Scientific Principles for the Protection of Groundwater Resources in Ghana

Wissenschaftliche Prinzipien für den Schutz der Grundwasserressourcen in Ghana

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Eidesstattliche Erklärung

Hiermit erkläre ich, Asare Asante-Annor geboren am 29.10.1976 in Koforidua, an Eides Statt, dass ich die vorliegende Arbeit selbständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus fremden Quellen direkt order indirekt übernommenen Gedanken sind als solche kenntlich gemacht. Die Arbeit wurde bisher in gleicher order ähnlicher Form keiner anderen Prüfungsbehörde vorgelegt und auch nicht veröffentlicht.

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Zusammenfassung

Grundwasser ist im subsaharischen Afrika eine wichtige Ressource für die Bereitstellung von Wasser in privaten Haushalten, Industrie, Bergbau, und zur Bewässerung in der Landwirtschaft. In Ghana sind die Grundwassermaßnahmen vorrangig zum Zweck der Trinkwasserbereitstellung eingesetzt worden. Um jedoch Nachhaltigkeit zu gewährleisten, muss auf langfristiger Sicht ein Grundwasser-Management-System eingerichtet werden. Eine mögliche Herangehensweise zum Ressourcenschutz kann die Festlegung von Schutzzonen sein. Ziel der Arbeit ist es, unter Beachtung der naturräumlichen Bedingungen des Landes sowie des hydrogeologischen Kenntnisstandes dafür die wissenschaftlichen Grundlagen zu erarbeiten. Um dieses Ziel zu erreichen, wurden die Untersuchungen auf drei Schwerpunkte ausgerichtet, erstens die *Verfügbarkeit der Grundwasserressourcen*, zweitens ihre *Anfälligkeit (Vulnerabilität) gegenüber Kontamination* und drittens die Erarbeitung eines *analytischen Modells* für die Ausweisung von Schutzzonen.

Die Regionen *Adansi, Lawra, Sunyani* und *Sekyere West* wurden als Untersuchungsgebiete ausgewählt, um die Hypothese dieser Arbeit anzuwenden. Detailliertere Untersuchungen erfolgten dabei in *Adansi*. Ziel war es, allgemeingültige Erkenntnisse aus dem Untersuchungsgebiet für die Ausweisung von Schutzzonen für die Grundwasserleiter *Granit, Phyllit, Schiefer, Sandstein* sowie *Verwitterungsgesteine* zu ermitteln und Empfehlungen für erlaubte und verbotene Aktivitäten innerhalb der Schutzzonen zu formulieren.

Die verfügbare Menge an Grundwasser eines bestimmten Brunnens wurde über die hydraulische Leitfähigkeit und die spezifische Brunnenleistung ermittelt. Zur Lokalisierung des verfügbaren Grundwassers wurden die Ergebnisse der hydraulischen Leitfähigkeit und der spezifischen Brunnenleistung mit der geotektonischen Karte verglichen. Zur Bestimmung der Anfälligkeit des verfügbaren Grundwassers wurde der Einflussradius der Brunnen mit Hilfe der Formeln von *Sichard* und *Dupuit* errechnet. Die Ausweisung der Schutzzonen erfolgte nach *Darcy*- bzw. der Volumenstromberechnung.

Die Ergebnisse der hydraulischen Leitfähigkeit, welche aus Pumpversuchen innerhalb der verschiedenen Gesteinstypen ermittelt wurden, ergaben eine trimodale Verteilung (10^{-5}, 10^{-6} und 10^{-7} m/s). Es zeigte sich eine Tendenz von abnehmender hydraulischer Leitfähigkeit mit abnehmender spezifischer Brunnenleistung und verminderter Transmissivität. Die Ergebnisse aus den Abhängigkeitsdiagrammen der spezifischen Brunnenleistung aufgetragen gegen den Durchlässigkeitsbeiwert zeigen, dass nur Gesteine mit einer hydraulischen Leitfähigkeit größer als 10^{-5} m/s nachhaltig Grundwasser spenden können. Drei Grundwasserleitertypen wurden im Untersuchungsgebiet angetroffen, nämlich Porengrundwasserleiter in fluviatilen Ablagerungen, im Regolith und Kluftaquifere im Festgestein.

Hohe hydraulische Leitfähigkeiten korrespondieren mit größeren Einflussradien und umgekehrt. Die Ergebnisse der hydraulischen Leitfähigkeit, der spezifischen

Brunnenleistung, den Einflussradien und der berechneten Schutzzonen wurden als Inputparameter zur Abschätzung der Eignung einer Grundwasser-Quelle verwendet. Eine Ranking-Matrix wurde entwickelt, um die Interpretation der geologischen Daten zu erleichtern. Dabei wurden die Inputparameter in eine einzige Score kombiniert. Die Ergebnisse aus der Ranking-Matrix wurden verwendet, um spezifische Regelungen für die verschiedenen Grundwasserleitertypen abzuleiten. Beispielsweise sollten innerhalb gebrochener Gesteine Brunnenstandorte mit $k \geq 10^{-5}$ m/s in Störungszonen anvisiert werden. Die spezifische Brunnenleistung kann in der Gewinnungsphase mit $15 m^3/s/m$ kalkuliert werden. Der intermediäre Schutzzonenbereich sollte mindestens 150 m betragen.

Die Erkenntnisse dieser Studie können in anderen hydrogeologischen Bereichen Ghanas angewendet werden und während der Erkundungs- und Gewinnungsphase sowie bei der Erstellung von Richtlinien zum Einsatz kommen.

Abstract
Groundwater is an important resource in Sub-Saharan Africa to supply water for domestic, industrial, mining and irrigation for agricultural purposes. In Ghana, groundwater supply program is mostly pragmatic to give people drinking water, however to ensure sustainability a long term groundwater management system is essential. One such approach is the use source protection (well protection) with the declaration and installation of protection zones. To achieve the goal of this research three hypothetical questions were asked which relates to the *Availability* and *Vulnerability* of groundwater, and the use of an *analytical model* to estimate source protection zones (SPZ). The regions of *Adansi, Lawra, Sunyani* and *Sekyere West* were chosen as study areas to test the hypothesis of this research with detailed investigation concentrating on *Adansi* area.

The overall aim from the study areas was to estimate SPZ for *Granite, Phyllite, Schist, Sandstone* and *weathered materials* and give recommendations as to which activity should be permitted or otherwise within each of these zones. The available groundwater for a particular well or location was determined based on its hydraulic conductivity and specific capacity of a well. Regionalization of the available groundwater was achieved by comparing the results of the hydraulic conductivity and specific capacity with the regional structural map. To determine the vulnerability of the available groundwater, the radius of influence (ROI) for the different boreholes was determined using *Sichard* and *Dupuits* formula whilst for Source protection zones, Darcy and the volumetric equation was used.

Results of hydraulic conductivity estimated from pumping test data for the five major rock types showed a trimodal distribution (10^{-5}, 10^{-6} and 10^{-7} m/s). There was a general trend of decreasing hydraulic conductivity to decreasing transmissivity. Results of plots of specific capacity verses hydraulic conductivity shows that only rock types with hydraulic conductivity greater than 10^{-5} m/s yields sustainable groundwater supply. Three aquifer types were encountered in the study areas which were pore aquifers in shallow or alluvial, regolith and fracture aquifers in bedrocks. High hydraulic conductivity from the different rock types corresponds to higher ROI. The results of hydraulic conductivity, specific capacity, ROI and SPZ are used as input parameters for the estimation of the suitability of a groundwater source. A ranking matrix was developed for easy interpretation of hydrogeological data by combining the results of the input parameters into a single score. Results from the ranking matrix were used to determine specific regulations for the various aquifers in the study areas. Within the fractured crystalline rocks with k $\geq 10^{-5}$m/s siting of wells should target fracture zones whilst pumping during abstraction phase can exceed $15 m^3/s/m$. The intermediate source protection zone should be at least 150m.

Conclusions from the study could be applied in other areas of Ghana and be implemented during the initial development, abstraction and groundwater policy phases of other groundwater projects.

Table of Contents

List of figures

List of Tables

List of Abbreviations

AY&A	AY&A Consult Limited
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BTU	Brandenberg Technical University
Cap-Net	An international network for capacity building in IWRM
CERCLA	Comprehensive Environment Response, Compensation and Liability Act
CIDA	Canadian International Development Agency
CSIR	Centre for Scientific and Industrial Research
CWSA	Community Water and Sanitation Agency
DANIDA	Danish International Development Agency
DoELG	Department of Environment and Local Government
DSS	Decision Support System
EAR	Environmental Assessment Regulations
EC	Electrol Commission
EC	Electronic Conductivity
EEA	European Environment Agency
EKS	Electrokinetic Signal
EPA	Environmental Protection Agency
ESRI	Environmental Systems Research Institute
EU	European Union
FC	Field Capacity
FM	Frequency Modulation
GGS	Ghana Geological Survey
GIPC	Ghana Investment Promotion Council
GIS	Global Information Systems
GLOWA	Global Change and the Hydrological Cycle
GLSS	Ghana Living Standards Survey
GSD	Geological Survey Department
GSI	Geological Survey of Ireland
GSS	Ghana Statistical Service
GW	Groundwater
GWCL	Ghana Water Company Limited
GWR	Groundwater Recharge
ID	Identification
IDW	Inverse Distance Weighted
IWRM	Integrated Water Resource Management
LI	Legislative Instrument
MDG	Millineum Development Goals
MOA	Ministry of Agriculture
MWRWH	Ministry of Water Resources Works and Housing
NGO's	Non-Gorvenmental Organisation
NRA	Natinal Rivers Authority
OB	Overburden
PCAs	Principal Component Analysis

pH	Measure of Acidity
PhD	Doctor of Philosophy
PRC	Population Resource Center
Q/S	Specific Discharge/Drawdown
RCRA	Resource Conservation and Recovery Act
ROI	Radius of Influence
ROI_D	Radius of Influence using Dupuit's equation
ROI_S	Radius of Influence using Sichard's equation
Rsp	Radius of source protection using Darcy's method
Rsp.ve	Radius of source protection using Volumetric equation
SARA	Superfund Amendments and Reauthorization Act
SARI	Savanna Agricultural Research Institute
Sat. Thick	Saturated Thickness
SPA	Source Protection Area
SPZ	Source Protection Zones
SPZ_D	Source protection zone using Darcy method with a 200day
SPZ_{VE}	Source protection using Volumetric Equation method with TOT of 1year
SRI	Soil Research Institute
SWL	Static Water Level
TOT	Time of Travel
TV	Television
UK	United Kingdom
US	United States
USEPA	United State Environmental Protection Agency
UTM	Universal Transverse Mercator
V/R	Volta Region
Wa-Net	West Africa Capacity Building Network
WaterNet	South Africa Capacity Building for Water Resources Management
WFD	Water Framework Directive
WHO	World Health Organisation
WHP	Wellhead Program
WHPP	Wellhead Protection Program
WHPZs	Wellhead Protection Zones
WRC	Water Resources Commission
WRI	Water Research Institute
WRIS	Water Resources Information Service

Chapter 1

1. Introducing the theme and purpose of research

1.1The term Scientific, Principle and Protection

The term scientific according to Roget's 21st century Thesaurus (Kipfer, 2006), is an adjective describing a systematic study of a matter; discovered through experimentation with synonyms such as accurate, clear, controlled, deductive, exact, experimental, logical, mathematical, methodical, objective, precise and sound. To be termed scientific, a method of inquiry must be based on gathering observable, empirical and measurable evidence subject to specific principles of reasoning.

The term principle describes a fundamental truth; a comprehensive law or doctrine, from which others are derived, or on which others are founded; a settled rule of action; a governing law of conduct; an opinion or belief which exercises a directing influence on the life and behaviour; a rule (usually, a right rule) of conduct consistently directing one's actions (Webster Dictionary, 2011).

Protection refers to the act of protecting whilst to protect means to shield or defend from attack, harm and injury (Webster Dictionary, 2011). Roget's 21st century Thesaurus (Kipfer, 2006); defines protection as care or guardianship with synonyms like assurance, barrier, buffer, conservation, cover, fix and safekeeping.

In the context of this dissertation, the terms scientific, regulation and protection are taken literally as have been defined above. However, their application throughout all the chapters applies solely to groundwater resources. There are two general approaches to groundwater protection which are resource and source protection. Resource protection aims on protecting the whole groundwater body and source protection aims on protecting a particular source, which may be a spring or well (DoELG/EPA/GSI, 1999). Goldscheider (2005), illustrates the two concepts of groundwater protection based on an origin-pathway-target model (Fig.1-1). The model was used to assess the intrinsic vulnerability of aquifer to pollution based on the protective cover and infiltration conditions.

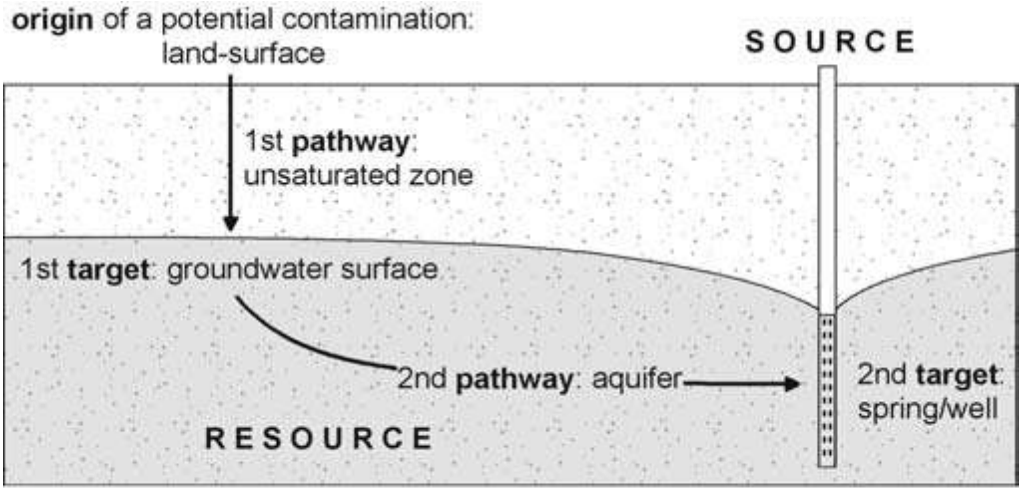


Fig. 1-1: Illustration of the origin-pathway-target model for groundwater vulnerability mapping and the concept of resource and source protection (Goldscheider, 2005)

1.2 Groundwater

1.2.1 A Natural Resource

Water in the subsurface can be divided into two major zones. That is water stored in the vadose zone (unsaturated zone) and water stored in the saturated zone. Apart from runoff entering surfacial water bodies and evaporation, water from precipitation will seep from the land surface through the vadose zone (consisting of soil water, intermediate vadose water to the capillary fringe) and further percolating to the saturated zone. The thickness of these zones depends on the type of soil, vegetation and the rock formation. Subsurface water includes both soil water and groundwater which is important in groundwater protection studies, as pollution of soil water will lead to the groundwater body when conditions are favourable and if not detected.

By definition, groundwater is the water below water table, filling entirely all rock interstices (void space) in the saturated zone (Kresic, 2007). Groundwater movement could be upwards, downward or lateral depending on the force controlling the movement. Movement of groundwater through the saturated zone occurs in response to two forces; gravity to pull water downwards and pressure to cause water to move upwards (Page, 1987). The occurrence of Groundwater within the Earth's crust and the emergence of springs at the ground surface are determined by the lithology of geological materials, regional geological structure, geomorphology of landforms and the availability of recharge sources (Hiscock, 2005).

The rock formation which stores the groundwater is called aquifer and could have local or regional influence depending on how wide and far it stretches. Groundwater also plays an important role in the global system of water movement usually called the hydrologic cycle. The cycle involves precipitation from the atmosphere to the ground surface as runoff to water bodies whilst some infiltrate and percolate to the groundwater. The water goes back to the atmosphere again by means of evaporation and transpiration from both water bodies (including groundwater) and plants. The infiltration of rainfall to the water table and the flow of groundwater in an aquifer towards a discharge area are governed by physical laws that describe changes in the energy of the groundwater (Hiscock, 2005).

The physical laws also termed physical properties include porosity, permeability, compressibility, storativity, viscosity and hydrodynamic dispersion (Soliman et al., 1998). A Groundwater resource becomes contaminated when its natural constituent is altered; posing a reasonable risk in its use or making it unusable for the purpose it serves. The alteration is a result of pollutants which are transported from the land surface from either a point or a diffuse source through the unsaturated zone to the water table. They may affect both aquifers in the saturated and unsaturated zone if conditions are favourable. Depending on the nature of the pollutant, some dissolve completely in water to form a solution whilst others do not, it is common practice to track chemical movement by studying movement of chemicals in the vadose zone.

However, some soils and rocks have natural defence mechanism in the subsurface environment to mitigate the effects of pollutant sources by reducing its concentration as it travels through the soil profile. Page (1987) names the processes to include the physical process of dilution of pollutants by recharge water, chemical process such as adsorption, decay and hydrolysis, and biological processes. These can permanently remove or alter chemical compounds that are contained in the contaminants.

Of the 2.75% of water in land masses and atmosphere, 25.07% are fresh water whilst the rest is locked up in ice caps and glacial ice (Hiscock, 2005). From this fresh water the relative importance of groundwater can be realized when it is considered that approximately 98.55% is stored underground (Hiscock, 2005).

Worldwide, more than 2 billion people depend on groundwater for their daily supply (Kemper, 2004). In Germany approximately 7711 x 10^6 m^3 is being abstracted per year for use representing about 13% of groundwater whilst in other regions such as Denmark, almost 99% (907 x 10^6 a^{-1}) of the groundwater are being exploited (European Environmental Agency, 1999).

In Ghana like other parts of the world groundwater occurrence depends on the following parameters (Dapaah-Siakwan et al., 2004):

– Rock type and Geological Structures - Fractures and weathering
– Porosity and Permeability
– Degree of pore interconnection
– Climate

The occurrence of groundwater in Ghana is associated with three main geological formations (Table 1-1) which are:

- Basement complex, comprising crystalline igneous and metamorphic rocks,
- Consolidated sedimentary formations underlying the Volta basin, and
- Mesozoic and Cenozoic sedimentary rocks.

The majority of the water bearing zones occurs in the crystalline rocks as a result of secondary permeability developed in faults, fracture joints and weathered zones (e.g. granite, phyllite and quartzite).

The depths of aquifers are normally between 10m and 60m and yields rarely exceed 6m^3/hr (Fig.1-2). In the Mesozoic and Cenozoic formations occurring in the extreme south eastern and western parts of the country, the aquifer depths vary from 6m to 120m. There are also limestone aquifers, some of which are 120m to 300m in depth with average yield of about 184m^3/hr.

Hydrogeological Provinces	Hydrogeologic sub provinces	Dominant lithology
Alluvial Province	-	Loose clay, loose sand and gravel
Coastal Provinces		
Coastal Plain Province.	Keta Basin	Mainly limestone with overlying sandy & pebbly clays
	Tano Basin	Sand & clay with occasional beds of gravel, fossiliferous limestone
Coastal Block Fault Province	Amisian Formation	Mainly sandstone and shale
	Accraian Formation	
	Sekondian Formation	
Upper Voltaian	Voltaian Group	Massive sandstone, conglomerate with thin beds of shale & mudstone
Middle Voltaian		Obosum beds- Mudstone, shale, sandstone, conglomerate, some limestone
Middle Voltaian		Oti beds- Arkose, sandstone, conglomerate, mudstone, shale, limestone
Lower Voltaian		Basal quartz sandstone with pebbly grits and grits
Basement complex		
	Buem Formation	Shale, sandstone, lava & tuff with some limestone, grit, conglomerate
	Togo Series	Sandstone, quartzite, schist, shale, phyllite and limestone
	Tarkwaian System	Sandstone, shale, conglomerate, quartzite, schist, phyllite
	Granitiod intrusives	Mainly granite, granodiorite and gneiss
	Upper Birimain System	Metamorphosed tuff lava (andesitic & balsatic)
	Lower Birimain System	Schist, phyllite, slate with greywacke & sandstone
	Dahomeyan System	Gneiss & migmatite with quartz & biotite schist

Table 1-1: The main hydrogeological provinces of Ghana Modified from (Gill, 1969;Dapaah-Siakwan & Gyau-Boakye, 2000)

Data from the 1998-1999 Ghana Living Standards Survey (GSS, 1998/1999) indicates at least 33.9% of the overall population depend directly on hand-dug wells and boreholes fitted with hand pump. According to Gyau-Boakye (2001), approximately 52% of the rural population relied on groundwater resources (all sources included) for water supply in 1998 while in 1984; the proportion was around 41%. While groundwater is particularly important in rural areas, its role is also crucial in some urban areas of Ghana such as the Upper East and Upper West Regions, where more than 80% of the urban population is served by groundwater-fed piped systems (Martin & van de Giesen, 2005).

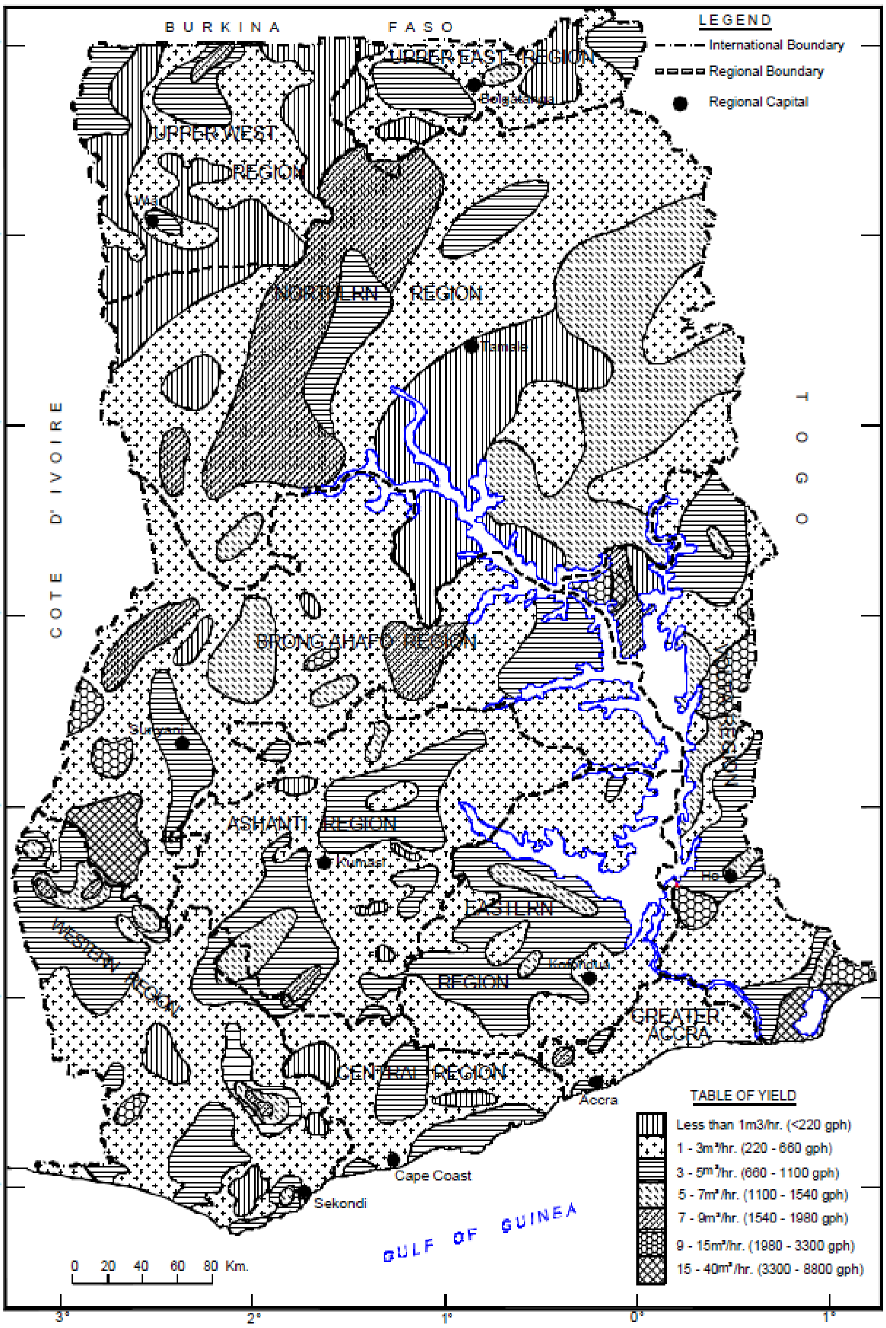


Fig. 1-2: Hydrogeological map of Ghana showing borehole yields (CWSA, 2004).

1.2.2 Drinking Water Source

Groundwater is preferred in certain municipalities as a source of drinking water because of its generally good quality in its natural state as compared to surface water. Another reason for its exploitation is its availability in large quantities as compared to other options (Denmark, Austria, Germany & Northern parts of Ghana). Also the cost for its development is less as compared to surface water treatment. Groundwater is also generally reliable during drought because of its large storage. In Germany, almost 72% of the country's drinking water supply is from groundwater whilst in Austria it is almost 99% (EEA, 1999). In Namibia groundwater is used for urban water supply, irrigation, mining, and rural water supply. In Ghana, a total of 33% of the population are being served by groundwater through boreholes, wells and springs as the main source of drinking water (GSS, 1998/1999). Although this supply is mainly for domestic supply, a fraction of it is also used for agriculture, mining and industries.

Ewusi (2006) developed a simple flow chart for groundwater exploration in Ghana (Fig.1-3). The phase following the exploration stage is the development stage which involves drilling and testing of aquifer to determine its hydraulic and chemical properties. The last phase is the construction stage for successful wells and boreholes.

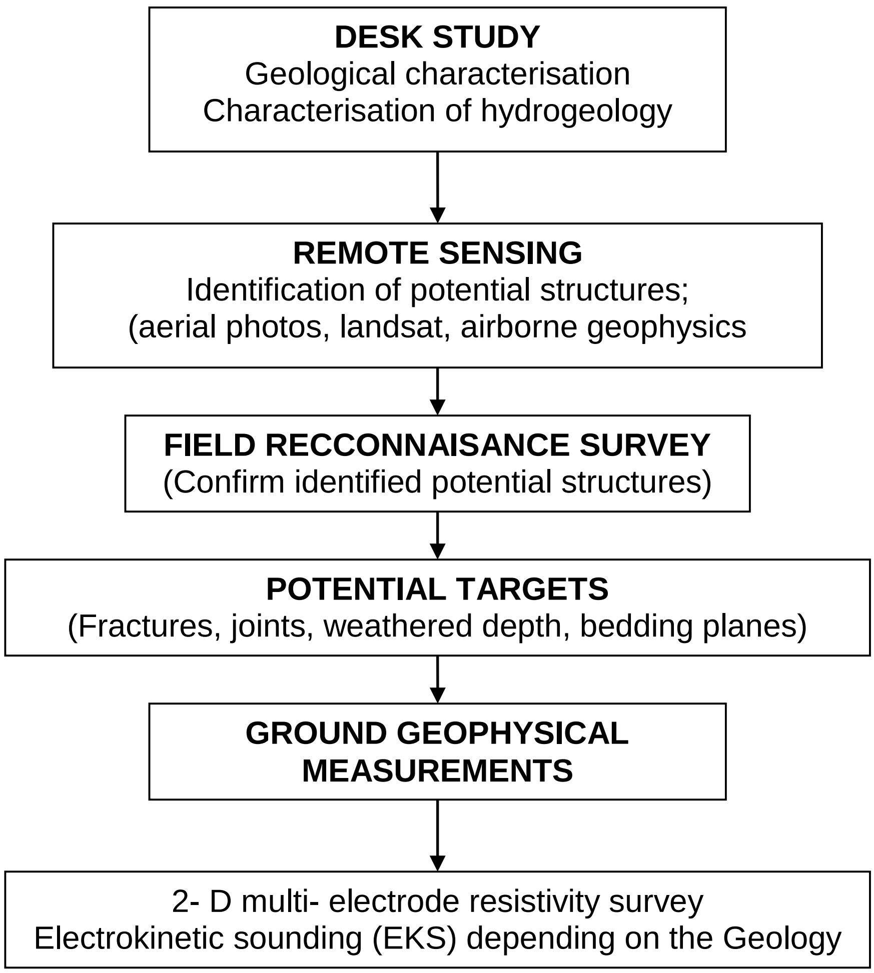


Fig. 1-3: Flow chart showing methodology for groundwater exploration in Ghana (Ewusi, 2006).

1.2.3 Socio-economic Issues

According to estimations in 2002, roughly one-sixth of humanity (1.1 billion people) lack access to any form of improved water supply within 1km of their home (Howard et al., 2006). Consequently, there is the need for adequate water supply to over a billion people from whatever available means. As discussed above, groundwater is an option based upon its availability in such regions of the world. However, in certain situations, groundwater like any other commodity in the world has other competing issues. One of the points in question is whether groundwater is used as the only source of drinking water or there are alternative options from other sources of water supply. Other competing issues include whether it should be used only for domestic water supply (for drinking and other domestic use), or for irrigation, agricultural purposes and for industries.

When it comes to groundwater management, the issue of groundwater protection zones limits the sort of activities which could be done in the demarcated zones. This may compete with certain local government developmental programs. The preference of one option will lead to the cost of forgoing the other option. Groundwater resources also have environmental benefits as they recharge certain streams and rivers, which supports aquatic life and other living organisms like vegetation growth. Bannerman (2004) states the following economic benefits for groundwater development in Ghana:

- Its development can be flexible and phased
- Its costs are generally lower than for alternate surface schemes
- Environmental impacts of development are generally low, and can even be positively beneficial.

Bannerman (2004) identified over 20,000 boreholes, 60, 000 hand-dug wells and numerous springs (143 in V/R) in use with the following purposes:

- Rural water supply
- Large and small urban water supply (e.g. Bolgatanga, Ho, Wa, Bawku, Nkawkaw, Akim Oda and Keta)
- Institutional supply (e.g. schools, clinics/hospitals)
- Industrial (e.g. Mining)

- Irrigation (small scale)
- Livestock watering
- Mineral water (bottled and bagged) production
- Fish farming

1.2.4 Public Health Concerns

Thompson (2007), estimates that waterborne infections accounts for 80% of all infectious disease in the world. Water-related disease remains one of the major health concerns in the world (Howard et al., 2006). Diarrhoeal diseases, which are largely derived from poor water and sanitation, accounted for 1.8million deaths in 2002 according to WHO report (WHO, 2004). Prüss-Üstün et al. (2004) estimated that 3.7% of the global disease burden is derived from poor water, sanitation and hygiene whilst this 'health burden' is primarily borne by the populations in developing countries and children. In 2004, a study by the Population Resource Centre found that 2.2million infants and children die each year from diarrhoea, which is caused largely by contaminated water and food (PRC, 2004). According to their estimates, polluted water in Africa and India causes 1.4million deaths each year; largely as a result of diarrhoeal diseases such as cholera and dysentery.

In Ghana, there are several cases which are a direct result of infections obtained from drinking contaminated surface waters. The morbidity for guinea worm disease in the Northern regions of Ghana is also another consequence of lack of adequate and hygienic water supply. Communities without appropriate water supply suffer severely, since people already infected with the disease re-infect local supplies as they stand in streams and rivers. On the contrary, communities with improved water supply like hand pump fitted boreholes and protected hand dug wells have seen decline in waterborne diseases.

These statistics show that throughout the world, water borne infections cause disease outbreaks and link adequate water supply to public health. Groundwater contamination both by chemicals and bacteria whether from anthropogenic or natural sources, will lead to disease outbreak especially if groundwater is the sole supply of drinking water. Because groundwater is naturally of good chemical and microbial constituents, there is the need to protect it at the point of abstraction and areas of recharge to prevent alteration of its natural quality.

Due to this fact, the WHO made the control of microbial quality of drinking water a high priority for all countries in 2004.

1.3 Groundwater Protection

Groundwater protection simply means the protection of groundwater resources; be it regional or locally against on-going contamination/pollution and possible future threats or vulnerability. It involves management programs and actions aimed at preventing groundwater from being overused, polluted with microbial and chemical contaminants. Although natural phenomena can cause undesirable groundwater quality, pollution here refers to the state in which anthropogenic contaminants have impaired the quality of the groundwater so that it does not support human use but rather has undergone a notable shift in its ability to support the biotic environment. Groundwater protection in terms of quantity involves the balancing of quantities of water use (abstraction) with the rate of groundwater recharge within the catchment areas.

In certain communities, it is necessary to recognize naturally occurring contaminants of health concerns and to have baseline studies to determine their natural threshold values. These values are helpful in characterising a shift in quality of both chemical and micro bacteria in groundwater as a result of anthropogenic sources. A correct assessment in this shift would involve an understanding of the geology, geochemical and hydrogeological characteristics of the aquifer. Measures to prevent contaminants possessing health risk from getting into groundwater sources at higher concentration imply the understanding of sources of pollution, aquifer vulnerability and specific attenuation.

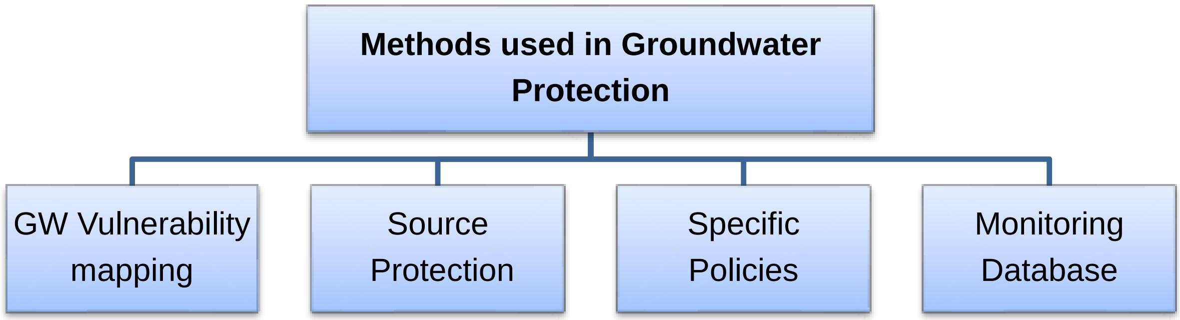


Fig. 1-4: General methods used in groundwater protection.

Based on literature research, there are four main categories of methods used to protect groundwater resources (Fig.1-4). A summary of the specific methodologies used in groundwater protection includes groundwater vulnerability mapping by land zoning, source protection, risk assessment, spatial planning, monitoring programs and specific policies or schemes. Depending on the available data, each of these methods is adequate to characterize the groundwater resource based on the objectives of the research. In areas where data regarding groundwater protection is sparse (especially in a developing country like Ghana) it is not uncommon to combine some of these methods in order to come up with regulations for groundwater resources.

Land zoning is the division of the entire land surface on the basis of the aquifer pollution vulnerability, which relates to protection of groundwater resources.This classification of groundwater vulnerability to pollution applies to both to areas where an effective soil cover exists for dispersed pollutants and to areas without an effective soil cover as in the case of point source discharges from soak ways and septic tanks.

Source protection is by means of groundwater protection zones. In this method, a series of special protection areas for individual sources is defined in which various potentially polluting activities are either prohibited or strictly controlled.

Specific policy describes legal statements on the control of groundwater quantity and quality, including groundwater abstraction, as well as waste disposal, contaminated land and other potentially polluting sources; and

Monitoring includes database and analysis. This is done by analysing records from groundwater source and resources to see if there have been some changes to the data and if so the cause of the changes.

Groundwater protection could either be based on regulatory or non-regulatory approaches. Regulatory controls make use of codes, ordinances, rules, and regulations whilst non-regulatory approaches include the use mass communication, education of landowners and in the various institutions. Soliman et al. (1998) states that it is important to understand the hydrogeological setting in order for groundwater programs to be effective. Such understanding requires complete knowledge of the rock type, stratigraphy and the geological structures. Thus, facilitating correct site selection for proposed monitoring wells, landfills, source protection and vulnerability zones.

1.4 The need for Groundwater Regulations in Ghana

Traditionally, various sources have been used for domestic water supply in Ghana, including streams and rivers, lakes and ponds, dugout, impoundment reservoirs, springs, rain harvesting and hand-dug wells (Dapaah-Siakwan & Gyau-Boakye, 2000). There were challenges associated with these traditional sources especially in the rural areas, these include contamination of surface water, insufficient quantities of water from rain harvesting and water related disease such as guinea worm, malaria, diarrhoea, cholera, bilharzias and typhoid fever (CIDA&WRC, 2006). As a result groundwater is being utilized to meet the rising water supply needs in Ghana.

Due to the expected increase in demand for groundwater especially in the rural areas, there is the need to protect this resource both now and the future for sustainable groundwater development. Currently in Ghana, there are some measures that are used by non-governmental organizations (NGO's) and other groundwater developers which help prevent contamination of groundwater resources from chemicals and micro-organisms. For example, borehole site should not be sited close to a refuse dump or a cemetery. However there are no agencies to enforce these rules.

There is also a lapse regarding chemical waste, especially those from car washing bays which can be seen all over the country running into nearby streams and recharge areas. In some communities, landfill sites have been located in abandoned quarry sites. Of much concern is that in some of these sites, previous mining went below the water table consequently leachate from waste having direct contact with groundwater when there is no properly designed and engineered barrier. Lastly, some mine tailings have also contaminated river bodies in the past and have a high probability of possibly affecting the groundwater regime. Although groundwater is of reliable quality, the following management problems have been identified both in terms of quantity and quality in certain localities.

Quantity problems

- Decline of water levels
- Reduction in source yields (caused by over-exploitation and poor watershed management)

Quality problems

- Low pH in the forest zones in the south
- High levels of Iron (Fe), Manganese (Mn), and Fluoride (F) in boreholes in certain localities
- Turbid and polluted water in some hand-dug-wells due to improper sitting and construction, as well as inadequate protection from surface runoff and contamination
- Aquifer contamination through poor drainage and sanitation in well fields and around well heads
- Aquifer contamination as a result of poor farming practices such as indiscriminate application of agrochemicals (fertilizers, pesticides and herbicides)
- Tailings from mining activities
- Chemical contaminants from car washing base
- Saline water intrusion

There is the need for a long term program to protect Ghana's groundwater resources for the following reasons:

- Sustainable use of groundwater resources
- Prevention of contamination from bacteria and chemicals
- Early detection of contaminants to help prevent loss of life and development of remediation strategies in worst case scenario.
- Long term rural supply of adequate water which improves health standards, extending to proper childcare and good education.
- Improvement in productivity (both in agriculture and industries) as a result of access to portable water through boreholes and irrigation.

All the problems illustrated above are of potential danger to the groundwater regime if measures are not put in place, which could have devastating effects on the people who depend mostly on this groundwater resource. Sustainable management will be crucial as the imminent increase in groundwater exploitation has to be carried with caution, even if actual groundwater production in Ghana is considered too small to affect regional water balance (Martin & van de Giesen, 2005).

Long term groundwater development in Ghana will have to include aquifer recharge and vulnerability concerns.

I propose that groundwater regulations in Ghana be based on the intrinsic properties of the aquifer/water bearing zone material. Protective measures will not be based on mere assumptions but based upon scientific data. Areas and zones for protection will then be based on the hydrogeological environment, land use and ecological considerations. Hopefully, this will provide a sound base for decision makers and at the same time provide a logical argument in favour of groundwater protection against contamination as opposed to previous reasoning for wellhead protection.

1.5 Formulation of the research purpose

The main aim of this research is to develop an overall regulation for the protection of groundwater resources in Ghana based upon the rock lithology, geological structures, average yield, specific capacity, hydraulic conductivity, groundwater vulnerability, source and catchment zones. To determine the overall groundwater regulation, three sub-goals (Fig.1-5) which are availability, vulnerability and modeling of groundwater were also developed. The available groundwater is first identified, and then vulnerability for the source groundwater is assessed. Modeling links the processing of acquired hydrogeological data into outputs used in the overall groundwater regulation (Fig.1-6).

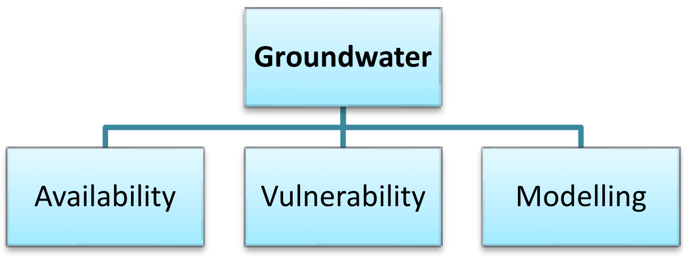


Fig. 1-5 Groundwater availability, vulnerability and modelling, main framework for the research

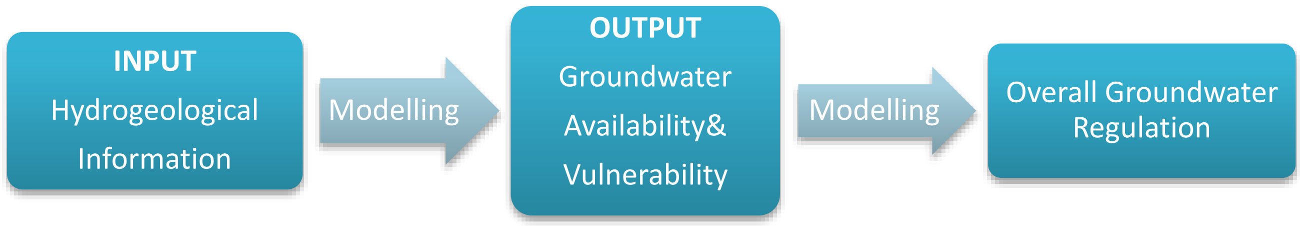


Fig. 1-6 Relationship between hydrogeological information, groundwater availability and vulnerability, and overall groundwater regulation

The hypothesis of this dissertation is applied in two study sites for detailed analysis with the aim that the conclusions drawn from the results of these study sites could be applied to other parts of the country with similar hydrogeological conditions. I hope to achieve the following results in Ghana:

- A means and guide to regulate activities within groundwater catchment zones.
- Together with monitoring wells, establish an early detection of contaminants in the worst case of accidental spills.
- An input in Integrated Water Resources Management (IWRM) program initiated by the government which focuses on the interaction between surface water, groundwater resources and the society at large with its ecological environment.
- Help to realise the Millennium Development Goals (MDG) with regards to water and health in Ghana.
- A guide to serve as a decision base tool for consultants, well developers, NGO's, Government/Ministries, water research institutes and lastly local communities.

1.6 Structure of the dissertation

This dissertation starts with an introduction where the context of the term scientific, regulation and protection is explained as applied throughout this research. A brief explanation of groundwater as a natural resource, drinking water source, and the socio-economic and public health issues are also highlighted. The chapter ends with an introduction to groundwater protection, the need for groundwater protection in Ghana and finally the formulation of the research purpose.

Chapter 2 deals with the literature research, which focuses on the global perspective of groundwater protection, groundwater management in the Sub-Saharan African countries and the current situation in Ghana regarding groundwater protection. The chapter ends with a review of Ghana water policies, research and monitoring activities and the way towards progress in protection and monitoring activities in Ghana.

In Chapter 3, the methodology for this research is discussed into detail and the study area is used as an example to apply the hypothesis. Chapter 4 discusses the results and data analysis whilst Chapter 5 analyses and interprets the maps produced. Chapter 6 discusses the modelling methods used for groundwater protection and lastly Chapter 7 gives the conclusions and recommendations resulting from this dissertation.

Chapter 2

2. Literature Research

2.1 Global Perspective of Groundwater Protection

Global approaches to the management and protection of groundwater resources have developed at the same time with our understanding of the economic and environmental implication of groundwater exploitation. For example in the UK, management and protection of groundwater commenced with the Water Act 1945 which provided legal control on water abstraction and prompted an era of water resources assessment that included surveys of groundwater resources assessment, the development of methods to assess recharge amounts and the initiation of groundwater studies (Hiscock, 2005). The Water Resources Act 1963 ushered in a decade of Groundwater resources management that required a licence for all abstractions within England and Wales. The Groundwater Act 1973 reflected the importance of water quality aspects and heralded the current interest in ground water quality (Hiscock, 2005). Table 2-1 gives a summary of the progress of management and protection of Groundwater in the UK.

Year	Act	Control/Measures
1945	Water Act	Legal control on water abstraction
1963	Water Resources Act	Formation of 27 catchment based authorities
1973	Groundwater Act	Groundwater quality, 10 catchment based authorities
1974	Control of Pollution Act	Extension of the control pollution act
1989	Water Act	Separation of water supply and regulatory function of regional water authorities
1990	Environmental Act	Control of direct and indirect discharge of
1991	Water Resources Act	harmful substances into groundwater
1998	Groundwater Regulation	Consolidation of all provisions of water resources Act 1963 regarding controlling of groundwater abstraction
2003	Water Act	Sustainable use of water resources and protect the new

Table 2-1. Progress of management & Protection of groundwater resources in the UK modified from (Hiscock, 2005).

The Control of Pollution Act 1974 extended the powers of the regional water authorities in controlling effluent discharge to underground structure and limited certain activities that could lead to polluting discharges.

Currently, the Environmental Agency is promoting a national framework for water resources protection in the context of emerging European initiatives. Water Act 2003 is one example of new legislation to further the sustainable use of currently exploited Water resources and protect those in development. The Act links water abstraction licensing to local water resource availability and moves from a licensing system based on purpose of use to volume consumed. There is a time limit on the license to allow flexibility in making changes to abstraction rights in the face of climate change and increased demand.

In the UK, decision on protection zones is taken on the basis of assessing the likely impact of a pollutant and the degree to which attenuation occurs in the geological strata influencing the source (Chave et al., 2006). According to the National Groundwater Protection policy (NRA, 1992) three distinct protection zones are recognised in the vicinity of the abstraction points.

In the European Union, the Water Framework Directive (WFD) establishes a framework for community action in the field of water policy, legislation governing water resources management and protection in the EU. The Directive (2000/60/EC) was adopted in December 2000 and requires member states to enforce appropriate measures to achieve good ecological and chemical status of all water bodies by 2015. The purpose of the directive is to establish a framework for the protection of inland surface waters, transitional waters (estuaries), coastal waters and groundwater to prevent further deterioration of aquatic ecosystem and wetlands (Hiscock, 2005).

Hiscock (2005) further explains that its implementation requires integrated approach to river basins and suggests sustainable water use based on long-term protection of available water resources. Specific measures are also adopted to prevent and control groundwater pollution whilst achieving good groundwater chemical status.
Proposed Groundwater Daughter Directive (EU Commission, 2003) includes;

- Measures for protecting groundwater from indirect pollution.
- Monitoring data with quality standards within the EU.

- Setting out specific criteria for the identification of significant and sustained upward trends in pollutant concentration, and defining starting points for when action must be taken to reverse these trends.
- Monitoring results obtained through the application of the Groundwater Daughter Directive being used to design measures to prevent or limit pollution of groundwater.
- A comprehensive program to prevent or limit groundwater becoming operational under WFD in 2012.

Groundwater management and protection in the US is highly fragmented, with responsibilities shared among a large number of federal, state and local programmes (Hiscock, 2005). At each level of government, unique legal authorities allow for the control of one or more threats to groundwater such as groundwater contamination arising from municipal, industrial, mining and agricultural activities. Major acts concerning groundwater management in the US includes;

- Federal Water Pollution Control Act 1972. Amended and followed by Safe Drinking Water Act 1974. Increased federal government's role in Groundwater management
- Resource Conservation and Recovery Act (RCRA) 1976, Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) and Superfund Amendments and Reauthorization (SARA) of 1986, established the federal government's current focus on groundwater remediation.
- In 1984 the USEPA created the office of groundwater protection to initiate a more comprehensive groundwater resource protection approach and to lead programmes aimed at resource protection.
    - Such programmes include Wellhead Protection and Sole Source Aquifer Program, which were established by amendments to the safe Drinking Water Act 1986.
    - The Wellhead Protection Program (WHPP) encourages communities to protect their Groundwater resources used for drinking water.
    - The sole Source Aquifer Program limits federal activities that could contaminate important sources of groundwater.

State groundwater management programmes are seen as critical to the future achievement of effective and sustainable protection of groundwater resources (USEPA, 1999). The United States' Environmental Protection Agency (U.S. EPA) has identified six methods that can be used to delineate a wellhead protection area. The methods, listed below, are in order of increasing technical sophistication:

- Arbitrary fixed radii
- Calculated fixed radii
- Simplified variable shapes
- Analytical models
- Hydrogeological mapping
- Numerical flow and transport models

In the developing world, groundwater is extensively used for drinking water supplies, especially in smaller towns and rural areas, where it is the cheapest source. Other uses include industries and irrigation for agricultural purposes. Groundwater schemes consist typically of large numbers of boreholes, often drilled on an uncontrolled basis, providing untreated, unmonitored and often unconnected supplies. Shallow dug wells continue to be constructed in some cases. Better yielding wells or boreholes (100l/s) are quite widely developed in larger towns to provide piped supplies. Even in these cases, raw water monitoring and treatment are often limited and intermittent. Based on experience elsewhere pragmatic time of travel approach has been adopted to define protection area boundaries in Ghana (Asante-Annor, 2005; Chave et al., 2006)

Country	**Wellhead protection zone or inner zone**	**Middle zone**	**Outer zone**
		Travel time and/or radius of zone	
Australia	50 m	10 years	Whole catchment
Austria	<10 m	60 days	Whole catchment
Denmark	10 m	60 days or 300 m	10-20 years
Germany	10-30 m	50 days	Whole catchment
Ghana	10-20 m	50 days	Whole catchment
Indonesia	10-15 m	50 days	Whole catchment
Ireland	100 days or 300 m		Whole catchment or 1000 m
Oman	365 days	10 years	Whole catchment
Switzerland	10 m	Individually defined	Double size of middle zone
United Kingdom	50 days and 50 m minimum	400 days	Whole catchment

Table 2-2: Example of Countries protection zones dimension (Chave et al., 2006)

Most countries (Table 2-2) have three different zones for protection except for few with two zones. The first zone is the wellhead protection zone or inner zone, the second is the middle zone and the last zone is the outer zone. There are different policies for each of the three zones which depend on the hydrogeological setting and the country in question. In Fig. 2-1 the conceptualised framework for groundwater protection is illustrated.

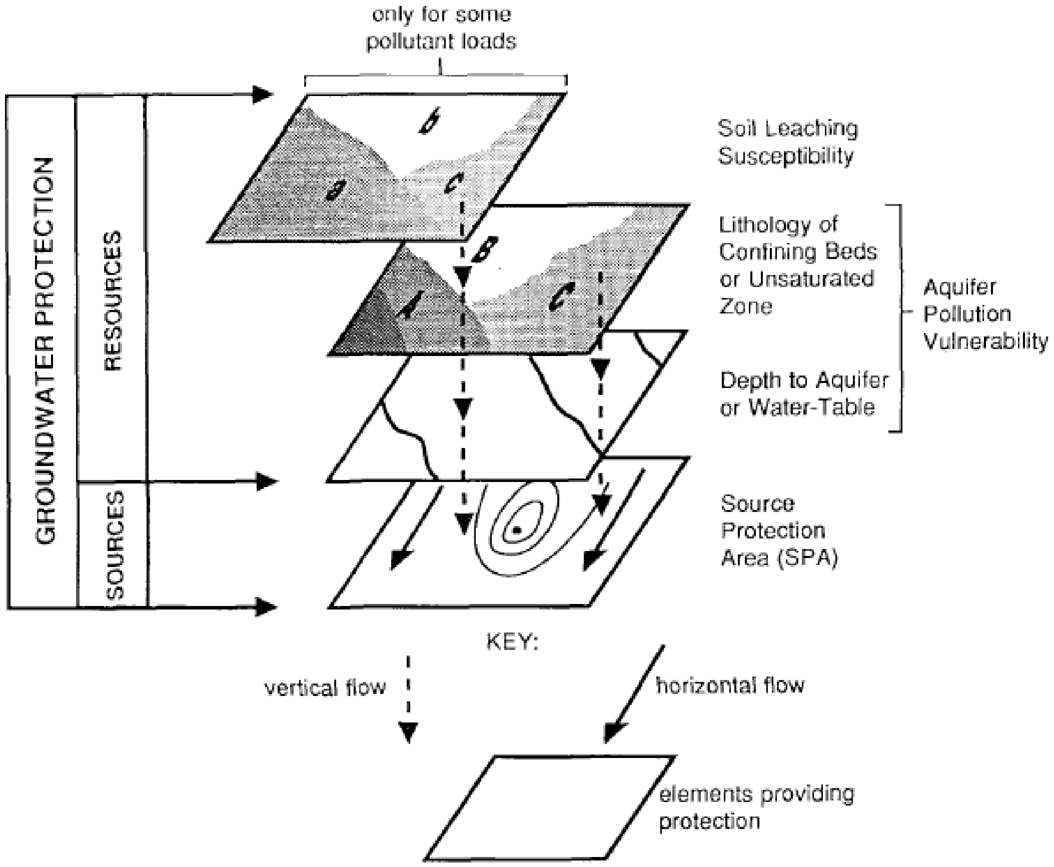


Fig. 2-1: Conceptual framework for groundwater protection (Adams & Foster, 1992)

At the first instance, certain pollutants are prohibited or restricted in a catchment zone; a map of such specific pollutants shows specific vulnerability maps. The next type of Resource protection is based on the lithology of the confining beds and the depth to the aquifer; it has been proven through experimentation that given the right conditions, certain pollutants can be degraded. The last method is for source or point water supplies where zones of protection are determined based on the hydrogeological characteristics of the source well. All these three elements are combined to facilitate general groundwater protection.

2.2 Groundwater Management in Sub-Saharan African Countries

Sustainable groundwater management in Sub-Saharan Africa includes a broad range of activities with the aim to make groundwater use technically possible and also to protect the resource base to secure the people that benefit from it in the long term. The climate summarized into three groups, with average annual rainfall around 2000mm/a, 1000mm/a, and those less than 500mm/a consequently having humid, semi-arid and arid conditions respectively. Areas prone to drought (less than 1000mm/a) depend largely on groundwater for survival and economic development. The area (Fig.2-2) is extensively underlain by two broad aquifer classes (Foster et al., 2006):

- Weathered crystalline basement forming a shallow, patchy, minor aquifer system of low storage.
- Consolidated sedimentary rocks which form generally deeper, but less extensive and geologically more complex, aquifers.

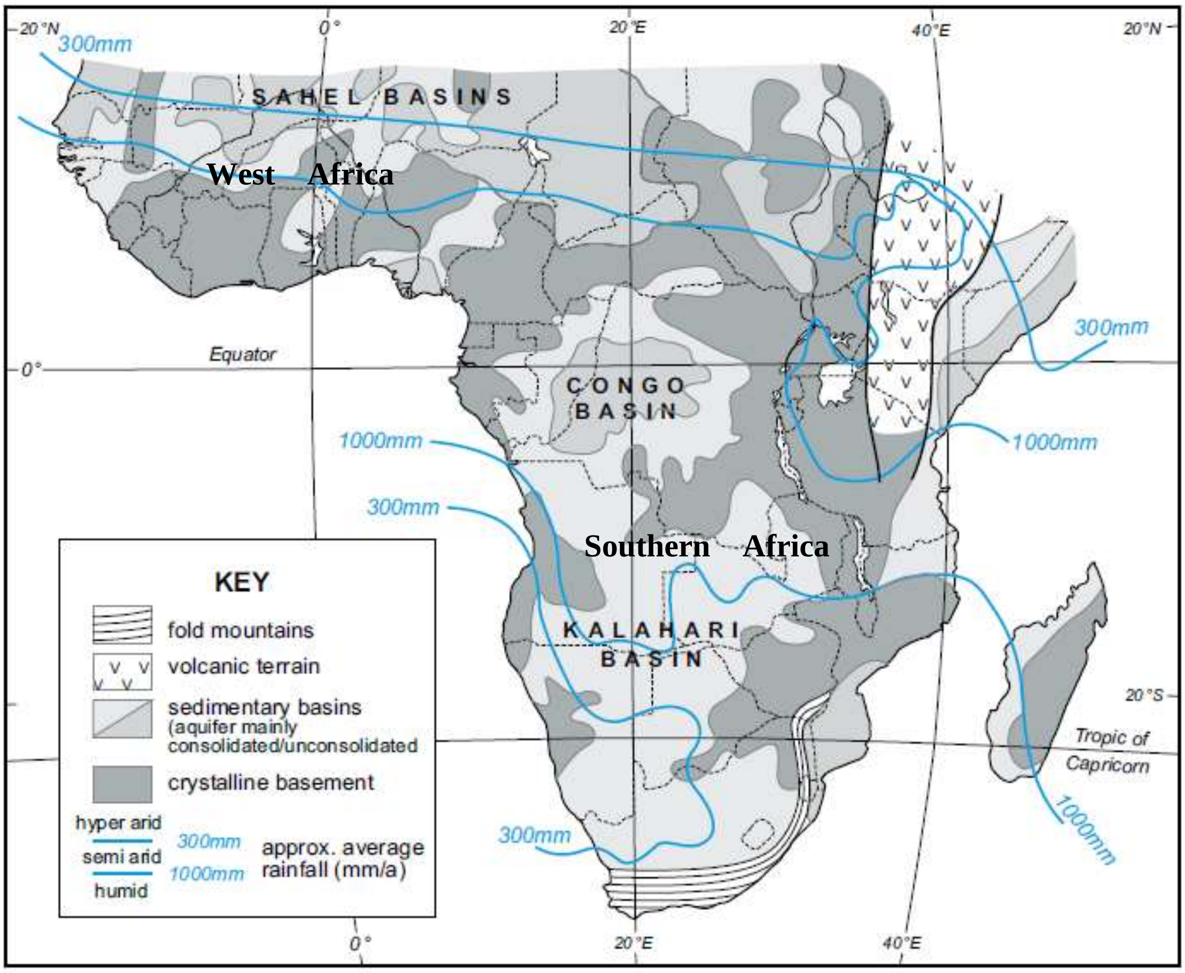


Fig. 2-2: Simplified hydrogeological map of Sub-Saharan Africa (Foster et al., 2006)

Management Issues	Groundwater Management in Sub-Saharan Africa	
	West Africa	**Southern Africa**
Hydrogeological Setting	-Precambrian basement (Magmatic and metamorphic rocks), -Primary to Quaternary Sedimentary basins, -GW stored in pore spaces and fractures, -Aquifer types: Continuous, discontinuous and mixed	-Crystalline rocks (about 65%) -Aquifer system developed in weathered regolith and in fracture, not extensive and unconfined, wellfields not possible -About 30% major GW basin, very extensive, exhibit primary porosity and permeability -Climate semi-arid to arid, and humid
Resource Use	-Water supply both in urban and rural areas, -Irrigation	-Water supply and irrigation especially in semi-arid and arid areas -Rural water supply in humid areas
Resource Assessment	-Low to average -Aquifers are not well known in their extension, -National data base exist -Resource not continuously monitored	-Well developed and managed data base, available at the central level -Nature of data: comprehensive with large scale (1:250,000 and 1:100,000) hydrogeological maps, water level and water chemistry data, and scientific studies on the major aquifer resources
Groundwater Development	-Major aquifers of great sedimentary basins are underdeveloped, -Capacity in borehole siting is insufficient in areas of complex hydrogeologic environment, -Increasing stress on GW can be expected with population growth rate in West Africa of about 3% per year	-There are additional under-utilized aquifer resources and demand for more groundwater -Drilling sector viable and adequate to meet demand but needs standardization of drilling data -Borehole test pumping is not carried out in a scientifically professional manner
Institution Arrangement	-Institutions tasked to manage water resources in general and GW are at the same time users of these resources, -Coordinating bodies like the “National Water Resources Council, or Committee” have been set up to coordinate the activities of water management institutions, -However, these bodies do not efficiently function.	-Various ministries manage GW, this region have adopted IWRM principles - Most organisations involved in GW development are concerned with: resource sustainability, information gaps, provision and maintenance of water supplies, water quality, finance, lack of qualified manpower. - Need for human resources development at all levels and an improved knowledge and understanding of the GW resource
Groundwater Protection and Environment	-Main GW threats are: lack of Sanitation, Seawater Intrusion, Fertilizers and Pesticides, Waste from Mining activities, -Legislation to protect GW against pollution and overexploitation exists in form of water code or environment codes.	-Pollution problems include; saline intrusion, nitrate, industrial effluents, acid mine drainage, domestic sewage effluents, over pumping, and natural geochemistry -Legislation in place to prevent pollution but more is to be done to monitor GW problems and to enforce the legislation.

Table 2-3: Management of GW in Sub-Saharan Africa modified from (BGR, Cap-Net, Wa-Net, & WaterNet, 2007).

A summary of the management issues is highlighted in Table 2-3 with a comparison between West and southern Africa (see reference for detailed report).

2.3 The current situation in Ghana

The main institutions involved in water resources in Ghana are Community Water and Sanitation Agency, Water Resources Commission, Environmental Protection Agency, Ghana Water Company limited and the Ministry of Water Resources Works and Housing. The various acts of the parliament of Ghana concerning water resource institutions and their mandates are presented in below (Table 2-4). Apart from these, the Water Research Institute, Ghana Geological Survey, District Assemblies and Ministry of Local Government, Rural Development and Environment are all involved in groundwater projects in areas of drinking water supply and sanitation.

No	Institution	Act of Parliament	Mandate
1.	Community Water and Sanitation Agency	CWSA Act, 1998 Act 564	Facilitate safe water and sanitation delivery to rural communities and small towns
2.	Water Resources Commission	WRC Act, 1996 Act 522	Regulate and manage the use of water resources of Ghana
3.	Ghana Investment Promotion Centre	GIPC Act, 1994 Act 478	Promote and coordinate private sector investment and involvement in Ghanaian economy
4.	Environmental Protection Agency	EPA Act, 1994 Act 490 EAR 1999, LI 1652 EAR (Amendment) 2002, LI 1703	Ensure compliance with laid down environmental procedures in the planning and execution of development projects
5.	Ghana Water Company Limited	GWCL Act, 1993 Act 461	Provide, distribute, and conserve water supply to urban Ghana.
5.	District Assemblies	Local Government Act, 1993 Act 462	Exercise political and administrative authority in the district and responsible for overall development

Table 2-4: *Legal, regulatory and administrative framework for water resources in Ghana modified from (Conteh, 2008).*

2.3.1 Ghana Water Policy

The Ministry of Water Resources Works and Housing (MWRWH) published the Ghana National Water Policy in June 2007. The policy is intended to provide a framework for sustainable development of Ghana's water resources. The target group for this policy includes all water users, water managers and practitioners, investors, decision makers and policy makers within the central Government and decentralised (district assemblies) structures, non-governmental organisations and international agencies. The policy also links with other cross-sectional related areas such as sanitation, agriculture, transport, energy, etc. The policy is divided into three main sections:

- Introduction and policy context
- Strategic Actions of Policy
- Policy Implementation Arrangements

The Strategic Actions of policy is further divided into three main sections, which are Water Resources Management, Urban Water Supply, and Community Water and Sanitation. The whole policy is represented in the Fig. 2-3.

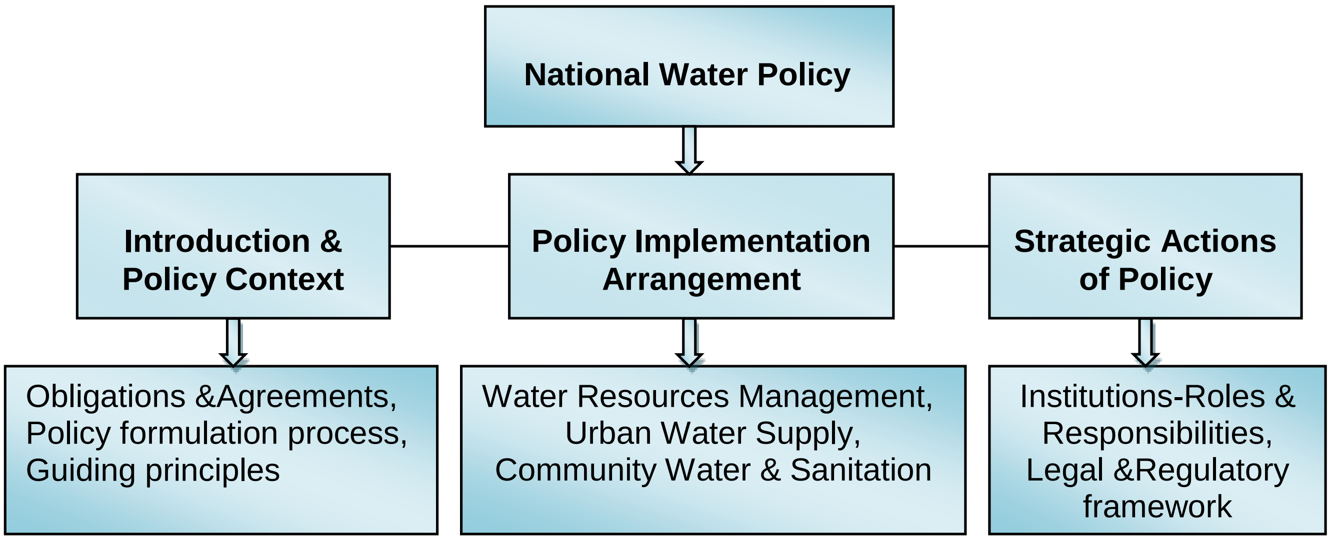


Fig. 2-3: Main components of Ghana's National Water Policy.

Main objective for Ghana's Water Vision for 2025 is to promote an efficient and effective management system and environmentally sound development of all water resources in Ghana. In order to achieve this, a holistic approach to water resources management and development is used. Integrated water resources management IWRM approach has also been adopted to enhance sustainable management of water resources and provide appropriate decision support systems for valuating competing uses of water.

The overall goal of the National Water Policy is to achieve sustainable development, management and use of Ghana's water resources to improve health and livelihoods, reduce vulnerability while assuring good governance for present and future generations. There are no clear regulations for groundwater and its protection although there is a high demand for portable water supply in rural areas.

2.3.2 Research and Monitoring Activities

The Groundwater Division of the CSIR Water Research Institute (WRI) is currently (2008/2009 during field work) undertaking 'DANIDA-funded Water Resources Information Services (WRIS-GW) Project'. As part of the decision to develop a decision support system (DSS) to implement the IWRM programme in the White Volta River Basin and Densu River Basin. Thirteen boreholes are currently being monitored in the White Volta basin whilst ten boreholes have been implemented with the installation of Data-logger divers (automatic water level recorders). Within the framework of the IWRM programme, the groundwater-monitoring programme is aimed at generating data to provide accurate information on the availability and future trends of groundwater resources for socio-economic development and safe environmental management. The monitoring boreholes are selected based upon a set of criteria such as geology, groundwater abstraction, water use, mining activities as well as locations close to existing irrigation dams.

Currently on-going projects such as Groundwater potential within the Northern Region by the Canadian Infrastructural Development Agency (CIDA) in collaboration with the Ghana Water Resources Commission (WRC) can also be incorporated into the groundwater monitoring program.

2.3.3 Water Resources Commission

The major laws that guide the regulation and management of water resources in Ghana are the Water Resources Commission (WRC) Act, (No.522 of 1996) and the Water Use Regulations, Legislative Instrument (LI 1692 of 2001). The water resources commission act was enacted in 1996 with one of its main functions in being responsible for the regulation and management of the utilization of water resources, and for coordination of any policy to them. Specifically, to (WRC, 1996):

a) Propose comprehensive plans for the utilization, conservation, development and improvement of water resources
b) Initiate, control and coordinate activities connected with the development of water resources
c) Grant water rights
d) Collect, collate, store and disseminate data or information on water resources in Ghana
e) Require water user agencies to undertake scientific investigation, experiments or research into water resources in Ghana
f) Monitor and evaluate programmes for the operation and maintenance of water resources
g) Advise Government on any matter likely to have adverse effects on the water resources of Ghana
h) Advise pollution control agencies in Ghana on matters concerning the management and control of pollution of water resources and
i) Perform such other functions as are incidental to the foregoing

2.4 The way towards Progress

During the field visits to Ghana, I had formal discussions at the Water Resources Commission WRC, Water Research Institute WRI of the Centre for Scientific and Industrial Research CSIR, World Vision, Environmental Protection Agency (EPA) and the Ghana Geological Survey (GSD). Apart from their support for this research, they also agreed that there is a need for general regulations for protection of groundwater resources in Ghana. However the major obstacles that were impeding its progress include the following:

- The need of financial support from both government and donor agencies involved in borehole development for groundwater management programs.
- Political will and funding for scientific research aimed at groundwater protection.
- Co-ordination of activities aimed at groundwater protection between NGO’s and governmental agencies such as WRC, WRI, EPA, GGS and MOA.
- Empowerment of Water Resources Commission (WRC) to enact regulations for Groundwater resources protection and its enforcement.

- Use of media to create public awareness of the need for Groundwater protection.
- Lack of capacity building for research and academic institutions, governmental agencies and NGO’s on Groundwater protection methods.

2.4.1 Protection and Monitoring Activities

There are a number of ways to achieve a given environmental target such as protection of groundwater resources. The instruments that can be used to influence the behaviour of consumers and producers towards less environmentally harmful behaviour range from informational measures to direct regulation, which bans certain activities. Fig. 2-4 gives a summary of some of the instruments and measures used in groundwater protection.

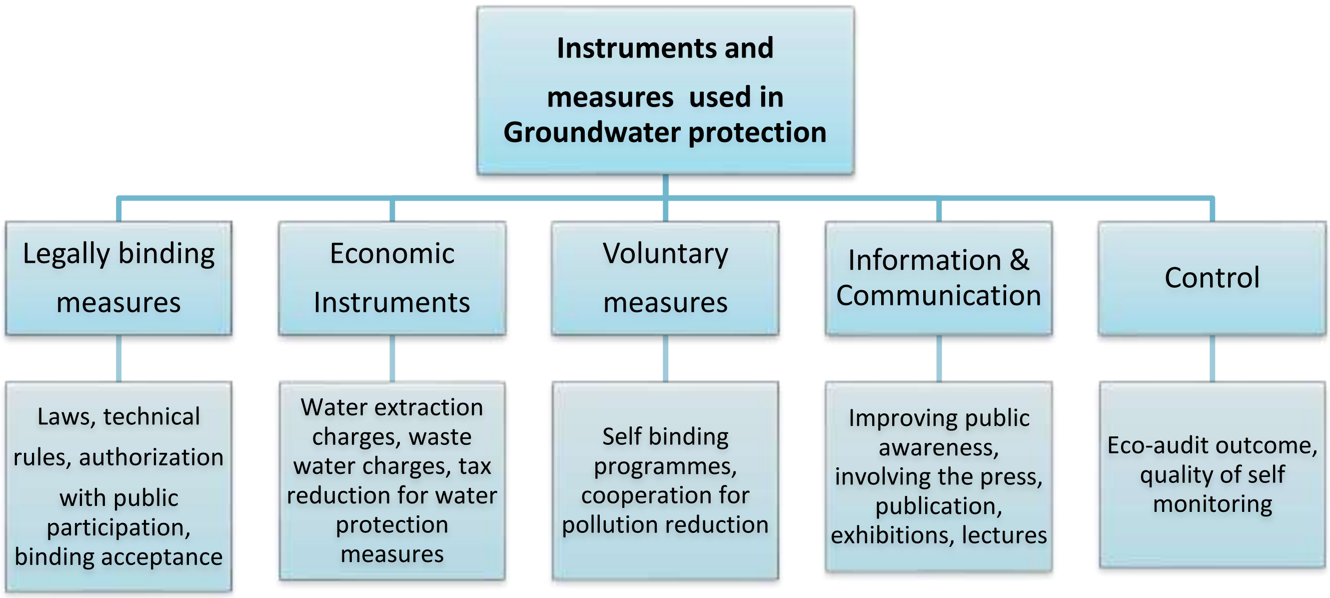


Fig. 2-4: Instruments used in groundwater protection regulation.

Among them are taxes and subsidies, tradable permits, cooperative agreements, standards and regulations and informational measures. The cooperative agreement is being effectively used in the German setup. Raucher (1983), states that the final outcome or the overall path to be taken will be depended on the cost.

The current monitoring programs by the WRI of the CSIR are a good step in the direction of groundwater management. Other measures that will help Ghana in developing a sound groundwater protection program will be, first of all, adhering to some of the concerns listed above that have impeded groundwater protection programs so far. Secondly, adopting of certain measures used in protecting groundwater provided they fit to the Ghanaian conditions. Most importantly if they are beneficial and economically viable considering both the pros and cons of having or not having it. Lastly a means of ensuring that research activities such as this dissertation and others, which aim at protecting groundwater, are reviewed by the Government. The review should look into the effectiveness of the various proposed protection schemes, further assessment and implementation of the recommendations which are essential and long overdue.

2.4.2 A general approach for Ghana

Fig.2-5 illustrates the general approach used for the determination of the overall groundwater regulation in Ghana based on literature work and field work; however this general approach was updated as more information was made available during further field visits to the study areas.

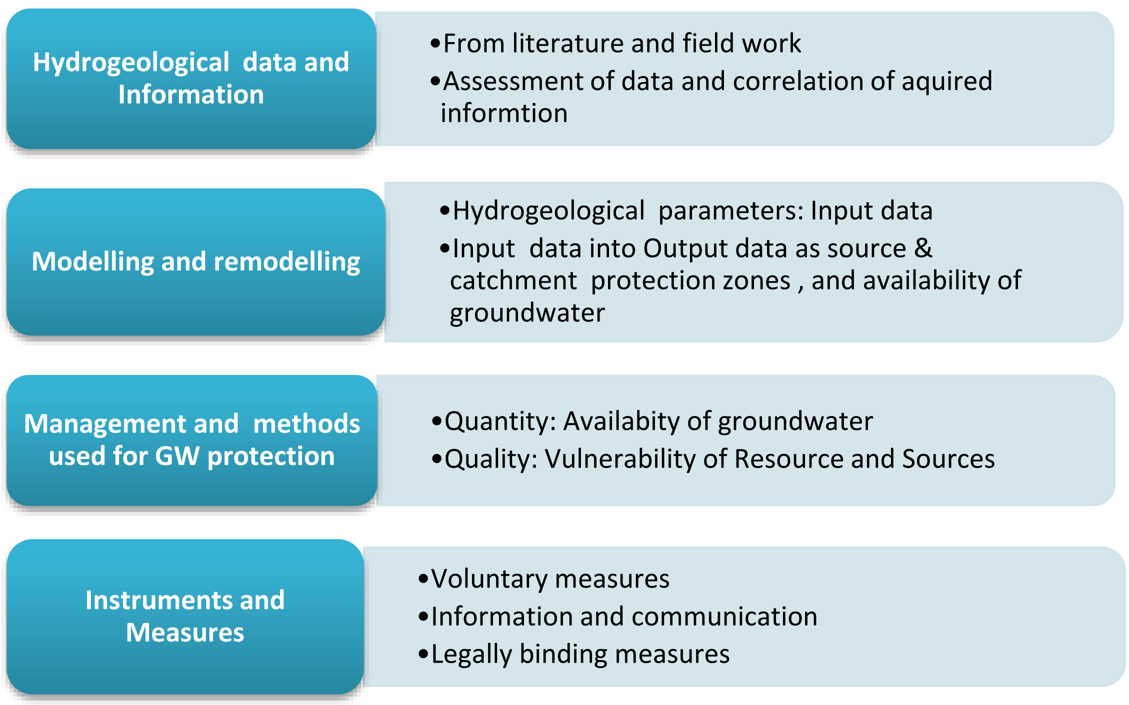


Fig. 2-5: A generalised approach for the determination of the overall groundwater regulation in Ghana.

Chapter 3

3. Methodology

The main framework of the methodology is based on the Manheim & Rich (1995) approach for any research design as illustrated in Fig. 3-1 below. The statement of the purpose of the research has already been dealt with in Chapter 1. This chapter deals with the statement of hypothesis, determination of the input hydrogeological parameters, theoretical basis for the input and output parameters, and site investigation for the experimentation of the hypothesis in the chosen study areas. Empirical work shows how the data obtained from the study areas is analysed and calculated, whilst in chapter 4 and 5 the results and maps are analysed respectively.

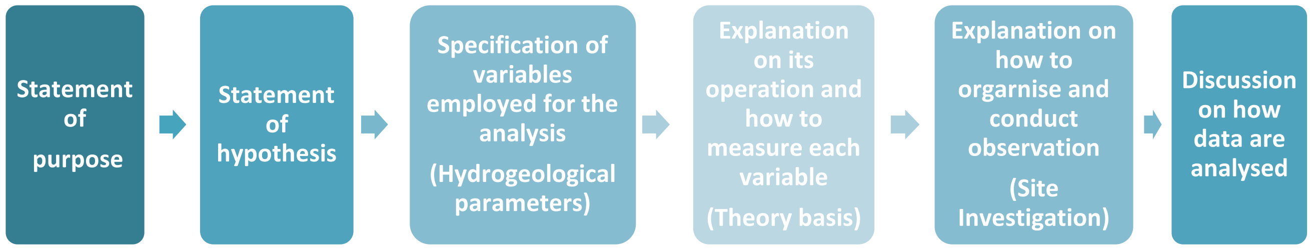


Fig. 3-1: Framework of the methodology.

3.1 Statement of Hypothesis

The aim of groundwater protection is to prevent groundwater from present and future contamination and overuse. Programs for groundwater protection could apply to water sources (single borehole) or resources (whole catchment or regional aquifer). To achieve the goal of groundwater protection, there is the need to understand the aquifer material, the hydrogeological setting and a combination of controlling measures. In areas of sparse data, it is a common tool in scientific research to use an integrated approach where more than one method is used to estimate an input parameter or a variable rather than a single parameter, which gives a reasonable estimate in comparison with areas of similar conditions.

To achieve the aim of this dissertation to have overall groundwater regulations for granite, sandstone, phyllite, schist, weathered clayey materials and alluvial aquifers (output parameters) in Ghana, an integrated approach was used. There was the need to ask certain questions which formed the basis of the statement of hypothesis.
These questions arose after literature research, initial field visit to some of the study areas, consultations with experts, and institutions involved with groundwater,

personal experience and forehand knowledge of the groundwater protection situation in Ghana. The questions that were asked to test the field work and the final analyses of the information gathered were as follows:

1. The availability of Groundwater
    a. How to access groundwater properties based on available hydrogeological data.
    b. How representative is the available information for the source and resource aquifers.
    c. Characterization and regionalization of groundwater availability
2. Vulnerability of Groundwater
    a. How to determine groundwater vulnerability
    b. Estimation of source and catchment protection zones
    c. Integration of other methods for groundwater protection
3. Modelling of Groundwater
    a. Conceptualization of the model in a study area
    b. Investigate the relationship between the input and output parameters
    c. Establish an analytical model to process input data into output data
    d. Suitability of the model and its applicability in other parts of Ghana

3.2 Methodological Approach

The methodological approach involved the initial desk study and consultation with experts, field work, analysis and evaluation of data and final report of the findings (Table 3-1). The first step of gathering scientific information about the groundwater resources is important because the occurrence of groundwater and springs are influenced by the nature of the geologic materials and landform, regional geologic structure, and the availability of recharge. The infiltration of precipitation to the water table and the transmission or storing of groundwater is also governed by physical properties of the material containing the water. In areas where data about the physical properties and nature of the hydrogeological materials were insufficient, additional field work was required to augment the missing data.

After the desk study, the next approach was to undertake field visits to the study areas. The study sites were selected based on the hydrogeological province, availability of data, research interest and goals, and available logistics.

The Lawra, Adansi, Sekyere West, Amansie and Sunyani study areas were visited two times during the research period from November 2006 to May 2007 and August to October 2008. The third step was analysing the acquired scientific data to identify groundwater availability. Areas with available groundwater were then modelled to estimate how vulnerable the groundwater resource is to pollution at the source level. General recommendations are given for groundwater resource vulnerability at the catchment level.

The results of the analysed data were presented as tables, graphs, GIS based maps and finally a ranking matrix which was used to develop an overall groundwater regulation for granite, sandstone, phyllite, schist and weathered clayey material. The resultant matrix is based on a model of groundwater suitability using discrete parameters which includes components of groundwater availability and vulnerability at the source level. The ranking level is based upon each parameter's contribution to groundwater protection for the particular rock type.

Steps for the Methodology	Components of Methodology	Specific task based on the components of the methodology
Desk Study ↓	**Desk Study**	Global Perspective of GW Protection, Hard rock hydrogeology, Ghana GW policies and management, estimating hydraulic properties
	Selection of Study Sites	Based on Hydrogeological provinces, availability of data, research interest/goals, logistics and financial consideration
Field Work ↓	**Field Work**	Collating of data from study areas, Consultation with stakeholders, verification of data on site, interview with local people
Analysis and Evaluation of Data ↓	**Analysis and Evaluation of Data**	Soil properties, hydraulic properties, aquifer characteristics, social issues, legislations, geophysical characterisation
GIS based Maps ↓	**GIS Maps**	GW Availability, GW vulnerability areas, source protection, catchment zones
Report of findings and overall regulations	**Findings and overall Regulations**	Groundwater suitability model &classification, groundwater suitability matrix: Regulations: - Quartzite, Granite, Sandstone, Schist, Phyllite and Alluvial aquifers

Table 3-1: Methodological approach for research work in Ghana.

3.3 Specification of variables for Groundwater Assessment

The WHO (2004), states that it is important the characteristics of the local catchment or aquifer of underground sources are understood and that the scenarios that could lead to water pollution are identified and managed. Table 3-2 provides examples of areas that should normally be taken into consideration as part of the assessment of the groundwater source-catchment system. In most cases, consultation with public health and other sectors, including land and water users and all those who regulate activities in the catchment, will be required for the analysis of catchments (WHO, 2004)

Information to consider for characterisation of Groundwater

Source level	Catchment level
Confined or unconfined	Geology and hydrogeology
Aquifer hydrogeology	Meteorology and weather patterns
Flow rate and flow direction	General catchment and river health
Dilution characteristics	Wildlife, competing water uses
Recharge area	Nature and intensity of development and land use
Wellhead protection	Other activities in the catchment that
Depth of casing	Potential release of contaminants into source water
Bulk water transport	Planned future activities

Table 3-2. Information necessary for assessing Groundwater and catchment component of the drinking water system modified from (WHO, 2004)

In Ghana, an integrated approach, i.e. a combination of two or more methods, was used to determine the available groundwater and its vulnerability to an intended contaminant or pollution (Fig.3-2).

The method used to estimate available groundwater included remote sensing, ground geophysical investigation, hydraulic conductivity and specific capacity. Remote sensing data is obtained from either satellite images or aerial photographs. Ground geophysical measurements were carried out in areas demarcated as promising during remote sensing survey, with the aim of targeting fracture zones since groundwater is usually stored within the fracture network in these crystalline rock terrains. Hydraulic conductivity for the various rock types was obtained from the analytical solution to pumping test results. The specific capacity is calculated after the pumping test as (Q/S) the specific discharge divided by the drawdown. Regionalisation of the available water was done with a comparison of the present available water in the study areas with the regional geological structure.

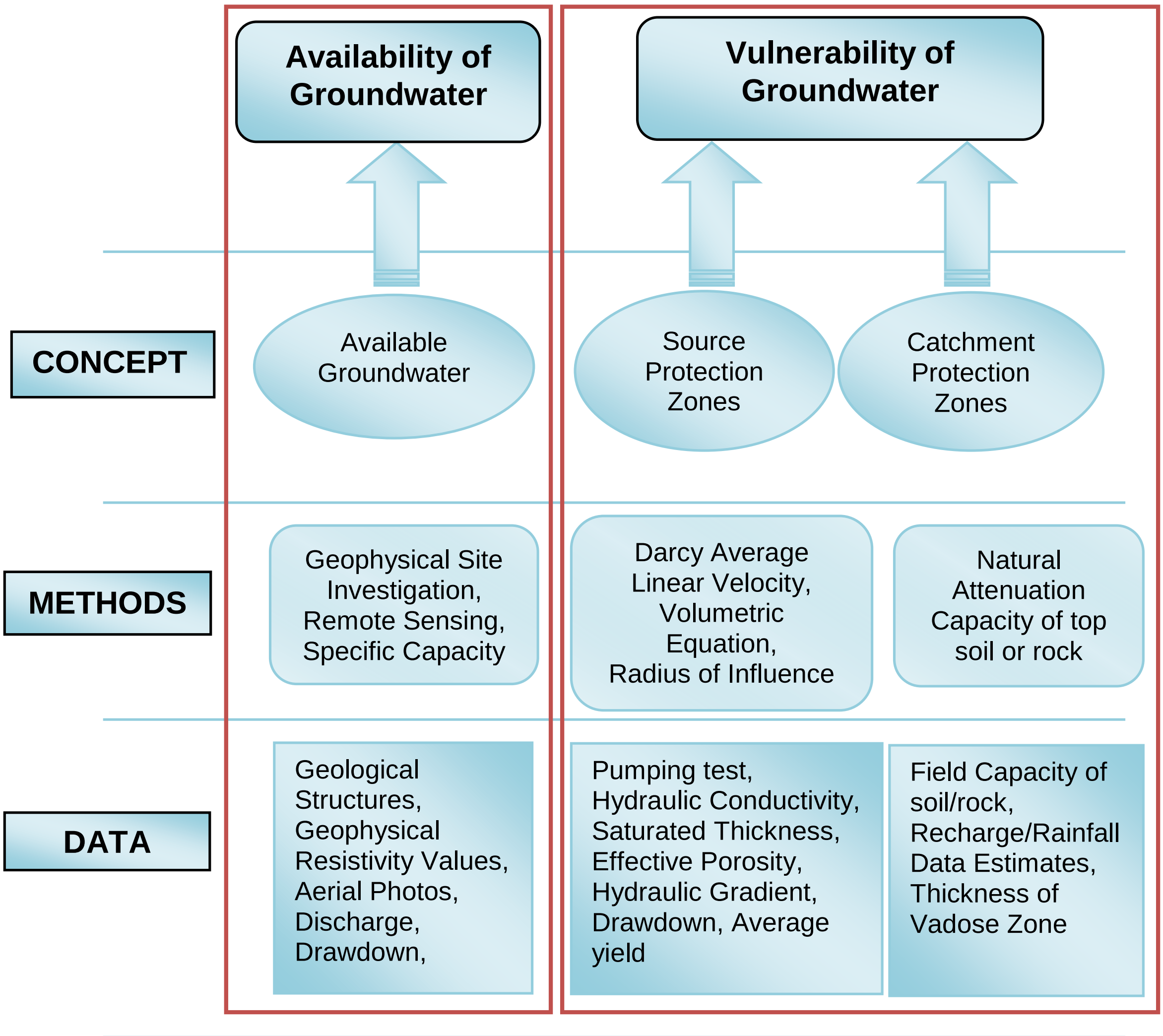


Fig. 3-2: Methods and Data requirement for the concepts of Groundwater Availability and Vulnerability for the study areas

Vulnerability of groundwater was grouped into source and resource (catchment) levels to estimate the vulnerability to an intended contaminant within the respective boarders. The method to estimate source protection zones were Radius of Influence (ROI), Darcy Average linear velocity , Transmissivity and the Volumetric Equation. The data requirement included average yield, pumping test results, hydraulic gradient, hydraulic conductivity, saturated thickness, effective porosity and time of travel (TOT). Determination of groundwater vulnerability at the catchment level involved the use of the concept of natural attenuation capacity of the top soil or rock material in preventing contaminants or pollutants reaching the groundwater body. A method developed at BTU (Voigt et al., 2004) to measure this intrinsic characteristic of the overlying strata was employed in this research. Data requirements included field capacity of soil or rock material, recharge from rain data estimates, and the thickness of the vadose zone.

3.4 Determination of Hydrogeological Properties

This section describes the analytical framework which includes the theories and determination of hydrogeological properties, vulnerability and available groundwater, and finally their characterisation. During the remote sensing phase and ground geophysical investigation, the rock type and its geological structures are identified. The specific hydrogeological information is confirmed during the drilling phase and groundwater pumping test.

3.4.1 Drilling Supervision

During the drilling supervision, specific information concerning the rock type, fractures, vadose and saturated zones, and confining rock materials were determined from drill cores. After completion of successful boreholes, static water level (SWL) was measured. In the process of drilling, cores were taken at each 10m interval. The rock types were determined based on regional geology, geophysical data, geological mapping and physical examination of the drill cores. Fracture zones were identified based on the following observations:

- the degree of jointing/fragmentation of the parent rock material
- freshness/weathered extent of the rock materials
- presence of veins or intrusive materials
- observed other geological structures such as geological boundaries, bedding planes, faulting, etc.

Upon encountering water, a temporary wedge is constructed to divert water into a measurable container which is used to estimate the volume of water. These volumes of water are measured at 1 minute intervals to estimate the average yield. Dry boreholes are backfilled and sealed with grouts whilst successful boreholes are cased and screened at water bearing zones for further development.

3.4.2 Pumping Test

After the completion of the development of the borehole, the next phase was the pumping test. The tests were conducted over a period of 12 hours for almost all of the boreholes for two stages. The first stage was the pumping stage in which water was pumped out of the borehole for 6 hours either at a constant rate or variable, after which the second stage of recovery follows. During the pumping and the recovery stages, water level measurements were recorded. The pumping tests were carried out by contracted drilling companies at the time of borehole construction. Only single well tests were carried out without the use of observation wells at the time of gathering information.

The time-drawdown data for the single pumping wells were analysed using the Cooper-Jacob method (Cooper & Jacob, 1946). It is commonly referred to as the Cooper-Jacob straight-line approximation method (Freeze & Cherry, 1979) and is a simplification of the Theis solution (Theis, 1935) for flow to a fully penetrating well in a confined aquifer. Theis (1935) published the analytical solution for flow to a well in a confined aquifer. The following assumptions apply to the analytical solution:

a) Aquifer has infinite extent, and is homogeneous, and isotropic.
b) Well discharge is at a constant rate.
c) Well fully penetrates the confined aquifer resulting in horizontal flow to the well and flow is laminar.
d) Aquifer has uniform thickness and is horizontal.
e) The potentiometric surface is horizontal initially
f) Aquifer is fully confined and discharge is derived exclusively from storage in the aquifer.

The equation for predicting drawdown (**s)** at the well is as follows:

$$\boldsymbol{S} = \frac{Q}{4\pi T} ln \frac{2.25\, T\, t}{r_w^2 s}$$

Where,

T = aquifer transmissivity (L^2/T),

Q = constant discharge rate (L^3/T),

s = storage coefficient (L/L),

S = drawdown (L),

t = time (T), and

r_w = the well radius (L).

The same assumptions apply to the Cooper-Jacob analytical solution as the Theis solution, but the well function W (u) is calculated for u < 0.01 in order to neglect all but the first two terms of the infinite series of the well function in the Theis equation. A straight-line approximation of W (u) is adequate for most applications even where u is as great as 0.1. For the Cooper-Jacob straight-line method, drawdown is plotted with an arithmetic scale on the y-axis versus time plotted with a logarithmic scale on the x-axis. Transmissivity (T) is estimated from the pumping rate (Q) and the change in drawdown per log-cycle (Δs) from the following equation:

$$T = \frac{2.3Q}{4\pi}\frac{1}{\Delta s}$$

Where,

Δs = change in drawdown per log-cycle (L).

π = constant (3.142)

The Cooper and Jacob method is based on linear curve fitting; it can be applied with a higher level of accuracy, and was therefore preferred for the evaluation of drawdown data.

3.4.3 Analyses of Pumping test data with Excel Spreadsheet

The pumping test data was analysed using a spreadsheet developed by Keith J. Halford and Eve L. Kuniansky for the USGS (Halford & Kuniansky, 2002). The aquifer-test spreadsheets are based on drawdown response to a pumping well or a flowing well. Each spreadsheet incorporates analytical solution(s) of the partial differential equation for ground-water flow to a well for a specific type of condition or aquifer. The spreadsheets were written in Microsoft Excel version 9.0 and have been tested for accuracy using datasets from different aquifer tests or generated from the analytical solution.

The transmissivity (**T)** is estimated and the horizontal hydraulic conductivity (**K)** is computed by dividing **T** by aquifer thickness. Aquifer properties for individual lithologies were derived from compilations of aquifer tests by the USGS and a variety of text books.

All of the spreadsheets for analyzing test data have four standard “SHEETS” (a tabbed page within the spreadsheet program) that are labelled: (1) COMPUTATION, (2) DEFAULT PROPERTIES and SETTINGS, (3) OUTPUT, and (4) DATA (Fig. 3-3). The Input data is added or pasted to the data page, whilst the default properties can be changed to suit local conditions. The DATA sheet of the spreadsheet is for the data logger information or drawdown measurements.

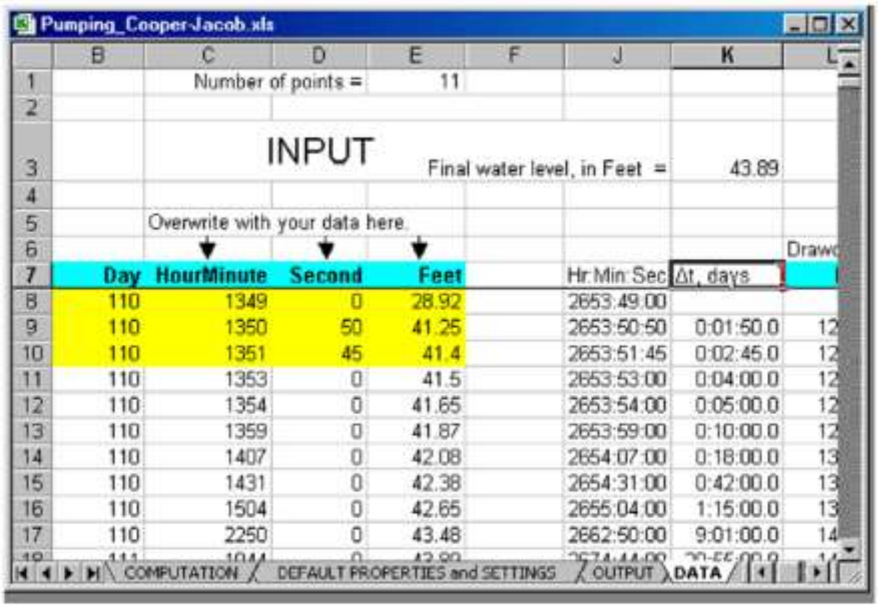


Fig. 3-3: View of the four pages common to most spreadsheets (Halford & Kuniansky, 2002) .

The OUTPUT sheet creates a summary report of a test that includes required information for an aquifer test analysis. Thus, information is entered into cells labelled “INPUT” on the “OUTPUT” sheet, such as, well construction, aquifer thickness, aquifer material, site ID, and remarks about the test. The drawdown curve is at the OUTPUT sheet and can be adjusted until the desired line of best fit is obtained.

3.5 Availability of Groundwater

In crystalline rock terrains such as those found in Ghana, water availability is difficult to predict due to the heterogeneous nature of water bearing materials developed in the weathered zone and in fractures of the bedrock.

Due to the difficult nature of the hydrogeological environment, there was a need to access the availability of groundwater by the use of different study sites with the aim that groundwater availability for the characteristic rock types like granite, phyllite, schist, sandstone and weathered clayey material found in these areas could be studied by comparing their hydrogeological characteristics. The results obtained could also be extended to other parts of the country with same or similar hydrogeological environment, in this way hydrogeological data acquired is optimized for groundwater in areas without adequate data. Assessment of groundwater availability in the study area in Ghana was achieved by the following steps:

- Analysis of pumping test
- Classification of hydraulic conductivity
- Regionalization of data
- Remote sensing data and geophysical data

The Analyses of pumping test using Cooper-Jacob straight-line method has been discussed in the previous section (3.4.3), from which transmissivity is determined. Knowing the pumping rate Q and drawdown S, the specific capacity which is a measure of available groundwater is calculated by the relation:

$$Specific\ capacity = \frac{Discharge\ \ (Q)}{Drawdown\ (S)}$$

Hydraulic Conductivity (m/s)	**Type of Aquifer**	**Permeability**	**Water bearing capacity**
$\geq 10^{-5}$	Aquifer	very high	Good-Very Good
$10^{-5} – 10^{-7}$	Aquitard	relatively low	Small-Medium
$\leq 10^{-7}$	Aquiclude	impermeable	Very Small

Table 3-3: Characterisation of aquifers and hydraulic conductivity modified from (Hölting & Coldewey, 2009).

The spatial extent of the specific capacity is represented as maps in ArcView GIS, as well as comparison of the various rock types and the hydraulic conductivity groups.

The characterisation of groundwater based on the hydraulic conductivity (Table 3-3) is classified into different groups (Hölting & Coldewey, 2009). Basically, rock types with hydraulic conductivity in metres per second (m/s) greater than 10^{-5}, between 10^{-5} - 10^{-7}, less than 10^{-7} are termed aquifers, aquitards and aquicludes respectively. By definition, aquifers are water bearing rocks; aquitards allow a certain amount of water whilst aquicludes are barrier rocks which do not easily transmit water. The characterisation of hydraulic conductivity for the study areas are presented and discussed in the results and empirical work section.

Regionalization of the hydraulic conductivity is done by comparing the various groups with regional geological structures. Two procedures were required, first preparation of the hydraulic conductivity map, second, acquisition of the regional geological map and an overlay of both maps. With this procedure, the extent of the available groundwater could be predicted.

Ground geophysical investigation and remote sensing are very important tools for regionalisation of available groundwater based on hydraulic conductivity. Aerial photographs are available in Ghana, although some are very old. Ewusi (2006) developed a methodological approach using geophysics to explore groundwater in Ghana. Three main groups were identified; group 1 and 2 consisting of granite and sandstone are of particular interest to this research. In the analyses, these groups are revised to estimate the accuracy of extending the results of the available groundwater to other parts of the country.

3.6 Vulnerability of Groundwater

Vulnerability of groundwater to pollution is a term that has emerged not so long ago and is still a subject being debated and brought to the forefront in institutions and countries. The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection for groundwater against natural and human impacts. Chilton (2006) describes this vulnerability as a function of the ease of access to the saturated aquifer for water and pollutants, and the attenuation capacity of the soil and geological strata between the pollution source and the groundwater. The term pollution vulnerability refers to the intrinsic characteristics of an aquifer that represent its sensitivity to being adversely affected by an imposed contaminant load. Natural attenuation capacity varies widely according to geological and soil conditions (Chilton, 2006)

According to Foster et al. (2002) the general principle underlying the concept of aquifer vulnerability and the need for mapping vulnerability distribution is that application of controls on all possible polluting activities everywhere is not cost effective. Consequently, it is more cost-effective and provides less severe constraints on economic development if the degree of control is varied according to the attenuation capacity. Based upon this definition of groundwater vulnerability to pollution, two scenarios (fig.1) are considered for groundwater protection one is at the source and the other at the resource level.

3.6.1 Protecting Groundwater using Vulnerability Maps

This method protects Groundwater at the resource or regional level and usually involves a whole catchment. Aquifer vulnerability maps provide information from which land use and associated human activities could be planned and or controlled as an integral part of an overall policy of groundwater protection at national, sub-national or catchment scale. Vrba and Zaporozec (1994) recognized that there could be more than one type of vulnerability: intrinsic (or natural) which was defined purely as a function of hydrogeological factors and specific which involves properties of specific pollutants (example, of specific maps; agricultural nitrates, pesticides). Vulnerability assessments involve evaluating likely travel times from the ground surface to the water table, or to the aquifer in the case of confined conditions.

The greater the travel time, the more potential there is for pollutant attenuation. The level of potential pollutant attenuation could be subdivided into five broad classes based on Foster et al. (2002) as extreme, high, moderate, low and negligible. Important factors to note concerning groundwater vulnerability are;

- Unsaturated zone travel time and aquifer residence time
- Vulnerable soil zone: soils functional natural protectiveness can be damaged by routine cultivation and tillage, irrigation, compaction and drainage.
- Unsaturated zone properties: thickness, lithology, and vertical hydraulic conductivities of the material.
- Depth and degree of weathering of the upper part of the unsaturated zone.

– Porosity, storage properties and groundwater flow direction may also be important.

Preparation of maps usually involves combining or overlaying several thematic maps of selected physical factors (Fig.3-4) that have been chosen to depict vulnerability.

Physical Properties considered for Vulnerability Maps		
Hydrogeologic Framework - The characteristics of soils and underlying materials	Groundwater Flow System - Direction and speed of groundwater movement	Climate - The amount and type of recharge

Fig. 3-4: Summary of physical properties considered during the preparation of vulnerability map Modified from (Vrba and Zaporozec, 1994).

A further general consideration is that vulnerability maps are normally prepared from existing information only, without the collection of new field data (Chilton, 2006). A number of approaches to the assessment and mapping of vulnerability have been developed, using varying combinations of soil, unsaturated and saturated zone factors. These can be considered in three groups (Chilton, 2006):

- Hydrogeological setting methods
- Parametric methods
- Analogical relation and numerical model methods

3.6.2 Protecting Groundwater using Source Protection Zones

This method of groundwater protection takes place at the source level and would usually involve a part of a whole catchment area. The concept of zone of protection for areas containing groundwater or abstraction point is based on restrictions around these areas or points. The degree of restriction becomes less as the distance from the abstraction point increases. It is common to include the area of the whole aquifer from which the water is derived in one of the zones and restrict activities in such areas in order to give a general long-term protection (Chave et al., 2006). Fig. 3-5 shows an illustration of a source well and the delineated groundwater protection zones. Commonly these zones are delineated to achieve the following levels of protection;

- A zone based on the time expected to be needed for a reduction in pathogen presence to an acceptable level (often referred to as the inner protection)
- A zone based on the time expected to be needed for dilution and effective attenuation of slowly degrading substances to an acceptable level (often referred to as outer protection zone). An additional consideration in the delineation of this zone is the time needed to identify and implement remedial intervention for persistent contaminants.
- A further, much larger zone sometimes covers the whole of the drinking water catchment area of a particular abstraction where all water will eventually reach the abstraction point. This is designed to avoid long term degradation of quality.
- A zone of immediate adjacency to the site of the well or borehole to prevent rapid ingress of contaminants or damage to the wellhead (often referred to as the wellhead protection zone).

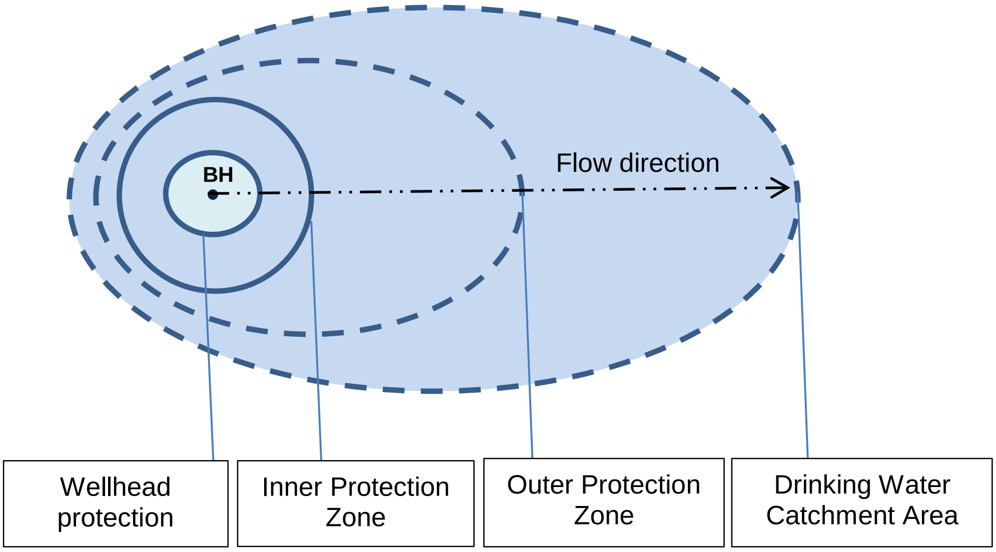


Fig. 3-5: An illustration of the various protection zones for a source well.

The number of zones varies from country to country usually between 2 and 4 and the concept can be applied to currently exploited groundwater and unexploited groundwater which might be used in the future. In Fig. 3-6 the common criteria used for the delineation of source protection zones are illustrated. In the US, the Wellhead Protection (WHP) Plan applies for any drinking water catchment. A wellhead plan essentially includes the integrated proactive management practice(s) that protect the quality of groundwater that is a source of drinking water.

Distance

- measurement of the distance from the abstraction point to the point of concern, such as discharge of effluent or the establishment of a development site

Drawdown

- the extent to which pumping lowers the water table of an unconfined aquifer,this is effectively the zone of influence or cone of depression

Time of travel

- the maximum time it takes for a contaminant to reach the abstraction point

Assimilative capacity

- the degree to which attenuation may occur in the subsurface to reduce the concentration of contaminants

Flow boundaries

- demarcation of recharge areas or other hydrogeological features which control groundwater flow

Fig. 3-6: Common criteria for the delineation of protection zones Modified from (Howard et al., 2006).

It consists of a multi-barrier system to reduce risks to public health from drinking and fits into the WHO Water Safety Plan. An important step in WHP is the delineation of one or more Wellhead protection zones (WHPZs) to form WHP area that includes surface and subsurface zone(s) that reasonably contribute water to well(s) that are being protected from potential sources of contamination. Typical steps for developing a WHP plan include the following:

- Defining the statement of purpose of the WHP
- Defining the members, roles and duties of the team
- Delineating WHP zones
- Inventory of the PCAs
- Assessing the vulnerability
- Developing management programs
- Developing contingency plans for alternative water supply
- Developing an optional source water protection program

Another factor to consider during the delineation of the zones to be protected is the criteria for the selection of the delineation method. Although experience is an essential part, there is the need for careful consideration of all the factors that will contribute to the overall management and protection of the aquifer.

Appropriate criteria selected for the delineation of groundwater protection zones offer a careful assessment of the following (Makinde-Odusola, 2005):

a) Regulatory acceptance
b) Susceptibility of the aquifer(s) to contamination
c) Available hydrogeological data
d) Computational and technical resources
e) Hydrogeologic setting of the aquifer

Delineation of WHPA by itself does not protect groundwater quality; it must be followed with the implementation of appropriate management strategies to prevent groundwater contamination and periodic evaluation of their achievements. Across the globe, different methods are being used by different countries to protect groundwater; Table 3-4 shows some of the countries and their method of groundwater protection.

Method of GW protection	Country implementing the method
Fixed radius and travel time	Ghana, Germany, UK, Australia
Combination of source protection areas and vulnerability mapping	UK, Ireland, Australia
Risk assessment	Netherlands
Prioritizing schemes	Denmark, Tunisia
Wellhead Protection Plan	US

Table 3-4: *Countries and the different methods used in groundwater protection*

Vulnerability of groundwater either as a source or resource after assessment needs to be reported in such a way that both users and policy makers will understand, knowing which options are available, the report being easily accessible. The USEPA states that reports describing the results of source protection and groundwater vulnerability studies should include:

(1) A clearly defined description of the objectives of the report

(2) A justification of the hydrologic techniques that were applied

(3) Assumptions inherent in the techniques

(4) A detailed assessment of the methodology used in the hydrologic analysis, and

(5) A complete and frank discussion of the limitations and uncertainty of the methods, data, and results

3.7 Estimation of Groundwater Vulnerability

3.7.1 Resource Mapping

Resource mapping means groundwater vulnerability mapping. According to Voigt et al. (2004) groundwater vulnerability is described as the probability with which a certain amount of a pollutant may reach the groundwater table in a particular time.The vulnerability of an aquifer to pollution is dependent upon a set of intrinsic characteristics of the strata separating the saturated aquifer from the land surface (Foster S. , 1987). In his assessment these intrinsic parameters will be used to access the sensitivity of the aquifer to quality deterioration as a result of an imposed contaminant load. Aquifer vulnerability would then be a function of:

(a) The inaccessibility of the saturated zone, in a hydraulic sense, to the penetration of pollutants; and

(b) The attenuation capacity of the strata overlying the saturated zone *as* a result of physicochemical retention or reaction of pollutants.

Vulnerability mapping uses geologic maps, soil maps, water table maps, aerial photographs, and mapping of surfacial features to identify areas of the landscape particularly vulnerable to groundwater contamination. It is estimated based on the recharge and the field capacity of the overlying material. This is appropriate tool for initial field assessment as it does not require much data but at the same time gives adequate information necessary for further characterization of an area, with regards to its protection against contamination. The following equation is used in the estimation of the groundwater vulnerability (Voigt et al., 2004):

$$t_s = \sum T_i \times FC_i / GWR = (T_1 \times FC_1 + T_2 \times FC_2 + \ldots + T_n \times FC_n) / GWR$$

Where:

ts = Dwell time of the percolation water in the non-saturated zone

GWR = New groundwater formation rate in mm/yr

FC_i = Capillary capacity of the entire groundwater overburden in % or mm/dm

FC_1.. FC_n =Capillary capacity of the 1st, 2nd... nth layer of soil, or the deeper groundwater overburden in mm/dm

T_i =Thickness of the entire groundwater overburden in dm

$T_1 \ldots T_n$=Thickness of the 1st, 2nd... nth layer of soil or the deeper groundwater overburden in dm.

Estimating Groundwater recharge

A prerequisite for sustainable groundwater resources management is the knowledge of recharge processes and the annual recharge rate. Recharge is defined as the amount of rainfall that is able to penetrate to the groundwater table after the processes of runoff and evapotranspiration, which is usually measured as a rate per year. Large uncertainties are typically inherent in any singular method to determine groundwater recharge (Martin N. , 2006) and for this reason, an integrated approach was developed for the Atankwidi catchment (close to the Lawra study area) which makes use of several field methods and combines results from these methods with water budget modeling. Field methods included in this approach are groundwater level observations, isotope analyses and a Chloride mass balance. In other areas of the study area without water balance models to estimate the groundwater recharge, estimation is made from the available rainfall data based on experience in Ghana and other African countries.

Soil Characteristics

The soil characteristics includes its texture, water holding capacities, attenuation abilities, porosity, form (consolidated or unconsolidated), and the thickness of the unsaturated zone. These are important properties for the vulnerability estimation of the underlying water bearing zones. There is no detailed soil map available for all the study areas. A detailed soil survey was not within the scope of this work. However, to get an impression of the predominant soil textures, soil profiles were taken within other parts of the study area using a hand auger to a depth of about 2 m and most of the results are compatible with the soil types indicated by the Ghanaian Soil Research Institute (SRI).

With regard to hydraulic properties of the soil types in the Northern section, results from a soil survey carried out for the GLOWA-Volta project by the Savanna Agricultural Research Institute at Nyankpala (SARI) can be transferred to the study area. This information obtained for the various soil types are used to estimate the field capacity of the top soils.

3.7.2 Source Protection zones

Source protection zones were estimated using Darcy average linear velocity method, radius of influence, the volumetric equation and transmissivity. For individual wells within the study areas, the Darcy average linear velocity was estimated based upon empirical data obtained from well logs and pumping test data during previous hydrogeological campaigns. The average linear velocity according to (Darcy, 1856) is:

$$V_A = \frac{K.i}{n_f}$$

Assuming velocity is equal to distance divided by time, a modification of the Darcy equation involving the radius and time will yield the following equation;

$$r = \frac{K.i.t}{n_f}$$

Where:

r = distance (radius in meters)

K= hydraulic conductivity in m/s

i = hydraulic gradient

t = time in seconds

n_f = effective porosity of the fractured media

The second method for estimating the source protection zones is the use of the volumetric equation. The volumetric equation (USEPA, 1987) states:

$$Qt = \pi nHr^2 \Rightarrow r = \sqrt{\frac{Qt}{\pi nH}}$$

Where;

Q= pumping rate of the well in m3/day

t = the time of travel in years

n= the porosity

H= the length of screen interval in meters

Π = constant of 3.142

r = radius (calculated fixed radius in meters)

There are limitations to both the Darcy and the volumetric equation as the material is assumed to be homogeneous and the flow is also assumed to be in the steady state. However, the equations have been used to give a fair estimate of the radius surrounding boreholes without adequate information. The hydraulic conductivity (K) is estimated from the pumping test results. To estimate the hydraulic gradient (i), one will need at least an observation well at a specified distance r from the pumping well. In Ghana, since most wells are developed for drinking water purposes, there were no observation wells. To estimate the hydraulic gradient (dh/dl), the following equation was used:

$$\mathbf{i} = \frac{S}{R}$$

The drawdown (s) is used as a measure of the change in head for the particular borehole with a corresponding radius of influence. The drawdown and hydraulic conductivity (k_f) are determined from the pumping test whilst the radius of influence (R) is estimated with the Sichard equation (Sichard, 1927):

$$R_o = 3000 \times S_w \times \sqrt{k_f}$$

Where

R_o= Radius of influence in meters

k_f = Hydraulic conductivity of the fractured aquifer

S_w= Steady state drawdown in borehole

The radius of influence is the area affected around a well or borehole during the pumping of water and usually monitored with observation wells. Since the Sichard equation is an empirical estimation, its accuracy was supported by the topography, subsurface information and structural geology of the particular area. Another method used to estimate the radius of influence is the Dupuits-Forchheimer equation (Dupuit, 1863; Forchheimer, 1930);

$$H^2 - h_w^2 = \frac{Q}{\pi k} ln \frac{r_e}{r_w}$$

Where

H = Initial water level in borehole before pumping

h_w = Water level in well after pumping has occurred

r_w = Well radius in meters

r_e = Radius of influence of the well (m)

Q = Discharge rate of the pumping borehole

K = Hydraulic conductivity of the aquifer

H-h = Drawdown

The effective porosity (n_f) is estimated based on the geologic material of the aquifer. The Darcy equation can also be used to obtain an estimate of regional groundwater flow from the hydraulic head gradient and hydraulic conductivity for a known geometry of the aquifer.

Chapter 4

4. Case Studies and Empirical Work

4.1 Study Areas

Five areas in Ghana were chosen as study areas (Fig. 4-1 A/B). These were Lawra District, Sunyani, Sekyere West, Adansi and Amansie area. A total of 256 boreholes from these areas were studied. More emphasis was placed on Adansi South and Lawra district areas because they contained representative rock types which characterise most aquifers in Ghana. Also, these areas had adequate data for the development of the module for this research.

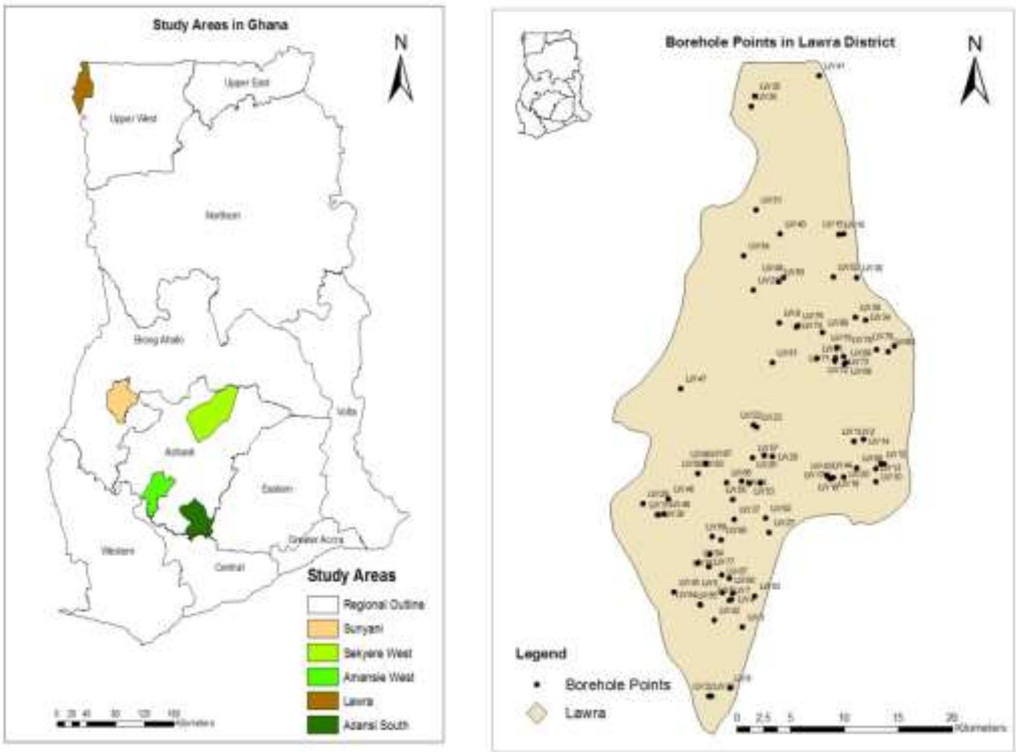


Fig. 4-1: A Ghana map showing all the study areas. B Lawra study area.

CRITERIA	Description of Criteria
Accessibility	Easy access to the area by road transport or by foot
Availability of Data	Topographical maps, geological and hydrogeological information, vegetation and climate data, soil data and geophysical data.
Geology and Hydrogeology	Rock formations representative of characteristic aquifer material in Ghana.
Spatial Effect and Climate	Northern and Southern Ghana has different climatic conditions. Lawra and Adansi used as study areas for detailed analysis were from the North and South respectively
Importance of Groundwater Resources	Some districts and communities rely strictly on surface water. Communities studied relied heavily on groundwater resources for their water supply.

Table 4-1: *Criteria for selecting study areas.*

4.1.1 Lawra Area

The district is one of the eight districts that make up the Upper West Region of Ghana and lies between longitude 2°25 W and 2°45W and latitude 10°20 and 11°00 (Fig. 4-1B). The total area of the district is approximately 1051.2 square km. The relief is gently rolling with a few hills ranging between 180-300m above sea level. The main river is the Black Volta with Kamba/Dangbang, Nawer, Duodaa and Kokoligu-baa as tributaries. The vegetation is within the Guinea Savannah zone which is characterized by short grasses and few woody plants. Common trees in the district consist of drought and fire resistant trees such as Baobab, Dawadawa, Shea trees and Acacia. The long period of dry season influences the vegetation. During this period, the grass becomes dry and the subsequent bush burning leaves the area patched and mostly without any vegetative cover.

The climate of the district is the tropical continental type with the mean annual temperature ranging between 27°C to 36°C. The period between February and April is the hottest. Between April and October, the tropical maritime air mass blows over the area which gives the only wet season in the year.

From November to January the district experiences the hamattan which is a cold and dry season with dust transported by the north-east trade winds blowing over the Sahara Desert. The mean annual rainfall ranges between 1016mm and 1270mm and is concentrated in one season from April to October. The average number of rainy days is 77 with maximum occurrence in August and September.

Geologically the area belongs to the Birimain group of rock formation with outcrops of granitic rocks. The rock types associated with the Birimain group in this area are phyllite, schist, and quartzite. There are minor occurrences of manganese, traces of gold and diamond, iron ore and clay. These rocks have a well-developed fracture pattern**.** The top soil is mostly lateritic which have been developed from the Birimain and granitic rocks which underlie the area. There are also strips of alluvial soils along the flood plains of the Black Volta as well as sandy loams along some of its tributaries. The Lawra district has a total of 3,152.2 hectares of forest reserves, however, the natural environment of the district has witnessed all kinds of degradation over the years to the extent that the vegetative cover has dwindled and soils have become poor.

4.1.2 Adansi South Area

The Adansi South study area (Fig.4-2) occurs within Adansi South and Adansi North districts of the Ashanti region of Ghana. The district lies within longitude 1°00 W and 1°38W and latitude 6°40 and 6°22. The land is flat to gentle undulating with average elevation of about 350 metres above sea level. Generally, the district is hilly with several streams and major rivers such as Pra, Fosu, Muma and Subin. The district experiences semi-equatorial climatic conditions with mean monthly temperatures ranging between 26°C and 30°C. The mean annual temperature is 27°C whilst February and March are the hottest periods in the year. The annual total rainfall is between 1,250 mm and 1,800 mm. A double maxima rainfall regime is experienced in the district. The major rains occur between April and July whilst the minor rains occur between September and December. Relative humidity is about 80% in the rainy season and 20% in the dry season. The temperature and rainfall pattern enhance the cultivation of many food and cash crops such as cocoa, oil palm citrus, vegetables, yams cassava, and cocoyam.

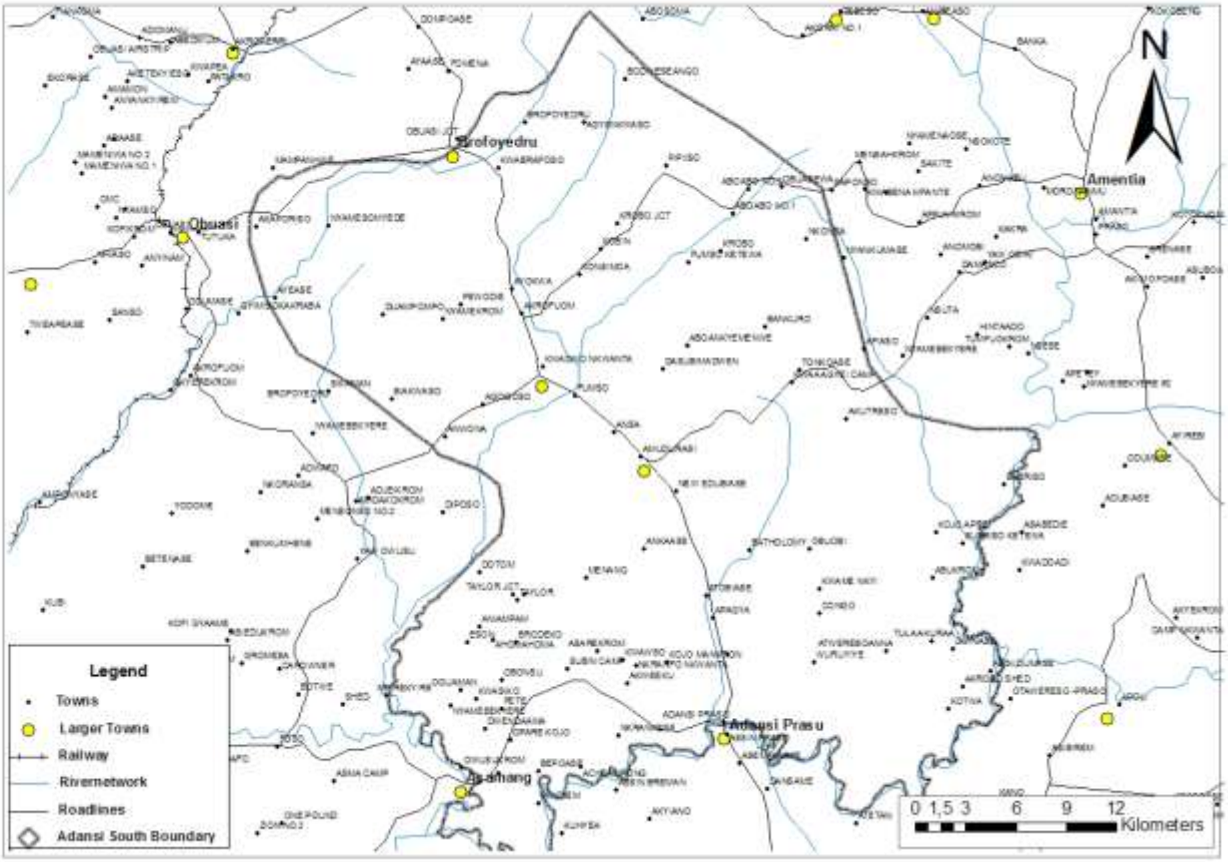


Fig. 4-2: Adansi South study area.

The vegetation is semi-deciduous forest with thick vegetation cover, and contains eight forest reserves occupying an area of about 178 square kilometres. Geologically, the area consists of Tarkwain (pre Cambrian) and upper Birimain rocks with granitic rock outcrops occuring at Akrokerri, Dompoase, Patakro and Kwapia. Most parts of the district lie within the gold belt. Town such as Mem, Hwidiem, Asokwa, Appiakrom, Nyankomase and Fumso Ketewa has been identified as having gold and diamond deposits. The major soil types in the area belong to the forest ochrosols, which are rich in humus content. There are large deposits of high quality clay and sand around Asokwa. The soils are well developed with well-defined profiles.

4.1.3 Others Areas

Other study areas were Sekyere, Sunyani and Amansie, but the first two study areas of Lawra and Adansi were used for detailed analysis. Amansie and Sekyere West have similar climatic and physiographic conditions such as Adansi.

These areas were added to apply the results of the detailed study from Lawra and Adansi to see how effective the module works and its applicability in different regions of Ghana. Table 4-2 shows the various physiographic characteristics of these study areas:

Town	Temp. (^{0}C)	Vegetation	Rainfall (mm/year)	Geology/ Soil
Sekyere-West	22-30	Semi-equitorial forest zone	1270	**Birimain- Sandstone, Schist**
Amansie	20-30	Semi-deciduous forest	1600-1800	**Birimain- Phyllite, Granite,Schist**
Sunyani	23-33	Semi-equitorial	946	**Birimain- Phyllite, Schist, Sandstone, Quartzite**
Adansi	26-29	Semi-deciduous Forest	1600-1800	**Birimain- Phyllite, Schist, Granite**
Lawra	27-36	Guinea savanna zone	1016-1270	**Birimain- Phyllite, Schist, Granite**

Table 4-2: *Physiographic characteristics of the study areas (Temperature range according to monthly variation).*

4.2 Empirical Work

The model for this research is based upon empirical data from the study sites. Hydrogeological data and information was obtained from WRC, WRI of CSIR, CWSA, GSD, Glowa-Volta project and AY&A Consult. All other information was obtained from the field during site visits and estimation based on experience.

4.2.1 Site Investigation

The investigation of the study areas in Ghana started with an orientation phase, during this phase there was an initial reconnaissance survey to all the demarcated study areas. Aerial photographs and existing geological and topographical maps were employed to delineate the geology and hydrogeological characteristics of the region. Information gathered from the field work was compiled in the base topographical maps of a 1:100 000 scale. Ground geophysical investigation, followed by the drilling campaign resulted in the establishing of drill logs. Information gathered from drill cores included overburden material and overburden thickness, geology and geological structures. Borehole development and pumping test followed and lastly pumping test analysis were applied to determine the transmissitivity and hydraulic conductivity (Fig. 4-3).

Phase - Activity

- Orientation - Maps, remote sensing
- Geophysical measurement - Borehole points location
- Drilling stage - Core logging and drilling report
- Borehole development - Screens, grouts, casing
- Pummping test - Time drawdown data

Data - Characteristics

- Base Map - Topographic maps , baseline information
- Resistivity values - Rock material and fluids
- Geological formation - Rock types
- Stratigraphy - OB material, rock type, geological structures
- Aquifer type - confined, unconfined, semi-confined, sat thickness

Fig. 4-3: Site investigation procedure and characteristics of data required (Sat. thickness- Saturated thickness of borehole, OB material- Overburden material of borehole).

4.2.2 Well log report

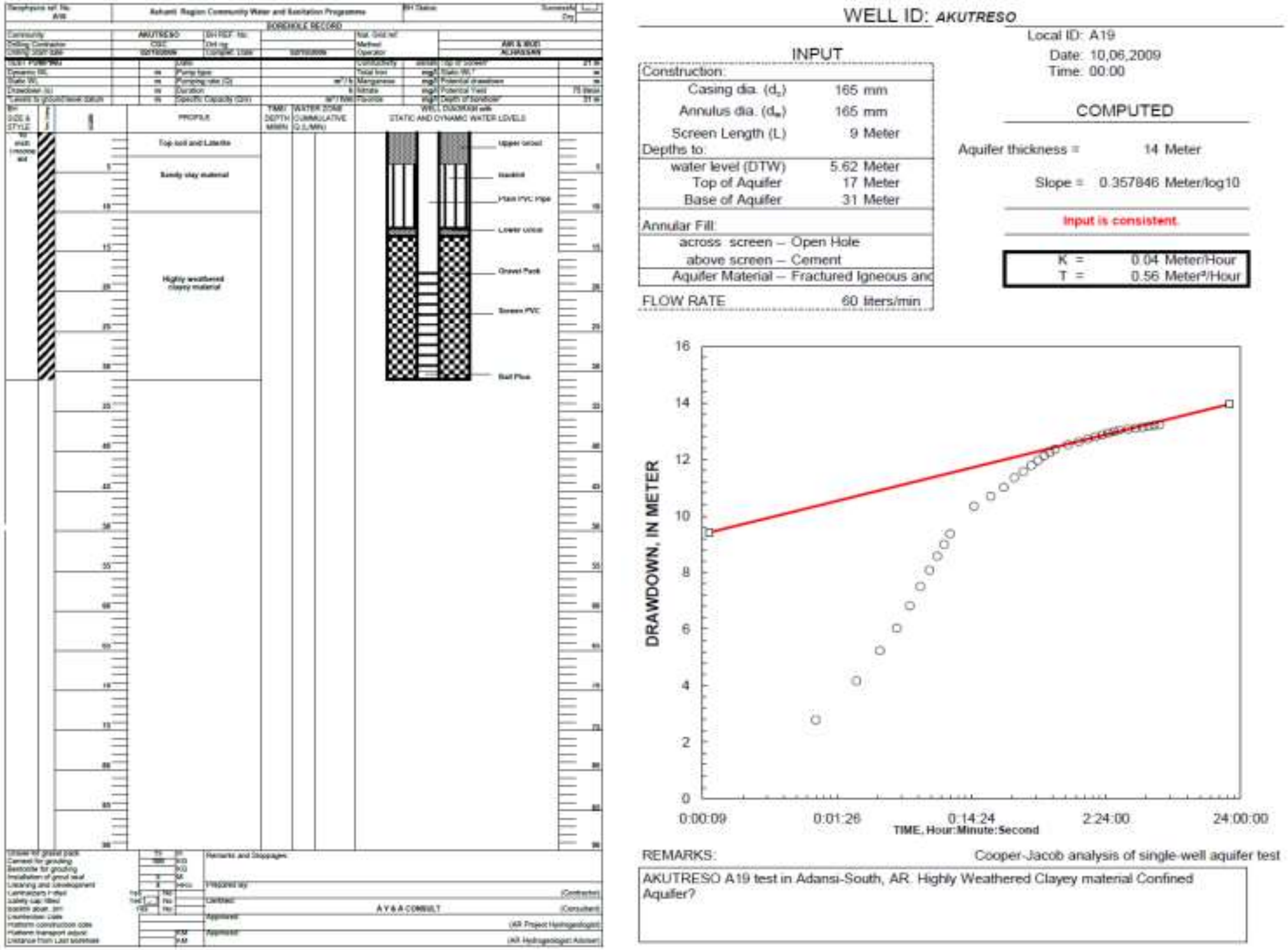
Well log reports was extracted from the borehole core logs for information such as type of rock material, thickness of saturated zones, presence of geological structures (fractures, joints, bedding plane, etc), soil profile, average yield, drilling type and rate. A brief summary of some of the well reports is presented (Table 4-3) and their diagrams are shown as examples in section 4.2.3.

Town/ Site	Sat. Thick(m)	S (m)	Q m^3/day	K(m/s)	Description of Geology
Akutreso	14	13,23	86,4	1,1E-05	Weathered clayey material
Ekour	18	7,22	144	2,3E-05	Slightly weathered to fresh Sandstone, fractures (16-19m)
Tuopari	13	16,97	100,8	1,9E-05	Weathered to fresh granite with fracture (27m)
Biakwaso	14	17,06	216	1,7E-05	Fresh phyllite
Gbengbee	15	9,08	112,32	2,3E-05	Weathered schist

Table 4-3: Summary of study sites presented as examples (Q =average yield, K (m/s) =hydraulic conductivity, S (m) = drawdown, and Sat.Thick. (m)= saturated thickness).

4.2.3 Examples of Core logs and Cooper-Jacob straight-line method

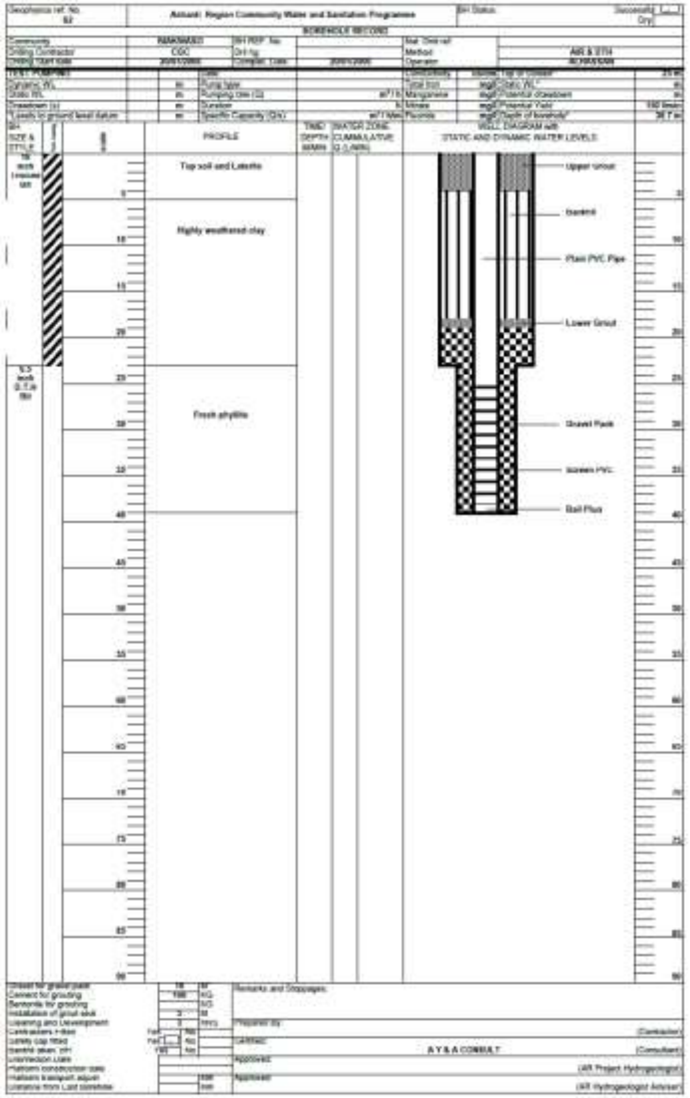
In Fig. 4-4 to 4-8, examples of the drilling core report sheet, pumping test data, and Cooper-Jacob straight-line method for estimating transmissivity are shown.

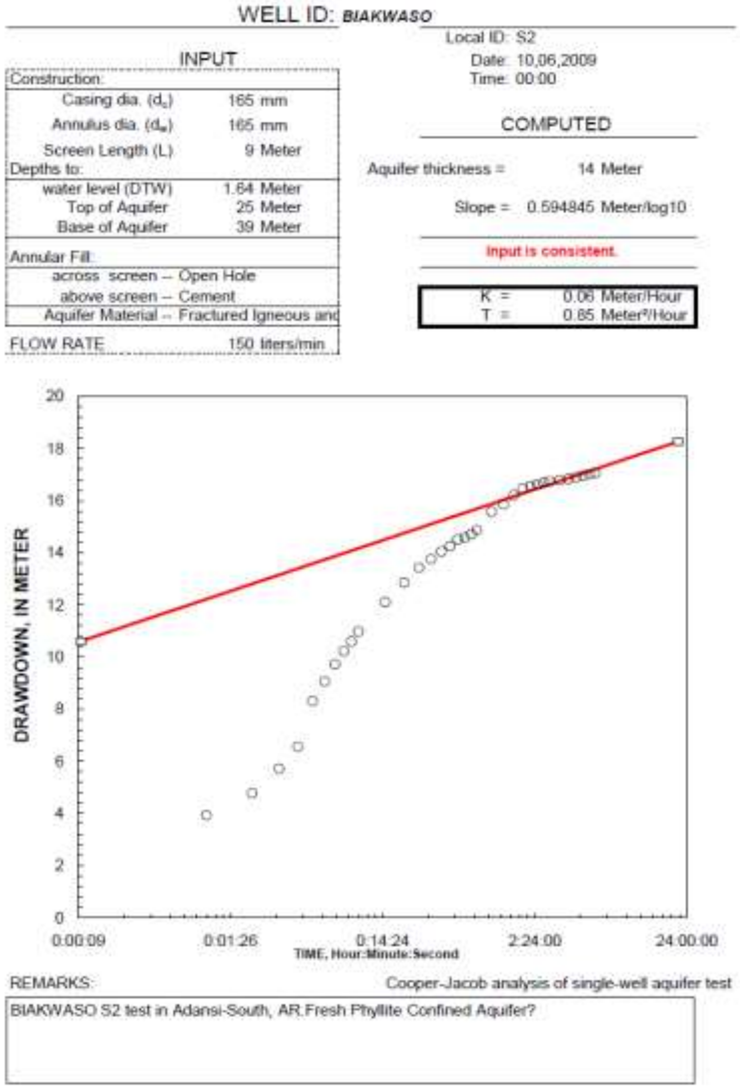


Reduced Data

Entry	Time, Date Hr:Min:Sec	Water Level Meter
1	4/19/00 0:00:00	5.62
2	4/19/00 0:01:00	8.40
3	4/19/00 0:02:00	9.78
4	4/19/00 0:03:00	10.86
5	4/19/00 0:04:00	11.65
6	4/19/00 0:05:00	12.44
7	4/19/00 0:06:00	13.13
8	4/19/00 0:07:00	13.71
9	4/19/00 0:08:00	14.20
10	4/19/00 0:09:00	14.62
11	4/19/00 0:10:00	14.99
12	4/19/00 0:15:00	15.97
13	4/19/00 0:20:00	16.32
14	4/19/00 0:25:00	16.64
15	4/19/00 0:30:00	16.98
16	4/19/00 0:35:00	17.20
17	4/19/00 0:40:00	17.41
18	4/19/00 0:45:00	17.59
19	4/19/00 0:50:00	17.75
20	4/19/00 0:55:00	17.87
21	4/19/00 1:00:00	17.98
22	4/19/00 1:15:00	18.14
23	4/19/00 1:30:00	18.25
24	4/19/00 1:45:00	18.34
25	4/19/00 2:00:00	18.43
26	4/19/00 2:15:00	18.50
27	4/19/00 2:30:00	18.56
28	4/19/00 2:45:00	18.61
29	4/19/00 3:00:00	18.66
30	4/19/00 3:30:00	18.70
31	4/19/00 4:00:00	18.73
32	4/19/00 4:30:00	18.77
33	4/19/00 5:00:00	18.80
34	4/19/00 5:30:00	18.83
35	4/19/00 6:00:00	18.85

Fig. 4-4: Weathered clayey material core log, Cooper-Jacob straight-line method, pumping test data from Akutreso site in Adansi area.





Reduced Data

Entry	Time, Date Hr:Min:Sec	Water Level Meter
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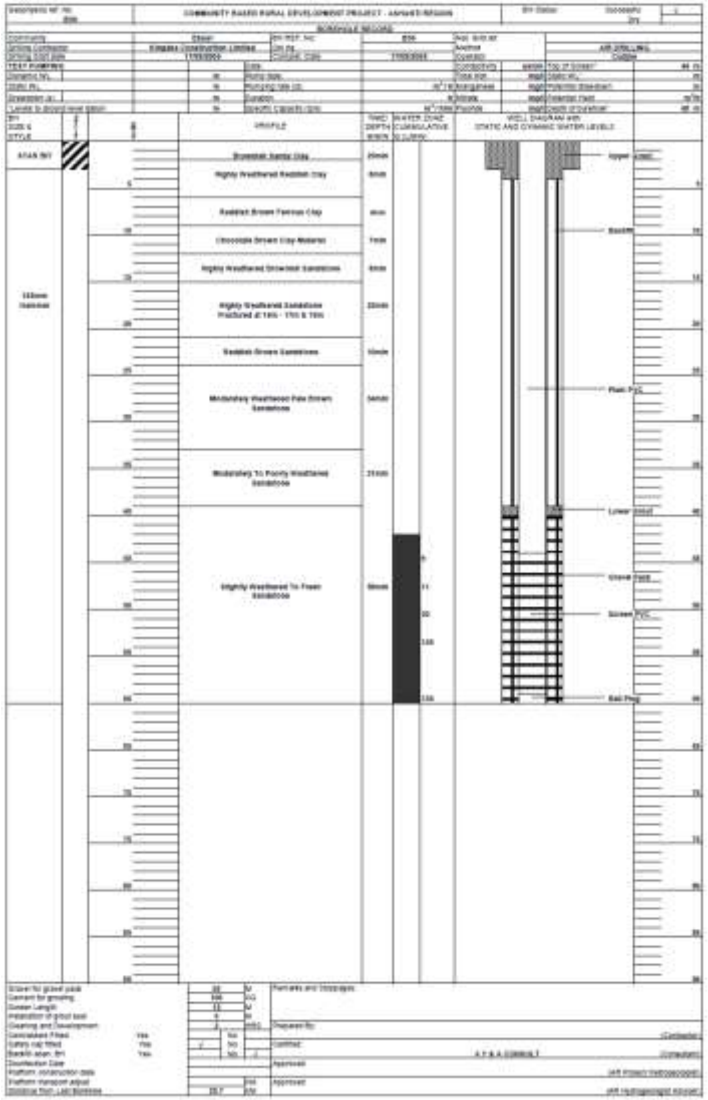
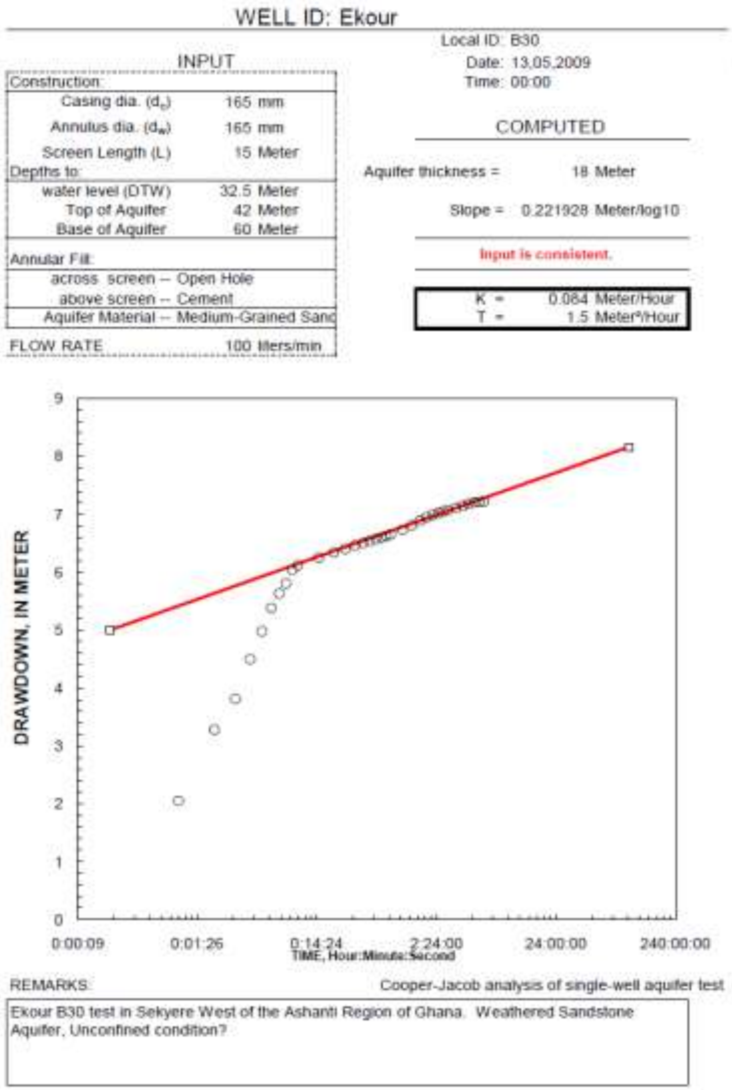
2	4/19/00 0:01:00	5.57
3	4/19/00 0:02:00	6.42
4	4/19/00 0:03:00	7.36
5	4/19/00 0:04:00	8.20
6	4/19/00 0:05:00	9.95
7	4/19/00 0:06:00	10.70
8	4/19/00 0:07:00	11.36
9	4/19/00 0:08:00	11.87
10	4/19/00 0:09:00	12.24
11	4/19/00 0:10:00	12.62
12	4/19/00 0:15:00	13.75
13	4/19/00 0:20:00	14.50
14	4/19/00 0:25:00	15.07
15	4/19/00 0:30:00	15.40
16	4/19/00 0:35:00	15.69
17	4/19/00 0:40:00	15.90
18	4/19/00 0:45:00	16.16
19	4/19/00 0:50:00	16.22
20	4/19/00 0:55:00	16.35
21	4/19/00 1:00:00	16.52
22	4/19/00 1:15:00	17.23
23	4/19/00 1:30:00	17.50
24	4/19/00 1:45:00	17.85
25	4/19/00 2:00:00	18.11
26	4/19/00 2:15:00	18.20
27	4/19/00 2:30:00	18.26
28	4/19/00 2:45:00	18.32
29	4/19/00 3:00:00	18.38
30	4/19/00 3:30:00	18.42
31	4/19/00 4:00:00	18.48
32	4/19/00 4:30:00	18.54
33	4/19/00 5:00:00	18.60
34	4/19/00 5:30:00	18.65
35	4/19/00 6:00:00	18.70

Fig. 4-5: Phyllite material core log, Cooper-Jacob straight-line method, pumping test data from Biakwaso site in Adansi area.

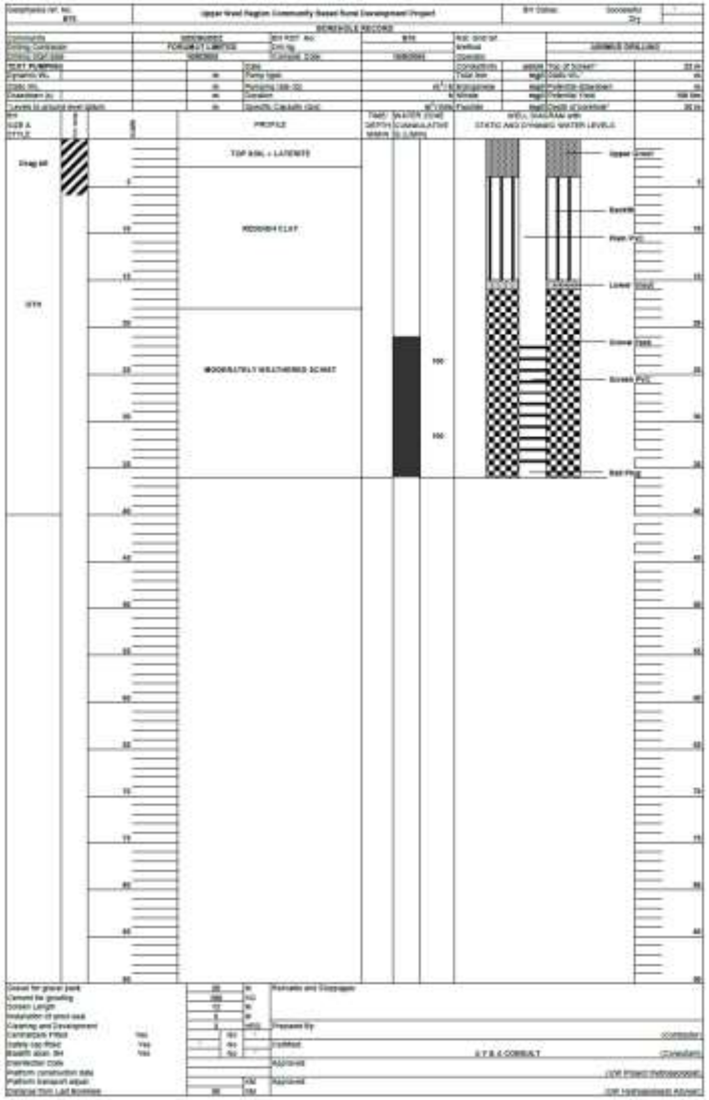


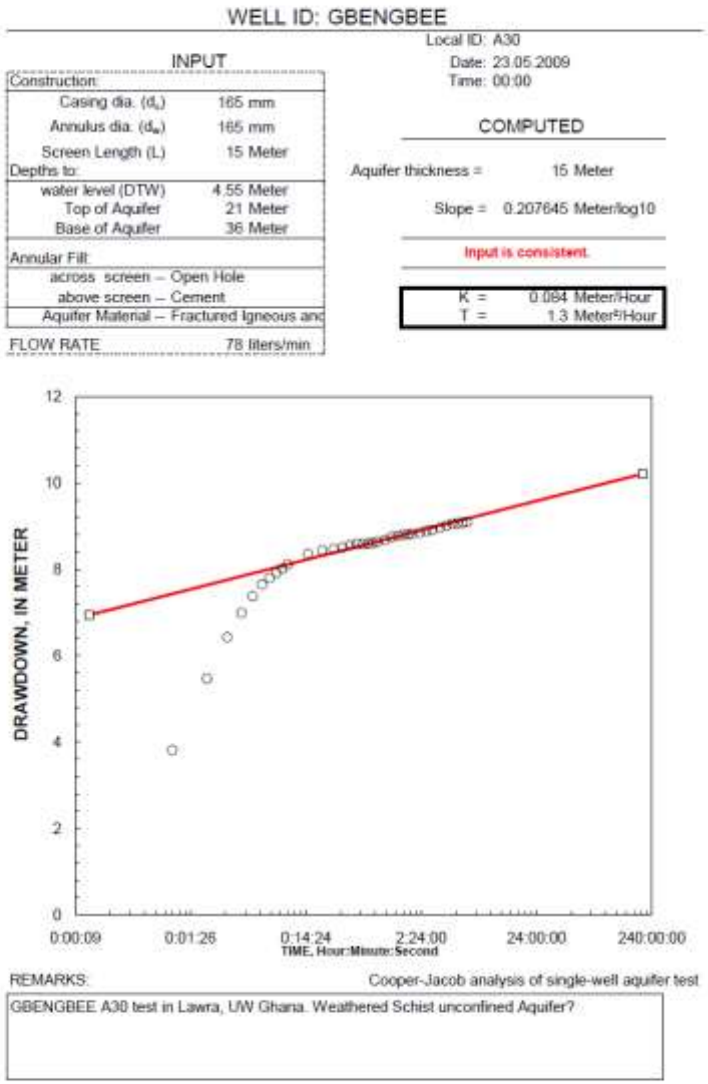


Reduced Data

Time, Date Hr:Min:Sec	Water Level Meter
4/19/00 0:00:00	32.50
4/19/00 0:01:00	34.55
4/19/00 0:02:00	35.78
4/19/00 0:03:00	36.31
4/19/00 0:04:00	37.00
4/19/00 0:05:00	37.48
4/19/00 0:06:00	37.88
4/19/00 0:07:00	38.13
4/19/00 0:08:00	38.31
4/19/00 0:09:00	38.54
4/19/00 0:10:00	38.62
4/19/00 0:15:00	38.75
4/19/00 0:20:00	38.84
4/19/00 0:25:00	38.90
4/19/00 0:30:00	38.96
4/19/00 0:35:00	39.00
4/19/00 0:40:00	39.04
4/19/00 0:45:00	39.07
4/19/00 0:50:00	39.10
4/19/00 0:55:00	39.12
4/19/00 1:00:00	39.15
4/19/00 1:15:00	39.23
4/19/00 1:30:00	39.31
4/19/00 1:45:00	39.39
4/19/00 2:00:00	39.45
4/19/00 2:15:00	39.49
4/19/00 2:30:00	39.52
4/19/00 2:45:00	39.55
4/19/00 3:00:00	39.57
4/19/00 3:30:00	39.61
4/19/00 4:00:00	39.65
4/19/00 4:30:00	39.68
4/19/00 5:00:00	39.70
4/19/00 5:30:00	39.71
4/19/00 6:00:00	39.72

Fig. 4-6: Sandstone material core log, Cooper-Jacob straight-line method, pumping test data from Ekour site in Sekyere-West area.

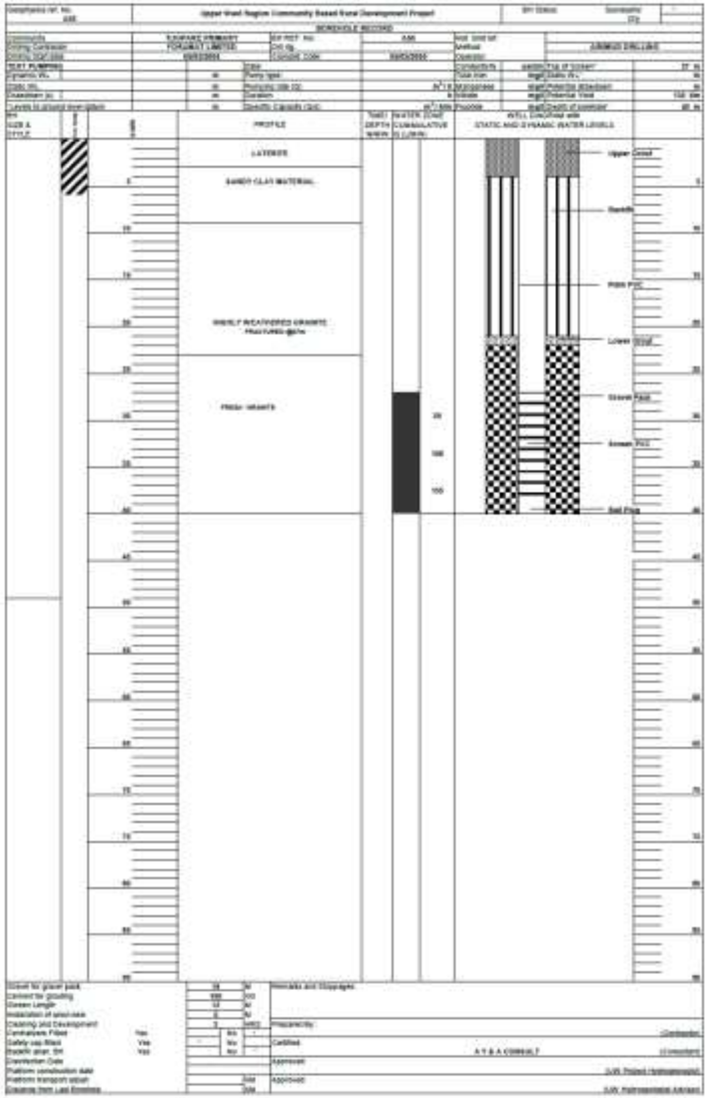


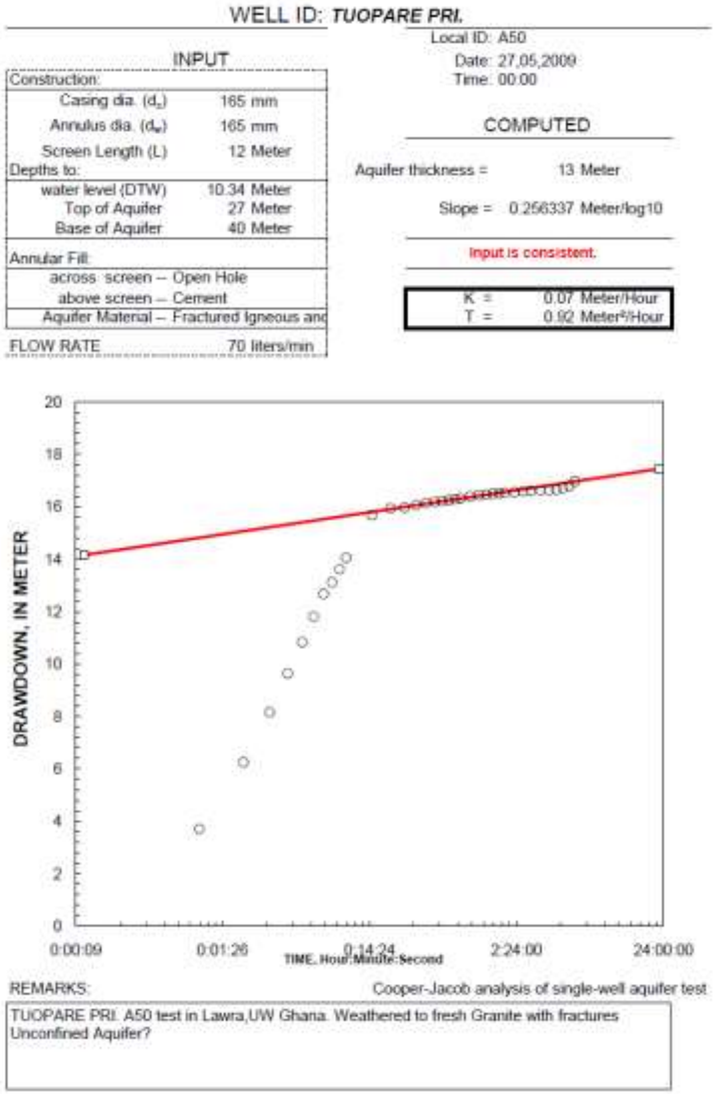


Reduced Data

Entry	Time, Date Hr:Min:Sec	Water Level Meter
1	4/19/00 0:00:00	4.55
2	4/19/00 0:01:00	8.37
3	4/19/00 0:02:00	10.02
4	4/19/00 0:03:00	10.98
5	4/19/00 0:04:00	11.54
6	4/19/00 0:05:00	11.93
7	4/19/00 0:06:00	12.20
8	4/19/00 0:07:00	12.35
9	4/19/00 0:08:00	12.47
10	4/19/00 0:09:00	12.57
11	4/19/00 0:10:00	12.66
12	4/19/00 0:15:00	12.91
13	4/19/00 0:20:00	12.99
14	4/19/00 0:25:00	13.02
15	4/19/00 0:30:00	13.06
16	4/19/00 0:35:00	13.11
17	4/19/00 0:40:00	13.14
18	4/19/00 0:45:00	13.14
19	4/19/00 0:50:00	13.15
20	4/19/00 0:55:00	13.16
21	4/19/00 1:00:00	13.19
22	4/19/00 1:10:00	13.23
23	4/19/00 1:20:00	13.30
24	4/19/00 1:30:00	13.33
25	4/19/00 1:40:00	13.35
26	4/19/00 1:50:00	13.36
27	4/19/00 2:00:00	13.37
28	4/19/00 2:20:00	13.40
29	4/19/00 2:40:00	13.44
30	4/19/00 3:00:00	13.46
31	4/19/00 3:30:00	13.52
32	4/19/00 4:00:00	13.57
33	4/19/00 4:30:00	13.61
34	4/19/00 5:00:00	13.62
35	4/19/00 5:30:00	13.63
36	4/19/00 6:00:00	13.65

Fig. 4-7: Schist (weathered) material core log, Cooper-Jacob straight-line method, pumping test data from Gbengbee site in Lawra area.





Reduced Data

Entry	Time, Date Hr:Min:Sec	Water Level Meter
1	4/19/00 0:00:00	10.34
2	4/19/00 0:01:00	14.05
3	4/19/00 0:02:00	16.59
4	4/19/00 0:03:00	18.50
5	4/19/00 0:04:00	19.98
6	4/19/00 0:05:00	21.18
7	4/19/00 0:06:00	22.16
8	4/19/00 0:07:00	23.02
9	4/19/00 0:08:00	23.46
10	4/19/00 0:09:00	23.96
11	4/19/00 0:10:00	24.40
12	4/19/00 0:15:00	26.02
13	4/19/00 0:20:00	26.28
14	4/19/00 0:25:00	26.31
15	4/19/00 0:30:00	26.41
16	4/19/00 0:35:00	26.48
17	4/19/00 0:40:00	26.53
18	4/19/00 0:45:00	26.56
19	4/19/00 0:50:00	26.59
20	4/19/00 0:55:00	26.63
21	4/19/00 1:00:00	26.67
22	4/19/00 1:10:00	26.74
23	4/19/00 1:20:00	26.78
24	4/19/00 1:30:00	26.81
25	4/19/00 1:40:00	26.84
26	4/19/00 1:50:00	26.86
27	4/19/00 2:00:00	26.88
28	4/19/00 2:20:00	26.90
29	4/19/00 2:40:00	26.93
30	4/19/00 3:00:00	26.95
31	4/19/00 3:30:00	26.97
32	4/19/00 4:00:00	26.98
33	4/19/00 4:30:00	26.99
34	4/19/00 5:00:00	27.07
35	4/19/00 5:30:00	27.14
36	4/19/00 6:00:00	27.31

Fig. 4-8: Granitic material core log, Cooper-Jacob straight-line method, pumping test data from Tuopare Pri. Site in Lawra area.

4.2.4 Examples of Source Protection Zones method

In Table 4-4, a summary of the source protection zones, radius of influence, transmissivity and geology of the towns used in the examples from the study sites are presented.

Radius of Influence method: Sichard and Dupuits equation

SPZ_D: Source protection zone using Darcy method with a 200 day year

SPZ_{VE}: Source protection using Volumetric Equation method with TOT of 1year

Site ID	SPZ_D (m)	SPZ_{VE} (m)	ROI_S (m)	ROI_D (km)	T (m^2/s)	Geology
Akutreso	128,0	69,1	132,6	5566	1,6E-04	W. Clayey material
Ekour	185,5	78,7	104,6	642	4,2E-04	Sandstone
Tuopari	169,3	77,5	224,5	3,6E+12	2,5E-04	Granite
Biakwaso	156,8	109,3	208,9	1,4E+5	2,3E-04	Phyllite
Gbengbee	185,5	76,2	131,6	1,5E+8	3,5E-04	Schist

Table 4-4: *Summary of the different source protection zone methods in different sites.*

4.3 Geographic Information Systems Application in Study areas using ArcGIS

A geographic information system (GIS) is defined as “an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information” (ESRI, 1992). A GIS provides an analytical tool that can be used to create and link spatial and descriptive data for problem solving, spatial modelling, and to present the results in tables or maps. The two most widely used GIS data formats are vector and raster. Vector data represent physical features as polygons, lines and points. Raster data are stored in a matrix of grid cells or pixels representing a rectangular geographic area. The main components of GIS software are the tools for data input and manipulation, database management, geographic query and analysis, and visualization and output. Using a GIS involves following basic steps including designing the GIS database, building the GIS database, analysing the data and presentation of results (Fig. 4-9).

In order to assess source and resource groundwater, elements of the design of a GIS database include establishing the study area and delineating the watershed, determining data needs, inventorying data sources, determining coordinate system and scale, and deciding on the GIS infrastructure. Building the database requires collecting data to characterize the study area, determination of the available groundwater and inventorying sources of contamination. Analysing the data entails assessing the potential sources of contamination, delineating source water protection areas, delineating groundwater vulnerability (resource) areas and producing display products.

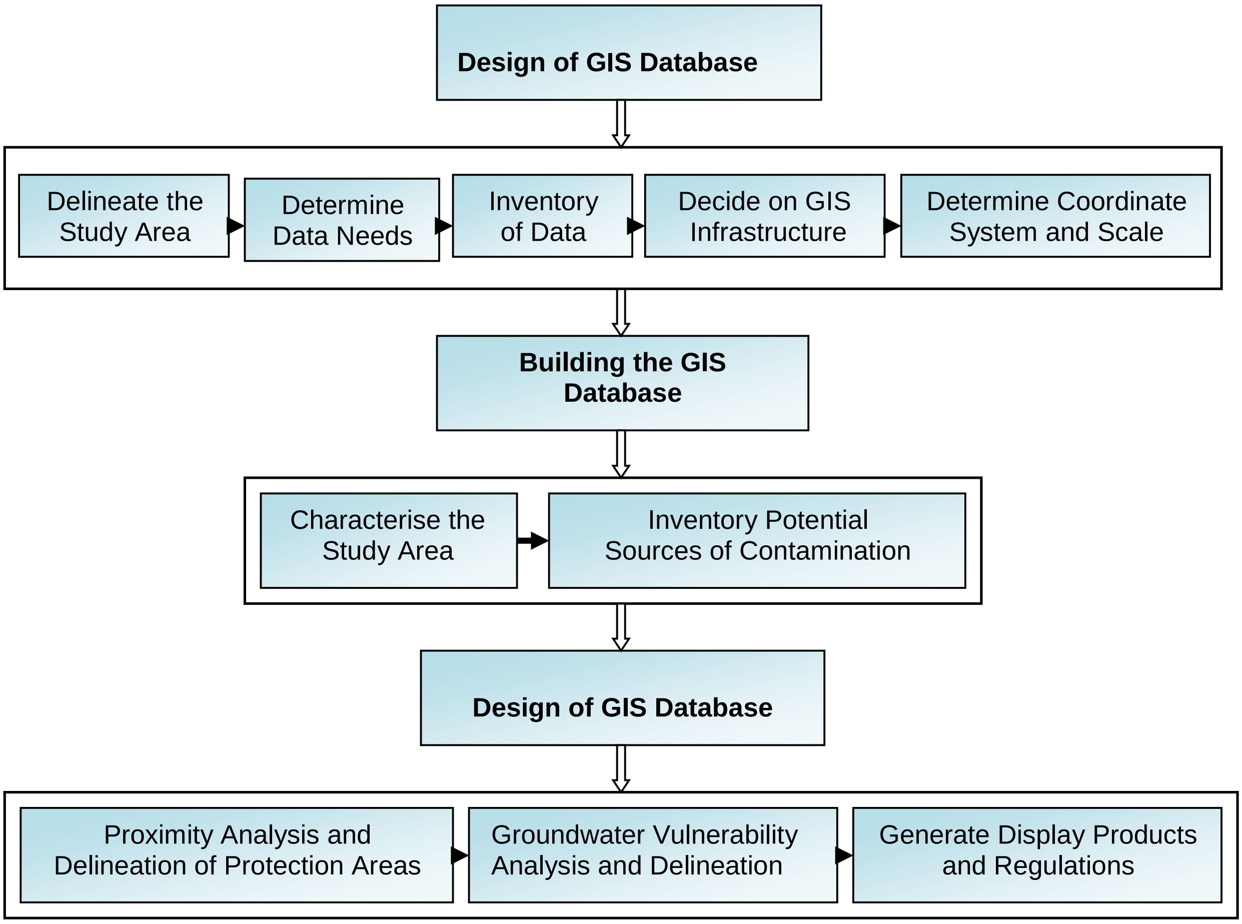


Fig. 4-9: GIS assessment in groundwater protection.

Several GIS packages are available, such as ArcGIS produced by ESRI consisting of three sub- programs namely ArcInfo, ArcEditor and ArcView. These sub-programs share the same core applications, user interface and development. ArcView with sub-components ArcMap, ArcCatalog, and ArcToolbox allows performing basic visualization, spatial query, editing and data integration, and basic modelling and analysis of your data. GIS was used for management of the data obtained from the hydrogeological characterisation and modelling of the input and output parameters. There were several 'layers' of information which needed to be utilized in different combinations dependent upon the activity under consideration.

The software ArcGIS 9.3 developed by ESRI for windows desktop was used to visualize, geoprocess and edit data obtained from the study areas. Using ArcMap application, data obtained with permission from the GLOWA Volta Geoportal was displayed in the data frame. These were shapefiles of points, lines, and polygons with their respective attributes imported and shown as layers. The layers included outlines of country, regions, districts, towns and communities of Ghana. Additional layers were major roads, railway networks and major river networks. These shapefiles were already georeferenced using UTM (Universal Transverse Mercator) zone 30N projection.

The next step consisted of coding. During this process, identification codes were given to all the towns in the study areas as well as the borehole locations and finally the hydrogeological parameters. For example the weathering code consisted of the following classification; highly weathered =1, moderately weathered =2, slightly weathered =3 and fresh material= 4. The structuring code consisted of; highly fractured=7, fracture=5, veins=9, and no fracture=1. As could be seen from these examples, all hydrogeological codes were chosen to describe the parent material and its relationship with the structural activity occurring within the location.

All data stored in Excel to be used in ArcView were converted to dbase files using the ArcToolbox. The geographical positions of boreholes points recorded in latitudes and longitudes were converted to decimal degrees. The dbase files of the borehole points were converted into shapefiles, georeferenced using UTM zone 30N projection.

The method of interpolation was used to display point shapefiles of hydraulic conductivity, drawdown and weathering activity for all borehole locations.

Inverse Distance Weighted (IDW) is a method of interpolation that estimates cell values by averaging the values of sample data points in the neighbourhood of each processing cell (ESRI, 2009). The closer a point is to the centre of the estimated cell, the more influence, or weight; it has in the averaging process. This method was chosen over other methods as hydraulic conductivity and other structural controlled activity in the area tends be unequally distributed; it increases in areas of high tectonic activity and decreases in areas where the rock is relatively fresh. The interpolation tool was assessed using the ArcGIS Spatial Analyst toolbar in ArcMap. The final procedure includes entering the xyz data, using a variable radius type, opting for the Inverse Distance Weighted method, and stating the output cell size. Colour ramp is used to distinguish the various groups of the hydrogeologic characteristics, for example hydraulic conductivity of E-05, E-08 shows red and green respectively. These digital maps are used as tools to aid the characterisation of the study areas in depicting the available groundwater, vulnerability to an intended pollutant and recommendation for the overall groundwater regulation.

Chapter 5

5 Results and Data Analysis

The results presented here are based on the methodology described in Chapter 4 and empirical work conducted in the case study areas in Ghana. These results are assembled into the characterization of available groundwater and vulnerability of groundwater, latter entailing source and resource protection.

5.1 Geology

A total of 286 boreholes were analysed in the study areas. The consolidated rocks were grouped into meta-sedimentary, sedimentary and igneous rocks (Table 5-1). The meta-sedimentary rocks encountered were phyllite, schist and quartzite. The Sedimentary group consisted of sandstone, siltstone, and Shale. The igneous rocks in the study areas were the granites, granitoids and the quartz veins. The unconsolidated materials were lose sand, gravel with quartz, lose quartz and the weathered fragments of the consolidated rocks.

ROCK TYPES – CONSOLIDATED		
Meta-Sedimentary	**Sedimentary**	**Igneous**
Phyllite	Sandstone	Granite
Schist	Siltstone	Granitiod
Quartzite	Shale	Quartz Vein
Weathered clayey material		

ROCK TYPES – UNCONSOLIDATED		
Lose Sand	Gravel with Quartz	Lose Quartz

Table 5-1: Major Rock types within the study areas.

These rock types in the study area are used to determine and characterize the different groundwater regime. The zones that yielded water were structurally controlled with fractures, faults, joints, bedding planes, and veins. These structural features have altered the parent rock in most areas, ranging from moderately weathered to highly weathered material.

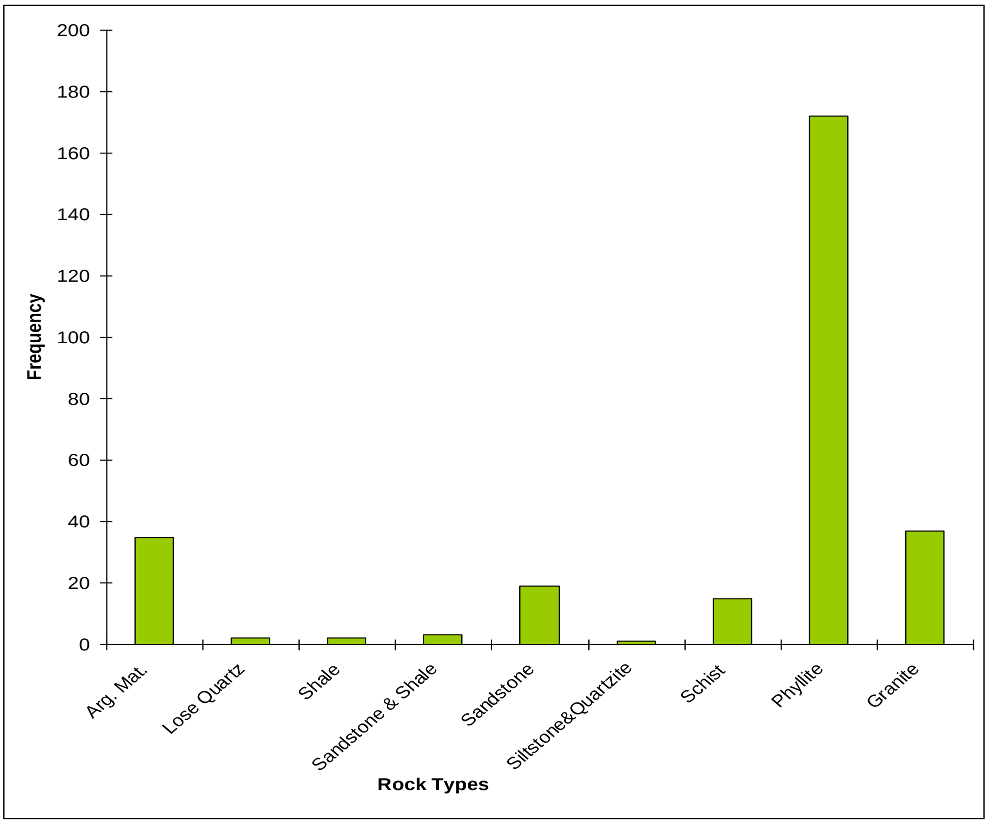


Fig. 5-1: Frequency distribution of the Geological formation in the study area

5.1.1 Meta-Sedimentary Rocks

Phyllite

Phyllite is the most predominant rock type occurring within the study area with over 60 % of the total areas studied (Fig.5-1). In Adansi South it covers over 75% of the land area. It is intruded with quartz veins or traces of quartz and is mostly weathered. Fractures are both regionally and locally influenced based on tectonics. Phyllite was encountered in Lawra, Adansi and Sunyani.

Schist

Schist is a higher metamorphic grade of phyllite as a result of intense heat. It formed 5.2% (Fig.5-1) of the total boreholes analysed and occurred in Sunyani, Lawra, Adansi and Amansie. It also occurs with quartz veins and is interbedded with shale. It belongs to the Tarkwain and Birimain group of geological formations in Ghana.

Quartzite

Quartzite is formed in the early stage of metamorphosis of sedimentary rocks. Three boreholes belong to this group; usually it was associated with schist or phyllite. In Sunyani area, it is interbedded with siltstone.

Argillaceous Material/Clayey material

The clayey materials are weathered components of the argillaceous meta-sediments. They constitute 12.2% of the total boreholes in the study area and are predominant in Adansi and Amansie area. These clayey materials have resulted from the weathering activity within the fracture zones of the crystalline rocks.

5.1.2 Sedimentary Rocks

Sandstone

Sandstone is found mostly in the Sekyere-West area and forms 6.6% of the total number of boreholes in the study area. Sandstone occurs as weathered to fresh, mixed with quartz pebbles and interlaid with shale at Atanosa.

Siltstone

Smaller in grain size than sandstones this formation occurs in the Sunyani area. It is interbedded with quartzite and schist.

Shale

Shale occurs within Sekyere-West and Sunyani areas and forms bedded formations with phyllite and schist.

5.1.3 Igneous Rocks

Granite

Four types of Proterozoic granitoids suites have been distinguished in Ghana; traditionally they have been referred to as Winneba, Capecoast, Dixcove, and Bongo granitoids (Junner, 1940; Kesse, 1985). In the study areas, the basin type of granitiod was encountered in Lawra, Sunyani and belongs to the Cape coast granite group (mica- rich). The granites formed 12.9% of the total number of boreholes in the study areas. They are intruded with quartz veins or traces of quartz. Other igneous rocks were quartz intrusive.

5.2 Hydraulic conductivity estimated by pumping test

The hydraulic conductivity of the study areas was estimated from pumping test results using the Cooper-Jacob straight-line method. A histogram of the hydraulic conductivity of phyllite, clayey material, granite, sandstone and schist was plotted (Fig. 5-2 to 5-6) showing the groupings of the hydraulic conductivity. Generally three groups were identified (I, II, III) according to the powers of 10^{-5}, 10^{-6} and 10^{-7}. A fourth group i.e. 10^{-8} was established only within sandstone. The classification of the hydraulic conductivity is presented in Table 5-2 and shows the relationship between the degree of fractures, hydraulic conductivity and the type of aquifer. For all the rock types, hydraulic conductivity of the range of 10^{-6} was the highly distributed whilst 10^{-5} and 10^{-7} where almost of the same low frequency of distribution. The least distribution is found for hydraulic conductivity within the range of 10^{-8} as occurring in sandstones and some minor shale encountered in the study area.

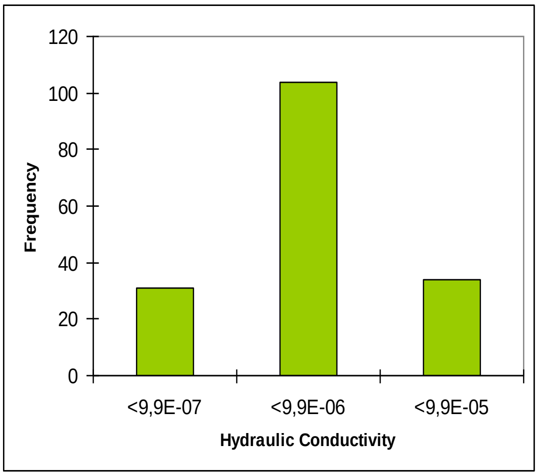


Fig. 5-2: Hydraulic conductivity of Phyllite in study areas.

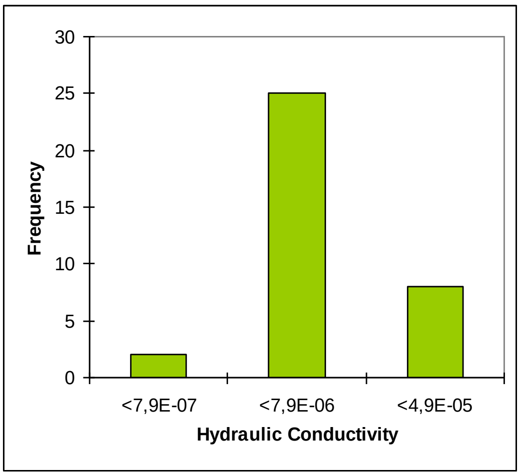


Fig.5-3: Hydraulic conductivity of Weath. material in the study areas.

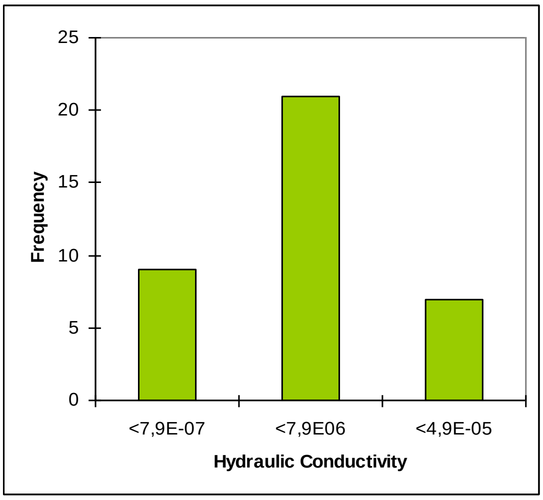


Fig. 5-4: Hydraulic conductivity of Granitic material in the study areas.

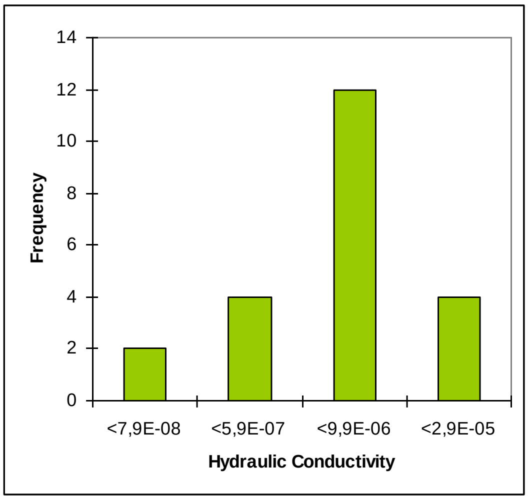


Fig. 5-5: Hydraulic conductivity of Sandstone in the study areas.

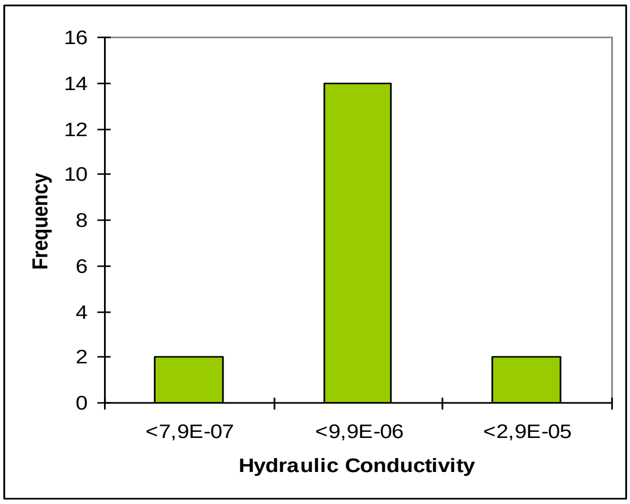


Fig. 5-6: Hydraulic conductivity of Schist in the study areas.

Phyllite rock formations contained the highest number of boreholes (169) of which 34 belong to the 10^{-5}, 104 to the 10^{-6} and 31 to the 10^{-7} group of hydraulic conductivity respectively. The granites had 7, 21 and 9 boreholes of groups I, II and III respectively. This can be deduced from Fig. 5-2 to 5-6.

K- Group	**Type of fracture**	**K_f (m/s)**	**Aquifer Type**
I	High fractures	1.0 - 9.9E-05	**Aquifer**
II	Medium fractures	1.0 - 9.9E-06	**Aquitard**
III	Low or No fractures	1.0 - 9.9E-07	**Aquitard**
IV	**Unconsolidated rocks**	**≥1.0 E-05**	**Aquifer**

Table 5-2: Classification of hydraulic conductivity results from the study areas

Examining Fig. 5-2 to 5-6 the following percentages of hydraulic conductivity values greater than 10^{-5} can be realized: for schist (12, 5%), phyllite (17, 6%), sandstone (22%), granite (21, 9%) and weathered clayey material (37%). From the classification of hydraulic conductivity in Table 5-2, this result implies that about three forth (75%) of the boreholes drilled from the five different rock types in the study areas cannot be classified as aquifers. To ascertain the validity of these results, the specific capacity for the five rock types were estimated for all the study sites and analysed based on the three groups of hydraulic conductivity.

5.3 Available Groundwater

Available groundwater was determined by analysis of pumping test and the classification of pumping test as described in section 5.2. In this section the results of specific capacity are presented and regionalisation of the resulting data is shown. A plot of the hydraulic conductivity groups against the saturated thickness (Fig.5-7) shows a general trend of increasing saturated thickness with decreasing hydraulic conductivity. A plot of hydraulic conductivity against the transmissivity (Fig.5-8) shows a decrease in transmissivity with decreasing hydraulic conductivity.

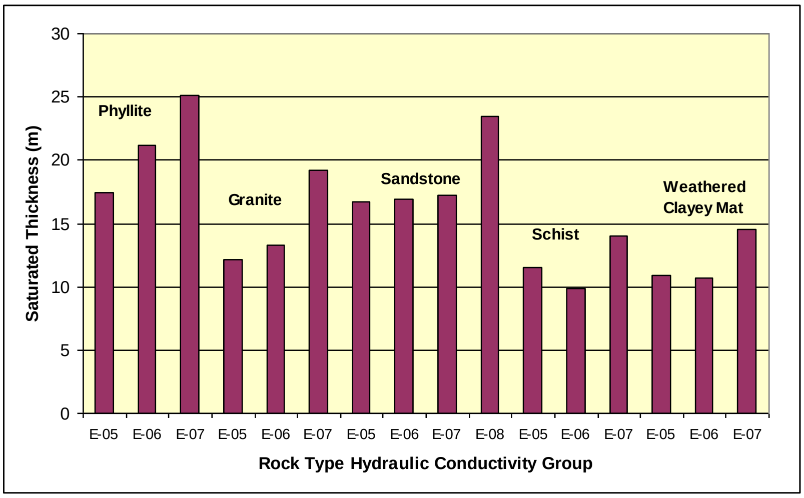


Fig. 5-7: Bar graph of hydraulic conductivity of the various rock types and saturated thickness.

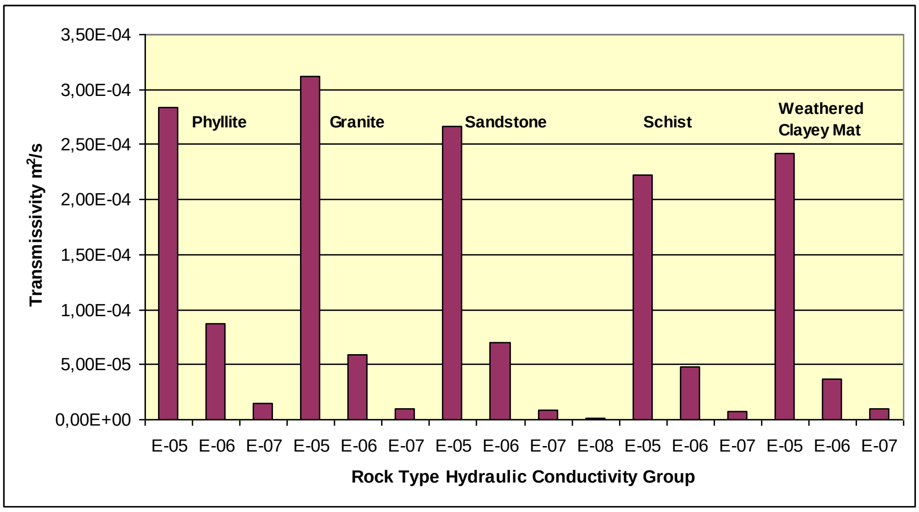


Fig. 5-8: Bar graph of hydraulic conductivity of the various rock types and transmissivity.

A plot of the hydraulic conductivity versus the specific capacity for the five main rock types in the study areas (Fig.5-9 to 5-13) shows an increasing specific capacity with increasing hydraulic conductivity.

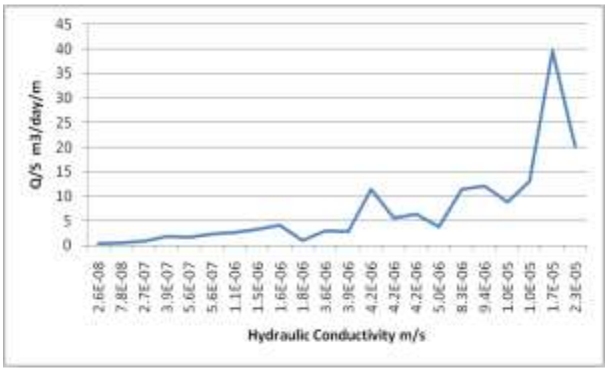


Fig. 5-9: K and Q/S XY line plot for Sandstone.

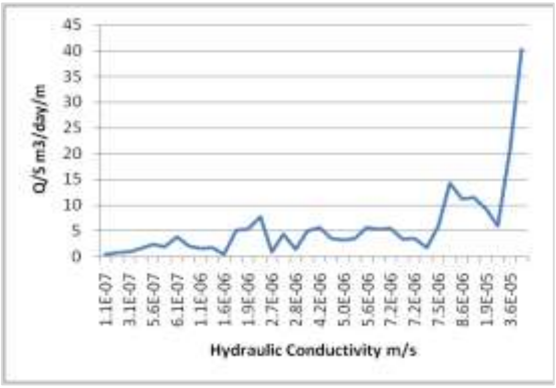


Fig. 5-10: K and Q/S XY line plot for Granite.

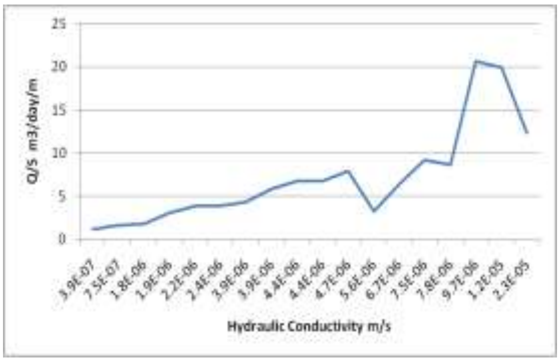


Fig. 5-11: K and Q/S XY line plot for Schist.

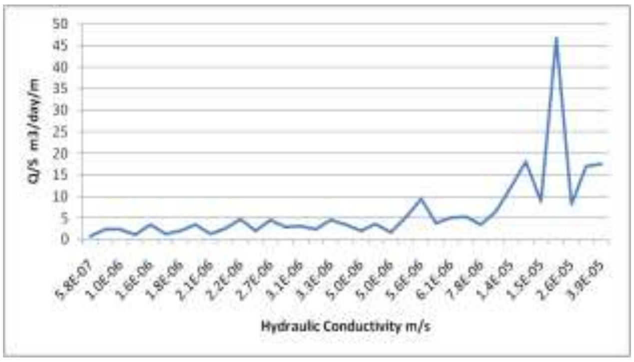


Fig. 5-12: K and Q/S XY line plot for weath. mat.

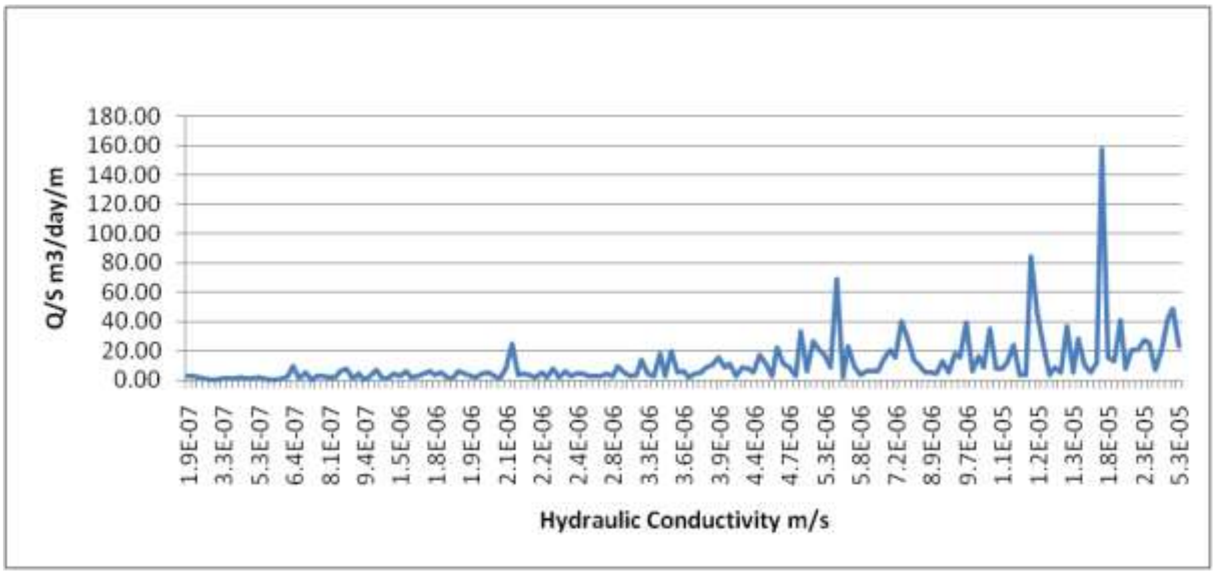


Fig. 5-13: K and Q/S XY line plot for Phyllite.

A summary of this trend above is seen in the plot of the groups of hydraulic conductivity against the specific capacity (Fig. 5-14) in which the specific capacity for the various rock types decreases with decreasing hydraulic conductivity.

This plot implies that, only rock types with hydraulic conductivity greater than 10^{-5} m/s yield sustainable groundwater supply.

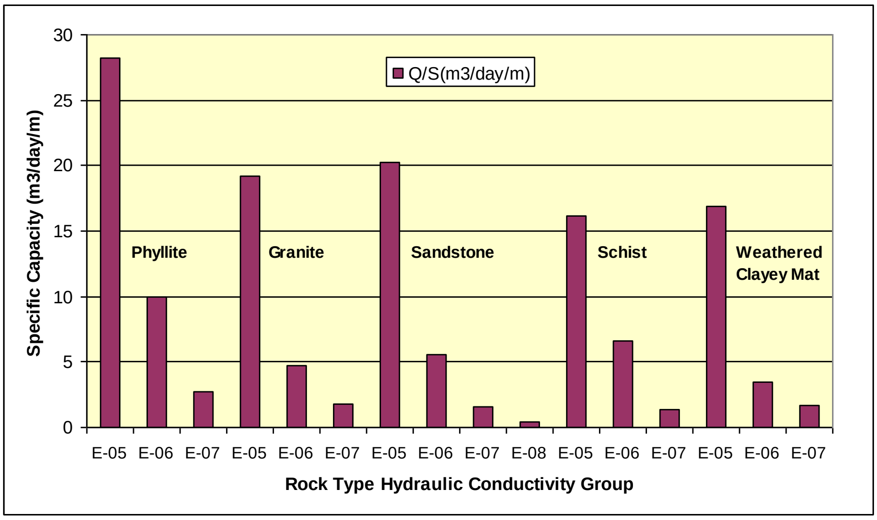


Fig. 5-14: Hydraulic conductivity of the various rock types and specific capacity.

Geology	K (m/s)	Sat thick(m)	OB (m)	T (m^2/s)	Q/S ($m^3/day/m$)
Phyllite	I E-05	17,4	3,9	2,84E-04	28,17
	II E-06	21,2	3,7	8,7E-05	9,98
	III E-07	25,2	3,9	1,46E-05	2,72
Granite	I E-05	12,1	3,3	3,12E-04	19,14
	II E-06	13,3	4,0	5,9E-05	4,76
	III E-07	19,2	3,2	9,25E-06	1,77
Sandstone	I E-05	16,8	3,3	2,67E-04	20,28
	II E-06	16,9	3,3	7,04E-05	5,55
	III E-07	17,3	2,5	8,27E-06	1,58
	IV E-08	23,5	4,0	1,2E-06	0,41
Schist	I E-05	11,5	3,0	2,22E-04	16,16
	II E-06	9,9	3,1	4,85E-05	6,58
	III E-07	14,0	3,5	7,79E-06	1,40
Weathered	I E-05	10,9	5,0	2,42E-04	16,94
Clayey	II E-06	10,7	4,8	3,74E-05	3,43
Material	III E-07	14,5	5,0	1E-05	1,65

Table 5-3: *Summary of hydrogeological parameters used to determine availability of groundwater in study areas.*

To determine the spatial extent, ArcView was used to show data (Table 5-3) of the hydrogeological information. A comparison of the hydraulic conductivity distribution in the Adansi area (Fig.5-15) and the regional structural geological map (Fig. 5-16) confirm that the areas with high hydraulic conductivities (aquifers with K greater than

10^{-5}m/s) are structurally controlled. The red areas, in Fig. 5-15 tend to a South-West to North-East direction; these are the areas in which pumping test results were greater than 10^{-5}m/s.

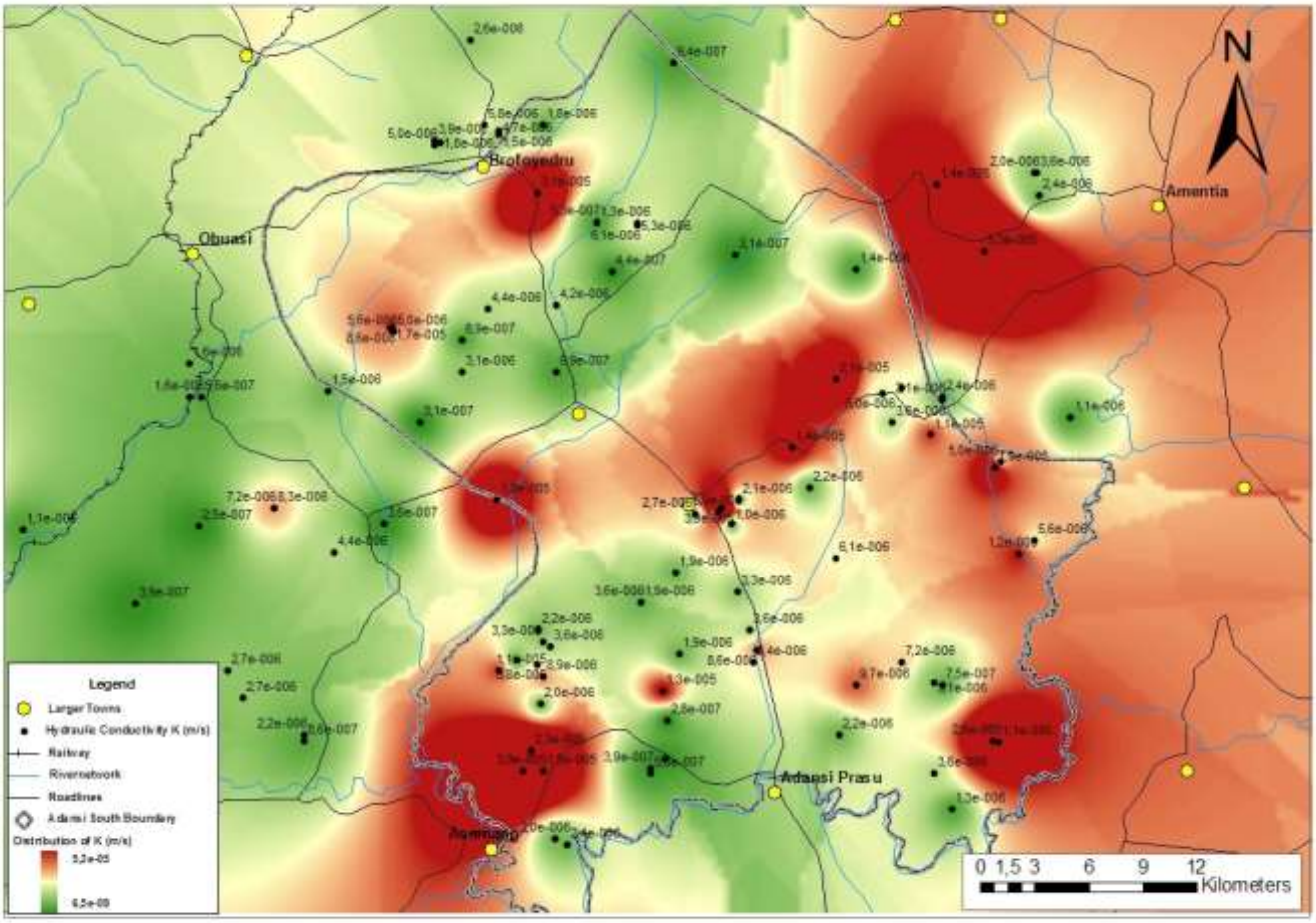


Fig. 5-15: Map of Adansi South area showing roads, rivers, towns and hydraulic conductivity distribution.

Hydrogeological Provinces	Hydrogeologic Sub province	Rock Types	K (m/s)	Type of GW
Alluvial	-	Lose sand and gravel	$\geq 10^{-5}$	Aquifer
Basement Complex	Weathered	Weathered clayey material	$\geq 10^{-5}$	Aquifer
			10^{-6}-10^{-7}	Aquitard
Basement Complex	Tarkwaian System	Phyllite	$\geq 10^{-5}$	Aquifer
			10^{-6}-10^{-7}	Aquitard
	Granitiod intrusives	Sandstone	$\geq 10^{-5}$	Aquifer
			10^{-6}-10^{-7}	Aquitard
	Birimain	Granite	$\geq 10^{-5}$	Aquifer
			10^{-6}-10^{-7}	Aquitard
		Schist	$\geq 10^{-5}$	Aquifer
			10^{-6}-10^{-7}	Aquitard

Table 5-4: *Main hydrogeological provinces of the study areas.*

The hydrogeological provinces of the study areas (Table 5-4) belong to the basement complex, which are Precambrian in age. These Precambrain crystalline rocks are sub divided according to the Ghanaian classification of the various rock formations as Tarkwaian System, Granitiod intrusives and Birimain System. The phyllite aquifer had the highest average specific capacity of about 28m^3/day/m whilst the sandstone, granite, weathered clayey material and schist had 20, 19, 17 and 16m^3/day/m respectively. Based on the hydrogeological system, three groundwater regimes were encountered which were shallow or alluvial, regolith and fractured aquifer.

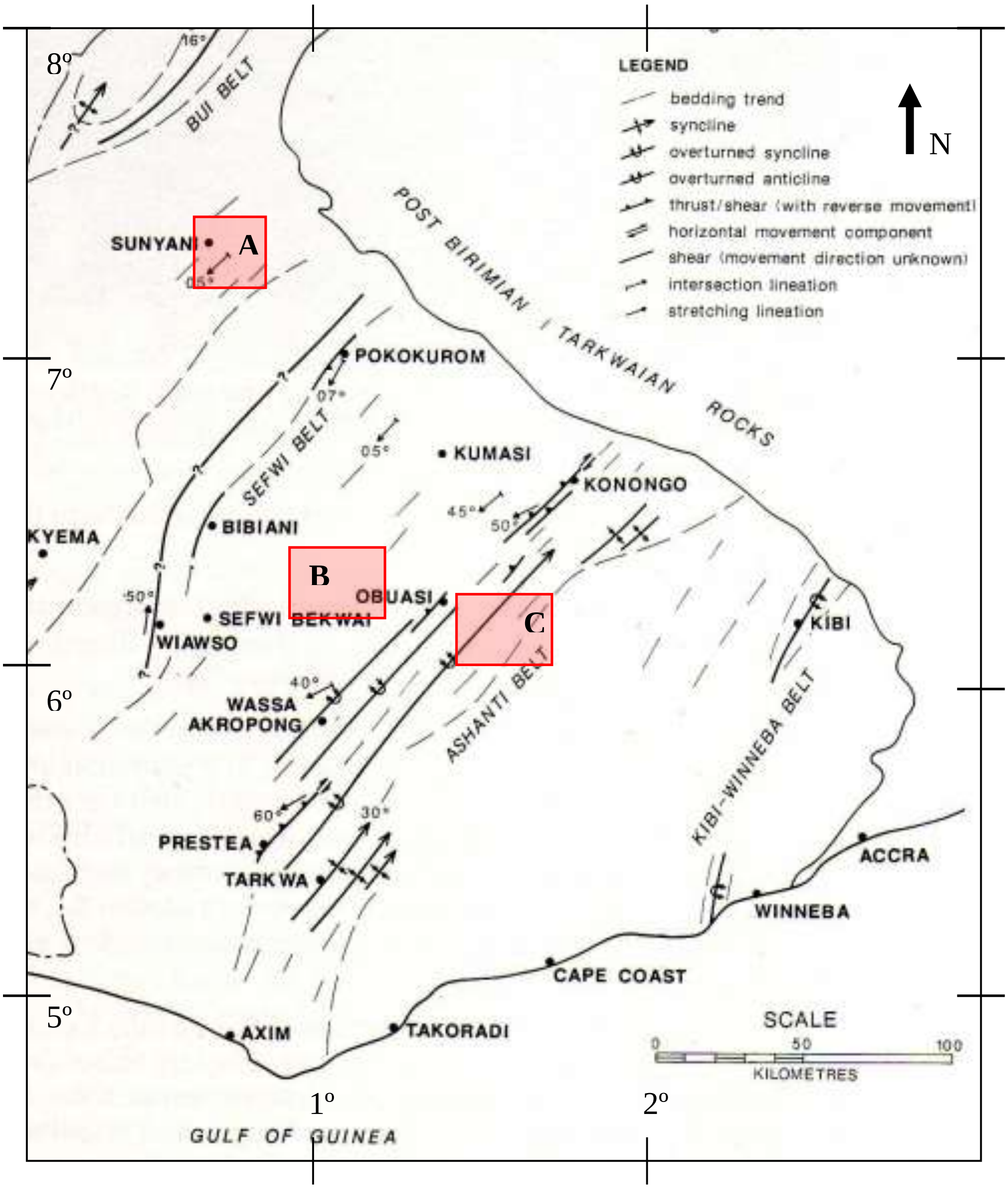


Fig. 5-16: Summary of geological structures in south western part of Ghana showing study areas A, B and C Modified from (Eisenlohr, 1989; Eisenlohr & Hirdes, 1992)

A- Sunyani study area

B- Amansie West study area

C- Adansi South study area

The target zones for groundwater exploration should be areas with fractures, joints and tectonic features as shown from the results of the study areas. These target zones shows the extent of the availability of groundwater for a particular area which could be exploited. The suitable manner to access these structural features within a particular area is through remote sensing and ground geophysical investigation.

Remote sensing data could be obtained from the Ghana Geological Survey offices in Ghana, where a host of geophysical methods are being used to explore groundwater. Ewusi (2006) developed a method for geophysical characterisation for groundwater (Table 5-5 and 5-6) based on the formation rock type, structural features, resistivity and its hydrogeological significance. This method could be useful in the orientation phase during groundwater exploration.

Rock Type		Resistivity (Ω-m)	Hydrogeology significance
Granite	Regolith	100-400	Good groundwater potential and main aquifer
	Jointed/fractured	150-700	Very good groundwater potential with high yields
	Consolidated	800-10000	Hard with poor groundwater potential
Sandstone	Regolith	30-100	Moderate groundwater potential
	Jointed/fractured	30-300	Very good groundwater potential with high yields
	Consolidated	200-1000	Poor groundwater potential

Rock Type		Resistivity (Ω-m)	Hydrogeology significance
Sandstone	Regolith	50-150	Water bearing and very good groundwater potential
	Jointed/fractured	100-700	Very good groundwater potential, highly fractured/jointed with high yields. Main aquifer in the group.
	Consolidated	200-5000	Moderate groundwater potential.

Table 5-5: *Lithology and resistivity range for obtaining groundwater in group 1and 2 modified from (Ewusi, 2006).*

Group	Formation	Communities
Group 1	Birimain, Tarkwain, Basal Sandstone & Granites. (Precambrian)	Tuna Sawla Bamboi
Group 2	Oti Beds. (Voltain sedimentary)	Gulubi quarters Kpandai

Table 5-6: *Summary of the various groups and study sites in the Northern region of Ghana modified from (Ewusi, 2006).*

5.4 Source Protection zone

After the determination of the available groundwater resource, the method of ROI, Darcy and volumetric equation is applied to estimate source protection zones from the available hydrogeological data. In Table 5-7, the results of both ROI methods are presented. The results from Sichard's formula gave values in the range of 20m to 143m whilst those from Dupuits equation were between 1.56m to 4, 31E+22 km. Şen (1995) states that experience in the field indicate the radius of influence for unconfined aquifers varies between 50 to 500m, whilst it is between 300m to 30km for confined aquifers. The low values form the Sichard's equation could be a result of the drawdown values which are ideally determined at the steady state. The extremely high ROI with the Dupuits equation could be a result of the high hydraulic conductivity within the fractured rocks.

The weathered clayey material with hydraulic conductivity in the range of E-05 had the highest ROI for both methods. The least ROI was determined within the sandstones with a range of E-08 (Table 5-7). There is a decrease in the ROI for all rock types dependent on the hydraulic conductivity. Hydraulic conductivity of the E-05-range tends to have higher ROI and the trend continues with lower ROI within the hydraulic conductivity of E-08 (Fig. 5-17). There is an inverse relationship between the ROI and the saturated thickness. The weathered clayey material of hydraulic conductivity E-05 had the highest ROI (144m) and has also almost the lowest saturated thickness of 10.9m, as seen in Table 5-3. The lowest ROI (20m) belong to Sandstone with hydraulic conductivity of E-08 had the second highest saturated thickness of 23.5m.

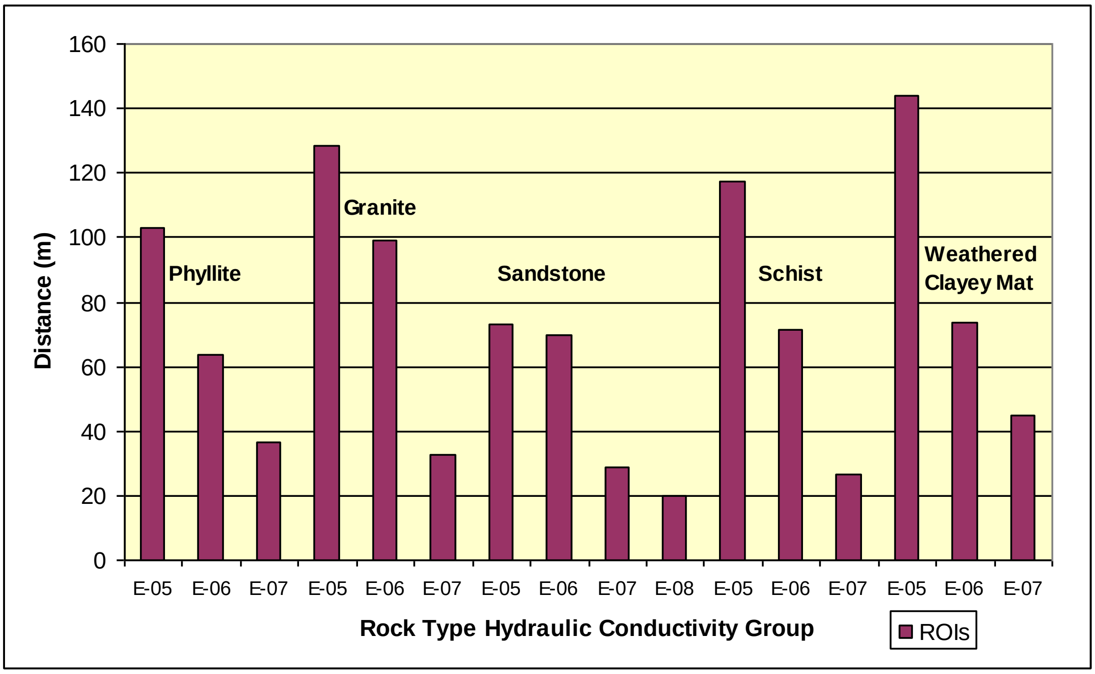
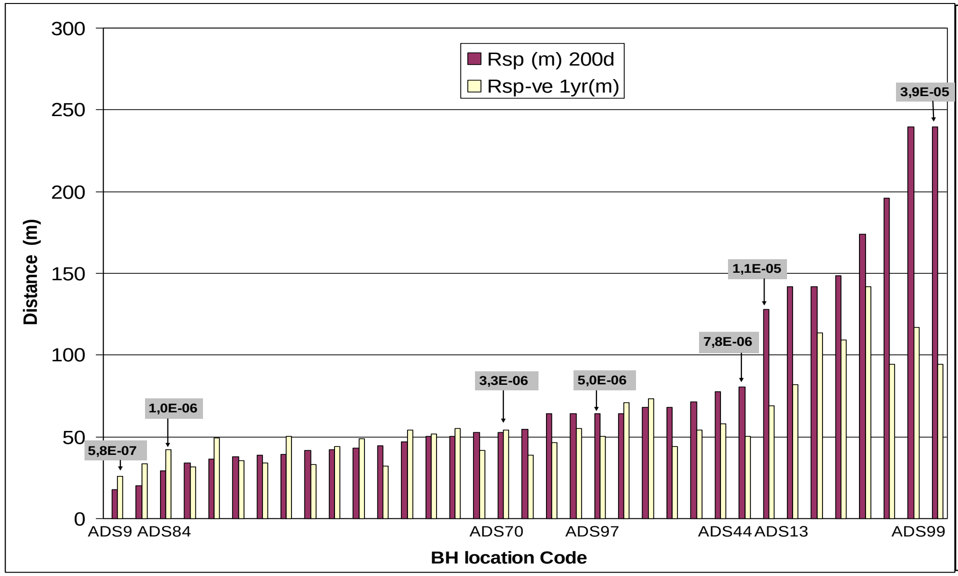


Fig. 5-17: Hydraulic conductivity of the various rock types and ROI using Sichard formula.

Added below in figures 5-18 to 5-23 is comparison between the radii of the source protection zones, using the Darcy equation (Rsp) and volumetric equation (Rsp.ve) for weathered clayey material, schist, granite, sandstone and phyllite. The calculation using Darcy equation assumed a travel time of 200 days whilst for the volumetric equation, a time of travel (TOT) of 1year was assumed. In all five different rock types, the Darcy method yielded high results whilst the volumetric equation method yielded lower results. Generally, three zones could be differentiated from the graphs, below 50m, 50-100m and those above 100m corresponding with 10^{-7}, 10^{-6} and 10^{-5} m/s hydraulic conductivities respectively.

This implies the highly fractured and jointed rocks with higher hydraulic conductivity within all the various rock types studied would require greater distances for protection than the less jointed or those with less fracture rocks. Since the degree of weathering activity is also influenced by the degree of tectonic activity within the area, higher tectonic activity would also require greater zones of protection. The overall protection zone should therefore include the available groundwater resource in the area whilst considering the degree of structural activity in the areas including the presence of joints, fractures and weathering activity.



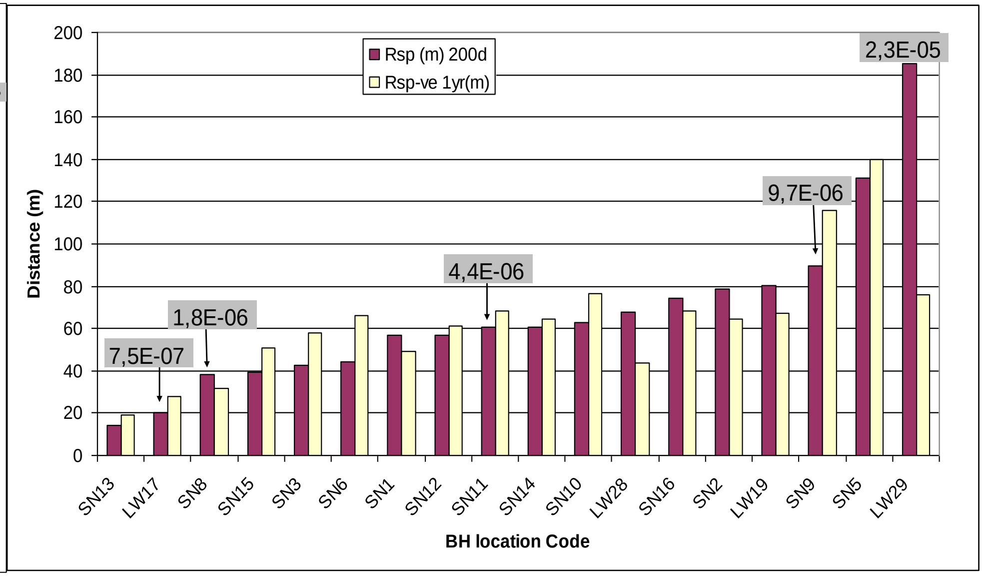
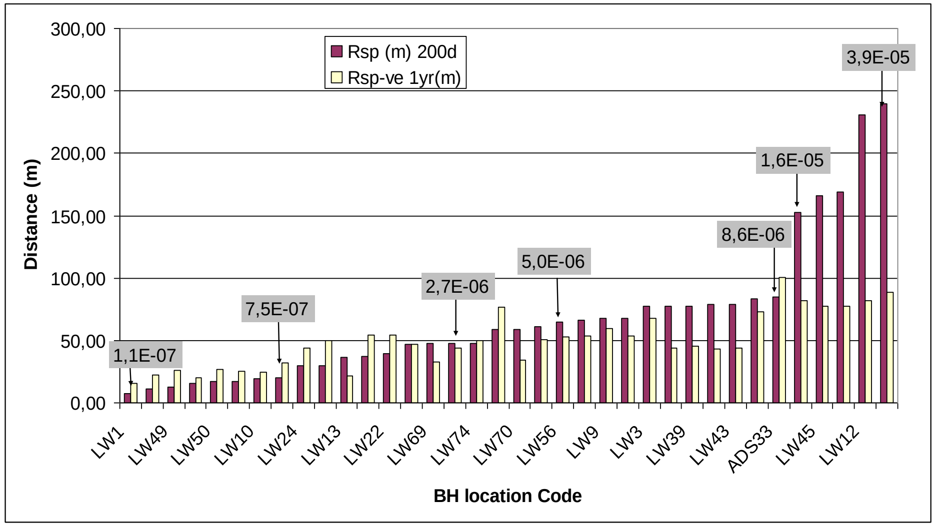


Fig. 5-18: *Comparison of source protection zones for clayey materials using Darcy method, t=200days (Rsp 200d) and the volumetric equation for 1year (Rsp-ve 1yr)*

Fig.5:19: *Comparison of source protection zones for schist using Darcy method, t = 200days (Rsp 200d) and the volumetric equation 1year (Rsp-ve1yr)*



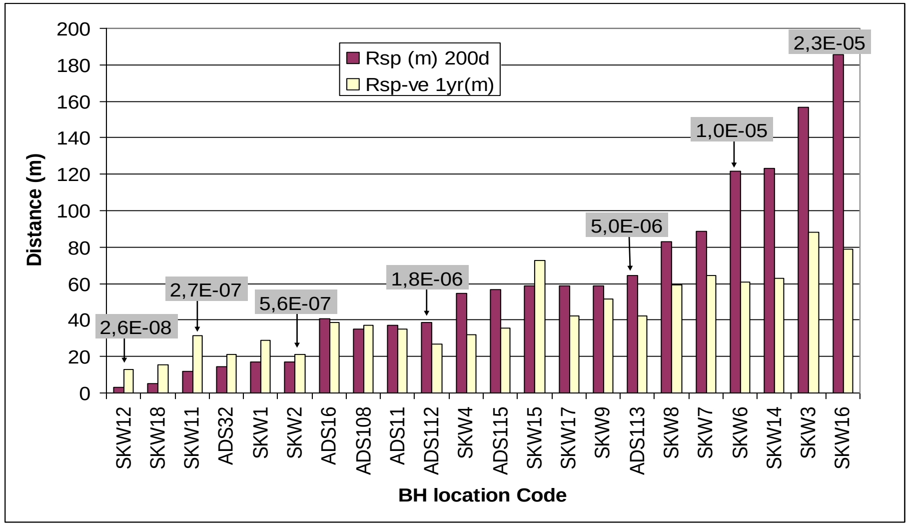


Fig. 5-20: *Comparison of source protection zones for granite using Darcy method, t=200days (Rsp 200d) and the volumetric equation for 1year (Rsp-ve 1yr)*

Fig. 5-21: *Comparison of source protection zones for sandstone using Darcy method, t= 200days (Rsp 200d) and the volumetric equation for 1year (Rsp-ve 1yr)*

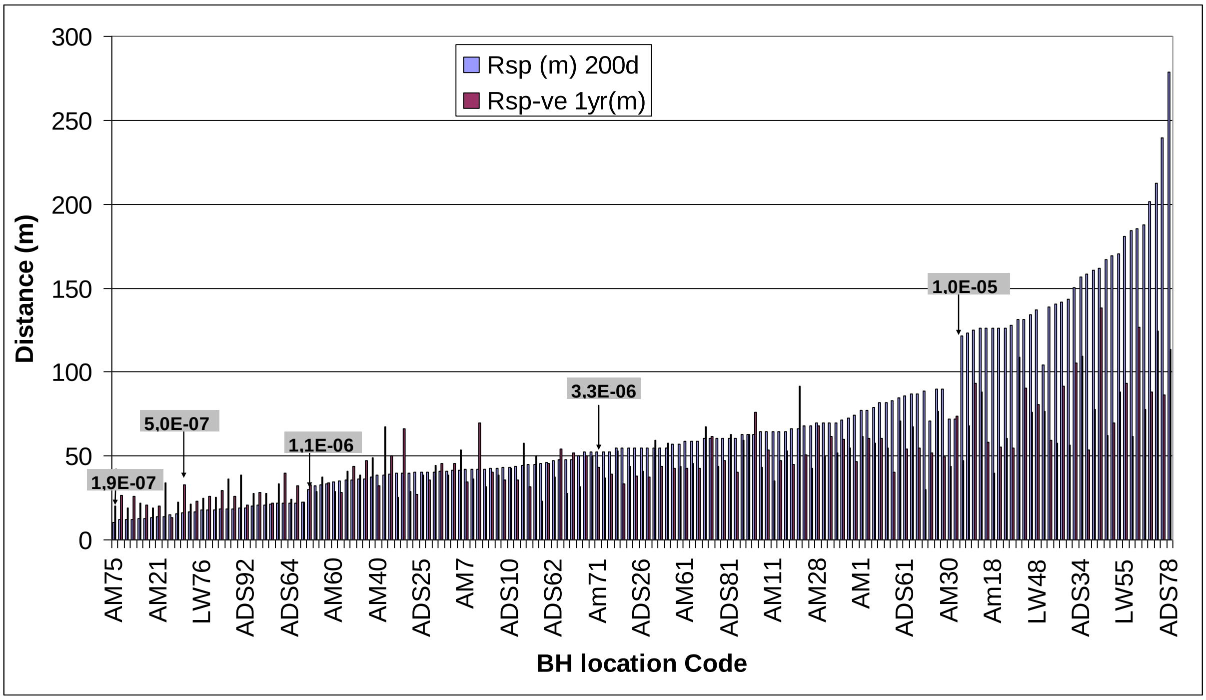


Fig. 5-22: Comparison of source protection zones for phyllite using Darcy method with t equal to 200days (Rsp 200d) and the volumetric equation for 1year (Rsp-ve 1yr).

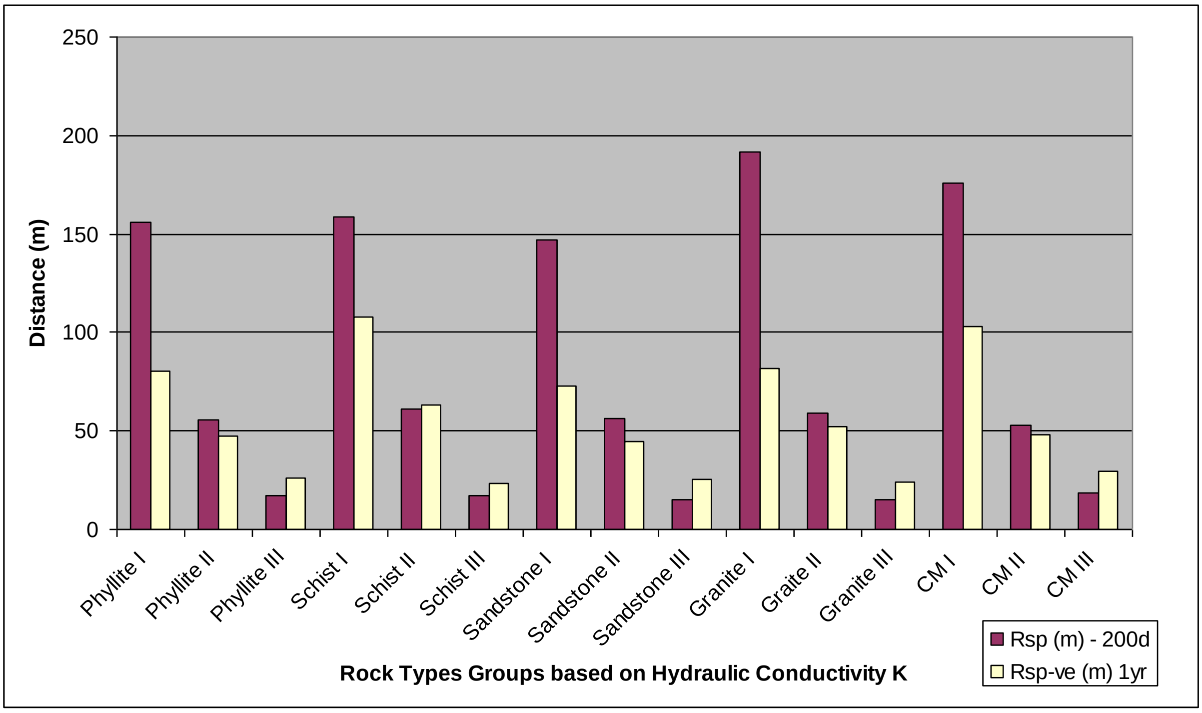


Fig. 5-23: Comparison of the source protection zones of the various rock type groups based on the hydraulic conductivity.

Geology	Group	K (m/s)	ROIs(m)	R (km)	SWL(m)	OB (m)	Rsp (m) - 200d	Rsp-ve (m) 1yr
Phyllite	I	E-05	103,22	3,87E+18	10,4	3,9	155,76	80,51
	II	E-06	63,56	1,2E+14	12,4	3,7	55,59	47,22
	III	E-07	36,73	160,99	11,0	3,9	17,15	25,92
Granite	I	E-05	128,54	1,05E+12	10,1	3,3	191,60	81,39
	II	E-06	98,90	9,98E+13	9,0	4,0	59,31	51,98
	III	E-07	32,44	0,024005	8,2	3,2	15,15	24,06
Sandstone	I	E-05	73,05	161,1102	29,0	3,3	146,70	72,72
	II	E-06	69,63	7,68E+11	17,8	3,3	56,27	44,74
	III	E-07	29,05	0,012605	15,2	2,5	15,18	25,65
	IV	E-08	19,78	0,00156	13,0	4,0	-	-
Schist	I	E-05	117,59	76796373	10,7	3,0	158,33	107,93
	II	E-06	71,59	1,37E+08	19,7	3,1	60,94	63,30
	III	E-07	26,46	0,06777	34,1	3,5	17,16	23,34
Weathered	I	E-05	143,85	4,31E+22	10,3	5,0	176,16	102,68
Clayey	II	E-06	73,80	1558036	10,9	4,8	52,71	47,92
Material	III	E-07	44,78	0,04213	18,3	5,0	18,78	29,72

Table 5-7: *Summary of hydrogeological parameters and methods used to delineate source protection zones.*

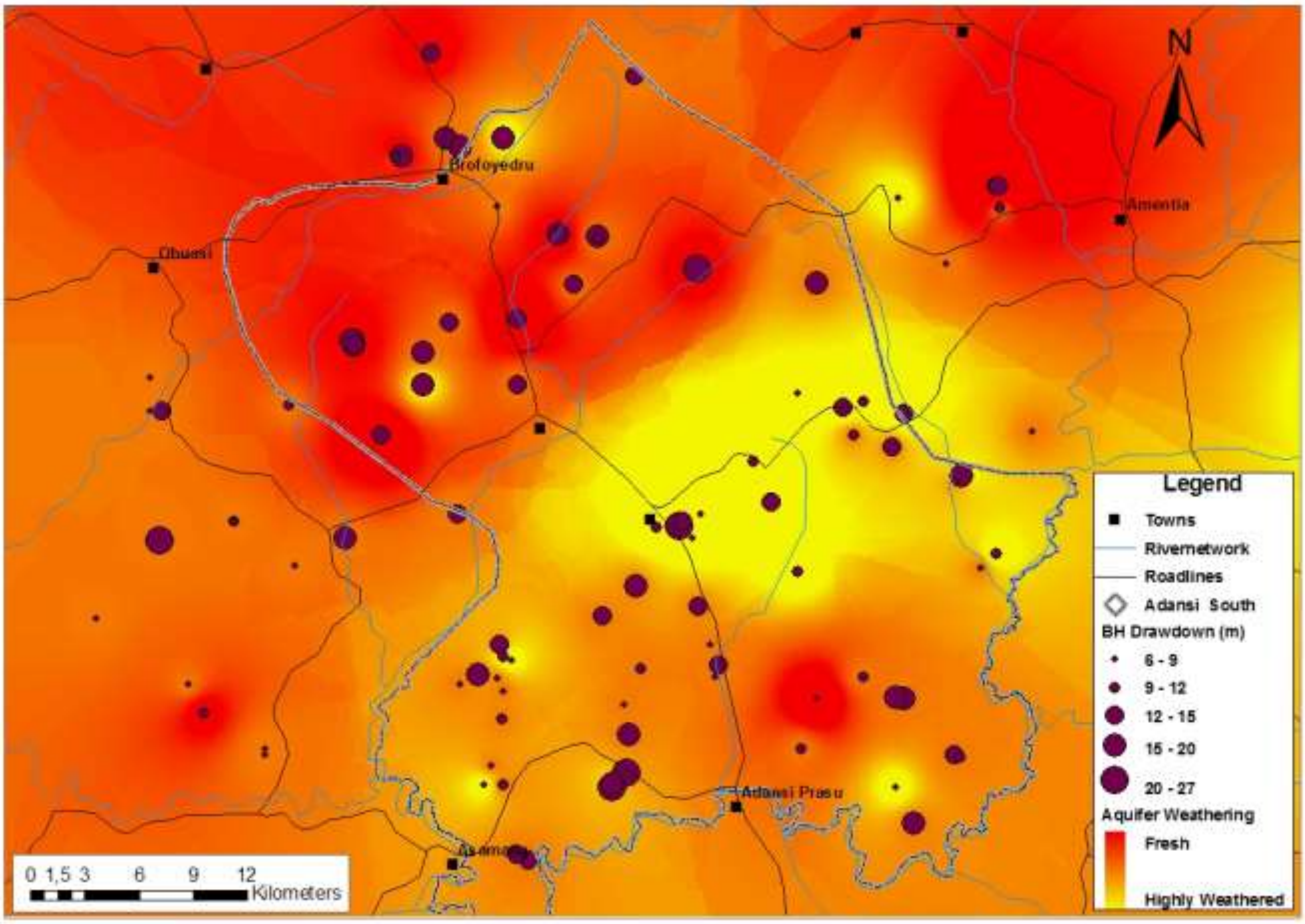


Fig. 5-24: Map of Adansi South area showing spatial distribution of drawdown and aquifer weathering activity

Adansi South area is characterised by both highly weathered and fresh aquifers (fig. 5-24). The highly weathered rocks were the regolith aquifers. Those with higher hydraulic conductivity (≥10^{-5}m/s) shows higher borehole drawdowns whereas with a lower hydraulic conductivity (≤10^{-7}m/s), shows lower borehole drawdown. The fresh rock types in the area were usually jointed and fractured due to the tectonic activity. These joints and fractures serves as conduits for underground water storage. This fresh but jointed aquifer showed higher borehole drawdown values in areas where the hydraulic conductivity was greater than 10^{-5}m/s. In areas with lower hydraulic conductivity they have very small borehole drawdown and in some areas serve as aquitards.

Chapter 6

6 Modelling for Groundwater Protection

6.1 Conceptualization of Model

In order to understand the whole study areas and the various factors that contribute to development or degradation of the Groundwater resource, a conceptual model was developed (fig. 6-1). The conceptual model shows factors important to Ghana's groundwater situation, including water cycle, water use, recharge of aquifers, possible sources of pollution and available groundwater. These interactions of elements in the ecosystem, water cycle and the influence of anthropogenic elements eventually affect both the volume of available groundwater and its quality as well. Using the known input parameters through modeling, both the available groundwater and its vulnerability to pollution was estimated.

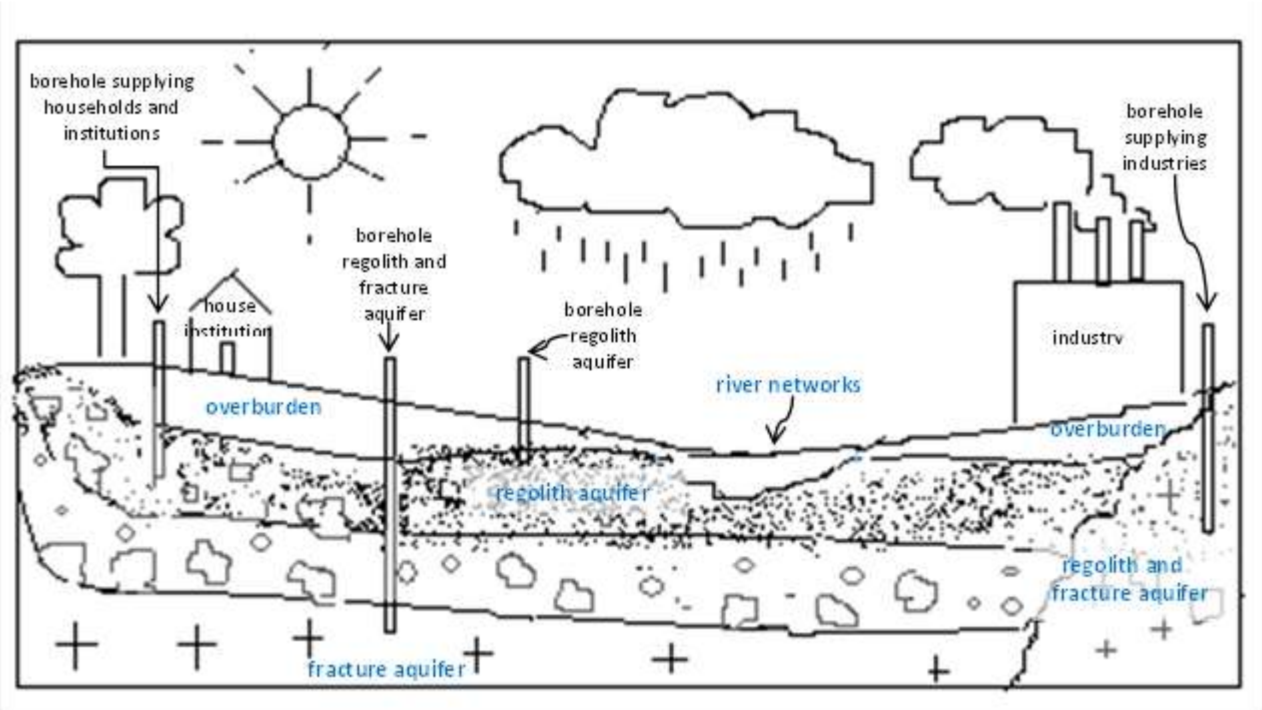


Fig. 6-1: Conceptual diagram of the study areas

6.2 Input and Output parameters

The initial hydrogeological data (Fig. 2-5) were used to estimate the input hydrogeological parameters which include specific capacity, hydraulic conductivity, radius of influence, source protection zones and groundwater vulnerability zones. These input hydrogeological parameters were modelled to obtain the initial output of available groundwater and vulnerability of groundwater (Fig. 6-2).

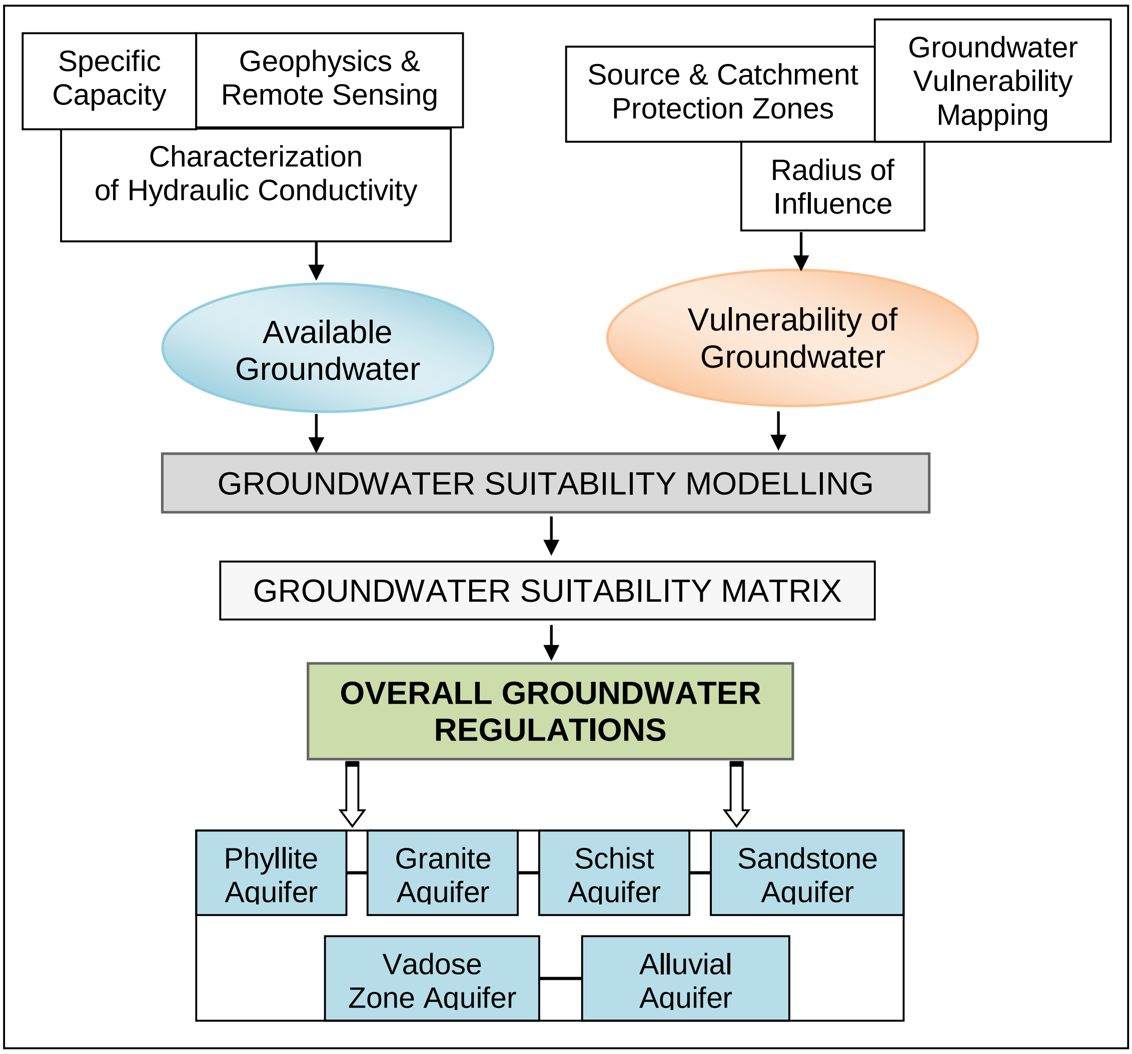


Fig. 6-2: Flow diagram of the Groundwater Suitability model.

The theories and methods used to obtain the input parameters, available groundwater and groundwater vulnerability have already been discussed in chapters three, four and five. Now, the main objective was to identify the available groundwater resources, after which an appropriate method of protection is proposed based on an investigation using source and resource protection concepts. The components of the available groundwater and vulnerability of groundwater now serve as input parameters for subsequent modelling.

This model is based on the concept of 'Groundwater Suitability' and is used to build a groundwater suitability matrix which is then used to develop the overall groundwater regulation for the various aquifers. The concept of groundwater suitability measures the usability of groundwater from the input parameters; based on its quantity towards groundwater production/use and based on its quality towards groundwater protection. The suitability of groundwater source in this model is estimated using discrete parameters.

6.3 Classification for Groundwater Suitability

The groundwater suitability classification ranks each of the parameters as high, moderate or low and assigns ranks 3, 2, 1 respectively (Table 6-1). In terms of quantity assessment, any available groundwater with specific capacity (Q/S) is judged high when it is greater than 15 and low when it is less than 4,9 all in $m^3/s/m$. Groundwater with hydraulic conductivity greater than 10^{-5}m/s is judged good for sustainable groundwater development whilst those less than 10^{-7}m/s are not suitable for groundwater development in the long term.

In terms of quality assessment, any available point source of groundwater with an estimated source protection zone (SPZ) greater than 150m is classified as high implying highly vulnerable or susceptibility to contamination. These boreholes or sources will require more attention and a greater area for source protection of wells within these areas than those with an estimated SPZ less than 50m. Results from the study sites shows areas with high SPZ were moderately weathered to fresh rock with fractures, joints and sometimes with quartz veins. Radius of influence (ROI) greater than 100m was also classified high and requires more attention with stringent measures for protection than those having ROI less than 49,9m. The ROI is determined by the degree of structural deformation, areas highly weathered turn to have less radius of influence as compared to fractured areas.

		Groundwater Resources Assessment				
		Quantity Assessment			Quality Assessment	
Classification		Available GW			GW vulnerability	
Class	**Rank**	**Q/S ($m^3/s/m$)**	**K(m/s)**	**T(m^2/s)**	**SPZ (m)**	**ROI (m)**
High	3	≥15	$\geq 10^{-5}$	$\geq 2{,}0\times10^{-4}$	≥150	≥100
Moderate	2	5-14,9	$\geq 10^{-6}$	$1{,}9\times10^{-4}$ -5×10^{-5}	50-149.9	50-99.9
Low	1	≤4,9	$\leq 10^{-7}$	$\leq 4{,}9\times10^{-5}$	≤49,9	≤49,9

Table 6-1: *Groundwater suitability classification based on availability and vulnerability of groundwater*

An overall groundwater suitability judgement is made for each rock type based on a combination of the five parameter mentioned above. Since groundwater vulnerability estimates are based on regional assessment, using the same criteria above to assess the suitability of the various rock types would mean knowing the lateral and vertical extent of each of these rock types. Regional groundwater vulnerability could be estimated from the depth to the parent rock, field capacity of the overburden material and the groundwater recharge estimates from rainfall data. From this type of assessment, areas could be classified high, moderate and low vulnerability depending on the area in question and not necessarily by the underlying rock type.

Highly available groundwater is associated with high specific capacity, high hydraulic conductivity and high transmissitivity. They also showed higher values of estimated SPZ and ROI. This means that the highly fractured crystalline rocks within the study sites with high amount of available groundwater will require more stringent regulations to protect the groundwater resources from possible contamination. Areas with highly weathered regolith aquifers can be developed for local use but would require a monitoring program, although these aquifers will have less stringent regulations due to the smaller radii of the estimated SPZ and ROI.

6.4 Development of Groundwater Suitability Matrix

The groundwater suitability matrix (Table 6-2) is a ranking matrix which ranks each rock type and hydraulic conductivity (K m/s) into groups from high (3), moderate (2) and low (1) in the context of groundwater suitability.

The rock type is ranked based on the relationship with source protection, radius of influence, specific capacity and transmissivity. The two different methods applied in estimating the SPZ and ROI were both used in the ranking matrix.

The following conclusions could be drawn from the matrix:

- The maximum number of attainable points from six parameters is 18 and the minimum is 6.
- 18 points implies a good aquifer ($Q/S \geq 15 m^3/s/m$) for water supply but involves SPZ and ROI greater than or equal to 150 and 100m respectively.
- 6 points implies a poor groundwater source with very low ROI and SPZ.

Rock Type	K (m/s)	SPZ-Darcy method		SPZ- Vol. Equation meth.		ROI-M1		ROI-M2		Specific Capacity Q/S		Transmissivity	
	Group	GWS	Rank	GWS	Rank	GWS	Rank	GWS	Rank	GWS	Rank	GWS	Rank
Phyllite	E-05	High	3	Mod.	2	High	3	High	3	High	3	High	3
	E-06	Mod.	2	Low	1	Mod.	2	High	3	Mod.	2	Mod.	2
	E-07	Low	1	Low	1	Low	1	Mod.	2	Low	1	Low	1
Granite	E-05	High	3	Mod.	2	High	3	High	3	High	3	High	3
	E-06	Mod.	2	Mod.	2	High	3	High	3	Low	1	Mod.	2
	E-07	Low	1	Low	1	Low	1	Low	1	Low	1	Low	1
Sandstone	E-05	High	3	Mod.	2	Mod.	2	Mod.	2	High	3	High	3
	E-06	Mod.	2	Low	1	Mod.	2	High	3	Mod.	2	Mod.	2
	E-07	Low	1	Low	1	Low	1	Low	1	Low	1	Low	1
	E-08	Low	1	Low	1	Low	1	Low	1	Low	1	Low	1
Schist	E-05	High	3	Mod.	2	High	3	High	3	High	3	High	3
	E-06	Mod.	2	Mod.	2	Mod.	2	High	3	Mod.	2	Low	1
	E-07	Low	1	Low	1	Low	1	Low	1	Low	1	Low	1
Weathered Clayey material	E-05	High	3	Mod.	2	High	3	High	3	High	3	High	3
	E-06	Mod.	2	Low	1	Mod.	2	High	3	Low	1	Low	1
	E-07	Low	1	Low	1	Low	1	Low	1	Low	1	Low	1
Rank Value		High ≥ 150m		High ≥ 150m		High ≥ 100m				High ≥15m^3/s/m		High ≥ 2,0E-04m^2/s	
		Low ≤ 49,9m		Low ≤ 49,9m		Low ≤ 49,9m				Low ≤ 4,9 m^3/s/m		Low ≤ 4,9E-05 m^2/s	

*Table 6-2: Groundwater Suitability Matrix indicating the hydraulic conductivity groups of the rock types, source protection zones, radius of influence, transmissivity , groundwater suitability index and their rank based on the rank value criteria; with GWS- Groundwater Suitability Index, K- Hydraulic conductivity, SPZ- Source protection zones (Darcy and Volumetric equation methods) ROI- Radius of Influence (Sichard **M1**and Theiss **M2** methods)*

Fig. 6-3 shows phyllite, granite, schist and weathered clayey material with hydraulic conductivity in the range of 10^{-5}m/s obtained 17 points whilst sandstones in the same range obtained 15 points. Granite, Sandstone, Schist and weathered clayey material with hydraulic conductivity in the range of 10^{-7}m/s or less were accredited with 6 points. All rock types with hydraulic conductivity in the range of 10^{-6}m/s had points between 7 and 13.

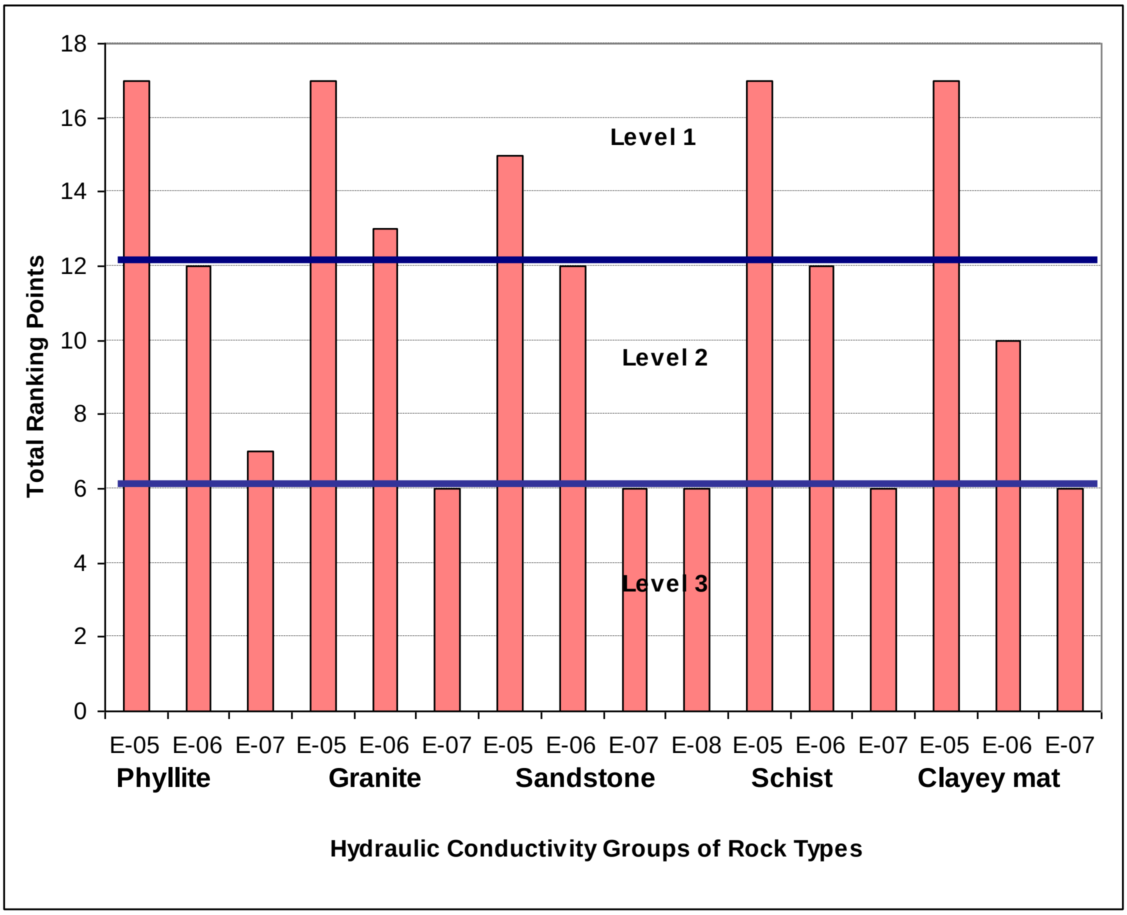


Fig. 6-3: Bar graph of rock type, hydraulic conductivities and total ranking points from the Groundwater Suitability Matrix.

The results from the total points of the ranking matrix were grouped into three levels as shown in Fig. 6-4. This was done to distinguish between the rock types with their associated hydraulic conductivity and their suitability for groundwater development, at the same time depicting their susceptibility towards groundwater pollution and/or the need for groundwater protection.

Group	Points	Rock type-K(m/s)	Recomendation
Level 1	12-18	Phyllite, Granite, Sandstone, Schist and Clayey material - 10^{-5}	Very good for GW development and piped system. Proposed zone of protection 150m -100m, monitored for GW quality.
Level 2	6-12	Phyllite, Granite, Sandstone, Schist and Clayey material - 10^{-6}	Good to limited GW development, for local use but should be monitored for overdraft. Proposed zone of protection 100m
Level 3	0-6	Phyllite, Granite, Sandstone, Schist and Clayey material - 10^{-7}	Limited and poor for GW development, may be used in exceptional cases, strict monitoring for overdraft. Zone of protection 50m

Fig. 6-4: Groundwater management for different rock types and hydraulic conductivity based on interpretation of the ranking matrix.

The first group (level 1) is characterized as very good aquifers with average specific capacity equal to or greater than 15m^3/s/m within the study areas. All the crystalline rock aquifers found in this category could be developed for pump systems in communities with high groundwater demand. There is the need, though, for further studies to determine the specific lateral extent of aquifers. This is the only group from the study areas that such groundwater abstraction could be deployed without serious concerns for groundwater overdraft. Again further monitoring would be needed for sustainable use of groundwater resources. Although groundwater availability in this group is very good, concerns about groundwater protection are very high, as have already been discussed, groundwater in these crystalline rocks tends to develop within the regolith and the fracture systems. The minimum distance to be considered for source protection zones based on results from the study areas is between 150-100m.

Level 2 to the represents the second group; these are good groundwater resources having specific capacities between 5 and 14,9m^3/s/m. These groundwater resources are suitable for local community water supply but not for piped systems of bigger towns due high risk concerns of groundwater overdraft based on results obtained from available groundwater estimates from the study areas. Crystalline rocks belonging to this group will need a minimum distance of 99,9m for source water protection. Detailed groundwater mapping should be carried out in such communities and areas. Additional new hydrogeological data and assessment could help determine the actual available groundwater resources. Based on that current information this assessment will determine whether the groundwater resource could also be used for piped systems without any serious threat of groundwater overdraft. Monitoring for groundwater overdraft in this group is very critical for sustainable groundwater use.

The last group (level 3) is characterized by very limited and poor available groundwater for sustainable development. They have a specific capacity of less than 4,9m^3/s/m. Due to its lower hydraulic conductivities (≤10^{-7}m/s), as compared to the other two groups (level 1 and 2), the resultant source protection zones from the study areas are much lower (≤49,9m) which could mean that there are less fractures present or possible perched aquifers with very limited lateral extent. As has been the case throughout, there will be the need for further hydrogeological mapping in this group to determine both vertical and lateral extent of groundwater resources. Further research will also need to investigate whether groundwater is completely outside fractured zones. The reasonable use of groundwater for this group will be for either private homes or very small communities with no other possibility for water supply. Piped system and irrigation networks will not be suitable within this group unless there is adequate data or updated hydrogeological information to characterise and quantify the resource to be otherwise.

6.5. Specific Regulations for Groundwater Resources in Study Areas

The specific regulations depicted in Table 6-3 are based on results and analyses of the available groundwater and groundwater vulnerability for the various rock types found in the study areas. The regulations are based on hydraulic conductivity, specific capacity and the source protection zone. These regulations are depends on the aquifer type and the specific rock types. Application of these regulations is discussed later in section 6.6 to include the initial groundwater development through the abstraction and policies where protection zones involve the whole catchment area.

Aquifer	Rock type	Regulations
Crystalline rocks (fractured)	Granite, Phyllite, Schist, Sandstone? $K \geq 10^{-5}$m/s	Siting should target fracture zones with $K \geq 10^{-5}$m/s. Pumping can exceed 15m^3/s/m. Minimum distance for source protection should be between 150 -100m.
Regolith	Weathered (various stages) of crystalline rocks $K \leq 10^{-6}$m/s	Siting should target fracture and weathered zones with $K \leq 10^{-6}$m/s. Pumping should be between 5-15m^3/s/m. Minimum distance for source protection should be 100m
Unconsolidated rocks	Sand, Clay, Quartz fragments	----
Highly weathered clayey material	Clayey material $K \geq 10^{-6}$m/s	----

Table 6-3. Groundwater regulations in study areas

6.6 Application of Model for Protecting Groundwater Resources in Ghana

Regulations serving as guiding tools for protecting groundwater resources within the study areas and other parts of Ghana with similar hydrogeological environment have been summarized under three main headings (Fig. 6-5).

The model achieved from this study applies to the initial groundwater development phase through to the groundwater abstraction phase and finally the policy or framework phase. The initial groundwater development phase includes regulations aimed at siting, drilling, development of wells and acquisition of hydrogeological data. The next stage of groundwater abstraction involves regulations for source and resource protection and groundwater overdraft. The last phase involves possible policies and frameworks which could be enacted by governmental agencies that could control the exploitation of groundwater resources to bring about sustainable use of aquifers.

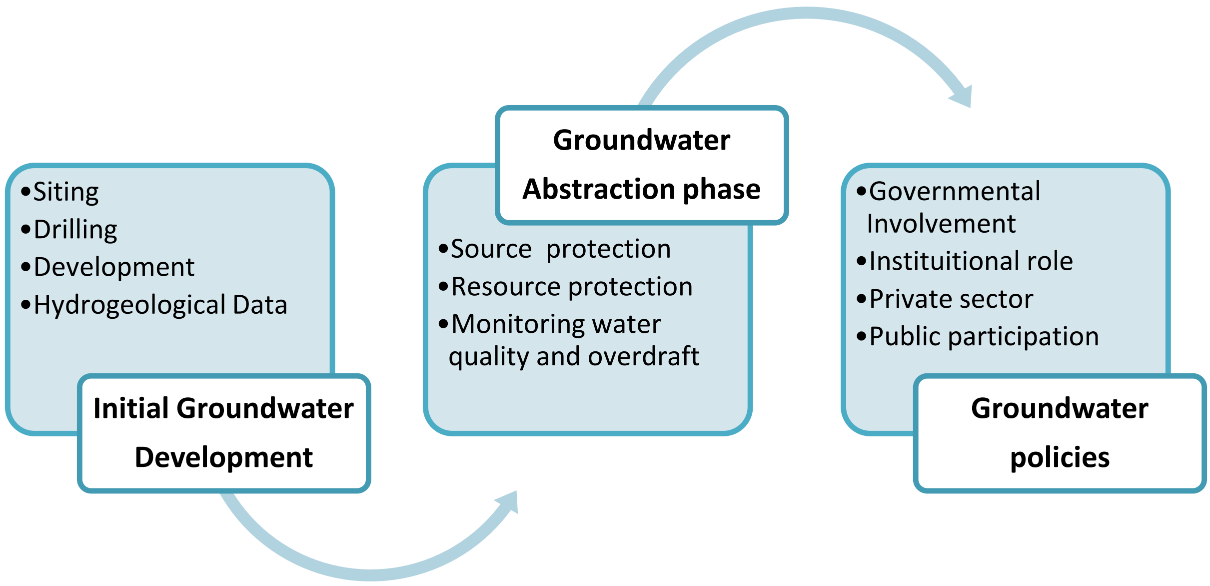


Fig. 6-5 Groundwater resources protection at various stages in Ghana

6.6.1 Initial Development of Groundwater

Siting of prospective areas for groundwater development should be made using remote sensing techniques (aerial photos, satellite images) and geophysical site investigation. These techniques in combination with GIS tools when used for groundwater exploration should target fractured zones and weathered regolith. Drilling should be done in areas with higher hydraulic conductivities (preferably K greater than10^{-5}m/s) whereas areas with lower hydraulic conductivities (K less than 10^{-7} m/s) should be avoided. As discussed above, areas with higher K produce higher specific capacities whilst those with lower K produce lower specific capacities, consequently only boreholes located in higher K will produce sustainable water supply within these crystalline rocks in the study areas.

During the drilling of boreholes, it is necessary that a standard method is used whereby hydrogeological data obtained is maximised and parameters standardized throughout the whole country. One activity which is more than overdue to be included in the drilling program of the study sites are smaller diameter piezometers to be used as monitoring wells for good interpretation of pumping test data. These piezometers are of smaller diameters than the main wells and its overall cost is inexpensive compared to benefit of the acquired information for the characterisation and management of the groundwater resource. Since most of these boreholes are drilled in the crystalline basement rocks, it is difficult to get 100 % success rate during drilling. I suggest marginally low yielding or dry boreholes should be sealed with grouting material and cement as backfill to prevent the possibility of being pathways for contaminant leak. Drill logs containing stratigraphy, geology, structures, saturated thickness and other measurements taken during borehole development like time-water levels and pumping rate should not only be a property of the various drilling companies but should also be kept in a national hydrogeological data base after being validated by experienced hydrogeologists.

6.6.2 Groundwater Abstraction Phase

During the groundwater use phase, there should be a delineation of source protection and resource protection for groundwater resources based on any of the methods used in this research or by other methods which have been approved by the Water Resources Commission (WRC). This will be particularly important in areas where large volumes of groundwater are being used for water supply, or areas of mining and heavy industrial activity. The aim will be to estimate areas around these sources which are in need to be protected against contaminants. Activities in these resource and source protection zones would be regulated, and only allowed by a permit issued from the WRC.

From the results of the study sites, the SPZ for the boreholes should be between 100 and 150 metres. It should be said that this zone of protection corresponds to the intermediate zone on a three level (inner, intermediate, outer) source water protection zones. The whole catchment area which includes the outer zone in certain cases should be protected if there is a high risk of groundwater contamination. In such cases, groundwater vulnerability mapping would be essential and could be combined with maps from the source protection zones. There should be established groundwater monitoring networks, where field measurements are done on a frequent basis for both overdraft and quality monitoring. Parameters to be monitored include piezometric levels, abstraction, EC, pH as well as other parameters the WRC will deem necessary to include. In order to ensure sustainability of monitoring systems, it is essential to identify ways to mobilise both financial and human resources to sustain groundwater monitoring and to update databases.

6.6.3 Groundwater Policies

The Ministry of Water Resources Works and Housing is the main government institution on water issues, its task being the overall management of water resources, supply of drinking water, policy formulation, coordination and programme evaluation. The Ministry of Local Government, Rural Development and Environment on the other hand is the Country's leading sanitation sector agency. It formulates, coordinates, monitors and evaluates the environmental sanitation policy. The Water Resources Commission, as discussed in chapter two, is mandated to regulate and manage the utilisation of water resources and coordinate policies in relation to them. It can also grant water rights and carry out scientific investigations or research into water resources. Other agencies are Community Water and Sanitation Agency (CWSA) to facilitate rural water supply and sanitation whilst the Environmental Protection Agency (EPA) protects water resources and regulates activities within catchment areas.

To achieve good results from policies the agencies in charge of groundwater resources, the sanitation agencies and research institutions should coordinate their activities. Government, institutions within the private and public sector should interact with each other in conferences, seminars, and public debates to create a general sense of awareness with regards to groundwater protection. In this way policy makers, policy implementers and consumer of groundwater resources could have a common platform where regulations for groundwater protection could be easily understood and accepted. The media such as Newspapers, TV and FM stations could also be involved in this process of public awareness with funding from both Government and NGOs.

Policies governing groundwater could act prior to the initial development or after development where the Groundwater resource is already in use and should aim at protecting both known and unknown groundwater sources. These policies should deal with the current situation and provide a comprehensive future plan to safeguard local and regional aquifers. Regulations should be passed as laws by the Government of Ghana and their enforcement should be monitored by the appropriate ministry, commissions and sanitation agencies.

Policies that are not yet established in the study areas but could be helpful in the context of groundwater resources protection have been listed below as recommendation to be considered by the appropriate ministry or agency.

- Standard method for initial groundwater siting and drilling for fractured crystalline rocks and regolith aquifers
- Standard pumping test with inclusion of piezometer tests and standard pumping time
- Standard nomenclature for well log report and common data base for all acquired hydrogeological parameters
- Definition of minimum hydrogeological parameters for groundwater characterisation
- Establishment of monitoring network for various catchment zones regulating groundwater quality and overdraft
- Acceptable methods for source and resource protection zone delineation
- Permits and regulated activities within various tier for groundwater protection
- Determination of necessary parameters that should be involved for monitoring programs and the frequency of taking measurements

Chapter 7

7. Conclusion

Groundwater is an important resource in Sub-Saharan Africa for water supply and irrigation, both in urban and rural areas. Its usage ranges from the domestic to industrial and agricultural purposes. There is a global concern for the protection of groundwater resources due to its finite extent and growing demand with increase in population and increasing threats of contamination from anthropogenic sources. Draught prone areas and rural areas where there is no access to surface water rely heavily on groundwater resources (in Ghana at least 33% of the entire population). In other areas with no treated surface water (54% of rural communities in Ghana), it is preferred due to its good water quality which helps reduce waterborne infection. Water related diseases in Ghana as a result of poor water quality, sanitation and hygiene are guinea worm, malaria, diarrhoea, cholera, bilharzia and typhoid fever. Groundwater resources are assessed either from springs, wells, and boreholes fitted with hand pumps or piped systems.

The groundwater supply program is mainly pragmatic to give people drinking water. However for sustainable groundwater development a long term groundwater management system should be in place. The management system takes into account the immediate environment of the aquifer, the beneficiaries and the support it gives to the ecosphere. This means groundwater is used for domestic, industrial and agricultural purposes, whilst its benefit to wildlife, plants, land system, water system and the climate is maintained without any considerable change both in quantity and quality. To achieve this in Ghana, there is the need to augment the water supply program with a groundwater protection program as part of the long term groundwater management system. This research focused on the aspect of source protection (well protection). Other groundwater investigation programs have started but usually end with the exploitation of the well without declaration and installation of protection zones.

The occurrence of groundwater in the crystalline rocks of Ghana is known to be high in the weathered regolith and fractured zones however the controlling parameters involving groundwater availability and groundwater protection are not fully investigated due to the limited funds. Available funds of NGO’s are only meant to provide adequate water for poor communities. This urgent need for groundwater protection in Ghana brought about the hypothesis of this research. The hypothetical questions were how to access and determine ‘Availability’’ and ‘Vulnerability’ of groundwater, and implore the use of an analytical model to estimate source protection zones (SPZ). The aim was to estimate SPZ for granite, phyllite, schist, sandstone and weathered materials and give recommendations as to which activity should be allowed or prohibited within each of these zones.

The methodology for this research focused on the three main concepts of availability, vulnerability and modelling of groundwater protection zones. To determine the available groundwater a combination of the hydraulic conductivity, transmissivity, specific well capacity and geologic structures was applied. Transmissivity and hydraulic conductivity values were estimated from the 12hours pumping test results and core logging information of 256 boreholes. The time-drawdown data for the single pumping wells was analysed using the Cooper-Jacob straight-line method assuming Theis’ assumption (Theis, 1935) for analytical solution for flow to a fully penetrating well in a confined aquifer. The pumping test data was analysed using spreadsheets developed by Keith J. Halford and Eve L. Kuniansky for the USGS. The aquifer-test spreadsheets are based on drawdown response to a pumping well or a flowing well. The spreadsheets were written in Microsoft Excel and the transmissivity was estimated whilst the horizontal hydraulic conductivity was computed by dividing the transmissivity by aquifer thickness.

To obtain specific well capacity (a measure of how water can be pumped from a well within a recoverable limit without groundwater overdraft) the discharge from the pumping well was divided by the drawdown. The geology and structural features of rock formations were assessed based on reports, maps and field visits to study areas. Additional information was gathered from geophysical data, geological mapping, drill cores and logs. Fractured zones were identified based on the degree of jointing/fragmentation of the parent rock material, freshness/weathered extent of the rock materials and presence of veins or intrusive materials. The available groundwater for a particular well or location is determined based on its hydraulic conductivity and specific capacity.

Regionalization of the available groundwater was achieved by comparing the results of the hydraulic conductivity and specific capacity with the regional structural map. The source protection concept was used to determine the vulnerability of the available groundwater. The main focus of the source protection zone methods was to estimate the vulnerability of single wells from different geological formations in Ghana. The radius of influence (ROI) for the different boreholes was determined using Sichard and Dupuits formula whilst for Source protection zones, Darcy and the volumetric equation was used. The drawdown (s) and hydraulic conductivity (k_f) are determined from the pumping test and used to estimate the ROI using Sichard (1927) equation. Since the Sichard equation is an empirical estimation, its accuracy was supported by the topography, subsurface information and structural geology of the particular area. In estimating the ROI using Dupuits equation, r_e is the calculated ROI whilst the effective porosity n_f was determined based on the geologic composition of the aquifer material.

Darcy's average linear velocity was estimated based upon hydraulic conductivity, hydraulic gradient and effective porosity of the material. Once the average velocity was known, the distance was calculated knowing the time of travel. Using Darcy's method, two scenarios were assumed for the time being, 50days and 200days. The volumetric equation was used to estimate the calculated fixed radius (r) based on the pumping rate, porosity, saturated zone thickness (H) and time. A time of travel (TOT) of 1year was assumed for this method. There are limitations to both the Darcy and the volumetric equation methods as the material is assumed to be homogeneous and the flow is also assumed to be in the steady state. However, the results from these methods are good enough for orientation survey and general recommendations for groundwater resources protection in Ghana. This will help protect current groundwater resources whilst further research based upon recommendations could later be developed.

Adansi, Lawra, Sunyani and Sekyere West were chosen as study areas to test the hypothesis of this research with detailed investigation concentrating only on Adansi area. The study areas were chosen based on easy access to the area, availability of data, geology and hydrogeological set up, and the importance of groundwater resources for these regions. The rocks types found in these study areas include granite, granitiod, phyllite, schist, quartzite, siltstone, shale, sandstone, and weathered clayey material. Temperature ranges from 20 to 36 degrees whilst rainfall averages between 946 to 1800mm, with vegetation from semi-equitorial forest to Guinea savanna zone. Boreholes from the different locations studied concentrated on five major rock types which where granite, phyllite, schist, sandstone and weathered clayey material.

A total of 256 boreholes were studied out of which 60 % were phyllite, 12.2 % weathered clayey material, 12% granite, 6.6% sandstone, 5.2% schist and 4% other rock types. Results of hydraulic conductivity estimated from pumping test data for the five major rock types showed a tri-modal distribution (10^{-5}, 10^{-6} and 10^{-7} m/s). The first group ($1.0\text{-}9.9\times10^{-5}$m/s) had high fractures and were considered as aquifers, group two ($1.0\text{-}9.9\times10^{-6}$m/s) of medium fractures were considered to be aquitards as well as the last group ($1.0\text{-}9.9\times 10^{-7}$m/s) with low or no fractures. Apart from these three groups, unconsolidated rocks with hydraulic conductivity greater than 1.0×10^{-5}m/s were also considered as aquifers. Three forth (3/4) of the boreholes drilled from the five different rock types in the study areas based on this criteria, could not be classified as aquifers. There is a general trend of decreasing hydraulic conductivity to increasing saturated thickness and decreasing transmissivity.

The results of plots of hydraulic conductivity versus the specific capacity for all the five different rock types shows an increasing specific capacity with increasing hydraulic conductivity and vice versa. It can be deduced from these plots of specific capacity that only rock types with hydraulic conductivity greater than 10^{-5} m/s yields sustainable groundwater supply. The phyllite aquifer had the highest average specific capacity of about 28m^3/day/m whilst the sandstone, granite, weathered clayey material and schist had 20, 19, 17 and 16m^3/day/m respectively. Three groundwater regimes were encountered in the study areas which were shallow or alluvial, regolith and fracture aquifer. A comparison of the hydraulic conductivity distribution in the Adansi area and the regional structural geological map confirms that the areas with high hydraulic conductivities (aquifers with K greater than 10^{-5}m/s) are structurally controlled in a south-west to north-east direction.

Results of ROI for all rock types from the different boreholes using Sichard formula gave values in the range of 20m to 143m whilst those from Dupuits equation was between 1.56m to 4, 31E+22 km. High hydraulic conductivity from the different rock types corresponds to higher ROI and vice versa whilst the ROI tend to have an inverse relationship with the saturated thickness. Results from both Darcy's method and Volumetric equation showed three major source protection zones. They were those below 100m, between 100-150m and those above 150m corresponding with 10^{-7}, 10^{-6} and 10^{-5} m/s hydraulic conductivities. The calculated distances was generally high using Darcy's method than the volumetric equation method for all the five different rock types.

The results of hydraulic conductivity, specific capacity, ROI and SPZ are used as input parameters for an analytical model based on groundwater suitability. The concept of groundwater suitability measures the usability of a groundwater from the input parameters depending on its quantity (production/use) and vulnerability to contamination. The five rock types are classified using the input parameters into high (3), moderate (2) and low (1) depending on their suitability for groundwater use. Specific capacity, hydraulic conductivity and transmissivity were judged high in term of water availability when it was greater than $15m^3/s/m$, $10^{-5}m/s$ and $2.0\times10^{-4}m^2/s$ respectively. A SPZ and ROI of 150 and 100m respectively were judged high in terms of its vulnerability. A ranking matrix was developed for easy interpretation of hydrogeological data by combining the results of the input parameters into a single score. The maximum number of attainable points is 18 and the lowest is 6. Three groups 0-6, 6-12 and 12-18 points were realised from the groundwater suitability matrix. The first group (12-18 total points) from the five major rocks (Phyllite, Granite, Schist and weathered clayey material with hydraulic conductivity in the range of $10^{-5}m/s$) were considered good for groundwater development and piped systems but involved protection zones between 100-150m. The second (6-12) and the third (0-6) groups were good to limited for groundwater development and should be monitored for groundwater overdraft if there is the need to tap this resources a source protection zone of 100m should be demarcated.

Results from the ranking matrix were used to determine specific regulations for the various aquifers in the study areas. The fractured crystalline rocks consisting of Granite, Phyllite and Schist with $K \geq 10^{-5}$m/s, siting should target fracture zones whilst pumping can exceed $15m^3/s/m$. Minimum distance for source protection should be above 150m.

The regolith aquifer consisting of the weathered (various stages) crystalline rocks $K \leq 10^{-6}$m/s, siting should target fracture and weathered zones. Pumping should be between $5\text{-}15m^3/s/m$ with minimum distance for source protection should be 100-150m. For the highly weathered clayey material and sandstone aquifers with $K \geq 10^{-6}$m/s, siting should target fracture zones whilst pumping can exceed $10m^3/s/m$. Minimum distance for source protection should be above 150m. These are distances for the intermediate zone, however protecting the whole catchment area should be considered in areas where groundwater is under high threat of contamination.

Applications of these specific regulations in the study areas could be implemented during the initial development, abstraction and groundwater policy phases. Siting of prospective areas for groundwater development should include remote sensing techniques (aerial photos, satellite images), Geophysical site investigation in combination with GIS tools. Areas demarcated for drilling within crystalline rocks should coincide with fractured zones and the weathered regolith. Drilling campaigns should target areas with K greater than 10^{-5}m/s whereas areas with K less than 10^{-7} m/s should be avoided. There should be implementation of protection zones during development of groundwater resources in Ghana with methods which have been approved by the Water Resources Commission (WRC). In order to achieve good results in groundwater protection, coordination of policies will be essential from both Government and players within the private and public sector. In this way policy makers, policy implementers and users of Groundwater resources could have a common platform where regulations for groundwater protection could be easily understood and accepted. Using the various forms of media will be a good tool in cementing the process of public awareness.

7.1 Recommendation

During the drilling of boreholes, it is necessary that a standard method is used whereby hydrogeological data obtained is unified throughout the whole country. It is also necessary that core logging sheets and information are unified and surveyed by a qualified hydrogeological officer to ensure accuracy of the recorded information. A national archive of all these hydrogeological information will be a great asset to the nation in the near future. During pumping test pumping needs to be done until there is stabilization in yield or where there is no stabilization; 72 hours of pumping will be necessary for meaningful interpretation of pumping test data. The water table must be a minimum of 2m above the screen. Small meter wells in the form of piezometers to serve as monitoring wells should be included in every groundwater exploitation program. All these measures will help to accurately determine hydraulic conductivity, drawdown, specific capacity, Darcy's average linear velocity and the radius of influence.

The proposed protection zones 1-3 for the alluvial, regolith and fracture aquifer must be discussed with headsmen, chiefs, local government for sanitary controls. To increase the awareness among the populace about the need for groundwater protection, it is important to extend this campaign through educative programs in schools, universities, radio and TV stations. Additionally, community based programs must be established whereby each community is aware of its groundwater resource, the dangers in pollution and the protection options available.

The Water Resource Commission (WRC) and other agencies in charge of groundwater resources in Ghana should come up with standard methods for source and catchment protection zones. Examples of such methods could be drawn from this research and other on-going research in Ghana. Mapping of catchment zones should distinguish between recharge and discharge areas which could be used as a first step for groundwater vulnerability characterisation. In this way more stringent measures will be applied to recharge areas whilst less stringent measures are applied in discharge areas.

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