيم الحديثة لوضع افضل الخطط لاستغلالها والاستفادة منها.

أهداف البحث (PURPOSES OF THE RESEARCH)

تم اجراء عمل ميداني وتحليلي نظري لواقع المياه الجوفية في منطقة زوارة شمال غرب الجماهيرية. تضمنت التجارب الحقلية اختبار مجموعة من الآبار الرئيسية في منطقة العقربية والمغذية لمدينة زوارة (27000 نسمة). حيث تم قياس المناسيب المختلفة للمياه داخل تلك الآبار اضافة الى قياس التصاريف الخارجة منها خلال فترات إيقاف وتشغيل دورية لتلك الآبار ولعدة أشهر من السنة. وتم جمع البيانات الميترولوجية الخاصة بالمنطقة.

في حين اشتمل الجانب التحليلي على معالجة تلك البيانات لغرض التعرف على كيفية تغير مناسيب المياه الجوفية مع عدة عوامل وتحت عدة ظروف.

موقع الدراسة (SITE OF STUDY)

تقع منطقة العقربية جنوب مدينتي زوارة والجميل وتبعد حوالي 25 km عن مدينة زاورة و15 km عن مدينة الجميل. تمتاز بمناخ متباين في درجات الحرارة حيث تتراوح بين °C(47-2) خلال العام[3] كذلك تتميز بانخفاض معدل السقيط المطري حيث لا يتجاوز 150.mm/y. الجزء الجنوبي من المنطقة جرداء ويغطي معظم سطحها الحصى والجبس اما الجزء الشمالي من المنطقة فعبارة عن اشجار او مستنقعات مالحة او كثبان رملية.

اما التركيب الجيولوجي للمنطقة فيميزه وجود فالق (قفصه - العزيزية) الموازي للساحل عند خط عرض (30 - 32) تقريباً ويمثل الفالق الحد الشمالي للطبقات الحاملة للمياه العذبة عدا العدسات الحاملة للمياه العذبة في تكوين الجفارة وتبلغ مساحة الجفارة 20 هكتار ويعيش عل عليها 50٪ من السكان وهي تحتوي على سهول مروية بواسطة المياه الجوفية والتي تمثل اكثر من 60٪ من المساحات المروية بالجماهيرية. ويشمل كل الترسبات الواقعة فوق تكوين العسة شمال الفالق وفوق ترسبات العصر الثلاثي جنوب الفالق.

وتوجد في المنطقة عدة خزانات مائية جوفية اهمها الخزان الأول الذي يمتد من البحر شمالاً الى فالق (قفصة - العزيزية) جنوباً وهو خزان غير مضغوط وسمكه حوالي 200m ومستوى الماء الساكن يتراوح بين 5m الى 35m تحت الأرض والسمك المشبع منه حوالي 160m[3].

العمل الحقلي (FIELD WORK)

تميز العمل الحقلي بدراسة مجموعة من الآبار تحت الخدمة الحالية لتغذية مدينة زوارة. ويمكن ملاحظة تفاصيل هذه الآبار من الجدول رقم (1) .

إشتمل العمل الحقلي على قياس مناسيب المياه داخل الآبار وقياس التصاريف الخارجة منها ولفترات مختلفة ولحالات متعددة اهمها:

اولاً :- قياسات المناسيب في حالة توقف جميع الآبار عن العمل.
ثانياً :- قياسات المناسيب والتصاريف في حالة تشغيل جميع الآبار معاً.
ثالثاً :- قياسات المناسيب والتصاريف في حالة تشغيل بئر واحد مع إيقاف الآبار عن العمل.

جدول (1) البيانات الخاصة بآبار الدراسة

رقم البئر	الاحداثي س	الاحداثي ص	مستوى الماء الثابت(m)	مستوى الماء المتحرك (m)	العمق الكلي (m)
411	20650	28450	72	66.92	90
414	21200	29800	75.4	70.4	102
82	81135	27735	77.8	71.21	99
81	20850	28375	64.1	47.2	81.5

وتتضمن هذه الفقرة بدورها مجموعة من التجارب الخاصة بتشغيل كل بئر لوحده.

أولاً :- قياسات المناسيب في حالة توقف جميع الآبار عن العمل :-

لمعرفة المناسيب الساكنة للآبار يجب ان تكون جميع الآبار خارج الأستخدام ولذا فقد تم إيقاف تشغيل المضخات لجميع الآبار لمدة لا تقل عن 48 ساعة تم بعدها قياس منسوب الماء داخل تلك الآبار. وتم تكرار هذه التجربة اربع مرات خلال أربعة أشهر ويبين الجدول (2) تلك النتائج.

جدول (2) المناسيب الساكنة للآبار

التاريخ	رقم البئر	المنسوب الساكن (m)	التاريخ	رقم البئر	المنسوب الساكن (m)
27/1/98	414	68.58	15/3/98	414	68.29
	411	64.51		411	63.90
	81	58.70		81	58.00
	82	69.70		82	68.35
31/2/98	414	68.33	15/4/98	414	68.00
	411	64.10		411	63.77
	81	58.06		81	57.50
	82	96.50		82	68.33

ثانياً :- القياسات في حالة تشغيل جميع الآبار :-

تميز هذا الجزء بقياس المناسيب المتحركة والتصاريف لجميع الآبار في نفس الوقت تقريباً وبعد فترة تشغيل مستمرة لجميع الآبار معاً لفترة لا تقل عن 24 ساعة. ويبين الجدول (3) نتائج تلك القياسات.

ثالثاً :- القياسات في حالة تشغيل بئر واحد مع ايقاف بقية الآبار :-

لغرض معرفة التداخل بين هذه الآبار ولمعرفة مقدار هذا التداخل تم اجراء مجموعة التجارب التالية :-

جدول (3) المناسيب المتحركة والتصاريف لجيمع الآبار في حالة تشغيلها معاً

التاريخ	رقم البئر	المنسوب H(m)	التصريف $Q(m^3/hr)4$
17/4/98	82	67,00	21,74
~	411	64,12	27,41
~	414	67,50	17,84
~	81	56,00	-
19/4/98	82	66,50	21,96
19/4/98	411	62,85	28,12
~	414	64,69	18,14
~	81	55,22	-
20/4/98	82	66,31	22,042
~	411	62,39	28,56
~	414	63,70	18,23
-	81	54,87	-
22/4/98	82	66,30	22,06
~	411	62,32	29,06
~	414	63,00	18,32
~	81	54,23	-
23/4/98	82	66,25	22,061
~	411	62,27	29,51
~	414	62,02	18,54
~	81	53,63	-
~	411	62,21	30,04
~	414	61,50	18,63
~	81	53,13	-
27/4/98	82	65,90	22,26
~	411	62,61	30,53
~	414	60,00	19,412
~	81	53,00	-
29/4/98	82	65,57	22,54
~	411	62,12	31,08
~	414	58,60	20,67
~	81	52,94	-
2/5/98	82	65,36	22,58
2/5/98	411	62,06	31,56
~	414	58,50	20,89
~	81	52,88	-
6/5/98	82	65,24	32,14
~	411	62,01	32,04
~	414	57,00	22,50
~	81	52,76	-

أ - التجربة الأولى :

تضمنت هذه التجربة إيقاف جميع الآبار عن العمل لمدة لا تقل عن 48 ساعة لغرض استقرار المنسوب الساكن داخلها. تم قياس هذا المنسوب لجميع الآبار. بعد ذلك تم تشغيل البئر 82 لوحده مع استمرار توقف بقية الآبار عن العمل. بعد 24 ساعة من التشغيل المستمر للبئر 82 تم قياس منسوب الماء المتحرك داخله ومقدار التصريف الخارج منه.

ب - التجربة الثانية :-

تم تكرار خطوات التجربة الأولى ولكن مع تشغيل البئر 411 لوحده.

ج - التجربة الثالثة :-

تم تكرار خطوات العمل بالتجربتين الأولى والثانية مع تشغيل البئر 414 لوحده. ويبين الجدول (4) نتائج تلك التجارب الثلاثة.

التحليل والمناقشة (ANALYSIS AND DISCUSSION)

تم في هذا الباب ايجاد معامل الأمرارية (T) الخاص بتربة المنطقة وذلك باستخدام طريقتي جاو (chow) وكوبر وجاكوب (Cooper and Jacob)[5] وقد اعطت الطريقتان قيم متقاربة جداً لمعامل الامرارية بلغ ($9.41\ m^2/hr$) إن هذا المعامل سيمثل اساس لحسابات قادمة.

التداخل بين الآبار (WELL INTERFERENCE)

لغرض معرفة مقدار التداخل بين الآبار إن وجد لا بد من حساب مقدار نصف قطر تأثير كل بئر. بما أن الطبقة الحاملة للماء هي طبقة غير مضغوطة فيمكن استخدام المعادلة العامة لإيجاد نصف قطر التأثير (R)[5].

$$Q = \pi k \frac{ho^2 - h^2w}{\ln R / r}$$

$$k = \frac{2T}{h1 + hw}$$

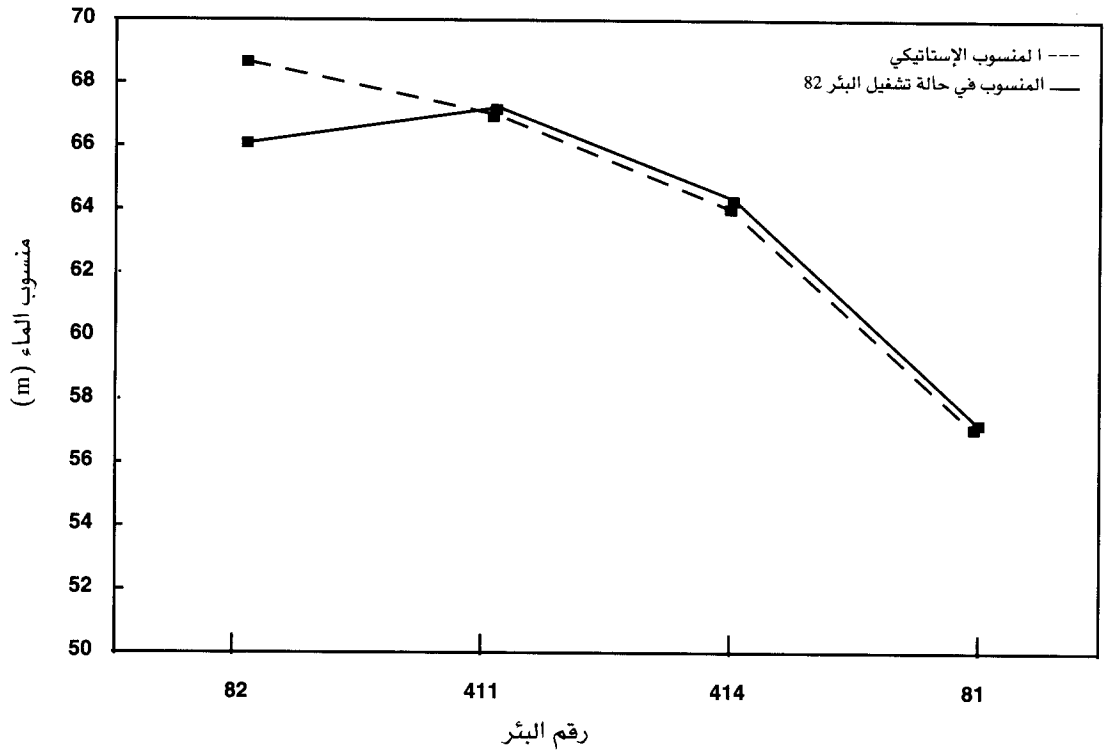
حيث Q : التصريف الخارج من البئر (L^3/T)
K : معامل نفاذية التربة (L/T)
ho : عمق الطبقة الحاملة (L)
hw : ارتفاع الماء داخل البئر (L)
T : معامل الامرارية (L^2/T)
h_1 : ارتفاع الماء عند مقطع قريب من البئر (L)

ويبين الجدول (5) نتائج حساب نصف قطر تأثير كل بئر.
لمنع حدوث التداخل بين الآبار وبالتالي لتفادي انخفاض انتاجية البئر تبعاً لذلك فلا بد ان تكون المسافة الصغرى بين الآبار لا تقل عن ضعف قيمة نصف قطر التأثير في حالة بئرين متماثلين ومجموع نصفي قطري التأثير للبئرين في حالة بئرين مختلفين.
لغرض معرفة مدى تأثير تشغيل البئر 82 لوحده على بقية الآبار يمكن ملاحظة الشكل (1) حيث يتضح أن تشغيل هذا البئر لا يؤثر على منسوب الماء في بقية الآبار الأخرى أي عند تغير منسوب الماء عند البئر 82 قبل وبعد تشغيله بقى منسوب الماء ثابتاً عند الآبار الأخرى أما في الشكل (2) فنجد أن تغير منسوب الماء داخل البئر 411 قبل وبعد تشغيله أدى الى تغير منسوب الماء داخل البئر 81 أيضاً في حين بقي المنسوب في الآبار الأخرى ثابتاً مما يدل على أن هناك تداخلاً بين البئرين ،411 ،81.
اما في حالة تشغيل البئر 414 لوحده فنجد عدم تغير منسوب الماء عند بقية الآبارالأخرى قبل وبعد تشغيل البئر .414

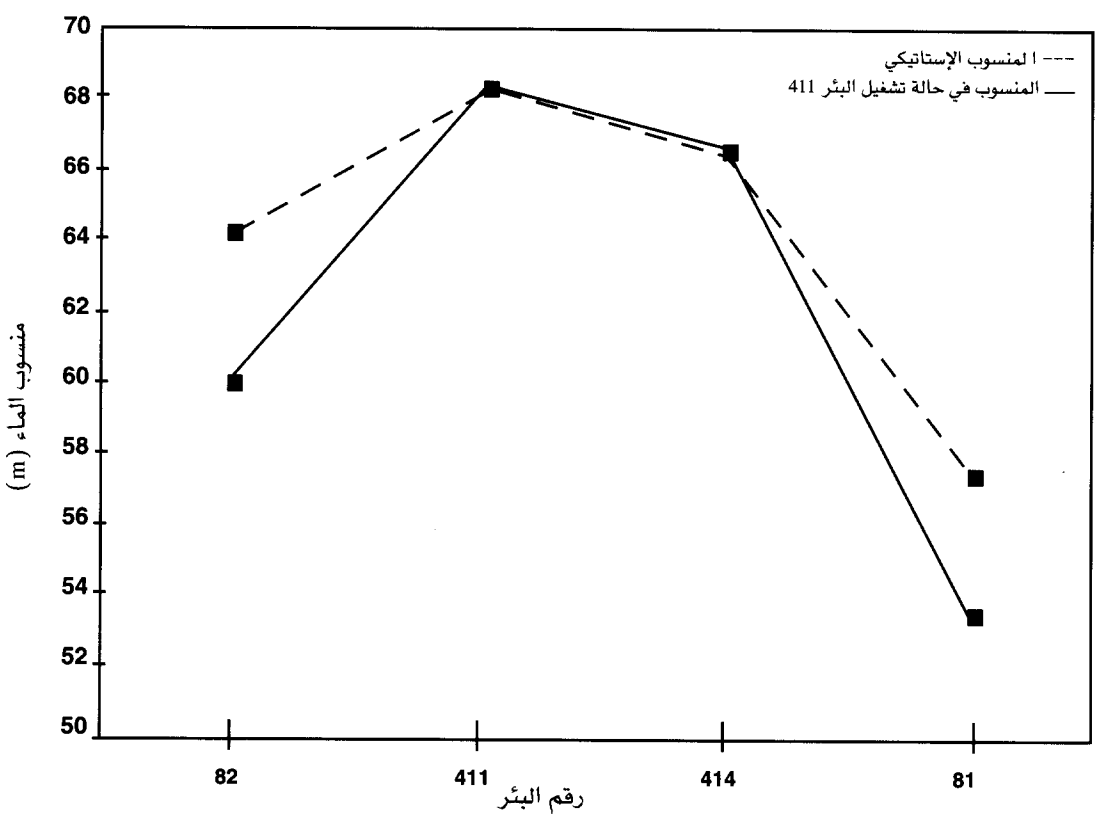
تغير منسوب الماء مع التصريف :-

لغرض التعرف على التغيرات التي طرأت على مناسيب المياه داخل الآبار فقد تم رسم البيانات المستحصلة من قياسات التصاريف الخارجة من كل بئر مع منسوب المياه داخلها في حالة اشتغال جميع الآبار معاً.

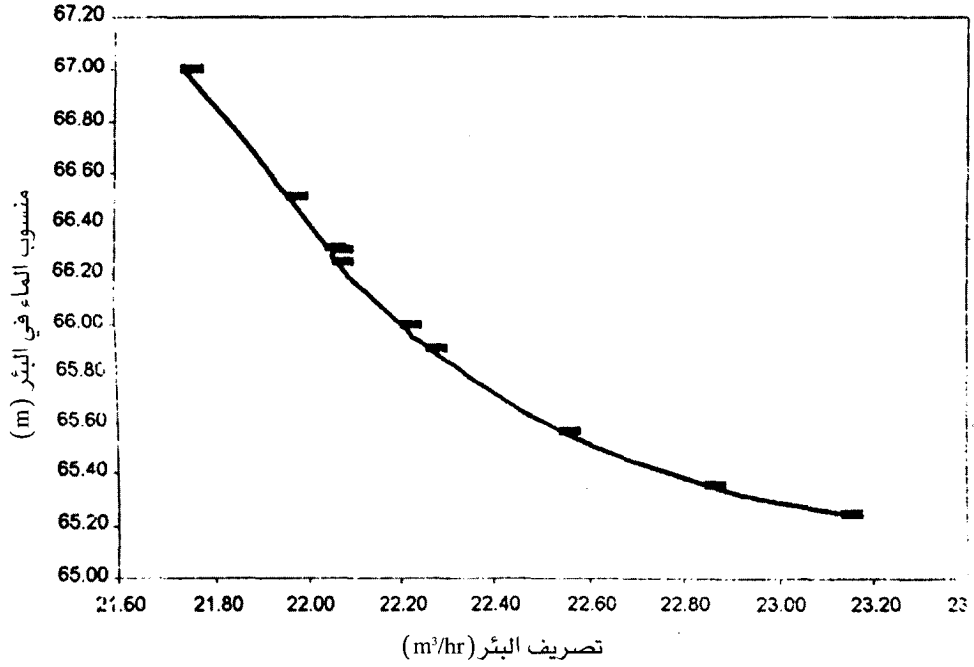
يبين الشكل (3) مقدار هذا التغير بالنسبة للبئر 82 في حين يبين الشكل (4) مقدار التغير في حالة البئر411 .



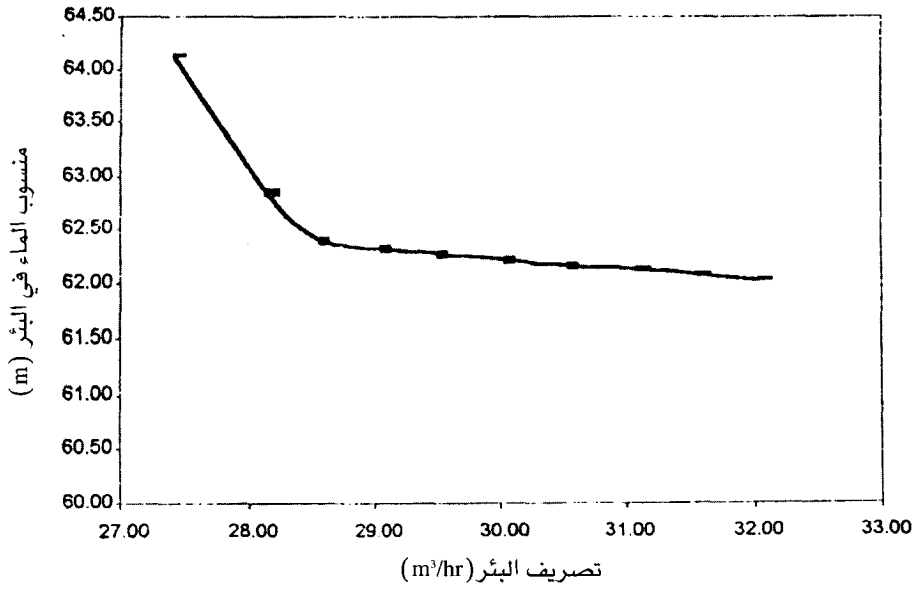
الشكل (1) مدى تأثير تشغيل البئر (82) لوحده على مجموعة الآبار الأخرى



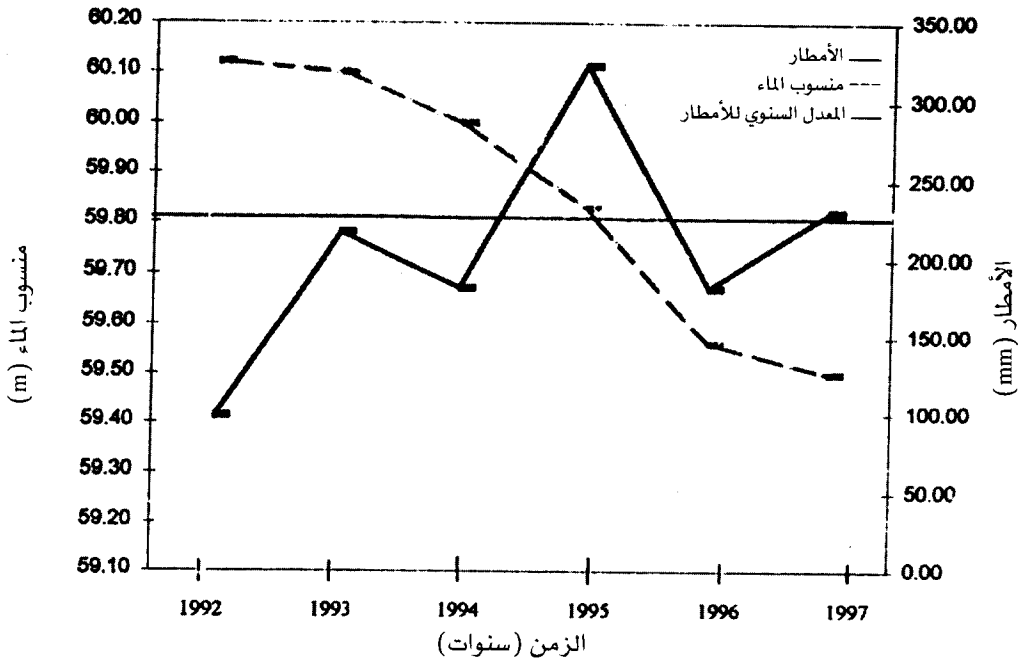
الشكل (2) مدى تأثير تشغيل البئر (411) لوحده على مجموعة الآبار الأخرى



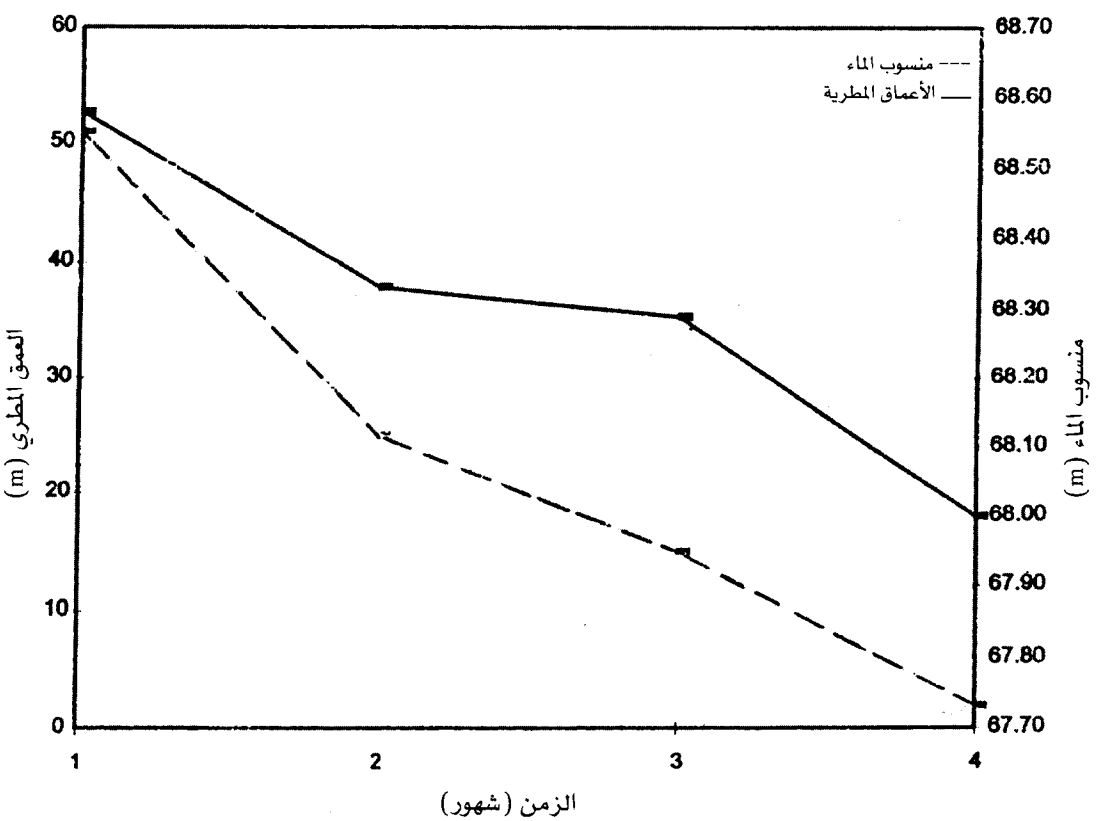
الشكل (3) تغير التصريف مع منسوب الماء داخل البئر (82).



الشكل (4) تغير التصريف مع منسوب الماء داخل البئر (411)



الشكل (5) تغير منسوب الماء في البئر (81) مع الأعماق المطرية
خلال الفترة من سنة 92 إلى 97



الشكل (6) تغير منسوب الماء في البئر (414) مع الأعماق المطرية
خلال الفترة من شهر 1 إلى 4 لسنة 1998

تغير منسوب الماء مع الأمطار :-

الأمطار هي المغذي الأساسي للمياه الجوفية ولهذا فمن الضروري الوقوف على حالة المياه الجوفية عند تغيّر كمية السقيط المطري. الشكل (5) يمثل منسوب المياه الجوفية مع المجموع السنوي للسقيط المطري لمنطقة الدراسة للفترة من (1992 - 1997) (7,6) نجد أن منسوب المياه الجوفية أخذ بالهبوط المستمر وبغض النظر عن كمية الأمطار سواء كانت أكبر أو أقل من المعدل السنوي.

أما عند رسم البيانات المقاسة حالياً (للأربعة أشهر الأولى من عام 1998) فوجد ازدياد نسبة هبوط منسوب المياه الجوفية بشكل مضطرد. أنظر الشكل (6). حيث كان مقدار الهبوط في المنسوب عند البئر 81 مثلاً خلال السنوات (1992 - 1997) 62 cm في حين بلغت قيمته خلال الأربعة أشهر الأولى فقط من عام (1998) 120 cm.

جدول (4) المناسيب والتصاريف في حالة تشغيل كل بئر لوحده

رقم البئر	المنسوب المتحرك (m)	Q (m3/hr)	الملاحظات
82	66.50	22.00	في حالة تشغيل البئر 82 لوحده
411	56.78	31.76	في حالة تشغيل البئر 411 لوحده
414	64.34	22.61	في حالة تشغيل البئر 414 لوحده

جدول رقم (5) إنصاف إقطار تأثير الآبار

رقم البئر	$h_o(m)$	$h_w(m)$	$Q(m^3/hr)$	$R_o(m)$
411	64.07	60.00	31.76	345.51
82	68.97	66.15	22.00	690.00
414	68.30	65.50	22.61	478.86

الإستنتاجات (CONCLUSIONS)

إن أهم الاستنتاجات التي تم التوصل اليها من خلال هذا البحث الميداني التحليلي يمكن تلخيصها بما يلي :-

1 - وجود تداخل بين البئرين 411 ,81 لأن المسافة بينهما أقل بكثير من مجموع نصفي قطر تأثيرهما لذا فإن أقرب مسافة يجب الإلتزام بها عند حفر الآبار في منطقة الدراسة يجب أن لا تقل عن 1168 m لأن اكبر نصف قطر تأثير للآبار بلغ 690 m وأدناه بلغ 345 m للتصاريف المحصورة بين m^3/hr (30 - 20) او أقل.

2 - استمرار الهبوط في منسوب المياه داخل جميع الآبار سواء الساكنة منها أو المتحركة وقد بلغ أكبر هبوط في المنسوب الساكن 8.83 m عند البئر 82 وأقل هبوط كان 6.04 m عند البئر 81.

أما أكبر هبوط في المنسوب المتحرك فقد بلغ 8.75 عند البئر 414 وأقل هبوط بلغ 4.47 عند البئر 411 إن هذه الهبوطات تمثل 16.22 ٪ من قيمة الأعماق السطحية للآبار وهي نسبة كبيرة بالمقارنة باعماق الآبار.

3 - لم تظهر علاقة واضحة بين كمية السقيط المطري ومنسوب المياه داخل الآبار خلال السنوات 1992 - 1997 .

4 - أن مقدار الهبوط في منسوب الماء داخل الآبار خلال الأشهر الأربعة الأولى من عام 1998 كان اكبر من مقدار الهبوط في تلك المناسيب خلال الفترة 1992 - 1997 فمثلاً عند البئر 81 كان مقدار الهبوط خلال الفترة 1992 - 1997 يساوي 62 cm في حين بلغ مقداره 120 cm خلال الأشهر الأربع الأولى فقط من عام 1992.

5 - من خلال فحص حالة المضخات المنصوبة ومقارنة قدرتها التصميمية مع القدرة الحالية نجد أن قدرتها قد هبطت بمقدار وصل في بعضها الى 31.5٪ من القدرة الحقيقية مما يؤكد حالة زيادة عمق المياه الجوفية الذي بدأ يؤثر سلباً على كفاءة تصريف المضخة.

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المحور الرابع : التأثيرات البيئية
الناتجة عن استغلال المياه الجوفية

إعداد الدكتور جان خوري

الموارد المائية الجوفية غير المتجددة
سماتها، تقييمها وآفاقها المستقبلية

المركز العربي لدراسات المناطق الجافة والأراضي القاحلة - دمشق - سوريا

الخلاصة

تشكل الموارد المائية الجوفية غير المتجددة الاحتياطي الاستراتيجي للمناطق الجافة، كما أنها تشكل مصدراً هاماً من مصادر المياه المتاحة للدول التي يقع جزء أو كامل أراضيها في اقاليم مناخية جافة، وبالرغم من تركيز اجندة القرن الحادي والعشرين على الموارد المائية العذبة المتجددة، فان الموارد المائية غير المتجددة سوف تلعب دوراً هاماً في حياة سكان المناطق الجافة، في حال تنظيم استثمارها وتخطيط استخداماتها استناداً الى تقييم جيد لامكاناتها.

تأتي أهمية الموارد المائية غير المتجددة كون أحواضها ذات مخزون ضخم وكون انظمتها المائية ذات امتداد واسع، وقد تكونت هذه الأنظمة المائية في غضون فترة امتدت عشرات آلاف السنين تميزت بتتابع فترات مطيرة وجافة، علماً بأنه منذ نهاية الفترة الأخيرة ما قبل 800 عام تقريباً كانت أنظمة تغذيتها وصرفها وتوازنها لا يختلف عن الأنظمة السائدة في المناطق المعتدلة وبعد دخول فترة الجفاف المعاصرة بدأت تفقد جزءاً من مخزونها وتتناقص كميات صرفها الطبيعي الذي لم يرفد بتغذية كافة لاستمراره كنظام مائي مستقر.

إن الاستثمار المكثف أو الموزع الذي شهدته معظم الأحواض غير المتجددة خلال القرن الحالي قد أدى الى ظهور مشاكل ذات طابع نوعي أو كمي في مواقع مختلفة من هذه الأحواض، سواءاً كانت خطط الاستثمار رشيدة ومحافظة أو طموحة وجائرة فانها وفرت امدادات هامة لسد حاجات اساسية للانسان في المناطق الجافة، كما وفرت ثروة قيمة من المعلومات يمكن أن تفتح المجال لادارة أفضل في المستقبل، فالضخ من المياه الجوفية يؤدي إلى زيادة كميات التغذية المحرضة أو تخفيض كميات الصرف الطبيعي أو كليهما ان امكن ذلك، فالمياه تأتي على حساب هذين العاملين عملاً بمبدأ الحفاظ على المادة، وبالنسبة للمياه الجوفية غير المتجددة فان الاحتمال الأول غير ممكن بسبب انعدام التغذية تقريباً، أما الاحتمال الثاني فيمكن تحقيقه على مقياس زمني بعيد الأمد وبصورة جزئية نظراً للامتداد الواسع للنظام المائي بين مناطق التغذية ومناطق الصرف كالسبخات، ومع تعذر امكانية العودة إلى حالة من التوازن في الحوض المائي يستمر السحب من المخزون وتستمر المناسيب بالهبوط وقد تتناقص تصاريف الآبار وتصبح الطبقة المائية مهددة بالاستنزاف.

من هذا المنظور استخدمت النماذج الرياضية كوسيلة فعالة لتقييم الموارد المائية الجوفية غير المتجددة على اساس استثمار منجمي بمحا ا كات الطبيعة وأصبح بالامكان صنع سيناريوهات لمستقبل الطبقة المائية واختيارحلول مناسبة تعتمد على ادارة ديناميكية وفعالة للطبقة المستثمرة للحد من استفحال بعض الآثار السلبية، عندما تتبدل صفات النظام الهيدروديناميكي. وأهمية استخدام النمذجة الرياضية تمكن بقدرتها على محاكات الواقع الهيدرولوجي تحت شروط طبيعية ومؤثرات بيئية واجتماعية واقتصادية متعددة الجوانب ليصبح التقييم متفاعلاً مع عملية صنع القرار واستخدام النموذج لاستقراء التبدلات التي ستطرأ على النظام المائي وفق الخطة المثلى وشروط مسبقة يحددها صانع القرار.

أما المشكلة التي تعترض عملية التقييم في احواض مترامية الاطراف كالحوض النوبي شمالي الصحراء الكبرى وحوض الحجر الرملي الكالاهاري في جنوب الصحراء هو عدم كفاية المعطيات وتوفرها بالدقة المطلوبة، وهذا أمر مفهوم في حوض تصل سماكة طبقاته المائية الى عدة آلاف من الامتار وامتداده الى عدة مئات آلاف الكيلومترات المربعة، وتدل التجارب السابقة بأنه يتعذر في غالب الاحيان توفير المعلومات المطلوبة لنماذج المحاكات بسبب صعوبة تحديد سمات الحوض وطبيعته والعمليات الهيدروجيولوجية والتبدلات التي تطرأ عليها في الزمان والمكان، وهو شرط ضروري لتطبيق الاسس التي ترتكز اليها النمذجة، وهذا بدوره يؤدي إلى عدم وجود حل وحيد أو تحديد قاطع لماهية النظام المائي ومدى استجابته لضغوط الاستثمار، وتصبح عملية التقييم عملاً مستمراً فلا بد من تغذية راجعة لإعادة المعايير والتأكد من مطابقة الحل للواقع المتبدل تحت تأثير الاستثمار وقد تستمر عملية التقييم المذكورة لأمد طويل أو تترافق وتتداخل مع عملية الاستثمار.

ولا يمكن تجاهل الواقع الجغرافي للاحواض المائية الجوفية غير المتجددة باعتبارها في الغالب واسعة الامتداد وتشكل احواض مشتركة لعدة بلدان متجاورة، ويسبب هذا الوضع الجغرافي مشكلات قانونية ومؤسسية تظهر الحاجة إلى التعاون لتقييم مواردها وادارتها واستخدامها بصورة منصفة وعقلانية، فالضرورة تقتضي محاكات الواقع بمقاييس مختلفة وتطوير نماذج على المستوى المحلي ومستوى الاحواض فالنموذج الاقليمي ضروري لتحديد الصورة والموازنة الاجمالية، وفائدته العملية تتمثل بتوفير معلومات عن الشروط الحدية لنماذج شبه اقليمية ومن ثم التدرج الى النماذج المحلية المستخدمة لتنظيم الاستثمار على مستوى حقول الآبار.

والتقييم النوعي لا يقل أهمية على التقييم الكمي بما في ذلك تقييم الآثار البيئية لايستخدام المياه في الري حيث يعود جزء من المياه المحملة بالاملاح الى الخزان المائي الذي يمكن فضلاً عن ذلك أن يواجه تدهور في النوعية نتيجة تزايد تركيز الأملاح الناجمة عن الضخ الجائر من خزان متعدد المستويات والنوعيات.

المقدمـــة

تشمل المناطق الجافة وشبه الجافة حوالي 40٪ من مساحة اليابسة، إلا أنها لا تحظى إلا بحوالي 2٪ من الجريان الذي ينساب عبر الأنظمة المائية السطحية في العالم. ونظراً للظروف المناخية المتطرفة فإن جزءاً محدوداً من هذه المياه المتجددة قابلة فعلاً للاستخدام من قبل سكان هذه المناطق، وتدل دراسات النظائر أن الجزء الأعظم من المياه الجوفية المتوافرة في المناطق الجافة وشبه الجافة قد تم تشكلها وتغذيتها خلال فترات مطيرة سابقة، وأن الفترة المطيرة الأخيرة التي شهدتها المناطق الصحراوية في شمال أفريقيا امتدت قبل 5000 و 8000 من الوقت الحاضر إلا أن جزءاً هاماً من الكتلة المائية تعود إلى فترات مناخية رطبة سابقة، أما الفترة المناخية الحديثة فهي فترة جافة لا تساهم إلا قليلاً في تغذية الطبقات المائية الجوفية.

وفي ضوء نتائج الدراسات الإيزوتوبية وغيرها من الأبحاث المتعلقة بالأنظمة المائية السائدة في المناطق الجافة وخاصة الأنظمة الاقليمية العميقة تبين أن الموارد المائية التي توفرها هي موارد غير متجددة أي موارد أحفورية Fossil وبالتالي فإن استثمارها مشابه إلى حد ما- إلى استثمار المكامن المعدنية إذ أنه استثمار منجمي Mining ، بالرغم من ديناميكية النظام المائي.

ومع تزايد الطلب على المياه في المناطق الجافة وتوافر مخزون كبير في خزانات واسعة الامتداد في العديد من المناطق فقد ارتفعت معدلات السحب من الموارد المائية الجوفية غير المتجددة وأصبح الاستثمار في العقود الأخيرة مكثفاً وجائراً في العديد من المناطق الأمر الذي أدى إلى استنزاف للمخزون بنسبة وصلت أحياناً إلى حوالي 25٪ من سماكة الطبقة الحاملة للماء.

وتدرك الدول التي تعاني من ندرة المياه العذبة المتجددة بأنه من الأهمية بمكان دراسة وتفهم أبعاد المشكلة المائية المتمثلة باستنزاف جزء هام من المخزون وهو الاحتياطي الاستراتيجي من المياه الجوفية غير المتجددة والذي يرافقه أحياناً تدهور في نوعيات المياه نتيجة التداخل بين مياه الطبقات العذبة والمالحة، كما تدرك هذه البلدان أيضاً أن استدامة التنمية تقضي بضرورة وضع استراتيجية بعيدة المدى لاستثمار وإدارة الموارد المائية الجوفية الأحفورية. ولابد من أن تنطلق أية استراتيجية بعيدة المدى من سياسة مائية تأخذ بعين الاعتبار احتياجات الخطط التنموية وأولياتها مع مراعاة الامكانات المائية المتاحة والتغيرات التي تطرأ عليها نتيجة الاستثمار المكثف أو الجائر، والذي تميزت به العقود الثلاثة الماضية.

وبما أن طبيعة وحجم الموارد المتاحة للاستثمار في الطبقات المائية غير المتجددة تتبدل باستمرار فإن عملية التقييم لهذه الطبقات يجب أن تكون مستمرة لتبيان ما يخرج منها من دائرة الاستثمار وما يمكن استغلاله مستقبلاً بصورة عقلانية انسجاماً وتحقيقاً لأهداف السياسة المائية. ومازالت الأسس التي يجب أن ترتكز إليها خطط استثمار الموارد المائية غير المتجددة قيد البحث والتطوير ولاشك بأن التحليل الموضوعي للتجارب الوطنية وتبادل الخبرات على المستوى الاقليمي والدولي في هذا المجال يمكن أن يساهم في توضيح الرؤى وبلورة مبادئ عامة وتوجهات لمعالجة المشكلات القائمة ووضع خطط واقعية وعقلانية للاستثمارات المستقبلية، علماً بأن لكل دولة خصوصيتها ولكل منطقة ظروفها التي يجب أخذها بعين الاعتبار عند وضع استراتيجية شاملة وخطط بعيدة المدى تضمن تحقيق الأهداف الوطنية.

السمات العامة للمياه الجوفية غير المتجددة

من المعروف أن الضخ من المياه الجوفية يؤدي إلى سحب المياه مباشرة من المخزون، ويرافق ذلك تدني لمنسوب المياه الجوفية الأمر الذي يولد ميلاً هيدروليكياً جديداً في النظام المائي، وهذا التبدل في الوضع المائي يؤدي إلى زيادة التغذية المحرضة Induced recharge (1994 Sun and Johnson) كما يؤدي إلى تخفيض كميات الصرف الطبيعي أو كليهما فالمياه التي يتم استثمارها تأتي على حساب هذين العاملين عملاً بمبدأ الحفاظ على المادة، وأن مثل هذا التغير في الوضع المائي ينشأ عادة في مناطق معتدلة أو رطبة تنال تغذية مائية كافية لتوليد ضاغط مائي وبالتالي حركة مائية جوفية من مناطق التغذية إلى مناطق الاستثمار أو مناطق الصرف الطبيعي.

أما بالنسبة للموارد المائية الجوفية غير المتجددة فإن احتمال زيادة كميات التغذية الطبيعية عن طريق التغذية الإضافية المحرضة غير ممكن بسبب انعدام التغذية أو ضآلتها في الحالات العادية، أما الاحتمال الثاني فيمكن تحقيقه نظرياً وبصورة جزئية على مقياس زمني طويل لا يتوافق مع فترات الخطط التنموية حتى الطويلة الأمد منها، ويعود ذلك إلى المسافة الكبيرة لمنطقة الحركة الجانبية Zone of Lateral Flow للنظام المائي قبل أن يتم صرف المياه (جان خوري، 1995)، والأمثلة على ذلك عديدة فالحركة الإقليمية للمياه التي تنشأ في شمال السودان وتشاد في الحوض النوبي تنتهي في شمال مصر وليبيا، وكذلك فإن حركة المياه الجوفية في «حوض الدمام وأم الرضمة» في شبه الجزيرة العربية تنتهي في الأحساء والبحرين في شواطئ الخليج العربي (خوري، 1996، 1987).

ونظراً لعدم وجود إمكانية لاستعادة حالة التوازن في الحوض المائي الجوفي يستمر السحب من المخزون وتستمر المناسيب في الهبوط كما تتناقص تصاريف الآبار ويجري استنزاف تدريجي للطبقة المائية.

فالسمة الأساسية للمياه الجوفية غير المتجددة هي عدم وجود اتصال فيما بينها وبين الدورة الهيدرولوجية المعاصرة أي انعدام التغذية الحديثة. إن هذه النتيجة صحيحة من الوجهة العملية، علماً بأن مثل هذا الاتصال لايمكن أن يكون معدوماً كلياً من الوجهة النظرية. ومن هنا تنشأ صعوبة تعريف الموارد المائية Water Resources بالنسبة للمياه الجوفية غير المتجددة باعتبار أن علم الهيدروجيولوجيا التقليدية يعتبر الموارد المائية المتاحة مفهوماً مرادفاً لمفهوم التغذية المائية السنوية الوسطية، إلا أنه لابد من التوصل إلى تعريف أكثر شمولية ينطبق على

المياه الجوفية المتجددة وغير المتجددة. فالموارد المائية تعرف من هذا المنظور بأنها «**المياه المتوافرة أو التي يمكن توافرها للاستخدام بكميات كافية ونوعيات مناسبة خلال فترة محددة من الزمن وملائمة للطلب المحدود على الماء**» فمثل هذه الموارد في الطبقات المائية غير المتجددة لا يمكن أن تأتي إلا من المخزون.

ومن الوجهة الهيدرولوجية يمكن تقدير وارد إجمالي للطبقة المائية الإقليمية في المناطق الجافة، إلا أن هذه التقديرات تستند إلى افتراضات اختبارها وتأكيدها إقليمياً في المساحات الكبيرة التي يعتقد أنها مناطق تغذية كما أن آلية التغذية والتغيرات المكانية والزمانية في نظام الهطول ترفع نسبة الخطأ إلى درجة يصعب عندها اعتماد موثوقية المعطيات الهيدرولوجية، وإذا تحقق ذلك جزئياً فإن استجابة مناطق الاستثمار لهذه التغذية سيكون محدوداً أو غير قابل للقياس. ويمكن التوصل إلى نفس النتيجة باحتساب النسبة بين الوارد السنوي والمخزون، فالطبقات التي تعود إلى حالة من التوازن في المناطق الرطبة تنال وارداً سنوياً يعادل 0.2 أو 0.1 من المخزون وفي الطبقات اللحقية فإن نسبة التغذية المائية إلى المخزون تكون أعلى من هذه القيم بقدر كبير بسبب ضآلة مخزونها، أما بالنسبة للموارد المائية غير المتجددة فإن المخزون قد يصل إلى 100,000 كم^3 أو أكثر (يقدر مخزون الحوض النوبي بحوالي 150,000 كم^3) ففي مثل هذه الظروف الهيدروجيولوجية يصعب دراسة العلاقة بين السحب والتغذية المائية إن وجدت وخلال فترة زمنية مناسبة، فتطور الوضع المائي الطبيعي للأنظمة المائية الاقليمية في المناطق الجافة يتم خلال مئات بل آلاف السنين.

ومن الواضح أن المقياس الزمني للسحب وما يتأتى عنه من استنزاف للمخزون لا يتوافق مع المقياس الزمني للتغذية المائية المحتملة.

ويعتقد البعض أن الصرف الذي يتم في السبخات أو الواحات مثل سبخة الموح في حوض تدمر أو شط الجريد في تونس وواحة الأحساء في السعودية وواحة سيوة في مصر هي مؤشر لوجود تغذية في المناطق العليا من النظام Upstream والصرف يمثل حصيلة ما يدخل النظام Input من مياه تعود للدورة الهيدرولوجية المعاصرة، إلا أن الاتجاه الآخر في هذا المجال هو تشكل ضاغط وميل أحفوري Fossil Gradient (Faraj, 1978) (Burdon, Lloyd and Thorweihe and Heinl, خوري وآخرون، 1996) الذي اعتمد على دراسة للنظائر لتحديد عمر المياه بين أن بناء الضاغط Potentiometric head قبل 8000 سنة تليه حركة مائية إقليمية ومحلية أدت إلى تفريغ جزء من المخزون في الواحات والسبخات المنتشرة في الجزء المصري والليبي من الحوض وأنه انطلاقاً من السطح الأحفوري قبل 8000 عام ووصولاً إلى السطح الحالي للمياه الجوفية تناقصت كميات الصرف من حوالي 2500 مليون م^3/سنة إلى حوالي 500 مليون م^3/سنة.

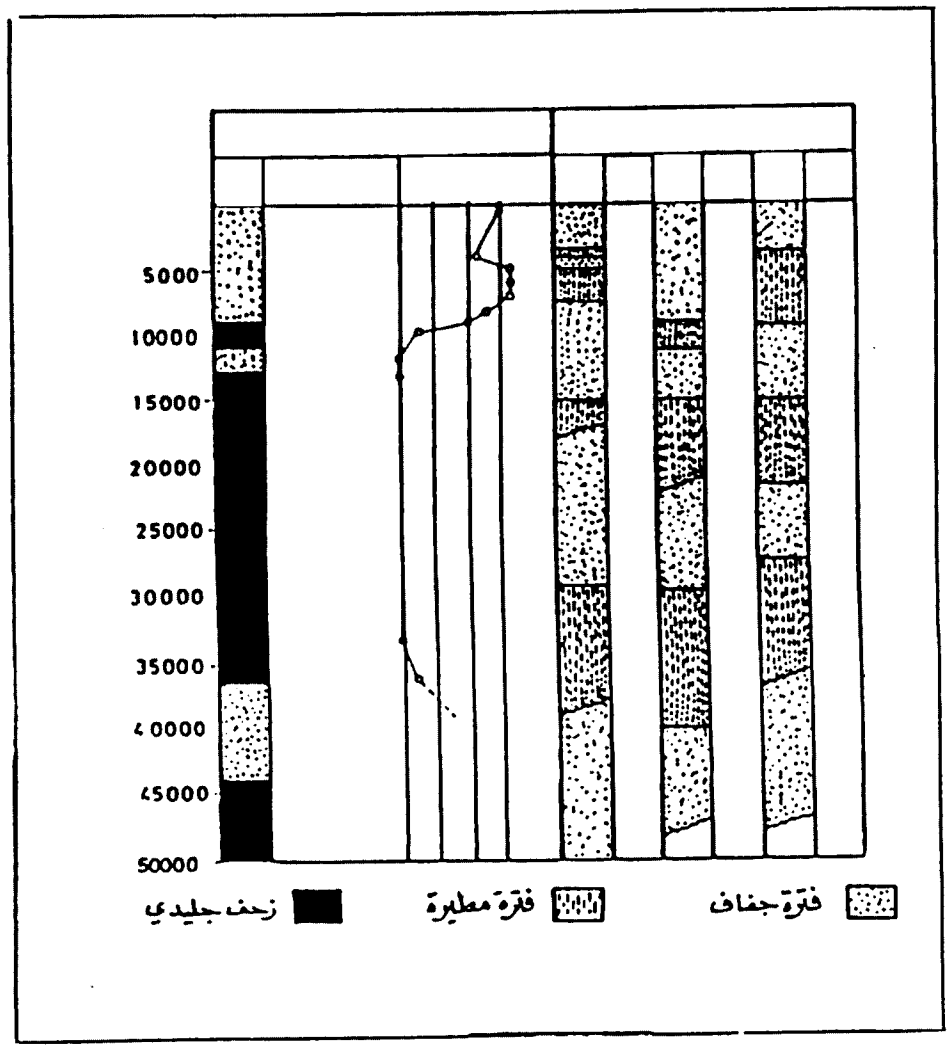
ولاشك بأن الظروف الطبيعية التي حددت السمات الهيدروديناميكية للنظام المائي والجوانب الكمية للموارد المائية انعكست على نوعية المياه وكانت عاملاً مؤثراً على الخصائص الهيدروكيميائية للمياه في الطبقات العليا والعميقة، فدرجات الحرارة المرتفعة انعكست على التركيب النظائري Isotopic والكيميائي في مناطق التغذية وكذلك فإن التبخر الشديد لعب دوراً هاماً في مناطق الصرف كالسبخات والمنخفضات الصحراوية التي يقترب فيها سطح المياه الجوفية من سطح الأرض.

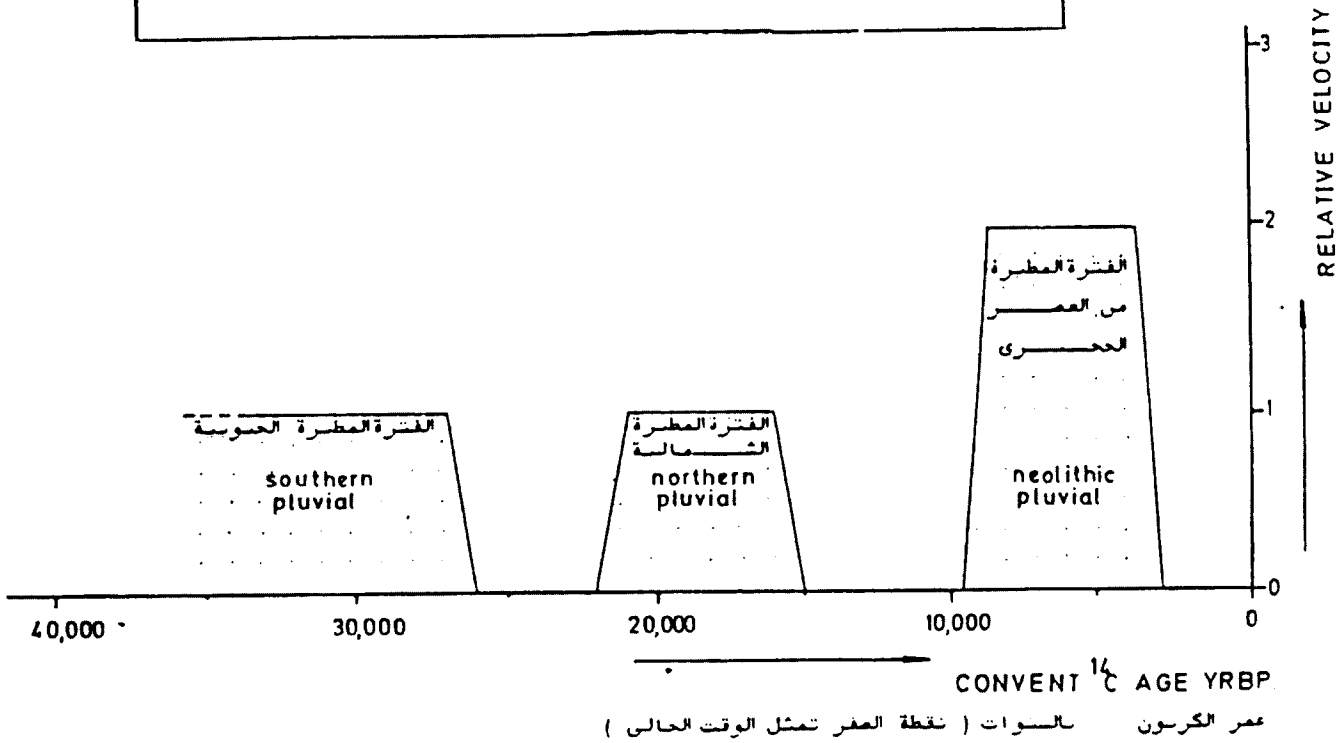
وبما أن التغذية القديمة Paleorecharge هي الأكثر أهمية في تكون الكتلة المائية غير المتجددة (شكل 1)، فإن الظروف المناخية التي سادت في الفترة المطيرة هي العامل الأساسي المحدد لنوعية المياه غير المتجددة وخاصة عندما يكون تأثير الأوساط الجيولوجية (كالطبقات الرملية السيليسية) محدوداً، وهذا ما يلاحظ في الطبقات المائية التي تشكلت في تكوينات الحقب الأول وهي على العموم مؤلفة من الحجر الرملي الذي تشكل من تآكل الركيزة البللورية. فالأملاح المنحلة في الطبقات المائية في تكوني الساق والمنجور في الجزيرة العربية والحجر الرملي النوبي في السودان ومصر وليبيا وتشاد محدودة، ومياه هذه الطبقات عذبة لا تتجاوز الأملاح فيها 500 ملغ/ليتر باستثناء أجزاء واقعة قرب مناطق الصرف أو مناطق تتداخل فيها السحنات الرملية مع سحنات كربوناتية وملحية (عمر سالم، 1995, Hefny,1991).

وعلى العموم فإن تأثير العوامل المناخية المتطرفة على التركيب الكيميائي للمياه في أعلى النظام المائي سيبقى محدوداً بالمقارنة بالتأثيرات الناجمة عن العمليات الكيميائية التي تجري لاحقاً في النظام المائي أثناء الحركة البطيئة للمياه وتفاعلها مع الوسط المسامي أو التشققي، وفي المناطق الجافة يلاحظ انتشار واسع للصخور الجصية والملحية في السلم الطبقي، والأوسع انتشاراً هو ما يعرف بطبقات الفارس الأسفل المؤلفة من سماكات كبيرة من الجص والانهدريت وأحياناً أملاح الصوديوم والبوتاس، وتعود هذه للنيوجين وخاصة الميوسين. تنتشر هذه الترسبات على نطاق واسع في إيران وشمال سوريا والعراق وفي دول الخليج العربية وخاصة السعودية والبحرين وقطر والإمارات العربية وسلطنة عمان (قضماني، 1995, عثمان، 1983, الزباري، 1998)، كما يلاحظ انتشار واسع لها في شمال مصر وليبيا. وفي حين تلعب الترسبات التبخرية النيوجينية (Mio-Pliocene) دوراً هيدروكيميائياً سلبياً يؤدي إلى تدهور نوعيات مياه الطبقات العليا للأنظمة المائية الإقليمية فإن الترسبات الملحية والجصية العائدة للحقب الأوسط وخاصة الترياسي تلعب دوراً هيدروديناميكياً أساسياً عند إجراء دراسة تحليلية «للشروط الحدية» لأسفل النظام المائي الجوفي الإقليمي إضافة للتأثيرات الهيدروكيميائية.

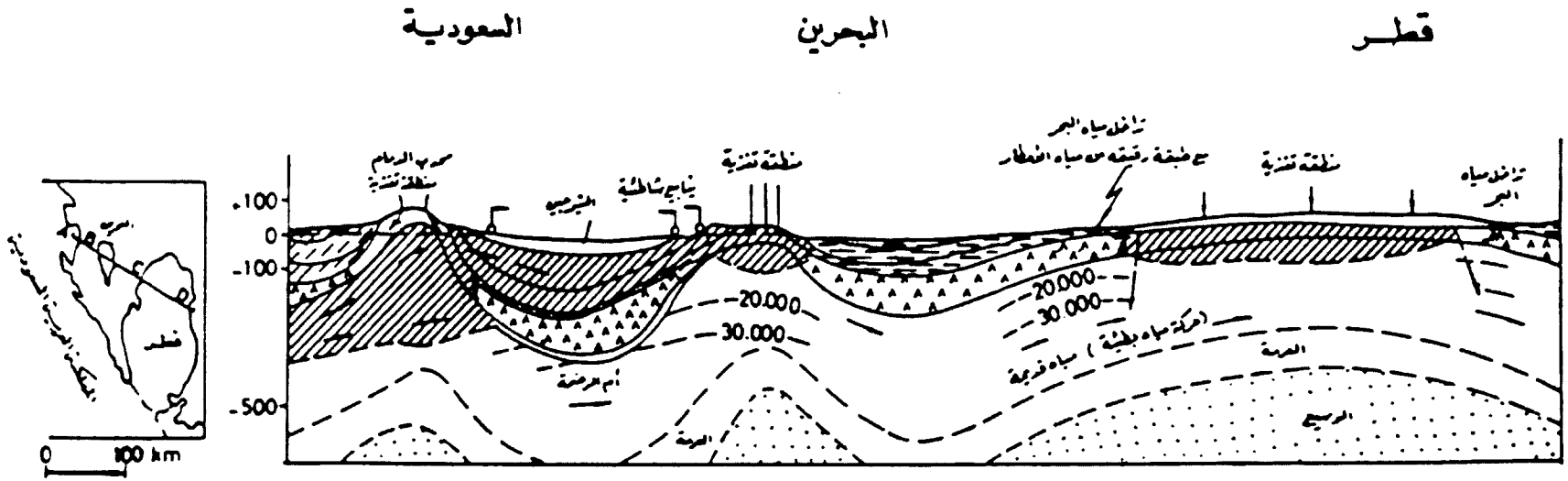
ويختلف تأثير السحنات الجصية والملحية Evaporite facies من منطقة لأخرى فعلى سبيل المثال تم انحلال طبقة الرس الجصية في خلال عصور جيولوجية سابقة في شمال قطر وأدى ذلك إلى تحسين نوعية المياه في طبقة الدمام- أم الرضمة الكلسية بينما يظهر تأثيرها السلبي على نوعية مياه النظام الإقليمي بصورة جلية في البحرين وشرقي المملكة العربية السعودية (شكل 2).

ويزداد الوضع الهيدروكيميائي تعقيداً في الأنظمة المائية الإقليمية في المناطق الصحراوية كلما اقتربت حركة المياه الجوفية من مناطق الصرف الرئيسية، وهذا مايلاحظ في الكويت والبحرين وقطر والإمارات وفي مناطق السرير وسيوة في ليبيا ومصر (شكل 2). ولابد من إجراء





شكل (1) نموذج باليومناخي للوطن العربي



شكل (2) مقطع هيدروجيولوجي إقليمي (المركز العربي1986)

دراسات مفصلة لهذه المناطق لتوضيح التطبق الهيدروكيميائي والتغيرات الرأسية والأفقية في نوعيات المياه قبل الشروع بتصميم الآبار الإنتاجية في إطار المشروعات التنموية، والتجارب السابقة تشير إلى إمكانية حدوث أخطار تتمثل باختلاط المياه العذبة والمالحة في الآبار أو اندفاع الأجسام المائية المالحة عمودياً أو تداخلها أفقياً مع مياه الطبقات العذبة والقابلة للاستثمار.

ويمكن تلخيص أهم سمات الموارد المائية الجوفية غير المتجددة بمايلي:

- إن نسبة الوارد إلى المخزون ضئيلة للغاية
- إن الضخ من الطبقة المائية أو النظام المائي الإقليمي يؤدي إلى سحب المياه مباشرة من المخزون، وتتعذر عملية إعادة التوازن على المدى المتوسط والقريب
- لا تعود الطبقة المائية الواقعة تحت تأثير ضغوط الاستثمار إلى حالة التوازن بل تستمر المناسيب بالهبوط ويستمر استهلاك المخزون
- إن نوعية المياه تتوقف بالدرجة الأولى على طبيعة الصخور في المعقد المائي وتلعب الرواسب التبخرية دوراً هاماً في المستويات العليا من الخزان المائي، كما تظهر الأجسام المائية المالحة في الجزء الأدنى من النظام المائي، وتتميز الطبقات الرملية - الكوارتزية للحقب الأول بمياه عذبة وذات نوعيات عالية، بينما تزداد الملوحة في طبقات الحقب الأوسط الكلسية- التبخرية وتحتل طبقات الحقب الثالث Tertiary والحديث موقعاً متوسطاً من حيث نوعية المياه باعتبارها مؤلفة من تعاقب رسوبات حطامية وكلسية أو تبخرية.

التوزع المكاني للموارد المائية الجوفية غير المتجددة

تكاد تتشابه أنماط الأحواض المائية الجوفية غير المتجددة وظروف التوزع المكاني لهذه الموارد في مختلف قارات العالم، وأهم سمات هذه الأحواض امتدادها الواسع حيث قد تتجاوز مساحتها 2 مليون كم^2 أحياناً، وفيها تتوافر طبقات مائية إقليمية Regional Aquifer Systems وأهمها تنتشر في شمال أفريقيا وجنوب غرب آسيا وأستراليا. وثمة طبقات أقل أهمية تنتشر في جنوب أفريقيا والولايات المتحدة الأمريكية (شكل 3).

يلاحظ أن النمط السائد هو أحواض رسوبية عميقة تشكلت في مناطق هبوط تكتوني في الركيزة Intraplatform basins وثمة نمط آخر أقل انتشاراً وهو أحواض بينية Intermontane basins أوشبه بينية Sub-montane basins (Kissin, 1978). وفي هذه الأحواض تراكمت سماكات كبيرة من الرواسب معظمها رملية أو حطامية مصدرها المناطق المرتفعة من الركيزة البللورية وتصل سماكة الطبقات الرسوبية إلى حوالي 3000 م أو أكثر من ذلك وبالتالي فإن ارتفاع حرارة المستويات العميقة يساهم في تنشيط الحركة الرأسية للمياه. وحسب توث (Toth 1963) فإن كامل كتلة الرواسب تتفاعل وكأنها نظام حركي واحد Unified flow system. وقد تابع توث أبحاثه في هذا المجال مؤكداً الاستمرارية الهيدروليكية Hydraulic continuity في الأحواض الرسوبية الكبرى (Toth, 1995). وتتشابه الخواص الهيدروديناميكية في الأحواض بصرف النظر عن أنماطها، إلا أنه يلاحظ الضاغط المائي في الأحواض البينية (الجبلية) أعلى بكثير من الضاغط الذي يتشكل في أحواض السطيحة (Kissin, 1978).

تنتشر في أستراليا المياه الجوفية غير المتجددة في المناطق الغربية الجافة من القارة وأهمها تتوافر من حوض Amadeus (160000 كم^2) وحوض Canning (430000 كم^2) الذي يمتد عبر الصحراء الرملية الكبرى، وتتألف الطبقات في الحوضين من طبقات من الحجر الرملي العائد للحقب الأول (الباليوزويك)، وقد بينت عمليات النمذجة و Cl-36 أن الحركة المائية الجوفية تتم في مسار يزيد طوله على 250 كم وعمقه على 6000 م، وأن المدة اللازمة لذلك Flow time تبلغ عدة ملايين من السنين (Brown et al, 1990). أما السحب فيتم من المخزون ويؤدي ذلك إلى هبوط في منطقة واسعة بمعدل متر واحد في السنة (Jacobson et al, 1999).

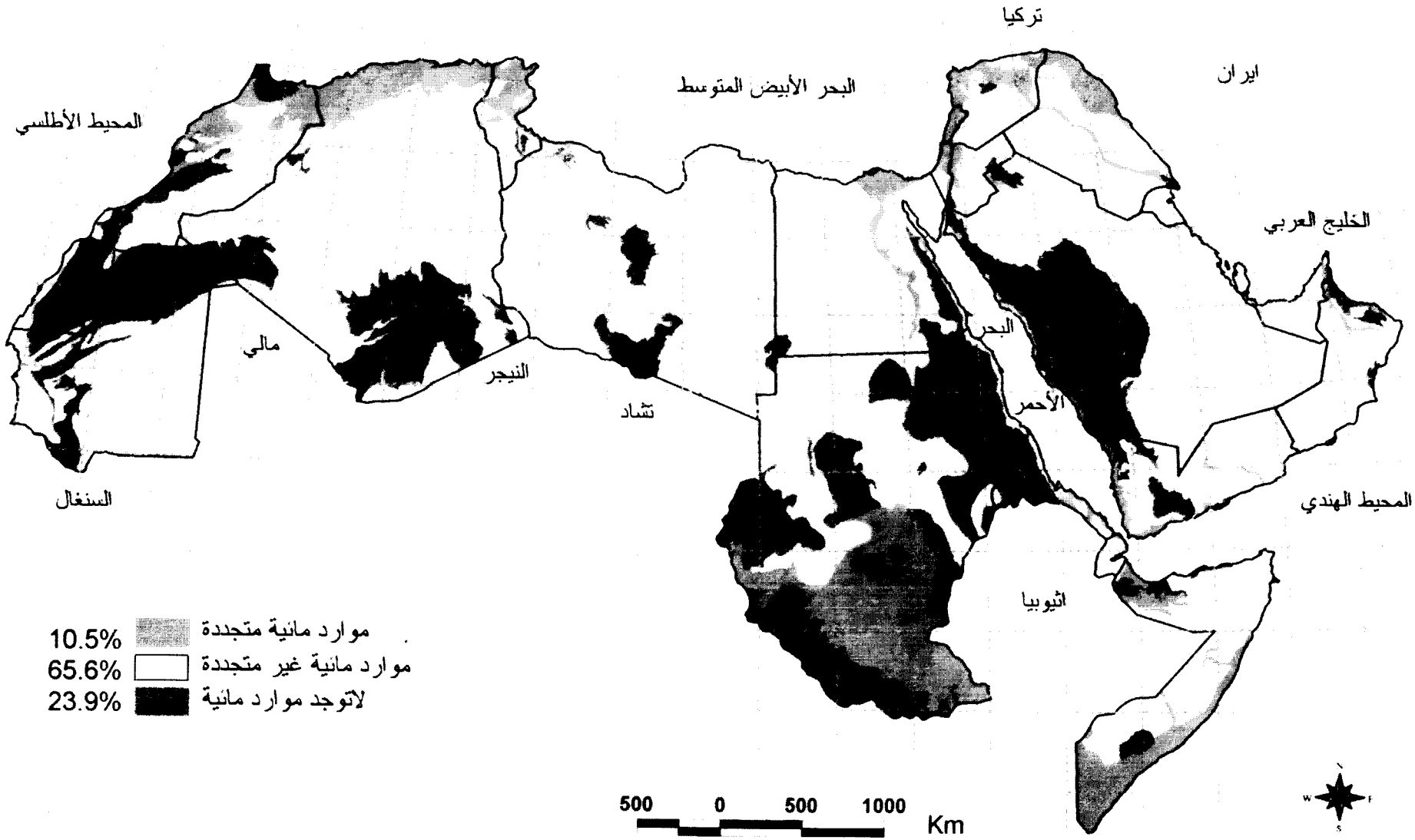
أما فترات التغذية القديمة فترجع إلى الحقب الثالث Tertiary والأحدث للبلستوسين أما والتغذية الحديثة تحدث مرة كل 20 عام (Barnes et al, 1994). إن هذه الخبرة والمعلومات المستقاة منها لا تختلف كثيراً عن المعلومات المستقاة من غيرها من المناطق الجافة في العالم، وتؤكد الخصائص الهيدروجيولوجية لحوض Canning هذه الصورة إذ تصل سماكة الطبقات المائية إلى 4000 م وهي مؤلفة من تكوينات من الحجر الرملي وثمة اتصال هيدروليكي بين الطبقات العميقة والضحلة أما سرعة الماء فتقدر بـ0.2 إلى 0.5 م في السنة. وفي الحوض الارتوازي الكبير Great Artesian Basin الذي يغطي مساحة 1,7 مليون كم^2 يصل عمر المياه إلى 2 مليون سنة حسب نظير Cl-36 المشع (Bently et al, 1986).

وتوضح هيدروجيولوجية الجزيرة العربية أيضاً السمات العامة للأحواض الكبرى التي تشكلت في الركيزة والتي تتميز باحتوائها على موارد مائية غير متجددة، فهبوط «الرصيف العربي» Arabian Platform أدى إلى تراكم مايقارب 5000 م من الرواسب الرملية والكلسية، وقد تم التمييز مابين (20) طبقة مائية منها 9 طبقات مائية رئيسية (عثمان، 1985).

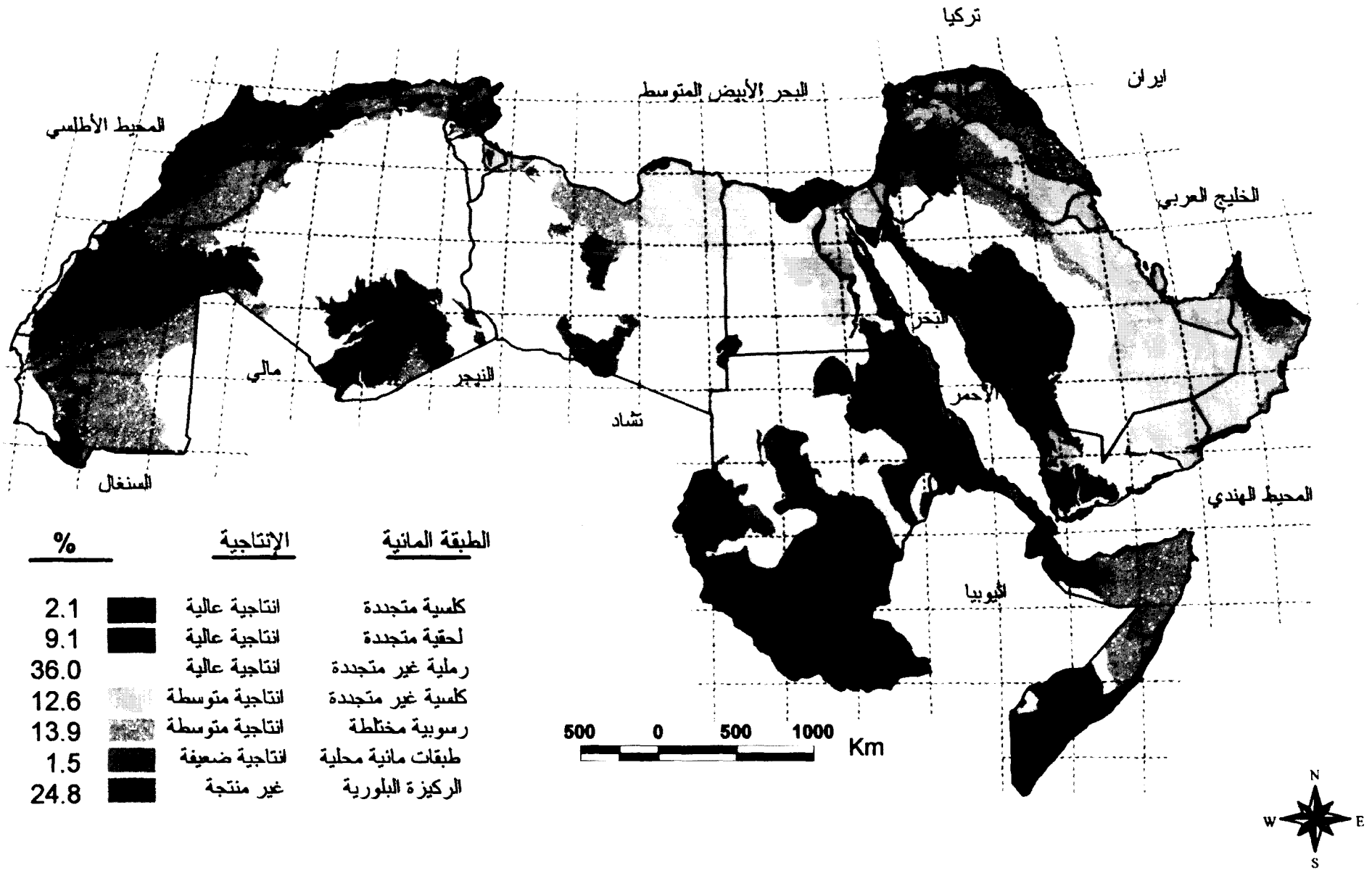
وقد خضعت هذه المنطقة لدراسات هيدروجيولوجية مكثفة بينت أن الحوض الرئيسي قابل للتقسيم إلى أحواض فرعية أهمها تقع في الرصيف الداخلي وتشمل حوض الربع الخالي وحوض الخليج العربي وحوض وادي السرحان الذي يمتد من شمال السعودية إلى شرقي الأردن وجنوب سورية.

واستناداً إلى الدراسات الهيدروجيولوجية للمناطق المختلفة يمكن التمييز بين ثلاثة وحدات هيدروجيولوجية رئيسية أو «أنظمة هيدروجيولوجية إقليمية»:

1. النظام الهيدروجيولوجي الإقليمي الأسفل Lower Regional Aquifer System، ويشمل أربعة طبقات مائية رئيسية مؤلفة جميعها من الحجر الرملي وتشمل الطبقات المائية في تكوينات الساق، تبوك، الوجيد والمنجور، والعائدة للفترة الجيولوجية كامبريان-ترياسي (شكل 4).
2. النظام الهيدروجيولوجي الإقليمي الأعلى Upper Regional Aquifer System ويشمل أربعة طبقات مائية رئيسية وهي طبقات البياض، الوسيع، أم الرضمة، الدمام (شكل 2).
3. النظام الهيدروجيولوجي الإقليمي الأوسط Middle Regional Aquifer System، ويشمل مجموعة من الطبقات المارلية-الكلسية وهي مجموعة ضعيفة النفاذية وتلعب دور «الغطاء» Confining Unit للنظام الأسفل والقاعدة Substratum للنظام الأعلى.



شكل (3) الموارد المائية الجوفية المتجددة وغير المتجددة في الوطن العربي



شكل (4) إنتاجية الطبقات المائية في الوطن العربي

وان هذا التصنيف للتطبق الهيدروجيولوجي يعكس ماهية الأنظمة الهيدروديناميكية الإقليمية في منطقة واسعة شديدة الجفاف Hyperarid. حيث تم تمييز نظامين إقليميين لحركة المياه الجوفية Regional Flow Systems (Khouri 1987, FAO 1979, Dubay 1991) فالنظام الأسفل اعتبر نظاماً أحفورياً غير مرتبط بالدورة الهيدرولوجية المعاصرة أو بالنظام الأعلى حيث يفصله عنه النظام الأوسط وهو مؤلف من وحدة هيدروجيولوجية كبيرة السماكة شبه نفوذة أو غير نفوذة، أما النظام الأعلى فإنه مازال نظاماً ديناميكياً على اتصال مع الدورة الهيدرولوجية المعاصرة ويتم صرف مياهه في عدد من الواحات (الأحساء) والسبخات أو الينابيع البحرية (في شواطئ البحرين)، إن هذا الامتداد الواسع للنظام الأعلى والاتصال الهيدروليكي بين طبقاته المختلفة وخاصة الطبقات الرملية والكربوناتية يجعله من أهم الطبقات المائية الإقليمية في شبه الجزيرة العربية. ويبدو أن منطقة صرف النظام كانت أكثر اتساعاً، كما يتبين من تحليل صور لاندسات والتي تظهر بوضوح امتداد السبخات القديمة على زخط صرفس يمتد موازياً للخليج وعلى الطبيعة يتعزز هذا الرأي حيث تبين أعمال المسح الحقلي أن سماكات كبيرة من الانهدريت Anhydrite قد ترسبت في ظروف قارية (FAO, 1979). وهذه الظاهرة للأنظمة الإقليمية تلاحظ أيضاً في حوض Amadeus في استراليا حيث يتم صرف المياه في منطقة صرف وسط أستراليا والتي تشمل «خط صرفي» مؤلف من عدد من السبخات والبحيرات المالحة يمتد لمسافة 500 كم وتصل ملوحة المياه في مناطق الصرف هذه إلى 100,000 ملغ/ليتر، إن نظام الصرف هذا يميز الأحواض الكبيرة ذات الميل الضعيف والطبقات ذات الامتداد الواسع شبه الأفقي.

إن تطوير هذا النموذج التصوري Conceptual model لحركة المياه الجوفية الإقليمية في الجزيرة العربية يمكن أن يقود إلى تطوير نموذج رقمي، علماً بأن النماذج الرياضية التي تم إنشاؤها لأجزاء من النظام المائي الإقليمي في البحرين وقطر والكويت والمناطق الشرقية للسعودية يمكن تطويرها باستمرار في ضوء الشروط الحدية التي يوفرها النموذج الاقليمي Regional flow model.

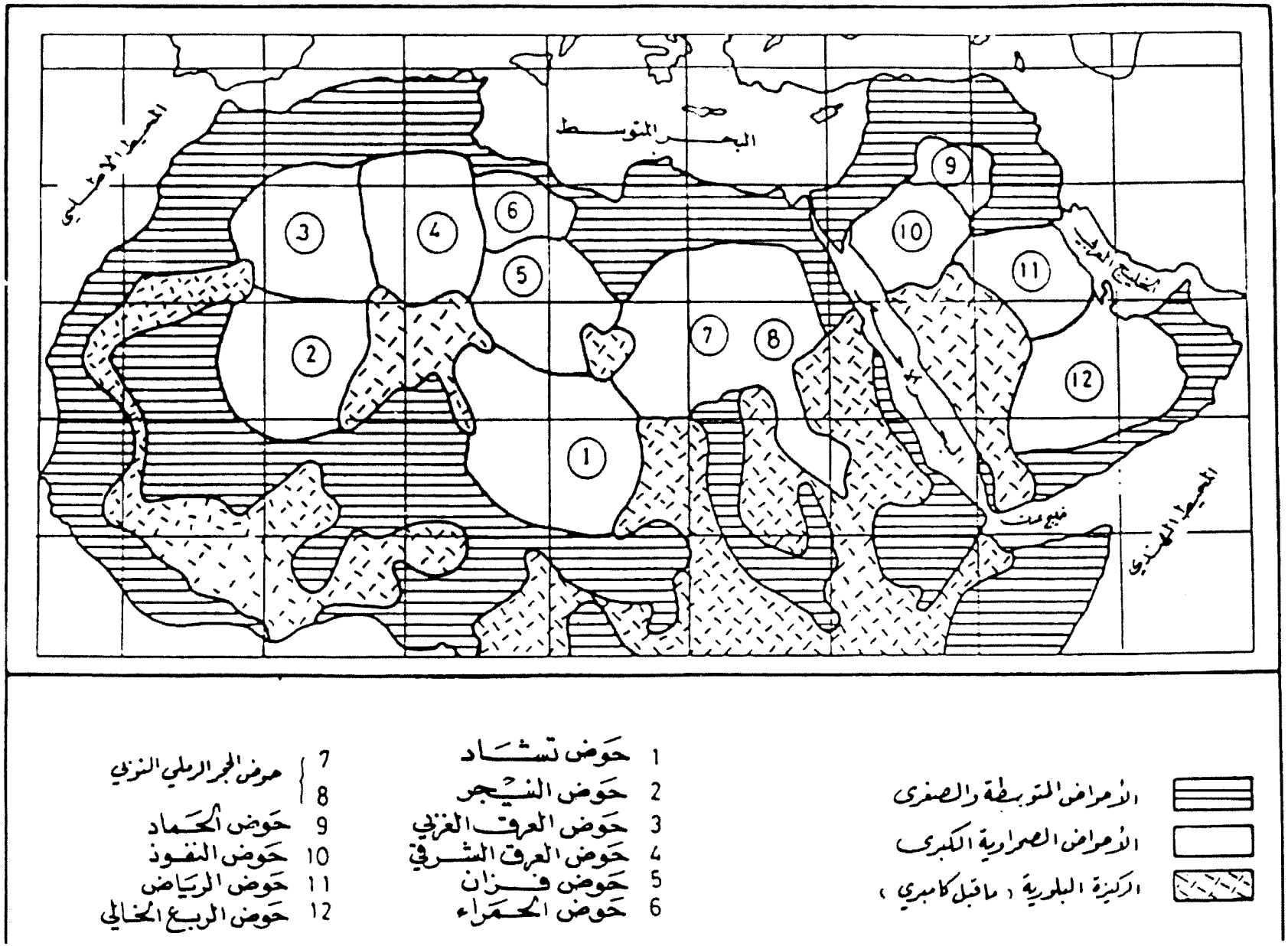
ولاشك بأن الأوضاع الجيولوجية والهيدروجيولوجية في القارة الأفريقية وفرت ظروفاً مناسبة لتشكل أحواض رسوبية كبرى تراكمت فيها كميات ضخمة من الرواسب الرملية ورغم تماسكها جزئياً فقد شكلت أوساطاً مسامية عالية النفوذية تشكل منها مخزون كبير من المياه الجوفية. وتعتبر أحواض السطيحة الأفريقية من أهم وأكبر الأحواض المائية الجوفية في المناطق الجافة ففي شمال القارة أمكن تحديد ثمانية أحواض كبرى أهمها الحوض النوبي وحوض مرزق وحوض الصحراء الكبرى في المنطقة العربية وحوض النيجر وحوض تشاد وحوض تاودني في منطقة الساحل الأفريقية (شكل 5)، علماً بأن معظم هذه الأحواض هي أحواض مشتركة بين عدة دول متجاورة عربية وأفريقية (جمال لطرش 1995، أحمد ممو 1995، اسكندر 1995، OSS-UNESCO 1995, OSS 1992).

ويعتبر «حوض كالاهاري» من أهم الأحواض المائية الجوفية التي تنتشر في المناطق الجافة (صحراء كالاهاري) في جنوب القارة الأفريقية.

وقد ألقت الأبحاث والدراسات المتعددة والمكثفة للمياه الجوفية غير المتجددة في الجزء الشمالي من القارة ضوءاً على أهم ما تتميز به هذه الموارد من الوجهة الهيدروديناميكية والجيوكيميائية، وأهمية الخبرة المتراكمة خلال قرابة نصف قرن هو دراسة استجابة الخزان الجوفي لأنماط مختلفة من الاستثمار سواء في مواقع الضخ في الواحات أو في مناطق بعيدة باستخدام وسائل نقل المياه من حقول آبار موزعة في أماكن مختلفة من الخزان المائي حددت استناداً إلى دراسات هيدروجيولوجية ونماذج رياضية محلية (عمر سالم، 1995)، إضافة لذلك فإن تأسيس لجان على مستوى الحوض تعتبر خطوة أساسية نحو إدارة أفضل للموارد المائية الجوفية المشتركة (Hefny 1991، عمر سالم 1995).

ومن التجارب الوطنية الهامة أيضاً في مجال دراسة واستثمار الموارد المائية الجوفية غير المتجددة هي تجارب الولايات المتحدة الأمريكية ومن أهم هذه التجارب استثمار النظام المائي الجوفي الإقليمي في تكوين Ogallala التي تنتشر في ولاية تكساس وكنساس ونبراسكا ونيومكسيكو في مساحة تقدر بـ 134000 ميل مربع، فقد تم خلال فترة ثلاثة عقود سحب ما يقارب 166 مليون Acre feet أدت إلى استنزاف 25٪ من كامل سماكة الطبقة المائية في مساحة تربو على 14000 ميل مربع. ولمعالجة المشكلات المائية الناجمة عن الاستثمار الجائر تم استخدام نماذج المحاكاة (Sun and Johnston 1994).

ونظراً للامتداد الواسع للطبقة المائية فقد تم تقسيمها إلى ثلاثة أجزاء وقد بينت النمذجة أن الضخ أكبر من الإمكانات المائية المتاحة بحوالي 30 ضعفاً، وأمكن وضع سيناريوهات مختلفة للضخ وتأثيراته على المنسوب والمخزون لغاية عام 2020.



شكل (5) الأحواض المائية الجوفية في الوطن العربي

نظام حركة المياه الجوفية

إن مفهوم «النظام» System أو المنظومة أصبح من الموضوعات البالغة الأهمية لدراسة ديناميكية الظواهر الطبيعية. وقد عرف Dooge (1967) النظام الهيدرولوجي الطبيعي بأنه «وسيلة أو بنية تربط مابين المدخلات Inputs والمخرجات Outputs أمادة كانت أو طاقة وتحديد المسببات والتأثيرات». فالنظام يشمل عناصر مترابطة مع بعضها البعض، وقد تم تطبيق هذا المفهوم على المياه الجوفية من قبل Mifflin (1968), Toth (1962) (maxy and Mifflin (1966)، و Engelen (1986). وبالرغم من أنه تم التعبير عن الهيكل الفيزيائي Physical framework للنظام بتسميات مختلفة مثل نظام المياه الجوفية Groundwater system أو النظام الهيدروجيولوجي Hydrogeological system فإن المفهوم اكتسب أهمية خاصة عند أخذ حركة المياه الجوفية بعين الاعتبار. وكان توث Toth أول من عالج الجوانب النظرية لنظام حركة المياه الجوفية مستخدمة تقانة النمذجة الرياضية فبين أنه تحت شروط حدية معينة يمكن التمييز بين ثلاثة أنواع من أنظمة حركة المياه الجوفية وهي الأنظمة المحلية والمتوسطة والإقليمية، وقد شكل ذلك خطوة نحو تحديد الأنظمة الحديثة في الطبيعة، ففي المناطق الشبه الجافة في ولاية نيفادا أمكن دراسة وتحديد 136 نظاماً استناداً إلى قياسات حقلية للكمون المائي Fluid Potential وغيره من المؤشرات كدرجة الحرارة والتركيب الكيميائي والأيزوتوبي (Miffilin, 1968).

أما تطبيق هذا الاتجاه الهيدروديناميكي إلى جانب الخواص الهيدرولوجية على الأحواض الكبرى فقد تم في أوروبا في الحوض الهنغاري (Erdelyi, 1976) وحوض تاغوس Tagus basin في اسبانيا (Llamas and De Abia, 1976) استناداً إلى معلومات حول الكمون المائي في الآبار العميقة وقد ألقت هذه الأبحاث وغيرها التي ألقيت في المؤتمر الهيدروجيولوجي الدولي حول هيدروجيولوجية الأحواض الرسوبية الكبرى والمنعقد في بوادبست في 1-4 حزيران من عام 1976 ضوءاً على التطبيق العملي لمفاهيم حركة المياه الجوفية التي تطورت بشكل ملموس استناداً إلى دراسات وتحليل نظري مبني على تقانة النمذجة، ففي المناطق الرطبة يلاحظ وجود الأنظمة الديناميكية الثلاثة التي استنبطت نظرياً وهي النظام المحلي والمتوسط والإقليمي. ومن الواضح أن الأنظمة المحلية مرتبطة بالوضع الطبوغرافي، بينما ترتبط الأنظمة الإقليمية مع الأوضاع الجيولوجية. ولهذه النوعية أهمية خاصة بالنسبة لدراسة النظم المائية الجوفية في المناطق الجافة، فضآلة أو انعدام التغذية في المناطق المرتفعة في الوقت الحاضر ينجم عنه غياب للأنظمة المحلية وتصبح الأنظمة الإقليمية هي الأنظمة الحركية السائدة، ويتحكم بالتالي في طبيعتها الشروط الجيولوجية، وتبقى العلاقة بين الطبقات المائية الضحلة والعميقة في هذه الأنظمة غير واضحة خاصة وأن القياسات للضاغط تبين وجود كمون مائي مرتفع في مركز الأحواض الرسوبية الكبرى مشيراً إلى وجود حركة رأسية وهذا الوضع يمكن تفسيره باستمرار التغذية في اطراف الأحواض الارتوازية في المناطق الرطبة والشبه الرطبة، إلا أنه يلاحظ تشكل أوضاع هيدروديناميكية مماثلة في الأحواض الكبرى الواقعة في المناطق الجافة والشديدة الجفاف Hyper-arid رغم انعدام أو ضآلة التغذية في أطراف النظام المائي الإقليمي.

ومن الطبيعي أن تتباين العوامل المؤثرة على نظام حركة المياه الجوفية في المستويات العليا والعميقة من الأحواض الكبرى فبينما يتوفر معطيات كافية حول أوضاع المياه الجوفية في المستويات العليا من الأحواض والتي تبين أنها تقع تحت تأثير العمليات الهيدرولوجية والهيدروديناميكية فإن المعلومات مازالت محدودة حول القوى والعوامل المؤثرة على حركة المياه الجوفية في المستويات العميقة، علماً بأن المتاح منها يشير إلى أن الطاقة الحرارية والضغوط الناجمة عن تماسك الرواسب Consolidation تلعب دوراً هاماً في الأعماق.

أما الحدود التي تفصل النطاق الهيدروديناميكي عن النطاق العميق الذي يخضع لتأثيرات وعوامل مختلفة بعض الشيء فتختلف من منطقة لأخرى، وعلى العموم تقع على أعماق تتراوح مابين 7000 م و 6000 م (Kissin, 1978). وهذه المعطيات يمكن أن تساهم في بلورة المفاهيم حول أهم العوامل المؤثرة على نظام حركة المياه الجوفية في الأحواض المائية الكبرى غير المتجددة والتي توقفت فيها التغذية المعاصرة منذ 8000 عام تقريباً ورغم الأهمية النسبية لمختلف العوامل المؤثرة في الطبقات العميقة فإن الضاغط الأحفوري Residual head وبالتالي الميل الأحفوري Fossil gradient يعتبر من أهم العوامل الواقعة المؤثرة على حركة المياه الجوفية في الأحواض الكبرى في المناطق الجافة. (Burdon, 1977, Lloyd and Farag, 1978).

والاتجاه الحالي هو تحديد النظام الإقليمي لحركة المياه الجوفية ومن ثم محاكاة هذا النظام لتوضيح طبيعته وأهم سماته ووضع سيناريوهات وبدائل لخطط الاستثمار للموارد المائية التي يمكن أن يوفرها ضمن شروط مناسبة.

ففي الولايات المتحدة الأمريكية أمكن تحديد 25 نظاماً لطبقات مائية ذات امتداد إقليمي (Sun and Johnston, 1994) خضعت لدراسات تفصيلية ومكثفة خلال /15/ عاماً (92-1978) ونشرت نتائجها في 900 تقرير صدر عن إدارة المساحة USGS والنظام المائي الجوفي الإقليمي تم تعريفه بأنه «نظام يشمل مجموعة من الطبقات المائية الرئيسية والفرعية وقد تشمل وحدات مائية غير مستمرة محلياً إلا أن كافة الطبقات المائية تشكل وحدة مائية تتكامل وتتصل مع بعضها البعض على المستوى الإقليمي»، وفي استراليا تم تحديد ثمانية أنظمة إقليمية للمياه الجوفية (Jacobson et al, 1999)، وفي العالم العربي تم تحديد ثمانية أنظمة مائية جوفية ذات امتداد إقليمي (خوري ودروبي، 1990).

ومن خصائص الأنظمة المائية الجوفية غير المتجددة هو تطورها عبر الزمن، فثمة دلائل على أن الأنظمة الحالية التي تقع تحت تأثير الفترة الجافة المعاصرة (التي تلت الفترة المطيرة منذ 5000-8000 سنة) كانت أكثر ديناميكية في الماضي، ففي الجزيرة العربية تدل معالم السبخات القديمة على أن منطقة الصرف كانت واسعة الامتداد وعلى شكل سبخات ممتدة على طول ساحل الخليج العربي كما أن الصرف في المشرق العربي كان يشكل بحيرات واسعة كما يستدل على توزع الرواسب البحيرية العائدة إلى الرباعي (خوري، 1995) وبمحاكاة النظام المائي الإقليمي للحوض النوبي تبين أن مناطق التغذية كانت واسعة الامتداد في مناطق أصبحت صحراوية في الوقت الحاضر وأن الصرف بواسطة أنظمة محلية باتجاه الواحات كان أكثر أهمية من الحركة الإقليمية الآتية من الجنوب. ونتيجة لتطور النظام المائي في الفترة الجافة انخفض

الصرف الطبيعي من 2400 مليون م3 إلى 500 مليون م^3 (Thorweihehe & Heinl, 1996).

وتبقى العلاقة بين الطبقات المائية العليا والعميقة مسألة قيد البحث وباستخدام تقنية النظائر تبين أنه يمكن تمييز نطاقات وشرائح يزداد عمرها مع ازدياد العمق: ففي المستويات العليا لا يتجاوز عمر المياه 8000-5000 سنة (حوض سرت) (Edmunds,) وفي جبل العوينات وهي منطقة نهوض يبلغ عمر المياه فيها حوالي 14000 سنة، ويتجاوز عمر المياه في الوادي الجديد الـ20,000 سنة (Brinkmann et al, 1986) أما عمر المياه العميقة فيصل إلى 1-2 مليون سنة (Brinkmann et al, 1986, Himida, 1969).

إن هذا التطبق الأيزوتوبي يطرح أسئلة جديدة قد يصعب الإجابة عليها حول العلاقة بين الطبقات الضحلة والعميقة، وحول تكون الكتلة المائية بأكملها وتطور النظام المائي الديناميكي وتجدده في الفترات المطيرة.

مفهوم السحب الآمن :

إن حماية المياه الجوفية حماية كاملة يتطلب أن لايتجاوز الصرف والسحب من الطبقة المائية التغذية المائية الواردة ولا يحدث التوازن عادة بصورة آنية أو حتى خلال فترة قصيرة وإنما ما يحدث هو هبوط مؤقت لسطح المياه الجوفية، ومن هذا المنظور تم طرح مفهوم «السحب الآمن» "Safe, sustained yield" وتم تعريفه بأنه «كمية الماء المراد ضخها سنوياً دون أن ينتج عنها آثار غير مرغوب فيها» (Walton, 1970) فهذا التعريف إذن يفترض أنه لكي يكون السحب آمناً أو مستداماً يجب أن لا يتجاوز «متوسط التغذية المائية السنوية» على المدى البعيد، أي أن السنوات العالية الأمطار تعادل السنوات العجاف، وبالتالي فإن مفهوم السحب الآمن يشير إلى حالة من التوازن المائي بينما يدل مفهوم السحب أو الاستثمار الجائر Over exploitation على وجود استنزاف للمخزون (جدول 1)

(Llamas,1992,Adam & MacDonald,1995) وحسب آراء عدد من الباحثين فإن الاستثمار الجائر هو مفهوم يصعب تعريفه بدقة، ومعظمهم يشير إلى الآثار السلبية الناجمة عن استثمار المياه الجوفية، وهذه التأثيرات تعكس اعتبارات اقتصادية واجتماعية إضافة إلى المؤشرات الهيدروجيولوجية، ويعرف Young (1992) الاستثمار الجائر هو «الإخفاق في الحصول على المردود الأعظمي من المورد المائي». وفي مجال الدراسات البيئية يعرف الاستثمار الجائر بأنه الاستثمار الذي تنعكس آثاره سلباً على البيئة وخاصة الأجسام المائية الضحلة Wetlands.

جدول (1) الاستثمار الجائر في بعض الأحواض المائية الجوفية الكبرى التي تحتوي على مياه جوفية غير متجددة

الدولة	الحوض	الوارد السنوي	الاستثمار		قرينة الاستثمار	السحب من المخزون	
		كم3/سنة	التاريخ	كم3/سنة	%	الفترة	كم3
استراليا	الحوض الارتوازي الكبير	101	1985	0.6	55	1973-1880	25
الجزائر - تونس	حوض الصحراء الكبرى الشمالي (المعقد القاري)	0.58	1992	0.74	127	1981-1900	3
السعودية	حوض الساق الحوض الباليوزوي	0.3	1984	1.43	477	1983-1970	2
الولايات المتحدة الأمريكية	الحوض الرسوبي اللحقي في اريزونا	0.37	1975 1985 1990	6.56 4.35 3.78	1773 1151 1022	1980-1920	202
الطبقة المائية في تكوين أوغالالا	حوض السهوب العليا	8-6	1980	22.2	300	1980-1940	196

المرجع : مارغات، 1999.

وفي المناطق الجافة حيث تتوافر موارد مائية غير متجددة لايمكن تطبيق مفهومي السحب الآمن والجائر وفق الأسس التي اعتمدت في المناطق الرطبة، فلابد من استنباط معايير وأسس تتوافق وطبيعة هذه الموارد، إلا أن كلاً من مفهوم السحب الآمن (والسحب الجائر) لم يخضعا لدراسات معمقة حتى الآن، بل بالعكس فثمة اتجاه بأن استثمار المياه الجوفية غير المتجددة هو «خطيئة بيئية» (Llamas, 1999 Hydromyth) يجب منعها قانونياً.

إلا أن بعض الدراسات أشارت إلى حساسية الأوساط المائية الجوفية في المناطق الجافة، وتم تعريف قابلية التأثير Groundwater Vulnerability بأن هذا المفهوم يشمل الجوانب الكمية والنوعية (Vrba & Zaporozec, 1994)، وقد تناولت الدراسات المتعلقة بقابلية التأثير أو قابلية الطبقات المائية للاستنزاف والتملح إضافة إلى قابلية التلوث، وقد استهدفت مساعدة المخططين على تخفيف الآثار السلبية لاستثمار الموارد المائية في المناطق الجافة.

وقد حظيت الجوانب الكمية لمفهوم حساسية الأوساط المائية مزيداً من الاهتمام في العقد الحالي (and MacDonald 1995, Llamas 1999 Adams) من أجل وضع معايير تعطي مؤشرات للأخطار التي تترتب على استثمار الطبقات الأكثر حساسية «للاستثمار الجائر Susceptibility Groundwater».

والاتجاه الحالي يتمثل بتطوير مفهوم «السحب الآمن» من الطبقات المائية الجوفية غير المتجددة حيث يتم التمييز بين:

1- السحب المنجمي الأعظمي Maximum Mining Yield

2 السحب المنجمي المقبول Permissive Mining Yield

فالسحب المقبول هو جزء من السحب الأعظمي الممكن الذي يتم في إطار خطة استثمار عقلانية ورشيدة حيث يأخذ بعين الاعتبار العوامل الاقتصادية والبيئية.

طرائق تقييم الموارد المائية الجوفية غير المتجددة

إن المنهجيات المتبعة في تقييم الموارد المائية غير المتجددة لا تختلف من حيث المبدأ عن الأساليب المستخدمة في تقييم الموارد المائية المتجددة، فعندما يقترب أحد المدخلات وهو التغذية المائية Recharge من الصفر فإن العلاقات المحددة لحركة المياه الجوفية مازالت سارية المفعول، علماً بأن التأثيرات Impacts على الطبقة المائية تصبح مثيرة للقلق.

ونظراً لضخامة أبعاد الخزانات المائية الجوفية غير المتجددة في معظم المناطق الجافة سواء من حيث الامتداد الأفقي الذي يصل إلى عدة مئات آلاف الكيلومترات المربعة أوالبعد الرأسي الذي يتجاوز 3000 م، فإن من الصعوبة بمكان توفير المعطيات اللازمة للتوصل إلى معلومات موثوقة حول الموارد المائية المراد تقييمها سواء استخدمت النمذجة أو غيرها من أدوات وطرق التقييم.

وتولي معظم البحوث جلّ اهتمامها لمنهجيات التقييم وخاصة منهجيات النمذجة Modeling إلا أنه من المفيد التذكير بأن نتائج التقييم تتوقف على مدى توفر المعطيات ودقتها، وهذه بدورها ترتبط بكفاية المعطيات الأساسية التي يتم جمعها حقلياً أو بواسطة الاستشعار عن بعد. وقد تم حديثاً وضع إرشادات عامة لتقييم «مدى كفاية المعطيات المائية» لأغراض التقييم (WMO-UNESCO, 1997) فأهم مايجب توفره لعملية التقييم يشمل:

أولاً - جمع المعلومات

- معلومات نقطية عن الدورة الهيدرولوجية
- معلومات نقطية عن وسائل استثمار واستخدامات المياه (الآبار، السدود، ...)
- معلومات مساحية فيزيوغرافية وسطحية وتحت سطحية (طبوغرافية، جيولوجية)

ثانياً- ربط المعلومات النقطية والمساحية للتوصل إلى صورة إقليمية Regionalization

واستخدام أدوات تقنية للتقييم الكمي والنوعي للموارد المائية، فهذه العملية التقييمية تحول المعطيات الأساسية Basic Data إلى معلومات Information عن توافر المياه الجوفية وخصائصها في المناطق المختلفة قيد الدراسة. ولاشك بأن الأخطاء المترتبة على هذه العملية التقييمية يجب أن تكون مقبولة وتتوقف درجة الدقة أو الخطأ المسموح به على طبيعة المشروع التنموي للمصدر المائي (WMO-UNESCO,1997).

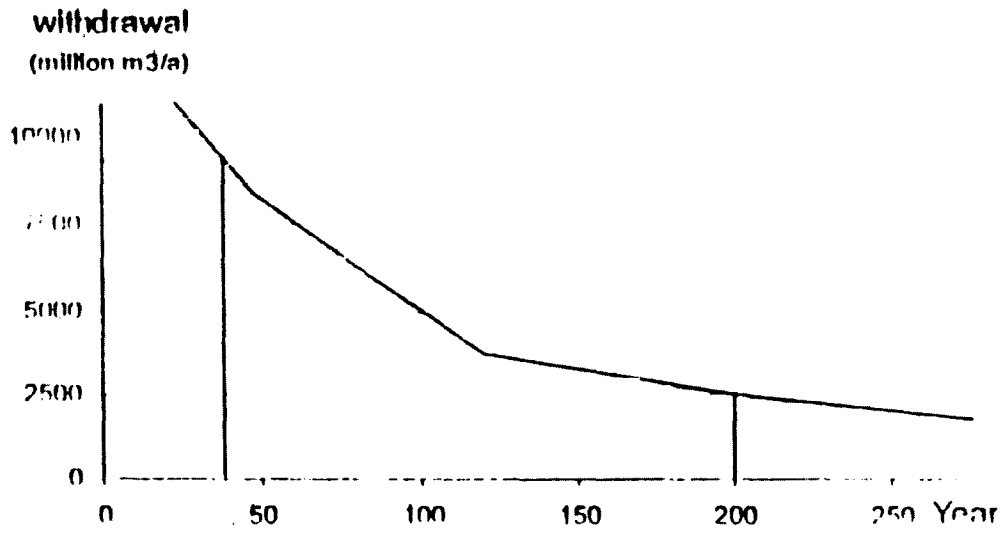
ويتوفر حالياً أدوات تقانية هامة لتسهيل عملية التقييم بمختلف مراحلها، ففي مرحلة جمع المعلومات تستخدم بنوك المعلومات المتقدمة على الحاسب كما تستخدم أنظمة المعلومات الجغرافية والتي أصبحت من أهم الأدوات التقانية للدراسات الهيدروجيولوجية وفي مرحلة التقييم الكمي نستخدم النمذجة وخاصة تقانات المحاكاة Simulation وال Optimization وعملية التقييم هي عمل علمي وتقاني مستمر، وفي مجال المياه الجوفية تكون التكاليف عادة مرتفعة نظراً للحاجة إلى حفر آبار اختبارية وآبار مراقبة لأعماق مختلفة ولذا فإن من المفيد تحسين الدقة أثناء مرحلة الاستثمار بواسطة «التغذية الراجعة»، وفي المناطق المعتدلة من العالم يمكن أن تقوم المؤسسات بعمليات التقييم المرتبطة

بأساليب تقدير التغذية المائية وتقديم نتائجها إلى صانعي القرار والمخططين لوضع الخطط التنموية وخطط إمدادات المياه، وقد يختلف الوضع بعض الشيء في المناطق الجافة إذ لابد من وضع سياسة مائية بعيدة المدى تكون إحدى الأسس التي تنطلق منها عملية التقييم.

السياسة المائية كأساس لعملية التقييم

لايمكن اعتبار عملية التقييم للموارد المائية الجوفية غير المتجددة عملية تستند إلى مبادئ علمية فحسب، خلافاً لما يتم عادة في مجال تقييم الموارد المائية المتجددة، إذ لابد من وضع سياسة مائية تأخذ بعين الاعتبار طبيعة وحجم الموارد المائية المتاحة (ولسن اسكندر 1995، عمر جودة 1995، Salama & Attia 1995)، وعندما تكون الموارد المائية الجوفية غير المتجددة هي المورد الأساسي أو تشكل الجزء الأعظم من الموارد المائية المتاحة، فإنه يترتب على واضعي السياسة المائية وبالتنسيق مع واضعي الخطة التنموية الشاملة تبني سياسة مائية على المدى الطويل تهدف: (شكل 6)

1. إما استثمار أكبر قدر ممكن من المياه الجوفية لرفع وتيرة التنمية الاجتماعية والاقتصادية وتعظيم الفائدة للأجيال الحالية.



شكل (6) العلاقة بين كميات السحب وفترة إنتاج المياه الممكنة في المملكة العربية السعودية

المرجع Neulqnd 1988

2. الحد من السحب من الخزانات الجوفية من أجل تحقيق تنمية أكثر استدامة ولفترة طويلة من الزمن.

وقد يؤدي الاستثمار المكثف حسب السيناريو الأول إلى آثار سلبية على المورد المائي نظراً لأن الضخ بكميات كبيرة يمكن أن يرافقه تدهور في النوعية.

ومهما كان الاتجاه الذي تسلكه الجهات المختصة في التخطيط لوضع سياسة مائية وطنية فإن الحقيقة الواجب استيعابها هي أن الموارد المائية غير متجددة والاستثمار هو استثمار منجمي وبالتالي له حدود زمنية، وبالتالي فإن السياسة المائية والاستراتيجية المنبثقة عنها يجب أن تشمل حلولاً بديلة على المدى البعيد، علماً بأن بعض الدول العربية باشرت بتطبيق مثل هذه الحلول كالتحلية وإعادة استعمال المياه. والتحلية كحل بديل تعتمد على الطاقة لإنتاج الماء وبالتالي فإن مدى توافر الطاقة يصبح العامل الرئيس المحدد لتوافر المياه، وبما أن الطاقة المستمدة من النفط هي أيضاً «طاقة أحفورية» فإن هذا الحل بحد ذاته يعد حلاً بديلاً مؤقتاً، والأمل معقود على إمكانية استبداله مستقبلاً بطاقة متجددة (جان خوري 1995).

إضافة لذلك فإن السياسة المائية يجب أن تتكامل مع السياسة التنموية نظراً لأن الماء يدخل في معظم الفعاليات التنموية وبالتالي لابد من تحديد أو تحديث أهداف الأمن الغذائي الذي تنشده معظم الدول وخاصة الدول العربية.. فالأمن المائي أصبح في حال الندرة يرقى إلى مرتبة متقدمة في سلم الأوليات الوطنية وهذا ما يترتب عليه إعادة التحصيص Re-allocation على الأقل في المرحلة المقبلة ريثما تشهد التقانة نقلة نوعية لإنتاج الغذاء باستخدام كميات محدودة من المياه.

تقانات تقييم الموارد المائية غير المتجددة:

لابد من استخدام التقانات الحديثة لتقييم الموارد المائية الجوفية غير المتجددة نظراً لأن الأوضاع المائية أصبحت بالغة التعقيد تحت ظروف الاستثمار المتزايد والجائر أحياناً لهذه الموارد، كما أن عدد الآبار ازداد بشكل ملحوظ وازداد السحب من طبقات أكثر عمقاً، واستخدام مزيد من المياه يرافقه طرح كميات كبيرة في البيئة لايمكن أحياناً تنقيتها ومعالجتها بالقدر الكافي لحماية المورد المائي أو البيئة نفسها، وبالتالي فإن الموارد المائية تصبح تحت تأثيرات وضغوط متزايدة من ناحية الكم والنوعية، فالتقييم في ظل هذه التأثيرات المختلفة أصبح بحاجة ماسة إلى تقانات قادرة على التعامل مع الأوضاع المعقدة مثل أنظمة المعلومات الجغرافية والنماذج الرياضية.

ونظراً لأن معظم الأنظمة المائية الجوفية السائدة في المناطق الجافة هي أنظمة ذات امتداد إقليمي فمن الأهمية بمكان **إنشاء نموذج إقليمي لتحديد الموازنة المائية الجوفية** على مستوى الحوض Regional Groundwater Budget وتحسين المعرفة عن حركة المياه الجوفية الإقليمية وتوفير معلومات أساسية حول الشروط الحدية للنماذج الشبه إقليمية والمحلية على مستوى حقول الآبار. فهذا التدرج بالنمذجة يسمح بتشغيل وإدارة الاستثمارات الوطنية والتنسيق على مستوى الأحواض.

وتشكل نماذج المحاكاة محور عمليات تقييم الموارد المائية الجوفية غير المتجددة باعتبارها قادرة على استيعاب تعقيدات الأنظمة الهيدروجيولوجية والعمليات الهيدرولوجية واستثمارات المياه الجوفية، وقد تحتاج عملية النمذجة إلى إعادة المعايرة لتحسين الدقة والمطابقة مع الواقع.

ونظراً لأن المخزون الجوفي أو الموارد غير المتجددة يشكل العمود الفقري لحفظ الاستثمار والتنمية المعقدة عليها، ثمة ضرورة لتقدير المخزون مع الأخذ بعين الاعتبار بأن التقديرات يجب أن تكون واقعية قدر الإمكان حتى لا يعتمد المخططون على قيم أعلى بكثير أو أقل بنسبة كبيرة Over-under Estimates من القيم الحقيقية، فتقييم الموارد المائية غير المتجددة يمكن أن يشمل الخطوات التالية:

1- **تقييم المخزون الجوفي**، ويعتمد هذ التقييم على تحديد أبعاد الطبقة المائية وهذا بدوره يعتمد على أسس هندسية دون أن يؤخذ عامل الزمن بعين الاعتبار، ويمكن استثناء الأجزاء المالحة أو العميقة، ويفترض استناداً إلى هذا المنهج أن هبوط المنسوب يتم بنفس القيمة في كامل الخزان المائي الجوفي وهذا بالطبع لايحدث على أرض الواقع. وعلى سبيل المثال، بافتراض أن المسامية الفعالة للحوض النوبي 7-10٪ فإن حجم الكتلة المائية أو المخزون يكون 150,000 كم3 (Thorweihe and Heis, 1996) وقدر المخزون الجوفي لعمق 110 م في الجزء المصري والليبي (في مساحة تربو على مليون كم2) من الخزان النوبي بـ1000 كم3. كما تم تقييم مخزون الطبقة المائية الإقليمية في شبه الجزيرة العربية بحوالي 40 ألف مليار م3 بينما قدر معدل التغذية السنوية بحوالي 3 مليار م3 (الزباري 1998, اسماعيل 1995, الطرباق، 1999)، أما المخزون الجوفي لعمق 300 م في دول الخليج العربية فقد قدر بحوالي 2175 كم3. وبالرغم من أنه يتعذر سحب كامل الكتلة المائية التي تشير إليها هذه القيم «النظرية» إلا أن توفير المعلومات عن المخزون مفيد بل ضروري لعملية التخطيط والتي يجب أن تتعامل معه بحذر شديد، فإذا أمكن تقدير استنزاف المخزون على المدى البعيد، فإن ذلك يعتبر مؤشراً هاماً لتوجيه الاستثمار مستقبلاً، ففي السعودية على سبيل المثال قدر استنزاف المخزون بحوالي 35٪ خلال النصف الثاني من القرن الحالي (الطرباق، 1999)، وهذه المعلومات كانت مفيدة لتطوير السياسات المائية والزراعية.

2- إجراء التقييم الكمي للموارد المائية الجوفية غير المتجددة باستخدام طريقة المحاكاة، وهذه الطريقة تسمح بتحديد الموازنة المائية الجوفية واستشراف المستقبل بتوليد سيناريوهات مختلفة والتنبؤ باستجابة الخزان المائي لدرجات متفاوتة من الاستثمار (الخطط البديلة).

وقد استخدمت النمذجة لتقييم الموارد المائية الجوفية غير المتجددة في الأحواض البينية Intermontane basins في الجبال التدمرية في سورية والمنهج الذي اتبع اشتمل على إعداد نموذج إقليمي ونماذج للأحواض الفرعية، فالطبقة المائية ذات الامتداد الإقليمي تتألف من مجموعة صخور كربوناتية معظمها يتكون من الحجر الكلسي والدولوميتي وبسبب طبيعة هذه الصخور فقد تولدت حركة مائية إقليمية عبر الأحواض الفرعية تنتهي في سبخة الموح.

وتتفاعل طبقات الحامل الأعلى المؤلفة من طبقات حطامية - بحيرية ترجع لعصر الرباعي مع طبقات الحامل الأسفل بينما لا تتصل مع بعضها البعض، والاتصال يتم عبر الحامل الأسفل ذو الامتداد الإقليمي ويتم صرف المياه لكافة طبقات النظام المائي الإقليمي في سبخة الموح وتشكل السبخة الجزء المركزي من الحوض حيث ترتفع ضغوط المياه في الأسفل وتصبح الآبار تدفقية وفي الحالة الطبيعية يتم صرف المياه بفعل الحركة الرأسية Vertical leakage.

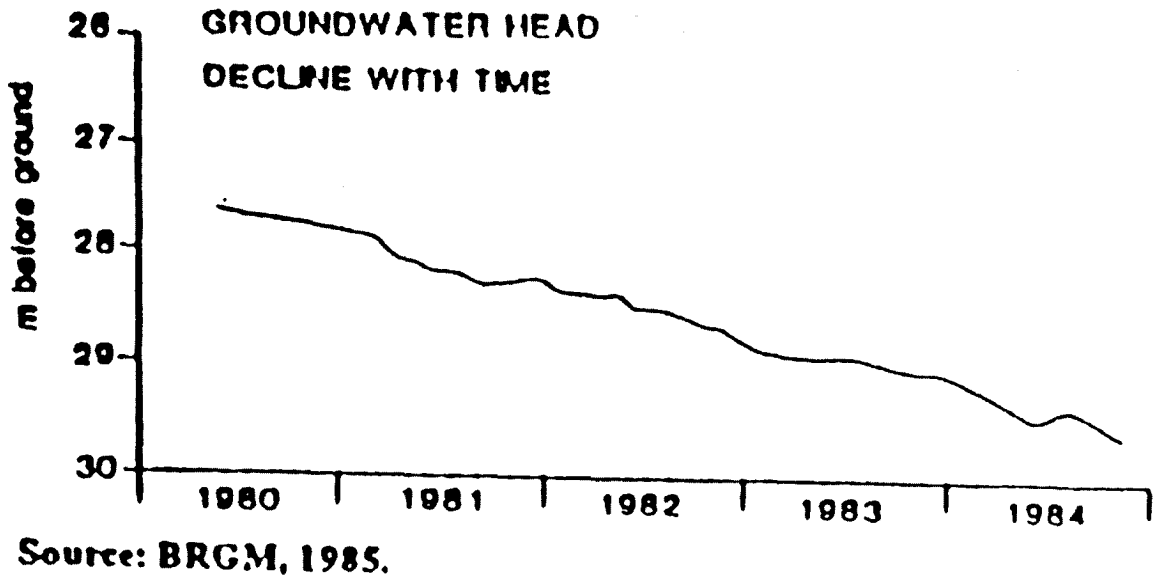
أعدت النماذج المحلية في حوض الدو لدراسة تقدم جبهة المياه المالحة في حوض الدوة الفرعي باتجاه المناطق الزراعية التي تستخدم المياه العذبة في الحامل الأعلى، كما أعد نموذج لحوض الصوانة الفرعي لتنظيم استثمار المياه الجوفية للأغراض المنجمية والصناعية، وقد استخدم نظام MODFLOW في إعداد النموذج الإقليمي ومثلت المنطقة البالغ مساحتها حوالي 18000 كم2 بـ1500 خلية وحملت بالمعطيات الخاصة بالأبعاد الهندسية للحامل الأسفل والأعلى والقيم الأولية للمعاملات الهيدروليكية واستخدم في بناء النموذج نظام المعلومات الجغرافي ونظام الجدولة الألكترونية بتفاعل تام مع نظام النمذجة المستخدم.

وقد تم معايرة النموذج لحالة الثبات وفق عام 1992 ولحالة عدم الثبات للفترة 1992-1996. وقد تمت دراسة الموازنة المائية لكامل الحوض ولمناطق الاستثمار، كما تم وضع مشاهد (سيناريوهات) مختلفة لخطة الاستثمار المقترحة (سيناريو 1) ودراسة هذه السيناريوهات للمناطق المختلفة المقترحة لفترة /50/ عام حتى عام 2046, وخاصة التبدلات في المنسوب وعناصر الموازنة المائية، وقد أمكن في ضوء هذه الدراسة وضع خطة استثمارية تنسجم مع الإمكانات المائية في الحوض (روفائيل، وآخرون 1998).

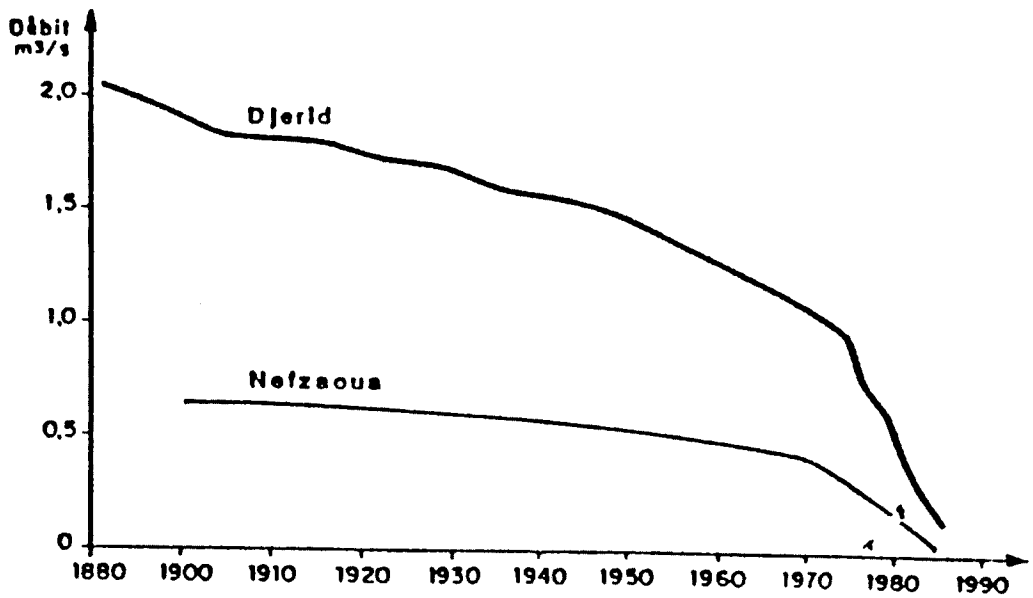
بعض المفاهيم الحديثة حول تقييم الموارد المائية في المناطق الجافة

نظراً للحاجة الماسة للمياه في المناطق الجافة بدأت استثمارات الموارد المائية الجوفية غير المتجددة بواسطة آبار السبر استناداً إلى أعمال مسح وتقييم أولي للموارد المائية. وجاءت عمليات التقييم التفصيلية والمتعمقة نسبياً متأخرة بعض الشيء وبعد أن قطع الاستثمار شوطاً، إلا أن هذا التقييم استفاد من المعطيات التي توفرت نتيجة لتطور الاستثمار كما استفاد من التقدم التقاني في مجال النمذجة الرياضية والحاسبات الالكترونية المستخدمة لإعداد النماذج، وقد أدى الاستثمار المكثف في عدد من الأحواض المائية غير المتجددة إلى ظهور آثار سلبية انعكست أحياناً على المشروعات التنموية المعتمدة على المياه الجوفية.

والاتجاه السائد هو دراسة التأثيرات الناجمة عن الاستثمار الجائر Over-exploitation بعد ظهورها وتفاقمها أحياناً (A posteriori)، (شكل 7) وقد اقترح (Adams, MacDonald, 1995) استخدام طريقة تعتمد على تحليل حساسية الطبقة Aquifer Susceptibility المائية مسبقاً قبل تعرضها لضغوط متزايدة Stress or over explantation أي تحديد حساسيتها «للاستثمار المكثف والجائر» قبل تكثيف الاستثمار أو حتى الشروع باستثمارات جديدة (A-priori) وهذه المجهودات تتكامل مع دراسة قابلية الطبقة للتلوث Vulnerability والتي أصبحت أساليب تقييمها واضحة وتخضع لتقانات متطورة يمكن تطبيقها في المناطق المعتدلة (Zabrozec, 1994) والجافة (Khouri & Miller, 1994) ولتحديد حساسية النظام المائي للاستثمار الجائر (Adams and MacDonald 1995) استخدمت طريقة تهدف تحديد مستويات مختلفة (للحساسية Susceptebility) استناداً إلى قيم (أوزان) للعوامل المؤثرة ومن ثم تحديد مؤشرات لتصنيف الحساسية النسبية، وكما هو الحال بالنسبة لقابلية التلوث فإن تحديد حساسية الطبقة المائية للاستثمار الجائر يمكن أن يساهم في تخطيط أفضل للمياه الجوفية في المناطق التي تشهد استثمارات مكثفة، كما يمكن تحديث الخطط القائمة استناداً إلى هذا التقييم، وخاصة وأن الطريقة المقترحة تأخذ بعين الاعتبار تأثيرات سلبية مثل الهبوط المستمر في المناسيب والتداخل بين المياه العذبة والمالحة في الطبقات المائية (Llamas, 1999).



تبدل مستوى المياه الجوفية في طبقة الساق (ديسي) في المملكة العربية السعودية
(عن Khori 1994)



هبوط تصاريف الينابيع في الجنوب التونسي

شكل (7) التأثيرات الناجمة عن الإستثمار الجائر

الآفاق المستقبلية

لقد تبين من الدراسات التي أجريت للأنظمة المائية الجوفية في المناطق الجافة والدروس المستقاة من التجارب الوطنية في مجال استثمار الموارد المائية غير المتجددة، أن هذه الموارد رغم كونها موارد أحفورية Fossil يمكن أن تلعب دوراً هاماً في مجال التنمية الاجتماعية والاقتصادية إذا ما تم وضع سياسة مائية واستراتيجية بعيدة المدى مبنية على تقييم دقيق للإمكانات المتاحة والحد من الآثار السلبية التي قد تنجم عن الاستثمار المكثف.

وكون هذه الموارد تشكل الاحتياطي الاستراتيجي من المياه لبعض الدول لايعني التوقف عن استثمارها بل يشير إلى ضرورة تنظيم استثمارها في ضوء سياسات مائية مبنية على أسس علمية تأخذ بعين الاعتبار الحلول البديلة في الوقت المناسب.

وثمة خطر بأن يصبح الماء عاملاً محداً لمسيرة التنمية في المناطق الجافة، وقد بينت الدراسات وعمليات التقييم الشامل لموارد المياه العذبة على المستوى الإقليمي (المركز العربي 1997). إن 15 دولة على الأقل تعاني من إجهاد مائي مرتفع (نسبة السحب إلى المياه المتوافرة تزيد على 40٪) معظمها تقع في الأقاليم المناخية الجافة، وأن ستة دول على الأقل واقعة في هذه الأقاليم تواجه إجهاداً مائياً متوسطاً (كميات المياه المستخدمة تبلغ 20-40٪ من المياه المتاحة) الأمر الذي يشير إلى وجود وضع مائي حرج أو خطير، وحسب تقديرات أكساد وصلت العديد من الدول في المنطقة العربية إلى درجة عالية من الإجهاد المائي تجاوزت 80٪، ويشير تقرير الأمم المتحدة (UN 1997) ان القدرة على مواجهة الأزمات المائية القائمة أو الكامنة تتوقف على مستويات الدخل مقاساً بمتوسط الناتج القومي الاجمالي السنوي للفرد، فالدول ذات الدخل المرتفع والإجهاد المائي المرتفع بدأت بدعم مواردها التقليدية من مصادر مائية غير تقليدية وخاصة تحلية مياه البحر وامتلاك بعض الدول النفطية لمخزون ضخم من الطاقة الأحفورية قد ساهم في زيادة موارده من مصادر غير تقليدية. وقد ازداد إنتاج الماء باستخدام تقنية التحلية في العقد الأخير بنسبة ملموسة فبلغت السعة الإجمالية لتحلية المياه في العالم حوالي 20 مليون م3/يوم في 1995 منها حوالي 12 مليون م3 في العالم العربي وأضحت الحاجة ماسة لتطوير تقنية التحلية مع تزايد نسبة استنزاف مخزون الموارد المائية الأحفورية في المناطق الجافة، وتدل الدراسات في هذا المجال إلى إمكانية تخفيض التكاليف بنسبة تصل إلى 25٪ (دباغ 1995) وثمة ضرورة لتطوير تقنية تحلية المياه عن طريق البحث العلمي للمساهمة في مواجهة الأزمات المائية المتوقعة في المناطق الجافة من العالم.

وفي البلدان ذات الدخل المنخفض والتي تعاني من إجهاد مائي مرتفع ومعظمها بلدان واقعة في المناطق الجافة وشبه الجافة ثمة حاجة ملحة لإدارة العرض والطلب، ومع ذلك فإنه نظراً للنمو السكاني السريع في هذه البلدان لابد له من تنمية كافية للموارد المائية لمواكبة هذا النمو، وبالرغم من تناقص نصيب الفرد في بعض الدول إلى حدود تنذر بالخطر فإن هذه الدول لا تجد حلولاً جذرية بل تسعى إلى سياسة

التقنين على المدى القريب ومن هنا تشتد الحاجة إلى التعاون لاستنباط وتنفيذ حلول بديلة.

وعلى العموم هنالك أوضاع متباينة لحالة المياه الجوفية غير المتجددة في العالم ولحالة الإجهاد المائي في المناطق الجافة أو شبه الجافة ففي شريط الساحل الأفريقي تمتلك الدول مخزوناً ضخماً علماً بأن استثمار هذا المخزون مازال محدوداً ويمكن، في ضوء التجارب السابقة، وضع سياسة مائية رشيدة لاستثمار هذا المخزون، وبما أن معظم دول الساحل تمتلك كميات ملموسة من الموارد المتجددة فإن ذلك يسمح بتخطيط استثمار الموارد غير المتجددة بالتكامل مع الموارد المتجددة، علماً بأن الجفاف الذي ساد في عقود ماضية وأدى إلى درجات متفاوتة من التصحر يعكس تغيرات في توافر الموارد المطرية ولا يعني شحاً كبيراً في موارد المياه، وبالتالي فإن الدروس المستقاة من انعكاسات هذه الفترة على البيئة يمكن أن تساهم في وضع خطة بعيدة المدى لمواجهة احتمالات المستقبل، وقد باشرت دول المنطقة باتخاذ خطوات هامة في هذا المضمار ويمكن أن تخضع المشكلات التي ظهرت في المناطق الجافة في الولايات المتحدة واستراليا المتمثلة باستنزاف نسبة هامة من المخزون إلى سيناريوهات مختلفة وبالتالي يمكن إيجاد الحلول الناجعة بإعداد الخطط ومراجعة السياسات المائية على المستوى الوطني باستخدام المنهج التكاملي Integrated approach (ESCWA, 1999) .

ولاشك بأن هنالك حالات متعددة وبالغة الصعوبة في بعض المناطق التي تشهد نمواً سكانياً مطرداً و تعتمد على الموارد المائية غير المتجددة اعتماداً كلياً أو أساسياً، إن هذه الحالات يجب دراستها إفرادياً وإيجاد وسيلة ناجعة لدراسة البدائل والحلول الممكنة، علماً بأن التعاون مابين دول المناطق الجافة أصبح حاجة ملحة مهما كانت درجة الإجهاد فيها أو مهما توفر لديها من إمكانات لإيجاد حلول بديلة فالبحث العلمي في إطار برنامج تدعمه المنظمات الإقليمية وهيئات الأمم المتحدة والدول المعنية يمكن أن يساهم في إيجاد حلول معالمها ليست واضحة حالياً بل يمكن أن تتبلور بشكل تدريجي عن طريق العمل المشترك.

الخلاصة والنتائج

من الممكن تلخيص نتائج هذه الدراسة في النقاط الأساسية التالية:

- ساهمت الموارد المائية الجوفية غير المتجددة في العمليات التنموية المتسارعة في القرن العشرين للبلدان الواقعة في المناطق الجافة وخاصة الدول العربية التي يقع معظمها جزئياً أو كلياً في الأقاليم المناخية الجافة، وقد كان استثمارها جائراً في بعض المناطق، ومن المتوقع أن تلعب هذه الموارد دوراً هاماً في القرن الحادي والعشرين إذا ما تمت الاستفادة من دروس الحاضر لتحسين سبل إدارتها واستخدامها مستقبلاً.
- يتوافر الجزء الأعظم من الموارد المائية غير المتجددة في أحواض كبرى مشتركة أحياناً وينتشر فيها أنظمة مائية إقليمية يقع معظمها في مناطق السطيحة وجزء محدود يتوافر في أحواض بينية أو شبه بينية Sub-montane جبلية، وتحتوي أحواض الركيزة على مخزون ضخم يشكل الاحتياطي الاستراتيجي للدول المعنية، ويعتقد البعض أن استثمار الموارد المائية الجوفية غير المتجددة «خطيئة بيئية» ولا يتوافق مع مبدأ التنمية المستدامة، إلا أن الدول التي تقع أجزاء هامة من أراضيها في المناطق الجافة أو شبه الجافة ترى أن الظروف الحالية تفرض استثمار هذه الموارد واختلاف الآراء يقتصر على حجم ودرجة هذا الاستثمار، ولم تتردد هذه الدول بالمضي قدماً في استثمار مواردها غير المتجددة استثماراً منجمياً لصالح التنمية الاجتماعية والاقتصادية.
- شهدت بعض الطبقات المائية الأحفورية Fossil استثماراً مكثفاً Intensive جائراً أحياناً Overdraft وخاصة عند استخدام هذه المياه للأغراض الزراعية لتحقيق الأمن الغذائي وقد تم سحب المياه من المخزون إلى استنزاف كبير يصل إلى 25٪ من الاحتياطي في بعض الأحواض، وفي بعض المناطق أدى هذ الاستثمار إلى تدهور نوعية المياه في الخزان المائي وخاصة في الأجزاء السفلى من النظام المائي الاقليمي قرب مناطق الصرف كما تم استخدام المياه للري في المنخفضات الصحراوية والواحات أدى إلى ظهور تأثيرات بيئية ضارة.
- إن التقدم الذي أحرز في مجال تقييم الموارد المائية الجوفية باستخدام النماذج الرياضية وقدرة هذه الوسيلة التقانية على التنبؤ بما سيؤول إليه الوضع المائي وفق سيناريوهات استثمارية مختلفة ولد قناعة لدى المخططين بأهمية استخدام هذه التقانة لتقييم الموارد المائية غير المتجددة وإدارتها أو لأهداف عملياتية Operational لتشغيل حقول الآبار وتطويرها.
- في ضوء التجارب السابقة تولدت قناعة لدى واضعي السياسات والخطط المائية أن استثمار الموارد المائية غير المتجددة هو استثمار منجمي Mining يتطلب وضع سياسة مائية بعيدة تشمل حلولاً بديلة في نهاية المطاف
- تشمل طرق تقييم الموارد المائية الجوفية غير المتجددة:
  - طريقة تشخيصية لتقييم حساسية الطبقة المائية للاستثمار والتلوث
  - طريقة تعتمد على النمذجة
  - طريقة تعتمد على تقييم المخزون

التوصيات

أولاً - توصيات على المستوى الوطني:

- وضع سياسات مائية بعيدة المدى تستند إلى الواقع المائي والبيئي والاقتصادي والاجتماعي في الدولة المعنية، ويتم مراجعتها وتحديثها في ضوء المستجدات على الساحة الوطنية والدولية.
- تحسين مستوى المراقبة والرصد للموارد المائية الجوفية وخاصة الموارد المائية غير المتجددة، على أن يشمل الرصد نوعية المياه ومناسيبها وكميات السحب.
- تحسين منهجيات تقييم الموارد المائية غير المتجددة واستخدام التقانة الحديثة وتحديث المعلومات ونتائج التقييم بصورة مستمرة بربطه بنظام متطور للرصد وأنظمة المعلومات الجغرافية.
- تحسين استخدامات المياه الجوفية غير المتجددة، ففي الاستعمالات المنزلية الحضرية يجب الحد من الهدر والفواقد وتخفيضها إلى أدنى مستوى، وفي الاستخدامات الزراعية يجب رفع الكفاءة إلى 75-80٪ باستخدام طرق الري الحديثة، وفي الصناعة ثمة ضرورة لاستخدام طرق تصنيع ذات استهلاك منخفض وتدوير مياه التبريد والصرف الصناعي.
- إعادة استخدام المياه العادمة المنزلية والصناعية ومياه الصرف الزراعي مع مراعاة ضوابط منظمة الصحة العالمية لحماية الصحة العامة وإرشادات منظمة الأغذية والزراعة والمنظمات العربية المخصصة لحماية البيئة والتربة من التملح.
- تعزيز أو تشكيل آليات مناسبة لإدارة مياه الأحواض المائية الجوفية الكبرى المشتركة وتبادل المعلومات وتحسين تقانات التقييم والإدارة والاستخدام للموارد المائية المتاحة.
- مراقبة التأثيرت كفِة الناجمة من استثمار الموارد المائية غير المتجددة واتخاذ الاجراءات اللازمة للحد من الآثار السلبية.

ثانياً - توصيات على المستوى الإقليمي والدولي:

- وضع استراتيجية إقليمية للتنسيق والتعاون في المجالات المتعلقة بالأحواض المائية الجوفية المشتركة وتطوير رؤيا إقليمية لعام 2025 وترجمة الاستراتيجية الإقليمية إلى مشروعات مشتركة على مستوى الأحواض.
- إحداث شبكات ونظم معلومات خاصة بالموارد المائية الجوفية غير المتجددة تربط بنوك المعلومات القطرية وتساعد على تبادل المعلومات الهيدروجيولوجية والتقانية.
- دعم لجان الأحواض المشتركة من الناحية الفنية والمالية وعقد ورشات عمل على مستوى الحوض المشترك أو الأحواض المشتركة المتكاملة في مجالات ذات الاهتمام المشترك.
- تعزيز الجهود الوطنية لتطبيق منهجيات الإدارة المتكاملة للموارد المائية المتجددة وغير المتجددة استناداً إلى مبدأ الاستدامة ومراجعة السياسات المائية وفق الرؤى الوطنية والإقليمية المعتمدة والتخطيط لحلول بديلة لضمان استمرار التنمية.
- إيلاء اهتمام كبير ومركز للتوعية والإرشاد وإيجاد صيغة للتعاون بين المؤسسات المائية والتنموية والإعلامية وتعميق الصلة بين المجتمع العلمي والمؤسسات الرسمية والمجتمع المدني وخاصة المنظمات غير الحكومية الريفية والزراعية وتعظيم دور المرأة في مختلف الفعاليات ذات العلاقة بالمياه.
- السعي لتحقيق الأمن المائي لارتباطه الوثيق بمستقبل التنمية القومية وإيجاد الارتباط فيما بينه ومابين الأمن الغذائي بما يكفل حماية الموارد والبيئة.

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اعداد المهندس بركات حديد

دراسة عن الآثار البيئية لاستثمار المياه الجوفية (التصحر)

معاون وزير الري
في الجمهورية العربية السورية

1 - المقدمة :

تكتسب الموارد المائية الجوفية في الوطن العربي بسبب محدوديتها وندرتها وعدم انتظام جريانها في الجزء الأعظم من الأقطار العربية التي تمتد معظم أراضيها عبر أقاليم جافة وشبه جافة تتميز بالمناخ الجاف والصحراوي، وقليل الأمطار.

وهذا ما أعطى الوطن العربي وضعاً متميزاً من حيث ندرة الموارد المائية وعدم أنتظام تجددها في معظم أحواضه المائية. وشهدت السنوات الأخيرة نشاطاً متميزاً في الأقطار العربية لاكتشاف المزيد من الطبقات المائية لتلبية الطلب المتزايد على الماء الذي شهد نمواً متسارعاً كما هو الحال في أنحاء العالم وكان هناك صراعاً واضحاً بين الاحتياجات المائية المتنامية والطلب على الماء من جهة والموارد المتاحة من جهة أخرى.

وكان للموارد المائية الجوفية النصيب الأكبر في تحمل الضغوط التي نجم عنها ظهور العديد من الآثار السلبية في معظم الأحواض المائية الجوفية تمثلت في التدهور النوعي والكمي.

ومع ذلك يمكن القول أن الوطن العربي بالإضافة لثرواته العديدة الطبيعية يتوفر فيه ثروة مائية كبيرة توجد في الأحواض المائية الجوفية الواسعة وذات المخزون الكبير والمنتشرة تحت رمال الصحراء غالباً، والمياه تمثل الحياة والتنمية في العديد من الأقطار العربية.

وقد تعرضت مشكلة استثمار مياه هذه الأحواض الغير متجددة لكثير من الجدل أخيراً حيث أن موضوع الجدوى الاقتصادية لاستغلال هذه المياه بقي السؤال الرئيسي المطروح وينتظر الجواب ومع ذلك فإن هذه الموارد المائية ما زالت تشكل المخزون الإستراتيجي الهام من المياه للعديد من الأقطار العربية مما دفع هذه الدول لإجراء المزيد من البحوث العلمية والاستقصاءات بغية التوصل إلى تفهم أفضل للنظام الهيدرولوجي لهذه الأحواض المائية. علماً أن الاستثمار بمعدلات تفوق معدلات المتجدد السنوي من مياه الأمطار فإن مصير مخزونها الاستنزاف.

2 - مظاهر وتأثيرات استثمار الموارد المائية الجوفية غير المتجددة :

أ - معرفة الوضع الجيولوجي والهيدرولوجي للمصدر المائي :

إن الطبقة المائية (Aquifer) عبارة عن تشكيلة جيولوجية أو عدة تشكيلات ذات خواص فيزيائية معينة تساعد على خزن المياه من مساماتها وتسمح بحركة هذه المياه (Flow) لتخرج من منطقة ضعيفة الطبقات مشكلة ما يسمى باسم الينابيع أو اصطناعي بواسطة الآبار.

غالباً ما تكون سماكة هذه الطبقات كبيرة وأعماقها كذلك لذا فإننا نستخرج جزءاً من المخزون لاعتبارات اقتصادية وفيه تكون مياه هذه الطبقات غالباً تحت ضغط كبير، وأحياناً أخرى تكون حرة. تتغذى هذه الطبقات برشح مياه الأمطار، أو المياه السطحية، وكلما زاد امتداد الطبقة وسماكتها كلما كان زمن انتقال الماء من خلالها أكبر، وهذا وضع الأحواض في المناطق الصحراوية. فهي عبارة عن أحواض رسوبية امتدادها كبير وتفتقر إلى الأمطار للتغذية نتيجة ندرة الأمطار. وإن سرعة انتقال الماء تعتبر بطيئة وسط هذه الطبقات مما يجعل زمن بقاء هذه المياه داخلها ألاف السنين وتطلق على هذه المياه إسم أحفورية (Fossril).

ويصعب تحديد الموازنة المائية لهذه الأحواض ونحن غالباً ما نتحدث عن استثمار الاحتياطي. وبما أن هذه المياه تكون تحت ضاغط كبير، أو تكون حرة أحياناً كما ذكرنا سابقاً ونظراً لأن الأعماق قد تكون كبيرة فهذا يعني أن الاستخراج للمياه يمون جزءاً من المخزون تبعاً للإعتبارات الفنية والاقتصادية.

وفي بعض الأحيان فإن عملية الاستثمار تؤدي لخفض الضغط أكثر مما تؤدي إلى تخفيض في حجم الماء وبالتالي فإن هذا الانخفاض بالضغط يؤدي لهبوط في مناسيب. وليس فقط انعدام تدفق المياه وإنما لأعماق يصبح فيها استثمار مياه هذه الطبقات غير اقتصادي حتى وقبل أن نبدأ في تخفيض حقيقي لحجم الماء المخزون ضمن الطبقات الجوفيه.

ب - التنبؤ بحالات الاستثمار :

لا بد من تحديد طريقة الاستثمار قبل البدء به ويقضي ذلك بتحديد طريقة الاستثمار بعد معرفة الطبقات الحاملة للماء وأعماقها ومواصفاتها. وبخاصة هل هي متجددة أم غير متجددة من خلال التركيز على معرفة مصدر التغذية ونوعيته. كما أن استثمار الموارد المائية الجوفية يتطلب كذلك ما يلي :

1 - كيفية تقدير المخزون أو الحجم من المياه القابل للاستثمار.

2 - التنبؤ بالتأثيرات المحتملة للاستثمار على الوضع الهيدروديناميكي للطبقة وبالتالي وضع الآبار وإنتاجيتها.

3 - التنبؤ بالتأثيرات المحتملة للاستثمار على تصاريف الآبار وهنا يدخل تأثير العامل الاقتصادي (نسبة الإنتاجية إلى الكلفة) بالإضافة لانخفاض المنسوب نتيجة الضخ وما ينتج عن ذلك من مشاكل فنية عديدة، وبخاصة تحول الآبارمن آبار تدفقية (Flowing) أحياناً إلى الضخ المباشر.

4 - من خلال العلاقة القائمة بين الطبقات المائية وتغذية الينابيع فيها يؤدي أحياناً استجرار المياه من هذه الطبقات بشكل جائر مما يؤدي إلى جفاف هذه الينابيع مما يؤثر على ري الواحات والأراضي المجاورة لها ويؤدي بالتالي لنتائج اجتماعية سلبية على المنطقة.

5 - تأثير الاستثمار على الوضع الجيوتكتوني للطبقة المائية. ويعني ذلك الانضغاط، أو بعض الحركات التكتونية الصغيرة.

6 - إن الاستثمار وانخفاض الضغط قد يؤدي لتداخل المياه المالحة المجاورة للمياه العذبة مع هذه المياه، فتختلط بها ويؤدي ذلك للتأثير على المياه العذبة ويؤثر على نوعيتها حيث أنها تتلوث وتتدهور نوعيتها.

7 - انسداد ثقوب الإكساء أحياناً نتيجة الترسبات الكلسية وهذا يؤثر كما نعلم على عملية الاستثمار، وكذلك وجود بعض العناصر الكيميائية المنحلة في المياه كما في الصحراء الجزائرية والتونسية، حيث يترسب الحديد على جوانب قمصان الإكساء أو مع الزمن يكون الصدأ الذي يؤدي لتآكل هذه القمصان. كما يجب معالجة وضع المياه المخزونة في بعض الطبقات قبل استثمارها إذا كانت درجات حرارتها مرتفعة تصل إلى 60 درجة مئوية. كما هو الحال في الجنوب التونسي.

8 - إن استثمار الموارد المائية يتطلب بادىء ذي بدء وضع استراتيجية واضحة تتمحور حول استثمار هذه الموارد بالطريقة النجمية أي أن الاستثمار يتوقف على المدى البعيد أو استثمار هذه الطبقات للوصول إلى حالة التوازن على المدى المتوسط. وهناك ثلاث حالات لاستثمار هذه الموارد :

- استثمار هذه المياه الجوفية من أجل تخفيض المنسوب للوصول إلى حالة توازن جديدة (Bear 1967).

- المحافظة على كميات ضخ تتجاوز التغذية الطبيعية وعلى فترة طويلة مما يؤدي للاستنزاف مما يؤدي بعضها لتخفيض كميات المياه المنتجة للحد الأدنى الذي يعادل التغذية، وإن الاستثمار غير المتوازن بين التغذية وكميات الضخ تؤدي إلى جفاف الينابيع القائمة على نفس الطبقات المائية التي يتم الضخ فيها بالآبار، وجفاف هذه الآبار المذكورة وهناك العديد حالياً من هذه الظواهر في سوريا كما في السلمية شمال شرق سوريا وفي منطقة القلمون وفي ينابيع الثريا وأم الدنانير في اليرموك.

ج - جفاف بعض الينابيع والآبار نتيجة الاستثمار :

يجب مراعاة واقع المصدر المائي قبل استثماره وعلى ضوئها كما ذكرنا تحدد طريقة الاستثمار وبحيث يكون هناك توازن بين كميات المياه المستثمرة والمتجددة والتخطيط الدقيق لاستثمار المياه الغير متجددة أو المتجددة مما يؤدي لظاهرة الجفاف بمنطقة معينة وبالتالي التغيير في مورفولوجيا وهيدرولوجيا وهيدروغرافيا المنطقة وتسود ظاهرة جديدة خطرة هي التصحر التي تنشأ بسبب نضوب المصدر المائي - وهناك العديد من الأمثلة في الأقطار العربية عن هذه الحالة.

ففي الجزيرة العربية تنحصر الموارد المائية بالموارد غير المتجددة وذلك بسبب الظروف المناخية السائدة وكان استثمار هذه الموارد بواسطة مياه العيون والأملاح التي تتشكل من الناحية الهيدرولوجية الجريان الطبيعي لمختلف الطبقات المائية الجوفية. ولكن التوسع في القطاع الزراعي أدى لاستثمار جائر في الموارد المائية تجاوزت بكثير الإمكانات المائية للطبقات فحدث تدهور بالمناسيب وأدى بالتالي إلى إغلاق عدد من الحقول المائية نتيجة لجفافها. وذلك واضح في تكوين المنجور في السعودية. وشمال غرب المملكة السعودية وكذلك بالكويت وقطر والبحرين.

وكذلك في المشرق العربي كما في منطقة الديستس في الأردن والمناطق التي ذكرناها سابقاً في سوريا. وفي المغرب العربي العديد من هذه المظاهر كما في الجزائر والجنوب التونسي.

د - التأثيرات على البيئة :

إن عملية التنمية يصاحبها انعكاسات سلبية على البيئة المحيطة وهذا ما حدث في استثمار الموارد المائية في الأحواض الصحراوية التي كان يسود فيها نظام الاستثمار الطبيعي للموارد المائية المتاحة في الواحات التي تنشأ نتيجة ظهور العيون أو الفجارات والتي يتم استخدام مياهها بطرق تقليدية. وتعتمد تشريعات محلية تنظم توزيع مياه هذه المناطق بين المزارعين وذلك من خلال ما يسمى بالعدان على مدار حوالي (12)

يوماً بحيث يقوم المزارع بري أرضه كل 12 يوماً ويأخذ كمية المياه المحددة والمخصصة له وأبين مثالاً على ذلك في سوريا حوض مجر القلمون الذي يوجد فيه عيون قرينة في يبرود. وفي النبك وفي دير عطية وفي قارة ولكن مع الأسف نتيجة التوجه نحو استثمار هذه الموارد المائية بواسطة آبار جوفية بلغ استخراج الماء بواسطتها حد الاستنزاف مما أدى لجفاف هذه العيون وتحول الري الطبيعي من العيون والفجارات والذي يعطي المياه لأصحاب الحقوق إلى ري بالآبار تقتصر ملكيته على المزارع القادر على تأمين متطلبات حفر الآبار وتنظيم المزارع وكان لهذا الحدث منعكسات اجتماعية سلبية خطيرة على المزارعين في المنطقة حيث خسر أصحاب الحقوق حقوقهم في المياه. ووجد مجموعة جديدة من المزارعين أخذت تستثمر المياه لصالحها مخالفة المقولة القائلة «إن المياه ملكية عامة للمواطنين».

وهذه الظواهر انتشرت بأشكال كثيرة في العديدة من الأقطار العربية كالبحرين -ومصر- وليبيا... إلخ. وهناك آثار بيئية عديدة منها :

1 - ظاهرة ارتفاع ملوحة المياه الجوفية نتيجة الضخ :

هي ظاهرة معروفة في معظم الأحواض المائية غير المتجددة بشكل خاص والمتجددة بشكل عام وتعتمد هذه الظاهرة إضافة للظروف الطبيعية للحوض المائي على نمط ومعدل استخراج المياه من قبل الإنسان وهي غالباً ذات علاقة وثيقة بهبوط مناسيب المياه الجوفية وتغير الضغوط الهيدروليكية للطبقات المائية المستثمرة وما يحيط بها من مياه مالحة.

والآثار السلبية الناتجة عن زيادة ملوحة المياه هي أهم وأخطر من ظاهرة هبوط مناسيب المياه الجوفية لوحدها. وأحياناً يزيد ارتفاع نسبة هذه الملوحة لحد يجعل المصدر المائي غير قابل للاستعمال بالرغم من القدرة الإنتاجية والمخزون للمصدر تكون جيّدة وهنا تصبح نوعية المياه هي العامل المحدد الرئيسي للاستخدام وليس الكم.

ومن أهم الآثار المترتبة على زيادة ملوحة المياه الجوفية المستخرجة في مجال الزراعة ما يلي :

- هناك علاقة عكسية بين إنتاجية المحاصيل وملوحة المياه.
- للمحاصيل درجات تحمل لملوحة المياه وارتفاع ملوحة مياه الري سيجبر المزارع لتغيير مثلاً المحاصيل المزروعة وقد تصل الملوحة لحد غير قابل للاستعمال.
- زيادة ملوحة المياه الجوفية في الزراعة يتطلب تأمين مياه إضافية لغسل التربة وهذا يتطلب زيادة الضخ. وإن زيادة مياه الري تؤدي لتسرب المياه السطحية إلى الجوفية حاملة معها أملاحاً ذاتية تملّح المصدر المائي بمجمله. وهذا يتطلب إقامة شبكات صرف مما يزيد الكلفة الاقتصادية.
- الاستمرار في ري التربة الزراعية الخصبة بمياه ذات ملوحة مرتفعة سيؤدي لتملح التربة ونقص إنتاجيتها وهذا ما يؤدي لظاهرة تصحر الأراضي الزراعية وزيادة البقعة الصحراوية.
- وإن تدني دخل المزارع يكون له آثار اجتماعية في هجر مهنة الزراعة. والهجرة من الريف إلى المدينة بحثاً عن العمل. وكميات المياه المطلوبة للزراعة تعتبر كبيرة نسبياً وتوفير مصادر مائية بديلة يكون باهظ الثمن.

وفي مجال الشرب فإن تملح المياه له آثار نفسية وصحية واجتماعية واقتصادية. وإن تملح المياه الجوفية تظهر مبكراً على استعمالات مياه الشرب ويبدأ عجز تدريجي في التزويد المائي والحاجة إلى توفير مصادر مائية بديلة تصبح ملحة وغالباً ما تكون هذه البدائل عالية الكلفة. وفي مجال الصناعة كذلك فالمياه المالحة لها تأثير كبير أثناء استعمالها في هذا المجال. مما يضطر قطاع الصناعة إلى معالجة هذه المياه أو جزء منها لتصبح صالحة للاستعمال.

وهناك طرق مختلفة يمكن بواسطتها تقييم الآثار الاقتصادية لفقدان أو استنزاف مصدر مائي سواء بسبب ارتفاع الملوحة أو هبوط الإنتاجية.

2 - ظاهرة تداخل المياه المالحة مع المياه العذبة نتيجة استثمار الموارد المائية :

إن البلدان الواقعة على شواطىء البحار والمحيطات تعاني من مشكلة تملح المياه. إلا أن هذه المشكلة لم تكن ملموسة منذ قرن من الزمن لأن عدد السكان كان أقل مما هو عليه الآن. ولم تكن قد اخترعت معدات الضخ. ومع ازدياد السكان والحاجة الكبيرة لمياه الشرب. والري. والصناعة. ومع تطور معدات الضخ ازداد استثمار المياه الجوفية. الأمر الذي أدى لإنخفاض منسوب المياه الجوفية. وتناقص جريانها نحو البحر لا بل انعكست الآية واتجهت مياه البحر المالحة بالجريان نحو الأحواض الداخلية فاختلطت مع المياه العذبة مما أدى لظاهرة التملح وتسمى هذه الظاهرة بظاهرة تداخل المياه المالحة من البحر مع المياه الجوفية العذبة.

ومن الامثلة الواضحة والمتميزة على هذه الظاهرة هو ما حدث في نقطة دمسرخو شمال اللاذقية وعلى بعد 2,5 كم عنها.

وتمتد إلى الشرق من شاطىء البحر حوالي 2 كم ويبلغ طول المنطقة حوالي 6 كم. وعرضها بحدود 2,5 كم أي أن مساحتها حوالي 15 كم^2 وهي عبارة عن سهل منبسط يميل بهدوء نحو الغرب باتجاه شاطىء البحر لا يتجاوز منسوب أعلى نقطة من نقاط منطقة الدراسة 15 م عن سطح البحر ومعظم الأراضي مشجرة بالحمضيات ويعتمد في إروائها على المياه الجوفية التي تضخ من الآبار العديدة المنتشرة في المنطقة. وتقع دمسرخو من الناحية المناخية في المنطقة تحت المدارية. متوسط الحرارة حوالي 19,5 درجة مئوية والرطوبة مرتفعة تتراوح بين 65٪ و74٪ ويتأثر معدل البخر بعدة عوامل اهمها التضاريس -طبيعة التربة- درجة الحرارة- رطوبة الهواء- السطوع الشمسي- الرياح. ويتفاوت معدل الهطول المطري بين سنة وأخرى وتهطل الأمطار في المنطقة حوالي 3 أشهر سنوياً وتصل لحوالي 800 مم/سنوياً وتهطل شتاء.

وتشكل هذه المنطقة جزءاً من المنطقة الساحلية نتيجة المسح الجيولوجي لها الذي يبين أنها تتغطى بالرسوبيات تعود للرباعي حيث ينتشر على طول ساحل المنطقة رسوبيات بحرية تؤلف مجموعة من المصاطب أو بقايا مصاطب بحرية وكثبان. وينتشر في الجزء المتبقي من المنطقة مجروفات سيلية ولحقيات.

ومن وجهة النظر الهيدروجيولوجية، وبناء على ما سلف يمكن القول أن أراضي دمسرخو تقع ضمن منطقة تشكيلات جيولوجية وعناصر جيومورفولوجية متشابهة إلى حد كبير حيث أنها مغطاة برسوبيات الرباعي. وتشكل مياه الأمطار المصدر الرئيس للتغذية والهطول غير منتظم ولذا يتأرجح منسوب المياه في الآبار الموجودة في المنطقة بين 0,5 -2 م نتيجة حركة المياه الجوفية في المنطقة من الشرق نحو الغرب والجنوب الغربي. وتتأثر التربة السفلى ونظام الماء الجوفي باستخراج المياه الجوفية لأغراض الري. وبلغ عدد الآبار التي حفرت في المنطقة عدة مئات يضخ منها كميات كبيرة من المياه خاصة أثناء الصيف الأمر الذي أدى لاضطراب الجريان في التربة التحتية إضافة إلى اضطراب نظام الجريان الحوضي وتعتبر العوامل التي أدت الى تشويه واضطراب الجريان في المنطقة هي التالية :

- البنية الجيولوجية.
- طوبوغرافية المنطقة
- استثمار المياه الجوفية بأحجام كبيرة مما سمح لمياه البحر بالطغيان نحو اليابسة أما الأسباب الرئيسية التي أدت إلى طغيان مياه البحر باتجاه الطبقات المائية الجوفية العذبة عديدة من أهمها :
- حفر العديد من الآبار في المنطقة بشكل عشوائي.
- زيادة من الآبار واستخدام مضخات ومحركات ذات استطاعة كبيرة.
- الاستثمار الجائر لهذه الآبار بدون تحديد الكميات الواجب استثمارها.

- أحد الأسباب الرئيسية وراء ذلك تعود إلى تشكيلات العصر الرباعي التي تغطي المنطقة والمؤلفة من مجروفات سيلية ولحقيات ذات تراكيب غضارية. رملية مارلية تتضاءل كميتها شرقاً حتى تتلاشى أي ان التغذية السطحية والجوفية من مياه الحوض الصباب خارج منطقة الدراسة معدومة تماماً والمصدر الوحيد لتغذية المياه الجوفية في المنطقة هو مياه الأمطار بالمقارنة بين كيمات المياه المغذية للحوامل المائية. وبين الكميات المسحوبة عن طريق الضخ من الآبار لوجدنا ان هناك عجزاً أدى لخفض منسوب المياه الجوفية. وبالتالي طغيان مياه البحر المالحة.

وهناك بعض الطرق المقترحة لدرء خطر تداخل مياه البحر ضمن الطبقات الحاملة للمياه قرب الساحل. ولازالت الدراسات لهذه الطرق مستثمرة ومن هذه الطرق :

-**تعديل الضخ** : أي إن تخفيض كميات الضخ من آبار اليابسة وإعادة تنظيم الضخ بشكل مدروس نموذجي وبهذه الطريقة يمكن الاستغناء عن كمية المياه الزائدة المأخوذة من الطبقة الحاملة للمياه. تلك الكمية المسببة لعملية التداخل وبالتالي يرتفع منسوب المياه الجوفية فوق منسوب مستوى سطح البحر. ويكتسب هذا المنسوب تدرجاً هيدروليكياً باتجاه البحر.

-**التغذية الطبيعية** : وذلك باستخدام أحواض ترشيح لتغذية طبقات المياه الحرة عن طريق الضخ في الآبار لتغذية طبقات المياه الارتوازية.

-**منخفض الضخ** : تحفر مجموعة آبار ضخ بمحاذاة الشاطىء فيحصل أثناء الضخ منخفض في سطح المياه الجوفية مشكلاً تدرجاً هيدروليكياً يحد من اندساس مياه البحر في الطبقات الارتوازية.

- **محدب الضغط** : تهدف هذه الطريقة إلى الحفاظ على ارتفاع المياه الجوفية العذبة فوق منسوب سطح البحر على طول الساحل. وهي عكس الطريقة السابقة حيث تضخ المياه العذبة من آبار حفرت بجانب الشاطىء ويتم الضخ حتى يتأمن تدرجاً هيدروليكياً كافياً لطرد المياه المالحة.

- **الحاجز تحت السطحي** : يمنع الحاجز تحت السطحي تدفق مياه البحر. لكن تطبيق هذه الطريقة ممكن في الطبقات الارتوازية الرقيقة كما أنها مكلفة جداً تعرف باسم الجدار مانع التسرب. ولإختيار إحدى الطرق أعلاه يجب الأخذ بعين الاعتبار :

1 - اختيار الطريقة المناسبة بما يحقق التلاؤم مع الظروف الهيدرولوجية والبيئية والزراعية.
2 - إجراء الدراسة الاقتصادية لكل طريقة وتبيان ما إذا كان المردود أكبر من الكلفة الاقتصادية.
3 - ربط الطريقة مع خصائص الطبقات المائية الجوفية واختيار الأفضل بما يتناسب وهذه الخصائص :
- كلفة مياه التغذية الواجب تأمينها.
- نفقات نقل المياه وتوزيعها.

3 - استثمار الطبقات المائية العميقة :

مياه هذه الطبقات غير مرئية وحركاتها وامتدادها غير معروفة بدقة وهذا يؤدي لصعوبة التنبؤ بالمستجدات التي تتم على الوضع المائي في هذه الطبقات نتيجة الاستثمار وهي غير متسايرة مع الحدود السطحية ولذا تتداخل بين العديد من الأقطار وهذا ما يزيد من صعوبة استثمار هذه الطبقات العميقة حيث أنها نتيجة هذه التداخل تمتد على مساحات واسعة تحت الأرض وتكون دولية مشتركة بين دولتين أو أكثر واقتصادية استثمار هذه الموارد يلعب دوراً هاماً في استثمارها. كما ان تحديد موارد هذه الطبقات صعب بسبب أعماقها الكبيرة.

ويحتل عملياً هذا الموضوع اهمية في العالم وبخاصة في الوطن العربي وخلافاً لما هو معروف في الأحواض المائية السطحية المشتركة فان تأثير أي استثمار على المجرى المائي في الاحباس العليا يظهر في الاحباس الدنيا. أما بالنسبة للطبقات المائية العميقة المشتركة فان الوضع مختلف تماماً فالمياه الجوفية غير مرئية وبالتالي فاتجاه حركتها وحدود امتدادها أفقياً وعمودياً تكون غير معروفة بصورة دقيقة وذلك نظراً لامتدادها الواسع وطبيعة تركيبها الليتولوجي وما يمكن إن تكون فيه من تداخلات ناجمة عن الظروف الجيولوجية والترسيبية التي سادت أثناء عملية التكوين وكل هذه العوامل تؤدي إلى صعوبة التنبؤ بالتطورات على الوضع المائي في هذه الطبقات نتيجة الاستثمار.

هذا النوع من الطبقات ينتشر في عدد من المناطق وهي غالباً ما تتجاوز الحدود السياسية للأقطار المعنية وحتى حدود الوحدات الجيولوجية فتراها تمتد عبر عدة وحدات جيولوجية والوطن العربي يزخر بهذا النوع من الطبقات المائية الجوفية المشتركة. مثال تكون الساق (يعود للبليوزويك) مشترك بين المملكة العربية السعودية والأردن. والنجور يمتد بين السعودية واليمن. إضافة لذلك فالوطن العربي يشترك مع عدد من الدول غير العربية في أفريقيا كما ان استثمار المياه الجوفية من نقطة معينة معناه أننا مستثمرين جزءاً معيناً من الجريان الطبيعي للطبقة وفي هذه الحالة فإننا نستثمر الكميات التي تعادل مقدار التغذية الواردة (للوصول لحالة توازن).

كما هو الحال في الطبقات المائية ذات الموارد المتحدة أو نستثمر دون الوصول إلى حالة التوازن. وهذا ما يحدث غالباً بالنسبة للطبقات المائية العميقة ذات الموارد المائية غير المتجددة فاستثمار الموارد غير المتجددة لا يؤثر فقط على المنسوب وإنما أيضاً على الاحتياطي. وهذا التأثير لا يكون متناسباً مع الضخ وقد ناقش مارغان (1992) عددا من المشاكل التي تنجم عن استثمار الطبقات غير المتجددة فاستثمار المخزون سوف يؤدي لتأثيرات عبر الحدود غير متوازنة. والقطر الذي يبدأ بالاستثمار ويسحب كمية اكبر هو الذي يستفيد اكثر من القطر المجاور وحصراً لحل الموضوع يقترح ان تكون هناك لجنة فنية مشتركة بين هذه الأقطار المشتركة لتكون إدارة موحدة ومشتركة لهذا المخزون تخطط وتنظم طريقة الاستثمار. وان تحقيق هذه الإدارة المشتركة يتطلب التعمق اكثر في الحصول على معلومات دقيقة جيولوجية وهيدروديناميكية وكيميائية مع متابعة لأعمال الرصد على المناسيب - كميات الضخ والنوعية ومثال هذا التعاون كما هو الحال بين تونس والجزائر وعملياً بدون هذا التعاون والإدارة المشتركة سيكون هناك احتمالات للخلاف.

4 - إدارة المياه الجوفية :

إن دراسة وتقييم الموارد المائية هي مرحلة أساسية تسبق مرحلة الاستثمار للموارد المتاحة إلا أن بعض الأقطار العربية وصلت لمرحلة الاستثمار متجاوزة المرحلة الأولى التي هي مرحلة تقييم الموارد المائية.

وبالرغم من النتائج السلبية التي ظهرت نتيجة استثمار الطبقات العميقة في معظم الأقطار العربية إلا أن عملية الاستثمار ما زالت مستمرة وسبب ذلك ندرة هذه الموارد في المنطقة العربية وزيادة الطلب على الماء لتلبية الاحتياجات التنموية وسد هذه الحاجة تم عن طريق الاستثمار ولكنه غالباً ما يكون كما ذكرنا استثمار غير متوازن إلا انه يسمح بتوطين سكان هذه المناطق الأصليين الذين كانوا يعيشون على الترحال وان هذا التوجه يتطلب مزيداً من الجهد والمراقبة المستمرة والتخطيط الواعي لهذه الجهود التنموية وحتى لا يتجاوز سلبيات هذه الجهود وإيجابياتها. واستثمار هذا النوع من الموارد يتركز على استخراج الاحتياطي بعيداً عن توازن هيدروليكي بعد فترة الضخ ويلازم ذلك هبوط في منسوب المياه وان استثمار هذا النوع من الطبقات هو خيار استراتيجي تتبناه الدول المعنية وكذلك فانه مع زيادة الاستثمار وهبوط المنسوب تزداد الكلفة إضافة لمشاكل تظهر كذلك مثل تدهور نوعية المياه نتيجة تداخل مياه مالحة مع حوامل مائية أخرى إضافة إلى صعوبة تقدير المخزون المائي بالفرصة المناسبة. وهذا ما يساعد الدخول إلى تقنية النماذج الرياضية التي تسمح بايجاد عدد من السيناريوهات للتنبؤ بالطور الذي يمكن إن يحصل للمناسيب خلال فترات زمنية مختلفة وبكميات ضخ محدودة إضافة إلى الناحية الكمية فانه لا بد أن تأخذ بعين الاعتبار الناحية النوعية والتطور. التي يمكن أن تطرأ على نوعية المياه نتيجة هذا الاستثمار.

ومن أهم المشروعات الزراعية التي اعتمدت على الموارد غير المتجددة هي مشروعات حوض الدو غربي مدينة تدمر. ونظراً لعدم لحظ الاستثمار للعوالم المؤثرة مثل محدودية المواد والمخزون والتغذية، فإن الاستثمار بعد فترة من الزمن أدى لتداخل المياه المالحة مع المياه العذبة المستغلة بواسطة آبار حفرت على مساحة قريبة من جهة المياه المالحة وعولجت هذه المشكلة من خلال نماذج رياضية أعدت من قبل أكساد وتم بواسطة وضع مخطط لاستثمار مرشد يضمن عدم تقدم الجهات المالحة باتجاه الطبقات العذبة ومن الأمور التي يجب التفكير بها قبل الشروع في الاستثمار في هذه الطبقات وصرف الأموال الباهظة في المشاريع التنموية ضرورة التفكير في البدائل مثال ذلك التفكير بنقل مياه النيل من خزان أسوان إلى الوادي الجديد وفي قطر يتم التخطيط لضخ 60 مليون/م^3/سنة لتغذية الطبقة المائية في الايوسين (تكوين الدمام) إن عملية الاستثمار للموارد المائية في التنمية تكون ذات فوائد هامة وفي نفس الوقت تتضمن بعض السلبيات. ويتم العمل على تخفيف أكبر قدر ممكن من هذه السلبيات ونذكر منها :

- التأثير على المنسوب المائي وجفاف بعض الينابيع والآبار السطحية التي تتغذى بالرشح العمودي من الطبقات العميقة (مثال الواحات).
- تدهور في نوعية المياه نتيجة الضخ الجائر من الطبقات المائية العميقة مما يؤدي لطغيان مياه البحر الساحلية أو طغيان المياه المالحة نحو العذبة.
- التأثير على البيئة نتيجة سوء استخدام المياه بالري الزراعي وحدوث التملح.
- تأثيرات جيوهندسية حيث حدث بعض الهبوطات في سطح الأرض مثال -الكفرة-السرير في اليبار- رأس العين في الجزيرة.

ومن أجل تحقيق التوازن بين السلبيات والإيجابيات التي ذكرناهما ومن أجل تحقيق الإدارة المثلى لاستثمار الطبقات العميقة يجب :

- اختيار إستراتيجية معينة للاستثمار متوسطة أو بعيدة المدى وذلك باستخدام نماذج رياضية بالاستناد إلى معلومات دقيقة حول وضع للطبقة المائية إضافة لمتابعة مستمرة لمستويات المياه وكميات الضخ والنوعية بغية تحديث النماذج الرياضية.
- التعاون المشترك باستثمار الطبقات بين الدول التي تملك طبقات مياه جوفية مشتركة
- يجب الأخذ بعين الاعتبار العامل الاقتصادي لاستثمار المياه العميقة حيث يتغير ذلك مع استمرارية الاستثمار. وبعد هبوط المنسوب لدرجة معينة تصبح كلفة الضخ العميق أكبر من أن يتحملها المشروع وهذا ندخل العامل الاجتماعي بعين الاعتبار إذ لا يمكن تهجير السكان المحليين بعد تجفيف العيون والفجارات والآبار السطحية نتيجة استثمار هذه الطبقات العميقة ولذا يجب اخذ كافة هذه النقاط بعين الاعتبار وتحليل بعناية ودقة بداية كل عمل.

- يجب الاستفادة من التجارب التي تمت في هذا المجال مثال مشروع استثمار الطبقات في شمالي الصحراء الذي قامت به اليونسكو عام 1970 وحدثت نموذجه الرياضي عام 1983. بالإضافة لوجود اللجان المشتركة التونسية-الجزائرية التي تجتمع كل عام مرة على الأقل لدراسة تطور الاستثمار. وتبين ان وضع نموذج رياضي إقليمي غير كاف لا بل يجب وضع نماذج رياضية محددة. وكذلك برنامج التنبؤ بنوعية المياه، وهناك أمثلة أخرى عديدة في الولايات المتحدة وغيرها يمكن تطبيقها على البلدان العربية وهناك العديد من المنهجيات التي تسمح باختيار أفضل الخيارات للخطط الاستثمارية وفق معايير يتم اعتمادها. ومن هذه المعايير خطر نوعية المياه-التأثير على البيئة. وهنا تبرز إمكانية اللجوء إلى حلول أخرى مثال تحلية المياه أو نقلها.

وهنا يبرز كذلك دور الإدارة الرشيدة في الأخذ بعين الاعتبار خيارات الاستثمار التي تتروح بين استثمار كامل المورد. أو استثماره لحد ما. أو عدم استثماره بالمرحلة الحالية وتركه للحاجات المستقبلية والأجيال القادمة.

وهذه النقطة هامة يجب أخذها بعين الاعتبار في استثمار كل مورد مائي منذ البداية وذلك من أجل عدم الوقوع في مرحلة الضخ الجائر. والوصول بالمنطقة التي تم بها ذلك إلى الكارثة والتصحر.

5 - التصحر :

هو تردي الأراضي في المناطق القاحلة وشبه القاحلة والجافة شبه الرطبة نتيجة عوامل مختلفة من بينها الاختلافات المناخية والأنشطة البشرية. وكذلك فإن التصحر ينجم عن تفاعلات معقدة من عوامل فيزيائية وإحيائية واجتماعية وثقافية واقتصادية. وإن نقص الماء أو جفافه هو إحدى العوامل التي تؤدي إلى التصحر. ويكون المؤثر بذلك هو الانسان.

أما الصحراء فهي عالم واسع وحيوي مليء بالموارد المستجدة مثال ذلك الصحراء العربية القديمة قدم الانسان فمنذ القديم وبهذه الصحراء وتأثيرها في حياة الفرد العربي من حيث أمجاده وتاريخه وسلوكه وظروف دخله وترحاله والصحراء متماثلة من حيث ندرة الماء، والحر، وجفاف الجو، وضعف الغطاء النباتي والحيواني، وقلة السكان.

إذن ليس عرضاً أن يسمى كوكب الأرض مجتمع أشكال الحياة تعتمد على قشرة التربة الحساسة التي تغطي القارات ولولا هذه التربة لما بزغت الكائنات الحية من المحيطات لليابسة.

هذا الغطاء يشكل الجوهر الحقيقي لكوكب الأرض، ولما كان هناك نباتات أو غابات... الخ. وإن الغطاء المذكور يتكون ببطء شديد ولكن يتدمر بسرعة إذا سيئت معاملته.

ووفقاً لتقديرات معهد الرصد العالمي تفقد القارات 24 مليار/طن من التربة السطحية. وفي السنوات العشر الأخيرة يخسر العالم ما يغطي المساحة المزورعة بالمحاصيل برمتها في الولايات المتحدة. والحالة تتجه للأسوأ وهناك حوالي 110 دول تتعرض أراضيها الجافة للتصحر وتشير تقديرات الأمم المتحدة أن التصحر يكلف سنوياً 42 مليار دولار أمريكي. والتكلفة البشرية أكبر ويواجه أكثر من 135 مليون نسمة خطر النزوح نتيجة التصحر. والتصحر ظاهرة سيئة تنتشر على شكل بقع تتلاقى وتشكل الصحراء.

وللتصحر أشكال منها :

- تدهور الموارد الطبيعية.
- تملح الأراضي الصالحة للزراعة بسبب ريها بمياه مالحة. أو ريها بكميات زائدة من المياه التي تزيد عن حاجتها.
- تحول البحيرات لسبخات ملحية بسبب التبخر أو السحب الزائد للمياه.
- زحف الرمال نحو المناطق الزراعية أو التربة الصالحة للزراعة.
- تحول الأراضي الزراعية إلى أرض غير منتجة نتيجة للاستغلال السيء.

- قطع أشجار الغابات.
- سوء إدارة المراعي والتحطب.
- التوسع الصحراوي على حساب المناطق الزراعية.
- استنزاف الموارد الطبيعية وبخاصة المياه.
- شح المياه الجوفية وجفاف الينابيع أو انخفاض الإنتاجية وتدهور النوعية.

وللتصحر آثار منها :

- تقليل مرونة الأرض لتقلب المناخ الطبيعي.
- تصبح التربة أقل إنتاجية وذلك لنقل الرياح والعواصف لجزء من غطاء التربة.
- تلف الغطاء النباتي : إن ضياع الغطاء النباتي نتيجة وسبب لتدهور الأرض في آن واحد.
- بعض الآثار يتحملها الناس الذين يعيشون من خارج المنطقة المتأثرة مباشرة وقد تؤدي الأرض المتدهورة إلى تخفيض نوعية المياه والترسب في الأنهار والبحيرات وامتلاء الخزانات وقنوات الملاحة بالطمي.
- تدهور إنتاج الأغذية للتصحر قضية بيئية وعالمية رئيسية أساساً بسبب الصلة بين تدهور الأراضي وإنتاج الأغذية. ويلاحظ أن ذلك في ازدياد ما لم يوقف التصحر ويلق مقاومة عامة من قبل البشرية جمعاء.

التصحر يسهم في المجاعات : إن الجفاف وتدهور الأرض يؤدي لقلة الغلات ويساهم بذلك في حدوث المجاعة.
- للتصحر آثار اجتماعية كثيرة : منها الاختلافات بين السكان مما يؤدي لهجرة بعض القبائل لبلدان أخرى نتيجة الجفاف وتدهور الأراضي الجافة... الخ.
- التصحر يستنزف الموارد الاقتصادية : ذكرنا الخسائر على المستوى الدولي مقابل التصحر. إلا أن قلة الإنتاج الغذائي الوطني يكون أكبر بكثير.

إجراءات مكافحة التصحر :

إن مكافحة التصحر مسؤولية عامة على سكان المعمورة، وتحتاج لجهد الجميع ويبدأ بوضع استراتيجيات وأولويات طويلة الأجل.
- إشراك المجتمعات المحلية في وضع البرامج.
- تعزيز التشريع القاضي بالحد من التصحر.
- دمج جهود مكافحة التصحر مع برامج التنمية الأخرى.

6 - الخلاصة والاستنتاجات :

بالرغم من الظواهر التي أوردناها سابقاً فإن استثمار الموارد المائية قد فتح آفاقاً تنموية جيدة للسكان. وساعد النمو الاقتصادي لهؤلاء السكان ووفر لهم المياه ذات النوعية المناسبة وبسعر معقول. وإن سوء التصرف في استخدام الموارد والذي ينجم عن غياب أو قلة المراقبة لا يبرر عدم استثمار هذه الموارد في مشاريع تنموية مدروسة. وفي غالبية البلدان العربية قد لا يكون خيار آخر وان استراتيجية استثمار هذه الموارد يستند للخيارات التالية :

1- استثمار كامل المورد وفق الإمكانيات الفنية والاقتصادية المتاحة.
2 - استثمار المورد لحد معين لفترة طويلة.
3 - عدم استثمار المورد وتركه للأجيال القادمة.
4 - ضرورة اللجوء الى التفكير بالبدائل المستقبلية مع هذا الاستثمار وفي حال نضوب المياه.

وهناك ضرورة لتوعية السكان المحليين حول افضل طرق استخدام المياه كما ان من الضروري بعد الاستثمار مباشرةً القيام بأعمال الرصد الكلي والنوعي وذلك من تحديث المعلومات، والرجوع الى النموذج الرياضي الاقليمي والمحلي لمعرفة مدى التأثير على منسوب المياه الجوفية.

كما يجب أن يتركز على الواقع الذي يبين ان غالبية المياه الجوفية في الطبقات المائية العميقة هي مشتركة بين عدد من الأقطار. ولذا لا بد من المراقبة المستمرة للضخ وتبادل المعلومات بين الدول المشتركة بهذه المياه وهنا لا بد من القول بأن هذا الموضوع هام ويستحق التعاون بين الدول. وتوفر الخبرات الجيدة لدى المنظمات الدولية لتوفير الاستشارات العالية اللازمة لتفادي أخطار التصحر لأن ذلك كالوباء له امتداد وانتشار وعدد مَن يجب التعاون في ايقافها عند حد ما.

دمشق في 1999/7م.

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الدكتور بيير هوبير
الدكتور محمد هشام التجار

نسخة إلكترونية تجريبية للقاموس الدولي للهيدرولوجيا

المدرسة الوطنية العليا للمناجم بباريس
فونتينبلو - فرنسا
كلية الهندسة المدنية - جامعة دمشـــق
دمشق - سوريا

لقد قامت اليونسكو ومنظمة الأرصاد العالمية (WMO) في العام ١٩٩٢ بإصدار الطبعة الثانية للقاموس الدولي للهيدرولوجيا. وقد تضمن هذا العمل التعاريف بأربعة لغات (إسبانية- إنجليزية - فرنسية - روسية) لـ ١٤١٨ مصطلح مستخدم بشكل دارج في الهيدرولوجيا. وعلى الرغم من أهميته الكبيرة واعتماده على المستوى الدولي فإن هذا المرجع الأساسي لكل أولئك الذين يعملون في مجال الهيدرولوجيا (مهندسين، باحثين، مدرسين، طلاب، الخ ...) لا يزال يعاني من محدودية انتشاره. من أجل معالجة هذا الموضوع، وبمبادرة من اللجنة الوطنية الفرنسية لبرنامج الهيدرولوجيا الدولي وبالتعاون مع العديد من الشخصيات والمنظمات في عدد من الدول، فقد تم إعداد نسخة إلكترونية تجريبية للقاموس. هذه النسخة يمكن الدخول إليها إما على الـ Web أو / وعلى CD-ROM، وهي تتضمن ثمان لغات (تمت إضافة الألمانية والعربية والصينية والرومانية إلى الطبعة السابقة) وأخرى سيتم إدخالها قريباً في هذا القاموس (خصوصاً الإيطالية، البرتغالية ، التركية واليابانية، دون أن تكون هذه القائمة نهائية).

وقد تم إغناء النصوص ببعض الأشكال التوضيحية (صور، رسوم وحتى صور فيديو متحركة). بمحتوياتها وبعمليات الربط المتوفرة فيها، فأن هذه النسخة الإلكترونية للقاموس الدولي للهيدرولوجيا يمكن أن تكون نواة لنظام واسع للمعلومات متعددة اللغات في مجالي الهيدرولوجيا وإدارة الموارد المائية والموجه لتعاون دولي مثمر في إطار البرامج الهيدرولوجية لليونسكو ومنظمة الأرصاد العالمية.

د. الدكتور صلاح الدين القضماني

الإدارة المائية للأحواض الجوفية غير المتجددة في المشرق العربي

كلية الهندسة - جامعة عمر المختار
البيضاء - ليبيا

الخلاصة

تتناول هذه الورقة الأسس والمبادىء التي استندت إليها دول المشرق العربي عند وضع خطط استثمار مواردها المائية في المناطق الجافة والتي يتوفر فيها بشكل رئيسي موارد غير متجددة نظراً لتزايد حجم الطلب على المياه في تلك المناطق لمختلف الاستخدامات البشرية والصناعية والزراعية.

تشمل هذه الدراسة الخزانات الجوفية غير المتجددة في المناطق الجافة الممتدة في شرق البحر المتوسط والممتدة عبر الأراضي السورية والأردنية وجزئياً في العراق وشمال السعودية (شمال خط عرض 30°).

إن الطبقات المائية في الأحواض الجوفية في المشرق العربي محدودة الامتداد بالتالي فإن المخزون المائي فيها محدوداً مقارنة مع الأحواض الكبرى المتشكلة في شمال أفريقيا.

تتصف أحواض المشرق بتغذية مائية ضئيلة للغاية نظراً لأن معظم مياهها ترجع إلى فترات مطيرة في عصر البليستوسين، وتلعب مناطق وأحزمة التصدع دوراً هاماً في تسريع أو إعاقة حركة المياه الجوفية في المنطقة.

إن الموارد المتاحة تحت الظروف الهيدروجيولوجية والمناخية السائدة في المشرق لا تسمح بتكثيف الاستثمار، لهذا عمدت دول المنطقة لتطبيق تقنيات متطورة بعد إجراء دراسات تفصيلية لتنظيم استثمار الموارد المائية غير المتجددة باستخدام نماذج رياضية للتوصل إلى تفهم أكثر عمقاً للنظام المائي ولتقدير الإمكانيات المائية التي يمكن أن توفرها الأحواض الرئيسية.

1 - المقدمة

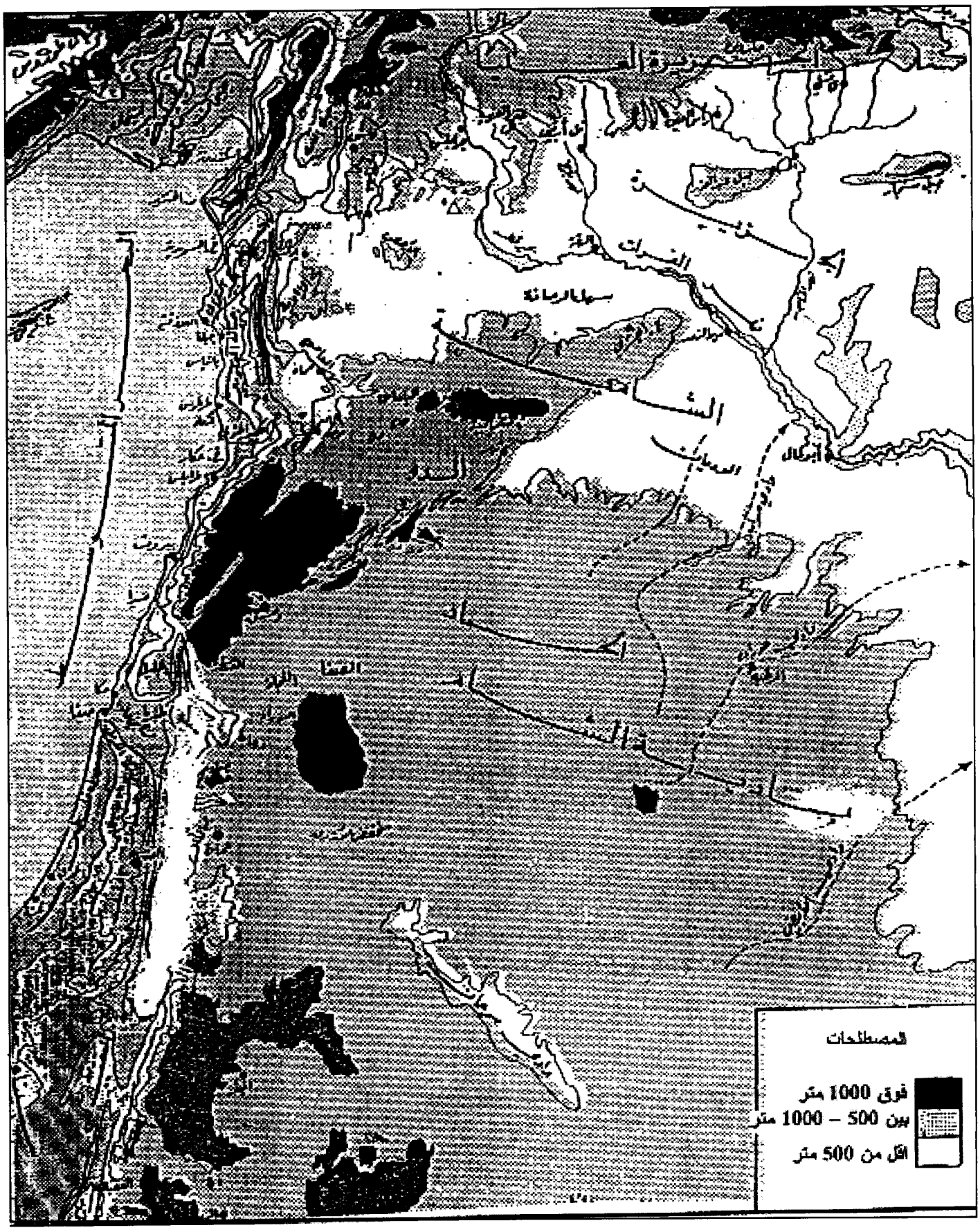
نتيجة ارتفاع الطلب على الماء في الدول العربية ومحدودية الموارد المائية المتجددة، فقد اهتمت معظم تلك الدول بالموارد غير المتجددة خلال العقد الماضي ومستهل العقد الحالي لتأمين الاحتياجات المتزايدة من المياه لمختلف الاستخدامات، لذا فإن الاتجاه نحو وضع سياسة مائية وخطط بعيدة المدى لاستثمار الأحواض المائية غير المتجددة على الرغم من وجود احتياطي كبير في معظم الأحواض أصبح أمراً ملحاً وضرورياً وخاصة بعد أن ظهرت بعض المشكلات نتيجة الاستثمار المكثف تشمل تدني مناسيب المياه وتناقص الضاغط المائي وبالتالي ارتفاع تكاليف الاستثمار وكذلك تردي نوعية المياه.

وفي هذه الورقة يتم التطرق إلى الأسس والمبادىء التي استندت إليها دول المشرق العربي عند وضع سياستها المائية في المناطق الجافة والتي يتوافر فيها بشكل رئيسي موارد غير متجددة، علماً بأن الضغوط السكانية وما ينتج عنها من تزايد متسارع في حجم الطلب قد أدى إلى تجاوز المبادىء التي استندت إليها خطط الاستثمار، ورغم الآثار السلبية للاستثمار المفرط في بعض المناطق فإن دول المنطقة اكتسبت خبرة واسعة وتفهم أكثر عمقاً لطبيعة الموارد المائية الجوفية المتاحة تحت ظروف الجفاف، وسوف يساعد ذلك دون شك على ترشيد استخدام هذه الموارد المحدودة.

تتناول هذه الدراسة الطبقات المائية في المناطق الجافة الواقعة شرقي البحر الأبيض المتوسط وتمتد بشكل أساسي عبر أراضي سوريا والأردن والعراق وشمالي السعودية (شمال خط العرض 30.00°).

2 - الظروف الطبيعية

يتكون الجزء الأعظم من المشرق العربي من الوجهة الجيومورفولوجية من بوادي منبسطة أو هضاب قليلة الارتفاع وينساب في هذه المنطقة الجافة نهري دجلة والفرات، ويفصل نهر الفرات ما بين «الجزيرة» أو «بادية الجزيرة» شمالاً والبادية الشامية جنوباً ويرتفع سطح الأرض في المنطقة الحدودية بين السعودية والعراق والأردن إلى ارتفاع 1000م تقريباً مشكلاً هضبة الحماد (شكل 1)، ويرتبط تشكيل هذه الهضبة بالوضع البنيوي للجزء الشمالي للسطحية العربية إذ ترتفع الركيزة البللورية إلى قرب سطح الأرض ويلعب هذا النهوض (نهوض الرطبة) دوراً هيدروجيولوجياً هاماً، إذ أنه من المعروف أن الوضع الجيو-تكتوني يتحكم في توزع الأنظمة المائية الجوفية الإقليمية Regional Flow Systems عندما يسود الجفاف. إن الفوالق الكبرى التي تخترق المناطق الجافة في البادية السورية تلعب دوراً هاماً في توجيه حركة المياه الجوفية أو الحد من الحركة والتغذية الآتية من الجبال الغربية ويتوقف الدور الذي تلعبه هذه الفوالق الكبرى على نوع هذه الانكسارات والظروف الجيولوجية التي تنشأ على جانبي الفالق.



شكل (1) الوحدات الطبيعية في المشرق العربي

ترتفع معدلات الأمطار في السلاسل الجبلية التي تحيط بالمناطق الجافة في المشرق العربي وتغذي هذه الأمطار أنهار كبرى وطبقات مائية مؤلفة في الغالب من الحجر الكلسي «الجيري» الذي ينتشر فيه أنظمة التشقق والمظاهر الكارستية بشكل واسع وكثيف، وينجم عن ذلك تدفق ينابيع ضخمة في جبال لبنان الشرقية والغربية. يرتفع الهطول المطري في سلسلة جبال لبنان الشرقية إلى حوالي 1500 ملم وتنخفض معدلات الأمطار شرقاً بصورة مفاجئة نتيجة تكون «الظل المطري» في معظم مناطق المشرق وتنال أمطاراً لا تتجاوز 100 مم وتنخفض الأمطار إلى 50 مم أو أقل من ذلك.

ويمتد عبر البوادي في المشرق العربي سلسلة من الهضاب والجبال القليلة الارتفاع هي السلسلة التدمرية وأهميتها تكمن ليس بتأثرها على نظام الهطول فحسب وإنما لكونها تعكس أوضاعاً جيولوجية هامة تحدد توزع الأنظمة المائية السائدة في هذه المنطقة، تشمل جبال «تدمر» سلسلتين : سلسلة شمالية تتميز بمحدبات مقببة ضعيفة الانحدار، وسلسلة جنوبية تتميز بالطي والتصدع الشديد وفي المنخفض الذي يفصل هاتين السلسلتين تكون حوض رسوبي امتلأ بسماكات كبيرة من رسوبات الحقب الثالث والرابع، ونظراً لتراكم مئات الأمتار من صخور المارل الكتيمة في هذا المنخفض فإنه يشكل فاصلاً هيدروجيولوجياً هاماً مانعاً لحركة المياه الجوفية بين السلسلة الشمالية والجنوبية.

3 - علاقة المياه الجوفية بالدورة الهيدرولوجية المعاصرة والقديمة

نشأت الدورة الهيدرولوجية مع نشوء العمليات الجيولوجية ما بعد عصر الكامبريان Cambrian وماقبله، ولعبت هذه المياه دوراً هاماً في تكوين السلم الستراتيغرافي، وما يقصد هنا بالدورة الهيدرولوجية المعاصرة هي الدورة الهيدرولوجية التي يعيشها الانسان منذ انتهاء الفترة المطيرة الأخيرة للبليستوسين، أي منذ حوالي 5000 سنة (Gey, 1982) فاعتباراً من نهاية هذه الفترة المناخية الرطبة دخلت المنطقة العربية وغيرها من المناطق الجافة في العالم بحقبة جافة نشأت بادئ ذي بدء بفعل عوامل طبيعية وقد تستمر لأسباب من صنع الانسان إذا استمرت درجة حرارة الأرض بالارتفاع. والموارد المائية المتجددة تشكل على المستوى العالمي الركن الأساسي للتنمية المستدامة، ويتوقف مدى تجدد المياه الجوفية على الوضع المناخي إذ يتراوح الهطول المطري في العالم ما بين عدة الآف الميليمترات في الأقاليم الرطبة وعدة ميليمترات في المناطق الشديدة الجفاف Hypr-arid، وعندما تنخفض معدلات الهطول عن عدة مئات من الميليمترات فإن التبخر في المناطق الجافة الذي يفوق معدلات الهطول بنسبة عالية يعيد إلى الجو الجزء الأعظم من الهطول فتتضاءل التغذية للطبقات وقد تنعدم من الوجهة العملية. وهنا تكمن المشكلة الأساسية التي تعترض استثمار الموارد المائية الجوفية في المناطق الجافة إذ يعتبرها البعض موارداً غير متجددة، أي أنها ليست على اتصال مع الدورة الهيدرولوجية الحالية، وإنما تم تكوينها وتغذيتها خلال فترات مطيرة سابقة، وتدل بعض الدراسات ان تطور هيدرولوجية الأحواض الكبرى لم يقتصر على العصر الجليدي وإنما بدأ في عصور سابقة امتدت إلى حوالي مليون سنة أو أكثر (أما ما يتم قياسه باستخدام 14C فهو يتراوح بين عدة آلاف و45000 عام وهو المدى الذي يسمح به هذا النظير)، ولا بد من الإشارة بأن الرسوبات الكلسية «الجيرية» والمظاهر الكارستية القديمة Paleokarst في المشرق هي دلائل على نشاطات الأنظمة المائية القديمة فالأنظمة النشطة في الصخور الكلسية المشققة والكارستية قد أزاحت الجزء الأكبر من المياه التي تراكمت قبل عصر البلستوسين ومن الطبيعي أن يتراجع الضاغط المائي الذي نشأ تحت ظروف الفترة المطيرة الأخيرة أو النظام المناخي الحالي، أما حركة المياه في الصخور المسامية Porous media وخاصة في الأحواض المغلقة Close basins أو التي يتم صرف مياهها من خلال حركة بطيئة لغاية متجهة إلى الطوابق المائية العليا التي تتمتع بمناطق صرف نشطة، فإنها ما زالت تحتفظ بجزء هام من الضاغط أو الميل الهيدروليكي الأحفوري Fossil gradient وقد أطلق على بعض الأنظمة المائية التي تتميز بهذا الوضع الهيدروليكي الأنظمة غير المفرغة Non-depleting aquifer systems لتميزها عن الأنظمة المفرغة التي يسمح نظام الصرف بها بتصريف مياهها.

من أهم مناطق صرف المياه الجوفية في الأحواض الصحراوية المغلقة في المشرق العربي سبخة الموح التي تمتد جنوبي مدينة تدمر التي يكون تراكم الأملاح كبيراً بسبب وجود امتدادات مستمرة للمياه الغنية بالأملاح التي تنقل مع حركة المياه الجوفية قبل ارتفاعها إلى سطح السبخة حيث تفقد المياه بالتبخر.

4 - الموارد المائية الجوفية غير المتجددة في المشرق العربي

يتم تصنيف الموارد المائية الجوفية إلى فئتين، موارد متجددة وموارد غير متجددة ليس بسبب انعدام التغذية وإنما نظراً لضآلتها بالنسبة للمخزون الضخم الذي تشكل خلال عصور مطيرة سابقة، كما يدل على ذلك التركيب الأيزوتوبي (النظائري) وخاصة عمر المياه. وعلى المعطيات المتاحة التي توفرت خلال العقدين الماضيين يمكن التمييز في المشرق العربي بين الأحواض الرئيسية التالية التي تحتوي بشكل أساسي على موارد مائية جوفية غير متجددة (شكل 2) :

- حوض تدمر
- حوض البادية الشامية
- حوض الجزيرة
- حوض الرطبة

بالإضافة إلى تكوين الديسي (الساق) الممتد في جنوب الأردن وشمال غرب السعودية.

لقد استخدم المصطلح (حوض) للدلالة على وجود وحدة هيدروجيولوجية يسود فيها نظام مائي إقليمي يتم في نطاقه حركة الماء تحت تأثير ضاغط نشأ في فترات مطيرة سابقة والحوض الرئيسي مؤلف في الغالب من معقد مائي (Aquifer complex) يشتمل على عدة مستويات أو طوابق

مائية ومجموعة من الأحواض الفرعية إلا أن هذه المستويات المائية تكون على اتصال هيدروليكي مع بعضها البعض كما تنظم الحركة المائية وفق نظام هيدروديناميكي ترفده الحركة المائية في الأحواض الفرعية وينتهي في مناطق صرف تعمل على تفريغ المياه التي تسمح ناقلية طبقاته بسريانها. ونظراً لضآلة حجم التغذية أو انعدامها عملياً فإن استجابة الطبقات المائية للاستثمار تتمثل عادة بهبوط مستمر بطيء أو سريع للمناسيب، وقد يستقر المنسوب خلال فترة من الزمن وهذا لا يعني توازن بين التغذية المائية والسحب، وإنما ينشأ عن تكيف النظام المائي مع المؤثرات الجديدة تحت تأثير ميل هيدروليكي محلي ولدته مراكز الضخ التي أدت إلى تصريف جزء من مياهه بصورة اصطناعية عوضاً عن تصريفها في نهاية المطاف في مناطق الصرف الطبيعية. وتعتمد معظم المشروعات على هذا المفهوم لتخطيط استثمار المياه الجوفية غير المتجددة إذ تفترض أن جزءاً من فواقد النظام بفعل التبخر يتم الاستفادة منها عن طريق استغلالها بالضخ لأغراض التنمية الاجتماعية والاقتصادية. وفيما يلي نبين أهم خصائص الطبقات غير المتجددة المنتشرة في أحواض المشرق العربي.

حوض تدمر :

وهو من أكثر الأحواض المائية في المشرق تعقيداً من الوجهة الهيدروجيولوجية والهيدروكيميائية. ونظراً لأهميته بالنسبة للجمهورية العربية السورية، فقد تمت دراسته دراسة مفصلة من قبل عدة جهات قطرية وقومية، ويتميز حوض تدمر بأنه حوض مؤلف من مجموعة أحواض فرعية أهمها حوض الدوة وحوض الصوانة، وقد تشكلت هذه الأحواض كنتيجة للطي والهبوط والأنضغاط الشديد، وقد أطلق عليه حديثاً أسم حوض سبخة الموح نظراً لأن هذه السبخة تشكل إحدى مناطق الصرف الرئيسية في الحوض. وقد رأينا تسميته في هذا البحث بإسم «حوض تدمر» نظراً لأهمية مدينة تدمر التاريخية والتي تحتل موقعاً متميزاً فيه.

تدل نتائج التحريات الهيدروجيولوجية أن حوض تدمر يشمل مجموعتين أساسيتين من الطبقات المائية :

1 - مجموعة هيدروجيولوجية ذات امتداد إقليمي وهي مجموعة الصخور الكلسية - الدولوميتية العائدة للكريتاسي الأعلى اعتباراً من السينومانيان حتى الكونياسيان.

2 - مجموعة هيدروجيولوجية ذات انتشار محدود أو محلي تشمل رسوبات حطامية «حتاتية» أو كلسية «جيرية» تعود إلى الرباعي والنيوجين.

يفصل المجموعتين في المناطق المركزية أو الهابطة Depressed areas مثل الدوة وسبخة الموح من الحوض طبقات سميكة من المارل أو الحجر الكلسي الحواري «الطباشيري» يتخللها أحياناً طبقات صوانية تعود إلى الكرتياسي والباليوجين. وتحت تأثير ضاغط عالي يمكن أن تخترق الحركة المائية هذه الطبقات كما هو الحال في سبخة الموح، أما في منخفض الدو حيث تزداد سماكات الطبقات المارلية إلى عدة مئات من الأمتار تنعدم تقريباً الحركة الشاقولية المتجهة نحو الأعلى.

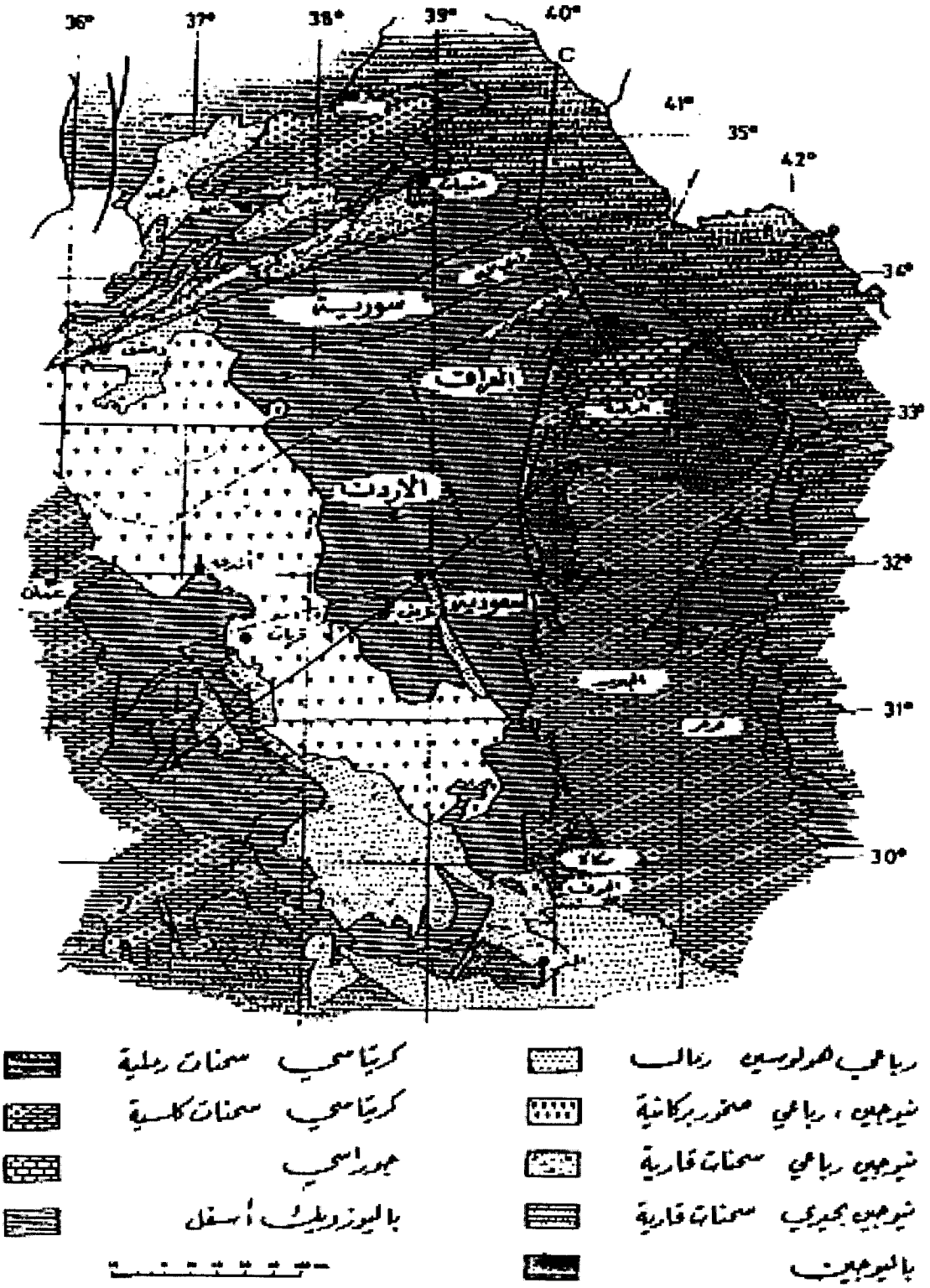
وحوض تدمر عبارة عن تتابع لسلسلة من المحدبات التي تتكشف في ذراها وسطوحها طبقات الحجر الكلسي، تفصلها مناطق هبوط تحدها في الغالب فوالق عكسية أو عادية وذلك حسب تعرض المنطقة لقوى الشد أو الضغط وثمة دلائل بأن الطبقة المائية العميقة ليست على اتصال مستمر مع الدورة الهيدرولوجية الحالية بل تم تغذيتها خلال أزمنة جيولوجية سابقة، بينما تستفيد المجموعة العليا من التغذية المباشرة أو غير المباشرة العائدة للدورة الهيدرولوجية المعاصرة ويدل توزيع التريتيوم في مياه الحامل المائي العلوي على أن التغذية تتم بشكل أساسي عن طريق السيول السطحية.

تؤثر في الحوض مجموعة كبيرة من الفوالق والصدوع ترافق اتجاه الطيات الضيقة التي تشكل السلسلة التدمرية الجنوبية وتأخذ الاتجاه جنوب غرب - شمال شرق برميات تصل إلى بضعة مئات الأمتار في الطرف الشرقي من الحوض مشكلاً حاجزاً هيدروليكياً فاصلاً لنظام حركة المياه الجوفية بين المنطقة الشمالية من الحوض والمنطقة الجنوبية منه (شكل 3) حيث تكون مستويات الحامل المائي العائد لكرتياسي الأعلى ذات أعماق كبيرة وبالتالي واقعة تحت ضغط عالي (حبيسة) وتبين الآبار المحفورة في تلك المنطقة أن المياه تدفقية (75 + متر فوق سطح الأرض) وحارة (53 درجة مئوية).

من خلال الدراسات والتحريات الهيدروجيولوجية التفصيلية التي نفذت في حوض تدمر خلال فترة 1990 - 1995 والمتضمنة حفر آبار استكشافية لأعماق مختلفة وصل بعضها إلى ما يقارب 1000 متر وتجاوز عددها 50 بئر بطول إجمالي أكثر من 30 ألف متر طولي، بالإضافة إلى تنفيذ مجموعة من البروفيلات الجيوفيزيائية والمسوحات الحقلية تضمنت حصراً للنقاط المائية وقياسات مناسيب المياه الجوفية بشكل دوري وكذلك تصاريف الينابيع وتصاريف الآبار الاستثمارية في المنطقة، ويمكن تلخيص الوضع الهيدروجيولوجي بما يلي : -

■ إن الحامل المائي الرئيسي في حوض تدمر هو الحامل (الثاني) ويتكون من رسوبيات الكرتياسي من السينومان وحتى الكامبان، وأن رسوبيات أعلى الكرتياسي العلوي من الماستريخت - دانيان وأسفل توضعات الباليوجين الطينية تشكل طابقاً شبه كتيماً يغلف الحامل المائي الرئيسي (الثاني) من الأعلى، تتوضع فوق هذا الطابق شبه الكتيم طبقات من الباليوجين والنيوجين والرباعي تشكل حاملاً مائياً علوياً (أول) تستثمر مياهه عن طريق آبار عربية أو سبور ضحلة العمق ولا يشكل حاملاً واعداً لاستثمارات كثيفة.

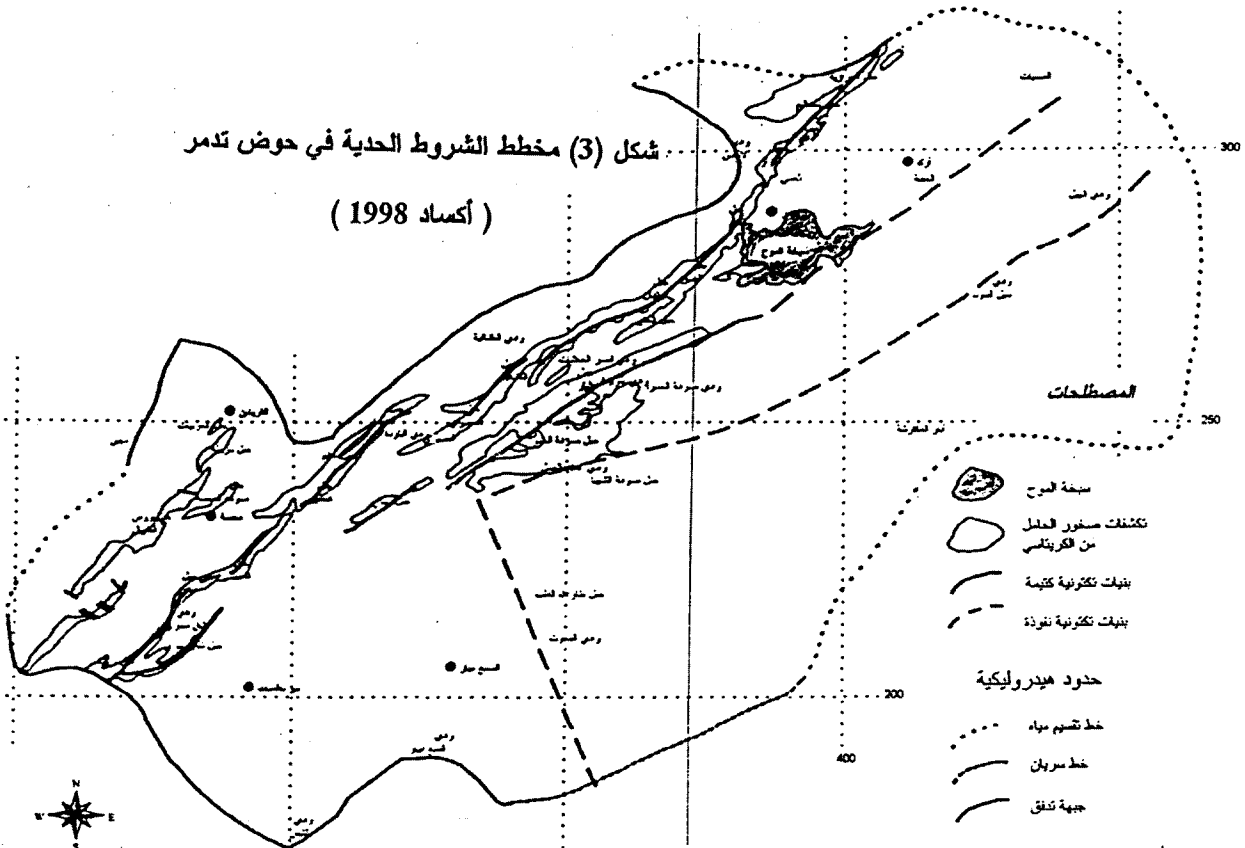
■ تتجه حركة المياه الجوفية في الحوض من الطرف الجنوبي الغربي نحو الشمال لتنصرف عن طريق البنية الفالقية المشققة باتجاه الشرق نحو سبخة الموح (جنوب مدينة تدمر)، كما تتحرك أيضاً باتجاه الشرق محاذية لخط توزع المياه الذي يحد الحوض من جهة الجنوب حتى سبخة الموح، وتشكل السبخة منطقة صرف لكامل نظام المياه الجوفية في الحوض (شكل 4). وفي منطاق النهوض المشكل للسلسلة التدمرية تتوزع حركة المياه خلال الحواجز البنيوية الكتيمة لتنصرف في النهاية أيضاً في سبخة الموح.

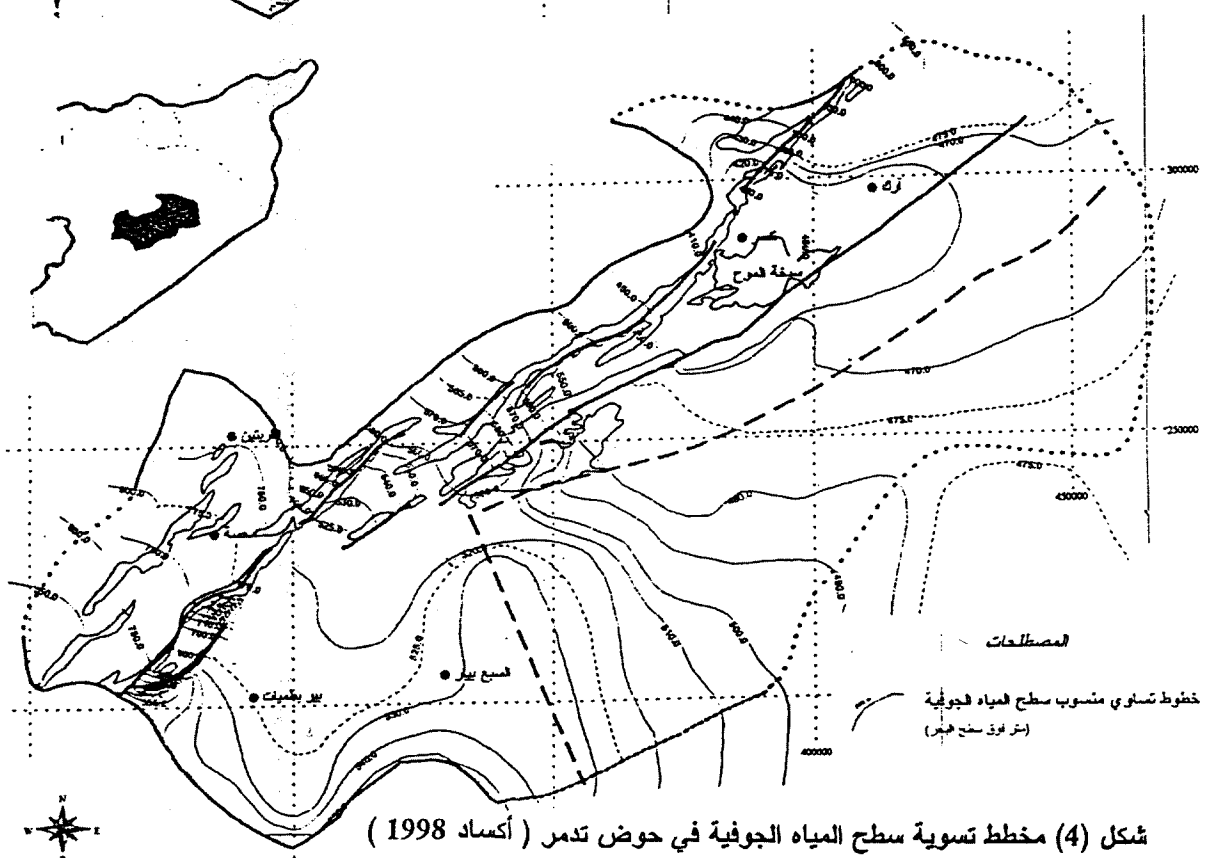


شكل (2) التشكيلات الجيولوجية في المشرق العربي (خوري 1982)

شكل (3) مخطط الشروط الحدية في حوض تدمر

(أكساد 1998)





شكل (4) مخطط تسوية سطح المياه الجوفية في حوض تدمر (أكساد 1998)

ومن خلال النموذج الرياضي لحوض تدمر (أكساد 1998) واستناداً إلى المعطيات المتاحة فقد تم ما يلي :

■ تحديد قيم المعاملات الهيدروليكية للحامل الرئيسي (الثاني) العائد للكرتياسي العلوي حيث تراوحت قيم النفوذية ما بين أقل من 2.5 متر/يوم إلى أكثر من 75 متر/يوم في بعض المناطق التكتونية، وحددت قيم معامل التخزين في مناطق المياه الجوفية الحرة بـ 3×10^{-2} وفي المناطق الحبيسة بـ 2×10^{-5} كما تم استنتاج توزع معامل الناقلية (T) حيث تراوحت قيمته ما بين أقل من 100 متر مربع/يوم في مناطق محدودة بنفوذية ضعيفة وسماكة قليلة ووصلت قيمته إلى أكثر من 10000 متر مربع/يوم في المناطق ذات النفوذية المرتفعة والسماكات الكبيرة.

■ إن نوعية المياه في حوض تدمر والتوزع المكاني للملوحة تعود بصورة رئيسية إلى تزايد زمن الاحتكاك بين الصخور الحاملة والمياه وانحلال بطيء لبعض الأملاح المنتشرة بشكل محدود في هذه الطبقات والتي لم تعطي أي مؤشر على ارتفاع الملوحة في الآبار المستثمرة في المنطقة منذ ما يزيد على ثلاثين عاماً، وبالتالي فإنه يمكن القول بأنه إذ لم يحصل اتصال هيدروليكي مع حامل مائي آخر ذو ملوحة مرتفعة فإن ملوحة المياه الجوفية سوف لن تزداد بشكل كبير ولن تتجاوز 2 غ/لتر وذلك وفق كميات المياه المستثمرة والمتوقع استثمارها مستقبلاً، أما في المناطق المحددة للاستثمار ولتأمين مياه الشرب في حوض تدمر فإن الملوحة في حال المحافظة على كميات الضخ التي حددتها الخطة الاستثمارية للحوض بواسطة النموذج الرياضي مع الهبوطات في مناسيب المياه الجوفية المتوقعة، فأن الملوحة لن تزداد بالشكل الذي يجعل هذه المياه غير قابلة للاستهلاك البشري بالنسبة للمناطق شبه الجافة وبحدود 1غ/لتر (دروبي 1998).

حوض البادية الشامية :

ويغطي مساحة واسعة تمتد اعتباراً من نهر الفرات في سورية والعراق وحتى شمالي الأردن والسعودية، تتألف الطبقات الحاملة للماء في هذا الحوض من تعاقب طبقات صوانية وكلسية مع طبقات حوارية أو مارلية، ومن أهم خصائص هذا الحوض عدم انتظام مستوياته المائية، ويعود عدم التجانس إلى تغيرات في السحنات (Facies) أو إلى درجة التشقق، فسريان المياه في الحوض وتوافره يتوقف على انتشار أنظمة التشقق وانغلاق الشقوق التي تنشأ نتيجة للطي والانضغاط أو الشد والتصدع، ويلاحظ أن معامل السريان (T) ضعيف في الجزء الأعظم من الحوض باستثناء مناطق التصدع البنيوي والتي تلعب دوراً هاماً في تحديد وتركيز مناطق الاستثمار في الحوض.

وقد أمكن من خلال التحريات الهيدروجيولوجية تحديد مجموعة من التكوينات الحاملة للماء والعائدة للحقب الثالث Tertiary والرابع Quaternary أهمها الحامل المائي الإقليمي في الحجر الكلسي الصواني العائد للايوسن الأسفل، فهذه الطبقة قد استجابت للقوى التكتونية التي تعرضت لها الصفيحة العربية فانتشر فيها أنظمة من الشقوق التي ولدت وسطاً مناسباً لتخزين وسريان الماء، أما المستوى الثاني فقد تشكل في مجموعة صوانية - كلسية تعود للكامبانيان وهي طبقات سريعة التأثر بقوى الانضغاط أو الشد بسبب تكوينها الليثولوجي و لاشك بأن هناك عاملين أساسيين يتحكمان بتوافر وحركة المياه : العامل الاول هو الوضع الليتوستراتيغرافي Lithostratigraphic والثاني الوضع الديناميكي وهو حركة المياه ونظام تغذيتها. أما تأثير العامل الأول، فقد اصبح واضحاً بفضل الدراسات الهيدروجيولوجية التفصيلية التي أجريت في الحوض والتي تم تعزيزها بحفر آبار اختباريه عميقة. تشير هذه الدراسات أن ارتفاع الركيزة البللورية العائد إلى ما قبل الكامبري Pre-cambrian basement في الرطبة أدى إلى تشكيل ثغرة ستراتيغرافية هامة وهذا بدوره أدى إلى زوال الطبقة المائية العميقة في المناطق المحيطة بنهوض الرطبة في العراق، كما أن هذا العامل الجيولوجي لعب دوراً هاماً في تفريغ المياه الأحفورية من هذه المنطقة الهامشية باتجاه مناطق الصرف شمالي نهر الفرات، ولهذا السبب أصبح جزءاً هاماً من السلم الطبقي جافاً، واعتباراً من هذه المنطقة المركزية في الحوض تنحدر الطبقات المائية باتجاه نهر الفرات في سورية والعراق كما تنحدر أيضاً جنوباً باتجاه وادي سرحان، ويكتسب المعقد المائي العلوي باتجاه الحركة الإقليمية المتجهة شمالاً وجنوباً (أو باتجاه الشمال الشرقي والجنوب الغربي) أهمية خاصة، ويصبح بالإمكان استثمار طبقتين مائيتين على الاقل في شمالي وجنوبي بادية الشام وتتوافر المياه بالتالي في المناطق الواقعة في الصحراء الشرقية للأردن وفي المنطقة المجاورة لنهر الفرات. أما الحوامل المائية فترجع للكامبانيان والايوسين والنيوجين والرباعي.

وهناك عوامل هيدروجيولوجية مختلفة يجب أن تؤخذ بعين الاعتبار عند استثمار مياه هذه الأجزاء من النظام المائي، وهذه العوامل لا ترتبط بناقلية وعمق الطبقات المائية فحسب، وإنما تتوقف أيضاً على التطور الهيدروكيميائي السريع الذي يحدث في هذا الحوض (بردن، خوري، 1973) ويزيد الوضع المائي تعقيد التغير المفاجىء بالسحنات Facies. فالسحنة الكلسية الصوانية الحاملة للماء تتبدل باتجاه وادي سرحان إلى سحنة طينية - مارلية كتيمة، كما تتغير السحنات الجيولوجية باتجاه الغرب من سحنات رملية - كلسية إلى سحنات مارلية.

حوض الجزيرة :

ويغطي منطقة تمتد ما بين نهري الفرات ودجلة، ويشكل نهر الفرات في الجزء الجنوبي حدوداً طبيعية له وفي سرير هذا النهر يتم الصرف من النظام المائي الإقليمي Regional aquifer system الذي ينشأ في الجزء الأعلى من هذا الحوض، ويفصل جزء بنيوي رئيسي هذا الحوض عن أحواض الجزيرة العليا، وأهمها حوض الرد، بينما يسود في الجزيرة العليا طبقات مائية متجددة كلسية وحطامية تغذي روافد الفرات في سوريا، ينتشر في الجزيرة السفلى طبقات مائية تحتوي بشكل رئيسي على مياه غير متجددة، وتتجه حركة المياه الجوفية بشكل عام جنوباً باتجاه نهر الفرات.

تشكل تشكيلات الفارس الأعلى والأسفل Lower and Upper fars العائدة للميوسين Miocene الطبقات المائية الرئيسية في الحوض، ولذا قد أطلق عليه بعض الباحثين اسم حوض الفارس الأعلى والأسفل، علماً بأن هذه الطبقات متوضعة فوق طبقات كلسية في منطقة جبل عبد العزيز وجبل سنجار اللذين يشكلان الحدود الشمالية للحوض وقد توضع فوق طبقات الفارس في أماكن مختلفة من الحوض رسوبات رباعية مؤلفة من الحصى والرمال تشكل طبقات محلية هامة، ويعتقد أنها تمثل مجاري قديمة لنهر الخابور أو لأحد الوديان الهامة التي اندثرت في العصر الحديث. وتتألف طبقات الفارس الأسفل من الجص والأنهيدريت Anhydrite الذي يتناوب مع طبقات كلسية وطينية محدودة السماكة، بينما يتألف تكوين الفارس الأعلى من طبقات من الحجر الرملي الناعم Siltstone ومن الحجر الرملي والرمال بنسبة ضئيلة، وتتناوب الطبقات الرملية مع طبقات طينية، فالوسط المائي الأعلى إذن هو وسط مسامي بينما تشكل تكوينات الفارس الأسفل طبقات مشققة وكارستية.

أما النظام المائي الإقليمي Regional Aquifer System السائد في الجزيرة السفلى فهو شبيه إلى حد كبير بالأنظمة السائدة في المناطق الجافة في شمالي أفريقيا والجزيرة العربية، فالتغذية المائية ترجع لعصور سابقة مع وجود نسبة ضئيلة من التغذية المرتبطة الدورة الهيدرولوجية المعاصرة، ولهذه التغذية تأثير محلي إذ لا تغذي النظام الإقليمي بشكل مستمر وملحوظ ويدل انتشار المظاهر الكارستية في الحزام الجصي المتاخم لجبل عبد العزيز وجبل سنجار بأن حركة مائية نشطة قد سادت في فترات مطيرة سابقة، إلا أن هذه الحركة لم تستمر في المناطق الجنوبية للحوض بسبب تناقص معامل السريان في كل من الفارس الأسفل (الصخور الجصية) والأعلى (الحجر الرملي الدقيق الحبات)، فالحركة المائية الرئيسية المتجهة جنوباً نحو نهر الفرات كانت بالتالي تنعطف شرقاً وغرباً وباتجاه نهر الخابور.

والتطور الهيدروكيميائي لمياه الجوفية في حوض الجزيرة يؤيد الملاحظات الهيدروليكية والهيدرولوجية، فتركيز الأملاح يرتفع بسرعة باتجاه الجنوب وثمة انتقال مفاجيء في المناطق الجنوبية من مياه ضاربة للملوحة Brackish إلى مياه مالحة، ويتبدل التركيب الكيميائي من مياه سلفاتية إلى مياه كلوريدية يدل على أن انتشار الجص ليس العامل الوحيد الذي يؤثر على طبيعة المياه من الوجهة الكيميائية فتناقص كميات المياه التي تنتقل عبر طبقات ضعيفة النفوذية والحركة المتباطئة للمياه الجوفية تلعب دوراً هاماً في تحديد نسبة الملوحة والتركيب الكيميائي.

تجاوز الاستثمار في حوض الجزيرة في منتصف التسعينات قيمة 900 مليون متر مكعب سنوياً (الحديدي 1995) من خلال ضخ 8000 بئر ولري مساحة تصل إلى 80 الف هكتار مما أدى إلى هبوط عام في المناسيب وتدهور في نوعية المياه.

حوض الرطبة :

بالرغم من أن الرطبة تحتل موقعاً غير مركزياً في الحوض، إلا أنها من أهم المناطق التي تؤثر على خواصه الهيدروجيولوجية، ولذا تم تسميته حوض الرطبة، يمتد هذا الحوض بالاتجاهين الشمال الشرقي والجنوب الشرقي، أما حدوده الغربية فليست واضحة تماماً بسبب انحدار طبقاته المائية إلى أعماق كبيرة في هذا الاتجاه، أو بسبب تغير السحنات الجيولوجية (طبيعة الصخور) أو لوجود ثغرة ستراتغرافية كما هو الحال في منطقة التنف في سورية، تتوافر المياه في حوض الرطبة في طبقات جيولوجية قديمة ترجع للحقب الأول Paleozoic والثاني Mesozoic ويمكن أن نميز فيه مجمرعتين من الصخور الحاملة للماء (معقدين مائين Aquifer complexes). تشكل المجموعة الأولى في الأسفل وسطاً مائياً مسامياً، بينما تشكل المجموعة الثانية وسطاً تشققياً، أما أهم التكوينات الحاملة للماء فتشمل ما يلي : -

أ - تكوينات الباليوزويك Paleozoic وتتألف من تتابع طبقات الحجر الرملي وطبقات من الطين الصفيحي Shale وأهم التكوينات المائية تشمل تكوين تبوك وتكوين الجوف - Ordovician Devonian وتكوين القعارة Permo-Carboniferous وقد تم تحديد مستويين في هذا التكوين الأخير.

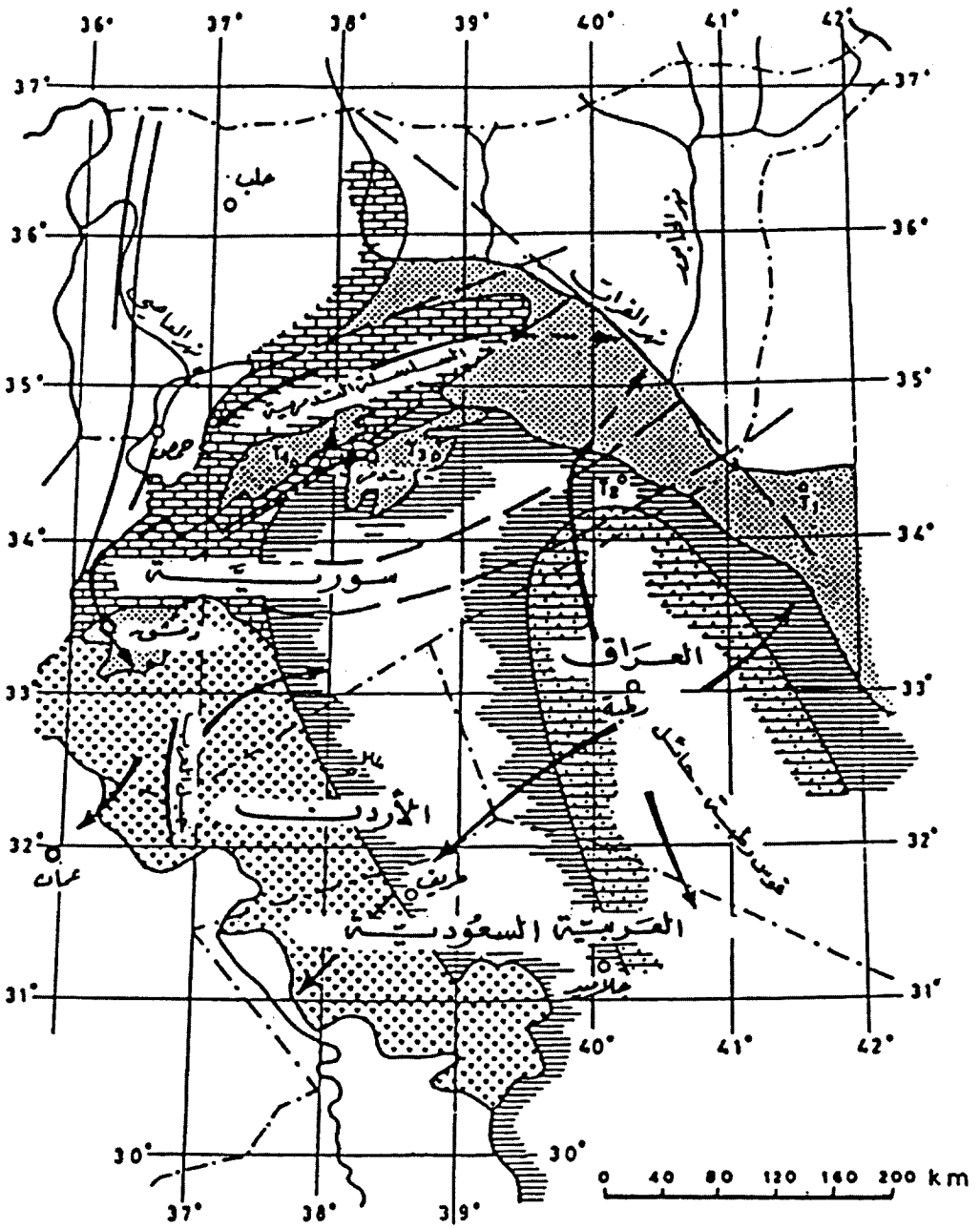
ب - تكوينات الحقب الثاني Mesozoic فهي أقل أهمية وترجع للجوارسي والترياسي، كما تم استكشاف عدة مستويات مائية في طبقات الكريتاسي ويلاحظ أن السحنات الفحماتية Carbonates الكريتاسية السائدة في حوض تدمر والبادية تتحول إلى سحنة رملية في حوض الرطبة باستثناء الأجزاء العليا منه من الكامبانيان والمايستريختيان، يمثله طبقات من الحجر الكلسي والدولوميت (تكوين الطيارات والعرمة) وكلاهما يستثمر على نطاق واسع في العراق وفي مناطق الطريف والجلاميد في السعودية. ورغم هذا التعقيد الهيدروستراتيغرافي في حوض الرطبة فإن النظام المائي السائد فيه هو نظام إقليمي، (خوري، 1982)، ويشكل الجزء الأعلى منه طبقة مائية حرة في «حجر رمل الرطبة». والعائد للكريتاسي الأسفل والسنومانيان، ويقع سطح المياه الجوفية على أعماق كبيرة (230-300 م).

ويبدو أن هذه الطبقة المائية الإقليمية قد تم تغذيتها في فترات مطيرة سابقة (Gey 1982) وتحت تأثير الحركة الإقليمية التي تم تصريف مياه هذا النظام باتجاه الشمال الشرقي أي باتجاه نهر الفرات وباتجاه الجنوب والجنوبي الشرقي إذ يزداد انضغاط الطبقات المائية في هذين الاتجاهين كما تزداد الإنتاجية (شكل 5).

أما حركة المياه الجوفية باتجاه الغرب (نحو الأردن) أو الشمال الغربي (نحو سوريا) فهي أقل أهمية من الناحية الكمية، ويعود ذلك إلى تناقص سماكات الطبقات المائية أو زوالها بفعل الحت في عصور سابقة أو بسبب انحدارها إلى أعماق كبيرة كما هو الحال في الأردن.

تكوين الديسي (الساق) :

يقع هذا التكوين في جنوب الأردن ويشكل امتداداً لتكوين الساق في شمال غرب السعودية والذي يعود لعصر الباليوزويك وهو عبارة عن حجر رملي تبلغ سماكته مئات الأمتار وقد يتجاوز الألف متر. وقد خضع هذا التكوين الذي تتميز مياهه بنوعية جيدة (500 - 1200 ملغ/متر) إلى



شكل (5) الأنظمة الإقليمية لحركة المياه الجوفية في المشرق العربي (خوري 1982)

استثمارات مكثفة في كل من الأردن والسعودية، حيث قدر الاستخراج الآمن منها في الاردن في حدود 30 مليون م^3 في حين وصل الاستثمار إلى 60 مليون م^3 /سنة (سلامة 1994) ويقدر هبوط المنسوب المائي في حدود 9 متر في بعض المناطق كما لوحظ وجود تدهور في نوعية المياه.

أما في السعودية فقد تجاوزت كمية المياه المستثمرة من تكوين الساق 300 مليون م^3 وهي تستغل بشكل أساسي لأغراض زراعية وقد تسبب هذا الاستثمار إلى هبوط واضح في المناسيب مع تدهور في النوعية (خوري 1994).

5 - استثمار وإدارة الموارد المائية غير المتجددة

تتمتع بلدان المشرق العربي بموارد مائية سطحية هامة، وبالرغم من أن حجم هذه الموارد يختلف من بلد لآخر فإنها تشكل الركن الأساسي للسياسات المائية وبالتالي تلعب دوراً فاعلاً في توجيه السياسة المائية لاستثمار الموارد المائية غير المتجددة.

وبالرغم من أن الاستثمار للموارد المائية الجوفية في أحواض المشرق كانت محدودة في مستهل النصف الثاني من هذا القرن (1950 - 1980) فإن العقد الأخير شهد تزايداً ملحوظاً في حجم الاستثمار، وتعددت مناطق الاستثمار لأغراض مياه الشرب والزراعة والصناعة كما ازداد عدد الآبار المنتجة في كل هذه المناطق. إضافة لذلك فإن المشكلة الأساسية التي تواجه أقطار المشرق العربي في المناطق الجافة تكثيف الاستثمار في مناطق محدودة لأسباب اجتماعية أو بسبب توافر بعض الثروات الطبيعية مثل الفوسفات.

ولتحقيق مبدأ «السحب الآمن» بحيث يتم استخراج أكبر كمية من المخزون المائي على مدى عمر الحوض وأفضل نوعية مياه تصلح للاستعمال المطلوب وبأقل كلفة اقتصادية وبما يحقق الأهداف الاجتماعية المرجوة على المدى البعيد، فقد أعطت دول المشرق العربي الأولوية لاستعمال المصادر المائية الغير المتجددة لغايات الشرب والاستخدامات المنزلية ثم للاستعمالات ذات المردود الاقتصادي والاجتماعي المرتفع مثل الصناعة والاستفادة من الثروة المعدنية وأخيراً كمصدر ثانوي داعم في مجال الزراعة لمصدر مائي آخر وفي إنتاج محاصيل زراعية عالية القيمة، وتجنب التوسع في الاستثمارات الزراعية المعتمدة على طرق الري التقليدية نظراً لضآلة المخزون والامتداد المحدود للطبقات المائية والتغيرات السريعة في السحنات وكذلك انتشار المياه المالحة.

أي يمكن القول بأنه نظراً لأن المياه الجوفية غير المتجددة في المشرق العربي تتميز بدرجة عالية من الندرة وبالتالي فإن استثمارها يجب أن يكون محدداً للغاية واستخدامها ينبغي أن يقتصر على المشاريع التنموية التي تستهلك كميات محدودة من المياه وتعطي مردوداً عالياً على المدى الطويل.

أجرت معظم دول المنطقة دراسات تعتمد على النماذج الرياضية لعدد من المناطق فيها ومن الأمثلة على ذلك ما تم في حوض تدمر فقد استخدمت نماذج محلية لمناطق الدو (البيضا) والصوانه استهدفت وضع خطط استثمار لهذه المناطق وأنجز أخيراً (أكساد 1998) إعداد نموذج إقليمي لتوضيح نظام حركة المياه الجوفية في الحوض وتحديد الموازنة المائية الجوفية له وكذلك تأثير خطة الاستثمار المقترح تطبيقها من الحالة الراهنة لاستثمارات الحوض عام 1992 وتطويرها باتجاه عام 2026 ومن ثم ثبات الخطة حتى عام 2046 ودراسة تنبؤ النموذج بتغيرات نظام حركة المياه الجوفية وعمق الهبوطات في مناطق الاستثمار الكثيف. ومن أهم نتائج تشغيل النموذج الرياضي ما يلي : -

■ تم تحديد قيم الاستثمارات المطلوبة في المناطق المقترحة لتطوير المياه الجوفية في الحامل الرئيسي العائد لكريتاسي العلوي اعتباراً من عام 1992 بحوالي 15 مليون متر مكعب/سنة وحتى أفق عام 2026 حيث بلغ مجموعها حوالي 33 مليون متر مكعب/سنة ووزعت قيم هذه الاستثمارات على هذه الفترة بمعدلات متغيرة خطياً وتم اعتبار مجموع الاستثمارات ثابتاً في الفترة الواقعة بعد 2026 ولفترة عشرين سنة (جدول 1) (شكل 6).

■ تمت دراسة الموازنة المائية لكامل الحوض ولكل منطقة من مناطق الاستثمار الكثيف المقترحة وتبدلاتها حتى أفق عام 2026 حيث تم توضيح مركبات التبادل المائي الأفقي والشاقولي. وقد تبين أن نظام حركة المياه الجوفية في حالة أتزان في تلك المناطق في عام 1992 (شكل 7)، وبمقارنة نتائج تشغيل النموذج للعام 2026 مع الوضع القائم في 1992 تبين أنه في بعض المناطق كان تأثير الاستثمار فيها ضعيف جداً ولم يتعدى الهبوط فيها نصف متر كما لوحظ بأن أكبر قيمة هبوط متوقع وصلت قيمته إلى حوالي 20 متر بينما كانت قيمة الهبوط في حدود 4 متر في معظم المناطق (شكل 8).

■ تم وضع مشاهد (سيناريوهات) مختلفة لخطة الاستثمار المقترحة التي اعتبرت بمثابة السيناريو الأول والتي بلغ مجمل الاستثمارات فيها حسب الخطة المقترحة 33 مليون متر مكعب/سنة وأصبحت في السيناريو الثاني 67 مليون متر مكعب/سنة (ضعف الاستثمارات) والسيناريو الثالث حوالي 100 مليون متر مكعب/سنة (ثلاثة أضعاف الخطة) وتبين أن هناك تبدلات في نظام حركة المياه الجوفية في الحوض نتيجة لذلك، فيلاحظ عدم استقرار في المناسيب بعد عام 2026 كما حدث في السيناريو الأول (الخطة المقترحة) كما ازدادت الهبوطات في المناسيب بشكل كبير.

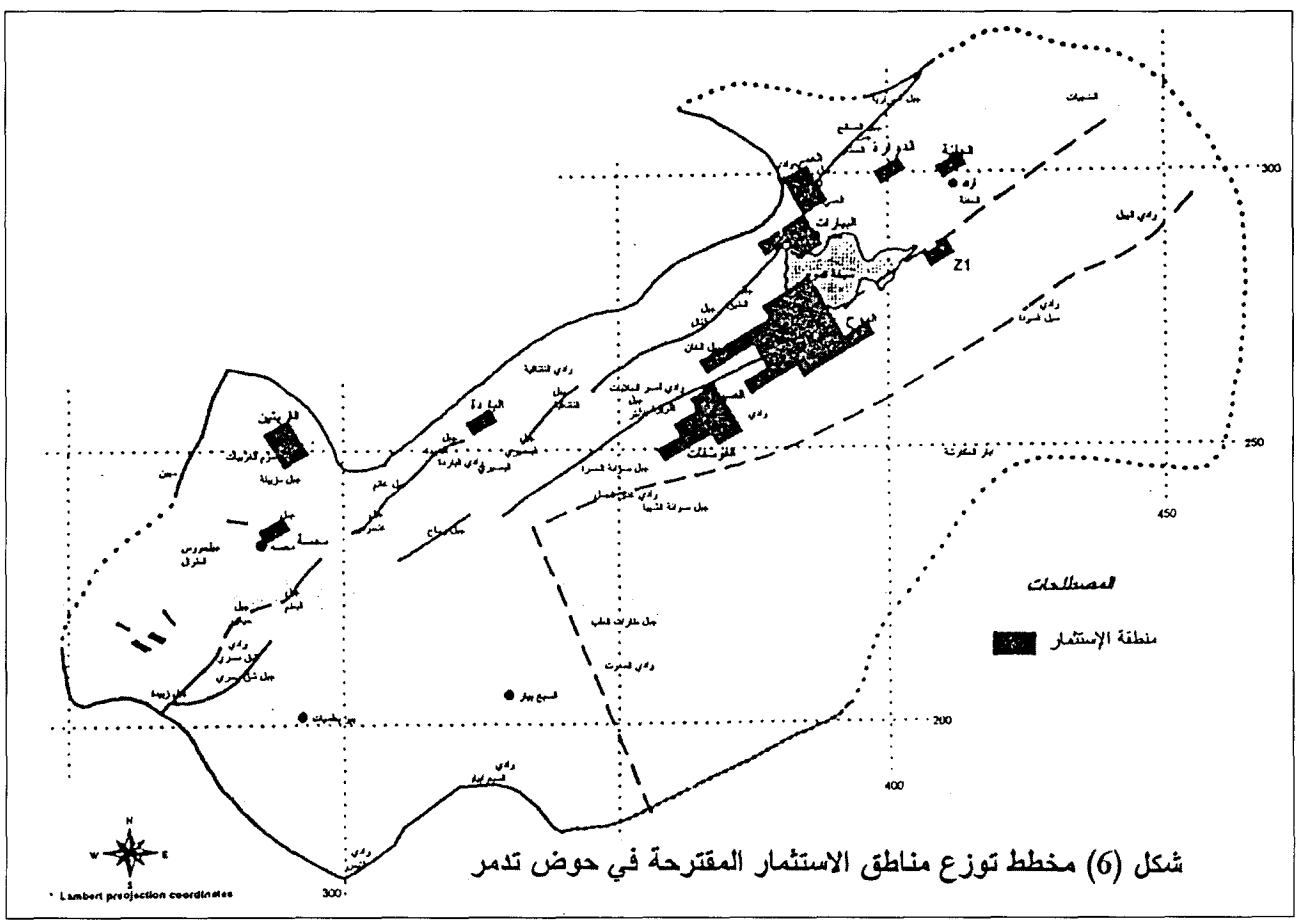
اعتماداً على ما تم التوصل إليه من نتائج تبين أن حوض تدمر يعتبر منطقة ذات موارد مائية محدودة، وأن الاستثمارات المقترحة فيها تنسجم مع إمكانياتها المائية ولا يوجد مبالغة فيها ضمن إطار الموازنة العامة للحوض.

وأخيراً لا بد من الإشارة إلى ضرورة إعادة معايرة النموذج الرياضي بعد فترة الاستثمار المكثف من المناطق المقترحة وإعادة تشغيل النموذج وحساب الموازنة في كل منطقة وذلك لتدقيق النتائج التي تم الحصول عليها وتحديثها على ضوء المراقبة الدورية الدائمة للمناسيب والتصاريف والنوعية التي يجب أن يوضع لها برامج واضحة ومتابعة من الجهات المختصة المسؤولة عن استثمار الحوض.

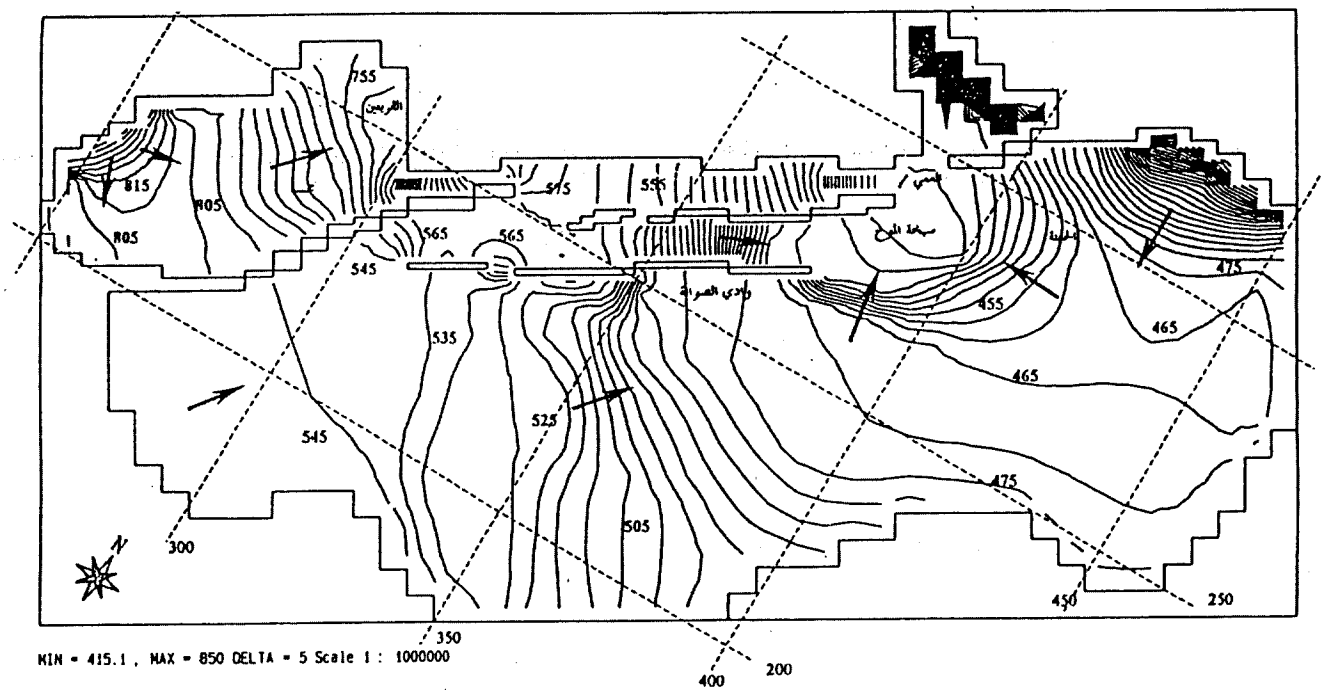
جدول (1) خطة الإستثمار المقترحة في المناطق المختلفة (مليون م^3/سنة)

مسلسل	الموقع/السنة	1992	1996	2000	2006	2016	2026
1	واحة الصوانة	0.514	0.514	0.514	0.514	0.514	0.514
2	معمل السماد	-	-	2	8	9	10
	معمل غسيل الفوسفات	0.62	0.62	1.82	2.22	2.62	3.22
3	سبخة الموح الزراعي	3.51	1.163	1.263	1.363	1.363	1.363
4	مياه شرب تدمر - العمي	1.927	2.278	0.32	-	-	-
5	مياه شرب تدمر - الدوارة	-	0.5	1.88	2.9	4.12	7
6	الحفنة	0.412	0.413	0.459	0.519	0.619	0.719
7	بساتين تدمر + L - 9	1.05	2.62	3.1	3.1	3.1	3.1
8	Z I	0.19	0.19	0.19	0.19	0.19	0.19
9	كهرباء الباردة	-	-	1.5	1.5	1.5	1.5
10	بحوث المحسة	2.868	0.358	0.358	0.358	0.358	0.358
11	القريتين + نبع القريتين	2.371	2.371	2.871	3.371	3.871	4.371
	نقاط مائية متفرقة	1.927	1.12	1.12	1.12	1.12	1.12
	الاجمالي	15.389	12.146	17.393	25.154	28.374	33.455

أكساد (1998)

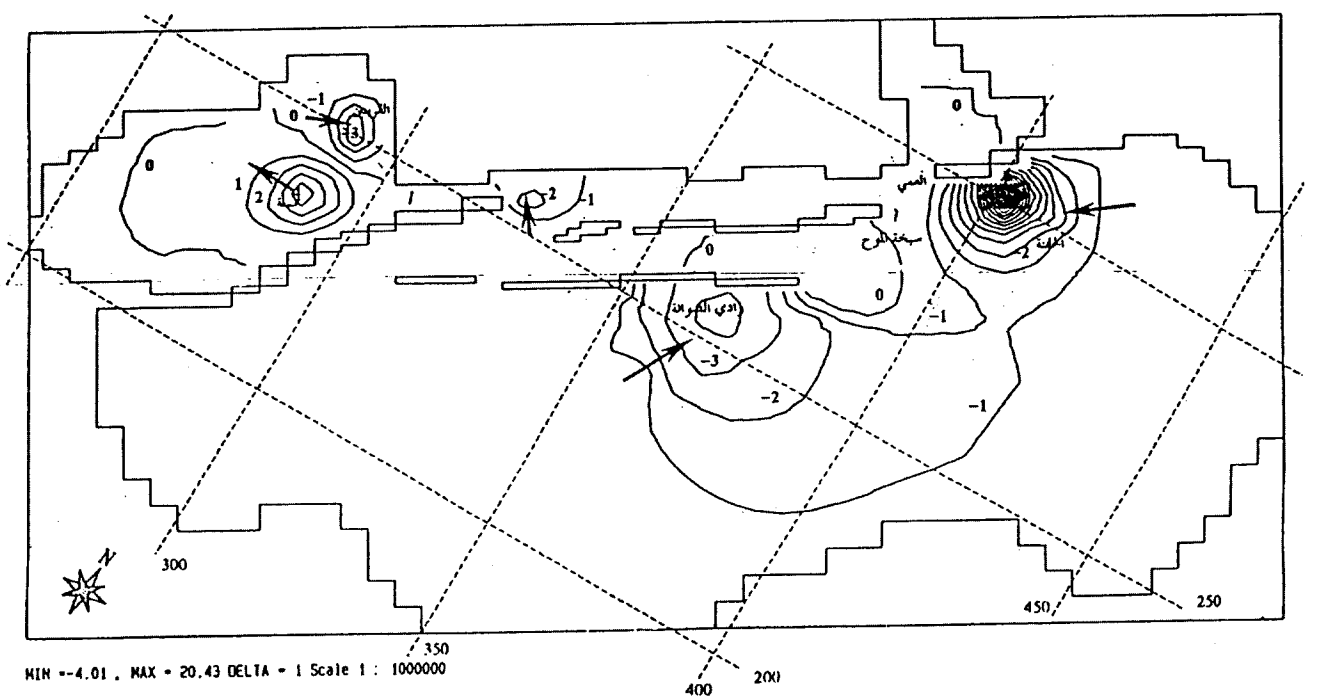


شكل (6) مخطط توزع مناطق الاستثمار المقترحة في حوض تدمر



شكل (7) مخطط تساوي مناسيب المياه الجوفية في حوض تدمر (أكساد 1998)

(معايرة النموذج لعام 1992 وفق الاستثمارات القائمة – حالة الثبات)



شكل (8) مخطط تساوي قيم الهبوط المتوقع لمناسيب المياه الجوفية في حوض تدمر

(تنبؤ النموذج لعام 2026 وفق الاستثمارات المقترحة)

الخلاصة والنتائج :

من الممكن تلخيص هذه الدراسة في النقاط الأساسية التالية :

1 - تتوافر الموارد المائية غير المتجددة في المشرق العربي في أربعة أحواض، وهي أحواض تدمر والجزيرة والبادية الشامية والرطبة وتمتد هذه الأحواض عبر أراضي أربعة دول عربية وهي سورية والعراق والأردن والسعودية (جدول 2).

2 - إن حجم الكتلة المائية (المخزون) في كافة أحواض المشرق محدود إذا ما قورن بالأحواض الكبرى المكتشفة في الصحارى العربية في شمال أفريقيا، كما أن الطبقات المائية في كل من هذه الأحواض محدودة الامتداد ومؤلفة من مجموعة أحواض فرعية، إنما يوجد اتصال هيدروليكي فيما بينها، الأمر الذي يجعلها تخضع لدراسات إقليمية كأحواض كبرى.

3- إن التغذية المائية ضئيلة للغاية في أحواض المشرق، وبالتالي فإن معظم مياهها ترجع لفترات مطيرة في عصر البليستوسين، علماً بأن معظم المياه المتراكمة في هذه الفترات تم تفريغها في مناطق الصرف، وبالتالي فإن الضاغط أخذ بالانخفاض تدريجاً ووصل إلى أعماق كبيرة في بعض المناطق، وتلعب مناطق التصدع دوراً هاماً في تسريع أو أعاقة حركة المياه الجوفية في المنطقة، ففي حوض تدمر يفصل فالق اقليمي ما بين النظام المائي في جبال لبنان والنظام المائي في حوض تدمر، وفي حوض الجزيرة يفصل حزام الطي والتصدع لجبل سنجار وجبل عبد العزيز ما بين مصادر التغذية في سفوح جبال طوروس والحوض الصحراوي في الجزيرة السفلى.

4 - إن الموارد المتاحة تحت الظروف الهيدروجيولوجية السائدة في المشرق لا تسمح بتكثيف الاستثمار أو توسيع آفاقه، ولهذا فإن دول المنطقة اتخذت منهجاً يتلاءم مع هذه الظروف، فركزت على الأنشطة الرعوية وتأمين مياه الشرب أو الفعاليات الاقتصادية العالية، كما اتخذت إجراءات للحد من التوسع في مناطق الاستثمار الزراعي المعتمد على الري من المياه الجوفية.

5 - اتخذت دول المنطقة منهجاً يعتمد على التكامل بين مختلف الموارد المائية وركزت على استثمار المياه الدائمة الجريان في أحواض الجزيرة والرطبة والبادية، بينما استفادت الأعمال التنموية في المناطق النائية من مياه الأودية العالية (التنف، وادي المياه...). واستخدمت دول المنطقة تقنيات متطورة لتنظيم استثمار الموارد المائية غير المتجددة، فأثر استخدام نماذج محلية قامت بإعداد نماذج إقليمية للتوصل إلى تفهم أكثر عمقاً للنظام المائي ولتقدير الإمكانيات المائية التي يمكن أن توفرها الأحواض الرئيسية.

الحوض	الحامل المائي	المنطقة	الناقلية المائية (السريان) م²/يوم	الملوحة العامة غ/ل
تدمر	رباعي - نيوجين	الدو - سورية	150 -35	20 -2
	كونياسيان-سينومانيان	الموح-سورية	1500-200	1.6-0.4
البادية الشامية	باليوجين-كامبانيان	التنف السورية	30-1	3-1.5
	باليوجين-كامبانيان	الاجفور-الاردن	100-20	1.5-0.7
الجزيرة	نيوجين (الفارس)	الجزيرة-سورية	10-1	5-2
الرطبة	باليوجين-كريتاسي اعلى	وادي المياه-سورية	20-1	5-1
	كامبانيان (طيارات)	الرطبة-العراق	600-7	2.5-0.7
	كريتاسى اسفل (الرطبة)	وادي الولج-العراق	360-120	2.5-1.5

جدول (2) المواصفات الهيدروجيولوجية للأحواض الرئيسية

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المياه الجوفية العميقة غير المتجددة والخيارات الاستراتيجية المستقبلية في ادارة الموارد المائية في سورية

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دمشق، سورية

مع تزايد حدة نقص إمدادات المياه في المناطق الجافة وشبه الجافة تزداد الحاجة الى البحث عن مصادر مائية جديدة لتلبية الاحتياجات المائية المستقبلية والمتنامية في معظم أصقاع العالم . وتلجأ الدول العربية الى خيارات تكنولوجية متعددة تتناسب وظروفها البيئية والاجتماعية والاقتصادية لمواجهة اختلال التوازن في معادلة الموارد المائية والطلب عليها .

يهدف هذا البحث إلى مناقشة الخيارات التكنولوجية المحتملة أمام سورية لمواجهة احتياجاتها المائية المستقبلية والتقصي عن دور المياه الجوفية العميقة كأحد أهم هذه الخيارات ، أستناداً إلى شواهد هيدروجيولوجية وجيوفيزيائية والى نتائج الحفر الاستكشافي العميق النفطي والمائي . ويتناول البحث خزانات المياه الجوفية العميقة الرئيسة في سورية في ضوء الآراء المختلفة والمتعارضة حول مفهوم المياه الجوفية العميقة ، ويبين البحث وزن المحددات الهيدروجيولوجية كالنوعية والتجدد وقابلية الاستثمار والإنتاجية في تحديد هذا المفهوم ، وصولاً الى بلورة مفهوم هيدروجيولوجي بنيوي محدد للمياه الجوفية العميقة مما يساعد على تنميتها وإدارتها بشكل سليم .

1- المقدمة

تاريخياً تعود أقدم الدراسات المائية الموثقة في سورية إلى عام 1933 (فرولو ودوبرتريه)، وقد توالت ومنذ ذلك الحين وبفترات متقطعة مئات الدراسات مختلفة المقاييس والأهداف والحجوم التي قامت بها خبرات محلية وأجنبية. ويمكن القول حالياً أن سورية قطعت شوطاً بعيداً في دراسة مواردها المائية، حيث غطت الدراسات المائية الأراضي السورية كافة على المستويين الإقليمي والمحلي، وبنتيجة ذلك تتوفر حالياً معلومات تفصيلية عن المستويات المائية العليا على مستوى القطر، وكذلك معلومات عن المستويات الأعمق للعديد من مناطقه. وقد استخدمت في الحصول على تلك المعلومات طرائق المسح الجيولوجي والهيدروجيولوجي والجيوفيزيائي والحفر المائي ونتائج الحفر الاستكشافي النفطي.

من جهة أخرى شهدت سورية في العقود الثلاثة الأخيرة تطوراً اقتصادياً واجتماعياً كبيراً وشاملاً في مختلف المجالات أدى إلى تزايد الاحتياجات المائية للسكان، وبالتالي إلى زيادة مضطردة في استهلاك المياه في مختلف القطاعات الأهلية والصناعية والزراعية والخدمات. وقد أدت المعدلات العالية للنمو السنوي للسكان والتي تصل إلى 3.7٪ إلى تصاعد ذلك الاستهلاك إلى الحد الذي بدأت فيه ظواهر العجز المائي* بالظهور في العديد من المناطق السورية وخاصة في تلك التي تقع جغرافياً في المناطق القاحلة وشبه القاحلة من القطر. وتتمثل هذه الظواهر بجفاف بعض الأنهار والينابيع والآبار أو بانخفاض مناسيب وتصاريف بعضها الآخر وبتلوث بعض المصادر المائية السطحية والجوفية وتدهور نوعيتها. وقد فاقمت دورات الجفاف التي تعرضت وتتعرض لها الأراضي السورية كلياً أو جزئياً ذلك العجز. وقد أدى هذا العجز إلى تعرض سورية كغيرها من العديد من دول العالم إلى نقص في إمدادات المياه العذبة الصالحة لمختلف الاستعمالات، مما وضع أمام المسؤولين فيها مهمة صعبة لمواجهة هذا التحدي الحالي والمستقبلي.

لم تألُ السلطات المسؤولة عن إمدادات المياه في سورية جهداً في مواجهة العجز المائي، فنفذت برامج كبيرة لإدارة الموارد المائية تضمنت تقويماً لتلك الموارد، وتنمية للموارد المائية السطحية بتكثيف عمليات إشادة السدود وأقنية الري ومنشآت حصاد مياه الأمطار. كذلك جرت تنمية الموارد المائية الجوفية باستثمار الينابيع وبحفر الآبار وبإقامة منشآت التغذية الاصطناعية للمياه الجوفية (ولو بشكل محدود) وباستثمار العديد من الطبقات والمستويات المائية الضحلة والعميقة. كما تم استثمار مياه الصرف الزراعي ومياه الصرف الصحي المعالجة في الزراعة. كذلك نفذت برامج كثيرة لترشيد استعمالات المياه ورفع كفاءة الري وشبكات مياه الشرب والصرف الصحي وحماية المياه السطحية والجوفية من التلوث، كذلك جرت عمليات نقل المياه السطحية والجوفية من مناطق الوفرة المائية إلى مناطق الشحة.

ومع ذلك لازال نمو الطلب على الماء يضغط على الموارد المائية المحدودة ويدفعنا إلى البحث عن خيارات استراتيجية لضمان استمرارية إمدادات المياه في العقود القادمة لمواجهة احتياجات السكان والتنمية، لهذا تهدف هذه الورقة إلى مناقشة أحد هذه الخيارات الاستراتيجية وهو استثمار المياه الجوفية العميقة انطلاقاً من حالة المعرفة الحالية بالموارد المائية واستعمالاتها.

2- الحالة الراهنة للموارد المائية في سورية

2-1 الأمطار:

يصنف مناخ سورية ضمن مناخ البحر المتوسط ذو الشتاء الرطب الممطر والصيف الجاف الحار، اللذين يفصل بينهما فصلين انتقاليين. تهطل معظم الأمطار بالسنوات العادية ما بين أشهر تشرين الأول وأيار من كل عام، كما تهطل الثلوج على المرتفعات الغربية بشكل رئيس ويبلغ الهطول حده الأقصى عادةً في شهر كانون الثاني، وتتصف أمطار القطر بعدم الثبات حيث تختلف كمياتها الهاطلة بحدود كبيرة من منطقة لأخرى، كما تختلف في نفس المنطقة من سنة لأخرى. وعموماً تتناقص كميات الأمطار من الغرب إلى الشرق ومن الشمال إلى الجنوب، كما يزداد الجفاف في تلك الاتجاهات. هذا ويراوح مجموع ما يهطل في القطر سنوياً من الأمطار وحسب مختلف التقديرات المنشورة مابين 35 و 60 مليار م3 تبعاً لكون السنة جافة أم مطيرة، كما يقدر وسطي الهطول السنوي حسب المراجع المختلفة بين 45 و 52.7 مليار م3، وحسب وزارة الري 46.6 مليار م^3 (1998). وتتوزع هذه الكمية على ثلاث شرائح هي:

- كمية الهطول المطري السنوي بمعدل أقل من 100 مم وتقدر بحوالي 0.47 مليار م^3 وهي تعادل 1٪ من إجمالي كمية الهطول في القطر وتسقط على 5.7٪ من أجمالي مساحته، وهي كمية عديمة الفائدة لأنها تضيع في التبخر بكاملها تقريباً.
- كمية الهطول المطري السنوي بمعدل بين 100-300 مم وتقدر بحوالي 22.41 مليار م3 مما يعادل 48.1٪ من إجمالي قيمة الهطول، تسقط على 69.7٪ من مساحة القطر. وايضاً تتعرض نسبة كبيرة من هذه الكمية إلى التبخر، إلا أنه يمكن الاستفادة منها جزئياً في تحسين أحوال المراعي الطبيعية.
- ما يتبقى من الهطول والبالغ 23.72 مليار م^3 يضيع جزء منه في التبخر وجزء في التسرب (ضياع ظاهري)، كما يخزن مقدار آخر في الترب السطحية، حيث يستفاد منه في عمليات النتح، أما ما يتبقى فيشكل الجريان السطحي الذي يضيع جزء كبير منه في التبخر والتسرب إلى باطن الأرض والصبيب إلى البحر.

* يقصد بالعجز المائي اختلال معادلة التوازن بين الموارد المائية المتجددة والمتاحة للاستثمار والطلب عليها، ويسمى أيضاً بالمسألة المائية أو بالفجوة المائية.

هذا ويعتقد أن حوالي ثلاثة أرباع الهاطل المائي (34.3 مليار م^3) يضيع في التبخر الذي تراوح معدلاته السنوية بين 1-2.8 م/سنة، كما ويشكل الجريان السطحي وسطياً حوالي 4.365 مليار م3من ذلك الهاطل (حيث قدر عامل الجريان السطحي بحوالي 9٪) ويذهب جزء منه إلى البحر، كذلك تؤمن الأمطار الهاطلة الرطوبة اللازمة للزراعة في حوالي أربعة ملايين هكتار من أراضي الزراعة المطرية و حوالي 8 مليون هكتار من المراعي والمروج الطبيعية ونصف مليون هكتار من الحراج. أما ما تبقى من الهاطل المائي ويقدر وسطياً بـ7.938 مليار م3 فيذهب لتغذية المياه الجوفية.

يتبين مما تقدم أن العائد من موارد الأمطار في سورية محدود عموماً، حيث أن معظمها يتعرض للبخر والضياع في البحر.

2-2 المياه السطحية:

توجد في سورية شبكة هيدروغرافية كثيفة نسبياً، إذا ما أخذنا بعين الاعتبار أن أكثر من ثلاثة أرباع مناطق القطر تعتبر جافة. وتتألف هذه الشبكة من العديد من الأنهار الدائمة والمؤقتة الجريان (عدة أشهر) ومن الوديان ذات الجريان الموسمي (عدة أيام)، وتتركز الشبكة في المنطقتين الغربية والشمالية الشرقية من القطر.

تتميز الأنهار الدائمة الرئيسة في سورية بكونها مشتركة مع الدول المجاورة، (ونذكر منها الفرات، دجلة، جغجغ، الساجور، اليرموك، الكبير الجنوبي، العاصي وغيرها)، مما يجعل جرياناتها الواردة إلى القطر غير ثابتة وتتأثر بحجوم الاستثمارات القائمة على تلك الأنهار خارج حدود القطر، بالإضافة إلى تأثرها بالعوامل الطبيعية السائدة في تلك الدول. أما باقي الأنهار الدائمة فتكون داخلية (ونذكر منها الخابور، البليخ،الكبير الشمالي،السن، بردى، الأعوج)، كما تنحصر معظم الأنهار مؤقتة الجريان في المنطقة الساحلية وتتميز بكونها أنهاراً جبلية قصيرة وسريعة الجريان وقريبة من البحر، مما يعرض جزءاً كبيراً من مياهها للضياع. وتفيد تقديرات وزارة الري السورية (ملكاني، 1999) أن متوسط حجوم مياه النهار والسيول ما عدا حجم حصة القطر من مياه نهري دجلة والفرات تبلغ 3.5 مليار م^3/سنوياً علماً بأن حجم مياه الينابيع لا يدخل ضمن تلك التقديرات، ويحسب على موارد المياه الجوفية. ويضاف إلى هذه الكمية 6.627 مليار م^3/سنة وهي الحد الأدنى لحصة سورية من مياه نهر الفرات بموجب بروتوكول عام 1987 الموقع مع تركيا (قاعدة الـ500 م^3/ثا على الأقل) والاتفاق السوري العراقي لعام 1989. وعليه نستطيع القول أن لدى سورية حالياً موارد مائية سطحية محدودة تصل إلى حوالي 10.127 مليار م^3/سنة ولكنها مع ذلك على درجة كبيرة جداً من الأهمية إذ أنها تشكل العمود الفقري لكافة خططها الزراعية، الأمر الذي يقتضي إيلائها العناية التي تستحقها، والسعي لتحقيق الاستفادة القصوى منها. وفعلاً نجد أن الهيئات السورية المعنية لا تدخر وسعاً في هذا المجال، فقد شيدت حتى الآن ما يزيد عن الـ155 سداً (كبير ومتوسط وصغير) وشبكات واسعة من أقنية الري، وتتابع نهجها هذا حيث تخطط لبناء العشرات من السدود والشبكات الأخرى.

2-3 المياه الجوفية

تعد المياه الجوفية المصدر الرئيس، بل الوحيد أحياناً لتأمين الاحتياجات المائية لسورية في العديد من مناطقها، حيث تنعدم مصادر المياه السطحية ووسائل استثمارها بشكل اقتصادي. لهذا أوليت الدراسات الهيدروجيولوجية اهتماماً كبيراً، مكن من بناء تصور واضح عن الطبقات المائية المنتشرة في القطر، وقد أظهرت تلك الدراسات وجود المياه الجوفية في معظم التشكيلات الصخرية التي تتكشف ضمن الأراضي السورية، كما بينت أن كمية وأعماق توضع تلك المياه ونوعيتها تعتمد على طبيعة الصخور الحاملة للماء وخواصها الفيزيائية وتوزعها الجغرافي وانتشارها المكاني، ويمكن حصر الطبقات المائية في سورية بالمجموعات الثلاث الرئيسة التالية:

- مجموعة الصخور الكاربوناتية المشققة والكارستية، وتتألف بشكل أساسي من صخور كلسية ودولوميتية وتكون ذات مسامية ونفاذية عاليتين وتحتوي على مياه ذات ملوحة منخفضة بشكل عام تراوح بين 250 - 500 ملغ/ل، وتتميز هذه الطبقات المائية بإنتاجية عالية وتغذي مئات الينابيع ذات التصاريف الكبيرة (الفيجة، السن، عين العروس، وغيرها)، وتنتشر بشكل رئيس في مناطق الساحل السوري وسهول حلب وحماه وحمص والجزيرة العليا والسلسلة التدمرية وتكون على أعماق كبيرة نسبياً يبلغ متوسطها 200-250 م.

- مجموعة الصخور الحطامية وتشكل أوساطاً مسامية في الصخور الرملية والغضارية والحصى مختلفة الحجوم والكونغلوميرا المنتشرة في السهول اللحقية (غوطة دمشق، الجزيرة..)، والأحواض والسهول بين الجبلية (جيرود، الدو...) ومصاطب أسرة الأنهار والوديان (الفرات، الخابور، الصواب...). تكون صخور هذه المجموعة أقل إنتاجية من سابقتها، وتحتوي على مياه تراوح مناسيبها بين 10 و 80 م، وتكون مياهها ذات نوعية جيدة عموماً.

- مجموعة الصخور البركانية، وتنتشر في الجزء الجنوبي الغربي من سورية بشكل واسع، بالإضافة إلى انتشار محدود في مناطق حمص والجزيرة، تتألف هذه الصخور من البازلت الذي يحتوي على المياه في النطاقات المشققة ضمنه، أو في العدسات الرملية الموجودة بين الصبات البازلتية المختلفة، وتتميز الطبقات المائية البازلتية بجودة نوعية مياهها (150-300 ملغ/ل) وبتفاوت تصاريف الآبار المحفورة فيها (5-15 ل/ثا) تبعاً لدرجة تشققها، وكذلك باختلاف أعماق النطاقات الحاملة للماء فيها (من 20-300م).

من جهة ثانية تجدر الإشارة إلى وجود طبقات مائية أخرى في سورية ولكنها ذات أهمية ثانوية نذكر منها:

- الطبقات المائية في الصخور الجصية المشققة التي تنتشر في الجزيرة السفلى وتتميز بإنتاجية عالية ولكن مياهها ذات نوعية سيئة وملوحة عالية تصل أحياناً إلى 26 غ/ل.
- الطبقات المائية في الصخور المارلية والصخور الكلسية الغضارية والصخور المارلية الحوارية وتنتشر في بعض أجزاء البادية وتتميز بنفاذية

منخفضة وبالتالي بتصاريف ضعيفة.

- الطبقات المائية في الصخور الكاربوناتية- الصوانية وتنتشر في مناطق الصوانة والقريتين والباردة وأرك وتتميز بإنتاجية عالية، ولكن مياهها تكون ذات ملوحة مرتفعة نسبياً (400-1100 ملغ/ل) وتحتوي أحياناً على شوائب بيتومينية.
- الطبقات المائية في صخور المعقد الافيوليتي في منطقة البسيط التي تتميز بمياه ذات نوعية جيدة ولكن بانتشار محدود وبتصاريف ضعيفة.

وقد بينت أحدث الدراسات الصادرة عن وزارة الري في سورية [13] أن حجم الموارد المائية الجوفية المتجددة في سورية يبلغ 7 مليار م^3/سنة علماً بأن الينابيع تحسب هنا على المياه الجوفية المتجددة.

في المحصلة نستطيع القول أن حالة المعرفة الحالية للموارد المائية في سورية (حسب معطيات وزارة الري) تسمح بتقويم مجمل هذه الموارد على الشكل التالي:

- 10.5 مليار م^3/سنة من المياه السطحية والجوفية المتجددة
- 6.627 مليار م^3/سنة الحد الأدنى لحصة سورية من مياه نهر الفرات

17.127 **مليار** م^3/سنة.

وإذا أضفنا لتلك الموارد تقديرات حصة القطر العادلة والمعقولة من نهري دجلة (5 مليار م^3/سنة*) والفرات (8.83 مليار م^3/سنة*) لارتفعت موارد القطر المائية إلى 24.33 مليار م^3/سنة.

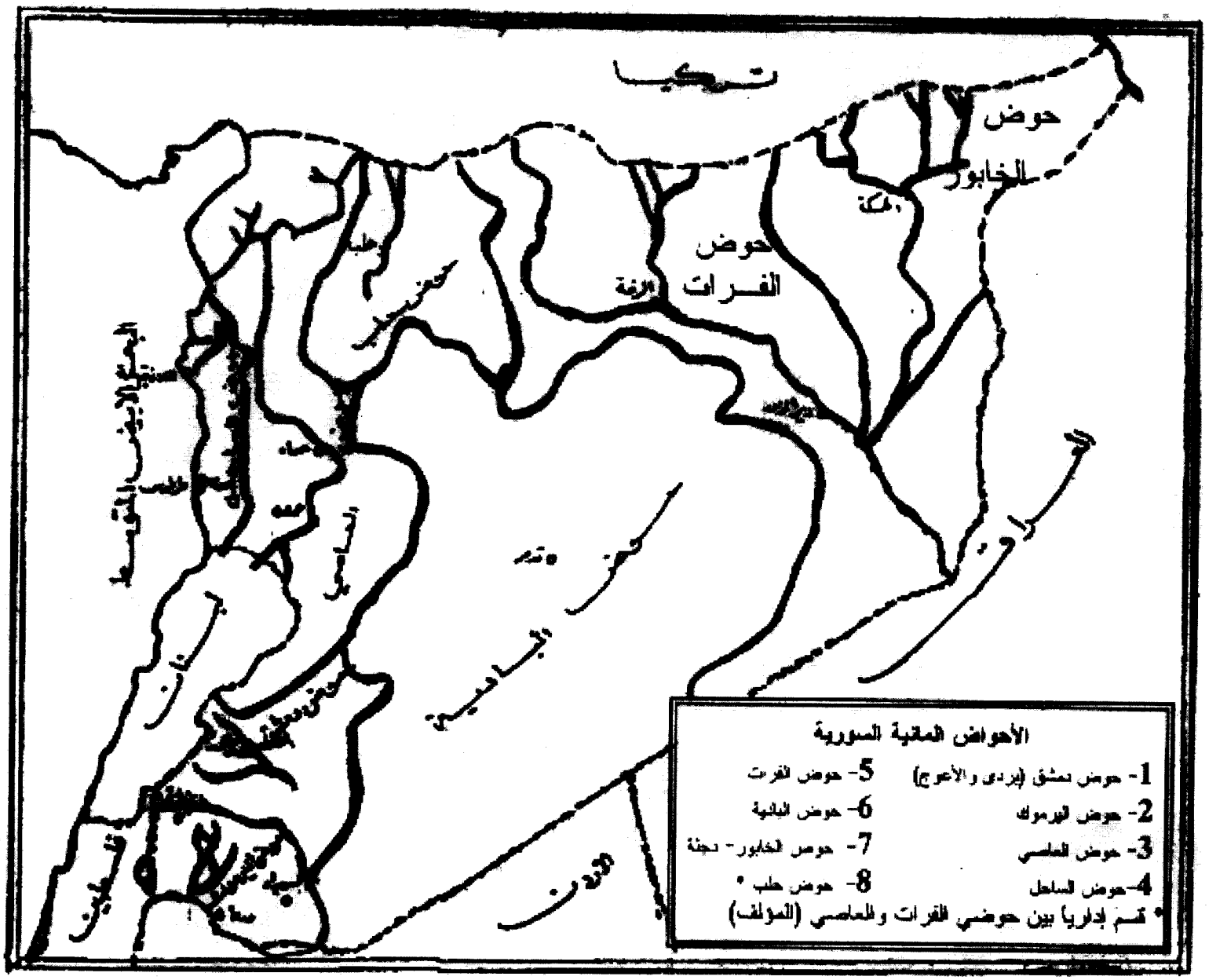
إضافة إلى ما سبق هناك وجهات نظر أخرى لخبراء مائيين كثر في تقدير حجم الموارد المائية في سورية بأكثر أو أقل من التقديرات الرسمية لوزارة الري، فإذا أخذنا أكثر التقديرات تفاؤلاً [4,1] لحصلنا على مايلي:

المياه السطحية (ماعدا مياه نهري دجلة والفرات)	4.356 مليار م^3/سنة
المياه الجوفية	7.938 مليار م^3/سنة
الحد الأدنى لحصة سورية من مياه نهر الفرات	6.627 مليار م^3/سنة
	18.921 مليار م^3/سنة

فإذا أضيف لهذه الكمية تقديرات حصة القطر العادلة والمعقولة التي أشرنا إليها أعلاه لحصلنا على السقف المتوقع للموارد المائية في سورية وقدره 26.124 مليارم^3

إذن يراوح حجم الموارد المائية في سورية بين حد أدنى متاح حالياً يقدر وسطياً بـ17 مليار م^3/سنة وحد أعلى متوقع يقدر وسطياً بـ26 مليار م^3/سنة. وتتوزع هذه الموارد على سبعة أحواض رئيسة هي دمشق (ويسمى رسمياً بردى والأعوج) واليرموك والعاصي والساحل والفرات والبادية ودجلة-الخابور (شكل رقم 1).

* تقديرات شخصية لخبير المياه الدولية المهندس ماجد داوود، منشورة عام 1998، ولا تعبر هذه التقديرات عن رأي أية جهة رسمية.



شكل رقم (١) الأحواض المائية في سورية (مأخوذة عن وزارة الري في سورية)

2-4 استخدامات المياه

تستخدم الموارد المائية المتاحة في سورية في كافة قطاعات الأنشطة الاجتماعية والاقتصادية السكنية والخدمية والصناعية والزراعية وبمعدلات تتفاوت تبعاً لنوع القطاع. وتشير التقديرات المتوفرة لدى وزارة الري السورية إلى أن حجم الموارد المائية المستثمرة في الاستعمالات الأهلية والصناعية والزراعية وفواقد التبخر في عام 1995 كان 12,176 مليار م^3/سنة وفي تقديرات أخرى كان 12.750 مليار م^3/سنة [1] و 13 مليار م^3/سنة [11]، وفي عام 1996 بلغ حجم تلك الموارد حوالي 14 مليار م^3/سنة [4]، وفي كل الأحوال استأثر القطاع الزراعي بـ91-92٪ من تلك الموارد لري ما يزيد عن 1.255 مليون هكتار من الأراضي الزراعية في عام 1997 .[2]

من مقارنة حجم الموارد المائية المتاحة (حتى في الحد الأدنى) وحجم المياه المستهلكة في سورية يظهر للوهلة الأولى أنه لازال هناك فائضاً من المياه على مستوى القطر وبالتالي يعطي انطباعاً خاطئاً بأنه ليس هناك عجز مائي، ولكن الواقع غير ذلك إذ يشير إلى وجود هبوط في مناسيب المياه الجوفية وانخفاض تصاريف بعض الينابيع والآبار وجفاف بعضها الآخر في أكثر من حوض كما في حوضي دمشق والعاصي على سبيل المثال. وإن سبب ذلك هو عدم تناسب حجوم الاستخدامات المائية القائمة مع حجوم الموارد المائية المتجددة على مستوى الأحواض، وبالتالي لا يعني وجود فائض أنه قابل للاستخدام في الزمان والمكان المرغوبين، كما أن بعض هذا الفائض قد يكون نظرياً نظراً لصعوبة استثماره هندسياً واقتصادياً. وفعلاً نجد أن معظم حجوم المياه الفائضة يتركز في حوضي الفرات والساحل بينما نجد أن باقي الأحواض إما تعاني من عجز (حوضي دمشق والعاصي) أو هي متوازنة وعلى حافة الوقوع في العجز (أحواض اليرموك والبادية والخابور-دجلة).

من جهة أخرى تشير مختلف السيناريوهات التي وضعت لتطور الطلب على الماء في سورية في ضوء معدل النمو السنوي للسكان (والذي يصل وسطياً إلى 3.7 ٪) وفي ضوء التطور الاقتصادي والاجتماعي لهؤلاء السكان، إلى أن القطر سيستهلك كمية من المياه تعادل تقريباً كافة الموارد المائية المتاحة له حالياً بالحد الأدنى في حلول عام 2000 عندما سيصل عدد سكان سورية إلى 17.5 - 17.8 مليون نسمة، فحسب رسول آغا (1991) ستبلغ هذه الكمية 18 مليار م^3/سنة، وحسب قضماني (1995) ستبلغ 17 مليار م^3/سنة، وحسب أشلق (1998) ستبلغ 14.6 مليار م^3/سنة وحسب ملكاني (1999) ستبلغ 20.4 مليار م^3/سنة. وبرأينا أن ساعة هذا الاستحقاق هي على الأغلب في عام 2005 وليس في عام 2000 نظراً للتوسع الحاصل في عمليات إعادة استعمال مياه الصرفين الصحي والزراعي في الري وعمليات ترشيد استعمالات المياه في الزراعة، كما أنها ستتأجل إلى أبعد من ذلك أيضاً في حال حصول سورية على حقوقها المائية العادلة والمعقولة في نهري الفرات ودجلة، والتوسع في استخدام مياه الصرفين الصحي والزراعي في عمليات الري.

ومع ذلك وفي كل الأحوال فإن العجز المائي الذي ظهر حتى الآن في أكثر من حوض سيستمر ويتفاقم مستقبلاً في ظل الخلل الحاصل من جراء التوزيع الإقليمي غير المتوازن مابين موارد المياه المتاحة وحجوم الاستهلاكات المترتبة عليها على مستوى القطر، على الرغم من وجود فوائض في حوضي الفرات والساحل بشكل رئيس. وحتى لو أمكن التغلب على هذه المشكلة في السنوات القليلة المقبلة فإن تطور المجتمع السوري وتنامي احتياجاته المائية سيفرض استهلاك سورية لمواردها المائية حتى في سقفها الأعلى المتوقع (26 مليار م^3/سنة) خلال العقدين القادمين*، الأمر الذي يتطلب منذ الآن ودون إبطاء التفكير بخيارات استراتيجية لإيجاد مصادر مائية جديدة تضمن استمرارية إمدادات المياه بالشكل المطلوب.

3- إدارة الموارد المائية

تعد الإدارة السليمة للموارد المائية الحل الأمثل إن لم نقل الوحيد لمواجهة العجز المائي. وتعرف هذه الإدارة عادةً بأنها عملية متشابكة تشتمل على كافة المراحل المتكاملة لأعمال التخطيط والتنفيذ والتشغيل والصيانة لتلك الموارد، آخذة بعين الاعتبار كافة المعوقات والعوامل المؤثرة والفاعلة في ذلك وساعية لتقليل المنعكسات السلبية على البيئة، ولزيادة العوائد الاقتصادية على المجتمع، ولإحداث التوازن بين الموارد المتاحة والطلب عليها، وتتصف هذه الإدارة بالسمات الثلاث التالية:

- الاستمرارية، حيث ان معظم العوامل المؤثرة والفاعلة في إدارة المياه هي متغيرات تابعة للزمن، تقتضي تقويم وتحديث وتطوير الإدارة بشكل دائم لتتناسب مع تطور تلك المتغيرات.

- تعددية المستويات فهناك إدارة موارد مائية على مستوى وحدات سياسية (دولة - محافظة- ناحية..) أو مستوى جغرافي (سهل - وادي - جبل،...) أو مستوى قطاعي (زراعة- صناعة ..) أو مستوى وحدات هيدرولوجية (حوض نهري- طبقة مائية...) لهذا يجب أن يكون واضحاً المستوى الذي تدار الموارد المائية لأجله.

- تنوع التخصصات، إذ لا يمكن تحقيق إدارة سليمة للموارد المائية إلا من خلال فريق مؤهل وكفؤ ومتكامل ومتعدد الاختصاصات وعلى علم وإطلاع بكافة فعاليات الدولة والمجتمع المتعلقة والمتأثرة بالموارد المائية.

وغالباً ما تتم إدارة الموارد المائية وفق ثلاثة محاور أساسية هي:

المحور الأول: تنمية الموارد المائية بكافة مكوناتها التقليدية وغير التقليدية.

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* حسب معطيات وزارة الري [13] ستبلغ الاستعمالات المائية لمختلف الأغراض في عام 2005 (24,831 مليار م^3) وفي عام 2010 (29,513 مليار م^3).

المحور الثاني: ترشيد استخدامات المياه في مختلف القطاعات المستعملة للمياه.

المحور الثالث: حماية الموارد المائية السطحية والجوفية من التلوث ومن تدهور نوعيتها.

علماً بأن هناك تأثيرات متبادلة وأنشطة مشتركة بين المحاور الثلاثة، وهذا أمر طبيعي نظراً لأنها في المحصلة تسعى لتحقيق الهدف نفسه والمتمثل في مواجهة العجز المائي. من جهة أخرى يتضمن كل محور من المحاور الثلاثة المذكورة خيارات استراتيجية تنسجم مع حالة المعرفة الراهنة للموارد المائية، ومع الاحتياجات المائية المستقبلية والإمكانيات الاقتصادية المتوفرة لتحقيق الخيار المطلوب، ونحن هنا سنركز اهتمامنا على المحور الأول فقط نظراً لعلاقته المباشرة بموضوع هذه الورقة مع التأكيد على الأهمية البالغة للمحورين الثاني والثالث في مواجهة العجز المائي. فترشيد استخدامات المياه، خاصة في قطاع الزراعة، وهو المستهلك الأكبر للموارد المائية، سيؤدي إلى رفع كفاءة استخدامات المياه والحد من الهدر (وهو سبب رئيس من أسباب العجز المائي)، وبالتالي إلى توفير كميات ضخمة من المياه، ولكن يجب الانتباه هنا إلى أن برامج ترشيد استخدامات المياه لن تؤتِ أكلها إلا إذا كانت عامة على مستوى الدولة وصبورة ويشارك فيها كافة المستهلكين على مختلف مستوياتهم وفئاتهم ومصالحهم دون استثناء وكل في قطاعه، ولا يخفى علينا مدى صعوبة تحقيق ذلك وتكاليفه الباهظة.

حماية الموارد المائية فهي إجراءات وقائية تمنع في النهاية من تدهور نوعية المياه (وهي سبب هام آخر من أسباب العجز المائي) وخروج كميات من المياه من رصيد الموارد المائية الصالحة للاستعمال.

أما ما يتعلق بمعالجة باقي أسباب العجز المائي كتنامي الطلب على الماء، والتوسع الزراعي لتحقيق الأمن الغذائي، والتوزع الإقليمي غير المتوازن بين مصادر المياه والاستثمارات المائية، وموضوع المياه المشتركة وغيرها فهي أمور تتعلق بالسياسات السكانية والزراعية والتخطيط الاقليمي والاعتبارات الخارجية للدولة، وكلها تخرج عن الموضوع الأساسي لهذه الورقة رغم علاقاتها الوثيقة دون أدنى شك ببرامج إدارة الموارد المائية.

إذا عدنا لاستعراض الخيارات الممكنة تكنولوجياً في تنمية الموارد المائية العذبة، انطلاقاً من تعريف تنمية الموارد المائية بأنها زيادة حجم الموارد المائية الصالحة والمتاحة للاستثمار، لوجدنا مايلي : [7]

آ - **خيار تنمية المياه السطحية**، ويأخذ هذا الخيار ثلاثة مناحي هي:

- منحى بناء السدود الكبرى والمتوسطة وأقنية وشبكات الري على الأنهار الدائمة
- منحى بناء السدود الصغيرة على الأنهار المؤقتة والوديان الموسمية
- منحى بناء إنشاءات حصاد مياه الأمطار بمقاييس محلية صغيرة.

وقد اعتمدت سورية هذه الخيارات الثلاثة بما يتناسب والظروف الهيدرولوجية السائدة في الأحواض المائية السبعة، نظراً لأن سورية اعتمدت مستوى الحوض المائي كوحدة متكاملة لإدارة موارده المائية. وقد أنشأت، كما أشرنا سابقاً، حتى الآن 155 سداً من مختلف الأحجام وفي الأحواض كافة، وكذلك العديد من إنشاءات حصاد مياه الأمطار خاصة في حوضي البادية والعاصي.

ب - **خيار تنمية المياه الجوفية**، ويأخذ هذا الخيار منحيين اثنين هما:

- منحى استثمار المياه الجوفية الضحلة الموجودة في الطبقات المائية القريبة من سطح الأرض وذات التكاليف الاقتصادية المقبولة نسبياً.

وقد سيطر هذا المنحى على تنمية المياه الجوفية في سورية واستخدم على أوسع نطاق في الأحواض السبعة دون استثناء، ولم يخل من العشوائية في الكثير من الأحيان، وهو الذي يقف وراء مشاكل التدهور الكمي والنوعي للمياه الجوفية.

- منحى استثمار المياه الجوفية العميقة الموجودة في الطبقات العميقة ذات الامتداد الاقليمي.

وهنا تجدر الإشارة إلى أن مفهوم الطبقات العميقة مفهوم نسبي وسنعالجه لاحقاً، هذا ويلاقي استثمار المياه الجوفية العميقة حذراً لسببين هما: الكلفة العالية للاستثمار والطبيعة المنجمية لهذا الاستثمار، لأن الطبقات المائية العميقة تكون إما غير متجددة أو أنها ضعيفة التغذية الحديثة للغاية. وقد أفرز السبب الثاني جدلاً حاداً وواسعاً يدور حول صحة هذا الخيار، فرأي يقول أن هذا الاستثمار هو تعد على حقوق أجيال المستقبل، والرأي الآخر يرى أنه لايمكن تأجيل استثمار المياه غير المتجددة (أو ضعيفة التغذية الحديثة) إلى ما لا نهاية بحجة المستقبل وأن التطور العلمي والتكنولوجي قادر على تلبية حاجات المستقبل.

وفي سورية لم يعتمد هذا المنحى كخيار استراتيجي على نطاق واسع وإن تم اللجوء إليه لحل مشاكل إمدادات المياه في مناطق متفرقة من القطر من قبل القطاعين الخاص والعام ولتلبية احتياجات مياه الشرب والري.

ج - **خيار تنمية الموارد المائية غير التقليدية**، ويضم أربعة مناحٍ هي:

- منحى إعذاب المياه المالحة البحرية منها والجوفية، وهو خيار ذو تكاليف اقتصادية عالية وليس لهذا المنحى دور فعلي في تنمية الموارد المائية في سورية ماعدا بعض الاستخدامات المحلية المحدودة.
- منحى معالجة مياه الصرف الصحي ذو الأهمية الثلاثية، فهو يساعد على حماية البيئة وعلى الحد من تدهور نوعية المياه السطحية والجوفية وعلى تنمية الموارد المائية الصالحة لمختلف الاستخدامات وخاصة الزراعية منها، إلا أنه مكلف اقتصادياً خاصة وأنه مرتبط بإنشاء شبكات نظامية للصرف الصحي.

هذا وقد اعتمدت سورية هذا الخيار وبدأت بإنشاء العديد من محطات المعالجة لإنتاج مياه ستستخدم في الري وقد وضع بعضها موضع التشغيل فعلياً.

- منحى معالجة مياه الصرف الزراعي، ولازال دوره في تنمية الموارد المائية في سورية محدوداً علماً بأنه يتوقع أن يصل حجم المياه المعاد استعمالها من مياه الصرف الزراعي إلى 1.5 مليار م3/سنة في عام 2000.
- منحى الاستمطار أو زراعة الغيوم، وقد نفذ في سورية مشروع للاستمطار أعطى في السنوات السابقة نتائج واعدة ومشجعة جعلته أحد الخيارات المطروحة مستقبلاً.

د - **خيار نقل المياه**، ويقصد بهذا الخيار عمليات نقل المياه العذبة بين الأحواض أو بين الدول وليس المقصود به أقنية وشبكات الري الملحقة بالسدود أو شبكات النقل والتوزيع العادية بين الينابيع أو حقول آبار مياه الشرب أو الأنهار أو السدود إلى مواقع الاستهلاك القريبة منها في الحوض نفسه، ولم تعرف سورية هذا الخيار إلا عندما تم نقل المياه من نهر الفرات لتأمين مياه الشرب الى مدينة حلب علماً بأن هناك العديد من عمليات نقل مياه ينابيع وحقول آبار وسدود لتأمين مياه الشرب للعديد من المدن السورية كدمشق واللاذقية والسويداء على سبيل المثال. ويتصف هذا الخيار بتكاليفه الاقتصادية العالية من جهة، وبإثارته لمشكلات الحقوق المائية المكتسبة على مصادر المياه المنقولة حتى ضمن الحوض الواحد أحياناً.

في المحصلة، إذا تمعنا بالخيارات السابقة لوجدنا أن بعضها يصلح لكافة الأحواض وبعضها الآخر يصلح لأحواض ولا يصلح لأحواض أخرى وذلك بسبب اختلاف الظروف الطبيعية للحوض ولطبيعة الاستثمارات القائمة فيه. هذا وسنناقش لاحقاً خيار استثمار المياه الجوفية العميقة في سورية كأحد الخيارات الاستراتيجية لمعالجة العجز المائي في بعض الأحواض.

4- المياه الجوفية العميقة

4-1 تمهيد

مع تزايد الاحتياجات المائية وانخفاض تصاريف الطبقات المائية الضحلة تزايد الاهتمام بالطبقات المائية الأعمق في كافة أقطار العالم التي تعاني من شحة في مواردها المائية، لهذا كثفت الدراسات والبحوث العلمية حول ما اصطلح على تسميته بالطبقات المائية العميقة Aquifers Deep لمحاولة استثمار مياهها بشكل مباشر في الاستعمالات الأهلية (إذا كانت عذبة)، وفي الاستعمالات الزراعية والصناعية بشكل مباشر أوبخلطها مع مياه عذبة (إذا كانت ضاربة للملوحة Brackishwater) أو بشكل غير مباشر عن طريق إعذابها (إذا كانت ضاربة للملوحة أو مالحة). إضافة إلى ذلك تكتسب هذه المياه حرارة عالية بفعل الأعماق التي توجد عندها مما يفسح المجال لاستعمالها كمصدر للطاقة الحرارية. ونظرياً إذا لم تكن الطبقات المائية العميقة صالحة لكل هذه الاستعمالات التي ذكرناها وكانت في الوقت نفسه راكدة هيدروليكيا Stagnant فمن الممكن أن تستخدم في خزن النفايات السائلة السامة والمشعة.

وقد جذبت هذه الآفاق الواسعة لاستعمالات مياه الطبقات العميقة اهتمام الدارسين والباحثين الذين تبين لهم أن هذه الطبقات تتميز بشحة البيانات Scarce Data المتوفرة حولها نظراً للأعماق الكبيرة التي توجد عندها، وعليه فإن معظم هذه البيانات والمعلومات تأتي من الحفر والاختبارات النفطية ومن الأعمال الاستكشافية الجيولوجية والجيوفيزيائية الإقليمية الموجهة بمعظمها لأغراض غير مائية.

ما حصل في سورية لم يكن مختلفاً عما حصل ويحصل في العديد من الدول التي تعيش الظروف الطبيعية والاقتصادية والاجتماعية نفسها التي تعيشها سورية. إذ تم التركيز هنا على الطبقات المائية العليا الضحلة التي اصطلح الخبراء السوفييت على تسميتها التشكيلة الأولى الحاملة للماء اعتباراً من سطح الأرض Schematic Map of The First Below the Surface Water Bearing Formation of Syria ووضعوا لها خارطة بمقياس 1/1,000,000 منذ عام 1961 [24] ، ثم تكثفت الدراسات حولها بمقاييس مختلفة وصلت إلى 1/50 000 في بعض المناطق، والجدير بالذكر أن هذه التشكيلة تضم وحسب المنطقة مستويات وطبقات، وفي بعض الأحيان معقدات مائية مختلفة المواصفات الجيولوجية واالبتروفيزيائية والهيدروجيولوجية (وخاصة فيما يتعلق منها بالانتاجية ونوعية المياه)، وقد استثمرت هذه الحوامل المائية على مستوى القطر بعشرات آلاف الآبار وعلى أعماق مختلفة راوحت من بضعة أمتار إلى 200-300 م تحت سطح الأرض.

والجدير بالذكر أن هذه الحوامل تعود إلى الرباعي والنيوجين بشكل رئيس وإلى الباليوجين بشكل أقل، علماً بأن الحوامل الكريتاسية اخترقت في بعض المناطق المحدودة، حيث كانت تمثل الطبقة المائية الأولى اعتباراً من سطح الأرض في تلك المناطق (السلسلتين الساحلية والتدمرية ونهوض الرطبة).

4-2 مفاهيم عامة

من الأمور الشائعة لدى العامة تعميق البئر كلما انخفض منسوبه وإنتاجيته دون أن يكون لهؤلاء أي تصور جيولوجي أو هيدروجيولوجي مسبق عن الطبقة المائية المستثمرة، وتتكرر الحالة كلما نضب مستوى حامل للماء واستعيض عنه بالأعمق منه، وهنا يبرز السؤال أي من هذه المستويات هو الحامل لمياه عميقة أم أن الأمر نسبي، فالمستوى الذي كان يعتبر اليوم أنه يحمل مياهاً عميقة سيفقد هذه الصفة عند اكتشاف مستوٍ أعمق

منه، وإذا استعرضنا مفاهيم المياه العميقة استناداً إلى معيار عمق ظهورها لوجدناها مختلفة ونسبية وتتعلق بالظروف والعوامل الجيولوجية والهيدروجيولوجية السائدة وبدرجة معرفتها. فعلى سبيل المثال اعتبر الكثيرون في سورية (وخاصة صفدي وبردن) أن الآبار التي تخترق الطبقة المائية الأولى، والتي يطلق عليها تجاوزاً الطبقة السطحية كناية عن قربها من سطح الأرض، هي آبار وصلت إلى المياه العميقة علماً أن هذه الأعماق لم تتجاوز الـ300 م في حينه. وفي الأردن اعتبر حجر رمل الكرنوب الحامل للمياه على عمق 12000 م في منطقة الأزرق من الطبقات المائية العميقة، [21]. وفي فلسطين يطلق على الطبقات المائية في صخور الجوراسي والباليوزويك الكاربوناتية والرملية التي توجد على أعماق 1000- 5000م في صحراء النقب طبقات مائية عميقة. أما في دولة الإمارات العربية المتحدة فإن الآبار التي تجاوزت الـ100 م فقط لتخترق الطبقات المائية الكربوناتية الموجودة تحت الطبقة المائية الحطامية في سهل الحصى اعتبرت آباراً عميقة) [17]. وفي المملكة العربية السعودية، التي لها باع طويل في استثمار المياه الجوفية العميقة، فقد اعتبرت آباراً عميقة تلك التي اخترقت مياه تكاوين الساق على عمق 2400 م وتبوك على عمق 1500 م والمنجور على عمق 3000م[10]. كذلك في تونس فقد وصفت بالعميقة مياه طبقة القاري الأوسط Continental Intercalaire التي استثمرت من أعماق تراوح بين 1500 و 2200 م [2]. وهناك أمثلة كثيرة أخرى من كافة أرجاء الوطن العربي والعالم والتي تشير إلى نسبية المفهوم الرقمي للمياه العميقة وعدم كفايته لتعريفها. وفعلاً ولتطوير هذا المفهوم، لجأ العديد من الباحثين إلى إدخال معايير جيولوجية وبنيوية وبتروفيزيائية لتعريف المياه العميقة حيث اعتبرت طبقات مائية عميقة تلك التي تنتسب إلى أحواض رسوبية كبيرة وذات امتداد إقليمي [23].

حول سورية نشر كل من غوتمان وشاتسكي وموصللي وولفرت [38,37,28,19] آراءاً متقاربة حول وجود جريانات مائية عميقة إقليمية تخترق سورية من شمالها إلى جنوبها عبر الفوالق الإقليمية ونطاقات التهشم التكتوني والبنيات الجيولوجية المنتشرة على طول الانهدام السوري وفي البادية السورية بشكل رئيس. كذلك اعتبر خوري أن الطبقات المائية العميقة في السهوب السورية والمناطق الجافة المحيطة بها في كل من العراق والأردن والسعودية هي تلك الطبقات التي تعود إلى الميزوزويك والباليوزويك وتتصف بانتشارها الإقليمي وتوجد على أعماق كبيرة تصل إلى حوالي 1000م [21]. من جهة أخرى اكتفى كل من دوبرتريه [16] والباحثون السوفييت [30] باعتبار أن صخور السينومانيان والتورونيان الكربوناتية المشققة في سورية تحتوي على مياه عميقة، وتوجد هذه المياه على أعماق 300-400 م وخاصة في مناطق البادية السورية، ولم يتطرق الباحثون بشكل مباشر إلى أية بنيات جيولوجية وامتدادات إقليمية لتلك المياه.

ثمة معيار آخر بدأ يؤخذ بعين الاعتبار في السنوات الأخيرة لتعريف المياه العميقة وهو تجددها أم عدمه، لأنه تبين أن الفصل بين المياه الجوفية المتجددة وغير المتجددة (بغض النظر عن كونها عميقة أم ضحلة) أمر ضروري لتخطيط استثمارها بشكل يضمن استمرارية التنمية. وعليه يقصد بالمياه غير المتجددة تلك التي ليس لها تغذية حديثة وبالتالي لاتكون على اتصال مع الدورة الهيدرولوجية المعاصرة التي يعيشها الإنسان منذ انتهاء الفترة المطيرة الأخيرة للبليستوسين (منذ حوالي 5000 سنة) وهي أكثر فترة رطبة شهدتها المنطقة (إسار وآخرون 1972, غاي 1982)، أي أن المياه غير المتجددة على عكس المياه المتجددة التي تتلقى تغذية مباشرة من الدورة الهيدرولوجية الحالية.

وفي رأي آخر يقصد بالمياه غير المتجددة تلك المياه التي تكون على أعماق كبيرة وتوجد في الأحواض الرسوبية الكبرى عادة وتشكل احتياطات مستحاثة Fossil Reserves ومخزون ضخم تشكل خلال عصور مطيرة سابقة امتدت إلى ما قبل عصر البليستوسين بحوالي مليون سنة وأكثر [23]. ويضيف أصحاب هذا الرأي بأنه من الصعب تصور وجود لأية مياه جوفية بشكل مستقل ومعزول بشكل تام عن الدورة الهيدرولوجية، وأن هذه المياه تتحرك ضمن مستويات متعددة وبسرع مختلفة وتقطع مسافات متفاوتة بحدود كبيرة للغاية وبأزمان قد تصل إلى آلاف السنين، وأن وصفها بالمياه المستحاثة يعني أنها وجدت في الطبقة لآلاف السنين ولكنه لايعني أبداً أنها راكدة لا تتحرك أو لا تتلقى أية تغذية مائية جديدة، ففي مثل هذه الطبقات العميقة والواسعة الانتشار فإن التجدد يكون وبكل بساطة بطيء للغاية، كما أن كميته ضئيلة نسبة إلى كمية المياه الضخمة المخزونة في هذه الطبقات. لهذا يقصد أصحاب هذا الرأي بالمياه غير المتجددة تلك التي تتلقى تغذية حديثة وضئيلة إذا ما قورنت بمخزونها الضخم الذي تشكل على مر العصور. وانطلاقاً من هذا المفهوم قد يكون من الصعب الفصل بين المياه المتجددة والمياه غير المتجددة بشكل قاطع. وفعلاً يؤكد غاي [18] أنه لاحظ في بعض الأحواض عدسات من المياه العذبة المتجددة التي تطفو فوق مياه مالحة قديمة وغير متجددة مما جعل من الصعب الفصل بينهما بدقة.

من جهة أخرى يربط بعض الباحثين تعريف المياه غير المتجددة بنمط الاستثمار المقرر لهذه المياه، فحسب مرصد الصحراء والساحل SSO تعرف الموارد المائية غير المتجددة في الطبقات المائية العميقة بأنها احتياطيات المياه الجوفية الطبيعية التي يمكن استثمارها دون أي اعتبار لضرورة الحفاظ على توازنها الديناميكي على المدى البعيد متبعين بذلك استراتيجية الاستثمار المنجمي Mining لهذه المياه [27].

في المحصلة نستطيع التأكيد على تعدد المفاهيم والآراء، المتوافقة أحياناً والمتعارضة أحياناً أخرى، حول تعريف المياه الجوفية العميقة. ويمكن أن نجمل المعايير التي اعتمد كل تعريف على بعض منها بمايلي:

- عمق الطبقة (أو منظومة الطبقات) الحاملة للماء
- الشروط الجيولوجية والبنيوية السائدة مع التأكيد على شروط توضع الطبقة الحاملة وأبعادها وامتدادها
- الخواص الفيزيائية لصخور الطبقة المائية
- النظام الهيدروديناميكي
- تجدد المياه
- مخزون الطبقة المائية واستراتيجية استثمارها

وبرأينا ان هذه المعايير بمجملها صحيحة ولكنها تختلف بأوزانها كمحددات لتعريف المياه العميقة، ففي حين تلعب المعايير الجيولوجية والبنيوية والهيدروديناميكية دوراً رئيساً في تحديد المياه الجوفية العميقة يكون لباقي المعايير دوراً أقل وزناً.

4-3 المياه الجوفية العميقة في سورية

رأينا سابقاً كيف أن المعايير الجيولوجية والبنيوية تلعب دوراً رئيساً في تقويم المياه الجوفية العميقة لدى العديد من الباحثين، لهذا كان لابد من تحليل هذه الأوضاع في ضوء السؤال المطروح من منطلق انعكاساتها على وجود المياه الجوفية العميقة في سورية.

4-3-1 الأوضاع الجيولوجية الإقليمية

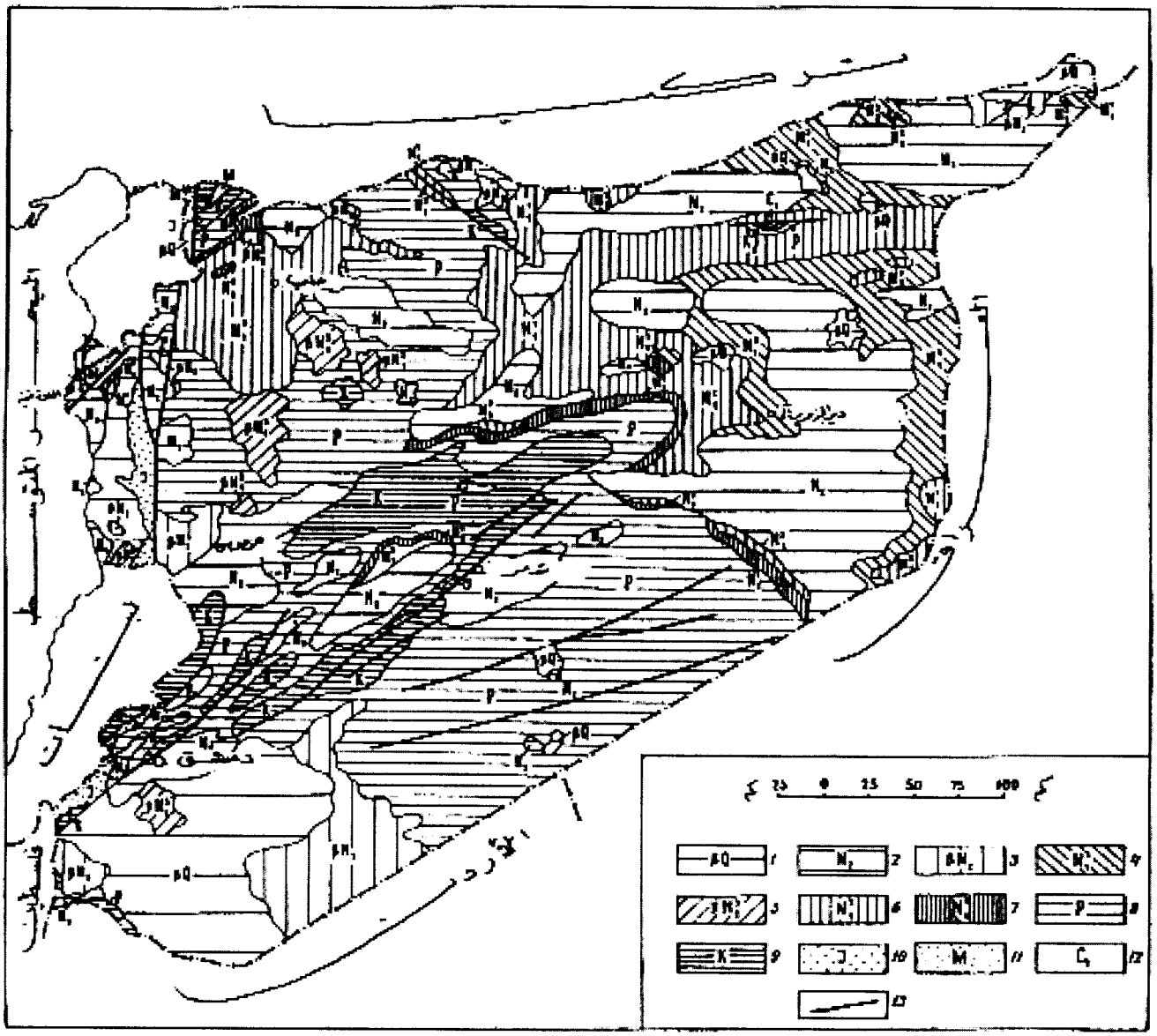
تحتل الأراضي السورية جزءاً كبيراً من المنحدر الشمالي للسطيحة Platform العربية والذي يميز به بين منطقتين، خارجية (شمالية) متحررة كة نسبياً وداخلية (جنوبية) مستقرة. وتعتبر الفوالق الجنوبية للسلسلة التدمرية الحد الفاصل بينهما. وتلعب التكسرات والانقطاعات مختلفة الأنماط والاتجاهات دوراً هاماً في البنية التكتونية للمنحدر الشمالي للسطيحة. وقد أشارت مطابقة المعطيات الجيوفيزيائية والجيولوجية للمنطقة إلى علاقة وثيقة بين تراكيب الغطاء الرسوبي وبلوكات الركيزة البللورية الموجودة على أعماق مختلفة. فقد بينت الدراسات الجيوفيزيائية السايزمية الإقليمية، أن هذه الركيزة متصدعة بشدة وذات تكتونية بلوكية بحيث تراوح أعماق البلوكات المختلفة بين 3 و 9 كم [32]. كما تبين أيضاً أن المخطط البنيوي للباليوزويك بملامحه العامة يوافق المخطط البنيوي للركيزة ويسايره بحيث أن أماكن ارتفاع بلوكات الركيزة تقابلها بنيات موجبة في معقد توضعات الباليوزوي وبالعكس. إضافة إلى ذلك أظهرت الدراسات الجيوفيزيائية أن الفوالق الضخمة تفصل بين بلوكات الركيزة وتأخذ الاتجاهات شمال-جنوب وشمال شرق - جنوب غرب، وبشكل أقل الاتجاه شرق-غرب. كما أفادت أعمال الحفر العميق عن النفط والغاز إلى وجود تشققات شديدة للغطاء الرسوبي مباشرة فوق البلوكات المزاحة [31].

أما المقطع الجيولوجي في سورية فيتشكل من قسمين متمايزين:

- الأسفل ويتألف من صخور متحولة ومتكسرة بشدة، تشكل القاعدة ذات التضاريس المتماوجة من عمر ماقبل الكامبري
- الأعلى ويتألف بشكل رئيس من الصخور الكاربوناتية للباليوزويك والميزوزويك والكاينوزويك، وتصل سماكته الإجمالية في بعض المواقع إلى 8-10 كم.

تتألف توضعات الباليوزويك من صخور رملية وغضارية إضافة إلى الصخور الكربوناتية، وقد وصلت أكبر سماكة لهذه الصخور إلى 4 كم اخترقت منطقة الصواب [14]. أما مجموعة صخور الميزوزويك الكاربوناتية فتصل سماكتها الإجمالية إلى 4-5 كم وتتكشف على امتداد مناطق شاسعة من القطر (الشكل رقم 2)، وتتميز بانتشار ظواهر التشقق والكارست بها على نطاق واسع. وتجدر الإشارة إلى تكشف صخور الافيوليت العائدة إلى الميزوزويك أيضاً في مواقع محدودة من منطقة البسيط. هذا وتغوص طبقات الميزوزويك عموماً باتجاه الشرق والجنوب الشرقي والجنوب تحت غطاء من الصخور العائدة إلى الكاينوزويك والذي تصل سماكته في بعض المناطق إلى 3 كم (منخفض الفرات). ويتألف هذا الغطاء من صخور متنوعة التركيب الليثولوجي ومنها الصخور البركانية التي تحتل مساحة واسعة من جنوب غرب البلاد وتصل سماكتها الأعظمية إلى 1200 م.

هذا وقد بينت الدراسات الحديثة للتطور التكتوني للأراضي السورية، التي تقع على الطرف الشمالي للصفيحة Plate العربية وإلى الجنوب من نطاق تصادم طوروس، ومارافق ذلك من تكون للبنيات الإقليمية المعروفة في المنطقة كالانهدام السوري في الغرب والسلسلة التدمرية في الوسط وجبال لبنان الشرقية والحرمون في الغرب، إن هذا التطور قد أدى إلى تشققات وتصدعات ذات اتجاهات مختلفة ساهمت إلى حد كبير مع نشاطات الأنظمة المائية القديمة في تطور بنيات تشققية-كارستية في الصخور الكاربوناتية للغطاء الرسوبي وهي ممتدة إقليمياً وتعد أماكن طبيعية مفترضة لتجمع وحركة المياه الجوفية.



شكل رقم (2) - الخارطة الجيولوجية السورية - مأخوذة عن الخارطة الجيولوجية السورية مقياس 1/مليون بونيكاروف عام 1964.

1- بازلت رباعي، 2- توضعات البليوسين، 3- بازلت البليوسين، 4- توضعات الميوسين الأعلى، 5- بازلت الميوسين الأعلى، 6- توضعات الميوسين الأوسط، 7- توضعات الميوسين الأدنى، 8- توضعات الباليوجين، 9- توضعات الكريتاسي، 10- توضعات الجوراسي، 11- أفيوليت من الميزوزيك، 12- توضعات الفحمي الأدنى، 13- فوالق

2-3-4 بيانات من الواقع Factual Data

تجمعت منذ بداية الثمانينات وحتى الآن بيانات ومعلومات تعتمد بشكل رئيس على نتائج الحفر العميق الموجه لأغراض الاستكشاف عن النفط والغاز وعن المياه ، كما تعتمد على نتائج الدراسات الهيدروجيولوجية والهيدروجيوفيزيائية ، وقد ألقت هذه المعطيات بمجملها الضوء على وجود المياه العميقة في سورية [5, 33].

ففي مجال النفط حفر في منطقة ديدي الواقعة في حوض البادية (شكل رقم 3) ، بئر اخترق على عمق 1505 م مستوى حامل لمياه ارتوازية ذات ملوحة 800 جزء/مليون ضمن الصخور الكاربوناتية المشققة والكارستية العائدة للكريتاسي الأعلى ، تورونيان سينومانيان وأعلى الالبيان (تشكيلة جودية). والملفت للنظر أن هذه المياه العذبة وجدت محصورة بين مستويين حاملين لمياه تصل ملوحتها إلى 150 غ/ل ، كما أنها تتمتع بضاغط مرتفع أدى إلى تدفقها على سطح الأرض من عمق 1,5 كم . إن هذه الحقائق تسمح بافتراض وجود منطقة تغذية اقليمية بعيدة لهذه المياه العذبة . والى الغرب من بئر ديدي وتحديداً في بئر السلمية النفطي الواقع إلى الشمال الغربي من السلسلة التدمرية ظهرت المياه العذبة في صخور الكريتاسي الأعلى الكربوناتية على أعماق 500 م ، كذلك اخترق بئر الشريفة النفطي الواقع إلى الجنوب من بئر السلمية ، وعلى أعماق 700-750 م من سطح الأرض كهوفاً كارستية ذات أبعاد كبيرة بلغت عدة أمتار تنتشر في صخور الميزوزويك الكاربوناتية مشيرة بذلك إلى الامكانيات الخزنية الكبيرة لهذه الصخور . وقد لوحظت نتائج مشابهة تقريباً في بئري الرصافة وبشري النفطيين الواقعين إلى الشمال من بئر ديدي حيث اكتشفت مياه جوفية على أعماق 1500 متر وفي صخور كاربوناتية مشققة وكارستية أيضاً تصل سماكتها إلى 500 متر، انما اختلف هنا ضاغط المياه ودرجة ملوحتها ، بفعل وجود مستويات انهدريتية . وتزداد الملوحة وتسوء نوعية هذه المياه أيضاً ، اذا اتجهنا باتجاه الشمال الشرقي أي باتجاه حوض الفرات ، حيث المكامن النفطية مع بقاء ظاهرة وجود المياه في صخور الكريتاسي الاعلى الكاربوناتية المشققة والكارستية (جدول رقم 1). أما في المناطق الجنوبية فقد ظهرت المياه في السينومانيان التورونيان في البئر النفطي شام -1- على أعماق 725 م ، وراوحت ملوحتها بين 1,5 و 2 غ/ل، كما ظهر في البئر نفسه وعلى عمق 1 كم مستو آخر يحمل مياه أقل ملوحة (1-1.5غ/ل) ، انما من صخور الجوراسي هذه المرة ، والى الشرق من هذا البئر حفر بئر نفطي في منطقة التنف أظهر وجود مستويات مائية عذبة مضغوطة وذات درجة حرارة تبلغ 20مْ على عمق 410 م في الصخور الكاربوناتية المشققة العائدة للجوراسي الأعلى أيضاً .

وتجدر الاشارة إلى ظاهرة تستحق الاهتمام فقد لوحظت في بئر فيديو-1 النفطي الواقع على الساحل السوري ، والذي اخترق الصخور الكاربوناتية المشققة - الكارستية الجوراسية تدرج حراري ضئيل يصل إلى 0,2/100 °، كما وصلت درجة الحرارة على أعماق 3400 م إلى 32 درجة مئوية فقط وهي قيمة منخفضة إلى حد كبير. وتشير هذه الظواهر الحرارية بوضوح إلى جولان مائي نشط على هذه الأعماق .

واذا دققنا بالشواهد المائية في بعض الآبار النفطية المدروسة لاحظنا مايلي :

- وجود المياه في صخور الكريتاسي الأعلى والجوراسي
- تمتع هذه المياه بضواغط عالية تصل إلى مئات الأمتار
- اختلاف نوعيات هذه المياه من مكان لآخر

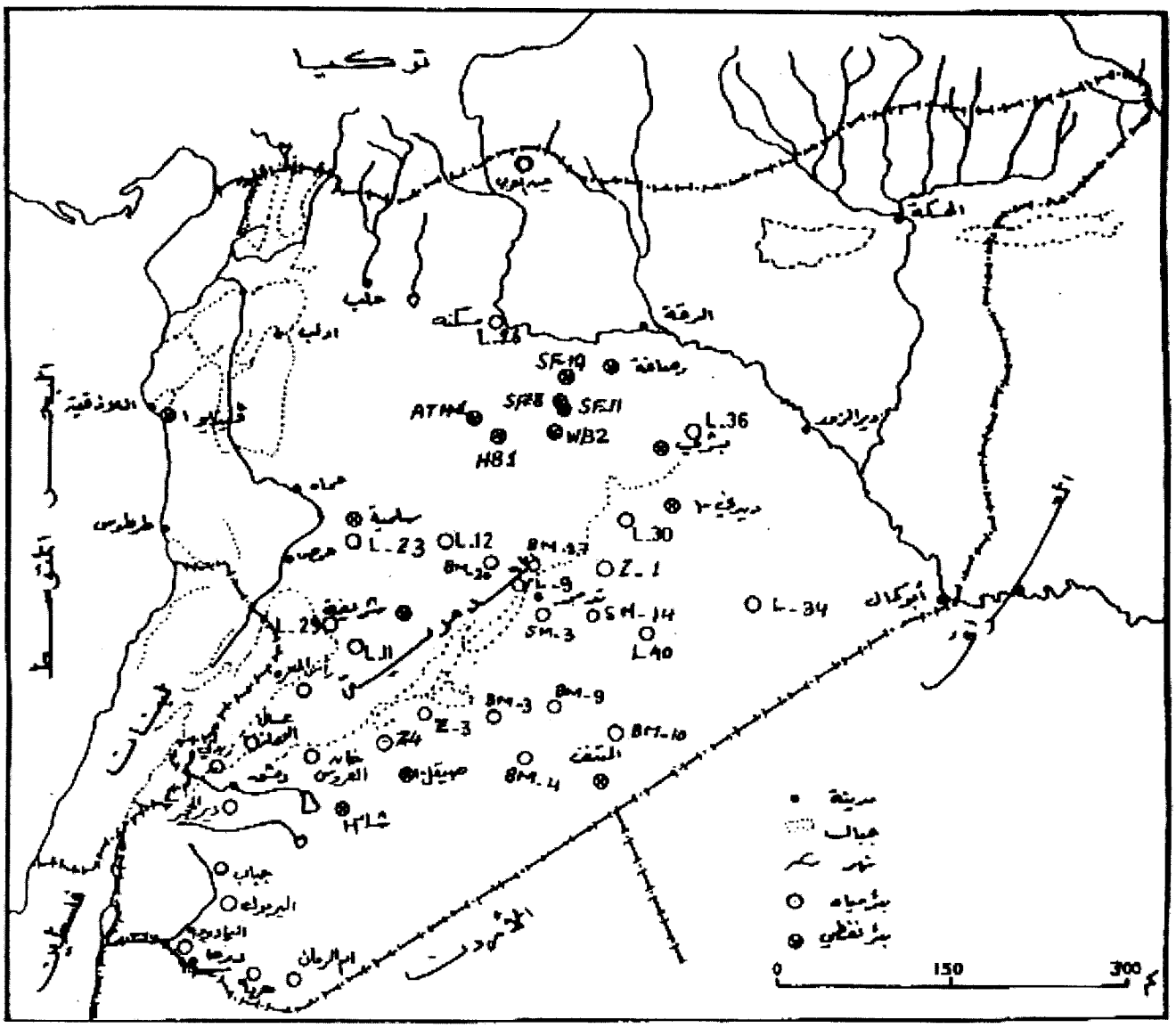
هذا وقد أكد الحفر الهيدروجيولوجي الذي جرى لأغراض استكشافية واستثمارية الملاحظات والظواهر التي بينتها الآبار النفطية ، ففي حوض دمشق اكتشفت المياه في الصخور الكاربوناتية المشققة الكارستية الكريتاسية والجوراسية على أعماق راوحت بين 350 و 1000 م (وفي بعض الحالات 180 م) ، وكانت في كل الأحوال عذبة إذ لم تتجاوز درجة ملوحتها الـ 0.3 غ/ل (جدول رقم 2) .

وقد جرت في السنوات الاخيرة دراسة استكشافية هيدروجيوفيزيائية ترافقت بحفر آبار عميقة في منطقة القلمون (مثال عليها آبار الحميرة والجراجير والسحل) ، دعمت الآراء القائلة بوجود مياه عذبة عميقة في توضعات الكريتاسي ، وفي حوض اليرموك تكررت الصورة نفسها تقريباً ، إذ ظهرت المياه في الصخور الكريتاسية على أعماق راوحت بين 400 و 920 م . أما في حوض البادية فقد نفذت عدة دراسات هيدروجيوفيزيائية حفرت على أساسها مئات الآبار الاستكشافية التي راوحت أعماقها بين 150 و 1100 م والتي اخترق عدد لايستهان به منها الطبقات المائية الكريتاسية وفي بعض الاحيان الجوراسية على أعماق راوحت بين 300 و1000م ، وفي بعض الحالات 33 م ، كما في البئر L-9 قرب تدمر ، وتتميز هذه المياه بدرجات ملوحة لاتتجاوز الـ 3 غ/ل عموماً علماً بأنها في كثير من الاحيان تراوح بين 0.5 و1غ/ل ، إضافة إلى ماسبق هناك شواهد مائية كثيرة في عشرات الآبار التي حفرها القطاع الخاص في أحواض حلب والعاصي والساحل تشير إلى ظهور مياه عذبة أو قليلة الملوحة في صخور الكريتاسي والجوراسي المشققة والكارستية من أعماق تراوح بين 500 و 1100 م نذكر منها على سبيل المثال :

- في غرب عين العرب في حوض حلب ظهرت المياه من الكريتاسي على عمق 1125 م واستقرت على عمق 35 م ، وأعطى البئر تصريفاً يقدر بـ 150 م^3/سا .
- في حوض الساحل ظهرت المياه من الجوراسي في آبار بيت زنتوت على عمق 625 م وفي آبار بيت ياشوط على عمق 480 م ، كما ظهرت المياه من الكريتاسي الاعلى في آبار القرداحة على عمق 400 م .
- في حوض العاصي ظهرت المياه من الكريتاسي في بعض الآبار على أعماق حوالي 1000 م .

وهنا أيضاً إذا دققنا بما تجمع من شواهد مائية من آبار المياه المدروسة لوجدنا مايلي :

- تأكيد وجود المياه في صخور الكريتاسي والجوراسي مع ملاحظة ان ظهور هذه المياه غير مشروط بأعماق محددة وكبيرة ، اذ تظهر أحياناً على أعماق لاتتجاوز بضع عشرات من الامتار .
- تأكيد وجود الضواغط مختلفة الشدة التي تتعرض لها هذه المياه ، إذ تبين ان بعضها يصل الى أكثر من 850 م ، ويؤدي أحياناً الى خروج المياه من أعماق كبيرة (من 870 م في بئر الضبيات) الى مافوق سطح الارض (25 م في البئر نفسه) .



شكل (3) أماكن توزع بعض الآبار النفطية وآبار المياه التي اخترقت مستويات مائية عميقة.

• تأكيد اختلاف نوعيات المياه حسب المواقع ولو بحدود أقل مما أظهرته الآبار النفطية .

لقد نبهتنا هذه الملاحظات وخاصة الأولى منها والمتعلقة بأعماق ظهور الماء الى النظر مجدداً ومن منطلق آخر إلى الينابيع عالية التصريف ودائمة الجريان المنتشرة في سوريه ، نظراً لأن ينابيع بهذه المواصفات تتعلق تغذيتها بلا شك من طبقات مائية ذات كمونية عالية وأبعاد ليست محلية .

تتصف الغالبية العظمى للينابيع المذكورة بانبثاقها من صخور كاربوناتية مشققة وكارستية ، وقد أكد بردن على انتشار الظواهر الكارستية، في كافة المناطق السورية ضمن الصخور الكاربوناتية العائدة للجوراسي والكريتاسي الأوسط والعصر الثلاثي وفي الصخور الهالوجينية العائدة للميوسين الأوسط [15]. وتكون الظواهر الكارستية على أشدها في المنطقة الغربية الساحلية نظراً لتميزها بالسماكات الكبيرة للصخور الكاربوناتية والجريان النشط للمياه الجوفية ، فقد بين بونيكاروف أن سماكة الصخور الكلسية المدلمتة العائدة للجوراسي في المنطقة الساحلية تصل إلى 2 كم ، كذلك تصل سماكة صخور السينومانيان تورونيان إلى 0,6-1 كم [29]. وهذا يفسر مانلاحظه من انتشار واسع لاعداد كبيرة من الينابيع مختلفة التصاريف في المنطقة الغربية(شكل رقم 4) . وترتبط معظم هذه الينابيع وخاصة الكبيرة منها بنطاقات التكسرات التكتونية ، وتعتبر مخارج طبيعية لمستويات مائية عميقة ذات ضواغط عالية . ويتم صرف مياه تلك الينابيع على مستويات طبوغرافية مختلفة بما في ذلك تحت مستوى سطح البحر، حيث أكتشف برنار نبعاً عذباً تحت بحري على عمق 14 م وعلى بعد 2 كم من مدينة طرطوس [20]. وقد توالت الاكتشافات فيما بعد والتي أكدت على وجود تفريغ تحت بحري للمياه الجوفية في المنطقة.

إضافة إلى ذلك يؤكد كلاينزوركه وغيره على أن سلسلة جبال لبنان الشرقية المؤلفة من الصخور الكاربوناتية هي كارستية حتى عمق 1 كم وعلى امتداد 100 كم [36]، وعليه من الطبيعي ان ينبثق على سفحها الشرقي نبع الفيجة الذي يعتبر من الينابيع الكلسية الكارستية النموذجية ومن أكبر الينابيع في المنطقة الغربية وأهمها (تصريفه الأعظمي يصل إلى 27 م^3/ثا والأدنى 1,2 م^3/ثا) . وقد أكد كازلوف وسولدي كوندراتيف إرتباط هذا النبع هيدروليكياً بكثير من الينابيع الكارستية المنتشرة على سفوح سلسلة جبال لبنان الشرقية [35]. ويوضح (الشكل رقم 4) هذا الأمر ، حيث نرى كيف أن العديد من تلك الينابيع يرتبط فعلاً بالنطاقات المحيطة بالفوالق الطولانية والعرضانية ، والممتدة من الشمال باتجاه الجنوب على طول الانهدام السوري الكبير . ويقودنا هذا الوضع إلى استنتاج إمكانية وجود منشأ ذو طبيعة واحدة لمياه تلك الينابيع. وتجدر الاشارة الى ان الينابيع المرتبطة بالصخور الكاربوناتية الكريتاسية والجوراسية لاتقتصر على المناطق الغربية من سورية بل تظهر أيضاً في المناطق الداخلية منها فعلى سبيل المثال نبع فاسريا الذي يقع الى الشمال الشرقي من مدينة دمشق مياهه من السينومانيان تورونيان الكاربوناتي أيضاً .

إضافة إلى ماسبق هناك معطيات حول تلقي بعض المستويات المائية الرباعية والنيوجينية لتغذية مائية عن طريق التسرب نحو الأعلى من الطبقات المائية العميقة المضغوطة، وعبر نطاقات التشقق المصاحبة للفوالق ، وقد لوحظت هذه الظاهرة في مناطق أرك إلى الشمال الشرقي من تدمر وغوطة دمشق [21]، كما لوحظت في حوض البادية عموماً وفي سبخة الموح بشكل خاص [3].

وهكذا نستطيع وبتعميم المعلومات والمعطيات السابقة ، أن نؤكد على وجود جريانات جوفية على أعماق كبيرة في الصخور المشققة والكارستية العائدة للميزوزويك ، وتنفرغ هذه الجريانات أحياناً من خلال الينابيع دائمة الجريان والمنتشرة بشكل واسع في القطر .

3-3-4 مناقشة وتعريف

أكدت المعطيات المتوفرة حتى الآن وجود المياه الجوفية في صخور الكريتاسي والجوراسي في سورية بكميات ونوعيات متفاوتة من منطقة لأخرى الأمر الذي يدعونا إلى البحث من وجهة نظر مائية في ماهية الطوابق المشكلة للميزوزويك بشكل عام والجوراسي والكريتاسي بشكل خاص لاستقراء مدى صلاحيتها لتشكل خزانات مائية صالحة للاستعمال من الناحيتين الكمية والنوعية ، وعليه إذا استعرضنا وباختصار شديد التشكيلات المختلفة التي تكون المقطع الجيولوجي في الميزوزويك على مستوى سورية لوجدنا مايلي :

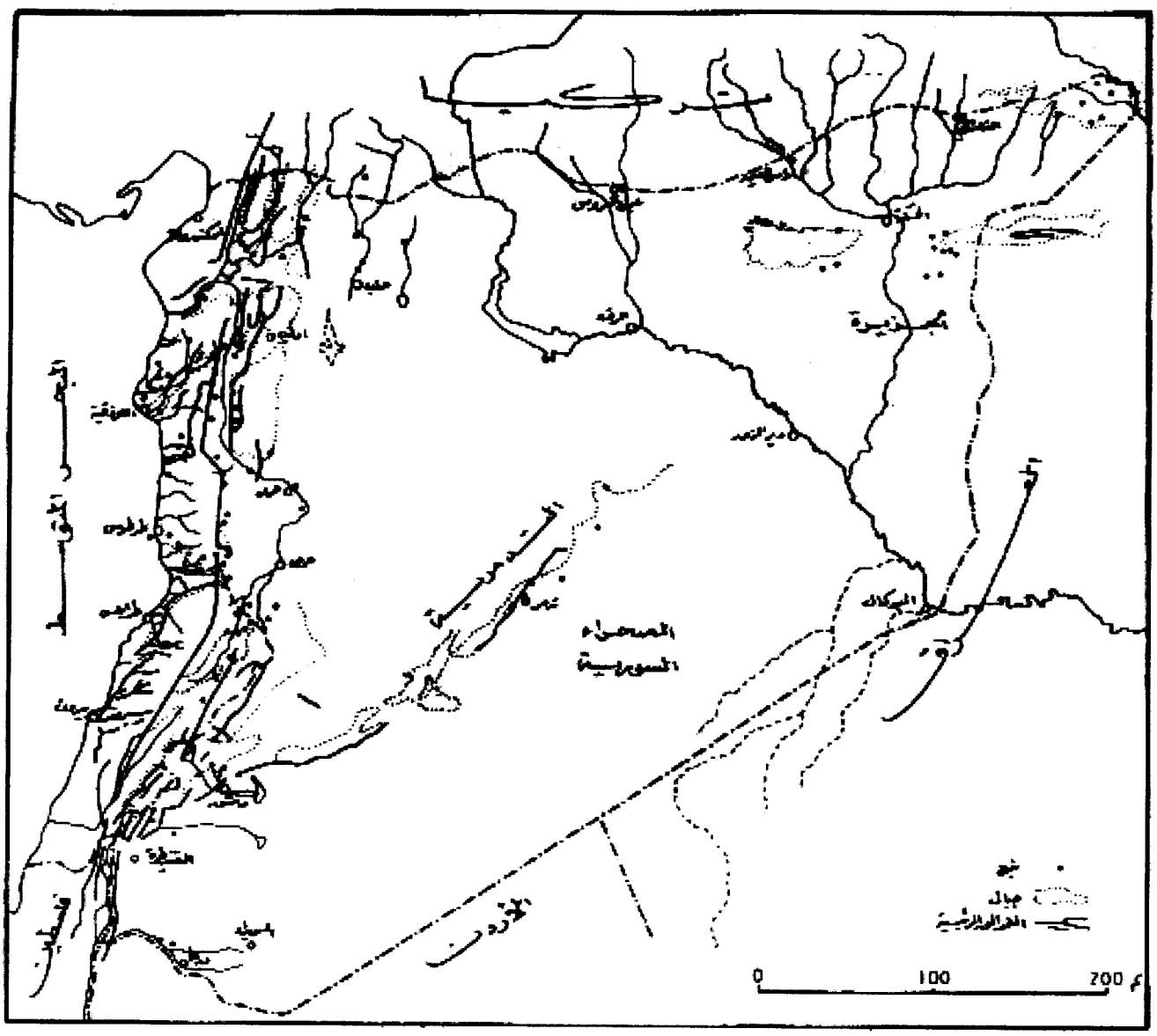
الترياسي :

- **الاعلى** : صخور تبخرية (جص وانهيدريت) في الأقسام العليا تتلوها صخور كربوناتية مع تداخلات مارلية
- **الأوسط**: أنهيدريت (تشكيلة كوراشينا الانهيدريتية)يتلوها الدولوميت (تشكيلة كوراشينا الدولوميتية)
- **الأدنى** : الشيل (تشكيلة الامانوس) والغضار الرملي

وكما نرى فإن الطبيعة الليتولوجية للترياسي تشير الى نتيجتين اثنتين الأولى منهما ضعف الخواص الخزنية بفعل وجود الغضار والمارل والشيل بشكل كبير ومتداخل مع الصخور الكاربوناتية ، والثانية وجود الصخور التبخرية ، التي ستؤدي إلى تدهور نوعية المياه ان وجدت، ويضاف إلى ذلك الشواهد النفطية والغازية التي لوحظت في الترياسي مما يزيد في تدهور نوعية المياه ، لهذا لايمكن اعتبار الترياسي مأمول مائياً على مستوى إقليمي .

الجوراسي :

ويتألف بأجزائه الثلاثة الاعلى والأوسط والأدنى من صخور كربوناتية مشققة وكارستية بشكل كثيف ومؤلفة من حجر كلسي ودولوميت يتخللها



شكل (4) - أهم الينابيع في سوريا

قليل من المارل ، وتغلب السحنة الكلسية في صخور الجوراسي الأوسط ، وقد أثبتت دراسات معطي [25] خلو الجوراسي من الصخور الجصية التي تعود الى الترياسي الأعلى وليس الى الجوراسي، كما كان يعتقد سابقاً .

إذن مع الواضح أن الجوراسي وعلى العكس من الترياسي مؤهل ليكون خزان مائي جيد من الناحيتين الكمية والنوعية .

الكريتاسي :

- **الاعلى :**

• الماستر يختيان مارل وحجر كلسي غضاري وبأجزائه السفلى صوان .

• الكامبانيان : حجر كلسي غضاري مع مستويات متداخلة من الصوان والمارل في قاعدته .

• السانتونيان : حجر كلسي قاعدته مارلية

• الكونياسيان : حجر كلسي مع مستويات مارلية وغضارية ورمال

• التورونيان : حجر كلسي دولوميتي مع مستويات مارلية قليلة في أجزائه العليا .

• السينومانيان: حجر كلسي ودولوميت مع قليل من المارل والغضار .

- **الأدنى :**

• الالبيان : حجر كلسي يصبح مارلي نحو الأسفل .

• الابسيان : توضعات رملية ورملية غضارية وغضار وأحياناً دولوميت .

وينتهي الكريتاسي عند الابسيان بثغره ستراتيغرافية ضخمة على مستوى سورية .

هذا وقد درس هذا الكريتاسي بشكل جيد وخاصة في البادية السورية فتبين ان كافة طوابقه تحتوي على مياه بكميات متفاوتة وبنوعيات جيدة الى مقبولة ، علماً بأن الماستريختيان يعد عملياً طبقة شبه كتيمة ، وكذلك الكريتاسي الأسفل ، لهذا اصطلح على تسمية المستويات المائية الموجودة في الكريتاسي الاعلى بالمعقد الحامل للماء على اعتبار ان تلك المستويات كما تبين على اتصال هيدروليكي مع بعضها البعض نظراً لأن الصخور الكربوناتية المؤلفة لها مشققة وكارستية . وفي كل الاحوال هناك مايؤكد على ان الكريتاسي بمجمله يعتبر مأمول مائياً من الناحيتين الكمية والنوعية وان كان يتميز به كل من التورونيان والسينومانيان بانتاجيتهما العالية نظراً لشدة المظاهر الكارستية فيهما .

اذن في المحصلة نجد ان تشكيلات الكريتاسي والجوراسي هي التشكيلات المأمولة مائياً بشكل عام ، فإذا نظرنا إلى انتشارها في سورية لوجدنا أنه ليس بالقدر نفسه ، ففي حين تنتشر تشكيلات الكريتاسي على عموم أراضي سورية تنحصر التشكيلات الجوراسية على طول الشريط الذي يغطي سورية الغربية من الشمال الى الجنوب مروراً بمدن حلب وحمص ودمشق ودرعا وحتى الساحل ، وفي المناطق المحيطة بالسلسلة التدمرية وبجبل سنجار . وتصل ثخانة التوضعات الجوراسية في التدمرية الشمالية الى 1200 م وفي المناطق الساحلية الى 800 م بينما لاتتجاوز الـ 250 م في حوض دمشق . وفي التدمرية يتألف الجوراسي من الجوراسي الأوسط (دوغير) والأدنى (لياس) فقط حيث يغيب الجوراسي الأعلى (مالم) بفعل ثغرة استراتيغرافية كبيرة وعليه يتوضع الكريتاسي الادنى المؤلف من الحجر الرملي الغضاري الحديدي (حجر رمل الأساس أو حجر رمل تدمر) فوق الصخور الكلسية والكلسية الدولوميتية فوق الجوراسي الأوسط والأدنى (تشكيلة السطيح) مباشرة [25]. أما في السلسلة الساحلية فيتوضع الكريتاسي الأدنى فوق الجوراسي الأعلى مباشرة وفي توافق استراتيغرافي طبيعي .

أما التشكيلات الكريتاسية ، التي تنتشر في عموم الأراضي السورية فتتغير سماكاتها بحدود كبيرة من 2600 م في مناطق سنجار وحتى الـ 200 م على الحدود السورية الاردنية العراقية وفي حوض دمشق تراوح هذه السماكة بين 500 و 1000 م ، وعموماً تتناقص هذه السماكة اعتباراً من السفوح الجنوبية للسلسلة التدمرية باتجاه نهوض الرطبة ، كما تتناقص في المنطقة الساحلية من 1000 وحتى 300 م . واذا تتبعنا سماكة تشكيلات التورونيان سينومانيان البيان ، وهي أفضل تشكيله حاملة للماء ضمن الميزوزويك ، لوجدنا أنها تراوح بين 950 م في منطقة مدينة حمص الى الصفر في أقصى الشرق على الحدود السورية العراقية ، كما أنها تصل الى 400 م في الساحل والى 750 م على الحدود التركية شمال مدينة حلب . أما في حوض دمشق فتراوح بين 400 و 800 م .

من جهة أخرى تختلف الآراء حول التغذية المائية لهذه الطبقات المائية الكريتاسية الجوراسية ، فمنها من ينفي حدوث أية تغذية حديثة لها مستنداً الى التحاليل الايزوتوبية الكثيرة التي أشارت الى أن أعمار المياه تراوح بين 7500 و 40000 سنة [3]. ومنها من يؤكد حدوث مثل هذه التغذية على الأقل في مناطق تكشفات الصخور الكريتاسية والجوراسية في المناطق التدمرية والساحلية . فعلى سبيل المثال بينت دراسات السوفيت لمياه نبع الفيجة الذي يتلقى مياهه من التورونيان سينومانيان أنه يمكن تقسيم مياهه حسب زمن بقاء المياه فيه إلى ثلاث فئات هي :

• الأولى حتى 3 سنوات وتشكل 62 ٪ من الكمية المحسوبة .

• الثانية من 8 حتى 12 سنة وتشكل 27 ٪ .

• الثالثة أكثر من 200 سنة وتشكل 11 ٪ .

وتعتبر هذه النتائج دليلاً على وجود نوعين من مناطق التغذية لنبع الفيجة قريبة وبعيدة [34]. وقد أيدت الدراسات الآيزوتوبية (C-14;TU) التي أجراها المركز العربي (أكساد) في المنطقة وجود تغذية محلية لنبع الفيجة [22] ، الأمر الذي يشير بكل الأحوال الى تغذية حديثة للنبع .

كذلك اعتبر المركز العربي في دراسة لحوض سبخة الموح في البادية السورية أن المعقد المائي في الكريتاسي الاعلى يتلقى تغذية سنوية من تسرب مياه الامطار من خلال تكشفاته المنتشرة على امتداد السلسلة التدمرية الجنوبية وجزء من السلسلة التدمرية الشمالية [8]. من جهة ثانية تشير زيادة تصاريف بعض الينابيع المنبثقة عن الصخور الكريتاسية والجوراسية في السنوات المطيرة وانخفاض (واحياناً جفاف) هذه التصاريف في السنوات الجافة، تشير بوضوح الى تأثر نظام الجريان بالتغذية الحديثة .

وثمة أمر آخر يثير الاهتمام وهو مالاحظناه من ضواغط كبيرة تميز مياه الكريتاسي والجوراسي ، التي أدت إلى اندفاع المياه في الآبار التي اخترقت تلك الطبقات المائية نحو سطح الأرض ، أو تفجرها على شكل ينابيع كارستيه عالية التصاريف تستمد مياهها من هذه الطبقات. فإذا كانت هذه الضواغط تعبيراً عن ضواغط متبقية لمياه قديمة غير متجددة تمت تغذيتها في فترات مطيره سابقة فكيف نفسر تذبذب مناسيب وتصاريف الآبار ، التي لوحظت فيها تلك الضواغط ، تبعاً لتناوب السنوات المطيره والجافة . أغلب الظن ان هذه الطبقات المائية تتلقى تغذية سنوية من أماكن متعددة ومتباعدة ولكن بشكل بطيء مما يفسر صغر التصاريف النوعية لبعض الآبار ولكن استمراريتها مع ذلك ، كما يفسر ذلك أيضاً اختلاف حرارة مياه تلك الطبقات بين باردة وحارة تبعاً لعمق جولان تلك المياه في الحالات المختلفة . وقد لوحظ في السنتين الجافتين الاخيرتين هبوط مناسيب بعض الآبار التي تستمد مياهها من الكريتاسي الاعلى ، ففي منطقة قارة على سبيل المثال هبط منسوب بئر حورتا (على الحدود السورية اللبنانية) بمقدار 25 متر (من 425 الى 450 م) دون أن يكون هناك أي استثمار في المناطق المحيطة به علماً بان درجة حرارة مياه البئر لم تتجاوز 16 م . كذلك يلاحظ دوماً انخفاض تصاريف ينابيع كريتاسية (الفيجة مثلاً) وجوراسية (بردى مثلاً) كلما انخفضت معدلات هطول الأمطار . ان كل هذه الظواهر تشير الى ان مياه مثل هذه الآبار والينابيع تخضع الى نظام هيدروديناميكي مترابط.

أما مايتعلق بعمق ظهور مياه الطبقات المائية الكريتاسية والجوراسية اعتباراً من سطح الأرض فكما رأينا يتراوح هذا العمق من الصفر (بالنسبة للينابيع) الى مايزيد عن الالف متر في حالات كثيرة ، كما ان المعلومات المائية المتوفرة حول المياه الجوفية في سورية أظهرت وجود مياه على أعماق كبيرة في توضعات كثيرة اخرى غير كريتاسية وجوراسية منتشرة في معظم الأحواض المائية السورية ، كما في بازلت النيوجين في ولغا بحوض اليرموك (1550م) وحطاميات النيوجين في عدرا (550 م) وفي الشيفونية (800 م) في حوض دمشق وفي الحجر الكلسي الايوسيني في الجزيرة (750 م) في حوض الفرات ، ولانعتقد أن معيار الأعماق يوحد بين هذه التشكيلات المختلفة جذرياً .

في المحصلة واستناداً الى كل ماتقدم نقترح المفهوم التالي للمياه الجوفية العميقة في سورية : بأنها المياه الموجودة في الصخور المشققة والكارستية العائدة للكريتاسي والجوراسي والمشكلة لمستويات ومعقدات مائية متعددة ومختلفة الغزارات والنوعية وعلى اتصال هيدروليكي أو معزولة عن بعضها البعض ، والمرتبطة بالفوالق العميقة ونطاقات التهشم التكتوني والتراكيب الجيولوجية الملائمة الناتجة عن البنية البلوكية للركيزة البللورية ، والخاضعة لضواغط هيدروليكية عالية ، وذات الانتشار الاقليمي ومناطق التغذية البعيدة نسبياً ، مع الاشارة الى ان قرب هذه المياه من سطح الأرض أو بعدها عنه يخضع للتغيرات البنيوية الجيولوجية ، ولايغير من وصفها بالعميقة طالما أنها جزء من النظام الهيدروجيولوجي العميق أصلاً ، كما أنه يمكن اعتبارها متجددة بشكل ضئيل عند التخطيط لاستثمارها .

والجدير بالذكر أن أهمية هذه المياه تختلف من منطقة لأخرى تبعاً لتغيرات سحنات الجوراسي والكريتاسي والخواص الفيزيائية لصخورهما ، فمثلاً الجوراسي في حوض البادية أقل أهمية مائية منه في حوض الساحل ، كذلك من الضروري دراسة العلاقات الهيدروليكية المتبادلة بين المستويات المائية المختلفة الموجودة في الكريتاسي والجوراسي بعناية قبل استثمارها حتى لاتختل التوازنات الهيدروليكية القائمة فتؤدي الى اختلاط المياه العذبة بالمالحة أو الى نضوب بعض المستويات على حساب مستويات أخرى أو كلاهما .

أخيراً نعتقد أن اطلاق تسميات الطابق الأول والثاني والثالث ...الخ على المستويات المائية الحاملة في توضعات الكريتاسي والجوراسي لتوصيف المياه العميقة هي تسميات اصطلاحية بحتة ومحلية ولاتصلح للتعميم على مستوى سورية ، لأن ترقيم الطوابق المائية يختلف من منطقة الى اخرى حسب طبيعتها الجيولوجية والهيدروجيولوجية فعلى سبيل المثال في حين يكون الكريتاسي الاعلى هو الطابق المائي الثاني في المنطقة التدمرية يكون الايوسين هو الطابق المائي الثاني في منطقة الجزيرة ، ومثل هذه الأمثلة كثير في سورية .

5-خيار تنمية المياه الجوفية العميقة في سورية

استعرضنا سابقاً خيارات تنمية الموارد المائية التي تنفذها سورية ضمن اطار برامج ادارة مواردها المائية ورأينا في حينه أن خيار تنمية المياه الجوفية العميقة لم يعتمد بعد كخيار استراتيجي على نطاق واسع . وفي ضوء ماعرضناه حول هذه المياه نعتقد ان هذا الخيار واقعي وجدير بالاهتمام وآن الأوان لاعتماده كأحد الحلول لمشاكل نقص امدادات المياه في مجال الاستعمالات الاهلية في أربعة أحواض تعاني من هذه المشاكل في سورية وهي أحواض دمشق واليرموك والعاصي والبادية . أما في الأحواض الثلاثة الأخرى وهي الساحل والفرات والخابور- دجلة ، فخيارات تنمية المياه السطحية هي الأنسب والأفضل برأينا خاصة وأن مشكلات نقص إمدادات المياه أقل حدة في تلك الاحواض . وبغية توضيح وجهة نظرنا هذه سنناقش (وكمثال) حالة حوض دمشق بشيء من التفصيل .

حالة حوض دمشق :

آ- الوضع العام للحوض

تبلغ مساحة حوض دمشق 8630 كم^2 (شكل رقم 1) ويتميز ببنية جيولوجية معقدة حيث تنتشر فيه صخور تختلف في تراكيبها الليتولوجية بحدود

واسعة ، إذ تصادف هنا صخور حطامية وكاربوناتية ورملية وهالوجينية وبازلتية ، وتراوح أعمار تلك الصخور بين الجوراسي والرباعي ، يضاف إلى ذلك انتساب الحوض إلى تآلف بنيات تكتونية مختلفة هي منخفض جبل العرب وانخفاس دمشق وتراكيب التدمرية ولبنان الشرقية المتصدعة ، وتشكل الصخور الكاربوناتية من الجوراسي والكريتاسي وخاصة (السينومانيان تورونيان) ، وكذلك التوضعات الرباعية والنيوجينية والصخور البازلتية المستويات المائية الرئيسة في الحوض، وقد فرضت البنية الجيولوجية المعقدة لحوض دمشق اتباع مسلك متميز في التعامل مع مسألة استكشاف المياه الجوفية العميقة فيه ، وقد إعتمد هذا المسلك على الحقائق التي كرسها العديد من الباحثين والقائلة بأنه لوحظ تخامد في نشاط وفعالية بعض الفوالق التكتونية مع الزمن ، الأمر الذي يظهر في تضاؤل شدة الأشكال التكتونية من الأسفل باتجاه سطح الأرض . وهكذا فإن الفوالق الكبيرة المثبتة بانزياحات بلوكات الركيزة البللورية على عمق عدة كيلومترات تستبدل نحو الأعلى بأشكال من الطي واللي ، وفي الأجزاء الأقرب من سطح الأرض تختفي تماماً أية مظاهر تخلعات . وكما أصبح معروفاً ، تتميز الصخور الكاربوناتية فوق مثل هذه الفوالق بالذات بدرجة تشقق وغزارة مائية عاليتين [39]، وعليه يمكن القول بأن التطور التكتوني للحوض هو الذي يحدد الانتشار المكاني لمثل هذه المناطق وبالتالي يشير إلى أماكن تجمع وحركة المياه الجوفية.

انطلاقاً من هذا المفهوم لحوض دمشق تركزت الأعمال الاستكشافية الهيدروجيوفيزيائية عن المياه الجوفية العميقة على دراسة البنية الجيولوجية العميقة للحوض ، وقد أظهرت هذه الأعمال البنية البلوكية للحوض الأمر الذي يؤكد ماسبق وأن ذكرناه بأن الركيزة البللورية في سورية متصدعة بشدة وذات تكتونية بلوكية (الشكل رقم 5) ، ويلفت النظر في المقطع المبين بهذا الشكل الأعماق الكبيرة التي تمتد إليها الفوالق والتكسرات التكتونية (5-6 كم) ومطالاتها الكبيرة أيضاً (1-1.5 كم) ، وكذلك البنية البلوكية للغطاء الرسوبي . وعلى مستوى الحوض بأكمله تبين وجود سلسلة من الفوالق الدرجية التي تتركز في الأقسام الغربية والشمالية الغربية من الحوض وتؤدي إلى غوص الركيزة من الغرب باتجاه الشرق .

من وجهة نظر مائية أظهر الربط بين البنية الجيولوجية العميقة للحوض والمياه الجوفية فيه ، أن الينابيع الكبيرة المنتشرة في الحوض تنتسب بشكل واضح الى نطاقات التكسرات والتصدعات التكتونية مما يؤكد على العلاقة التي تربط بين هذه المياه الخارجة إلى سطح الأرض عن طريق الينابيع والفوالق العميقة ، فعلى سبيل المثال نجد أن نبع الفيجة يرتبط بفالق عميق يتجه شمال - جنوب ، وكذلك نبع منين يرتبط بنطاق تصدع يمتد شرق - غرب وهكذا. وقد سمحت هذه الوقائع بالوصول إلى نتيجة حول وجود مستويات مائية عميقة تغذي هذه الينابيع من خلال الفوالق ونطاقات التصدع .

وقد أشارت الدراسات الجيوفيزيائية التي نفذت في منطقة الزبداني إلى وجود نطاق سميك حامل للماء من الصخور الكاربوناتية المشققة الكريتاسية والجوراسية تصل سماكته إلى 1,5 كم [26]. وقد أكد بئر الزبداني الذي حفر في تلك المنطقة إلى عمق 1150 م على وجود مثل هذه السماكات المشققة الكبيرة والحاملة للماء ، كما قدم معلومات على درجة كبيرة من الأهمية، نذكر منها غياب التدرج الحراري حتى عمق 500 م اعتباراً من سطح الأرض ومن ثم تغيره بمعدلات صغيرة نسبياً من 15.3م على سطح الأرض إلى 21.5 مْ على عمق 1030 م مما يؤكد وجود جولان نشيط للمياه الجوفية . كذلك كشفت معطيات البئر عن وجود جريان عمودي إلى البئر من عمق 960 م ونحو الأعلى، وأعطى البئر مياهاً عذبة وتصريفاً نوعياً بلغ 71/5.6 ل/ثا/م . وعموماً كشفت القياسات الجيوكهربائية الحلقية العميقة RVES (AB=8KM)، في عدة مواقع من حوض دمشق عن وجود ظواهر انيزوتروبية للصخور على أعماق كبيرة ، ففي منطقة الغوطة على سبيل المثال تظهر الأنيزوتروبية على عمق 1500 م في الصخور الكاربوناتية [26].

مما تقدم نجد أن المعلومات المتجمعة من الدراسات الجيوفيزيائية وأعمال الحفر في حوض دمشق تسمح بالوصول إلى نتيجة تفيد بأن هناك انتشاراً اقليمياً فعلياً لنطاقات تشقق شديد للصخور الكاربوناتية في حوض دمشق ترتبط مع البنية التكتونية العميقة ، الأمر الذي خلق ظروفاً ملائمة لتشكل وجولان المياه الجوفية العميقة في تلك النطاقات . ولابد هنا من الاشارة إلى أن هذه المياه غير متجددة عملياً خاصة إذا ماقيس حجم ماتتلقاه سنوياً إلى احتياطيها الطبيعي الكامن .

ب - المشكلة

يشير الميزان المائي المعتمد حالياً من قبل مديرية الري العامة لحوض بردى والأعوج [9] الى ان حجم الموارد المائية المتجددة في حوض دمشق (الذي تهطل عليه وسطياً 2659 مليون م^3 من الامطار من السنة) يبلغ 850 مليون م^3 ، في حين يصل حجم الاستهلاك إلى 1500 مليون م^3 تستخدم في تأمين امدادات المياه للاستعمالات الاهلية، لما يزيد عن 3 ملايين نسمة يقطنون الحوض ، وللصناعة ولري حوالي 75340 هكتار، وتستخدم الزراعة مامجموعه 75٪ من حجم المياه المستهلكة، ويجري تعويض النقص في امدادات المياه للزراعة عن طريق اعادة استعمال مياه الصرف الصحي ومياه الري الراشحة (تدوير المياه) وجزء من المخزون الجوفي الساكن (الاحتياطي الطبيعي) مما أدى الى تسجيل هبوط ملحوظ في مناسيب المياه الجوفية في العديد من المناطق (وصل في بعضها الى 60 م). وهذا يعني ان حوض دمشق دخل الآن مرحلة العجز المائي والذي سيتفاقم مستقبلاً مع تزايد عدد السكان وتنامي الطلب على الماء ، وتقدر مديرية الري العامة لحوض بردى والأعوج الطلب على المياه للاستعمالات الاهلية والصناعة فقط لعام 2000 بـ 563 مليون م3 و لعام 2010 بـ 846.4 [37] أي أنه خلال عشر سنوات فقط لن تكفي موارد الحوض بكاملها لتغطية احتياجات قطاعي مياه الشرب والصناعة فقط ، مما يتطلب العمل ومنذ الآن على ايجاد الحلول العملية والفعالة لمواجهة العجز المائي ومنع تفاقمه .. علماً بأنه بحال مرور سنوات جافة، فإن الامور ستزداد سوءاً بفعل شحة الموارد وسندخل في مرحلة تقنين حتى امدادات مياه الاستعمالات الأهلية ، كما حصل في عام 1998 - 1999 .

ج - الخيارات المتاحة

اذا استعرضنا الخيارات المتاحة لحل مشكلة المياه في حوض دمشق في ضوء الخيارات الممكنة تكنولوجيا في تنمية الموارد المائية العذبة والتي ذكرناها سابقاً ، لوجدنا أن خيار تنمية المياه السطحية والمياه الجوفية الضحلة قد أخذ مداه عملياً على العكس من باقي الخيارات والتي سنناقش واقعيتها لاحقاً .

1- استخدام مياه الصرف الصحي

تستخدم هذه المياه حالياً في الزراعة على نطاق واسع ولكن دون معالجة ، وقد انجزت حديثاً محطة متطورة لمعالجة مياه صرف دمشق الصحي وهي قيد التشغيل التجريبي ، وهناك خطط للتوسع في انشاء مثل هذه المحطات في الحوض . ولاشك ان هذا الخيار على درجة كبيرة من الأهمية نظراً لمنعكساته البيئية والتنموية ومن الضروري والهام جداً برأينا التوسع في هذا المجال من حيث المبدأ فهو سيساهم بلاشك في حل مشكلة مياه حوض دمشق ، حتى أن البعض يذهب الى القول بأن حل مشكلة مياه حوض دمشق حلاً جذرياً تكمن في تحويل كافة موارده المائية (أي الـ 850 مليون م^3) لأغراض الشرب مع تخفيض الهدر في شبكات مياه الشرب الى الحد الادنى المقبول عالميا (10-15٪) وتخصيص مياه الصرف الصحي بعد معالجتها للأغراض الصناعية والزراعية مع رفع كفاءة استعمال المياه في الزراعة .

ومع احترامنا لهذا الرأي والى دعمه بيئياً الا أنه لن يشكل الحل المطلوب في المستقبل المنظور للأسباب التالية :

• ان انشاء شبكات للصرف الصحي على مستوى الحوض ومحطات لمعالجة مياهه ومايتبعها من تمديد وتجديد لشبكات امدادات المياه للاستعمالات الأهلية بغية وقف التسرب منها والحصول على أكبر عائد ممكن من مياه الصرف الصحي ، وبالتالي تنفيذ برنامج وطني لرفع كفاءة استخدام المياه في الزراعة وتعميم تقانات الري الحديثة في الزراعة ومحطات معالجة المياه الصناعية ، ان تنفيذ كل ذلك يتطلب جهوداً جبارة على مستوى القطاعين العام والخاص والأفراد وأموالاً طائلة وزمناً طويلاً لايقل عن عشر سنوات من العمل اليومي الدؤوب .

• يجب ان لايغيب عن بالنا بأن مياه الصرف الصحي والصرف الصناعي وحتى أجزاءاً من الصرف الزراعي المتسرب الى المياه الجوفية والمياه المتسربة من شبكات مياه الشرب ومياه الصرف الصحي يعاد استخدامها عملياً وإلا كيف نفسر أن الحوض يستهلك ضعف موارده منذ سنوات ؟!

إذن نستطيع القول ان هذا الخيار وعلى أهميته لن يشكل في المدى المنظور حلاً لنقص امدادات المياه الحالي في الحوض ، والذي لايستطيع الانتظار سنوات طويلة ، مع التأكيد على ضرورة السير فيه بلا شك ، لما سيوفره من كميات إضافية مستقبلاً ولما سيؤمنه من حفاظ على البيئة وخاصة المائية منها .

2- اعذاب المياه المالحة

تعد تقانة اعذاب المياه المالحة أحد الخيارات الاستراتيجية المطروحة نظرياً لحل مشاكل امدادات المياه لأغراض الاستعمالات الاهلية وتشكل المياه الجوفية الضاربة للملوحة أو مياه البحر المياه الخام التي يتم اعذابها . ويمتاز هذا الخيار ، في حالة اعذاب مياه البحر ، بتأمينه لمصادر مياه عذبة بالكميات المطلوبة وبشكل دائم، ولكنه من جهة اخرى يمتاز بارتفاع تكاليفه الرأسماليه وتكاليف التشغيل أيضاً ، إذ تراوح تكاليف اعذاب المتر المكعب الواحد من مياه البحر بين 1 و 4.15 دولار أمريكي [7] ، وفي أكثر التقديرات تفاؤلاً لاتقل عن دولار أمريكي الواحد*. ولكن هذه التكلفة تنخفض الى النصف بحالة اعذاب المياه الجوفية الضاربة للملوحة . وبالنسبة لحوض دمشق بالذات ليست هناك موارد مائية جوفية ضاربة للملوحة كافية ودائمة للقيام باعذابها ، مما يبقى الخيار ممكناً (من الناحية النظرية) لاعذاب مياه البحر المستجرة من الساحل السوري فقط ، الأمر الذي يضيف الى تكاليف الاعذاب تكاليف النقل أيضاً وهي كبيرة كما سنرى لاحقاً . ويؤدي هذا الواقع الى رفع تكلفة المتر المكعب الواحد من المياه المحلاة واصلاً الى الحوض الى دولارين أمريكيين في أفضل الاحوال ، الأمر الذي يجعل هذا الخيار مستحيلاً من الناحية الواقعية في الظروف الاقتصادية الحالية لسورية ، ولكن أخشى مانخشاه أن يفرض هذا الخيار نفسه علينا في نهاية المطاف .

3- نقل المياه من خارج الحوض

يناقش هذا الخيار بجدية ومن منطلق أنه قد يشكل حلاً جذرياً ولفترة طويلة من الزمن لمشكلة نقص امدادات المياه في الحوض نفسه وفي التجمعات السكنية الواقعة على امتداد خط النقل ، وقد نوقشت عدة مصادر مائية ليتم النقل منها ، وبرأينا أن المصدرين الذين يتوافقا مع منطلق الحل الجذري ومع الواقع المائي للأحواض السبعة هما حوض الساحل ونهر الفرات .

يتمتع حوض الساحل بثروة مائية كبيرة تصل حسب تقديرات وزارة الري الى 2300 مليون م^3/سنة ، كما يبلغ المعدل الوسطي السنوي لهطول الأمطار في الحوض 4880 مليون م^3 في حين لم تتجاوز كميات المياه المستثمرة منه لغاية عام 1995 الـ 620 مليون م^3 [12] ، مما يشير الى وجود فوائض كبيرة في هذا الحوض . من جهة أخرى قدرت الدراسات السوفيتية حجم المياه السطحية والجوفية التي تذهب الى البحر سنوياً بـ 1,5

* كحالة خاصة قدرت تكاليف اعذاب متر مكعب واحد من مياه البحر باستخدام الطاقة النووية في اوكرانيا بـ 0,8 دولار أمريكي ، وتتركز البحوث حالياً للوصول الى رقم 0,2 دولار أمريكي دون استخدام الطاقة النووية.

مليار م^3 [30] ، علماً بأن أكثر الآراء تحفظاً على هذه الكميات تسلم بضياع نصف مليار م^3 على الأقل . اذن من حيث المبدأ يتوفر في الحوض المصدر المائي الذي يمكن ان يتم النقل منه ، وهناك احتمالين لإجراء ذلك هما :

• ان يتم النقل من بحيرات السدود القائمة أو التي هي قيد الانشاء وبكميات محدودة لاتتجاوز الـ 100 مليون م^3 سنوياً ، وعليه فقد درس احتمال نقل مياه نهر الحصين (5 كم الى الشمال من مدينة طرطوس) بواسطة خط جر طوله 300 كم وبارتفاع ضخ يبلغ 842 م الى مدينة دمشق ، فوجد أن تكلفة المتر المكعب الواحد من الماء واصل المدينة ستبلغ حوالي 0.7 دولار أمريكي ، وسيستغرق تنفيذ المشروع خمس سنوات .

• ان يتم النقل من منظومة متكاملة من السدود وحقول الآبار المرتبطة مع بعضها الى مركز تجميع محدد يتم الضخ منه وبكميات كبيرة تصل الى 500 مليون م^3 ونقلها الى حوض دمشق . ولاشك أن التكاليف الرأسمالية لمثل هذه المنظومة ستفوق أضعاف تكاليف الاحتمال الاول إلا أنها ستمنع الى حد كبير من ضياع المياه السطحية والجوفية في البحر، كما أنها ستؤمن حلاً جذرياً لنقص امدادات المياه في حوض دمشق .

ولاشك ان الاحتمال الثاني أفضل من الأول لأنه يؤمن كميات كبيرة من المياه لنقلها، ويخفض من تأثير عوامل الجفاف والتبخر والاطماء والاستثمارات المحلية والنزاعات حول الحقوق المائية المكتسبة ، على كميات المياه المتاحة للنقل . ولكن وبكلا الحالتين تعترض هذا الخيار التكلفة العالية للانشاء والتشغيل والمدة الزمنية الكبيرة التي يحتاجها للتنفيذ (خاصة الاحتمال الثاني) ، إلا أنه ومع ذلك يظل خياراً وارداً .

أما النقل من نهر الفرات فهو لايقل تكلفة عن النقل من حوض الساحل ، ويفوقه صعوبات فنية نظراً للطبيعة الطوبوغرافية لمساره ، كما ان للنهر بحد ذاته وضع خاص كنهر دولي مشترك لم يتم الاتفاق بعد على حصص عادلة ومعقولة بين الدول الثلاث المشتركة فيه ، إلا أنه كمصدر مائي للنقل أفضل من مياه حوض الساحل من حيث الكمية ووحدانية المصدر وعدم الحاجة الى أية انشاءات جديدة لتجميع المياه تمهيداً لنقلها.

اذن في المحصلة نستطيع القول ان خيار نقل المياه من خارج حوض دمشق اليه خيار صحيح وممكن ، إلا أن تكاليفه الرأسمالية والجارية عالية كما يحتاج الى فترات زمنية طويلة لتنفيذه وقطف ثماره .

4- استثمار المياه الجوفية العميقة

استناداً الى التعريف الذي اقترحناه سابقاً حول المياه الجوفية العميقة فإن هذه المياه تستثمر حالياً في حوض دمشق من خلال الينابيع التي تتغذى من الطبقات المائية الكربوناتية المشققة والكارستية العائدة للكريتاسي والجوراسي (ينابيع الفيجة ، بردى ، فاسريا ، عرنة ، بيت جن، وغيرها) ، كما أن هناك بعض الآبار التي اخترقت تلك الطبقات في مناطق دوما وحرستا وضاحية الأسد ، لتأمين المياه للاستعمالات الاهلية، ولاتستعمل المياه العميقة حالياً في الزراعة إلا في مناطق سرغايا وسهل الزبداني .

هذا وقد خطت المؤسسة العامة لمياه الشرب والصرف الصحي في مدينة دمشق والمسؤولة عن امدادات المياه خطوة على طريق استثمار هذه المياه الجوفية العميقة فحفرت مجموعة من الآبار في محيط نبع بردى اخترقت المستويات المائية الكاربوناتية في الجوراسي وبدأت باستجرار 100 ألف م^3 يومياً من هذه الطبقة لدعم شبكة مياه الشرب في مدينة دمشق . كذلك فعلت المؤسسة العامة لمياه الشرب والصرف الصحي في ريف دمشق في منطقة القلمون والكسوة فحفرت آبار لآعماق كبيرة تجاوز بعضها الـ 1000 م لاستثمار المياه العميقة في الكريتاسي لأغراض مياه الشرب أيضاً .

ومن الواضح ان هذا الخيار هو أقل الخيارات التي ناقشناها تكلفة وأسرعها تنفيذاً ، مما يساعد على حل مشاكل نقص امدادات المياه القائمة حالياً ، كما أنه يمكن تقنياً تخطي عقبة ارتفاع درجة حرارة المياه في بعض المناطق التي تغوص بها الطبقات المائية لأعماق كبيرة لهذا فإننا نعتقد بضرورة اعتماد خيار استثمار المياه العميقة كحل لمشكلة امدادات مياه الشرب في حوض دمشق على المدى المنظور مع تحريم استعمال هذه المياه لغير الاستعمالات الاهلية حيث انها ذات تجدد ضئيل كما أسلفنا . وفي الوقت نفسه يجب متابعة العمل والتوسع في خيار استخدام مياه الصرف الصحي كأولوية ثانية ثم خيار نقل المياه فخيار اعذاب مياه البحر كحل أخير .

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المحور الخامس : مراقبة
استخراج المياه الجوفية
والتأثيرات البيئية

إ. علي عبد النبي شاكي *
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تقييم الوضع المائي بمنطقة غدوة «بحوض مرزق»

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** قسم علوم الأرض-كلية العلوم- جامعة سبها
*** استاذ علوم المياه-جامعة الفاتح-ذات العماد-طرابلس/ليبيا

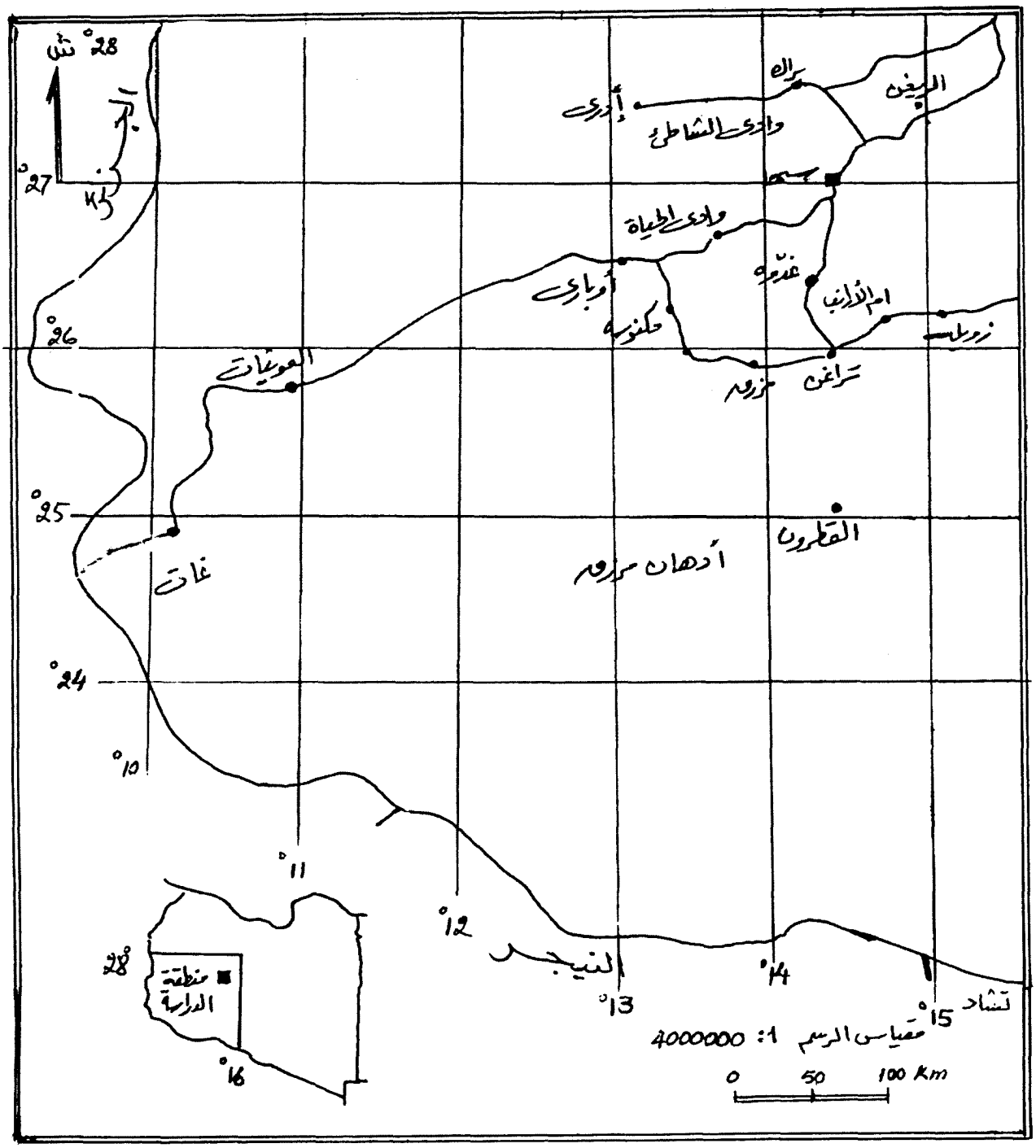
المستخلص

أقيمت هذه الدراسة في منطقة غدوة والتي تقع على بعد 70 كم جنوب غرب مدينة سبها بين خطي عرض 26°، 27° شمال خط الاستواء وخطي طول 14°، 15° شرق خط جرينتش في الفترة ما بين 8 - 1995 ف حتى 10 - 1996 ف.

أستهدفت هذه الدراسة تقييم الوضع المائي بمنطقة غدوه من الناحيتين الكمية والنوعية ففيما يتعلق بالناحية الكمية فقد تم تقدير الإنتاجية في عدد من الآبار ومن ثم قدرت الكميات المسحوبة من المياه خلال فترات الاستغلال الماضية والتي قدرت بـ 562014478 متر مكعب من الطبقتين السطحية والعميقة وأيضاً تم حساب مقدار الهبوط في منسوب المياه الذي نتج عن سحب هذه المياه، فقد وصل معدل الهبوط في الطبقات السطحية والتي تمثلها آبار المزارعين الخاصة إلى 0.108 متر/سنة وفي الطبقات العميقة والتي تمثلها آبار المشروع وصل إلى 0.343 متر/سنة وأجريت محاولة لمعرفة كفاءة استخدام هذه المياه للزراعة بإعتبارها الجانب الأكثر إستهلاكاً للمياه مع إهمال الاستهلاك المنزلي فقد وجد أن كفاءة استخدام المياه خلال فترة العشر سنوات الأولى انخفضت من 70٪عند بداية نشأة المشروع (الهيئة التنفيذية للزراعة بمنطقة فزان 1978 ف) إلى 61.3 وازدادت في الإنخفاض في الفترة الأخيرة حتى وصلت إلى 97 ، 57٪ تقريباً. كما تم تقدير متوسط المسامية الكلية بطبقات الأحجار الرملية التي تستمد منها الآبار العميقة مياهها حيث بلغت حوالي 17٪. وبعض المعاملات الهيدروليكية لهذه الطبقات فتم حساب معامل الانتقالية لعدد من الآبار العميقة في المنطقة فقد وجد أن متوسط الانتقالية لمجموعة هذه الآبار هي 4.1 x 10 $^{-2}$م^2/ث وتعذرحساب معامل التخزين وقد بلغ هذا المعامل في المناطق المجاورة لها كسبها على سبيل المثال والتي تستمد مياهها من نفس الطبقات إلى 2.0 x 10 $^{-4}$م^2/ث في المجموعة العلوية و4.2 x 10 $^{-4}$م^2/ث في المجموعة السفلية بحقب الحياة المتوسطة (الشاعر 1900).

أما فيما يتعلق بالناحية النوعية تم تحليل مياه عشرين بئراً منها عشرة سطحية وعشرة أخرى عميقة وقدرت فيها العناصر الرئيسية والنادرة. اتضح أن مياه هذه المنطقة تتميز عموماً بأيون الصوديوم (الكاتيونات) وأيون الكلوريد (الانيونات) بالنسبة للآبار السطحية والعميقة، إلا أن الآبار العميقة تتميز بان اغلب مياهها متكافئة في نسب الأيونات. كما أظهرت نتائج هذا التحليل أن مياه الآبار العميقة جميعها لم يتجاوز تركيز الأملاح الذائبة الكلية (TDS) بها 345.6 (جزء في الميلون) وعند تقيمها للري تبعاً لتصنيف مختبر الملوحة الأمريكي فمعظم مياهها وقعت ضمن الصنف الأول أي (مياه قليلة الملوحة - قليلة الصودية) حيث يمكن استخدامها لري معظم المحاصيل ولمعظم الترب. أما عند تصنيفها تبعاً لدليل منظمة الأغذية والزراعة الدولية فلا توجد أي مشكلة في استعمال معظم مياه هذه الآبار.

أما الآبار السطحية فقد تراوح تركيز الأملاح الذائبة الكلية (TDS) بها بين 609-5990 (جزء في المليون) فعند تصنيفها للري تبعاً لتصنيف مختبر الملوحة الأمريكي وقعت معظم المياه تحت أنواع عديدة تراوحت ما بين الصنف الثاني (متوسط الملوحة -قليل الصودية) حتى الصنف السادس عشر (مياه عالية جداً في الملوحة-عالية جداً في الصودية) وعند تصنيفها تبعاً لدليل منظمة الأغذية والزراعة العالمية أظهرت النتائج أن استعمال بعض مياه هذه الآبار تؤدي إلى زيادة في المشاكل المترتبة على استعمالها والبعض الآخر تكون المشاكل حادة جداً.



شكل (1) خريطة توضح موقع منطقة غدوة «منطقة الدراسة»
بالنسبة لخطوط الطول والعرض.

المصدر - (الأطلس التعليمي للمرحلة الأساسية - 1985)

المقدمة

تعتبر المياه العمود الفقري لجميع مجالات الحياة، ولأي تنمية زراعية أو صناعية أو إجتماعية وما يصاحبها من تطور إقتصادي وإجتماعي سريع يعتمد على مدى وفرة المياه، وقد صحب هذا التطور زيادة في معدلات الإستهلاك الذي أصبح يشكل أزمة مائية لأكثر من 43% من سكان العالم (المعتاز 1989 ف) .

وفي المناطق الجافة وشبه الجافة من العالم تزداد مشاكل توفر الموارد المائية الملائمة للإستغلال حيث يندر تساقط الأمطار والظروف المناخية التي تساعد على التصحر عموماً، فدرجات الحرارة العالية خصوصاً في فصل الصيف مع إنخفاض الرطوبة الجوية وشدة إشعاع وطول فترة سطوع الشمس كل هذه العوامل تزيد من معدلات فقد المياه وندرتها.

وتعد ليبيا من المناطق التي تعاني من نقص حاد في توفر الموارد المائية، لتغطية الإحتياجات في شتى مجالات الحياة، حيث تقع معظم أراضيها في نطاق المناطق الحارة الجافة، ويلعب كل من مناخ البحر المتوسط والمناخ الصحراوي دوراً أساسياً في خصائص المناخ في شمال البلاد وجنوبها، ويعتمد إعتماداً كبيراً على المياه الجوفية كمصدر رئيسي لجميع الأغراض والأنشطة الإقتصادية المختلفة، ونظراً للتزايد المضطرد في إستهلاك المياه نتيجة لتطور أساليب الحياة والنمو السكاني المتزايد ترتب عليه إستغلال مكثف لهذه المياه مما أدى إلى حدوث خلل في الميزان المائي لمعظم الخزانات الجوفية.

وتعتبر المياه الجوفية في جميع أنحاء حوض مرزق هي المصدر المائي الوحيد الذي يتم إستغلاله حالياً على نطاق واسع لأغراض الشرب والزراعة والصناعة، ولا يوجد أي مصدر مائي بديل في المنطقة، ويقع حوض مرزق في الطرف الجنوبي الغربي من ليبيا بين خطي عرض 20° - 21° شمال خط الإستواء وبين خطي طول 9°، 17°، شرقي خط جرينتش. ونتيجة للإستهلاك الكبير للمياه الجوفية والذي شمل في السنين الأخيرة بعض الخزانات الجوفية لحوض مرزق حدث هبوط ملحوظ في مستوى الماء الجوفي وبالتالي في كمية المياه المخزونة، فمن خلال القياسات الدورية في بعض المشاريع الزراعية والمناطق الآهلة بالسكان بحوض مرزق لوحظ أن معدلات الهبوط في سطح الجوفي تراوحت ما بين 0.07 متر/سنة في القطرون إلى 2.3 متر/سنة في أشكده الشاطي (كولان 1995) كما أدى هذا الإستهلاك إلى تغير واضح في نوعية المياه حيث تملحت مياه خزانات دهر الحياة المتوسطة والمستغلة على نطاق واسع نتيجة لتداخلها مع المياه السطحية بدهر الحياة الحديثة التي تعلوها (الشاعر 1987) . وعلى ضوء ذلك تطلب الأمر دراسة وتقييم الوضع المائي لهذه الخزانات والتي أستغلت مياهها لأكثر من عشرين سنة ولم يجر لأغلب المناطق بالحوض أي تقييم حتى الآن، من هنا إنبثق موضوع هذه الدراسة وأختيرت منطقة غدوة لإجراء هذه الدراسة، والأمر الذي شجع أكثر على إختيار هذه المنطقة هو وقوعها بعيداً على المثيرات الطبيعية للخزانات من تغذية أو سحب لا يمكن السيطرة عليها مما يؤدي إلى دراسة عملية على أساس جيد.

الهدف من الدراسة : -

أ - تحديد الكميات المسحوبة من المياه خلال فترة الإستغلال وتقدير بعض الخواص الهيدروليكية للخزانات والتي تساعد في تحديد الإمكانيات المائية بالمنطقة لأجل وضع سياسة مائية مستقبلية على ضوء هذه الإمكانيات.

ب - دراسة نوعية المياه بالمنطقة لمعرفة مدى ملاءمتها للزراعة.

طرق البحث

1 - حساب الكميات المستهلكة خلال الفترة الماضية

تم حساب متوسط الإنتاجية للآبار السطحية والعميقة بطريقة التيار النفاث (Jet Stream Method)

Q Gallon / min = A. K.....(1) (JAMES A 1979)

حيث :

K = **تحسب على أساس قطر الأنبوب الداخلي (بالبوصة) وتأخذ من جداول خاصة.**

A = **يتم قياسها في الحقل.**

وبمعرفة متوسط عدد ساعات التشغيل تم حساب الكمية المسحوبة من المياه خلال تلك الفترة.

2 - حساب المسامية الكلية

من خلال نتائج التصوير الجيوفيزيائي يمكن تقدير المسامية الكلية للأحجار الرملية المكونة للخزانات الجوفية المائية عن طريق حساب المقاومة النوعية وذلك بتطبيق معادلة أرس (ARCHIE)

$$Q = \left(\frac{a.\ Rmf)}{Rxo}\right)^{m} \qquad ...(2)$$

(حيث

Q = المسامية الكلية

a = معامل إنتشار السائل في الطبقة الصخرية وهو عامل تم تحديده من خلال التجارب المعملية لبعض الصخور ووجد أنه = 0.81 للحجر الرملي (Sand Stone)

m = معامل المادة اللاحمة (Cementation Factor) وعادة يؤخذ 2 لكل الصخور كمتوسط.

Rmf = المقاومة النوعية القصيرة العادية 16 لسائل الحفر

Rxo = المقاومة النوعية للقيمة المشبعة لسائل الحفر وتؤخذ من الحساب الجيوفيزيائية لبقية البئر.

3 - حساب الانتقالية ومعامل التخزين

يمكن حساب معامل الانتقالية من نتائج الضخ وقياسات زمن رجوع الماء إلى حالة السكون وذلك بتوقيع الزمن (الدقائق) مقابل الهبوط في سطح الماء على ورق بياني نصف لوغرتمي.

لحساب معامل الانتقالية من زمن الرجوع تم توقيع (t/t`) (حيث T هو الزمن الكلي مضاف إليها زمن الرجوع t مقسوماً على t` مقابل الإنخفاض المتبقي بالمتر وبذلك يمكن حساب T، S من معادلة جاكوب (COOPER & JACOB 1964) :

$$T = \frac{Q(m^3 / sec) \times 0.183}{\Delta s} \qquad ...(3)$$

$$S = \frac{0.3Tto}{r^2} \qquad ...(4)$$

حيث

T = الانتقالية (بالمتر المربع/ثانية)

Q = الإنتاجية (بالمتر المكعب/ثانية)

Δs = ميل المنحنى (معدل الهبوط)

S = معامل التخزين

R = بعد المراقبة عن البئر الإنتاجي بالمتر

t0 = تقاطع الخط المستقيم مع تدرج الزمن

3 - التحليل الكيميائي

جمعت عشرون عينة خلال فترة الدراسة عشرة من آبار الطبقة السطحية، عشرة من آبار الطبقة العميقة وأخذت للمعمل لغرض تحليلها وتم تقدير التالي :

1- التوصيل الكهربي (EC) قدرت بواسطة (Conductivity Meter)
(ومنها حساب الأملاح الكلية الذائبة (TDS) كجزء في المليون (عباوي 1990).
2 - درجة التفاعل (PH) بواسطة (PH - Meter Corning) (عباوي 1990).
3 - تقدير العناصر الرئيسية : Na, K تم تقديرها بواسطة (Flame Photometer)
- Mg++Cl, Ca++, SO_4 -- بطريقة المعايرة بواسطة محلول الفرسنيت EDTA (عباوي 1990).
- NO3 - بواسطة جهاز كلدال (عباوي 1990).
4 - العناصر الثقيلة النادرة : - تم تقديرها بواسطة جهاز الإمتصاص الذري Atomic Absorption (ASTM 1985).

النتائج

الكميات المستهلكة

بعد تقدير متوسط الإنتاجية للآبار السطحية والعميقة والتي قدرت بـ 27.5 $م^3$/ساعة و107 $م^3$/ساعة على التوالي وبمعرفة ساعات التشغيل أمكن تقدير الكميات المسحوبة من الطبقتين كما هي مدونة في الجدول رقم (1). وبعد توقيع هذه البيانات على منحنى يربط بين الكميات المسحوبة من المياه مع الزمن اتضح زيادة الكمية المسحوبة من الآبار السطحية بشكل واضح عنها في الآبار العميقة ويرجع السبب إلى التوسع الشديد في حفر الآبار السطحية، ويوضح ذلك الشكل رقم (2).

مناسيب المياه والتغيرات التي طرأت عليها

بعد معرفة الكميات المسحوبة من المياه خلال الفترة الماضية والتي قدرت بـ 406306478 $م^3$ من الطبقات السطحية تراوحت معدلات الهبوط لسطح الماء ما بين 0.055 إلى 0.20 م/سنة وكان المتوسط العام لمجموعة من الآبار يساوي 0.108 م/سنة ويتضح ذلك من خلال البيانات المدونة في الجدول رقم (2) بينما الكميات المسحوبة من الطبقات العميقة خلال الفترة الماضية قدرت بـ 15570900 $م^3$ الجدول رقم (1).

أدى سحب هذه الكمية إلى هبوط وقدره 7.9م (القياسات الدورية لبئر المراقبة رقم (4004) بالمنطقة) خلال السنوات الماضية أي بمعدل هبوط وقدره 0.343 م/سنة وبمقارنة معدل هذا الهبوط الذي حصل في منسوب المياه العميقة بمنطقة غدوة مع بعض معدلات الهبوط الحاصلة في المناطق المجاورة لها فقد بلغ معدل الهبوط في منطقة المكنوسة 0.396 م/سنة وفي منطقة زويلة إلى 0.53 م/سنة وهذا متقارب مع معدل الهبوط الحاصل في منطقة غدوة بينما تعدى ذلك كثيراً في منطقة سبها حيث بلغ 1.3 م/سنة (بئر المراقبة الموجود في مشروع الأبقار) ويتضح ذلك من خلال الشكل رقم (3).

تقييم كفاءة استخدام المياه للزراعة بالمشروع الزراعي لمنطقة الدراسة

قسمت فترة استغلال المياه في المشروع إلى فترتين كل فترة حوالي عشر سنوات، تبدأ الفترة الأولى من بداية نشأت المشروع حتى سنة 1984، 1985 ف والأخرى من تاريخ نهاية الفترة الأولى حتى سنة 1996 ف.

يمكن التعرف على كفاءة استخدام المياه من خلال المعادلة التالية :-

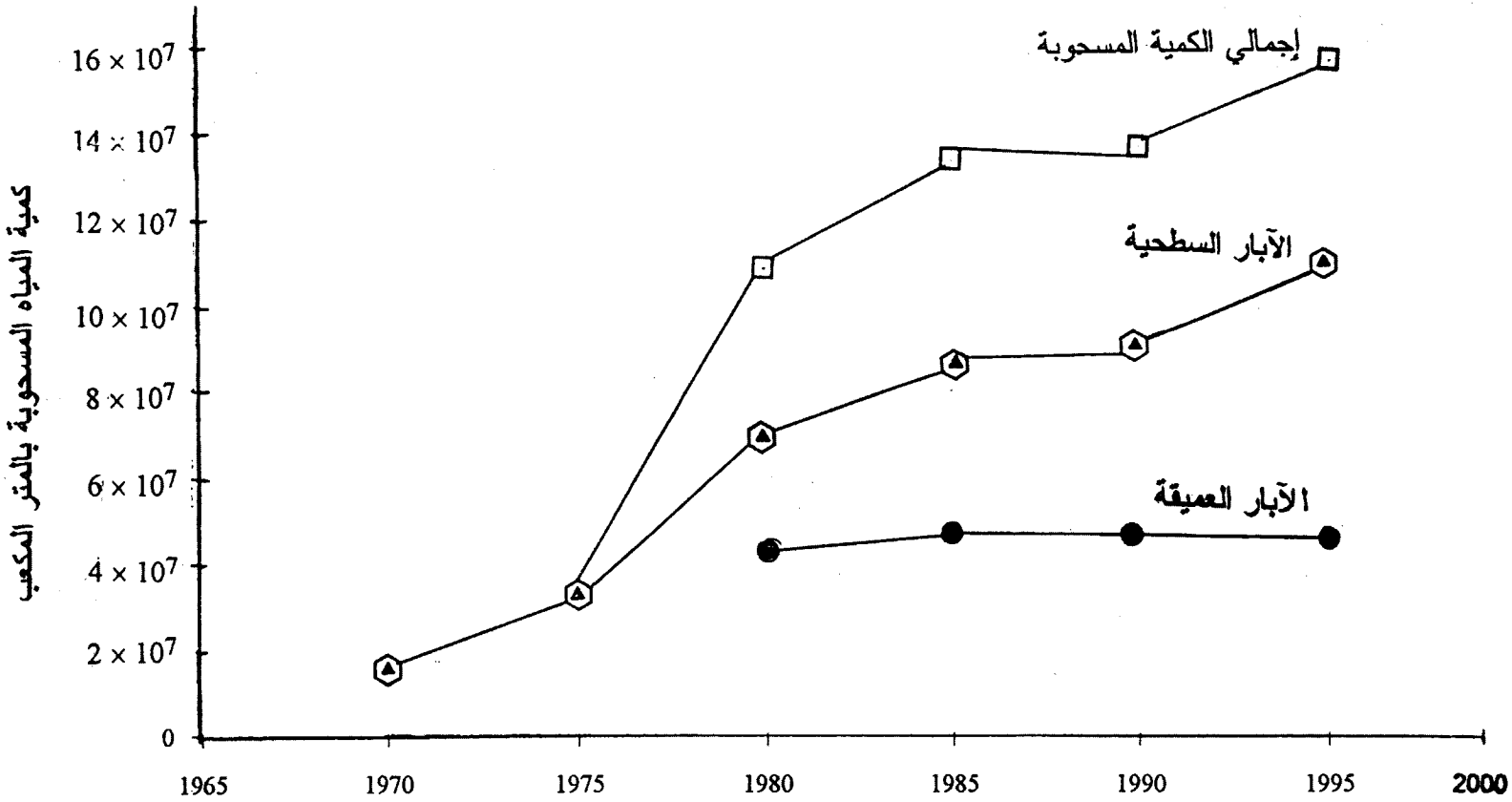
$$\text{كفاءة إستخدام المياه} = \frac{\text{كمية المياه المطلوبة لري المحاصيل}}{\text{كمية المياه المسحوبة من الآبار}} \times 100$$

الجدول (1) الكميات المستهلكة من المياه (بالمتر المكعب) من الآبار السطحية والعميقة خلال السنوات الماضية

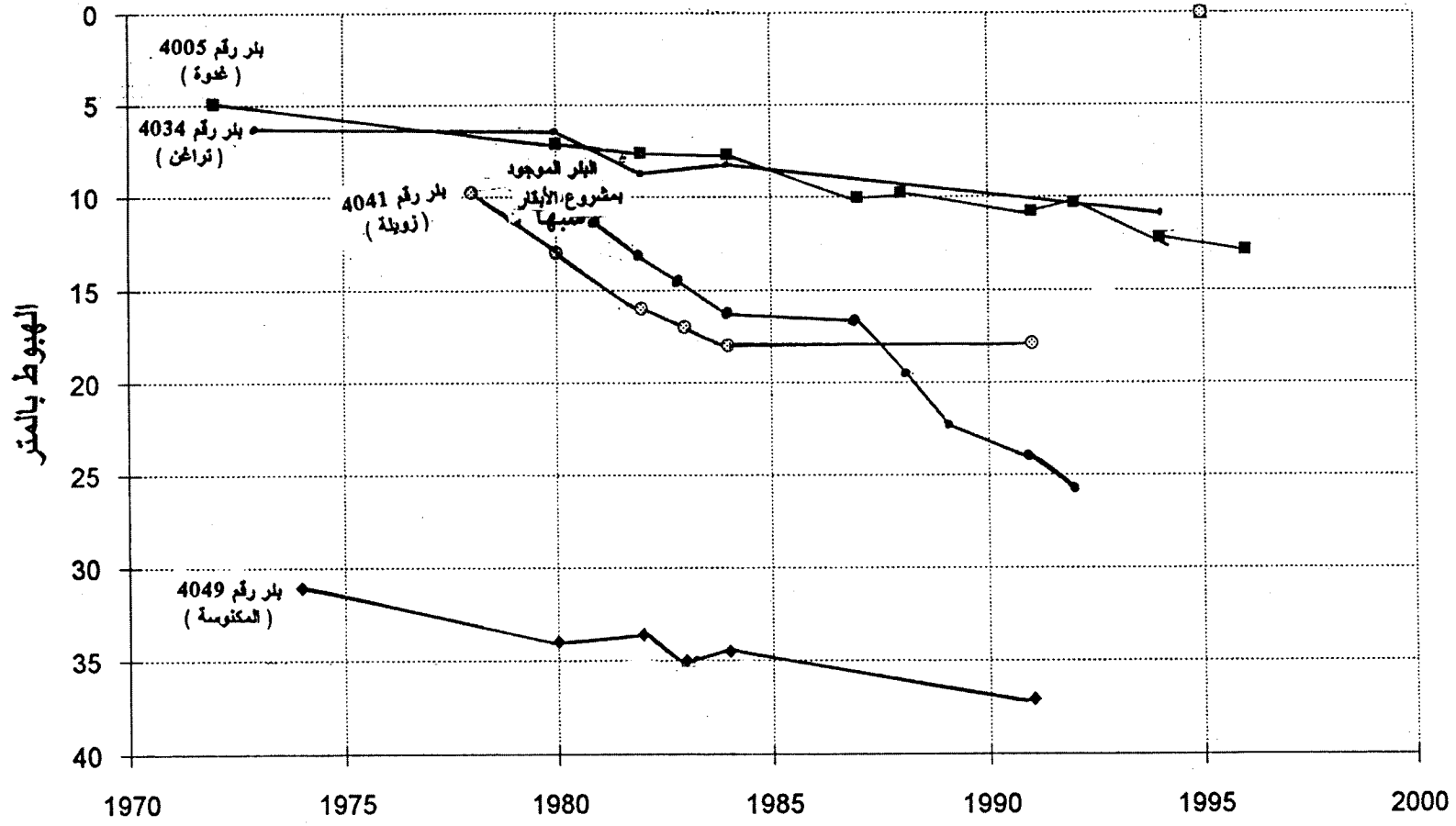
الفترة بالسنوات	كمية المياه المسحوبة من الآبار العميقة(م³)	كمية المياه المسحوبة من الآبار السطحية(م³)	الإجمالي (م³)
(1970)-		16260750	16260750
(1975-70)		32521500	32521500
(1980-75)	41610000	70147068	111757068
(1985-80)	43800000	86272312	130072312
(1990-85)	35149500	90698849	125848349
(1995-90)	35149500	110404999	145554499
الاجمالي	155709000	406305478	562014478

جدول (2) يبين معدل الهبوط لمستوى الماء الثابت للآبار السطحية (آبار المزارعين الخاصة)

رقم البئر	مستوى الماء السابق		مستوى الماء عند آخر قياس		اجمالي الهبوط بالمتر	معدل الهبوط السنوي بالمتر
	السنة	العمق بالمتر	السنة	العمق بالمتر		
1	1969	12	1993	14,5	2,5	0.104
2	1983	8	1995	10	2	0.166
3	1968	6.5	1995	8	1.5	0.055
4	1968	12	1993	14	2	0.080
5	1964	4	1995	6.5	2.5	0.080
6	1974	8	1994	10.5	2.5	0.125
7	1969	12	1977	12.6	0.6	0.075
8	1990	7	1995	10	3	0.020
9	1977	7	1995	9	2	0.111
10	1972	8	1995	10	2	0.080
المعدل						0,107



شكل (2) يوضح التغير في الكميات المستغلة من المياه (بالمتر المكعب) من الطبقتين السطحية والعميقة بالمنطقة خلال الفترة الماضية.



شكل (3) يوضح معدل الهبوط في آبار المراقبة لمنطقة غدوة وبعض المناطق المجاورة لها.

المرحلة الأولى

بمعرفة كمية المياه المطلوبة لري المحاصيل خلال الفترة الأولى والتي قدرت بـ 5236046 م^3 الجدول رقم(3). وكمية المياه التي سحبت خلال تلك الفترة والتي قدرت بـ 8541000 م^3 الجدول رقم (1) تكون كفاءة استخدام المياه لهذه الفترة 61.3٪.

المرحلة الثانية

كمية المياه المطلوبة لري المحاصيل لتلك الفترة هي 4005360 م3 الجدول رقم (4) وكمية المياه التي سحبت خلال تلك الفترة قدرت بـ 7029900 الجدول رقم (1) وبذلك تكون كفاءة استخدام المياه لهذه الفترة هي 56.97٪.

من خلال الحسابات السابقة نجد أن كفاءة استخدام المياه قد انخفضت إلى61.3٪ عما كانت عليه قبل بداية نشأت المشروع والتي قدرت بـ 70٪ (دراسة الإحتياجات المائية بمشاريع الهيئة التنفيذية للزراعة بمنطقة فزان سنة (1997). أما في الفترة الثانية فأمتازت بانخفاض شديد في كفاءة استخدام أنظمة الري إلى الحد الذي وصلت فيه إلى 56.97٪ ويعزى هذا الإنخفاض في الكفاءة بالدرجة الأولى إلى تلف وانهيار أجزاء شبكات توزيع المياه والناتجة من قدم وعدم صيانة هذه الشبكات واستبدال المواسير التالفة، ويرجع السبب الأخر إلى زيادة المفقودات المائية وانخفاض كفاءة الري نتيجة الري خلال فترات النهار وخاصة في فصل الصيف.

والملاحظة الجديرة بالذكر أيضاً عدم نمو النباتات في الأراضي الواقعة في الناحية الغربية في المشروع وهذه المناطق تتميز بوجود تركيزات عالية من الأملاح والتي تظهر أحياناً على شكل صخور ملحية مع أن هذه الأراضي تروى بمياه ري جيدة (نتائج التحليل الكيميائي) ولفترة طويلة بالرغم من أن قوامها خفيف حيث نجد أغلبها (طمى رملي - رملي طمى) (الهيئة التنفيذية للزراعة بمنطقة فزان 1978) أي تسمح بنفاذية جيدة مع وجود كميات من الجبس تمنع تكون ترب صودية رديئة الصرف وفي اعتقادي أن ذلك يرجع إلى تأثير هذه الأملاح التي لم تغسل من قطاع التربة لعدم إضافة كميات كافية من المياه تتضمن الاحتياجات الغسيلية لهذه الأراضي.

معامل الانتقالية (Transmisivity)

تم الاستعانة بالمعلومات الخاصة بتجارب الضخ الموجودة في التقارير الفنية للآبار العميقة وتم تحليلها بنفس الطريقة المشار إليها سابقاً (وجد ان متوسط معامل الانتقالية لهذه الآبار 4.1×10^{-2} م^2/ث.

جدول (3) الاحتياجات المائية للمحاصيل المزروعة والمساحات التي تغطيها لسنة 1984 - 1985 إفرنجي

المحصول	الإحتياجات المائية متر^3/هكتار	المساحات المزروعة هكتار	الإحتياجات المائية الكلية متر^3
قمح وشعير	*5454.4	**153	834523.2
صفصفة (قصب)	*23938.3	**104	2489578
خضروات	*24640.0	**34	837760
فاكهة	*21483.7	**50	1074185
المجموع			5236046.2

جدول (4) الاحتياجات المائية للمحاصيل المزروعة والمساحات التي تغطيها لسنة 1995 , 1996 إفرنجي

المحصول	الإحتياجات المائية متر^3/هكتار	المساحات المزروعة هكتار	الإحتياجات المائية الكلية متر^3
قمح وشعير	5454.4	***120	654528
صفصفة (قصب)	23938.3	***144	3447108
خضروات (دلاع)	24640.0	***20	492800
المجموع			4005360

* دراسة الاحتياجات المائية لمشاريع الهيئة بمنطقة فزان سنة 1997 إفرنجي.

** خرائط التصوير الجوي التي تم تنفيذها من قبل شركة IMP الألمانية لحصر الأراضي المستغلة زراعياً لمنطقة غدوة 1984إفرنجي.

*** القياسات الحقلية التي اجريت من قبل الباحث.

المسامية الكلية (Total Porosity)

(تم حساب المسامية الكلية عن طريق حساب المقاومة النوعية 16 وذلك بتطبيق معادلة (آرسي) لعدد 7 آبار عميقة تستمد مياهها من الأحجار الرملية لحقب الحياة المتوسطة (المجموعة الثانية) وكان متوسط المسامية الكلية لهذه الطبقات هو 17٪ كما هو موضح بالجدول رقم (5).

التحليل الكيميائي

من خلال النتائج المدونة في الجدول رقم (7.6) والمتضمن نتائج التحليل الكيميائي للآبار السطحية والعميقة يتضح تفاوت كبير في تركيز الأملاح الذائبة الكلية بين مياه الآبار السطحية حيث تراوح التركيز ما بين (609 إلى 5990) جزء من المليون بينما لم يتعدى تركيزها (345.6) جزء في المليون بالنسبة للآبار العميقة. ويتضح ان مياه هذه المنطقة تتميز عموماً بأيون الصوديوم (الكاتيونات) وأيون الكلوريد (الأيونات) بالنسبة للآبار السطحية والعميقة وهذا التركيز العالي للأملاح في الآبار السطحية راجع إلى أسباب جيولوجية ومناخية مرت بها المنطقة خلال العصور القديمة (الشاعر 1990). إلا أن الآبار العميقة تتميز بأن أغلب مياهها متكافئة في نسب الأيونات.

تقييم المياه للري

لتصنيف المياه للري هناك عدة معايير ومؤشرات تستخدم لغرض الحصول على أنواع مختلفة من مياه الري تختلف من ناحية النوعية التي تعكس لنا مدى صلاحية هذه المياه لأغراض الري. وقد اقترحت عدة مخططات لتصنيف مياه الري سوف نطبق أهمها في هذه الدراسة :-

1 - نظام تصنيف مياه الري المقترح من قبل مختبر الملوحة الأمريكي

اقترح هذا النظام في الخمسينات ويعتبر من أكثر الأنظمة استعمالاً في العالم حتى الآن حيث يأخذ بنظر الاعتبار المؤشرين الأساسيين لتقييم مياه الري وهما التركيز الكلي للأملاح (الملوحة) معبراً عنها بالتوصيل الكهربي (EC) ونسبة امتزاز الصوديوم (SAR).

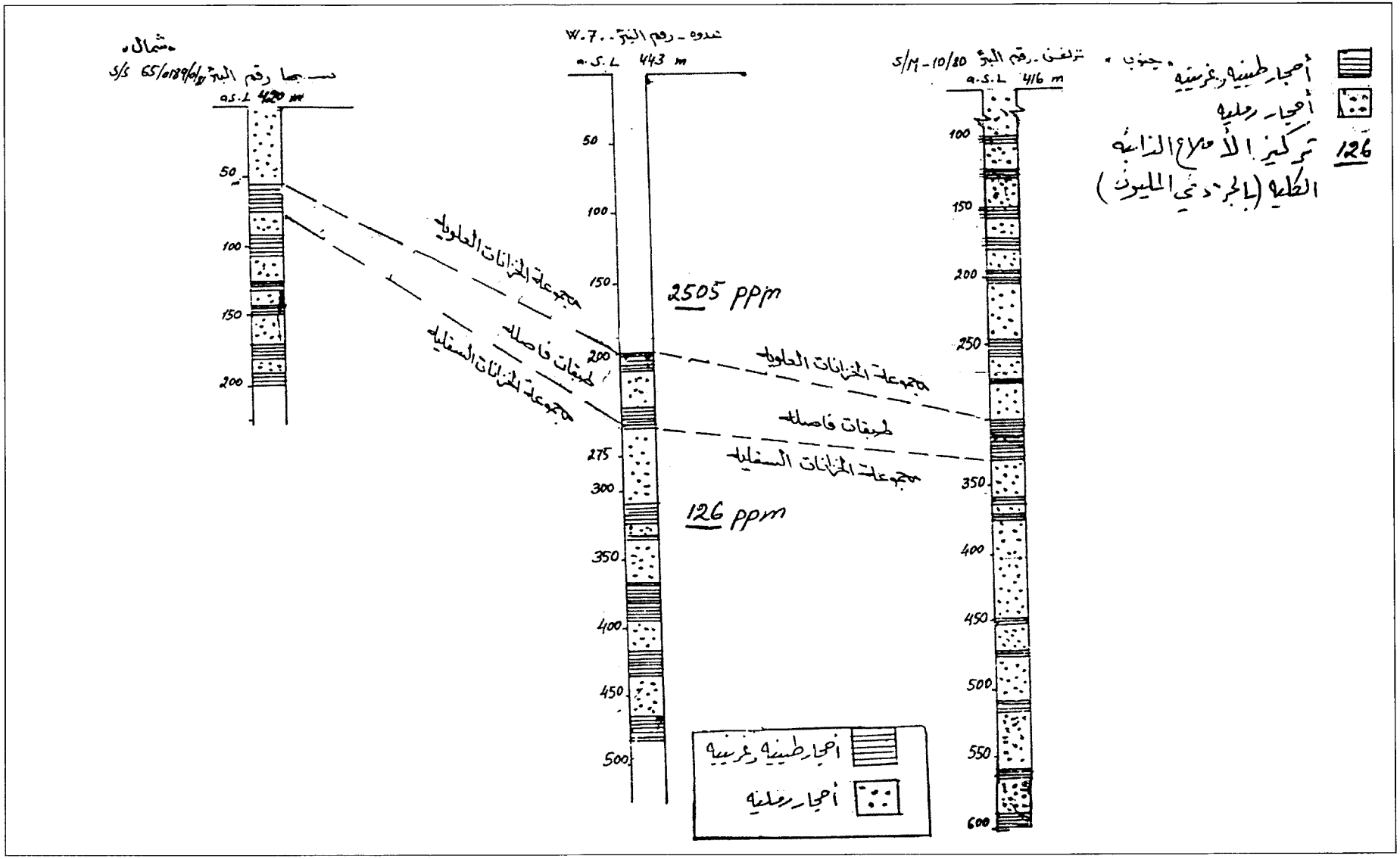
بعد توقيع قيم التوصيل الكهربي ونسبة امتزاز الصوديوم الموجودة في الجدول رقم (7.6) على المخطط المشار إليه اتضح ان كل الآبار العميقة (آبار المشروع) وقعت ضمن النوع الأول (C1S1) (مياه قليلة الملوحة - قليلة الصودية) أي يمكن استخدامها لري معظم المحاصيل ولمعظم الترب دون ان تسبب في اظهار ملوحة في التربة أو مشكلة في النفاذية ما عدا البئر رقم (10) وقع ضمن النوع الثاني (C2S1) مياه متوسطة الملوحة - قليلة الصودية، وهذا الماء ملائم للنباتات جيدة التحمل للملوحة. مع احتمال ظهور مشكلة نفاذية للترب التي تزيد بها نسبة الطين مع العلم ان الترب الموجودة في المشروع ذات قوام متوسط إلى خشن.

بينما نلاحظ ان الآبار السطحية (آبار المزارعين الخاصة) وقعت تحت أنواع عديدة فنجد أن البئرين رقم (3,2) وقعت تحت نفس النوع السابق ذكره (C2S1) والبئر رقم (5.1) وقعا ضمن الصنف (C1S3) (مياه عالية الملوحة قليلة - قليلة الصودية) وهذه المياه لا تصلح للمحاصيل الحساسة خاصة الحمضيات ويصلح استخدامها فقط في الترب ذات النفاذية الجيدة (الرشح الجيد) لأن الترب المستعملة لهذا النوع من مياه الري تحتاج إلى غسيل، أما البئر رقم (7) وقع ضمن النوع (C2S3) مياه عالية الملوحة - متوسطة الصودية) وهذه المياه تتطابق في صفاتها مع النوع السابق فضلاً عن تطور مشكلة النفاذية خصوصاً في الترب الطينية. أما البئر رقم (4) وقع ضمن النوع (C4S2) (مياه عالية جداً في الملوحة - متوسطة الصودية) وهذا النوع يستخدم في الترب جيدة الصرف ذات القوام الخشن وازدياد الصوديوم ربما بسبب مشكلة النفاذية كما يستخدم للبناتات ذات التحمل العالي للملوحة بينما الآبار رقم (10.8.6) وقعت ضمن النوع (C4S3) (مياه عالية جداً في الملوحة - عالية في الصودية) وهذه المياه غير صالحة في الظروف الاعتيادية ويمكن استخدامها في حالات معينة عند الترب ذات النفاذية العالية جداً كالترب الرملية وصرف ذو كفاءة عالية ومحاصيل ذات تحمل إلى جداً للملوحة. أما البئر رقم (9) وقع ضمن النوع (C4S4) (مياه عالية جداً في الملوحة - عالية جداً في الصودية) وهذه المياه تعتبر غير صالحة لإغراض الري إلا في حالات معينة عند توفر كميات من الجبس الشكل رقم (6 - 7) يوضح هذا التصنيف

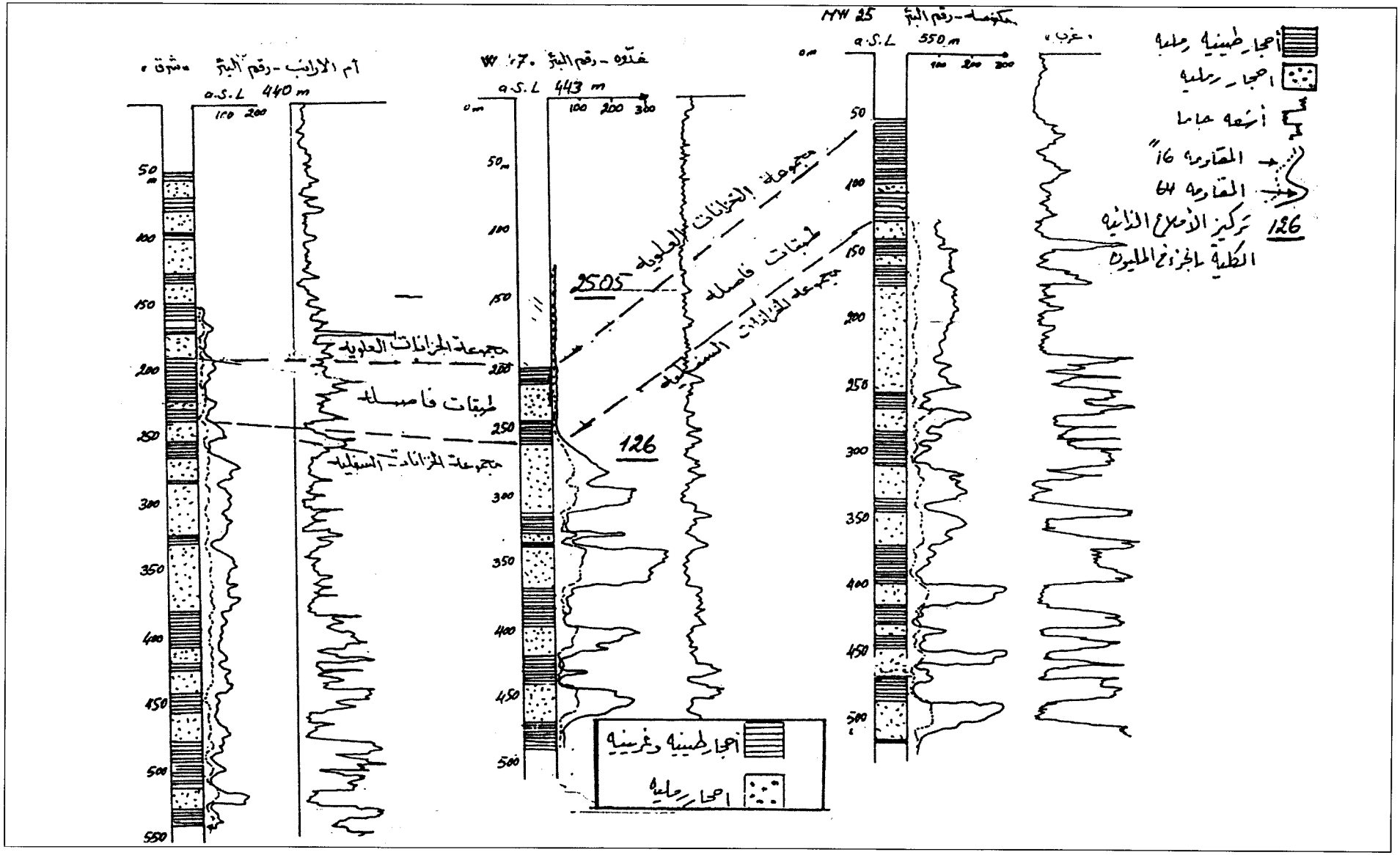
جدول (5)

البيانات اللازمة لحساب المسامية الكلية في الأحجار الرملية التي تستغل مياهها.

رقم البئر		G 5	G 6	G 7	G 8	G 9	G10	G 11	المتوسط
Rmf ohm/m at T°C		2.1 at 27oC	3.8 at 24	7 at 20	1.8 at 24	2.6 at 24	2.2 at 30	2.6 at 30	
الأحجار	العمق (m)	279 - 289	282 - 298		285 - 305	289 - 302			15.9
	Rxo ohm/m	80	90		80	70			
	Ø %	0.145	18.4		13.5	17.3			
الرملية	العمق (m)	338 - 350	331 - 335	336 - 360	331 - 362	334 - 365	349 - 366	354 - 374	16.2
	Rxo ohm/m	100	110	110	95	90	80	60	
التي تم	Ø %	13.0	16.7	22.7	12.3	15.3	14.9	18.7	
	العمق (m)	382 - 404	388 - 398	376 - 389	383 - 406	395 - 415	396 - 413	397 - 419	17.8
فيها	Rxo ohm/m	90	90	100	60	60	70	60	
	Ø %	13.7	18.4	23.8	15.5	18.7	15.9	18.7	
حساب	العمق (m)	440 - 455	434 - 455	443 - 464	450 - 470	442 - 465	441 - 464	452 - 471	18.0
	Rxo ohm/m	80	80	90	85	70	80	80	
المسامية	Ø %	14.5	19.6	25.0	13.1	17.3	14.9	16.2	
	المتوسط	13.9	18.2	23.8	13.5	17.0	15.2	18.2	% 17



شكل (4) مضاهاة ليتولوجية تبين مجموعة الخزانات العلوية والسفلية
لحقب الحياة المتوسطة (شمال-جنوب)



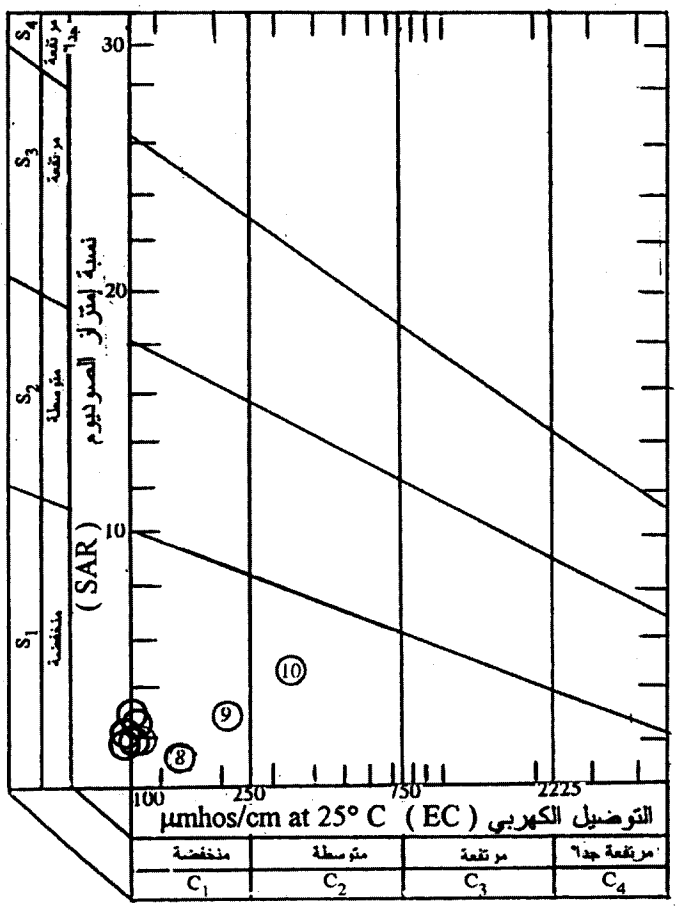
شكل (5) مضاهاة ليتولوجية هيدروجيولوجية تبين مجموعة
الخزانات العلوية والسفلية لحقب الحياة المتوسطة (شرق-غرب)

جدول (6) نتائج التحليل الكيميائي للعناصر الرئيسية لمياه الآبار السطحية (آبار المزارعين الخاصين)

رقم البئر	عمق البئر (m)	درجة الحرارة °C	الرقم الهيدروجيني pH	التوصيل الكهربي mmohs/cm at 25°C	الأملاح الذائبة الكلية (ppm)	Na^{+} meq/L (ppm)	k^{+} meq/L (ppm)	Ca^{++} meq/L (ppm)	Mg^{++} meq/L (ppm)	cl^{-} meq/L (ppm)	HCO_3^{-} meq/L (ppm)	$SO_4^{=}$ meq/L (ppm)	NO_3^{-} meq/L (ppm)	CO_2	Na %	SAR	adj SAR	RSC meq/l
1	41	26	6.9	2.820	1805	10.783 247.94	2.462 95.94	9.68 193.6	4.68 56.16	11.50 408.25	3.2 195.20	12.08 579.84	1.65 102.30		39.0	4.02	14.08	-11.16
2	28	27	7.1	0.952	609	3.896 89.70	2.564 99.84	3.32 66.4	2.44 29.28	4.7 166.85	1.5 91.50	4.48 215.08	0.88 54.56	41.48	31.9	2.3	6.43	-4.26
3	27	26	7.1	0.960	614	4.66 107.18	2.564 99.84	2.64 52.8	1.52 18.24	5.0 177.50	1.5 91.50	4.08 195.84	0.48 29.76	48.8	40.9	3.23	8.40	-2.66
4	44	26	6.9	4.010	2563	20.174 463.90	2.00 78.00	6.92 138.4	6.24 74.88	27.0 958.50	1.39 84.79	10.76 516.48	2.44 151.28		57.1	7.86	29.09	-11.77
5	8.5	25.5	6.9	1.660	1060	9.565 220.11	1.692 65.91	3.08 61.6	1.88 22.65	7.5 266.25	1.86 113.46	8.16 391.68	0.33 20.46		59	4.17	13.34	-3.1
6	11	25.5	6.8	5.036	3222	26.783 615.94	2.359 39.04	13.68 273.6	5.92 71.04	25.2 89.60	3.7 225.70	11.04 529.92	1.23 76.26		54.9	8.51	34.04	-16.11
7	76	27	7.3	2.170	1389	12.348 284.05	0.821 32.02	3.84 76.8	0.56 6.72	14.6 518.30	1.52 92.72	2.68 128.64	1.04 64.48	56.12	70.3	8.33	26.64	-2.88
8	34	26	7.2	6.152	3937	27.826 640.09	2.564 99.84	20 400.0	6.6 79.2	42.3 1501.65	2.42 147.62	10.32 495.36	2.95 182.90		48.8	7.63	30.52	-24.18
9	32	25.5	7.0	9.360	5990	50.783 1167.94	4.821 187.98	22.2 444.0	10.4 124.8	66.9 2374.95	3.34 203.74	12.52 600.96	3.7 229.4		57.6	12.58	55.34	-29.26
10	33	25	7.9	6.032	3861	28.174 649.91	3.128 122.07	15.28 305.6	6.72 80.64	39.80 1412.90	2.28 139.90	10.72 514.65	2.60 161.2		52.9	8.48	33.97	-19.72

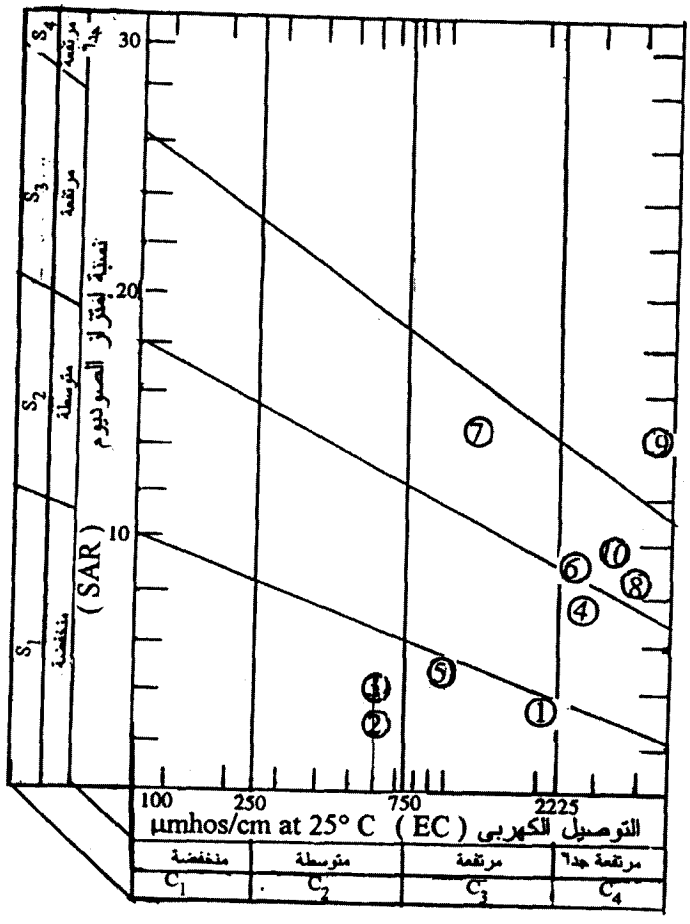
جدول (7) نتائج التحليل الكيميائي للعناصر الرئيسية لمياه الآبار العميقة (آبار المشروع الزراعي)

رقم البئر	(m)	درجة °C	الرقم الهيدروجيني pH	التوصيل الكهربي mmohs/cm at 25°C	الأملاح الذائبة الكلية (ppm)	Na^+ (ppm)	k^+ (ppm)	Ca^{++} (ppm)	Mg^{++} (ppm)	cl^- (ppm)	HCO_3^- (ppm)	$SO_4^=$ (ppm)	NO_3^- (ppm)	CO_2 (ppm)	Na %	SAR	adj SAR	RSC meq/l
W2		33	7.0	0.120	76.80	0.223 5.129	0.359 14.000	0.20 4.0	0.80 9.6	0.50 1.75	0.90 54.9	 13.44	- -		14.1	0.311	0.373	-0.1
W3		33	6.6	0.094	60.16	0.129 2.967	0.154 6.006	0.22 4.4	0.50 6.0	0.45 15.975	0.81 49.41	0.48 23.04	0.01 0.62		12.8	0.217	0.286	-0.09
W4		34	6.5	0.103	65.92	0.184 4.232	0.103 4.017	0.26 5.2	0.54 6.48	0.50 17.75	0.67 40.87	0.44 21.12	0.01 0.62		16.9	0.285	0.570	-0.13
W5	467	32	6.5	0.146	93.44	0.696 16.008	0.308 12.012	0.24 4.8	0.48 6.76	0.80 28.4	0.69 42.09	0.76 36.48	0.05 3.10	111.63	40.4	1.170	1.544	-0.03
W6	470	34	6.7	0.120	76.80	0.181 4.163	0.359 14.000	0.28 5.6	0.56 6.72	0.45 15.975	0.76 46.36	0.56 26.88	- -	95.16	13.1	0.278	0.556	-0.08
W7	475	35	6.7	0.103	65.92	0.129 2.967	0.309 12.051	0.2 4.0	0.64 7.68	0.50 17.75	0.82 50.02	0.28 13.44	0.01 0.62	68.32	10.1	0.200	0.400	-0.02
W8	482	34	6.7	0.223	142.70	0.974 22.402	0.410 15.99	0.22 4.4	0.58 6.96	1.3 46.15	0.82 50.02	0.52 24.96	0.03 1.86	84.18	44.6	1.534	2.224	+0.02
W9	475	34	6.6	0.412	263.70	2.296 52.90	0.462 18.018	0.28 6.5	0.96 11.52	2.8 99.4	0.82 50.62	1.04 49.92	0.06 3.72	81.14	57.4	2.920	5.840	-0.41
W10	478	34	6.5	0.540	345.60	3.061 70.38	0.513 20.007	0.32 6.4	1.16 13.92	3.55 126.03	0.77 46.97	0.80 38.4	0.03 1.86		60.6	3.557	7.825	-0.71
W11	483	34	6.6	0.112	71.68	0.153 3.519	0.256 9.984	0.16 3.2	0.44 5.28	0.50 17.75	0.82 50.02	1.02 48.96	0.07 4.34		15.1	0.274	0.219	+0.22



شكل (6) مخطط تصنيف مياه الآبار العميقة لأغراض الري تبعاً لتصنيف مختبر الملوحة الأمريكي.

(Richards-1954)



شكل (7) مخطط تصنيف مياه الآبار السطحية لأغراض الري تبعاً لتصنيف مختبر الملوحة الأمريكي.
(Richards-1954)

2 - نظام تصنيف مياه الري المقترح من قبل منظمة الغذاء والزراعة

لقد اعتمد في هذا الدليل أربعة مؤشرات أساسية لتقييم مياه الري وهي الملوحة والنفاذية والسمية ومشاكل تأثيرات عرضية أخرى. واستخدم في هذا الدليل اسلوب آخر لتقييم مدى تأثير هذه المؤشرات على التربة والنبات فتم تقسيم شدة الخطورة الناتجة من استخدام المياه المختلفة النوعية إلى ثلاثة أصناف وهي : لا توجد مشكلة No Problem وزيادة في المشكلة Problem increasing ومشكلة حادة Problem Sever بدلاً من الرموز التي استخدمت في مخطط مختبر الملوحة الأمريكي.

ان كثيراً من الافتراضات التي اشترطها الدليل متوفرة ومتطابقة إلى حد كبير جداً مع منطقة الدراسة وعند تطبيق نتائج التحليل الكيميائي على هذا الدليل اتضح ما يلي :

1- بالنسبة لمؤشر الملوحة :

في الآبار العميقة (آبار المشروع) وجد ان التواصل الكهربي (EC) اقل من 0.75 ms/cm بمعنى لا توجد مشكلة لاستعمال هذه المياه في الري أما بالنسبة لآبار المياه السطحية (آبار المزارعين الخاصة) فتختلف درجة المشكلة بالنسبة للآبار (1) و(2) و(3) و(5) و(7) واحتمال ظهور مشكلة حادة نتيجة استعمال مياه الآبار (4) و(6) و(8) و(9) و(10) فعند استعمال هذه المياه للري يجب استخدام محاصيل زراعية متحملة للملوحة من اجل الحصول على إنتاج مناسب.

2 - بالنسبة لمؤشر سمية بعض الأيونات :

1 - سمية أيون الصوديوم (نسبة امتزاز الصوديوم المعدلة) في الآبار العميقة (آبار المشروع) وجد انه لا توجد مشكلة عند استعمال مياه هذه الآبار عدا البئرين (9) ، (10) فهناك احتمال زيادة في المشكلة عند استخدام مياهها أما بالنسبة للآبار السطحية فتختلف درجة المشكلة من (زيادة في المشكلة) إلى احتمال ظهور (مشكلة حادة) فنجد ان الزيادة في المشكلة تنتج من استعمال البئرين رقم (2) ، (3) أما باقي الآبار فاحتمال ظهور مشكلة حادة جداً عند استخدام مياهها.

ب - سمية أيون الكلور، لا توجد مشكلة سمية بأيون الكلور عند استخدام مياه الآبار العميقة (آبار المشروع) أما بالنسبة للآبار السطحية (آبار المزارعين) فنجد الآبار (2) ، (4) ، (5) توجد زيادة في المشكلة وباقي الآبار فهناك احتمال ظهور مشكلة سمية حادة حيث يزيد فيها تركيز الكلور عن 10ملي مكافىء /لتر.

3 - مشكلة التأثيرات المتنوعة.

1 - تأثيرات النيترات :

بالنسبة للمياه العميقة (آبار المشروع) جميعها لم يتجاوز تركيز النيترات بها 5 إلى 30 (جزء في المليون).

أما باقي الآبار فجميعها تجاوزت 30 (جزء في المليون) فهناك احتمال ظهور مشكلة حادة عند استعمال هذه المياه نتيجة ازدياد النتروجين في المياه والذي يسبب في النمو الخضري وتأخر نضج المحصول.

ب - تأثير البيكربونات :

من ناحية تأثير البيكربونات لا توجد مشكلة بالنسبة لاستعمال مياه الآبار العميقة (آبار المشروع) حيث ان جميعها لا تتجاوز 1.5 ملي مكافىء/لتر أما بالنسبة للآبار السطحية (آبار المزارعين) فلا توجد مشكلة أو أي تأثير للبيكربونات الموجودة في مياه الآبار (2) و(03) و(4) أما بالنسبة لباقي الآبار فهناك احتمال ظهور زيادة في المشكلة تتمثل في ظهور بقع بيضاء على ورق بعض المحاصيل خاصة التي تروى بطريقة الرش.

ج - تأثير الأس الهيدروجيني :

جميع الآبار المدروسة تقع في المدى الاعتباري للرقم الهيدروجيني والذي يتراوح بين (6.5 إلى 8,5).

جدول دليل منظمة الأغذية والزراعة الدولية لتصنيف مياه الري.

مشكلة الري (المؤشر)	درجة المشكلة		
	لا توجد مشكلة	زيادة في المشكلة	مشكلة حادة
الملوحة (تؤثر على جاهزية الماء) التوصيل الكهربائي للماء (ECw) ملي سيمنز / سم أو ديسي سيمنز/م)	أقل من 0.75	3.0 - 0.75	أكثر من 3.0
النفاذية (تؤثر على سرعة غيض التربة) التوصيل الكهربائي للماء (ECw) (2.1*) نسبة امتزاز الصوديوم المعدلة (Adj . SAR) في حالة كون المعدن السائد :	أكبر من 0.5	0.5 - 0.2	أقل من 0.2
1- المونتوربلونايت	أقل من 6	9 - 6[3]*	أكبر من 9
2- الالايت - الفيرميكولايت	أقل من8	16 - 8[3]*	أكبر من 16
3- الكاؤلينايت - الاكاسيد الثلاثية (اكاسيد الحديد والالمنيوم)	أقل من 16	24 - 16[3]*	أكبر من 24
سمية بعض الايونات (تؤثر على المحاصيل الحساسة)			
الصوديوم (نسبة امتزاز الصوديوم المعدلة [4و5]*	أقل من 3	9 - 3	أكبر من 9
الكلوريد (ملي مكافئ/لتر)[4و5]*	أقل من 4	10 - 4	أكبر من 10
البورون (ملغم/لتر)	أقل من 0.75	2.0 - 0.75	أكبر من 3.0
تأثيرات متنوعة (تؤثر على بعض المحاصيل)			
النترات (نتروجين) أو الامونيوم (نتروجين) ملغم/لتر	أقل من 5	30 - 5	أكبر من 30
البايكاربونات (ملي مكافئ/لتر) في حالة الري بالرش	أقل من 1.5	8.5 - 1.5	أكبر من 8.5
الاس الهيدروجيني	(المعدل	الاعتيادي 6.5 - 8.4)	

*(1) نسبة امتزاز الصوديوم المعدلة (Adj.SAR) يتم حسابها بالطريقة التي أشرنا إليها في صفحة (390).

*(2) ان القيم المذكورة أعلاه ترتبط بنوع المعدن (معدن الطين) السائد في التربة خاصة وان ثباتية البناء (التركيب) تختلف تبعا لاختلاف معدن الطين (Rallings 1966 and Rhoads 1975).

وتكون مشكلة النفاذية أقل حدوثا إذا كانت ملوحة مياه الري عالية، ويحتمل حدوثها في حالة الملوحة الواطئة لمياه الري.

*(3) يستخدم المستوى الواطئ (المدى الواطئ) إذا كانت قيمة التوصيل الكهربائي لمياه الري اقل من (4) ملي سيمنز/سم. ويستخدم المدى المتوسط إذا كانت قيمة التوصيل الكهربائي لمياه الري تتراوح (0.4 - 1.6) ملي سيمنز/سم. ويستخدم المدى الأعلى عندما يكون التوصيل اكهربائي لمياه الري أكبر من (1.6) ملي سيمنز/سم.

*(4) معظم محاصيل الأشجار واشجار الزينة تكون حساسة للصوديوم والكلور (تستخدم القيم المذكورة أعلاه) وبالنسبة للمحاصيل الفصلية التي تعتبر غير حساسة لهذين الايونين (يفضل استخدام جداول تحمل الملوحة التي أشرنا إليها سابقا).

*(5) في حالة الري بالرش بالنسبة للمحاصيل الحساسة. كما أن ايونات الصوديوم والكلوريد، وعندما تكون بتراكيز أكبر من 3 ملي مكافئ/لتر وفي ظروف معينة يمكن أن تسبب تدهور المحصول وامتصاصها من قبل الأوراق بكميات زائدة.

المصدر - (AYERS & WESTCOT)

المناقشة المفتوحة

1 - الانتقالية

حسابات معامل الانتقالية للطبقات السطحية تقدر نتيجة لعدم وجود آبار قريبة لبعضها يمكن أجراء التجربة عليها واقرب مسافة كانت في حدود 200 متر وعند ضخ أحد الآبار لم يتأثر سطح البئر الثاني وكل اعتقادي ان المياه المسحوبة من البئر يتم تعويضها الطبقات الحاملة للمياه.

أما معامل الانتقالية في الطبقات العميقة فتم حسابها بطريقة جاكوب وكانت النتائج جيدة.

2 - معامل التخزين

بطريقة جاكوب المشار إليها سلفاً لم نتمكن من حساب معامل التخزين (storage ceofficient) لعدم وجود آبار مراقبة سوى للطبقات السطحية أو العميقة. وبئر المراقبة الذي يراقب الطبقات العميقة كان يبعد مسافة 700 متر عن اقرب بئر انتاجي ولم يتأثر سطح الماء به وبعد زمن رجوع وقدره 43 ساعة أبتدأ الضخ لمدة 40 ساعة وحدث هبوط بمقدار 2 سم ولم نتمكن من تحليل هذه النتائج بالطريقة المعروفة فعملية قياس معامل التخزين تحتاج إلى حفر آبار مرامية بالقرب من الآبار حتى يمكن تقدير هذا المعامل.

3 - المسامية

تقرير المسامية :- هناك إمكانية جيدة من تطبيق المعادلة المشار إليها والتي أعطت نتائج جيدة.

غياب آبار مرامية لملاحظة منسوب المياه وبالتالي وضع خريطة بيزومترية للمنطقة وعدم إمكانية تقدير معامل التخزين ومعامل الانتقال حال دون استخدام نموذج رياضي (modeling) للتنبؤ بالامكانيات المائية للمنطقة وبالتالي وضع سياسة مائية مستقبلية على ضوء هذه الإمكانيات.

4 - التحاليل الكيمائية

تحصلنا على نتائج جيدة أمكن استعمالها وتطبيقها في تحديد صلاحية المياه للري حسب الطرق الأكثر انتشاراً في العالم وأكثر ملائمة لأغلب الظروف والأماكن.

ولكن الذي ينقص هذه الدراسة ومن الواجب التأكيد عليه لكي تكون الدراسة اكثر شمولية هي دراسة التربة وتتبع التغيرات التي طرأت عليها خلال الفترات الماضية نتيجة لريها بهذا النوع من المياه. وذلك لوضع سياسة زراعية تكون اكثر شمولية.

التوصيات

- حفر آبار المراقبة بالمنطقة للتمكن من مراقبة مناسيب المياه الجوفية.
- تحديد مناسيب مواقع الآبار فوق سطح البحر خاصة العميقة منها تحديداً جيداً لإمكانية وضع خريطة بيزومترية تساعد على دراسة الوضع المائي من الناحية الكمية.
- صيانة شبكات توزيع المياه بمزارع المشروع الزراعي وبعض المضخات الغاطسة.
- الحد من التوسع في استعمال المياه السطحية للزراعة لرداءة نوعيتها الأمر الذي قد يؤدي إلى تدهور بعض الخواص الكيميائية والفيزيائية للتربة وسوء إنتاجية المحاصيل والأشجار المثمرة.
- إجراء بعض الدراسات على التربة بالمنطقة وملاحظة التغيرات التي طرأت عليها خلال الفترة الماضية وخاصة الترب التي تروى بمياه الآبار السطحية ذات المياه الرديئة.

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