Water Supply Enhancement in Cyprus through Evaporation Reduction

by

Chad W. Cox
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Abstract

The Republic of Cyprus is prone to periodic multi-year droughts. The Water Development Department (WDD) is therefore investigating innovative methods for producing and conserving water. One of the concepts being considered is reduction of evaporation from surface water bodies. A reservoir operation study of the Southern Conveyor Project (SCP) suggests that an average of 6.9 million cubic meters (MCM) of water is lost to evaporation each year. The value of this water is over CY£ 1.2 million, and replacement of this volume of water by desalination will cost CY£ 2.9 million.

The WDD has investigated the use of monomolecular films for use in evaporation suppression, but these films are difficult to use in the field and raise concerns about health effects. Another method of evaporation reduction is by artificial destratification of storage reservoirs. Mixing a reservoir lowers the surface water temperature and thus decreases evaporation. Some studies suggest that evaporation reductions may be as high as 30%, but a simplified model using Cypriot meteorological data indicates reductions may be more on the order of 10%. The five major reservoirs of the SCP could be destratified by installing air bubbler, pump, or impeller mixing systems. If artificial destratification is capable of yearly evaporation reductions of 10%, then 0.6 MCM of water will be saved at a cost of CY£ 0.17/m^3. If evaporation reductions are as high as 30%, then 1.9 MCM will be saved at a cost of CY£ 0.05/m^3.

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I would like to thank those people who have advised and assisted me in the completion of this study. This report on evaporation reduction, and the companion report on water banking represent a huge investment in time and energy by a number of people. On behalf of all those who have devoted such considerable effort to these projects, I would like to express my hope that these studies will be useful to the people of Cyprus.

I am very grateful to Dr. Eric Adams, my academic advisor here at MIT. Dr. Adams displayed considerable open-mindedness when he approved of the concept of doing research in Cyprus. Then he went to bat for my colleagues and me to help us secure funding for our study trip to the Republic of Cyprus. He has been of tremendous assistance to me in my research on evaporation reduction through artificial destratification. Dr. Adams is a true scholar and a gentleman.

The generous assistance and cooperation of many Cypriot professionals made the study possible. Many people shared their time, knowledge, and data with me. I hope that this report is useful to them as they work to provide Cyprus with the water it needs. Special thanks go to:

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Table of Contents

List of Tables

List of Figures

Chapter 1 INTRODUCTION

Water is arguably the most precious resource in Cyprus. Recent scarcity has certainly made water resources management one of the highest priority issues facing the Republic of Cyprus today. The tenuous nature of the water supply was made painfully evident in 1998. In hydrologic terms, 1998 was the worst year ever recorded. Not only was the total rainfall for the year extremely low, but the three previous years had also been very dry. As a result, available water supply dropped to an all-time low at the same time as a growing economy was demanding more and more water. Rationing of supplies to the cities meant that water came to homes in most areas only two or three times a week. Many farmers had their allocation of irrigation water severely curtailed or stopped altogether. By the end of 1998, the majority of the surface reservoirs in Cyprus were virtually empty, and groundwater tables were dropping towards or even below sea level.

It cannot be said that this situation came about due to a lack of expertise on the part of the Cypriots. Surface water storage in the Republic of Cyprus has been developed to virtually the fullest practical extent. The massive Southern Conveyor Project is perhaps the best example of Cypriot engineering skill. This system of large reservoirs, pipelines, and pump stations collects water from areas of relative abundance in the mountainous southwest. This water is then conveyed and distributed to the drier areas of the eastern coast and central plains. The Cypriots have also made remarkable strides in the use of efficient irrigation technology. The vast majority of irrigation systems use pressurized drip pipes or mini-sprinklers which have efficiencies of 80 – 85% (Tsiourtis, 1995, p.73). Yet in 1998 there was simply not enough water to go around.

Because the majority of conventional water resources in Cyprus have been developed, Cypriots are beginning to look to non-conventional sources and innovative water management strategies. Continued economic growth will require that Cypriot engineers and managers expand the horizons of water resources engineering in order to utilize all available water resources in the most efficient way possible. In addition to impressive gains in irrigation efficiencies, the Cypriot government has investigated water management techniques such as demand reduction through pricing, cloud seeding, water importation, and others. Currently, desalination is viewed as the most promising method for alleviating water shortages. Yet even with new reverse-osmosis technology, the cost of desalinated water is still very high. Desalination is an important component in Cypriot water resources development, but there are other innovative concepts that offer considerable cost savings that have yet to be applied. Water banking is one example of a management technique that offers great promise as a part of Cyprus' overall water management strategy (Hatem-Moussallem, et. al., 1999). Another process, which could potentially be used to increase water supply in Cyprus at relatively low cost, is evaporation reduction.

Water evaporates from all puddles, ponds, lakes, and reservoirs. Rain, runoff, and evaporation drive the hydrologic cycle and sustain the climate that makes life on earth possible. Evaporation, on the whole, is a necessary and beneficial function, but there are times when evaporation works counter to human interests. The collection, storage, and utilization of surface waters in Cyprus, as elsewhere, generally involves the impoundment of runoff into a reservoir. The cost and effort involved in the construction of dams and reservoirs is generally very large, so it is important to capture the maximum amount of water possible. Once flow has been impounded, it is desirable to minimize losses out of the reservoir until the water can be released to serve a useful purpose. Surface water reservoirs offer the advantage of being able to store large quantities of water which is available for immediate or future use, but evaporation extracts a price on such storage. As the amount of water contained in a reservoir increases, the surface area of the reservoir increases. Because the amount of water lost to evaporation is proportional to the surface area of a body of water, the amount of evaporation also increases. Thus the more water which is stored in a reservoir, the more water that is, on average, lost to evaporation. As an example, the reservoir behind Kouris Dam has a maximum normal pool capacity of 115 millions of cubic meters (MCM). Assuming a constant normal surface area, an average of 4.68 MCM (~4%) is lost to evaporation over the course of a year. Desalination of an equivalent quantity of water would cost nearly CY£ 2,000,000 per year under the newest Build-Own-Operate-Transfer contract.

Evaporation is generally thought of as a stochastic and uncontrollable process – similar to wind and rain. The Mediterranean climate of Cyprus means that evaporation rates are quite high but also reasonably constant from year to year. Historic data allows accurate predictions of evaporation losses, but such losses are considered inevitable. However, processes do exist which can theoretically reduce evaporation from surface water reservoirs. The application of such processes offers the potential to increase the yield from existing reservoirs without major new construction. This is particularly attractive in Cyprus since the majority of dam sites have been developed (Min. of Agriculture, 1998). The former permanent secretary of the Ministry of Agriculture stated in a national water policy review, "Evaporation suppression from water surfaces is... a potential incremental source of water supply (Papasolomontos, 1992, p. 4)."

Possible methods for reducing evaporation are vegetative control, radiation barriers, floating covers, and wind barriers. Another method currently being investigated in Cyprus is the use of monomolecular films which coat the surface of a reservoir and slow the transfer of water vapor into the air. This report will propose a new method for evaporation reduction through artificial reservoir destratification. Artificial destratification has been shown to have the potential to reduce evaporation by up to 30% using inexpensive processes which are also beneficial to water quality (Cox, 1992).

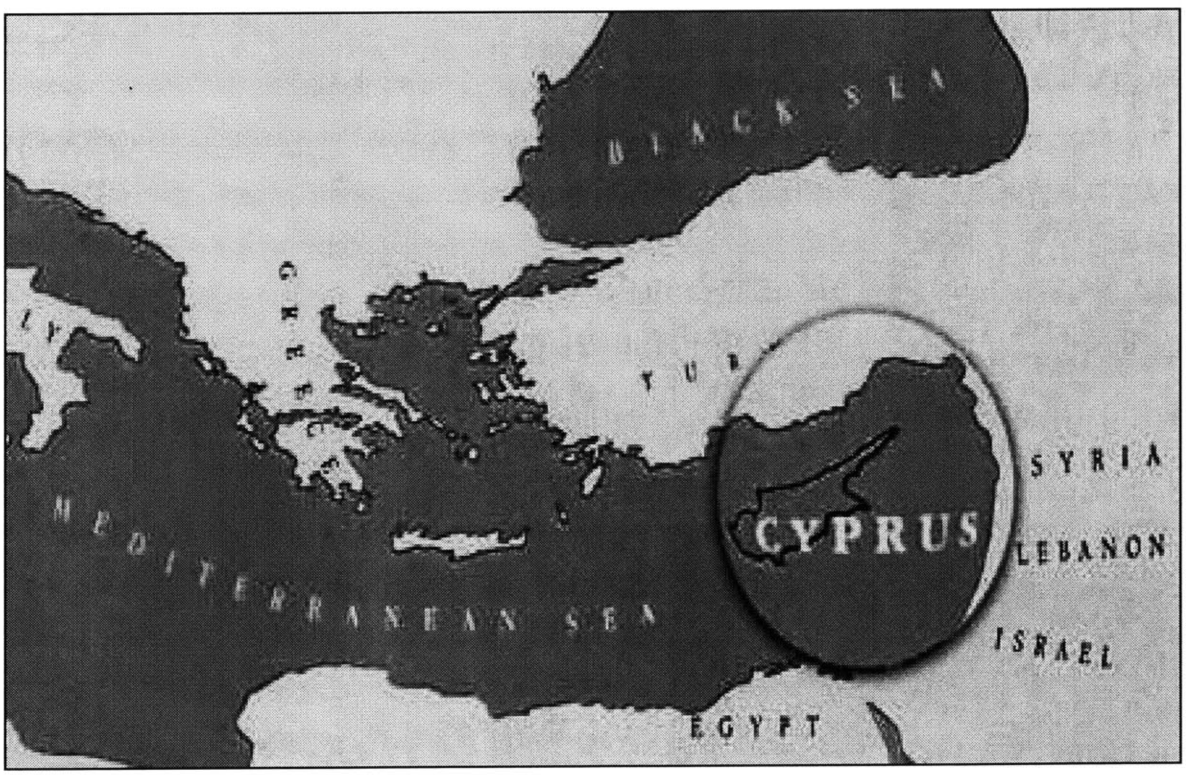
This report examines the potential for water supply enhancement in Cyprus through evaporation reduction. Chapter 2 presents the background and conditions that underlie water scarcity in Cyprus. Chapter 3 focuses on the physical process of evaporation and the data available in Cyprus. Chapter 4 catalogs the surface water resources of Cyprus and assesses evaporative losses. Chapter 5 presents an operation simulation of the Southern Conveyor Project used to assess the benefits of reducing evaporation through generic means. Chapter 6 describes the potential methods for evaporation reduction and makes the case for artificial destratification. Chapter 7 explains artificial destratification in detail, presents a simplified computer model, and examines the costs of the method. Finally, Chapter 8 contains a summary of this study and makes specific recommendations for the investigation and application of evaporation reduction in Cyprus.

Chapter 2 BACKGROUND

2.1 Location and Physical Description

The island of Cyprus is located in the northeastern Mediterranean Sea, some 70 kilometers south of the coast of Asia Minor (See Figure 2.1). The island lies between latitudes 34°33’ to 35°41’ North and between longitudes 32°30’ to 34°35’ East. The total area of the island is 9,251 square kilometers with a length of approximately 222 km and a maximum width of approximately 95 km. The coastline is irregular and is 782 km long. Cyprus is the third largest island in the Mediterranean Sea.

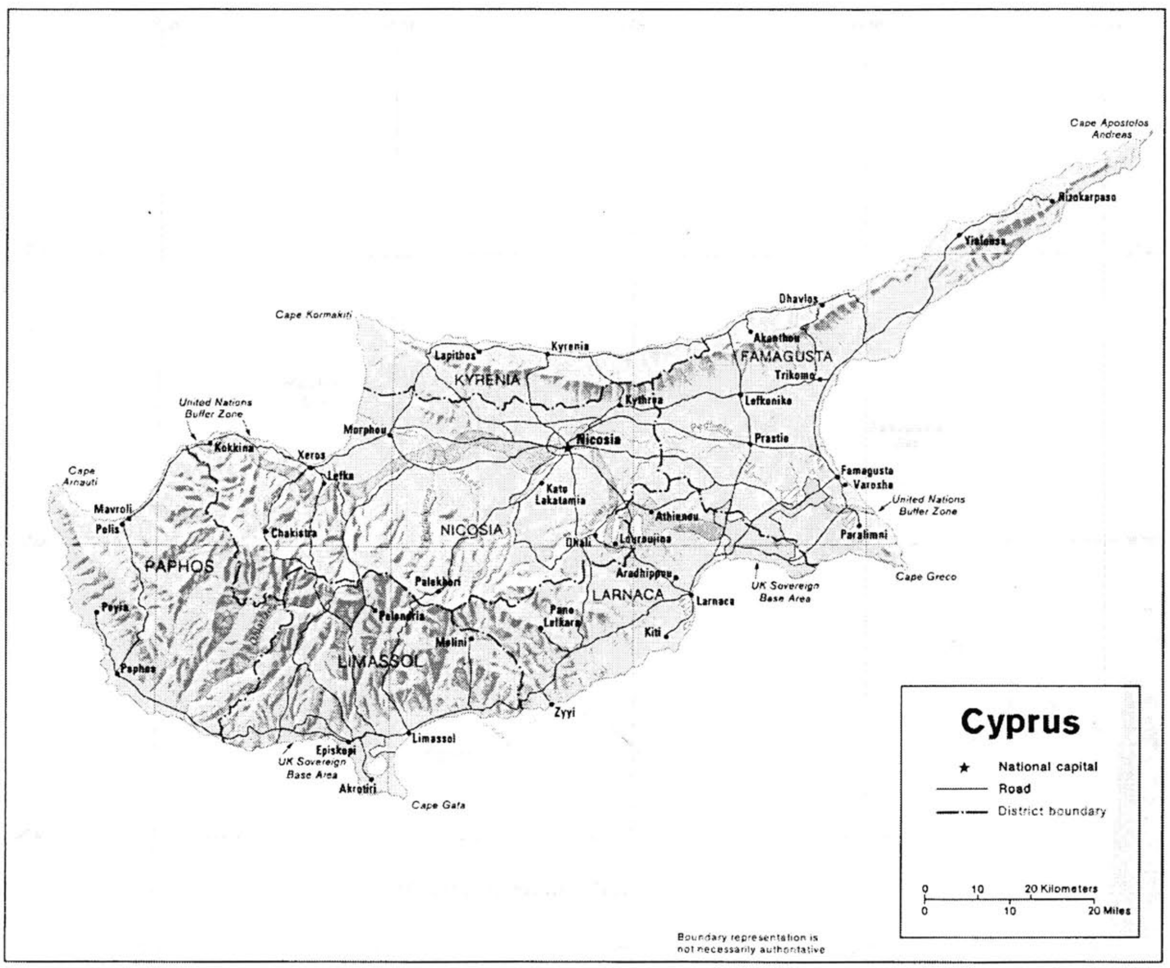
FIGURE 2.1
MAP OF MEDITERRANEAN SEA
SHOWING LOCATION OF CYPRUS



Source: Central Bank of Cyprus

The topography ranges from sea level to the peak of Mt. Olympus at elevation 1,219 m. The coasts are in general low and shelving. Sandy beaches bounded by dunes do exist, but for the most part the shores are rocky or stony. The principal physiographic features of Cyprus are two main mountain ranges separated by a wide sedimentary plain called the Mesaoria. The Kyrenia Mountain Range runs along the northern coast and extends towards the Karpas Peninsula – the "panhandle" of Cyprus. The Troodos Range is in the south-central part of the island and is visible from most of the island. Mt. Olympus is located in the Troodos Range. A map of the island of Cyprus is shown in Figure 2.2 (Solsten 1991, xiv).

FIGURE 2.2
MAP OF CYPRUS



2.2 Geology

In contrast to many of the neighboring karst islands of the Mediterranean, the geology of Cyprus is highly variable and complex. In general, approximately 80% of the island's surface geology is composed of calcareous sediments while the remaining 20% is formed from basic igneous rocks. The northern mountain range is mostly limestone and marbles with scattered basaltic sills and dykes. The southern Troodos Range is an igneous range with a variety of rock types. This range is bounded by white chalky marls and limestone. Some of the oldest known copper mines in the western world are located on the slope of the Troodos Range. The wide central plain was originally part of the ancient sea bed, but it is now overlain by recent alluvial deposits eroded from Pliocene and Pleistocene crusts and the nearby mountains. The sedimentary rocks of the central plain include calcareous sandstone, marls, and conglomerates.

The soils on Cyprus are likewise varied due to the numerous parent rocks. In general, the soils are thin and subject to heavy erosion during the intense winter rains. The central Mesaoria plain is the most fertile area and receives newly eroded silts each year during the peak runoff period. The long history of human habitation on Cyprus has led to extensive modification of soils in many areas due to agriculture and forestry (Thirgood, 1987, 23-27).

2.3 Climate

The climate in Cyprus is typical of the Mediterranean area. The summers are hot and dry, and the winters are mild and relatively wet. The average maximum summer temperature is 35° C in August, and the average minimum winter temperature is 9° C in December. The warmest temperatures are recorded at lower elevations while the cooler temperatures occur in the mountain ranges. Intermittent snow is not unusual on the slopes of the Troodos Range during the winter (Lytras, 1994).

Precipitation is highly variable over both elevation and time. The average annual rainfall over all of Cyprus is estimated between 470 mm to 515 mm. Average annual rainfall varies between 250 mm per year in the Mesaoria Plains to 1100 mm per year on the peaks of the Troodos Range. The isohyetal lines of equal rainfall roughly correspond with elevation contours – producing higher average rainfall at higher elevations. The majority of rainfall comes from late October to early May. On average, half of the average precipitation falls during December and January (Tsiourtis, 1995, p.79). Estimates of the total average precipitation volume which falls on Cyprus each year range from 4,500 million cubic meter (MCM) per year to 4,650 MCM per year (Min. of Agriculture, 1998).

2.4 History

The history of Cyprus is long and distinguished. Neolithic cultures existed in Cyprus as early as 7,000-6,000 BC. Remnants of these societies may now be found in the Museum of Antiquities in Nicosia. Almost 5,000 years ago, copper was first discovered on the island; in fact, the Greek word for copper is *Kypros*. Copper and timber resources, along with Cyprus' strategic location along the maritime trade routes, drew the interest of many foreign powers. Indeed, throughout history, Cyprus has been subject to invasion and colonization by a host of civilizations and empires. A list of powers which have played a part in Cypriot history includes the Hittites, Egyptians, Greeks, Phoenicians, Romans, Byzantines, Arabs, Franks, Venetians, Turks, and British. Greek settlers originally came to Cyprus in several waves in the 11th, 12th, & 13th centuries. These settlers brought with them the Hellenic culture, religion, and language which is prevalent on the island today.

Cyprus has been host to some of the most important personalities in the history of the Western world. Alexander the Great freed the island from the Persians in 333 BC. Cicero was sent as a Roman governor. St. Paul visited the island in 45 AD. Richard the Lionhearted stayed several years while returning from the Crusades. Of particular importance to the history of Cyprus was the establishment of the Orthodox Church in the 5th Century AD and conquest by the Turks in the late 16th Century. These two events are among the keys to the current social and political situation on the island (Thurgood 1987, pp. 3-16).

The recent history of Cyprus might be said to have begun when the British took control of Cyprus from the Ottomans in 1878. Many Cypriots fought alongside troops from other Allied nations during the Second World War. After the war was won, Cypriots called for independence, but the British were reluctant to leave the island. In 1955, an armed liberation movement began. In the late 1950's there was open rebellion among the Cypriots against British rule. Finally, in 1960 Cyprus became an independent republic, although the British did retain several Sovereign Base Areas on the island. Development in Cyprus advanced rapidly after independence, but tensions between the ethnic Greek and Turkish communities were continually a concern. In 1974, a military junta staged a coup. During this period of crisis, Turkey landed large numbers of troops on the northern part of the island and invaded. The resulting war left the island divided with Turkish occupation of the north and Government of the Republic of Cyprus control of the south. A UN peacekeeping force now patrols the cease-fire line (Solsten 1991, pp.23-45).

This report and proposal deals only with water resources in the government-controlled areas of the Republic of Cyprus. The water resources of the island are inseparable, but the de facto division of the island has led to the separate development of water infrastructure and usage.

2.5 Society

The current total population of the island of Cyprus is approximately 746,000. The population living in the southern part of Cyprus is 654,000, while the other 90,000 reside in the occupied area. These figures do not include approximately 90,000 persons who have settled in the Turkish-occupied areas since 1974. The capital of the Republic of Cyprus is Nicosia, which is located in the lowland plains in the center of the island. Other large cities include Larnaca, Limassol, and Paphos. Famagusta and Kyrenia are in the occupied area. Approximately 70% of the southern population live in urban areas.

For administrative purposes, Cyprus is divided into six districts. Nicosia, Larnaca, Limassol, and Paphos are in the government-controlled area while Famagusta and Kyrenia are not (Planning Bureau of Cyprus, 1997).

2.6 Economy

The unit of currency in Cyprus is the Cypriot Pound (CY£). The exchange rate fluctuates around two US Dollars per Cypriot Pound. The Gross Domestic Product of the Republic of Cyprus in 1997 was CY£ 3.48 billion (US $ 6.96 billion). The primary sector of the economy, including agriculture and mining, accounted for 4.7% of the economy. The secondary sector, including manufacturing and construction, accounted for a further 22.5%. The remaining 72.8% of economic production was produced in the tertiary sector, which includes tourism, transport, finance, and services (www.kypros.org, 1999). Of all economic activities in Cyprus, the single largest industry is tourism. On average, over two million tourists visit Cyprus every year.

The standard of living in Cyprus is relatively high. The average per capita yearly income is CY£ 6,700 (US$ 13,400). Unemployment and inflation have both been relatively low recently with rates of 3.1% and 3.0% respectively (www.kypros.org, 1999).

2.7 Water Resources

Cyprus is an island. This inescapable fact defines Cyprus' water resources situation. Ultimately, the only naturally available fresh water comes or came from precipitation which fell from the skies onto the island. Even groundwater is related to precipitation since at some point in the past it infiltrated down from the surface, and the aquifers can only be recharged from the surface. Desalination has recently become an option to enhance water supply, but it is expensive and current production rates are relatively small.

The total average quantity of precipitation that annually falls over Cyprus was calculated based on average annual precipitation and total surface area. This quantity does not, however, represent the actual annual total available volume of fresh water. The climate, vegetation, and soil all combine to produce a yearly evapotranspiration rate of more than 80% of precipitation. Thus for every 100 cubic meters of rain which falls on Cyprus, more than 80 cubic meters of water returns directly to the atmosphere without the possibility of human usage. A commonly stated figure for average annual "usable" water is 900 MCM. Of this amount, approximately 600 MCM is in the form of surface water. Dams divert 190 MCM of surface water, another 150 MCM is diverted directly from rivers, and the remaining 260 MCM flow straight to the sea. Groundwater accounts for the other 300 MCM. Currently 270 MCM is estimated to be pumped or extracted from springs while 70 MCM flows to the sea. The total annual average amount of fresh water currently available for use throughout the entire island of Cyprus is thus 650 MCM. An estimated 40 MCM of this quantity is thought, however, to be overpumping, which results in the unsustainable "mining" of groundwater. Only 63% of the land area of Cyprus is controlled by the government of the Republic of Cyprus, so straight linear extrapolation would suggest average freshwater diversion and extraction of 385 MCM in the government controlled areas of the island. Government estimates state that overall agricultural water demand is 193 MCM per year while municipal, industrial, and tourist demands sum to another 64 MCM. The total demand is thus 257 MCM per year, or about 67% of that suggested by the water balance. Yet water is scarce in Cyprus, either due to periodic droughts, overestimation of supply, or both.

2.8 The Southern Conveyor Project

The Water Development Department (WDD) began planning the large scale development of water infrastructure in the 1960's after the nation gained its independence. These plans included five major schemes to interconnect and form a complete loop around the island with the Troodos mountains in the center. This loop would allow any local excess of water to be distributed to areas with shortages. The plans also proposed the construction of many dams to increase the surface water storage dramatically. The slogan to summarize this new policy was stated as "not a drop of water to reach the sea".

TABLE 2.1
URBAN AND RURAL CENTERS SERVED BY THE SCP

	Nicosia Area	Limassol Area	Larnaca Area	Famagusta Area
Urban Centres	Nicosia	Limassol	Larnaca	Famagusta
Rural Centres				
1	Lymbia	Episkopi	Aradhippou	Pyla
2	Pyrga	Kolossi	Klavdia	Xylotymbou
3	Kornos	Erimi	Trersephanou	Xylophaghou
4	Psevdas	Kandou	Kiti	Ormidhia
5	Sha	Phinikaria	Pervolia	Avgorou
6	Mosphiloti	Moutayiaka	Meneou	Liopetri
7	Alambra	Ayios Tykhonas	Dhromolaxia	Paralimni
8	Nisou	Parekklisha	Kalokhorio	Phrenaros
9	Perakhorio	Pyrgos	Livadhia	Dherinia
10	Dhali	Moni	Voroklini	Sotira
11	Yeri	Monagroulli	Mazotos	Ayia Napa
12	Laxia	Pendakomo	Alethriko	Akhna (Akhna Forest)
13	Xeri	Asomatos	Pano Lefkara	Vrysoules
14	Lythrodhontas	Trakhomi	Kato Lefkara	Ayia Thekli
15	Lakatamia	Amathus Dev.Area	Vavla	E.A.C. Area
16	Anthoupo1is	Episkopi	Zygi	Dhekelia
17	Mammari	Akrotiri	Kalavasos	Ayios Nicolaos
18	Dhenia	Berengaria	Maroni	Troulli
19		Kato Polemidhia	Psematismenos	
20		Ypsonas	Covernor's Beach	
21			Marj	
22			Menoyia	
23			Kofinou	
24			Anafotia	
25			Agglisides	
26			Kivisili	
27			Kelia	

Notes:

1. For convenience, the Larnaca villages of Pyla, Xylotymbou, Xylophagou and Ormidhia are included under Famagusta Area. Similarly, the Larnaca villages of Kornos, Pyrga, Mosphiloti and Psevdas are included under Nicosia Area.
2. The suburbs and adjacent villages included in the urban centers are given below
   Nicosia: Eylenja, Kaimakli, Ayios Dhometios, Engomi, Strovolos and Pallouriotissa. The Turkish occupied sector of Nicosia is also included as it receives water from the same sources.
   Limassol: Ypsonas, Polemidhia, Ayia Phyla. Ayios Athanasios, Mesa Yitonia, Yermasoyia, Potamos tis Yermasoyias and the SBA married quarters of Berengaria.
   Larnaca: Aradhippou

FIGURE 2.3
SCHEMATIC OF THE SOUTHERN CONVEYOR PROJECT

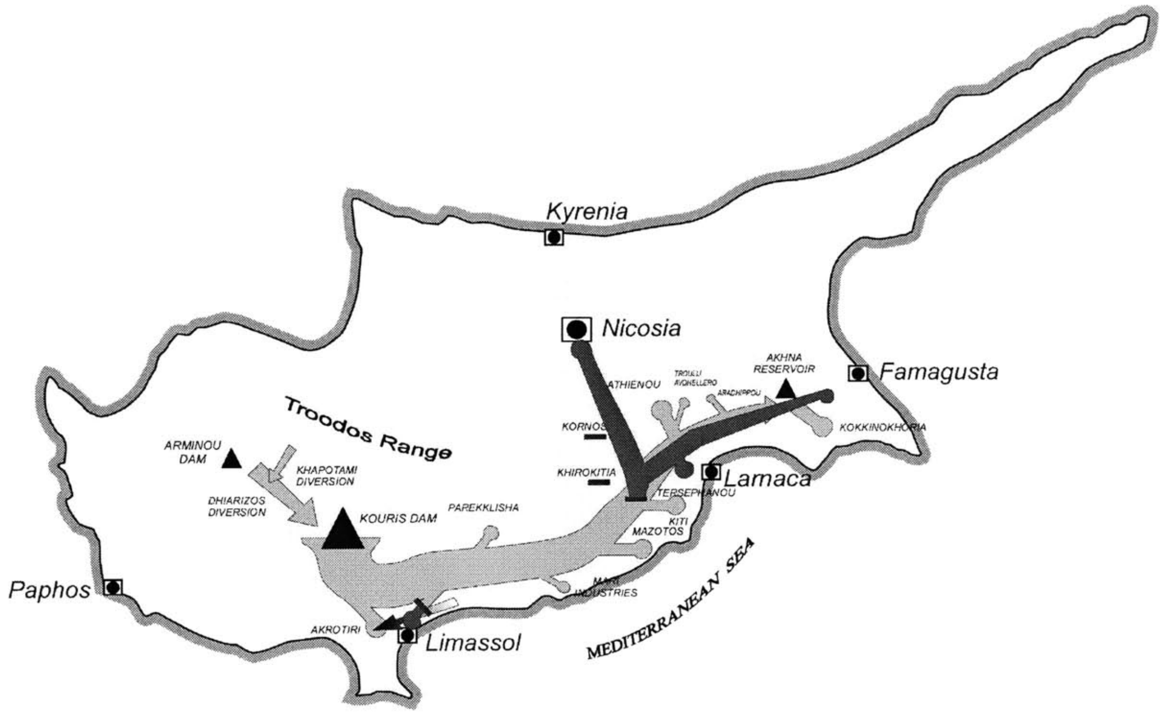


Figure 2.3 shows the SCP with the general direction of flow from west to east. Kouris Dam is shown as the principal source because it has the largest capacity at 115 MCM and height at 110 m. This earthfill dam was constructed in 1988. The total surface water storage for the SCP is 176 MCM, and the bulk of these dams were constructed in the 1980s. The Southern Conveyor proper consists of a ductile iron pipeline of 1.8m diameter and 100km length. The Dhiarizos diversion tunnel is 14.5km long, while the Tersephanou-Nicosia conveyor is 36.5 km in length. The dams are very impressive due to their massive dimensions and large spillways designed for maximum probable floods. The entire scheme is monitored and controlled by a modern SCADA system from the WDD headquarters in Nicosia. The important parameters like reservoir levels, pipeline flows, and pressures are recorded. Urban and rural areas served by the SCP are listed in Table 2.1

The relatively new Dhekelia desalination plant is not shown, but is located to the east of Larnaca. After expansion, the plant now has the capacity to treat 40,000 m^3 /day of saline water extracted from the Mediterranean Sea. It is connected to the Tersephanou – Nicosia conveyor just downstream of Khirokitia Treatment works. The desalination plant receives power from an adjacent oil-fired power plant for all but 3 hours a day. Between 5 and 8pm the peak domestic energy demand forces a short daily shutdown. A second desalination plant is to be constructed in the year 2000 with the same capacity, thus doubling the supply from the saline source.

Limassol has a newly constructed sewage treatment works capable of tertiary treatment located 15km east of the city. It is currently operating below its full capacity as only a small percentage (10%) of the town's sewage is connected to the main interceptor. Connection to the main sewer has been impeded by the age of the city, its buildings, and the narrowness of its streets. Only 3 MCM of tertiary treated sewage is now produced. This water has gained acceptance for agriculture in the last several years and is used strictly for agricultural purposes only. A new sewage treatment works at Nicosia is at planning stages and will increase the water available for reuse substantially (World Bank, 1996).

Previous to the construction of the SCP, land was irrigated to a lesser extent using groundwater pumps. These pumps are generally still in operation, but are costly to operate because of the relatively large drop in water table levels The irrigation water supplied by the WDD is cheaper. The total available storage in the aquifers in the SCP regions greatly outweighs the surface water storage, but the introduction of high lift pumps in the last few decades has facilitated extreme mining of the groundwater so that the SCP is practically a surface water supply system at this stage.

The irrigation areas developed to date in both the SCP and Cyprus are listed in Table 2.2.

TABLE 2.2
IRRIGATION AREAS OF CYPRUS AND THE SOUTHERN CONVERYOR PROJECT

Type of Crop	All Government-controlled Cyprus (including SCP) (ha) **(% of total)**	Southern Conveyor Project		
		Government Irrigation Schemes (ha)	Non-Government Irrigation Schemes (ha)	SCP Total (ha) **(% of total)**
Permanent Crops				
Irrigated	21,886 (18.3%)	3,098	3,738	6,836 (43.3%)
Non-Irrigated	17,933 (15.0%)	0	0	0 (0%)
Total Permanent	39,819 (33.3%)	3,098	3,738	6,836 (43.3%)
Seasonal Crops				
Irrigated	13,584 (11.4%)	5,575	3,238	8,813 (55.9%)
Non-Irrigated	65,474 (54.9%)	0	0	0 (0%)
Total Seasonal	79,058 (66.3%)	5,575	3,238	8,813 (55.9%)
Greenhouse & Tunnel Crops	454 (0.4%)	75	50	125 (0.8%)
Cropped Area				
Irrigated	35,924 (30%)	8,748	7,026	15,774 (100%)
Non-Irrigated	83,407 (70%)	0	0	0 (0%)
Total Cropped Area	119,331 (100%)	8,748	7,026	15,774 (100%)

2.9 Other Projects

Apart from the SCP a number of other major water resource developments have taken place recently. The first to be mentioned is the Paphos Irrigation Project which receives most of its supply from the Troodos mountains also. The irrigated area developed in the region around Paphos is only 5,000 ha, so that there has been an excess of water here during years when severe drought has been experienced on the eastern coast. Preliminary designs of a connection between the Paphos system and the SCP have been undertaken for costing purposes, but there are currently no plans to begin this project. The town of Paphos is supplied from wells pumping an aquifer that is recharged adjacent to the Asprokremmos Dam (capacity 51 MCM).

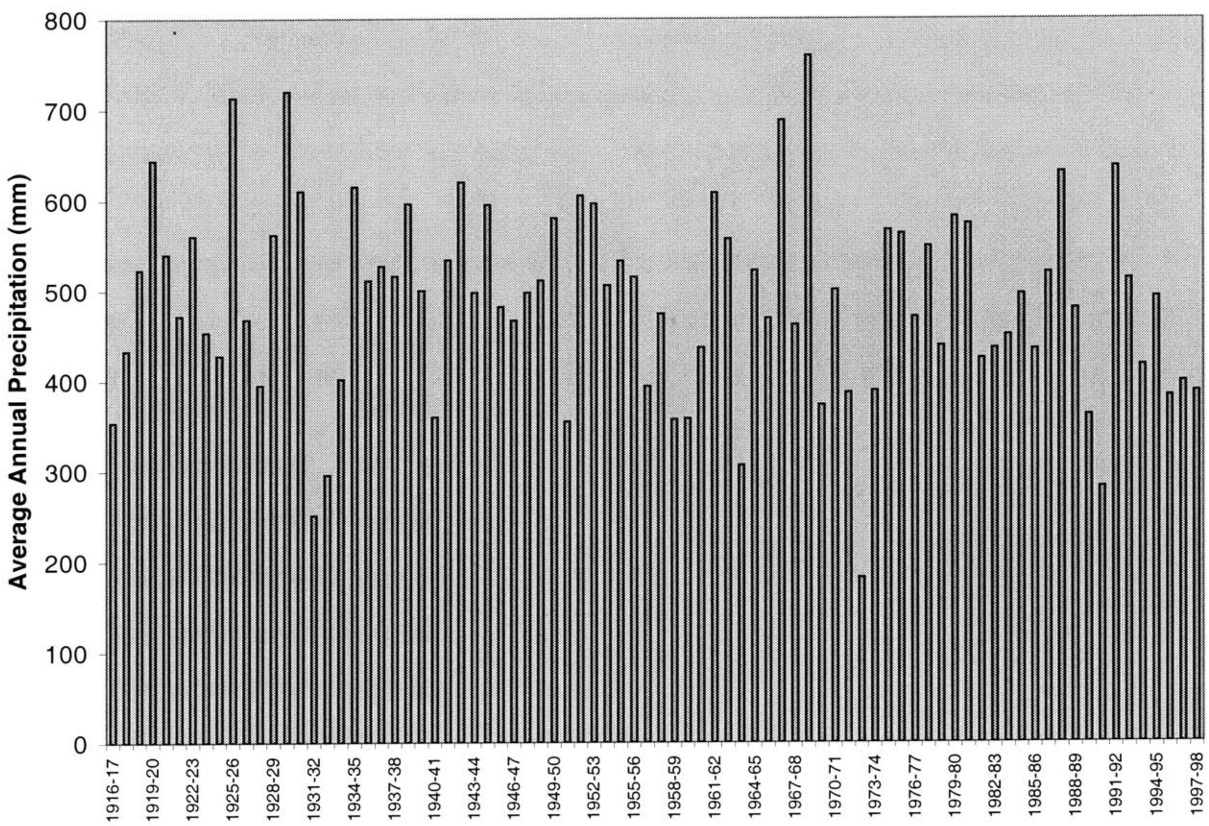
Also on the West Coast is the Khrysokhou Irrigation, smaller than the Paphos system with an irrigation area of 3,100 ha.

2.10 Drought

Based on the average values of rainfall and runoff shown above, Cyprus should not have a water scarcity problem. The problem is that over time, half of the measured values of rainfall and runoff will be below the averages. Moreover, historic data indicates that rainfall over Cyprus is extremely variable so the actual amount of available water may be significantly below the norm in any given year or series of years (See Figure 2.4). Several consecutive years of rainfall significantly below normal can lead to drought conditions. The construction of surface water reservoirs was meant to provide a certain amount of resilience to the water resources system during rainfall-poor years by creating multi-year storage; however, the total storage volume of all reservoirs in government-controlled Cyprus is only 274 MCM. When compared to the estimate of a total demand of 248 MCM per year, it is apparent that water supplies could become scarce after only a few consecutive years of poor rainfall.

Most recently, low rainfall in the years from 1996 to 1999 have produced drought conditions in Cyprus. In the last four years, annual rainfall has been less than 400 mm per year. At the end of March 1998, storage levels in Cypriot reservoirs were at an historic low. The total reservoir storage was only 38 MCM, or 14% of capacity (Socratous, 1998), and the situation became worse later in the year. The drought has caused a variety of problems for Cyprus. Water allocations have had to be severely curtailed to both agriculture and municipal, industrial, & tourist users. Rationing to cities was instituted such that water was only delivered once every three days to cities and towns. Irrigation water to seasonal crops was almost completely restricted, and water allocated to seasonal crops was reduced to close to the absolute minimum level needed for survival. The consequences of such reductions in water supply are many. Domestic users must contend with the inconvenience of intermittent and limited water. Hotels must restrict landscaping activities and ask tourists on holiday to be conscious of water usage. Business and industry may be required to reduce production. All of these users may also choose to supplement their own individual supplies at a significantly higher cost through purchases from private water vendors. Agriculture suffers even more during such times of severe shortage because crop yields are significantly or completely reduced. Potato exports in 1995, before the drought, totaled CP£ 44,300,000, but by 1997 exports had fallen to CP£ 8,400,000 – an over 80% reduction. It is interesting to note, however, that over the same period the value of citrus exports actually increased from CP£ 16,000,000 to CP£ 17,300,000 (Planning Bureau of Cyprus, 1997). Water scarcity also constrains growth and new development in all sectors of the economy.

FIGURE 2.4
AVERAGE ANNUAL RAINFALL RECORDED IN CYPRUS



Water scarcity is very real in Cyprus. Droughts of three or more years must be expected. During these extended droughts it must be assumed that demand for water will certainly exceed supply. Extraordinary measures will be required of the Water Development Department, farmers, and all other citizens of Cyprus in order to properly manage water during these periods of drought. Innovative ideas will be needed to cope with such severe water scarcity.

Chapter 3 EVAPORATION IN CYPRUS

Evaporation is -- or should be -- a major consideration in water resources planning. Water evaporates from all surface reservoirs where water is stored, and in hot, arid climates where the need to store water is the greatest, evaporation rates are the highest. Mean evaporation from water surfaces in some areas of Cyprus can be up to 0.7 cm per day in July. Evaporation from all ponds and reservoirs in Cyprus may represent a substantial loss of water. In order to quantify the extent of evaporative losses from water bodies in Cyprus, the physical processes that cause evaporation must first be understood. Empirical data from meteorological stations will then be used to estimate the absolute values and spatial distribution of evaporation around Cyprus. With an understanding of the extent and magnitude of evaporation from ponds and reservoirs on Cyprus, estimates will then be made of the economic value of the water that is lost. Such information will allow an examination of the extent to which it is economically viable to attempt to reduce evaporation in existing and planned reservoirs.

3.1 Physical Process of Evaporation

Evaporation is defined as "the conversion of a liquid substance into the gaseous state" (Grolier, 1995). This is the root of the "problem" caused by evaporation since our engineering works are designed to capture, store, and transport *liquid* water and our industrial and agricultural systems (including, of course, human beings) primarily utilize *liquid* water. As water evaporates, liquid water is changed into water vapor which escapes into the atmosphere and is therefore essentially unusable until it re-condenses and falls back to earth in the form of precipitation. Such precipitation may fall at a considerable distance from the original source of liquid water. This is the root of the inefficiency caused by evaporation from a reservoir since most water lost into the atmosphere may not be recaptured by that reservoir or may be returned at a time when it is less valuable. The goal of any water supply system is that water be used as efficiently as possible, since it is generally cheaper to save water that has already been impounded than to go out and try to produce more water to make up for losses. This is especially true in an arid country such as Cyprus where water is scarce. Reduction of losses to evaporation is the motivating factor behind the change from flood and large diameter sprinkler irrigation to more efficient drip and mini-sprinkler systems.

There are essentially two dominant physical factors which influence the rate of evaporation occurring from surface water reservoirs. These are "the supply of energy to provide the latent heat of vaporization and the ability to transport the [water] vapor away from the evaporative surface (Chow, et. al., 1988, p. 80)." Latent heat of vaporization is the amount of energy required to change liquid water into water vapor. This energy is supplied by the environment in which the reservoir exists. The majority of energy input into a reservoir is from solar radiation going directly into the water. Other energy inputs are from the overlying atmosphere, the soil surrounding the reservoir, and inflowing water, although all of these may be energy sinks as well. The ability to transport water vapor away from the evaporative surface refers to the movement of water vapor away from the liquid water source after evaporation has occurred. If this movement is slow, then evaporation is also slow because there is nowhere for additional water vapor to go except for back into solution in the liquid water. The rate of water vapor transport is a function of the vapor pressure gradient, which is, in turn, a function of the wind speed over the reservoir, the ambient air temperature, and the water temperature at the surface of the reservoir. While obvious, it is also worthwhile to state that evaporation can only take place at the interface between water and the atmosphere; therefore the absolute amount of evaporation from a reservoir is directly proportional to the surface area of the reservoir.

In summary, the factors which most affect evaporation from surface water reservoirs are the amount and intensity of sunlight, the air temperature, wind speed, surface water temperature, and the surface area of the reservoir. With the exception of surface area, these factors are large scale, macro-climatic phenomena that are generally beyond human control. This is the reason that there has generally been little or no effort to control evaporation from reservoirs.

3.2 Measurement and Estimation of Evaporation Rates

The most preferable way of determining the rate of evaporation from a body of water such as a pond or reservoir is through direct measurement. In the absence of other inflows and outflows, evaporation rates can be found by measuring the change (fall) in water surface level over time. In practice, however, this is very difficult to do in all but the most controlled conditions. Most ponds and reservoirs have numerous inflows and outflows occurring simultaneously and at rates which vary over time. Many of these processes, such as seepage to or from groundwater and transpiration, are also hard to quantify and also affect the water surface level. Thus direct measurement of water levels, combined with information about inflows and outflows, generally allows only the quantification of "losses" – a term which encompasses many processes including evaporation.

Due to the difficulty of measuring evaporation directly from a pond or reservoir, evaporation pans are many times used as a proxy. The instrument used in Cyprus is the same one which is standard in the United States, the Class A Pan. The Class A Pan is a metal tank which is 1.21 m in diameter and 0.254 m deep placed 0.15 m above the ground on an open-timber framework. A photo of the pan found at the meteorological station at Kalopanayiotis Dam is shown in Figure 3.1. The advantage of using a pan to measure evaporation is that all terms in the water balance are easily controlled and measured. Evaporation rates are computed based on the change in the depth of water in the pan over a particular time interval, accounting for any input from rain or water added during that same time period. Uncorrected data from evaporation pans should not, however, be used directly to infer evaporation from open water surfaces. The ASCE Hydrology Handbook states, "Due to the differing thermal characteristics between the pan and large water bodies, the pans tend to overestimate the total amount of evaporation (ASCE 1996, p. 145)." In order to correct for this effect, a coefficient must be applied to the pan evaporation data in order to convert it to lake evaporation rates. Both ASCE (1996, p. 145) and the WDD (Socratous, Personal Correspondence 4/23/99) recommend using coefficients of between 0.65 to 0.85.

FIGURE 3.1
CLASS A EVAPORATION PAN

(photo by author, 1999)

The Cypriot government maintains an extensive network of meteorological stations in all areas of the government-controlled portion of the island. Many, if not most, of these stations include a Class A Pan for the calculation of evaporation rate. Table 3.1 summarizes the mean monthly pan evaporation rates measured at 31 meteorological stations located in various parts of the island. Table 3.2 presents the same data but now converted to mean lake evaporation through the application of a pan coefficient of 0.7.

Table 3.1

Mean Monthly Class A Pan Evaporation Data from Various Meteorological Stations in Cyprus

				Average Measured Class A Pan Evaporation in Millimeters (1976-1990)												
No.	Station ID	Station Name	Elev. (m)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Total
1	731	LARNACA (AIRPORT)	1	79	87	125	174	237	279	306	282	237	174	114	85	2179
2	94	ASPROKREMMOS (DAM)	89	82	81	107	175	209	263	282	268	236	184	126	96	2108
3	889	PARALIMNI (HOSPITAL)*	80	64	71	99	143	225	261	298	277	213	155	88	71	1966
4	572	KALAVASOS (DAM)*	160	61	74	106	171	226	254	280	259	213	147	96	67	1954
5	63	EVRETOU DAM*	110	50	59	93	139	212	263	299	279	214	138	85	60	1891
6	466	PHARMAKAS*	860	52	56	91	154	208	269	316	275	204	131	73	51	1876
7	82	PAPHOS (AIRPORT)	10	87	94	126	156	200	216	236	222	189	147	106	96	1875
8	640	NICOSIA (P.W.D.)	160	42	52	86	143	215	268	301	266	197	128	67	42	1806
9	666	ATHALASSA (RADIOSONDE)*	25	43	56	84	135	211	263	303	264	190	133	76	45	1803
10	429	YERMASOYIA (DAM)	70	53	65	96	141	205	251	272	248	194	139	85	54	1801
11	338	POLEMIDHIA PANO (DAM)	120	65	70	98	137	181	239	257	242	194	146	89	66	1786
12	81	AKHELIA (OLV NURS. GRDN STN)	45	73	71	99	140	189	221	236	220	185	144	102	77	1757
13	592	LEFKARA PANO (DAM)	420	49	53	82	125	186	248	292	260	190	131	76	51	1743
14	800	AKHNA (FOREST NURS STN.)*	50	52	61	88	125	200	221	271	252	198	140	76	53	1734
15	415	ASTROMERITIS (EL. SCHOOL)	160	50	58	90	144	201	241	266	233	181	128	68	53	1710
16	493	AY. IOANNIS-MALUNDA (E.S./PR)	350	46	57	83	125	192	243	274	253	192	129	69	47	1709
17	377	AGROS	1015	48	62	96	140	191	232	262	235	191	123	74	48	1701
18	41	POLIS (TECHNICAL SCHOOL)	15	59	64	85	115	173	226	258	240	189	136	83	60	1687
19	320	SAITTAS (NURS. GRDN NEW STN)	640	44	57	87	134	188	235	266	241	183	120	70	45	1671
20	810	XYLOPHAGOU (POLICE STN.)*	49	50	65	95	139	174	216	242	228	176	138	76	61	1657
21	630	ZYYI (A.R.I. EXPER. STN.)	40	54	68	100	142	178	201	224	210	174	134	76	56	1613
22	440	PANAYIA BRIDGE (FOREST STN.)	440	36	43	72	115	172	231	267	235	172	118	61	40	1562
23	402	KALOKHORIO-L/SOL (POL. STN.)	740	35	44	68	114	172	229	263	247	179	106	56	38	1549
24	51	KHRYSOKHOU*	67	47	47	75	99	157	224	249	235	173	116	68	49	1539
25	579	DHEFTERA (EL. SCHOOL)*	275	33	41	68	127	168	214	244	222	162	99	55	37	1470
26	168	LIMNITIS (SAW MILL)	260	41	39	76	108	163	208	236	222	163	102	53	41	1452
27	225	PRODHROMOS (FOR.ST COLLGE)	1380	28	44	68	119	157	201	230	208	146	94	52	29	1377
28	330	PHASSOURI (PLANTATIONS)	15	36	43	82	110	164	186	205	183	156	101	62	38	1367
29	120	PANAYIA PANO (POLICE STN.)	820	51	57	68	93	131	187	226	198	128	93	65	42	1339
30	130	STAVROS TIS PSOKAS (FOR STN.)	780	33	39	60	99	134	179	213	197	138	90	48	32	1261
31	310	PLATANIA (FOREST STN.)	1120	17	24	46	83	124	157	187	164	103	55	23	15	998
	National Average Mean Monthly Pan Evaporation			50.32	58.13	87.06	131.10	185.26	229.87	260.03	237.58	182.58	126.42	74.77	53.06	1675.52

NOTE * for these stations the records are 5 to 10 years

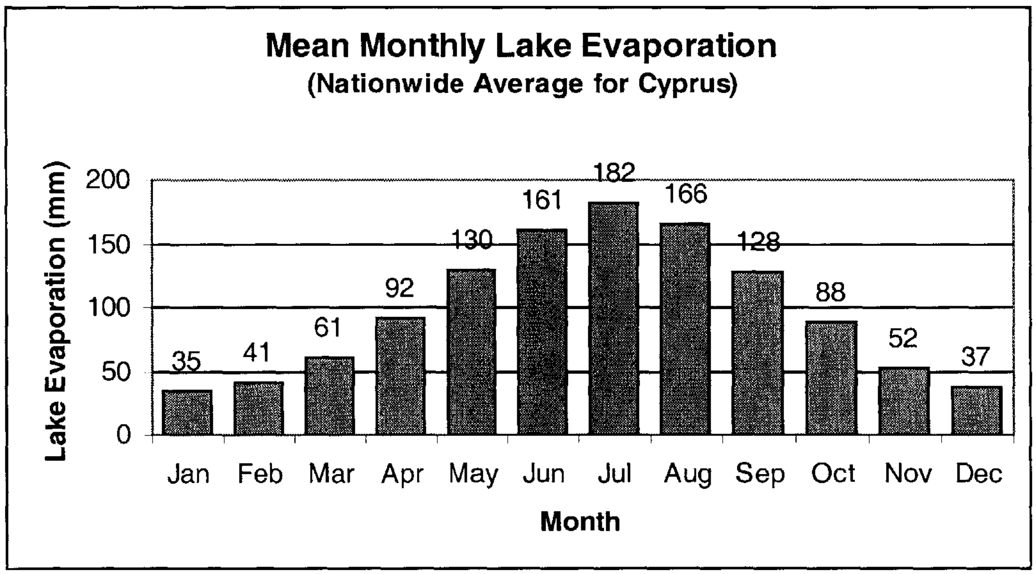
Table 3.2
Mean Monthly Lake Evaporation Data from Various Meteorological Stations in Cyprus
(Pan Coefficient = 0.7)

				Average Lake Evaporation in Millimeters (1976-1990)												
No.	Station ID	Station Name	Elev. (m)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Total
1	731	LARNACA (AIRPORT)	1	55.3	60.9	87.5	121.8	165.9	195.3	214.2	197.4	165.9	121.8	79.8	59.5	1525.3
2	94	ASPROKREMMOS (DAM)	89	57.4	56.7	74.9	122.5	146.3	184.1	197.4	187.6	165.2	128.8	88.2	67.2	1475.6
3	889	PARALIMNI (HOSPITAL)*	80	44.8	49.7	69.3	100.1	157.5	182.7	208.6	193.9	149.1	108.5	61.6	49.7	1376.2
4	572	KALAVASOS (DAM)*	160	42.7	51.8	74.2	119.7	158.2	177.8	196	181.3	149.1	102.9	67.2	46.9	1367.8
5	63	EVRETOU DAM*	110	35	41.3	65.1	97.3	148.4	184.1	209.3	195.3	149.8	96.6	59.5	42	1323.7
6	466	PHARMAKAS*	860	36.4	39.2	63.7	107.8	145.6	188.3	221.2	192.5	142.8	91.7	51.1	35.7	1313.2
7	82	PAPHOS (AIRPORT)	10	60.9	65.8	88.2	109.2	140	151.2	165.2	155.4	132.3	102.9	74.2	67.2	1312.5
8	640	NICOSIA (P.W.D.)	160	29.4	36.4	60.2	100.1	150.5	187.6	210.7	186.2	137.9	89.6	46.9	29.4	1264.2
9	666	ATHALASSA (RADIOSONDE)*	25	30.1	39.2	58.8	94.5	147.7	184.1	212.1	184.8	133	93.1	53.2	31.5	1262.1
10	429	YERMASOYIA (DAM)	70	37.1	45.5	67.2	98.7	143.5	175.7	190.4	173.6	135.8	97.3	59.5	37.8	1260.7
11	338	POLEMIDHIA PANO (DAM)	120	45.5	49	68.6	95.9	126.7	167.3	179.9	169.4	135.8	102.2	62.3	46.2	1250.2
12	81	AKHELIA (OLV NURS. GRDN STN)	45	51.1	49.7	69.3	98	132.3	154.7	165.2	154	129.5	100.8	71.4	53.9	1229.9
13	592	LEFKARA PANO (DAM)	420	34.3	37.1	57.4	87.5	130.2	173.6	204.4	182	133	91.7	53.2	35.7	1220.1
14	800	AKHNA (FOREST NURS STN.)*	50	36.4	42.7	61.6	87.5	140	154.7	189.7	176.4	138.6	98	53.2	37.1	1213.8
15	415	ASTROMERITIS (EL. SCHOOL)	160	35	40.6	63	100.8	140.7	168.7	186.2	163.1	126.7	89.6	47.6	37.1	1197
16	493	AY. IOANNIS-MALUNDA (E.S./PR)	350	32.2	39.9	58.1	87.5	134.4	170.1	191.8	177.1	134.4	90.3	48.3	32.9	1196.3
17	377	AGROS	1015	33.6	43.4	67.2	98	133.7	162.4	183.4	164.5	133.7	86.1	51.8	33.6	1190.7
18	41	POLIS (TECHNICAL SCHOOL)	15	41.3	44.8	59.5	80.5	121.1	158.2	180.6	168	132.3	95.2	58.1	42	1180.9
19	320	SAITTAS (NURS. GRDN NEW STN)	640	30.8	39.9	60.9	93.8	131.6	164.5	186.2	168.7	128.1	84	49	31.5	1169.7
20	810	XYLOPHAGOU (POLICE STN.)*	49	35	45.5	66.5	97.3	121.8	151.2	169.4	159.6	123.2	96.6	53.2	42.7	1159.9
21	630	ZYYI (A.R.I. EXPER. STN.)	40	37.8	47.6	70	99.4	124.6	140.7	156.8	147	121.8	93.8	53.2	39.2	1129.1
22	440	PANAYIA BRIDGE (FOREST STN.)	440	25.2	30.1	50.4	80.5	120.4	161.7	186.9	164.5	120.4	82.6	42.7	28	1093.4
23	402	KALOKHORIO-L/SOL (POL. STN.)	740	24.5	30.8	47.6	79.8	120.4	160.3	184.1	172.9	125.3	74.2	39.2	26.6	1084.3
24	51	KHRYSOKHOU*	67	32.9	32.9	52.5	69.3	109.9	156.8	174.3	164.5	121.1	81.2	47.6	34.3	1077.3
25	579	DHEFTERA (EL. SCHOOL)*	275	23.1	28.7	47.6	88.9	117.6	149.8	170.8	155.4	113.4	69.3	38.5	25.9	1029
26	168	LIMNITIS (SAW MILL)	260	28.7	27.3	53.2	75.6	114.1	145.6	165.2	155.4	114.1	71.4	37.1	28.7	1016.4
27	225	PRODHROMOS (FOR.ST COLLGE)	1380	19.6	30.8	47.6	83.3	109.9	140.7	161	145.6	102.2	65.8	36.4	20.3	963.9
28	330	PHASSOURI (PLANTATIONS)	15	25.2	30.1	57.4	77	114.8	130.2	143.5	128.1	109.2	70.7	43.4	26.6	956.9
29	120	PANAYIA PANO (POLICE STN.)	820	35.7	39.9	47.6	65.1	91.7	130.9	158.2	138.6	89.6	65.1	45.5	29.4	937.3
30	130	STAVROS TIS PSOKAS (FOR STN.)	780	23.1	27.3	42	69.3	93.8	125.3	149.1	137.9	96.6	63	33.6	22.4	882.7
31	310	PLATANIA (FOREST STN.)	1120	11.9	16.8	32.2	58.1	86.8	109.9	130.9	114.8	72.1	38.5	16.1	10.5	698.6
	National Ave. Mean Monthly Lake Evaporation			35.23	40.69	60.95	91.77	129.68	160.91	182.02	166.31	127.81	88.49	52.34	37.15	1172.86

3.3 Monthly Variation in Evaporation

The mean monthly lake evaporation averaged for all of the meteorological stations shown in Table 3.2 may be taken to approximate the overall national average since the given stations have a broad geographic distribution. The use of such an average shows that the overall annual mean lake evaporation in Cyprus is approximately 1173 mm. The greatest rate of evaporation occurs in July, when the mean lake evaporation is 182 mm per month, or 5.87 mm per day. January has the slowest rate of lake evaporation with a mean of about 35 mm per day, or 1.13 mm per day.

FIGURE 3.2
MEAN MONTHLY LAKE EVAPORATION RATES FOR CYPRUS



There is a significant spatial variation in lake evaporation rates in Cyprus. This is due to the highly variable topography of Cyprus which extends from sea level at the coast up to 1,219 m at the top of Mt. Olympus. Differences in elevation also influence mean temperature and precipitation. In general, evaporation rates are greater at lower elevations where the temperature is higher. There is also a trend towards lower evaporation rates northwest of the Troodos Mountains, most likely due to the prevailing winds. Figure 3.3 shows lake evaporation rates at the Larnaca Airport, which has the highest evaporation of the 31 listed stations. Figure 3.4 shows lake evaporation at the Platania Forest station, where evaporation is the lowest.

FIGURE 3.3
HIGHEST LAKE EVAPORATION

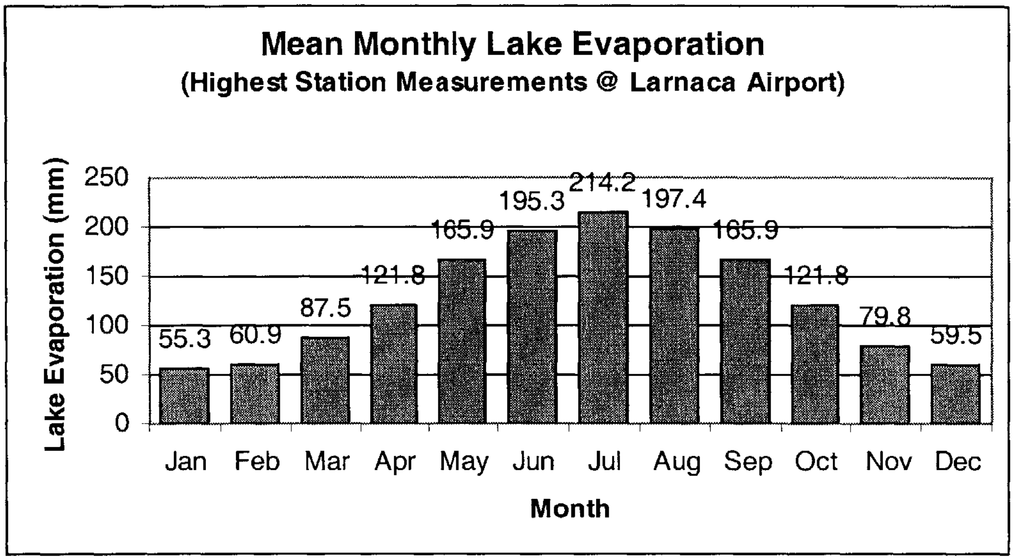
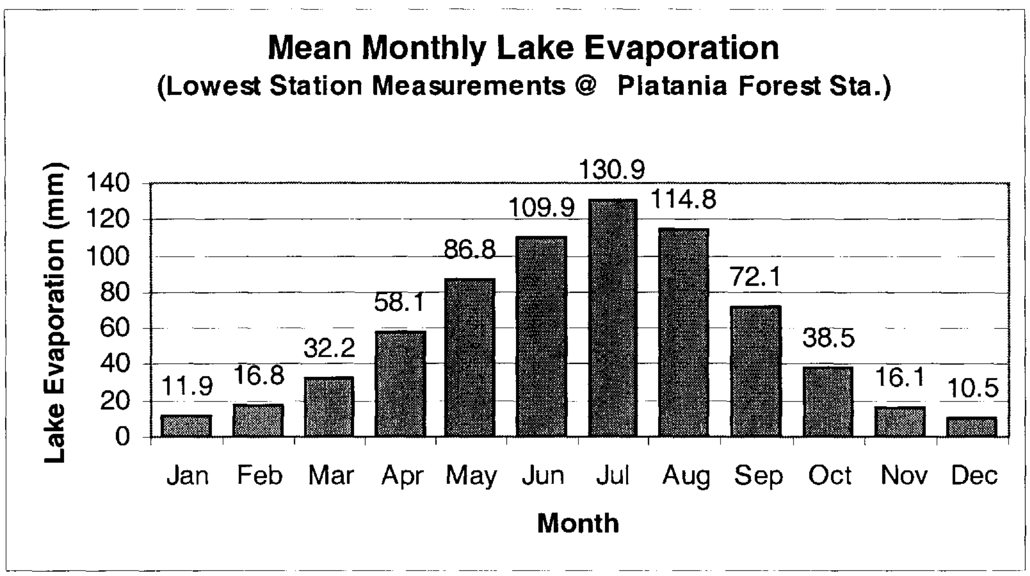


FIGURE 3.4
LOWESET LAKE EVAPORATION



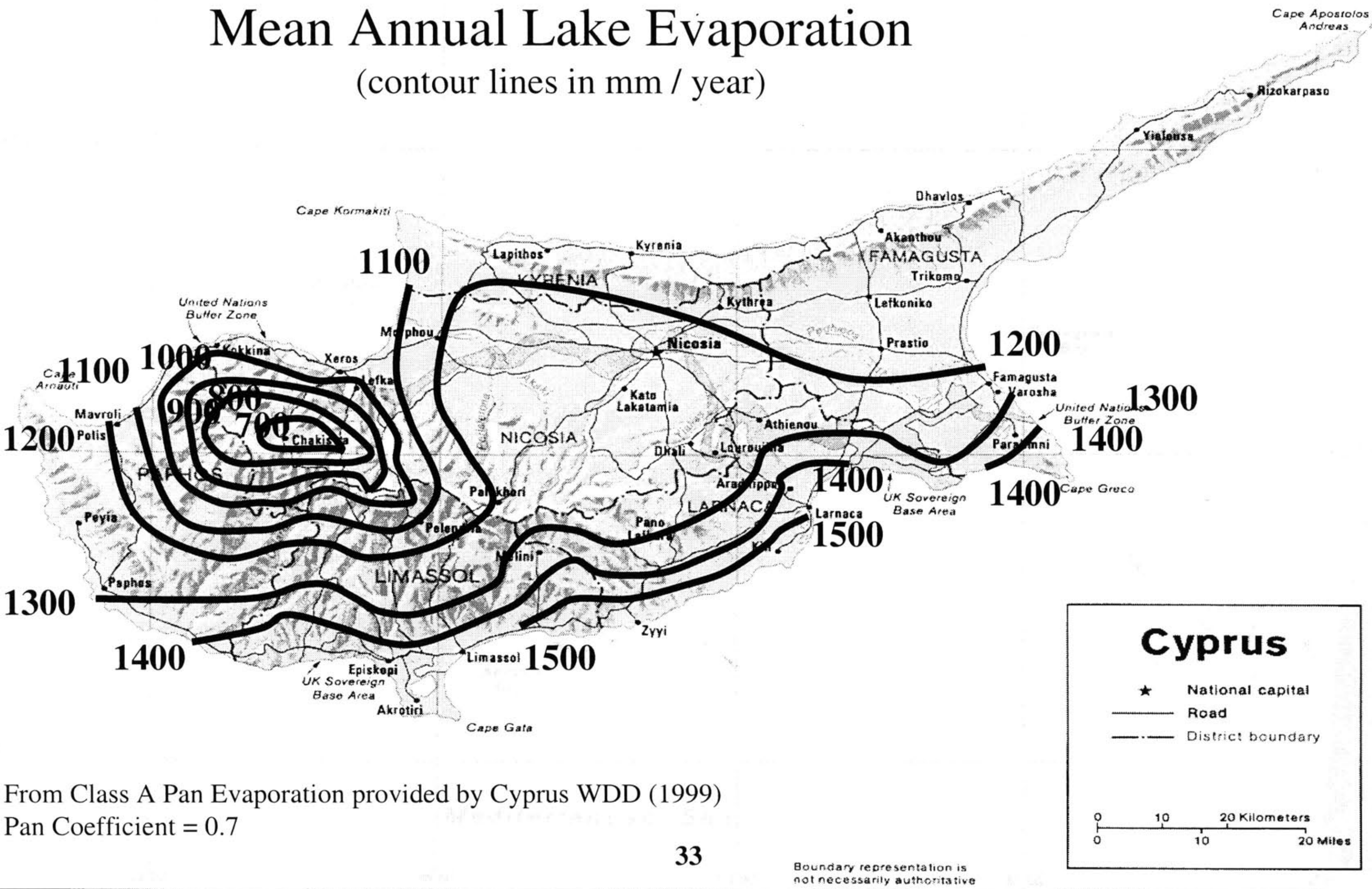
3.4 Spatial Variation of Evaporation

By combining the evaporation data from all 31 meteorological stations plus an additional one at Akrotiri within the UK Sovereign Base, a map showing the spatial variation in lake evaporation for Cyprus can be generated. Such a map of Cyprus is presented in Figure 3.5

FIGURE 3.5

Mean Annual Lake Evaporation

(contour lines in mm / year)



From Class A Pan Evaporation provided by Cyprus WDD (1999)
Pan Coefficient = 0.7

The contours on Figure 3.5 represent lines of equal annual lake evaporation. The contours are spaced at intervals of 100 mm of lake evaporation. Contouring was done manually using information from the 31 meteorological stations previously shown (plus Akrotiri). No data are available for the occupied territory. Comparison of Figure 3.5 with a similar map produced by the Cypriot government showing pan evaporation confirms the reasonableness of the figure.

3.5 Annual Variation in Evaporation

In addition to spatial variation, there is variation of evaporation rates over time. Data from the meteorological station at Akrotiri presented in Table 3.3 shows mean monthly lake evaporation rates over a 10-year period from 1987 to 1996. Examination of the data clearly shows the significant variation in evaporation throughout the course of a single year. From year to year, however, the monthly evaporation rates remain relatively constant. Standard deviations of monthly mean lake evaporation rates at Akrotiri range from 5% to 13% of the mean. Figure 3.6 presents 10 years of monthly mean lake evaporation data from the Akrotiri station.

FIGURE 3.6
MONTHLY MEAN LAKE EVAPORATION OVER TIME

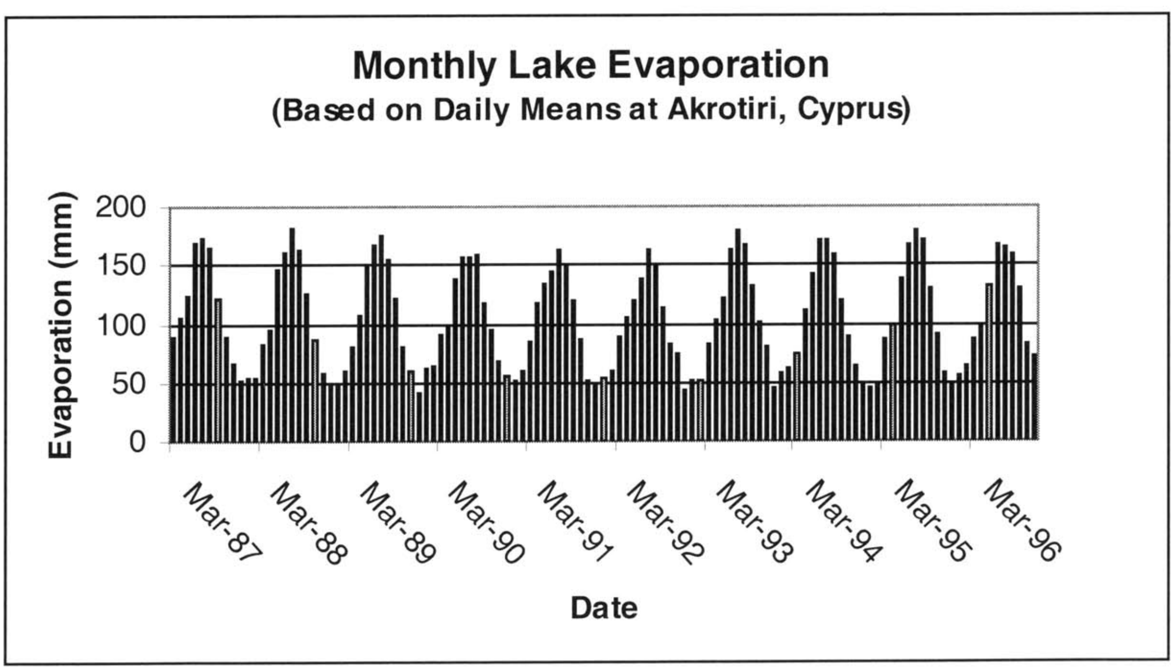


TABLE 3.3

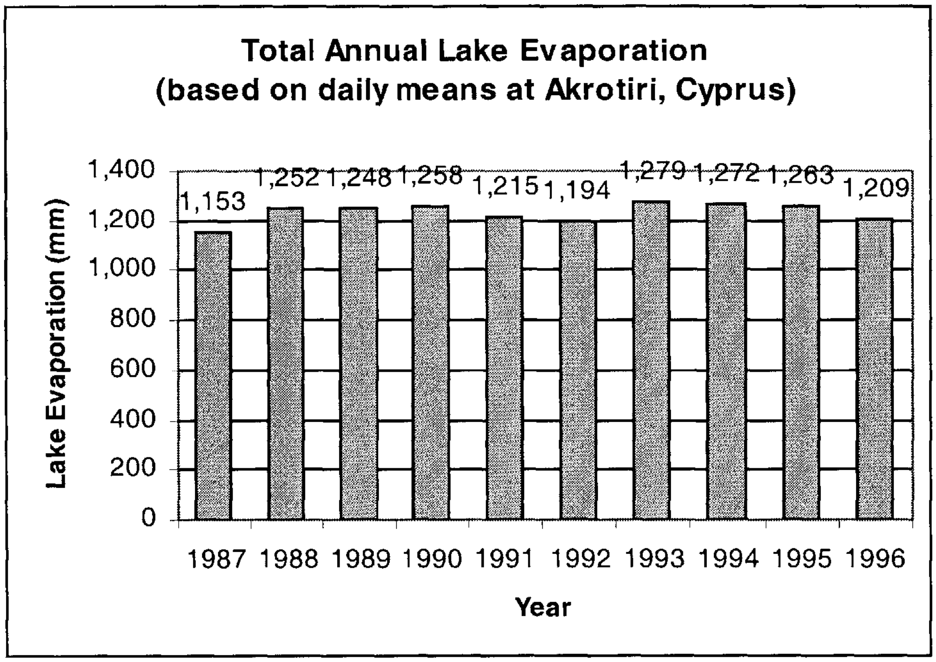
MONTHLY MEAN LAKE EVAPORATION AT AKROTIRI, CYPRUS FROM 1987 TO 1996
(Evaporation Pan Coefficient = 0.7)

	Monthly Lake Evaporation Based on Mean Daily Data (mm)												Lake Evap. (mm)	
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Overall Average Monthly	Yearly Totals
1987	53.50*	58.20*	89.40	104.37	123.69	169.26	172.73	165.57	120.96	88.97	65.94	52.51	105.43	1265.11
1988	53.38	53.39	82.46	94.92	145.39	160.65	180.98	162.10	125.37	85.93	57.75	49.26	104.30	1251.58
1989	48.39	60.37	79.86	107.10	151.47	166.95	174.69	154.72	121.80	80.94	59.85	41.66	103.98	1247.79
1990	62.06	62.92	90.27	98.70	137.58	157.29	156.89	157.98	116.76	93.96	68.88	54.90	104.85	1258.19
1991	52.51	60.17	85.28	117.81	134.97	144.90	161.88	151.47	119.28	85.72	51.87	49.04	101.24	1214.91
1992	54.47	60.49	88.97	105.42	119.35	138.60	163.84	149.95	113.40	82.68	73.29	43.40	99.49	1193.85
1993	51.65	51.94	81.59	102.69	121.95	161.91	179.68	167.96	132.30	101.99	80.64	44.70	106.58	1279.00
1994	57.94	62.52	74.21	110.88	142.79	171.36	171.65	159.06	118.65	88.75	64.47	49.26	105.96	1271.54
1995	44.70	49.20	86.15	98.28	139.10	168.00	178.37	170.56	129.15	91.14	58.59	49.69	105.24	1262.93
1996	56.20	63.13	87.45	97.86	132.15	166.32	164.49	158.19	129.15	82.89	71.61	48.30*	104.81	1257.75
Ave.	**53.48**	**58.24**	**84.56**	**103.80**	**134.84**	**160.52**	**170.52**	**159.76**	**122.68**	**88.30**	**65.29**	**48.27**	**104.19**	**1250.27**
Std. Dev.	4.82	4.97	5.05	6.93	10.61	10.86	8.30	6.83	6.11	6.28	8.60	4.04	2.19	26.29
Std. Dev. (%)	9.01%	8.54%	5.97%	6.68%	7.87%	6.77%	4.87%	4.27%	4.98%	7.12%	13.17%	8.36%	2.10%	2.10%

*Data missing and replaced with monthly average

The variation in the total yearly lake evaporation is even less than that for the monthly values. The standard deviation in the 10 years of annual totals is only 2.1% of the mean. This suggests that for long-term planning and design purposes, evaporation is a quantity which can be estimated and predicted with a high degree of certainty for any specific location in Cyprus. Figure 3.7 shows the total annual lake evaporation rates at Akrotiri for the period between 1987 and 1996.

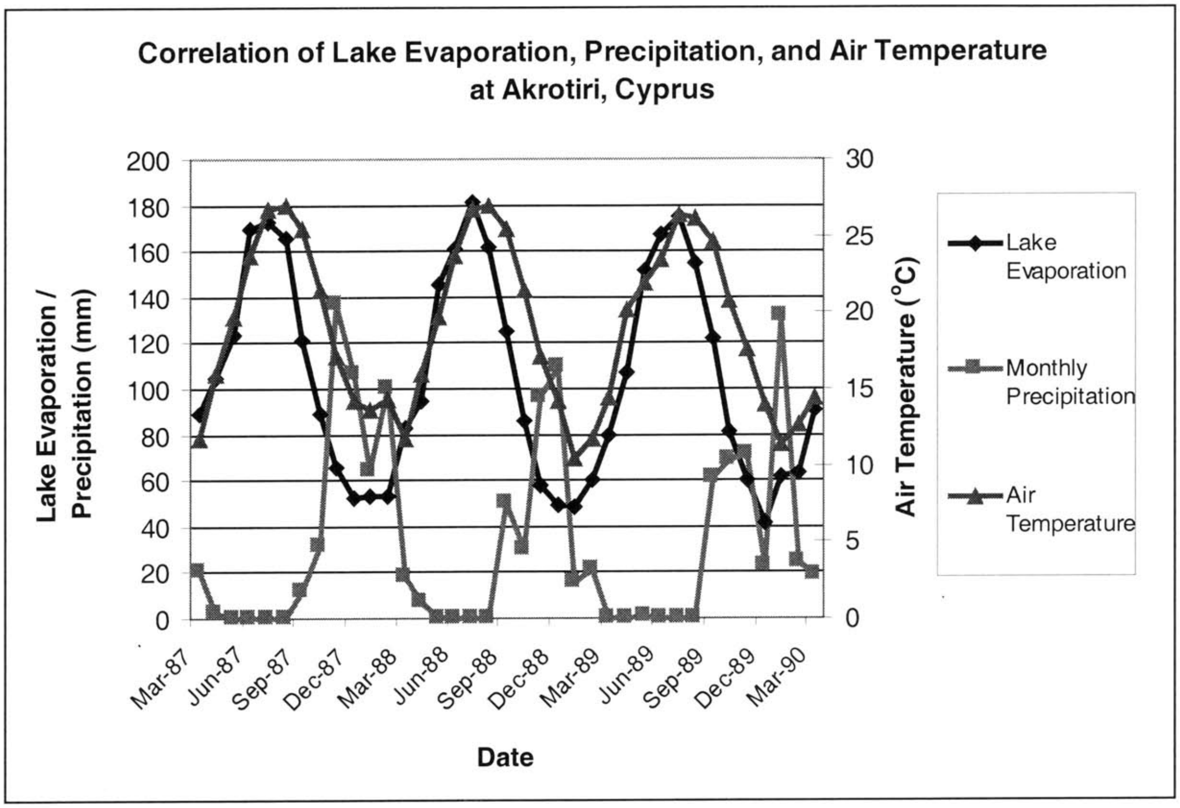
FIGURE 3.7
TOTAL ANNUAL LAKE EVAPORATION OVER TIME



3.6 Correlations with Other Climatic Factors

Additional data from the Akrotiri station allows for an investigation of the connections between evaporation and other climatic factors. Three years of monthly data were investigated to determine possible correlations between evaporation and temperature and/or precipitation. Figure 3.8 shows monthly variation in these three factors over the period between 1987 to 1990.

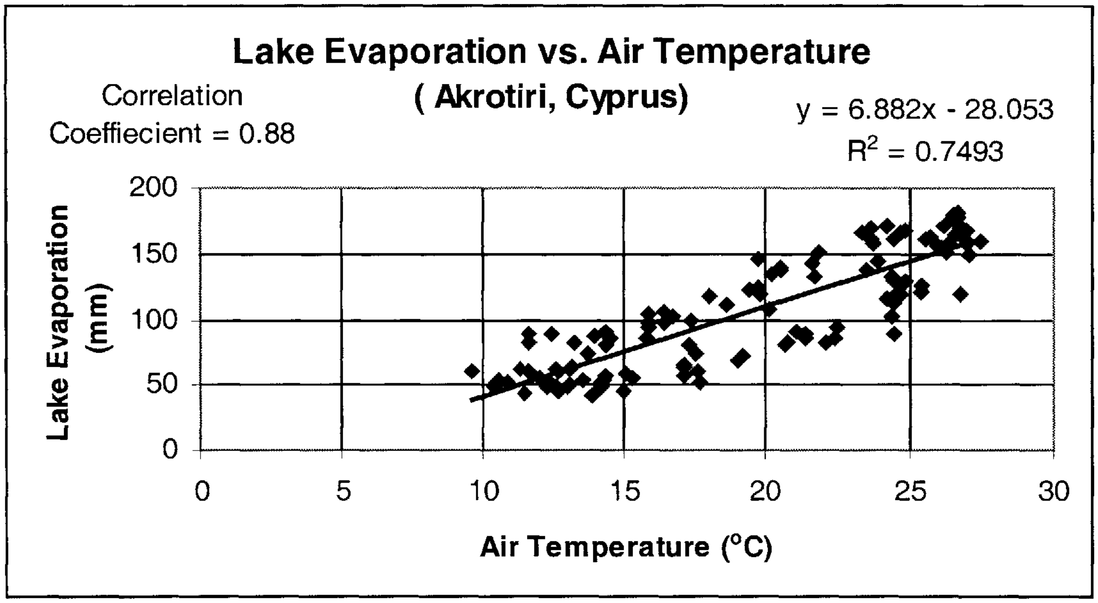
FIGURE 3.8
LAKE EVAPORATION, PRECIPITION, AND AIR TEMPERATURE
MEAN MONTHLY VALUES OVER TIME



Evaporation is shown to be strongly and directly related to air temperature, with a correlation coefficient of 0.88. This is as expected since evaporation and air temperature are both driven by solar radiation. A linear function can be defined which relates mean monthly lake evaporation to mean monthly temperature, as shown in Figure 3.9. It may be noticed that evaporation rates generally decrease with elevation in the mountainous regions of Cyprus, which is also true of air temperature.

Evaporation is inversely related to precipitation, but the correlation is not very strong. The correlation coefficient is –0.65. It is, however, generally true that evaporation is the lowest during the cool winter rainy season when the majority of precipitation occurs.

FIGURE 3.9
CORRELATION BETWEEN LAKE EVAPORATION AND AIR TEMPERATURE,



3.7 Estimating Evaporation with Equations

In addition to the use of direct measurements of evaporation (water balance or pans), there are several theoretical or semi-empirical equations which make use of other climatic variables in order to compute evaporation. These methods use information about the actual physical processes which drive evaporation to estimate evaporation rates. Several of these are presented below:

3.7.1 Simplified Energy Balance Method

Evaporation is driven by energy. Energy must be added to a body of water in order to allow individual water particles to overcome the latent heat barrier and escape into the air in the form of vapor. For virtually all ponds and reservoirs, the primary energy input source is sunshine. Solar radiation which is directly intercepted by a body of water is converted into thermal energy. If the temperature of the water is constant and there are no other energy sources or sinks, then all energy supplied by solar radiation may be assumed to drive evaporation. Equation 3.1 presents the Simplified Energy Balance Equation of evaporation.

$$E_r = (8.64 \times 10^7)\, R_n / (l_v\, \rho_w)$$

(Equation 3.1)

Where:

E_r = Evaporation Rate (mm / day)

R_n = Net Radiation (W/m^2)

l_v = Latent Heat of Vaporization = 2500 – 2.36 x Air Temp (kJ / kg)

ρ_w = Density of Water (kg/m^3)

If air and water temp. of 20°C are assumed, the equation can be expressed as follows:

$$E_r = 0.0353\, R_n$$

(Equation 3.2)
(Chow et. al. 1988, p. 90)

Of course the simplifying assumptions implicit in this equation are not generally valid in the field. There are many other processes which affect the energy balance of a body of water – Albedo, back radiation, advection, etc. In order to properly account for these terms, numerical methods are generally applied (see Section 8.)

3.7.2 Aerodynamic Methods

The rate of evaporation from a body of water is not only a function of available energy, but also of the ability of water vapor to be transported away from the water surface. The rate of transport is governed by the vapor pressure gradient in the atmosphere immediately above the free water surface and the wind speed across that surface. Analysis of these two parameters led to the development of aerodynamic methods for computing evaporation rates. Aerodynamic equations are among the most widely applied for computing evaporation from ponds and reservoirs (ASCE 1996, p. 148). There are several forms of aerodynamic equations, but most generally follow the form proposed by Dalton in 1802 (Henderson-Sellers 1984, p. 51).

The U.S. Geological Survey developed one permutation of the Dalton aerodynamic equation during evaporation studies on Lake Hefner. The basic Lake Hefner form is reprinted below as Equation 3.3.

$$E_r = 0.097\ (e_{sw} - e_a)\ u$$

(Equation 3.3)
(ASCE, 1996, p. 148)

Where:

E_r = evaporation rate (mm / day)

e_{sw} = saturation vapor pressure at the surface water temperature (Pa)

e_a = vapor pressure of water in air at the air temperature (Pa)

u = Wind Speed at z_2 (m / sec)

3.7.3 Combined Methods

Because evaporation is governed both by energy input and vapor transport, a third class of equations was developed to account for both factors. Combined methods can produce the most accurate calculations of evaporation rates when all the required data are available and the assumptions are valid. The chief assumption underlying most combined methods is that there is steady state energy flow and that changes in heat storage over time in the water body are not significant (Chow, et. al., 1988, p. 88). The combined method therefore may not be appropriate for application to large lakes that have significant heat storage capacity. The most common form of the combined equation was developed by Penman in 1948 (ASCE 1996, p. 151). Over large areas, energy balance has been found to be the primary factor in evaporation.

Priestley and Taylor developed a combined equation, presented below as Equation 3.4.

$$E_r = \alpha \left(\Delta / [\Delta + \gamma]\right) E_{renergy}$$

(Equation 3.4)
(Chow et. al., 1988, p. 88)

Where:

E_r = evaporation rate (mm / day)
α = 1.3 (aerodynamic factors taken as 30% of energy factors)
Δ = gradient of the saturated vapor pressure curve (Pa / ° C)
$= 409\ e_s / (237.3 + \text{Air Temp.})^2$
γ = the psychrometric constant (Pa / ° C)
$E_{renergy}$ = evaporation rate from energy balance method

3.8 Estimating Evaporation with Numerical Methods

Due to the dynamic nature of the factors which govern evaporation rate, the use of a single equation to compute evaporation is overly simplistic. In addition to not accounting for the stochastic nature of the inputs, many variable are ignored or neglected. For example, the simplified energy balance method assumes all incoming solar radiation is used to drive evaporation. Aerodynamic methods are tied to the vapor pressure gradient, which changes as water temperature changes. A full energy balance method must account for all energy inputs and outputs as well as the changes in water temperature. The rate of evaporation computed then causes feedback to the energy budget.

Computer models are ideal for the application of such numerical methods. An energy budget of a specific body of water can be constructed and data may be input from actual climate stations. Such a computer model is capable of predicting energy fluxes, water temperatures and evaporation rates. Based on the net energy flux at any time step and the total energy in the previous time step, the temperature of a body of water may be computed. The water temperature is then used to solve an aerodynamic form of evaporation equation. Evaporation, in turn, causes both latent and sensible heat losses. Models for two reservoirs in Oklahoma in the US were created by the author (Cox, 1992) specifically to study evaporation rates.

Chapter 4 EVAPORATION FROM PONDS AND RESERVOIRS IN CYPRUS

Having characterized the magnitude and variability of evaporation around Cyprus, estimates can now be made of how evaporation affects the Cypriot water supply system. By compiling an inventory of the major ponds and reservoirs, the total quantity of impounded water that is subject to evaporation will be quantified. Combining information about the surface areas of these bodies of water with the evaporation rates determined in the last chapter will allow estimates of the total average volume of water lost to evaporation yearly to be made. Since accurate data are available from the extensive meteorological station network around Cyprus, pan data will be used to estimate evaporation rates. Once the quantity of evaporated water is determined, the value of this water will be estimated in order to establish the economic consequences of evaporation losses from ponds and reservoirs.

4.1 Inventory of Ponds and Reservoirs

The Cypriot government has made significant progress since 1960 in the construction of ponds and reservoirs for irrigation and water supply. In 1960, the total capacity of all ponds and reservoirs was 6 MCM; by 1998, the total capacity had increased to 298 MCM (Min. of Agriculture, 1998, p.3). Table 4.1 lists the 58 major ponds and reservoirs in the government-controlled area of Cyprus. The total gross storage capacity of these facilities, below the normal storage pool, is 273.76 MCM. The combined surface area of all the impoundments, again at the normal pool, is 14,479,000 m^2. Most of the structures listed are small irrigation ponds, many of which are located in the Troodos Mountains. The 10 largest reservoirs actually make up over 94% of the total storage capacity and account for over 89% of the surface area. These 10 reservoirs are all located at lower elevations, in the foothills near the coast.

TABLE 4.1
MAJOR PONDS AND RESERVOIRS IN THE GOVERNMENT-CONTROLLED AREA OF CYPRUS

Serial No.	Name of Dam/Pond	River	District	Dam Type	Dam Ht. (m)	Crest Length (m)	Gross Reservoir Capacity ($x1000m^3$)	Normal Reservoir Surface Area ($x1000m^2$)	Pur-pose
1	Agridhia Pond	Off-stream	Limassol	TE	18	497	59	12	I
2	Agros Dam	Kouris	Limassol	TE	26	180	99	15	I
3	Akapnou-Ephtagonia Pond	Off-stream	Limassol	TE	18	640	132	24	I
4	Akhna Dam	Off-stream	Famagusta	TE	23	272	5,800	1,250	I
5	Akrounda Dam	Yermasoyia	Limassol	PG	7	25	23	10	I
6	Arakapas Dam	Yermasoyia	Limassol	PG	23	97	129	20	I
7	Arakapas No. 1 Pond	Off-stream	Limassol	TE	12	714	192	30	I
8	Arakapas No. 2 Pond	Off-stream	Limassol	TE	12	823	120	26	I
9	Argaka Dam	Magounda	Paphos	ER	41	173	1,150	107	I
10	Asprokremmos Dam	Xeropotamos	Paphos	TE	56	700	51,000	2,590	I
11	Athalassa Dam	Pedhieos	Nicosia	TE	18	447	791	230	I
12	Ayia Marina Dam	Xeros	Paphos	ER	33	142	311	33	I
13	Ayii Vavatsinias Dam	Vasilikos	Larnaca	VA	19	58	53	12	I
14	Ayii Vavatsinias No. 1 Pond	Off-stream	Larnaca	TE	17	434	55	11	I
15	Ayii Vavatsinias No. 2 Pond	Off-stream	Larnaca	TE	25	405	43	9	I
16	Dhierona Pond	Off-stream	Larnaca	TE	24	730	159	27	I
17	Dhypotamos Dam	Pendaskinos	Larnaca	ER	49	390	15,000	1,000	S/I
18	Ephtagonia No. 1 Pond	Off-stream	Limassol	TE	16	550	92	17	I
19	Ephtagonia No. 2 Pond	Off-stream	Limassol	TE	13	728	127	25	I
20	Ephtagonia No. 3 Pond	Off-stream	Limassol	TE	12	490	65	13	I
21	Esso Galata Pond	Off-stream	Nicosia	TE	27	428	35	8	I
22	Evretou Dam	Stavros tis Psokas	Paphos	ER	70	260	25,000	1,250	I
24	Galini Dam	Kambos	Nicosia	PG	11	19	23	5	I
25	Kafizes Dam	Xeros (Morphou)	Nicosia	PG	23	27	113	20	I
26	Kalavasos Dam	Vasilikos	Larnaca	ER	57	482	17,000	875	I/S
27	Kalokhorio (Klirou) Dam	Akaki	Nicosia	PG	9	37	82	13	I
28	Kalopanayiotis Dam	Marathasa	Nicosia	TE	40	137	391	47	I
29	Kandou Dam	Kouris	Limassol	PG	15	53	34	12	I

TABLE 4.1 (CONT.)

Serial No.	Name of Dam/Pond	River	District	Dam Type	Dam Ht. (m)	Crest Length (m)	Gross Reservoir Capacity (x1000m^3)	Normal Reservoir Surface Area (x1000m^2)	Pur-pose
30	Kato Mylos Pond	Off-stream	Limassol	TE	23	630	104	20	I
31	Khandria Pond	Off-stream	Limassol	TE	35	522	70	14	I
32	Khirokitia Pond	Off-stream	Larnaca	TE	16	784	205	31	I
33	Kiti Dam	Tremithos	Larnaca	TE	22	990	1,614	360	I
34	Kouris Dam	Kouris	Limassol	TE	113	550	115,000	3,600	I/S
35	Kyperounda Pond	Off-stream	Limassol	TE	27	851	273	36	I
36	Lagoudhera Pond	Off-stream	Nicosia	TE	36	518	70	14	I
37	Lefka Dam	Marathasa	Nicosia	PG	35	149	368	45	I
38	Lefkara Dam	Syrkatis	Larnaca	ER	74	240	13,850	650	I
39	Liopetri Dam	Potamos	Famagusta	TE	18	579	340	74	R
40	Lymbia Dam	Tremithos	Nicosia, Laranaca	PG	12	122	220	90	I
41	Lower Lythrodhonda Dam	Yialias	Nicosia	PG	11	21	32	10	I
42	Upper Lythrodhonda Dam	Yialias	Nicosia	PG	10	42	32	15	I
43	Mavrokolymbos Dam	Mavrokolymb os	Paphos	TE	45	528	2,180	175	I
44	Melini Pond	Off-stream	Larnaca	TE	22	500	59	13	I
45	Ora Pond	Off-stream	Larnaca	TE	18	504	62	12	I
46	Palekhori Kambi Dam	Akaki	Nicosia	PG	33	131	620	110	I
48	Pelendria Pond	Off-stream	Limassol	TE	18	580	123	21	I
49	Perapedhi Dam	Kouris	Limassol	PG	22	62	55	12	I
50	Pharmakas No. 1 Pond	Off-stream	Nicosia	TE	18	328	21	6	I
51	Pharmakas No. 2 Pond	Off-stream	Nicosia	TE	24	480	61	12	I
52	Polemidhia Dam	Garyllis	Limassol	TE	45	196	3,864	110	I
53	Pomos Dam	Livadhi	Paphos	ER	38	302	859	83	I
54	Prodhromos Reservoir	Off-stream	Limassol	TE	10	756	122	26	I
55	Pyrgos Dam	Katouris	Nicosia	PG	22	66	285	30	I
56	Trimiklini Dam	Kouris	Limassol	PG	33	76	340	23	I
57	Xyliatos Dam	Lagoudhera	Nicosia	ER	42	155	1,250	96	I
58	Yermasoyia Dam	Yermasoyia	Limassol	TE	49	409	13,600	1,100	I/S
	Totals						**273,757**	**14,479**	

(Source: WDD Map)

Dam Types: TE = Earthfill; ER = Rockfill; PG = Gravity; VA = Arch

Purposes: I = Irrigation; S = Water Supply; R = Groundwater Recharge

4.2 Average Quantity of Evaporative Losses

By locating the 58 listed ponds and reservoirs on the evaporation contour map developed in the last chapter (Figure 3.5), the average annual rate of evaporation at each reservoir site can be estimated. Application of Equation 4.1 then allows the computation of the total average annual quantity of water evaporated from each pond or reservoir.

$$Q_e = E_r \bullet SA \bullet (10^{-9})$$

(Equation 4.1)

Where:

Q_e = Total Quantity of Water Evaporated (MCM / year)

E_r = Evaporation Rate (mm / year)

SA = Surface Area of Reservoir at Normal Pool Level (m^2)

The key assumption underlying Equation 4.1 is that the depth and thus the surface area of each pond or reservoir remains constant at the normal pool level. This assumption is not very realistic since water levels will fluctuate during the year. During drought periods especially, the water level in most bodies of water will tend to be lower than normal, thereby reducing the surface area and total volume of water evaporated. A more precise estimate of surface areas requires historic data or a reservoir simulation (See Chapter 5), but Equation 4.1 provides a reasonable first approximation of the magnitude of evaporative losses from ponds and reservoirs in Cyprus.

The total average annual quantity of water lost to evaporation from the major ponds and reservoirs is just over 19 MCM, which is more than one third of the current total domestic demand for the whole nation. The ponds and reservoirs listed in Table 4.2 are listed in descending order by total quantity of water lost to evaporation. Again, the 10 largest reservoirs account for the bulk of losses – 17.29 MCM or over 90%. Kouris Reservoir alone evaporates an average of 4.68 MCM, or almost a quarter of the total evaporative losses.

TABLE 4.2
AVERAGE ANNUAL EVAPORATION FROM MAJOR PONDS AND RESERVOIRS IN CYPRUS AND VALUE OF LOST WATER

Serial No.	Name of Dam / Pond	Gross Reservoir Capacity (x1,000m^3)	Normal Reservoir Surface Area (x1,000m^2)	Mean Lake Evaporation Rate (mm/year)	Est. Ave. Annual Volume of Water Evaporated (MCM)	Value of Water (CP £)	Cost of Water from Desalination (CP £)
34	Kouris Dam	115,000	3,600	1,300	4.680	£842,400.00	£1,965,600.00
10	Asprokremmos Dam	51,000	2,590	1,475	3.820	£687,645.00	£1,604,505.00
22	Evretou Dam	25,000	1,250	1,325	1.656	£298,125.00	£695,625.00
4	Akhna Dam	5,800	1,250	1,300	1.625	£292,500.00	£682,500.00
58	Yermasoyia Dam	13,600	1,100	1,260	1.386	£249,480.00	£582,120.00
17	Dhypotamos Dam	15,000	1,000	1,300	1.300	£234,000.00	£546,000.00
26	Kalavasos Dam	17,000	875	1,375	1.203	£216,562.50	£505,312.50
38	Lefkara Dam	13,850	650	1,220	0.793	£142,740.00	£333,060.00
33	Kiti Dam	1,614	360	1,500	0.540	£97,200.00	£226,800.00
11	Athalassa Dam	791	230	1,250	0.288	£51,750.00	£120,750.00
43	Mavrokolymbos Dam	2,180	175	1,250	0.219	£39,375.00	£91,875.00
52	Polemidhia Dam	3,864	110	1,250	0.138	£24,750.00	£57,750.00
46	Palekhori Kambi Dam	620	110	1,150	0.127	£22,770.00	£53,130.00
9	Argaka Dam	1,150	107	1,100	0.118	£21,186.00	£49,434.00
40	Lymbia Dam	220	90	1,250	0.113	£20,250.00	£47,250.00
39	Liopetri Dam	340	74	1,350	0.100	£17,982.00	£41,958.00
57	Xyliatos Dam	1,250	96	1,000	0.096	£17,280.00	£40,320.00
53	Pomos Dam	859	83	1,050	0.087	£15,687.00	£36,603.00
32	Khirokitia Pond	205	31	1,400	0.043	£7,812.00	£18,228.00
37	Lefka Dam	368	45	850	0.038	£6,885.00	£16,065.00
28	Kalopanayiotis Dam	391	47	800	0.038	£6,768.00	£15,792.00
7	Arakapas No. 1 Pond	192	30	1,250	0.038	£6,750.00	£15,750.00
35	Kyperounda Pond	273	36	1,000	0.036	£6,480.00	£15,120.00
12	Ayia Marina Dam	311	33	1,050	0.035	£6,237.00	£14,553.00
16	Dhierona Pond	159	27	1,250	0.034	£6,075.00	£14,175.00
8	Arakapas No. 2 Pond	120	26	1,250	0.033	£5,850.00	£13,650.00
55	Pyrgos Dam	285	30	1,050	0.032	£5,670.00	£13,230.00
3	Akapnou-Ephtagonia Pond	132	24	1,250	0.030	£5,400.00	£12,600.00
19	Ephtagonia No. 2 Pond	127	25	1,200	0.030	£5,400.00	£12,600.00

TABLE 4.2 (CONT.)

Serial No.	Name of Dam / Pond	Gross Reservoir Capacity ($x1,000m^3$)	Normal Reservoir Surface Area ($x1,000m^2$)	Mean Lake Evaporation Rate (mm/year)	Est. Ave. Annual Volume of Water Evaporated (MCM)	Value of Water (CP £)	Cost of Water from Desalination (CP £)
56	Trimiklini Dam	340	23	1,150	0.026	£4,761.00	£11,109.00
6	Arakapas Dam	129	20	1,250	0.025	£4,500.00	£10,500.00
54	Prodhromos Reservoir	122	26	960	0.025	£4,492.80	£10,483.20
48	Pelendria Pond	123	21	1,100	0.023	£4,158.00	£9,702.00
30	Kato Mylos Pond	104	20	1,150	0.023	£4,140.00	£9,660.00
18	Ephtagonia No. 1 Pond	92	17	1,200	0.020	£3,672.00	£8,568.00
42	Upper Lythrodhonda Dam	32	15	1,250	0.019	£3,375.00	£7,875.00
25	Kafizes Dam	113	20	850	0.017	£3,060.00	£7,140.00
2	Agros Dam	99	15	1,100	0.017	£2,970.00	£6,930.00
20	Ephtagonia No. 3 Pond	65	13	1,200	0.016	£2,808.00	£6,552.00
27	Kalokhorio (Klirou) Dam	82	13	1,200	0.016	£2,808.00	£6,552.00
44	Melini Pond	59	13	1,200	0.016	£2,808.00	£6,552.00
36	Lagoudhera Pond	70	14	1,100	0.015	£2,772.00	£6,468.00
13	Ayii Vavatsinias Dam	53	12	1,250	0.015	£2,700.00	£6,300.00
29	Kandou Dam	34	12	1,250	0.015	£2,700.00	£6,300.00
45	Ora Pond	62	12	1,200	0.014	£2,592.00	£6,048.00
51	Pharmakas No. 2 Pond	61	12	1,200	0.014	£2,592.00	£6,048.00
5	Akrounda Dam	23	10	1,400	0.014	£2,520.00	£5,880.00
14	Ayii Vavatsinias No. 1 Pond	55	11	1,250	0.014	£2,475.00	£5,775.00
31	Khandria Pond	70	14	950	0.013	£2,394.00	£5,586.00
49	Perapedhi Dam	55	12	1,100	0.013	£2,376.00	£5,544.00
41	Lower Lythrodhonda Dam	32	10	1,250	0.013	£2,250.00	£5,250.00
1	Agridhia Pond	59	12	1,000	0.012	£2,160.00	£5,040.00
15	Ayii Vavatsinias No. 2 Pond	43	9	1,250	0.011	£2,025.00	£4,725.00
50	Pharmakas No. 1 Pond	21	6	1,200	0.007	£1,296.00	£3,024.00
21	Esso Galata Pond	35	8	800	0.006	£1,152.00	£2,688.00
24	Galini Dam	23	5	1,000	0.005	£900.00	£2,100.00
	Totals	**273,757**	**14,479**		**19.097**	**£3,437,466**	**£8,020,754**

4.3 Value of Water Lost to Evaporation

The average estimated total quantity of water lost to evaporation has been shown to be substantial, but the economic value of the water must also be estimated to determine the significance of the losses. If the value of the water being lost to evaporation is not very high, then any efforts to reduce evaporation may be economically unfeasible. Alternatively, new sources of water might be used to supplement supplies in lieu of attempting to recover water now being lost to evaporation.

Assigning a "value" to the water being lost to evaporation may be done in numerous ways. To determine the true economic value of the water, the shadow values of the water would need to be known. The shadow value of water represents the value that each additional unit of water adds to the overall national welfare. The computation of shadow values requires the use of demand curves for each sector, and the value changes based on the total availability of water from all sources in any year. Evaluation of shadow values is beyond the scope of this chapter. Another possible method of assigning value would be to use the price at which water is sold. This tactic would require a choice of which sale price would be used, since water is treated, sold to municipal water boards and then resold to domestic consumers all over Cyprus for different prices. Water is also sold directly to farmers for irrigation at a price which is subsidized by the central government.

The method chosen to assess the "value" of the water lost to evaporation from ponds and reservoirs utilizes the average capital recovery cost of the development of the water storage and distribution system. This is the price at which water must be sold in order to repay the capital expenditures used to build the dams and pipelines over the design life of the projects. Any extra water saved by the reduction of evaporation could be sold by the WDD at this price (which excludes the cost of pumping). This represents a gross value since the cost of evaporation reduction is not included in the calculation. This price may be expected to be reasonably consistent for the large, recently constructed projects, but may vary somewhat for the smaller ponds. However, as has been shown, the smaller structures encompass only a minor percentage of the total storage volume in Cyprus. The capital recovery cost chosen, CY£ 0.18, is that stated by the WDD for the SCP (Pikis, 1995, p.58). The value of the evaporated water is calculated as shown in Equation 4.2.

$$Val = Q_e \bullet P_{cap} \bullet 10^6 \qquad \text{(Equation 4.2)}$$

Where:

Val = Value of Water Evaporated (CY£ / year)

Q_e = Total Volume of Water Evaporated (MCM / year)

P_{cap} = Capital Recovery Cost (CY£ 0.18 / m^3)

Table 4.2 lists the average annual value of water evaporated from the major ponds and reservoirs in Cyprus. The total value is estimated at approximately CY£ 3,440,000. This figure may overstate the actual value somewhat since the evaporation estimate is likely too high due to use of a constant surface area, but it does show that the water evaporated does represent a significant loss of economic resources. As a comparison, the total amount of water used for irrigation in the SCP is 91 MCM. At the average government-subsidized price of CY£ 0.07 / m^3, this quantity of water is sold for a total of just over CY£ 6.4 million.

The other way of establishing the value of the water lost to evaporation is to determine the cost of replacing that water from some other source. Because the majority of feasible dam sites and diversions have already been utilized, additional surface water cannot be substituted for evaporated water. Increased groundwater pumping is likewise not desirable since many or most aquifers are already being overpumped and subjected to saltwater intrusion. The WDD has therefore turned to desalination of seawater for the provision of additional water supply. The current desalination capacity in Cyprus is approximately 14.6 MCM per year from the existing plant in Dekahlia, but a new contract has just been tendered for another plant. The new plant will be constructed under a BOOT contract and will produce an additional 14.6 MCM per year using the reverse osmosis process. The contract price for water provided by this plant is to be CY£ 0.42 / m^3. Substituting this price, P_{desal}, into Equation 4.2 for P_{cap}, the cost of replacing evaporated water (raw) with desalinated water (treated) may be estimated. Table 4.2 lists the figures. The total cost of a volume of desalinated water equivalent to the total average amount of water lost to evaporation is approximately CY£ 8,021,000.

4.4 Evaporation from the Southern Conveyor Project

The Southern Conveyor Project (SCP) is of special interest when discussing water supply in Cyprus. The SCP includes many of the largest dams and serves most of southeast and central Cyprus. The SCP is a multi-purpose project that supplies water to most of the major municipalities as well as numerous planned irrigation schemes. Current domestic demand within the SCP is 49 MCM, which is almost 90% of the estimated total national domestic demand. The demand for irrigation water supplied by the SCP is currently 91 MCM, most of which goes to the large lowland citrus orchards (World Bank, 1996). The total storage capacity of the SCP is 174 MCM. The reservoirs which comprise the SCP have been broken out of Table 4.2 and re-listed in Table 4.3.

TABLE 4.3
AVERAGE ANNUAL EVAPORATION FROM RESERVOIRS IN THE SCP AND VALUE OF LOST WATER
(Subset of Pond and Reservoirs Inventory)

Serial No.	Name of Dam/Pond	District	Gross Reservoir Capacity (x1,000m^3)	Normal Reservoir Surface Area (x1,000m^2)	Mean Lake Evaporation Rate (mm/year)	Est. Ave. Annual Volume of Water Evaporated (MCM)	Value of Water (CY £)	Cost of Water from Desalination (CY £)
34	Kouris Dam	Limassol	115,000	3,600	1,300	4.680	£842,400	£1,965,600
58	Yermasoyia Dam	Limassol	13,600	1,100	1,260	1.386	£249,480	£582,120
17	Dhypotamos Dam	Larnaca	15,000	1,000	1,300	1.300	£234,000	£546,000
26	Kalavasos Dam	Larnaca	17,000	875	1,375	1.203	£216,563	£505,313
38	Lefkara Dam	Larnaca	13,850	650	1,220	0.793	£142,740	£333,060
	Totals		**174,450**	**7,225**		**9.36**	**£1,685,183**	**£3,932,093**

All of the above reservoirs are multi-purpose reservoirs that supply water for both domestic and irrigation uses. There are several other smaller impoundments in the SCP area, but cumulatively their storage is small and they are listed as for irrigation only. Only the five dams listed above will be considered for the purposes of evaluating evaporation from the SCP.

The total average annual volume of water estimated to evaporate from the SCP reservoirs is 9.36 MCM, which is equivalent to almost 20% of current domestic demand. The value of the lost water in terms of capital recovery costs is CY£ 1,685,000, and the cost of substituting desalinated water for the water lost to evaporation is CY£ 3,932,000.

4.5 Farm Irrigation Ponds

One final potentially significant source of evaporation losses is from the farm ponds used by some farmers for irrigation. These ponds are used of collect water from irrigation distribution pipelines. Water is then pumped from the ponds into individual irrigation systems for application onto the fields or orchards. Many of these ponds are lined to prevent infiltration, but most seem to be open to the air and therefore subject to evaporation. Specific data on the number and sizes of these ponds are not available to the author; however, by making some gross assumption, the problem of irrigation ponds can be evaluated for significance.

The 1985 Agricultural Census listed 47,248 separate agricultural holdings (Land Consolidation Dept., 1993). If 15% of these holdings included a farm pond, that would put the total number of ponds at around 7,000. Assuming that these ponds are spread evenly throughout the country and that they are on average 3 m by 3 m, the total amount of irrigation can be calculated by using Equation 4.3.

$$Q_e = E_r \bullet SA \bullet N \bullet 10^{-9}$$

(Equation 4.3)

Where:

Q_e = Total Quantity of Water Evaporated (MCM / year)
E_r = Evaporation Rate – National Average (1173 mm / year)
SA = Surface Area of Individual Farm Pond (9 m^2)
N = Total Number of Ponds (7,000)

This gross approximation of evaporation from farm ponds suggests that 0.074 MCM of water is lost per year to evaporation. If the total number of farm ponds were equal to the total number of holdings, then evaporative losses would approach 0.50 MCM per year. The true number is likely somewhere between these two estimates, but is likely closer to the former. Taking the average cost of irrigation water to the farmer to be CY£ 0.07, the economic consequences to all Cypriot farmers of evaporation from farm ponds is probably a loss of around CY£ 5,180 per year, but losses might be as high as CY£ 35,000 per year. Since this translates to a loss to the individual farmer of less than CY£ 1 per year, the problem of evaporation from farm ponds does not seem to be significant.

Chapter 5 SOUTHERN CONVEYOR PROJECT OPERATION SIMULATION

Estimates of the average annual quantities of water lost to evaporation were presented in Chapter 4. These calculations are useful as initial estimates of the magnitude of losses caused by evaporation into the atmosphere. However, as stated, the major limiting assumption is that the surface areas of the reservoirs remain constant. This is an unrealistic condition for reservoirs which function for irrigation and domestic water supply. Withdrawals from the reservoir, as well as losses, will act to lower the reservoir level and thus decrease the surface area, while inflows will raise the water level and increase the surface area. In Cyprus in particular, withdrawals and inflows come at different times of the year, so reservoir levels will tend to fluctuate. Droughts also have an effect since withdrawals will exceed inflows causing storage and thus surface area to decrease over a multi-year period. As shown in Chapter 4, evaporation losses are directly related to the surface area over which evaporation occurs. It is therefore necessary to have a more accurate way of estimating the surface areas of reservoirs.

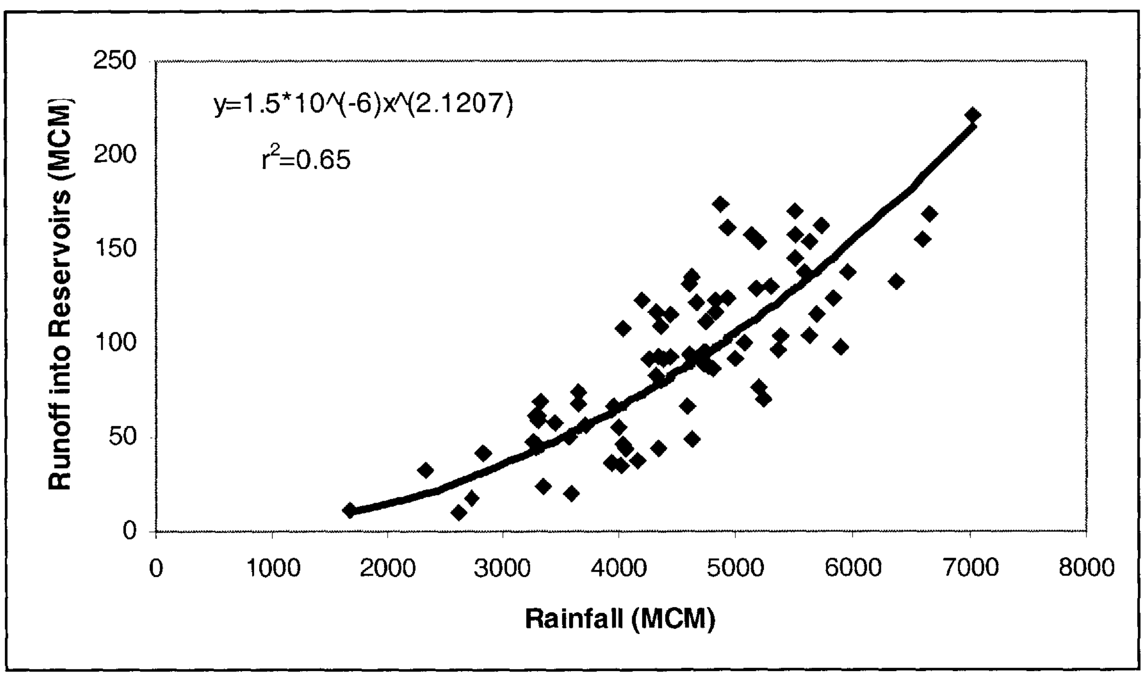
5.1 Baseline Operation Simulation

An operation simulation is one way of estimating the change in reservoir surface area over time. An operation simulation is simply a method of tracking all the inflows to and outflows from a reservoir or system of reservoirs. Once all inflows and outflows in the system are accounted for, the difference between the two is either added or subtracted from reservoir storage. Reservoir storage can then, in turn, be related to depth and surface area. After completing the computations for one time step, the entire process is repeated for the next time step, and so on.

In the following operation simulation, the SCP will be considered as a whole, and it will be assumed that inflows and outflows are divided proportionally between all the reservoirs within the system. The simulation time step will be defined as one year. The variables used in the reservoir simulation are defined as follows:

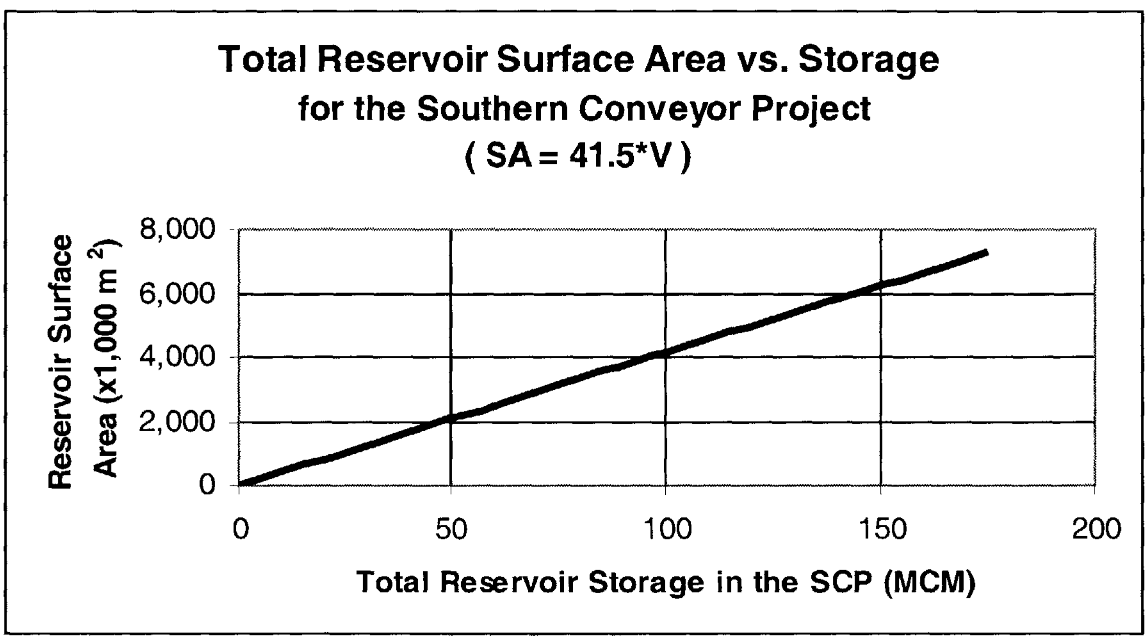
1. Rainfall (mm): Rainfall is the primary source of input into the system of reservoirs. Rain falls on to the watersheds above the dams and runs off into the rivers which supply the reservoirs. Rainfall is generally a difficult variable to define for an operations simulation since it is a random, stochastic variable. For this simulation, the actual historic rainfall data shown in Figure 2.4 will be used. A significant amount of data is available, and being actual measurements, the data require no manipulation. Because there are 81 years of historic data, the simulation will have 81 time steps.
2. Rainfall (MCM): The units of rainfall may be converted to MCM by multiplying the annual depth of rain by the total area of the watershed.
3. Inflow to Dams (MCM): Not all the rain that falls in a watershed above a dam actually ends up being stored in a reservoir. Much, if not most, of the water is evaporated, transpired, or infiltrated long before it has a chance to flow into a reservoir. Therefore, it is necessary to establish a relationship between rainfall and runoff by plotting historic data and fitting a curve as shown in Figure 5.1. Rainfall and runoff data is from the WDD (World Bank, 1996).

FIGURE 5.1
RAINFALL - RUNOFF RELATIONSHIP FOR THE SCP



4. Evaporation (MCM): Evaporation is the variable of interest in the simulation, but it is also an outflow from the reservoir system which in turn affects the simulation. This simulation uses a weighted average of the mean annual lake evaporation rates for each of the reservoirs in the SCP. Evaporation rates were found using Figure 3.5, and the average (weighted by surface areas) was determined to be 1,295 mm per year. Equation 4.1 is used to calculate the total volume of evaporation. Here the simulation uses the storage in the previous time step to compute the total surface area of all reservoirs in the system. The computed surface area is then input into Equation 4.1 and multiplied by the average evaporation rate to find the total annual evaporation from the system. The assumed relationship of total surface area to total storage was inferred from the generalized shape of reservoir area and capacity curves. Normally surface area and reservoir capacity are related to depth by some form of exponential curve and related to each other by a generally linear function. The assumed relationship of total SCP reservoir surface area to total reservoir storage volume is shown in Figure 5.2. Based on the storage in the previous simulation time step, the surface area and thus evaporation is calculated. The total volume of evaporation is treated as an outflow during the current time step.

FIGURE 5.2
TOTAL RESERVOIR SURFACE AREA vs. STORAGE IN THE SCP



5. River Diversion (MCM): This input is from runoff which is not stored but is diverted directly from a river into the system or another river. The major example in the SCP is the Dhiarizos Diversion. The inflow available from diversion is related to runoff and thus rainfall. Input from river diversion is assumed to be 0.5% of total rainfall, with a maximum flow of 20 MCM. This assumption is based on historic diversion flow rates data given in the World Bank report (1996).
6. Groundwater (MCM): Groundwater inputs come from pumping wells and capturing springs. For the purposes of sustainability, this simulation links the rate of groundwater extraction to potential recharge from runoff. Safe groundwater yield is taken to be 0.65% of total rainfall with a maximum extraction rate of 35 MCM (World Bank, 1996).
7. Wastewater Reuse and Desalination (MCM): Currently waste water reuse is approximately 3 MCM and desalination is almost 15 MCM. This term is taken to be constant at 18 MCM (World Bank, 1996).
8. M&I Demand: Current estimated domestic demand in the SCP, including municipal, industrial, and tourist uses, is estimated at 49 MCM. It is assumed that demand is constant and the price of water remains unchanged.
9. Irrigation Demand: The present full irrigation demand in the SCP is 91 MCM. The simulation assumes the full demand is met whenever possible and does not account for rationing. Price and demand are assumed constant.
10. Change in Storage (MCM): This term is the net difference between all inflows and outflows. A positive number indicates an increase in storage for the year while a negative value indicates a decrease in storage.
11. Storage (MCM): This term shows the total volume of water stored in all reservoirs in the SCP at the end of the current time step (year). Storage may not drop below 0 MCM nor go above the maximum capacity of 174 MCM.

All inflows, outflows, storage volumes, and evaporation rates for the entire simulation period are shown in Table 5.1. The results of the SCP operation simulation using historic, deterministic data and evaporation rates are shown in Figure 5.3. Total quantities of water lost to evaporation in each year are displayed on Figure 5.4.

TABLE 5.1
SCP RESERVOIR OPERATION SIMULATION

Sim Yr.	Rain fall (mm)	Rainfall (MCM)	Inflow to Dams (MCM)	**Evapor-ation (MCM)**	River Diversion (MCM)	Ground -water (MCM)	Waste-water Reuse and Desal-ination (MCM)	M&I Demand (MCM)	Irrigation Demand (MCM)	Change in Storage (MCM)	**Storage (MCM)**
1	354	3274.50	42.72	**1.00**	16.37	21.28	18	49	91	-42.62	**0.00**
2	433	4005.25	65.49	**0.00**	20.00	26.03	18	49	91	-10.47	**0.00**
3	523	4837.75	97.75	**0.00**	20.00	31.45	18	49	91	27.19	**27.19**
4	644	5957.00	151.98	**1.46**	20.00	35.00	18	49	91	83.52	**110.72**
5	540	4995.00	104.61	**5.95**	20.00	32.47	18	49	91	29.13	**139.84**
6	472	4366.00	78.64	**7.52**	20.00	28.38	18	49	91	-2.50	**137.34**
7	560	5180.00	113.00	**7.38**	20.00	33.67	18	49	91	37.29	**174.00**
8	454	4199.50	72.41	**9.35**	20.00	27.30	18	49	91	-11.64	**162.36**
9	428	3959.00	63.90	**8.73**	19.80	25.73	18	49	91	-21.30	**141.06**
10	713	6595.25	188.60	**7.58**	20.00	35.00	18	49	91	114.02	**174.00**
11	468	4329.00	77.23	**9.35**	20.00	28.14	18	49	91	-5.98	**168.02**
12	395	3653.75	53.90	**9.03**	18.27	23.75	18	49	91	-35.11	**132.90**
13	562	5198.50	113.86	**7.14**	20.00	33.79	18	49	91	38.50	**171.41**
14	720	6660.00	192.55	**9.21**	20.00	35.00	18	49	91	116.33	**174.00**
15	610	5642.50	135.47	**9.35**	20.00	35.00	18	49	91	59.12	**174.00**
16	251	2321.75	20.61	**9.35**	11.61	15.09	18	49	91	-84.05	**89.95**
17	296	2738.00	29.23	**4.83**	13.69	17.80	18	49	91	-66.12	**23.84**
18	402	3718.50	55.95	**1.28**	18.59	24.17	18	49	91	-24.57	**0.00**
19	615	5688.75	137.83	**0.00**	20.00	35.00	18	49	91	70.83	**70.83**
20	511	4726.75	93.05	**3.81**	20.00	30.72	18	49	91	17.97	**88.81**
21	527	4874.75	99.34	**4.77**	20.00	31.69	18	49	91	24.26	**113.06**
22	516	4773.00	95.00	**6.08**	20.00	31.02	18	49	91	17.94	**131.00**
23	596	5513.00	128.96	**7.04**	20.00	35.00	18	49	91	54.92	**174.00**
24	500	4625.00	88.86	**9.35**	20.00	30.06	18	49	91	7.57	**174.00**
25	360	3330.00	44.27	**9.35**	16.65	21.65	18	49	91	-48.78	**125.22**
26	534	4939.50	102.16	**6.73**	20.00	32.11	18	49	91	25.54	**150.75**
27	620	5735.00	140.22	**8.10**	20.00	35.00	18	49	91	65.12	**174.00**
28	498	4606.50	88.11	**9.35**	20.00	29.94	18	49	91	6.70	**174.00**
29	595	5503.75	128.50	**9.35**	20.00	35.00	18	49	91	52.15	**174.00**
30	482	4458.50	82.21	**9.35**	20.00	28.98	18	49	91	-0.16	**173.84**
31	467	4319.75	76.88	**9.34**	20.00	28.08	18	49	91	-6.39	**167.45**
32	498	4606.50	88.11	**9.00**	20.00	29.94	18	49	91	7.05	**174.00**
33	511	4726.75	93.05	**9.35**	20.00	30.72	18	49	91	12.43	**174.00**
34	580	5365.00	121.73	**9.35**	20.00	34.87	18	49	91	45.25	**174.00**
35	355	3283.75	42.98	**9.35**	16.42	21.34	18	49	91	-50.61	**123.39**
36	605	5596.25	133.12	**6.63**	20.00	35.00	18	49	91	59.49	**174.00**
37	596	5513.00	128.96	**9.35**	20.00	35.00	18	49	91	52.61	**174.00**
38	506	4680.50	91.13	**9.35**	20.00	30.42	18	49	91	10.21	**174.00**
39	533	4930.25	101.76	**9.35**	20.00	32.05	18	49	91	22.45	**174.00**

TABLE 5.1 (CONT.)

Sim Yr.	Rain fall (mm)	Rainfall (MCM)	Inflow to Dams (MCM)	**Evaporation (MCM)**	River Diversion (MCM)	Groundwater (MCM)	Wastewater Reuse and Desalination (MCM)	M&I Demand (MCM)	Irrigation Demand (MCM)	Change in Storage (MCM)	**Storage (MCM)**
40	515	4763.75	94.61	**9.35**	20.00	30.96	18	49	91	14.22	**174.00**
41	394	3644.50	53.61	**9.35**	18.22	23.69	18	49	91	-35.83	**138.17**
42	474	4384.50	79.34	**7.43**	20.00	28.50	18	49	91	-1.58	**136.59**
43	357	3302.25	43.49	**7.34**	16.51	21.46	18	49	91	-47.87	**88.72**
44	358	3311.50	43.75	**4.77**	16.56	21.52	18	49	91	-44.93	**43.79**
45	437	4042.25	66.78	**2.35**	20.00	26.27	18	49	91	-11.30	**32.49**
46	608	5624.00	134.53	**1.75**	20.00	35.00	18	49	91	65.78	**98.27**
47	557	5152.25	111.72	**5.28**	20.00	33.49	18	49	91	37.93	**136.20**
48	306	2830.50	31.37	**7.32**	14.15	18.40	18	49	91	-65.40	**70.79**
49	522	4828.50	97.35	**3.80**	20.00	31.39	18	49	91	22.93	**93.73**
50	469	4338.25	77.58	**5.04**	20.00	28.20	18	49	91	-1.26	**92.47**
51	688	6364.00	174.85	**4.97**	20.00	35.00	18	49	91	102.88	**174.00**
52	462	4273.50	75.14	**9.35**	20.00	27.78	18	49	91	-8.43	**165.57**
53	759	7020.75	215.34	**8.90**	20.00	35.00	18	49	91	139.44	**174.00**
54	373	3450.25	47.73	**9.35**	17.25	22.43	18	49	91	-43.94	**130.06**
55	501	4634.25	89.23	**6.99**	20.00	30.12	18	49	91	10.37	**140.43**
56	387	3579.75	51.61	**7.55**	17.90	23.27	18	49	91	-36.77	**103.66**
57	182	1683.50	10.42	**5.57**	8.42	10.94	18	49	91	-97.79	**5.87**
58	389	3598.25	52.18	**0.32**	17.99	23.39	18	49	91	-28.76	**0.00**
59	567	5244.75	116.01	**0.00**	20.00	34.09	18	49	91	48.11	**48.11**
60	563	5207.75	114.29	**2.59**	20.00	33.85	18	49	91	43.55	**91.66**
61	471	4356.75	78.28	**4.93**	20.00	28.32	18	49	91	-0.32	**91.33**
62	549	5078.25	108.34	**4.91**	20.00	33.01	18	49	91	34.44	**125.77**
63	439	4060.75	67.43	**6.76**	20.00	26.39	18	49	91	-14.93	**110.84**
64	582	5383.50	122.62	**5.96**	20.00	34.99	18	49	91	49.66	**160.50**
65	574	5309.50	119.07	**8.63**	20.00	34.51	18	49	91	42.96	**174.00**
66	425	3931.25	62.95	**9.35**	19.66	25.55	18	49	91	-23.19	**150.81**
67	436	4033.00	66.46	**8.10**	20.00	26.21	18	49	91	-17.43	**133.38**
68	451	4171.75	71.40	**7.17**	20.00	27.12	18	49	91	-10.65	**122.73**
69	496	4588.00	87.36	**6.60**	20.00	29.82	18	49	91	8.58	**131.31**
70	435	4023.75	66.14	**7.06**	20.00	26.15	18	49	91	-16.77	**114.54**
71	520	4810.00	96.56	**6.16**	20.00	31.27	18	49	91	19.67	**134.22**
72	631	5836.75	145.55	**7.21**	20.00	35.00	18	49	91	71.34	**174.00**
73	480	4440.00	81.49	**9.35**	20.00	28.86	18	49	91	-1.00	**173.00**
74	362	3348.50	44.80	**9.30**	16.74	21.77	18	49	91	-47.99	**125.00**
75	282	2608.50	26.38	**6.72**	13.04	16.96	18	49	91	-72.34	**52.66**
76	637	5892.25	148.50	**2.83**	20.00	35.00	18	49	91	78.67	**131.33**
77	509	4708.25	92.28	**7.06**	20.00	30.60	18	49	91	13.83	**145.16**
78	417	3857.25	60.47	**7.80**	19.29	25.07	18	49	91	-24.98	**120.18**
79	493	4560.25	86.24	**6.46**	20.00	29.64	18	49	91	7.42	**127.61**
80	383	3542.75	50.49	**6.86**	17.71	23.03	18	49	91	-37.63	**89.98**
81	399	3690.75	55.06	**4.84**	18.45	23.99	18	49	91	-29.33	**60.65**
82	388	3589.00	51.89	**3.26**	17.95	23.33	18	49	91	-32.09	**28.56**

FIGURE 5.3
SIMULATED SCP STORAGE OVER TIME

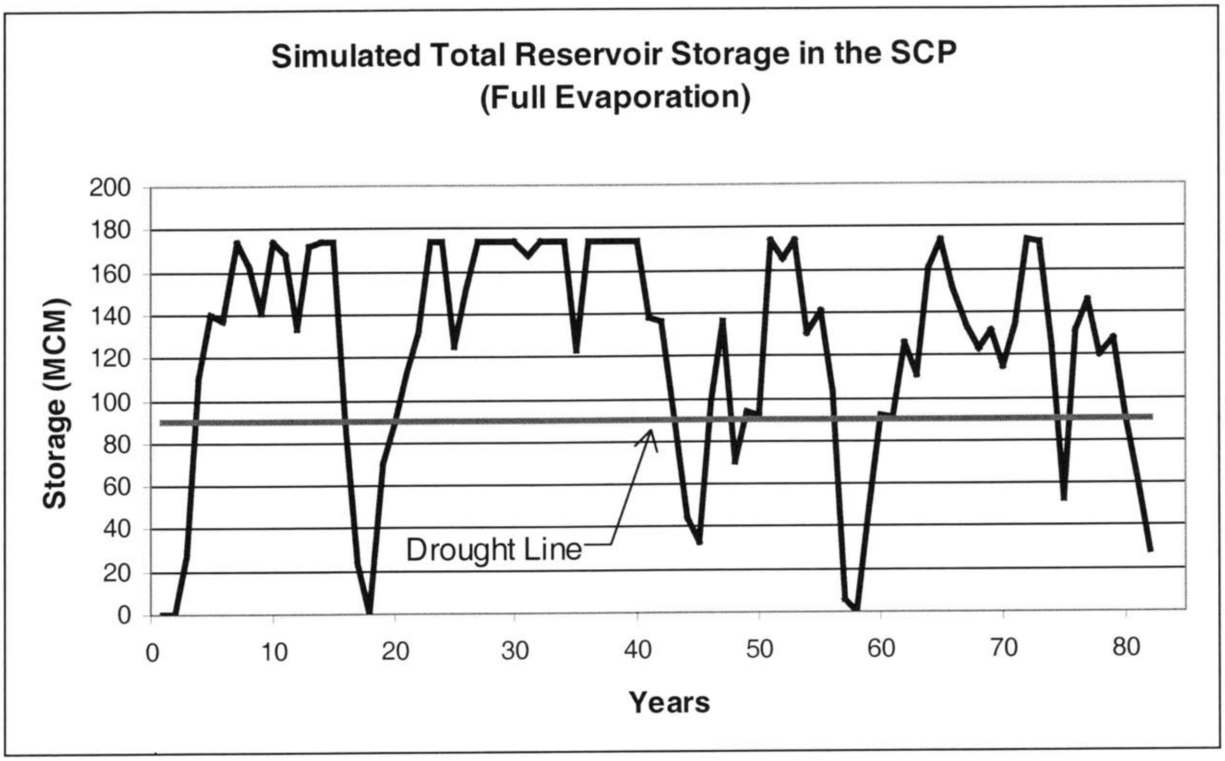
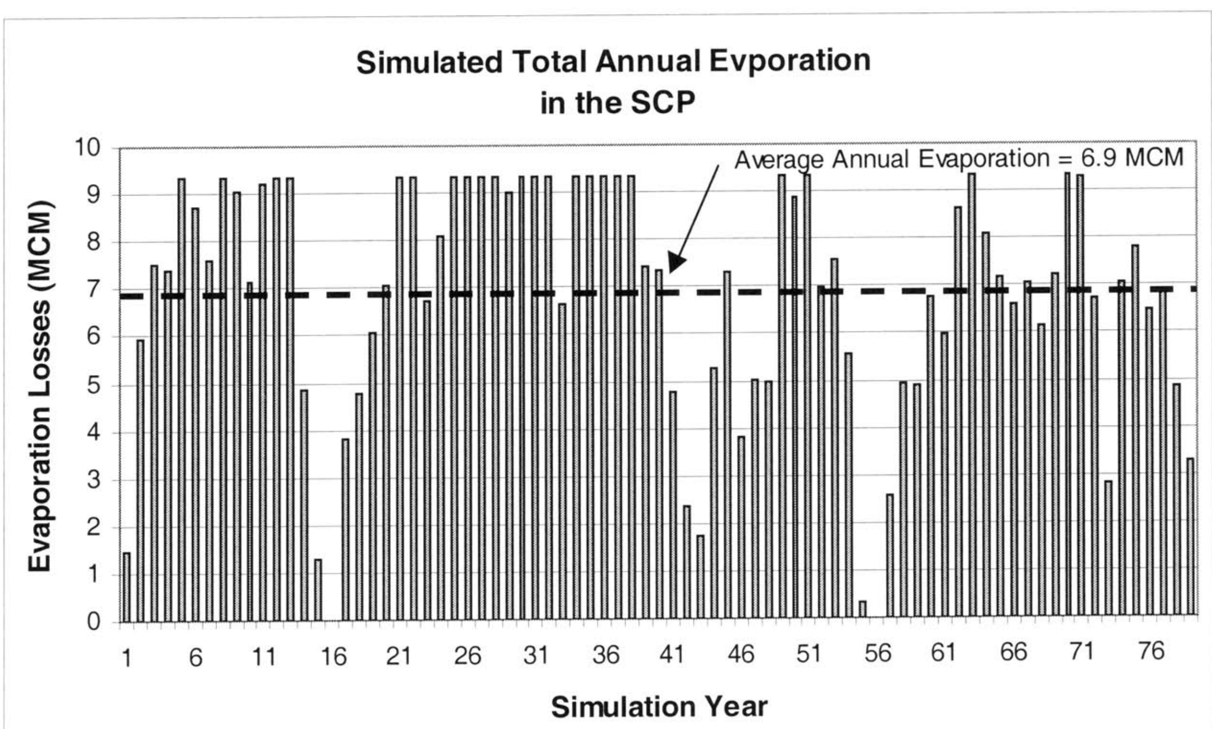


FIGURE 5.4
SIMULATED SCP ANNUAL EVAPORATION OVER TIME



With evaporation occurring at normal, unreduced rates, the reservoir simulation predicts average losses to evaporation from the entire SCP are 6.9 MCM per year. The average storage in SCP reservoirs, based on these losses, is approximately 127 MCM (73% of maximum capacity). However, total storage dropped below the 90 MCM drought level over 20% of the time. The drought level was set at 90 MCM because that is the minimum carry-over storage required to insure that all demands are met in the next year even if no rain falls (assuming 50 MCM from desalination, wastewater reuse, and groundwater (over) pumping.) During the drought years, the average storage was just over 50 MCM.

5.2 Benefits of Evaporation Reduction

The operation simulation also allows an examination of the consequences of evaporation reduction in a dynamic system. If the evaporation term is reduced by a given percentage and the simulation re-run, the benefits of a specific level of evaporation reduction can be assessed. The consequences of evaporation reduction are not entirely obvious since a reduction of total loss in one year may lead to increased evaporation in the next year due to increased storage and larger surface area. By examining the amount of water conserved through evaporation reduction, as well as the increased system reliability gained, it is possible to evaluate the potential benefits of evaporation reductions of various levels.

The SCP reservoir operation simulation was run repeatedly with varying degrees of evaporation reduction. Reduction within the operation model was accomplished by affixing a reduction coefficient to the evaporation rate. The specific method by which the reductions are accomplished are discussed in Chapter 6. Table 5.2 and Figures 5.5 through 5.7 detail the operational statistics for the SCP simulation for various degrees of evaporation reduction.

TABLE 5.2
SCP OPERATION SIMULATION WITH EVAPORATION RATE REDUCTION

Evaporation Rate Reduction	Average Evaporation (MCM)	Reduction of Evaporation (MCM)	Average Storage (MCM)	Increase in Average Storage (MCM)	Incidence of Drought	Average Storage in Drought Years (1) (MCM)	Increase in Average Storage in Drought Years (MCM)
0%	6.9	0.0	126.9	0.0	20.3%	49.7	0.0
10%	6.3	0.6	128.3	1.5	16.5%	51.9	2.3
20%	5.6	1.3	129.7	2.9	15.2%	54.2	4.5
30%	5.0	1.9	131.2	4.3	15.2%	56.6	6.9
40%	4.3	2.6	132.6	5.8	15.2%	59.0	9.3
50%	3.6	3.3	134.1	7.3	13.9%	61.5	11.8
60%	2.9	3.9	135.6	8.8	12.7%	64.0	14.3
70%	2.2	4.7	137.2	10.3	12.7%	66.7	17.0
80%	1.5	5.4	138.7	11.9	12.7%	69.4	19.7
90%	0.8	6.1	140.6	13.7	12.7%	72.6	22.9
100%	0.0	6.9	142.3	15.5	12.7%	75.8	26.1

(1) Based on drought years predicted when no evaporation reduction occurs

FIGURE 5.5
SIMULATION-PREDICTED EFFECTS OF ANNUAL EVAPORATION RATE REDUCTION ON TOTAL EVAPORATION FROM SCP RESERVOIRS

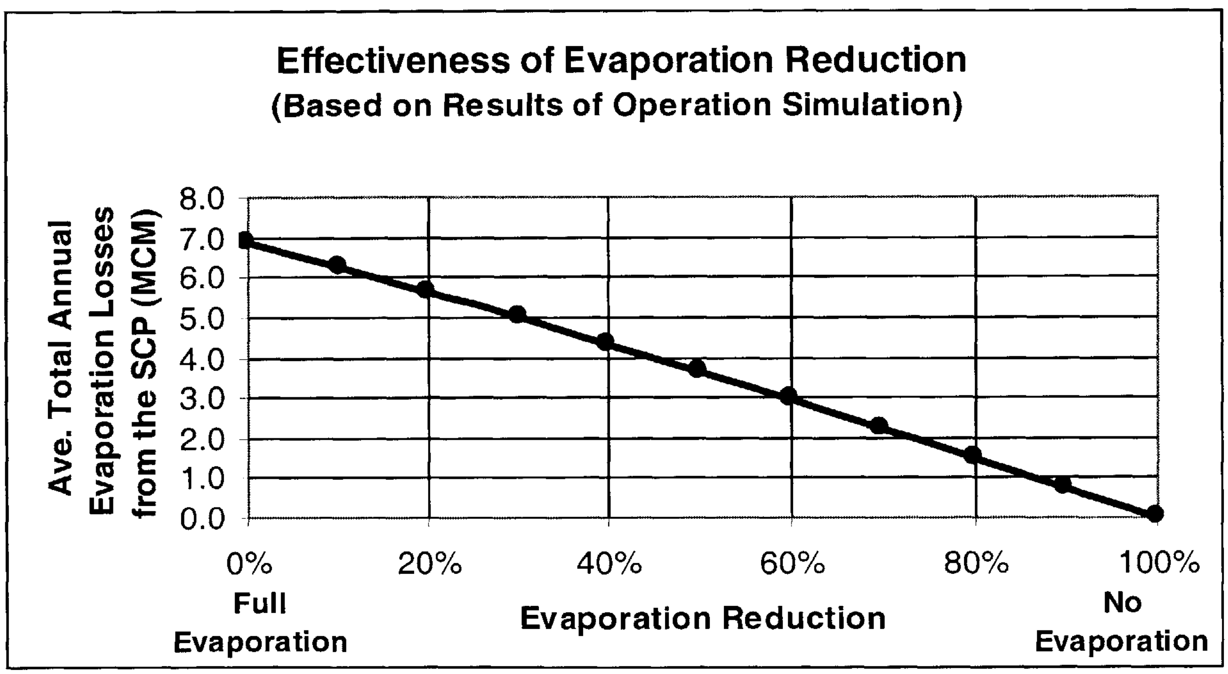


FIGURE 5.6
SIMULATION-PREDICTED EFFECTS OF EVAPORATION RATE REDUCTION ON FREQUENCY OF DROUGHT IN THE SCP

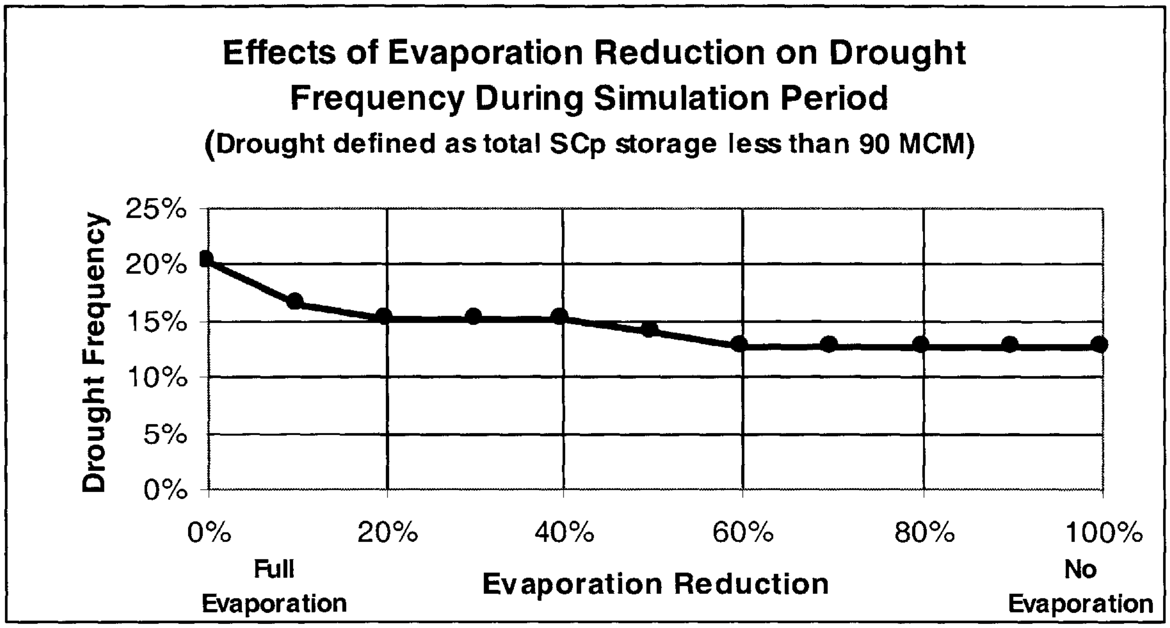
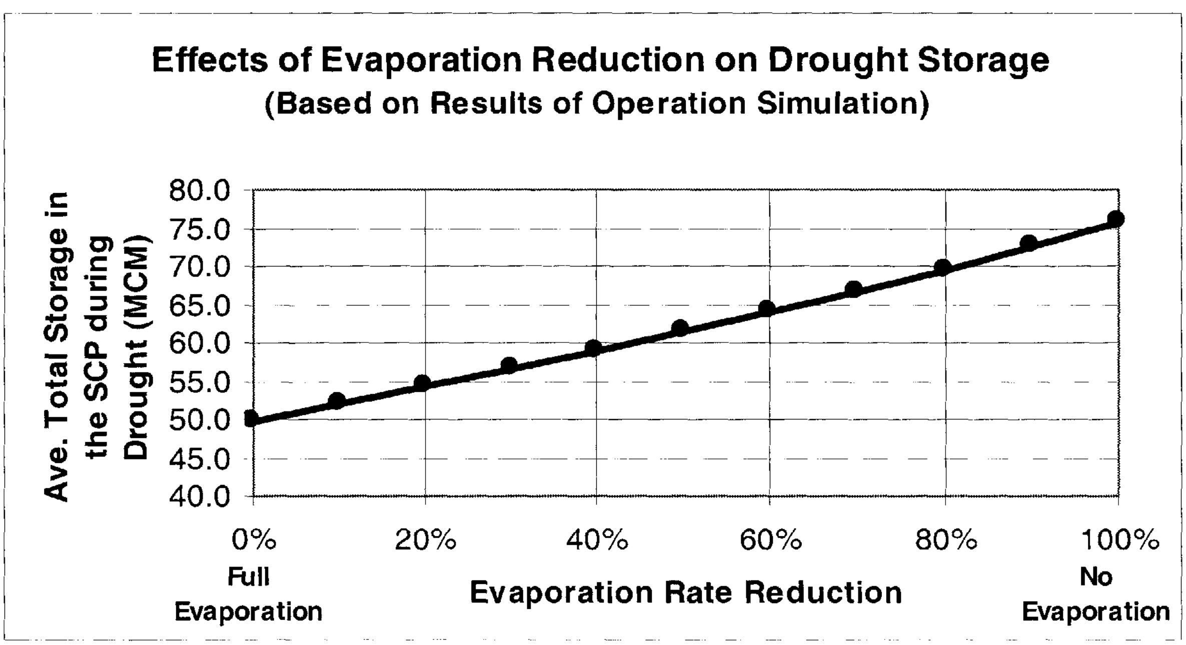


FIGURE 5.7
SIMULATION-PREDICTED EFFECTS OF EVAPORATION RATE REDUCTION ON TOTAL SCP STORAGE DURING DROUGHTS



Examination of the previous table and figures reveals that there is some feedback in the reduction of evaporation rates. The effect is very small but it may be seen in Figure 5.5 that reducing the evaporation rate by 50% leads to a reduction in the total losses to evaporation of slightly less than half (47.3%). The surface area feedback effect does not appear to be of serious consequence to the effectiveness of evaporation reduction (at least when the simulation is run using a one-year time step.)

On the other hand, the quantity of water saved by evaporation rate reduction is potentially substantial. This windfall of extra water might be utilized in two ways. It could be used immediately to supplement supply. In other words, water conserved due to evaporation reduction could be considered as an addition to a reservoir's firm yield. In this case the conserved water could be withdrawn in the same year and used to meet increasing demand or as a substitute for groundwater. If this is done, the surface area feedback is eliminated since no extra water would be left in storage at the end of a year, and groundwater is not subject to evaporation. Alternatively, evaporation reduction could be used to provide added reliability against droughts. All water conserved by evaporation reduction would be left in the reservoirs to provide extra storage, which is the case in the simulations. This extra storage is then available for withdrawal during years when rainfall is below normal. Under normal conditions the probability of the occurrence of a drought (storage below 90 MCM) is over 20%. When evaporation is reduced, the probability of drought is also reduced as shown in Figure 5.6.

If the years in which drought occurs when there is no evaporation reduction are considered "normal drought years," then the average storage during these normal drought years is one way of estimating the severity of the droughts. As shown in Figure 5.7, with evaporation reduction, the average storage in the original "normal drought years" increases with evaporation reduction. This indicates that evaporation reduction can reduce the severity of droughts and thus decrease the need for rationing and other drastic conservation measures.

The economic benefits of evaporation reduction can be estimated by computing the value of the water conserved. Table 5.3 lists the average annual quantities of water conserved by evaporation reduction and the value of that water in terms of capital recovery costs and replacement-by-desalination costs. The values shown are gross benefits because the cost of installation and operation of the evaporation reduction system have not yet been considered.

TABLE 5.3
VALUE OF WATER SAVED BY EVAPORATION REDUCTION AS PREDICTED BY THE SCP OPERATION SIMULATION

Evaporation Rate Reduction	Average Annual Quantity of Water Conserved (MCM / yr)	Value of Water Conserved By Evaporation Reduction (1) (CY£ / yr)	Cost of Water from Desalination (2) (CY£ / yr)
0%	0.0	£0	£0
10%	0.6	£111,680	£260,586
20%	1.3	£226,409	£528,288
30%	1.9	£343,635	£801,816
40%	2.6	£463,366	£1,081,188
50%	3.3	£585,688	£1,366,604
60%	3.9	£710,741	£1,658,395
70%	4.7	£838,644	£1,956,835
80%	5.4	£969,320	£2,261,748
90%	6.1	£1,102,646	£2,572,841
100%	6.9	£1,239,386	£2,891,901

(1) Based on Capital Recovery Cost excluding pumping costs

(2) Based on desalinated water price from most recent BOOT contract

For comparison, based on agricultural demands of 91 MCM and domestic demands of 49 MCM and prices of CY £ 0.07 and CY £ 0.20 respectively, the total gross annual revenue to the WDD from water sales is approximately CY £ 16 million. Based on the gross benefits listed above, the net benefits of evaporation reduction can be estimated once a specific technique is chosen and efficiencies and costs determined.

Chapter 6 POTENTIAL METHODS OF EVAPORATION REDUCTION

Based on the estimates of the amount of water lost to evaporation from ponds and reservoirs and the potential economic value of that water, it is reasonable to seek methods of reducing rates of evaporation. While it is virtually impossible and perhaps unwise to completely eliminate evaporation from all ponds and reservoirs, even a small reduction could prove to be useful and profitable. If evaporation rates in the SCP were reduced by only 10%, this would result in approximately 600,000 extra cubic meters of water annually without the construction of additional reservoirs or desalination plants. This is enough water to supply over 1,100 households or provide for an extra 1,200 tourist-days.

There are potentially several methods of reducing evaporation from surface water reservoirs. These methods seek to control the factors which drive evaporation. Most of these methods, however, have serious drawbacks which significantly limit their usefulness, and most have never been applied on a significant scale.

6.1 Vegetation Control

This is not strictly a method of reducing evaporation -- rather it is a way of controlling *transpiration*. Transpiration is defined as the process by which water in plants is transferred as water vapor to the atmosphere (ASCE, 1996, p. 252). During this process, the roots of a plant draw water from the soil and into the body of the plant. That water then passes upward to the leaves of the plant, where most is lost through the stomata to the air in the form of water vapor. Transpired water comes from the soil. The loss of soil moisture can cause a reduction in the water table which can reduce the amount of groundwater inflow into a pond or reservoir, or even lead to a net outflow of groundwater. Some types of trees have been shown to cause effects to the water table at depths ranging to 20 meters.

All plants transpire, but at very different rates. The potential evapotranspiration, defined as when soil moisture is unlimited, is similar for most plants in a given climate, but such conditions are not the typical case. Under most conditions the ability of plants to draw water from the soil is governed by the size and extent of the root system. In the western part of the United States, observations have shown that water losses by short grasses are as low as 25 cm per year per unit area (2,500 cubic meters per hectare) while losses by Pacific Douglas firs are up to 150 cm per year per unit area (15,000 cubic meters per hectare) (Chow 1964, p. 6-22). Such losses can be controlled through selective planting and cultivation of plantlife along and near the shores of reservoirs. By encouraging the growth of plants which tend to transpire less, the amount of water lost from nearby surface water bodies can be reduced. Experimental clear-cutting of forest land in the U.S. by the U.S. Forest Service led to an average 30% increase in streamflows in the area – in part due to decreased transpiration (Chow 1964, p. 6-24). In extremis, efforts to reduce transpiration might lead to the total removal of all vegetative cover in an area since bare soil loses less water than vegetation. "Under semiarid and arid conditions, transpiration [not direct evaporation] is the main cause of loss of water from soils (Chow 1964, p. 11-20)." Of course, this is not recommended because of the impacts on wildlife, sedimentation rates, downstream flooding, slope stability, micro-climate, aesthetics, etc.

6.2 Surface Area Reduction

The total volume of water lost to evaporation is a function of both the evaporation rate and the area over which evaporation can occur. Therefore, decreasing the reservoir surface area exposed to the atmosphere can reduce evaporation from a body of water. This simple principle is of limited use in reducing evaporation from existing reservoirs but can be applied to the siting of new reservoirs. Alternative reservoir locations may be compared in regards to normal pool surface area. A location that results in a reservoir with a smaller surface area is preferable in regard to minimizing evaporation. All else being equal, a deep reservoir in a steep, narrow canyon or valley will lose less water to evaporation than a broader, more shallow reservoir of equal capacity because of the smaller surface area of the deep reservoir. Constructing a single large reservoir rather than several smaller ones can also generally reduce the surface area-to-storage ratio. Evaporation, however, is only one of many concerns which must be addressed when planning a dam, and most times it will not be the deciding factor. Even if evaporation is a significant decision variable, the value of conserved water might not be enough to justify choosing one site over another. In Cyprus, the point is nearly moot in any case since many of the best dam sites have already been utilized.

Storing water underground in natural aquifers is another way of reducing the amount of water which might potentially be evaporated. Cyprus already has a limited program of groundwater recharge from surface water reservoirs. Significantly more surface water could be stored underground by expanding these schemes and adding injection wells. While aquifer storage leads to reduced losses from evaporation as well as protection from saltwater intrusion, other problems may offset these benefits. Water stored underground requires energy in order to be recovered, and a certain amount of control is forfeited. Water in a surface water reservoir is easily quantified and withdrawals can be easily monitored, but groundwater is subject to extraction by any well which taps the aquifer.

6.3 Radiation Barriers

The use of radiation barriers amounts to essentially shading a reservoir to prevent the interception of incoming solar radiation. This method is extremely effective in reducing evaporation, but its usefulness is limited by the area that needs to be shaded. This method is only practical for ponds or very small reservoirs. High evaporation rates might make replacement of small farm ponds with covered tanks desirable. As shown in Chapter 4, there is little economic incentive for farmers to do so at current water prices, but this assumes that water is available to be purchased to replace that lost to evaporation. During times of severe drought, the amount of water to be allotted to each farmer is fixed, so the utility of conserving water might go up high enough to justify covering small farm irrigation ponds.

6.4 Floating Covers

A cover floating on the surface of a reservoir decreases the area of the water exposed to the atmosphere and therefore reduces evaporation. Covers also prevent direct heating of water by solar radiation, thus decreasing water temperature and slowing evaporation. Covers may be made out of a variety of materials ranging from wood, bamboo, wax, plastic, or polystyrene. Plants such as lily pads have also been proposed. When such a cover is made of a material with a highly reflective surface to reflect incoming solar radiation, floating covers have been shown to reduce evaporation by up to 95% (Jones, 1992, p. 170). Covers may be rigid or flexible and may consist of a single unit or multiple pieces connected together.

This significant reduction in evaporation must be weighted against the side effects of floating covers. There are clearly drawbacks to covering the entire surface of any body of water. It may be overly expensive or physically impossible to deploy floating covers on large reservoirs. Even on small bodies of water maintenance of the covers might be difficult. A floating cover would need to be secured in place so as not to float out of position or blow away, but it would also need to be able to move up and down with the water surface. Floating covers also limit the use of the lake surface for navigation, fishing, recreation, and by wildlife. The covers might also interfere with diffusion of oxygen into the lake and therefore be harmful to fish and other wildlife. The covers would also interfere with photosynthesis by aquatic plants and algae. Application of floating covers seems limited to the same types of situations where radiation barriers could be applied and subject to the same caveats. Since floating covers do not need to span above the water, they may be more economical than radiation barriers when applied to larger ponds.

6.5 Wind Barriers

One of the two prime factors in evaporation from a free water surface is the rate at which water vapor is transported away from the water body. Atmospheric advection, i.e. wind, plays the key role in the transport of evaporated water vapor. This is the theory behind the aerodynamic methods for calculating evaporation presented in Chapter 3. It is therefore possible that if wind speeds over a reservoir surface can be reduced, the rate of water vapor transport can be slowed and thus evaporation reduced. Physical barriers may be placed around and/or in a reservoir to block, slow, or divert the wind. Wind barriers may be in the form of walls, earthen berms, or trees and other vegetation (though these may increase transpiration.) Wind barriers should be situated to take advantage of the natural topography and block the prevailing winds. Wind barriers on the shore are definitely a feasible option; however, as the open water fetch of the lake increases, the effectiveness of these barriers decreases. Thus the effectiveness of on-shore wind breaks is probably inversely proportional to the surface area of a reservoir, even thought the per unit area cost of the berms would decrease. One study found that non-vegetable wind barriers around small reservoirs could reduce evaporation by 9% when the average wind speed was 16 kph (Frenkiel 1965, p. 66). It is possible that baffles might be constructed across or in a reservoir. Such barriers might be installed on piers set into the reservoir bottom or on moored rafts. The cost of wind barriers within the perimeter of a reservoir might be an issue, and such barriers would cause some of the same problems as floating covers, in terms of navigation, wildlife, and aesthetics.

6.6 Multimolecular Films

When hydrocarbon oils are introduced onto the surface of a body of water, they form a film across the surface of the water. Oils, which float on top of water due to the density difference, form layers that are multimolecular in thickness. A film of oil floating on the surface of water retards evaporation due to the slow rate of diffusion of water through the oil film. Thin multimolecular oil films may be formed on a water surface with the aid of chemical spreading agents. Experiments with multimolecular films as thin as 5 microns produced evaporation reductions of up to 85% in the lab. Field trials have not been as successful (Frenkiel 1965, p. 14-15). Wind, waves, rain, and dust easily damage oil films. The films easily break up and then do not reform, and most oils are subject to chemical and biological degradation. Of even greater concern is the toxicity of oils to plants, animals, and humans. Conserving water is pointless if the water becomes unusable. For these reasons, multimolecular oil films are not in use for evaporation reduction from ponds and reservoirs.

6.7 Monomolecular Films

Monomolecular films make use of alcohols or organic acids to coat the surface of a body of water. But unlike the oils described in the previous section, these films are only a single molecule in thickness. The existence of monomolecular films has been recognized since the early 20th Century. Investigations into their structure began soon after. The polar molecules which form monolayers consist of one end which is hydrophobic (water-repelling) and one end which is hydrophilic (water-attracting). When such molecules are spread on a water surface, molecular-level forces cause the hydrophilic end to submerge into the water while the hydrophobic end remains out of the water (Frenkiel 1965, p. 13). This causes the individual molecules to literally stand on-end and form a film which is so tight that water molecules cannot penetrate nor escape from it. Monomolecular films are for the most part, however, pervious to oxygen and carbon dioxide; therefore, the films do not inhibit normal gas exchange between the water and the atmosphere (Chow, 1964, p. 11-15).

Monomolecular films have the ability to significantly reduce evaporation. Theoretical reduction factors have been estimated at up to 60%. Experiments in the laboratory have proven the ability of monofilms to inhibit evaporation. In 1925, experiments were conducted using an inverted U-tube. The surface of the water in one arm of the tube was coated with a monomolecular film. The other arm of the tube was cooled in an ice bath. Evaporation was measured by collection of the condensate from the cooled end of the tube. When compared to the same experiment using just water and no film, evaporation was found to be reduced by as much as 50% (Frenkiel 1965, p. 14). While these results are encouraging, field testing has not been able to obtain reduction rates of the same magnitude.

Compounds used to form monomolecular films include long-chain alcohols, and oleic and stearic acids – or so-called fatty acids (Jones, 1992, p. 109). Typical film-forming materials include hexadecanol and octadecanol. When these types of materials are to be applied to sources of potable water, there is concern about potential toxicity to humans. Effects on plant and animal life are also a concern. Early research concluded that these films do not produce harmful effects to either humans or other plant and animal life. Before full-scale tests of monofilms were conducted in Lake Hefner, the main water supply reservoir of Oklahoma City in the U.S. (the author's home city), a statement was issued which discounted possible health effects. The statement, issued by the U.S. Public Health Department among others, stated, "Insofar as criteria of water quality including taste, odor, color, toxicity, and other chemical qualities are concerned nothing has been determined from this study to preclude further consideration of Lake Hefner for large-scale evaporation reduction investigation (Frenkiel 1965, p. 35)." It should be noted however that these tests were conducted 40 years ago. Since then, public health standards have become stricter, and chemical detection and analysis technology has improved greatly. Even in the 1950's, there was concern about possible degradation products of materials such as hexadeconal when exposed to actual environmental conditions.

Formation of an evaporation-inhibiting film is not in itself enough to lead to evaporation reduction in the field. Obviously, the film must float and be capable of spreading evenly over the surface of a body of water. The film must then be robust and resistant to degradation by the action of wind, waves, sunlight, dust, biological degradation (which has been found to be especially destructive to monolayers), and disturbance by wildlife. Monomolecular films tend to be more robust than multimolecular films, but they are still subject to loss of effectiveness over time. Degradation due to these factors requires that monolayer film producing agents be repeatedly or continuously applied in order to maintain the integrity of the film.

Several methods of monolayer application and spreading have been studied. Petroleum based solvents have been proposed as a spreading agent, but were rejected in the U.S. due to concerns about toxicity and flamability. Several American and Australian field studies had reasonable success in applying the film-producing material in powder form with a boat-mounted agricultural duster. Fatty alcohols or acids may be applied as an emulsion or slurry using water as the suspending agent. Application may be made from a boat or barge. Another way of applying emulsions and slurries is by pumping the liquid into the reservoir through perforated hoses. Hot spray application has been shown in field tests to be one of the most effective application methods. Film-producing material is melted in tanks and then sprayed through nozzles mounted on the shore of the lake or on fixed barges. Individual dispensers are activated based on wind speed and direction in order to maximize the dispersion of the spray over the water surface. The U.S. Bureau of Reclamation sponsored several tests of applying evaporation retarding chemicals to large reservoirs from aircraft. The initial results of these trails were favorable in terms of cost effectiveness but inconclusive in terms of evaporation reduction efficiency (Frenkiel 1965, p. 40-48).

Field testing of monomolecular layers has been conducted at the evaporation pan scale as well as on ponds and reservoirs. Much of this testing was conducted in the late 1950's and early 1960's. A review of the tests shows that the apparent evaporation reductions vary widely. Results from pan tests ranged from 25% to 64% reduction efficiency. Tests on ponds and reservoirs generally indicated that expected evaporation reductions are somewhat less. On small ponds, the results ranged from no reduction when very windy conditions were encountered to average reductions of up to 27% under better conditions. Large scale tests of monomolecular layers in the U.S. were conducted in Oklahoma and Arizona – both arid states. The average evaporation reduction at Sahuaro Lake in Arizona was 14%. The study at Lake Hefner in Oklahoma in 1958 was perhaps the most comprehensive investigation of evaporation suppression using monomolecular layers. The total average saving of evaporation over the 86-day test period was found to be 9% (Frenkiel 1965, p. 29-37).

Information about the cost of evaporation reduction through the use of monomolecular films is required to evaluate the overall economic feasibility of the procedure. Information from the test in the United States suggests that the cost of evaporation reduction at Sahuaro Lake and Lake Hefner averaged around US$ 0.05 to US$ 0.055 per cubic meter of water saved (approximately CY£ 0.03/m^3) in the late 1950's. Converting to today's currency using U.S. Bureau of Labor Statistics figures, the cost of this process would be equivalent to US$ 0.27 to US$ 0.30 per cubic meter (approximately CY£ 0.15/m^3). The cost data from the U.S. apply to evaporation reduction from large reservoirs. The cost of evaporation reduction per unit of water saved may be greater for smaller reservoirs and ponds due to fixed costs for application machinery. In addition, there is evidence that more film-producing material is needed per unit area for a small pond due to film losses resulting from the larger perimeter to surface area ratio. Some estimates are that the cost of water saved might increase by an order of magnitude or more (approximately CY£ 1.50/m^3 or more).

6.7.1 Cypriot Experiences with Monomolecular Films

The use of monomolecular films for evaporation reduction has been proposed quite recently in Cyprus. Cypriot hydrologists and engineers are aware of the problem of evaporation losses from surface reservoirs and its general magnitude. Dr. George Socratous, director of the Water Development Department, stated:

> "My experience is that the volume of evaporated water from water surfaces (i.e. reservoirs) in Cyprus is about 7% of the volume of water stored in the reservoirs. A rough calculation reveals that the total evaporated water from the existing dams is 10-12 MCM per year."
>
> (Socratous, 4/23/99, personal correspondence)

This estimate of evaporation is basically in line with the calculations made in Chapter 5 of this report. Knowing the extent of the problem, there is interest among the Cypriots in attempting to artificially reduce evaporation rates and thus conserve water. In a report on measures for combating drought in Cyprus, Socratous states that it may be possible to:

> "Suppress evaporation from irrigation ponds by using a thin layer of fatty alcohol. Suppression is as high as 25% -45%, while the cost is as low as CY£ 0.08/m^3 of saved water."
>
> (Socratous 1998, p. 4)

Currently, monomolecular layers are the preferred hypothetical method of evaporation reduction in Cyprus. The use of monolayers is still in development though, and has not yet reached the reservoir trial stage, but smaller scale experimentation has been carried out. Mr. Iacovos St. Iacovides, head of the Division of Hydrology for the WDD, has described the state of research and development of evaporation reduction in Cyprus as follows:

> "Our experimentation on evaporation suppression with fatty alcohols has been limited to the evaluation of evaporation reduction in Class A pans. Continuous introduction of this substance on a daily basis over two years has resulted in an overall reduction of evaporation by 50%. Following this experiment, we introduced fatty alcohols in a concrete storage pond (800 m^2) where all the other water balance parameters were controlled. Even at such small area, problems with the wind were experienced which were interfering with the continuity of the film. A continuous supply pattern was finally improvised by introducing the fatty alcohol substance in a solid form (soap-like) into a net and allowing [the alcohol] to be gradually dissolved by the water action. This approach enabled a more or less continuous application, overriding, somewhat, the interruption by the wind, at the expense of introducing larger quantities of the substance. On successful attempts and when wind action was low, the evaporation suppression was of the order of 30%. Other work on the same subject was the investigation of spraying techniques from around the perimeter of the lake, especially at the windside as recommended by the suppliers of the fatty alcohol. The technique was found useful especially under ideal conditions of no wind action. No large scale experiment has been carried out, under the present phase of research. Plans for introducing the fatty alcohol in a large reservoir are still in abeyance awaiting clearance on the toxicity and other environmental impacts. In the meantime we are planning to proceed with our experimentation on an even larger concrete reservoir offering controlled conditions for evaluation of the technique."

(Iacovides, 4/22/99, personal correspondence)

Cypriots clearly feel that monomolecular layers are the system of choice for reducing evaporation from surface water bodies. There are certainly advantages to this method which include: high theoretical reduction of evaporation, easy and rapid application over large surface areas, possible low cost, and minimal visual aesthetic impacts. But there are numerous potential disadvantages as well: actual evaporation reduction may be significantly less than expected, the film may be disrupted by strong winds or activity on the surface of the lake, costs may be higher than anticipated, and water quality may be affected by the chemicals used to generate the film. The widespread use of monomolecular films for reservoir evaporation reduction seems to have been abandoned in the US decades ago due to some of these factors. In fact, a recent text on evaporation stated:

> "While evaporation reductions of about 60% have been achieved under ideal conditions, actual reductions were much lower, and the use of monomolecular films to reduce evaporation from free water surfaces has found <u>no practical application</u> [emphasis added]."
>
> (Jones, 1992, p. 120)

Monomolecular layers have not yet been applied on a wide scale in Cyprus for evaporation reduction. Cypriot hopes for evaporation reduction are high, however. One 1998 WDD document shows that evaporation reduction is expected to yield up to 5 MCM per year in additional, low-cost water. Because of the potential problems with monofilms, it may be reasonable to investigate other methods of evaporation reduction for possible application. Several have been described above, but most have serious drawbacks and limitations. The next section and chapter detail a proposed "new" method for evaporation reduction which may have great potential for application in Cyprus.

6.8 **Artificial Destratification**

Most deep ponds and reservoirs undergo a natural process known as thermal stratification. This occurs in the summertime when, "Heat enters the surface water and is mixed downward for a limited distance by wind action. The result is the formation of an upper layer of water, of varying thickness, in which temperatures are relatively uniform and higher than those in the rest of the water (Chow, 1964, p. 23-18)." Stratification is caused by density differences which induce the segregation of the reservoir into two separate layers of water which do not readily mix. The result of stratification is that incoming solar radiation and sensible heat from the atmosphere heat only that volume of water in the upper layer. The water at the surface of a stratified reservoir is therefore warmer than it would otherwise be were the reservoir fully mixed.

The increased temperature of the water at the surface of a stratified reservoir leads directly to an increased rate of evaporation, when compared to evaporation from the same lake in a well-mixed state. This is because the rate of evaporation from a free water surface is related to the vapor pressure gradient above the water. The vapor pressure gradient is in turn related to the temperature of the water at the surface of the reservoir. Warmer water leads to an increased vapor pressure gradient, which then leads directly to increased evaporation.

Most ponds and reservoirs are naturally stratified to some degree during at least some portion of the year. Since this stratification of ponds and reservoirs causes increased evaporation, it follows that *destratifying* such ponds and reservoirs could cause a reduction in evaporation rates. Destratification is the process of mixing a body of water to prevent or remove stratified conditions.

Ponds and reservoirs may be artificially mixed or destratified. This is a mechanical process which induces circulation of water across the full depth of a reservoir. This is a process that has been widely studied for the improvement of reservoir water quality. "The use of artificial destratification as a management technique for lakes has been practiced for at least 40 years (Robertson, et. al., 1991)." Several techniques have been developed for reservoir mixing. Low speed impellers mounted below floating rafts may be used to push surface water down deeper into the reservoir. One such device is known as a Garton pump, and may be powered by a gasoline or electrical engine (Garton, 1978). Destratification may also be achieved by pumping surface water to the bottom of the lake or vice versa through conventional pumps and piping (Dortch, 1979, p. 13). Another method uses air bubblers at the bottom of the reservoir to entrain water behind rising air bubbles thereby mixing water from the bottom with that at the top (Burns & Powling, 1981, pp. 180-182).

Destratification has apparently never been used specifically for evaporation reduction. Most destratification projects and studies have centered on water quality, but some have suggested that evaporation reduction would also result (Dorch, 1979, p. 5). One researcher has speculated that, "A first order approximation suggests that a (realistic) 2K [2° C] drop in summer surface temperature would result in a 10% decrease in evaporative losses. In an area where the annual evaporation is 1800 mm per year (taking into account the summer stratification period of about three months), this gives a total water savings of about 50mm. (Henderson-Sellers, 1984, pp 306-307)." In a field test of thermal destratification by means of air-bubbling made in California in 1962, reservoir mixing was determined to have actually reduced evaporation by lowering the summer surface water temperatures (Koberg, 1964, D191). Destratification of Lake Wohlford was shown to have produced a maximum decrease in water surface temperatures of 2.2° C. A maximum evaporation rate decrease of 15% was observed during the summer months with a net decrease of 5% overall.

A study of the effects of destratification on evaporation rates was conducted by Cox (1992) using a finite difference computer model to simulate energy budgets of two separate lakes. Using actual climate data, the model predicted yearly evaporation reductions of between 6.4% to 11.2% for a small lake similar in size to Lake Wohlford. Evaporation reductions at a larger reservoir were predicted to range from 26.1% to 34.5%. The increase in predicted evaporation suppression in the latter case is due to the greater depth of the reservoir modeled in the simulation. Deeper, well-mixed reservoirs have a greater thermal inertia due to a greater mass to surface area ratio and therefore warm at a slower rate. This slower warming yields lower evaporation rates mainly during the spring and summer months when the surface temperature of the stratified reservoir would be much warmer.

The cost of water conserved by destratification is dependant on the capital costs of the mixing system, the operational costs, and the amount of evaporation reduction achieved. Cost of destratified water in the study by Cox (1992) was approximately US$ 0.06 per cubic meter of water saved (CY£ 0.03/m^3), if the lower percentage of evaporation reduction was assumed. If evaporation reduction is on the high end of the scale, costs could drop to as low as US$ 0.03 per cubic meter of water saved (CY£ 0.02/m^3). Chapter 7 of this report further develops evaporation reduction data and cost estimates specific to Cyprus.

Artificial destratification has been shown by theory, numerical simulation, and field trials to reduce evaporation. The process is cost effective and may be implemented using existing and proven technology. Destratification is an environmentally benign process which actually improves water quality. Based on these clear advantages, artificial destratification is recommended for further study as the most promising method for evaporation reduction in Cyprus.

Chapter 7 EVAPORATION REDUCTION THROUGH ARTIFICIAL DESTATIFICATION

Investigation of numerous methods of evaporation reduction in the last chapter showed that there are significant problems with many of the possible schemes. In particular, monomolecular films have serious problems with film degradation due to environmental and biological factors. These problems significantly reduce the theoretical effectiveness of monomolecular layers in terms of evaporation reduction. Despite substantial research on monolayer films, application of this technology in the U.S. has been abandoned. Water managers in Cyprus hope to use these films for evaporation reduction, but they have also encountered problems with use of such films under field conditions.

Artificial destratification of ponds and reservoirs has been proposed as an alternative method of evaporation reduction. Many bodies of water are known to undergo thermal stratification. This phenomenon leads to increased surface water temperatures and thus increased evaporation. Mixing stratified reservoirs has shown the potential to reduce surface water temperature and cause a corresponding reduction in evaporation. The process of stratification will be investigated further in this chapter, along with methods of destratification, and predicted evaporation reduction efficiencies.

7.1 Thermal Stratification

Thermal stratification occurs when a layer of warm water at the top of a reservoir (the epilimnion) floats on top of a layer of cold water at the bottom of a reservoir (the hypolimnion). When these two layers reach significantly different densities, mixing between the two layers virtually stops. Stratification occurs because incoming solar radiation enters a pond or reservoir only from the surface of the water. As incoming radiation penetrates the water, it is converted to thermal energy, thus heating the water. The depth of radiation penetration is limited, though, and heating decreases significantly with depth. Transfer of sensible heat from the atmosphere, which inputs energy into a reservoir in the summertime, also occurs only at the air/water interface. Therefore the surface of a reservoir heats faster than the deeper portions.

As the temperature of the surface water changes, its density also changes. Above 4° C, there is an inverse relationship between water's temperature and density. Therefore as the surface water temperature increases due to solar heating, the density of that same water is reduced. The decreased density of the surface water tends to cause it to float on the heavier water below. The lighter water at the surface thus has a tendency to stay at the surface where it continues to be heated by the sun. This process creates a self-propagating system or positive feedback process. As surface water is warmed it becomes less dense so it stays on the surface of the pond or reservoir where it continues to be warmed and continues to become less dense. Finally, the density differences between the surface water and the water at depth become so distinct that the two layers effectively segregate and cease to advectively mix with one another. This is the process of thermal stratification.

7.2 Evaporation Reduction By Artificial Destratification

Due to the feedback process by which only warm epilimnion water continues to be heated by the sun, the temperature of water at the surface of a stratified pond or reservoir increases faster than it would were the same body of water well mixed and therefore not stratified. Effectively, the same quantity of energy in the form of incoming sunlight is being input into two very different bodies of water when the same reservoir is considered in either a stratified or a well-mixed condition. When the reservoir is well mixed, the incoming energy must be used to heat the entire volume of water contained in the reservoir since surface water eventually circulates across the entire depth. If the reservoir is stratified, solar energy input reaches only the epilimnion where it is effectively trapped due to the buoyancy differences. The volume of the epilimnion is by definition less than that of the entire reservoir. The change in temperature of any body is related to the energy flux and the mass of the body. In the case of a reservoir, the rate of energy input is constant regardless of stratification (though not regardless of water temperature) since the majority of energy exchange takes place at or near the free surface (Henderson-Sellers, 1984, p. 33). Because of the limited mixing between the epilimnion and hypolimnion in a stratified reservoir, the volume, and thus the mass, of water to be heated differs greatly between the stratified and well-mixed conditions. In a stratified reservoir, only the epilimnion is subject to heating, while if the same reservoir were well-mixed, the same energy input would be spread across the entire volume of the reservoir. Therefore, the surface temperature of a stratified reservoir tends to increase more rapidly during the spring and summer months when incoming radiation and heat are the greatest.

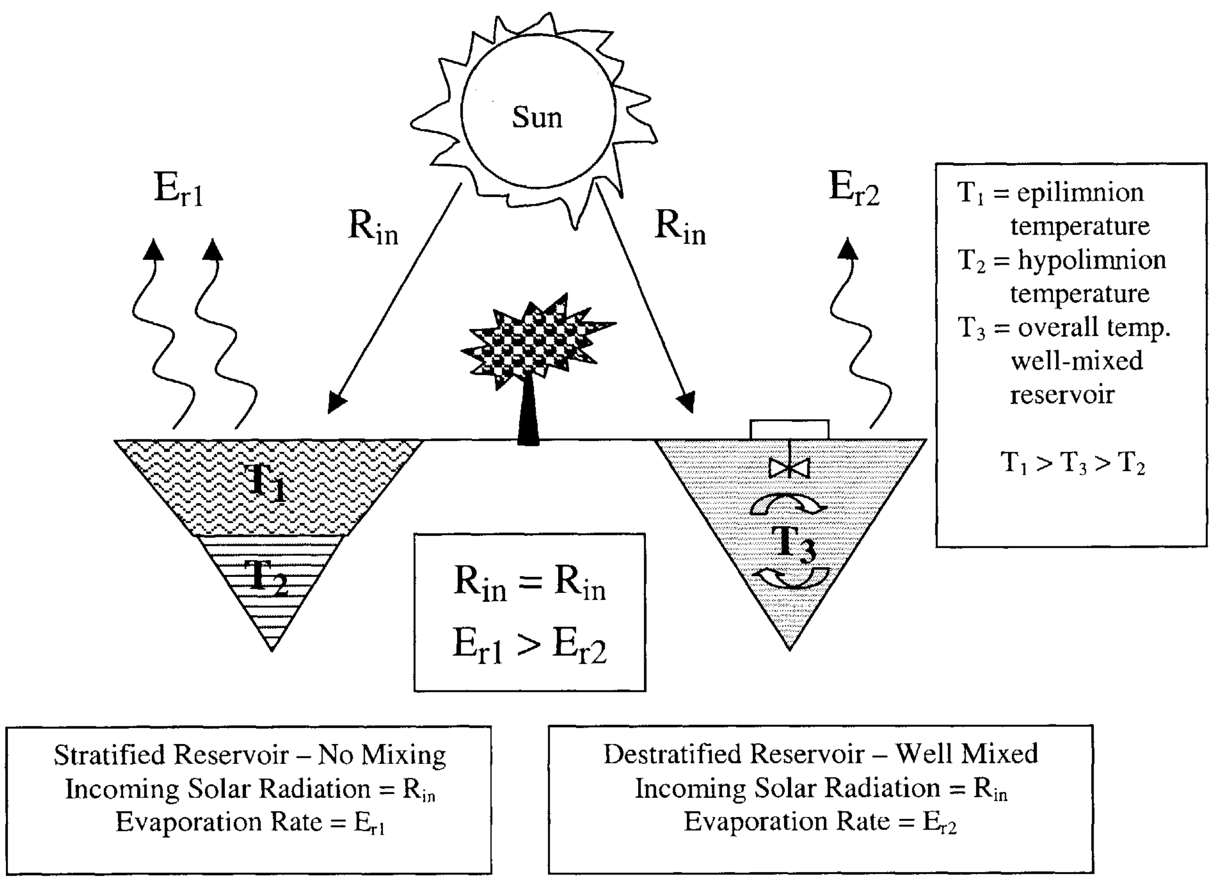
If a stratified reservoir is instantaneously mixed, the total energy content does not immediately change. The total energy is merely spread throughout the entire volume of the lake, thus causing a cooling of the epilimnion and a warming of the hypolimnion (assuming summertime stratification). The new state of the reservoir then influences the rate of energy flux into and out of the reservoir since evaporation, backradiation, and sensible heat are functions of surface water temperatures.

Summertime thermal stratification leads to ponds and reservoirs which are warmer on the top than on the bottom, and surface temperatures which are warmer than those expected in a well-mixed reservoir. This has implications on evaporation rates because evaporation obviously only occurs at the surface of a body of water. As seen in Chapter 3, the rate of evaporation from a water surface is linked to the vapor pressure gradient just above the water surface. In the Dalton form of the aerodynamic equation for evaporation reduction (Equation 3.3), the vapor pressure gradient is a function of the surface water temperature. As is intuitively obvious, the rate of evaporation from a body of water increases as the surface temperature increases.

Thermal stratification of reservoirs leads to evaporation rates that are higher than rates that would be predicted from a well-mixed reservoir. Thermal stratification, however, occurs naturally and is the norm for the majority of reservoirs. "Most reservoirs undergo a period of stratification, and it is not uncommon for the water of a lake to be temperature stratified for the major part of the year. (Fischer, et. al., 1979, p. 169)." *If the thermal stratification of a pond or reservoir could be prevented or eliminated, it may be expected that the actual observed rates of evaporation would be reduced.*

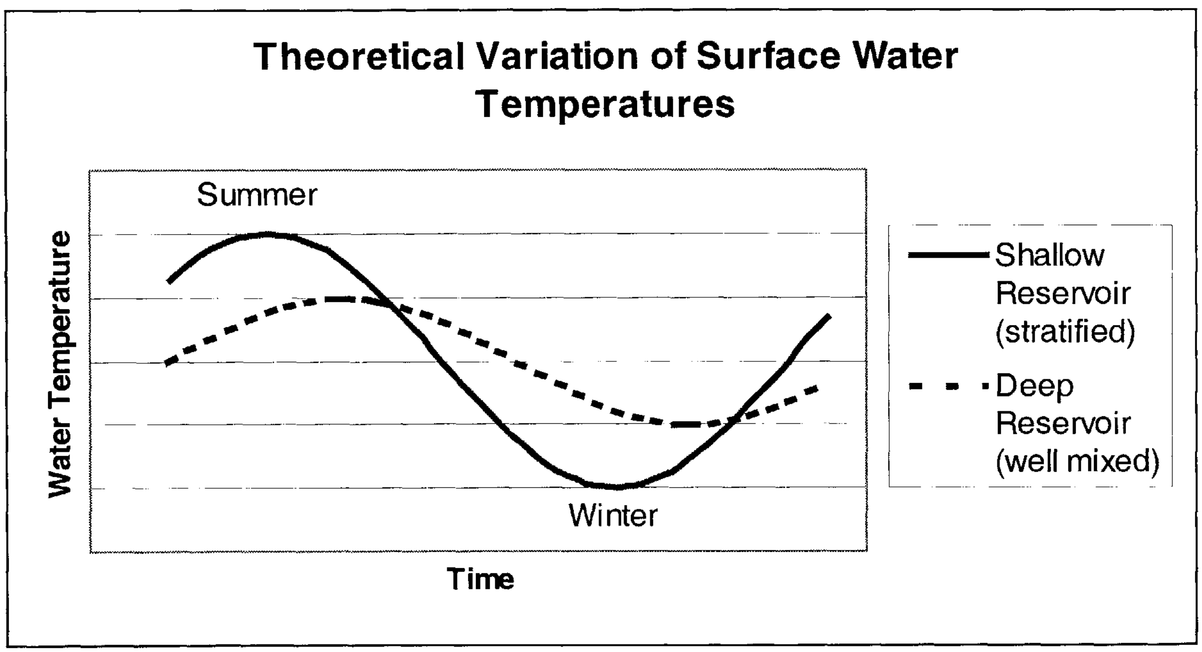
Mechanical mixing of a pond or reservoir can prevent or eliminate thermal stratification. If a pond or reservoir begins in a well-mixed condition, then mechanical mixing stops the formation of distinct layers and distributes incoming energy throughout the entire volume of the lake. If the pond or reservoir is already stratified, then mixing leads to *destratification*. Once the reservoir is destratified, the temperature of the surface of the reservoir will increase less rapidly during warming and decrease less rapidly during cooling. A net decrease in evaporation may result in comparison to the reservoir in its naturally stratified condition. Figure 7.1 illustrates the concept.

FIGURE 7.1
CONCEPTUAL DIAGRAM OF EVAPORATION REDUCTION BY ARTIFICIAL DESTRATIFCATION
(During Warming Period)



The well mixed reservoir has a larger volume of water which is affected by energy fluxes – both into and out of the reservoir. This leads to increased thermal inertia, meaning that the well mixed (deeper) reservoir warms more slowly since a greater total amount of energy must be input across the same surface area. Conversely, the well mixed reservoir also cools more slowly since more total energy must be shed. A comparison of the general trend in surface water temperatures is shown in Figure 7.2. Net reductions in evaporation can result if the lower surface water temperatures in the summer are more influential than the higher winter water temperatures, due to other meteorological considerations.

FIGURE 7.2
CONCEPTUAL COMPARISON OF RESERVOIR WATER TEMPERATURES IN STRATIFIED AND WELL MIXED CONDITIONS



Stratification has consequences beyond increased evaporation rates. In fact, the majority of research and interest in stratification centers on its environmental effects. The separation of the epilimnion and hypolimnion causes not only differences in temperature but also in other physical and chemical properties as well. One of the most significant environmental problems caused by stratification is reduced oxygen content in the hypolimnion. Oxygen diffuses into a reservoir mainly thorough the free water surface which is in contact with the atmosphere. Density stratification significantly slows the transfer of oxygen from the top layer of the reservoir to water at depth. When biological processes at the bottom of the lake consume oxygen, the oxygen cannot be replaced. The bottom of stratified lakes thus tend to become oxygen deficient. This condition may lead to fish kills and poor water quality. Nutrients and other chemicals can collect in the hypolimnion when stratification persists for a long time. Algae blooms can also occur when a stratified lakes "turns over." Taste and odor of water withdrawn from stratified reservoirs may become undesirable when anoxic conditions develop and dissolved chemical concentrations become elevated.

7.3 Artificial Destratification

Due to the environmental problems associated with stratification, processes for destratification have been studied in the past primarily for their benefits to water quality. Lake mixing has been applied in order to maintain oxygen content through a lake to prevent fish kills. Destratification has also been used to correct water quality problems in drinking water reservoirs. As a result of this work, much has been learned about mixing reservoirs, and many different systems have been developed to do so. It is a happy coincidence that this method of evaporation reduction is also generally beneficial to the environment

A reservoir may be mixed in a variety of ways. Many bodies of water are mixed via natural processes. If stratification is weak, turbulence caused by strong winds may be enough to mix a shallow reservoir. In temperate climates, stratified lakes may "turn over" in the fall and/or spring. Turnover occurs when the densities of the epilimnion and hypolimnion invert. This normally happens in the autumn season when cold air leads to rapid cooling of the surface of the lake. In cold winters, reverse stratification may happen if the temperature of the epilimnion drops below 4° C. In lakes or reservoirs where this does occur, turnover may happen again in the spring when the surface of the water again begins to warm.

Artificial destratification is a way of accelerating or inducing turnover in a stratified reservoir. A reservoir may also be continuously mixed in order to prevent stratification from ever occurring. Continuous mixing in the summer months is probably preferable when evaporation reduction is the goal. Several different methods of destratification have been developed. Each uses a different type of mechanical system, but the goal is the same in each case -- circulation of water throughout all depths of a reservoir. The three principal systems that are used for destratification are described below. There are a variety of specific arrangements of each type of system, but in general most destratification schemes may be grouped under these three catagories:

7.3.1 Air Bubblers

Destratification systems which use air bubblers cause mixing through the pneumatic action of air rising through a column of water. Robertson, et. al. (1991) provide the following description, "Of the methods used [for destratification], compressed air systems have been the most widespread. Such systems operate by introducing a contiuous stream of bubbles from holes drilled in a pipeline located near the bottom of a reservoir. As the bubbles rise through the density stratified water column, they entrain water which is subsequently mixed with the overlying water (Robertson, et. al., 1991, p. 167)." Air compressors located on the shore are used to push air through the perforated pipelines at the bottom of the lake.

The efficiency of a destratification system is expressed in terms of the total energy input into the system versus the work actually required to overcome the buoyancy differences in a stratified lake. For most air bubbler systems, the standard assumed efficiency is approximately 4% (Schladow, 1993, p. 351). However, depending on the system design, efficiencies can range from as low as 1% up to 12% (Stephens and Imberger, 1992, p. 439).

7.3.2 Pumps

Pump systems are used to hydraulically destratify a reservoir. Pumping systems withdraw water from one layer of a stratified reservoir and discharge it into the other (Ditmars, 1971, p. 3-5). In this manner, water is directly transferred between layers through the system. Pumping methods also take advantage of density differences in order to assist the mixing process. Water pumped from layer to layer will either float or sink, depending on the configuration of the system, and create circulation currents independent of velocities imparted by pumping. Four different pumping configurations have been studied by the U.S. Army Corps of Engineers at its Waterway Experiment Station in Vicksburg (Dorch, 1979): (1) withdraw water from the hypolimnion and discharge it horizontally into the epilimnion, (2) withdraw water from the epilimnion and discharge it vertically upward into the hypolimnion, (3) withdraw water from the epilimnion and discharge it horizontally into the hypolimnion, (4) withdraw water from the hypolimnion and discharge it vertically downward into the epilimnion.

7.3.3 Mechanical Mixers

Systems that are based on mechanical mixing utilize motor–driven propellers submerged in the water column which literally "mix" the water. The most common configuration for mechanical mixers is a raft or barge mounted propeller (impeller) which pushes water from the epilimnion down into the hypolimnion. The lighter surface water then tends to rebound and spread laterally at its level of neutral buoyancy, thereby causing circulation within the lake. The Garton Pump (Garton, 1978) is one type of low-energy mechanical axial flow mixer. It is raft-mounted and may be powered by either a gasoline or electrical motor. It has been used for local destratification in the vicinity of outlet works (Busnaina, 1981, p. 2) and for total mixing of small ponds (Garton, 1978). Experimental results indicate that efficiencies of up to 12%, which are comparable to those of bubbler systems, may be obtained from mechanical mixing systems (Stephens and Imberger, 1992, p. 455).

The choice of what type of system to use in order to obtain optimal reduction of evaporation is an open question. The choice of destratification systems may be dominated by criteria specific to the location of the reservoir to be mixed, but some generalizations might be worth considering. Air bubbling systems cause agitation of the surface of reservoirs. Such agitation might actually lead to increased evaporation in the local area around the bubble plume, though this effect is probably of minimal concern in large reservoirs. Pumping systems should be able to avoid this problem by choosing a configuration which minimizes disturbance to the surface. The most serious potential limitation to floating mechanical mixers is the limited vertical range that may prevent complete mixing of deeper lakes. Assuming that evaporation reduction efficiencies are independent of the type of destratification system, the choice of systems should be made based on the overall lifetime (discounted capital + O&M) cost.

7.4 Predicted Evaporation Reduction Efficiencies

The studies cited in Chapter 6 give an indication of the ranges of evaporation reduction efficiencies which may be expected due to artificial destratification. The overall annual reductions range from 5% to almost 35%. Experimental data on evaporation reduction due to artificial destratification is very limited for two reasons. The first is that reservoir destratification has not been extensively studied (if at all) specifically for its effects on evaporation. The second reason concerns the difficulty in measuring evaporation reduction. Measuring actual evaporation has been shown in Chapter 3 to be difficult in itself. Measuring the change in evaporation is even more complicated because both the actual evaporation must be estimated as well as the theoretical evaporation which would have occurred were the reservoir to have remained stratified. Data from reservoir destratification projects which have been done for water quality purposes can certainly be reanalyzed, but not many such studies have been undertaken.

One of the most effective ways of attempting to predict how evaporation from reservoirs will be affected by destratification is through the use of computer models. Computer models are available for studying the thermal structure of reservoirs before, during and after destratification. Evaporation is one of the processes modeled by these algorithms since evaporation is a key component of surface heat transfer in a reservoir. By using these types of models, evaporation rates can be compared for the same reservoir, under the same environmental conditions, in both stratified and well-mixed states. In response to an inquiry about the affects of destratification on evaporation rates, Professor Jorg Imberger of the Centre for Water Research at the University of Western Australia stated, "We explored this a few years back using DYRESM. The effect is quite noticeable!" DYRESM is a 1-D (vertical) reservoir computer model (Fischer, et. al., 1979).

Another one-dimention finite difference computer code was used by Cox (1992) to study the effects of artificial destratification on evaporation rates. The model used data from two reservoirs in Oklahoma, in the central plains of the United States. The smaller of the two is called Ham's Lake, which has a maximum capacity of 2.5 MCM, a surface area of 410,000 square meters, and a volume to surface area ratio of 6.1 meters. The larger reservoir, the Lake of the Arbuckles, was constructed by the U.S. Bureau of Reclamation. It has a maximum capacity of 135 MCM, a surface area of 9,010,000 square meters, and a volume to surface area ratio of 15 meters. Energy budgets for both reservoirs were modeled using hourly and three-hourly meteorological data from NOAA climate stations. The energy budget models accounted for all energy entering or leaving the reservoirs in each time step. Energy inputs into the lake included: (1) solar radiation, (2) atmospheric longwave radiation, (3) sensible heat transferred from the atmosphere. Energy is lost by the lake through the following mechanisms: (1) longwave backradiation out of the lake, (2) latent heat of evaporation, (3) thermal energy removed from the lake by exiting water vapor, (4) sensible heat transferred to the atmosphere. Energy transfers due to inflows and outflows and energy transfer through the lake bottoms were neglected.

When used to model the lakes in a stratified condition, the algorithm predicted the temperature of both the epilimnion and the hypolimnion over time, and simulated the movement of the boundary or theromocline. Destratification could be turned on or off at any time, and was assumed to cause rapid mixing. Evaporation rates were computed using a version of Dalton's Equation (Henderson-Sellers, 1984, p. 51). The two reservoirs were modeled in both stratified (natural), and artificially mixed conditions. The modeling period was one year, using historical data from each year from 1975 to 1978. The models were also allowed to run for the full four-year period.

The results of the models show that artificial destratification can indeed cause a significant net decrease in evaporation when compared to the lake in a stratified condition. Surface water temperatures were found to be lower when the reservoirs were destratified. Maximum reductions in evaporation rates were found to occur around June while in early autumn, evaporation rates were sometimes actually higher for the mixed lake. These increased rates are due to the fact that the mixed lakes have more thermal inertia and thus cool more slowly than the epilimnion of the stratified lake. Field data verify this effect (Koberg, 1964, p. D191). Nonetheless, the models predicted a net decrease in total evaporation for both reservoirs. At Ham's Lake, evaporation was reduced by an average of 7.6% over the four one-year trial periods. A mean annual savings of 27,300 cubic meters resulted. At the Lake of the Arbuckles, evaporation was reduced by an average of 29.4% and a mean annual volume of 2.89 MCM of water was conserved. This amounted to a 11% increase in the reservoir firm yield at the Lake of the Arbuckles. The four-year continuous model period led to a slight decrease in evaporation reduction due to heat storage, down to 6.3% for Ham's Lake and 28.4% for Lake of the Arbuckles.

The differences in the evaporation reductions produced at each reservoir are due to the differences in average depths of the reservoirs. Ham's Lake has a maximum depth of 10 meters while the maximum depth at the Lake of the Arbuckles in 24 meters. The temperature of the deeper reservoir rose slower in comparison to that of the shallow reservoir because there was more mass to be heated. Indeed, a sensitivity analysis demonstrated that increasing the depth of the reservoirs led to increased evaporation reduction.

The reservoirs in the Southern Conveyor Project all have capacities greater than Ham's Lake but less than the Lake of the Arbuckles. The surface areas of the SCP reservoirs are also greater than that of Ham's Lake and significantly less than that of Lake of the Arbuckles. All of the Cypriot reservoirs are deeper than both of the American lakes which were used for the model. Temperature profile data is not available for any Cypriot reservoir, but it is expected that stratification is typical. Based only on the SCP reservoir geometries (maximum reservoir depths between approximately 30 to 80 meters), it is expected that evaporation reduction due to artificial destratification will be comparable to those predicted for Lake of the Arbuckles. It is expected that destratification will lead to evaporation reductions of between 20% to 30%.

7.5 Simplified Computer Evaporation Model

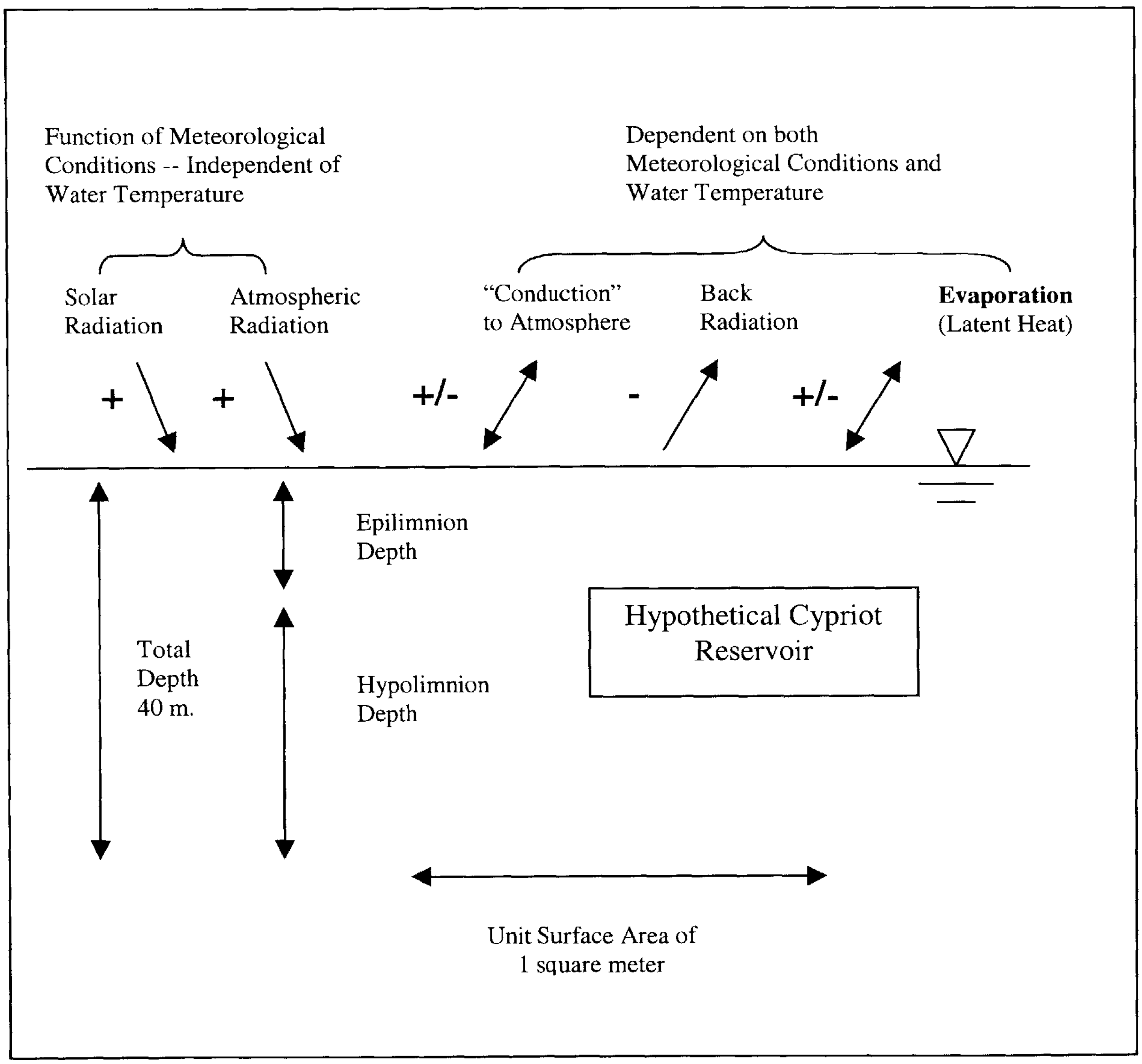
The thermal structure of reservoirs and ponds may be simulated by means of an energy budget model -- essentially an accounting program which sums all energy fluxes from a body of water over a series of time steps and tracks its total energy content – and thus the water temperature. Energy budget models are useful in studying evaporation because evaporation is a function of surface water temperature and is also a major component of energy flux out of a body of water.

7.5.1 Model Development

A simplified energy budget model has been created to study evaporation from reservoirs using the meteorological input specific to the Mediterranean climate of Cyprus. The model was then used to predict the effects of destratification on evaporation rates and estimate reduction efficiency. Data on meteorological inputs were taken from stations on Cyprus whenever possible; otherwise, they were estimated using standard procedures. Figure 7.3 shows the energy flux parameters which were accounted for by the model.

FIGURE 7.3

ENERGY FLUXES FOR SIMPLIFIED MODEL



1. Solar Radiation: Based on Average Daily Insolation Chart by Hamon (1954) using a latitude of 35° N which displays incoming radiation in langleys per day. Then Equation 7.1 was applied.

$$SR = \alpha \bullet (L/2.064) \bullet (1 - 0.65 \bullet C^2) \qquad \text{(Equation 7.1)}$$

Where:

SR = Incoming Solar Radiation (W/m^2)
α = Albedo = 0.94
L = Solar Radiation in Langleys per day
C = Fraction Cloud Cover (Assumed ave. 0.4)

2. Atmospheric Radiation: Based on monthly average air temperatures from Akrotiri Station. The energy flux was computed using Equation 7.2 (Swinbank, 1963).

$$AR = 0.97 \bullet 5.31 \bullet 10^{-13} ((\text{Tair} + 273)^6) \bullet (1 + 0.17 \bullet C^2) \qquad \text{(Equation 7.2)}$$

Where:

AR = Incoming Atmospheric Radiation (W/m^2)
Tair = Air Temperature (° C)

3. Back Radiation: Back radiation into the atmosphere causes a net loss of energy from the reservoir (as denoted by the negative sign) and is a function of the temperature of the water. The flux is computed via Equation 7.3 (Adams, et. al., 1981).

$$BR = -0.97 \bullet 5.67 \bullet 10^{-8} \bullet (\text{Twat} + 273)^4 \qquad \text{(Equation 7.3)}$$

Where:

BR = Back Radiation (W/m^2)
Twat = Temperature of the Surface Water (° C)

4. Evaporation Latent Heat: When water is transformed from the liquid to the gaseous state, it consumes a fixed quantity of energy called *Latent Heat*. The loss of latent heat is a function of the amount of water which evaporates from the reservoir. Latent heat transfer is computed using Equation 7.5 (Adams, et. al., 1981). A correction factor has been applied to this computation to normalize the computed annual evaporation rate with observed data. Meteorological data from Akrotiri was used, but average annual lake evaporation data from Larnaca (1,525 mm per year) was used for comparison to the model (as explained below). The value of the correction factor was chosen by running the model and varying the factor until the steady state annual evaporation from the stratified reservoir was approximately 1,525 mm. The same correction factor is applied to any flux that is connected to the evaporation rate, such as "conduction" and of course the evaporation mass flux.

$$LH = \mu \bullet (-3.75) \bullet W\,(esat - eair) \qquad \text{(Equation 7.5)}$$

Where:

LH = Latent Heat Transfer (W/m^2)
μ = Correction Factor
W = Average Wind Speed (m/s)

5. "Conduction" to Atmosphere: Interaction with the air above the reservoir can serve to transfer energy into or out of the water, depending on the temperature differential. Equation 7.4 is used to compute the flux (Adams, et. al., 1981).

$$CA = \mu \bullet (-0.61) \bullet LH \bullet [(Twat - Tair) / (esat - eair)] \qquad \text{(Equation 7.4)}$$

Where:

CA = Conduction to Atmosphere (W/m^2)
esat = Saturation Vapor Pressure (mbar) at Twat
eair = Vapor Pressure (mbar) at Dew Point Temp

Where:

$$e = 1.333 \bullet 4.596 \bullet \exp^{(17.27 \bullet T/(237.3+T))}$$

6. Evaporation Mass Flux: The actual loss of water from the reservoir due to evaporation may then be computed by simply dividing the computed latent heat transfer by the value of latent heat per unit of water as shown in Equation 7.6 (Adams, 1981).

$$Evap = \mu \bullet LH / L \qquad \text{(Equation 7.6)}$$

Where:

Evap = Depth of Evaporation (mm/s)

L = Latent Heat of Vaporization = $2.46 \bullet 10^6$ J/Kg

For simplicity, a uniform column of water with a unit surface area (1 square meter) was modeled. The total depth of the insolated reservoir column was 40 meters. Normal conditions (with the provision for lake mixing) were simulated by assuming that the reservoir is naturally well mixed in the winter months due to cooling of the epilimnion. In mid-April, the reservoir is assumed to stratify, so the model separates the epilimnion from the hypolimnion. The temperature of the hypolimnion is then fixed, and all subsequent energy fluxes occur only from the epilimnion. The reservoir continues to be stratified until early November when the water temperatures of the two layers are virtually the same, and turnover is assumed to take place. The reservoir is then again modeled as well mixed until the following spring.

In the case of reservoir mixing for evaporation reduction, stratification is not allowed to develop. It is assumed that the mixing system is turned on prior to stratification and allowed to operate until natural turnover would occur. The depth of the reservoir that is subject to heat fluxes is therefore constant at 40 meters throughout the year.

A reasonable initial water temperature (thus total energy) was chosen at the beginning of the modeling period, and then all energy fluxes were computed and summed. The new total energy in the reservoir was then calculated by adding the sum of the energy fluxes over the entire time step to the initial total energy. A positive flux leads to heating of the water, a negative flux indicates reduced water temperatures. The new total energy was used to calculate the new water temperature, as shown in Equation 7.7, and the process was begun again in the next time step. While evaporation mass flux was computed, it was assumed that the depth of the reservoir remained constant, energy contained in the mass of evaporated water is therefore not removed from the reservoir.

$$Twat = TE / (c_p \bullet V / \rho wat) \qquad \text{(Equation 7.7)}$$

Where:

TE = Total Energy (J)

c_p = Specific Heat of Water = 4,190 J/Kg

V = Volume of Reservoir (m^3) = Depth • Area

ρwat = Density of Water = 1,000 Kg/m^2

The time step for modeling was chosen as one week. Larger time steps were attempted but the results did not converge for the assumed range of depths used in the model. The model was also allowed to run for several years by repeating the meteorological input data in order to achieve steady state conditions. After steady state conditions were met, mixing began in the next year and thereafter. The evaporation rate correction factor was chosen for the stratified reservoir along with an initial epilimnion depth. Then the correction factor and the epiliminion depth were also iterated and the root mean squared values (RMS) of monthly evaporation rates for each depth were compared using Equation 7.8. The RMS compared predicted monthly evaporation rates with "measured" lake evaporation from the Larnaca station. Larnaca data was used because it has the highest evaporation rates and produced a more reasonable basis of comparison for the model. Akrotiri climate data was used, but Akrotiri is within 10 km of Larnaca, and the refinement of the data is very crude in any case. Figure 7.4 depicts the RMS values for a range of epilimnion depths. Based on the minimum RMS, a depth of 5 meters has been assigned for the epilimnion in order to minimize the RMS and simultaneously maintain the stability of the model. The actual epilimnion depth may be slightly less, but the model oscillates unacceptably at shallower depths due to the time step used. Evaporation reduction efficiency improves with lesser depths, so 5 meters is conservative.

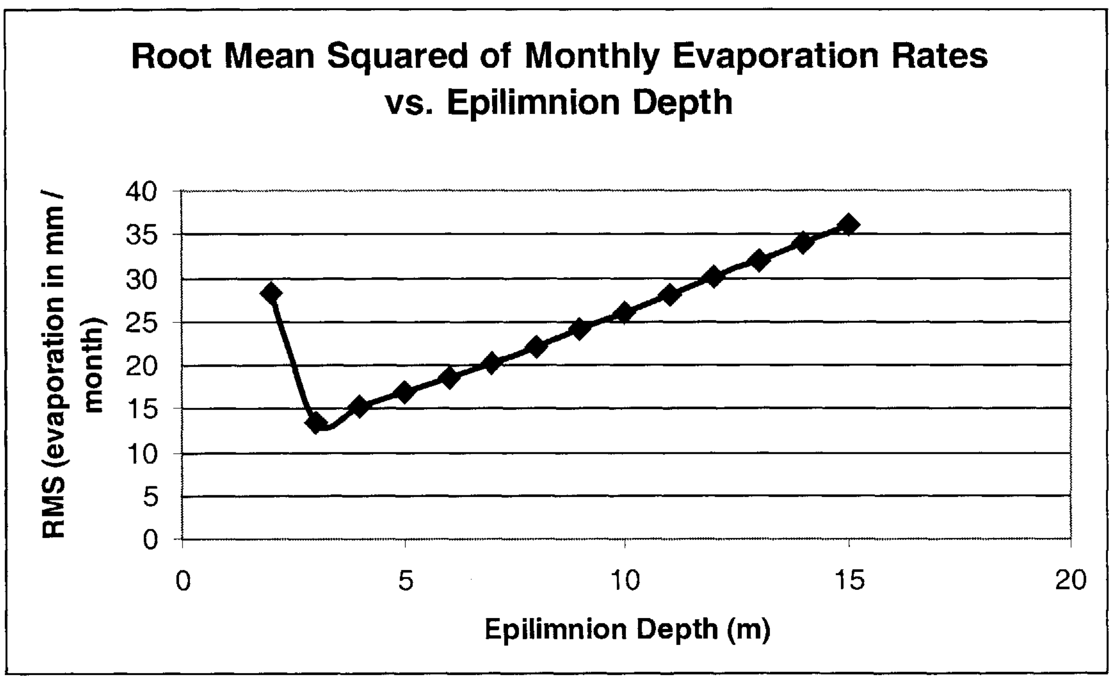
$$RMS(d_{epi}) = [\ (1/12) \bullet \Sigma\ (EVAP_{predicted} - EVAP_{\text{``measured''}})^2\ ]^{1/2}$$

(Equation 7.8)

Where:

$RMS(d_{epi})$	=	Root Mean Squared of Monthly Evaporation as a function of Epilimnion Depth
$EVAP_{predicted}$	=	Monthly Evaporation Rate predicted by the Model
$EVAP_{\text{``measured''}}$	=	Monthly Evaporation Rate based on Corrected Pan Evaporation Data at Akrotiri

FIGURE 7.4
COMPARISON OF <u>RMS</u> VALUES vs EPILIMNION DEPTH

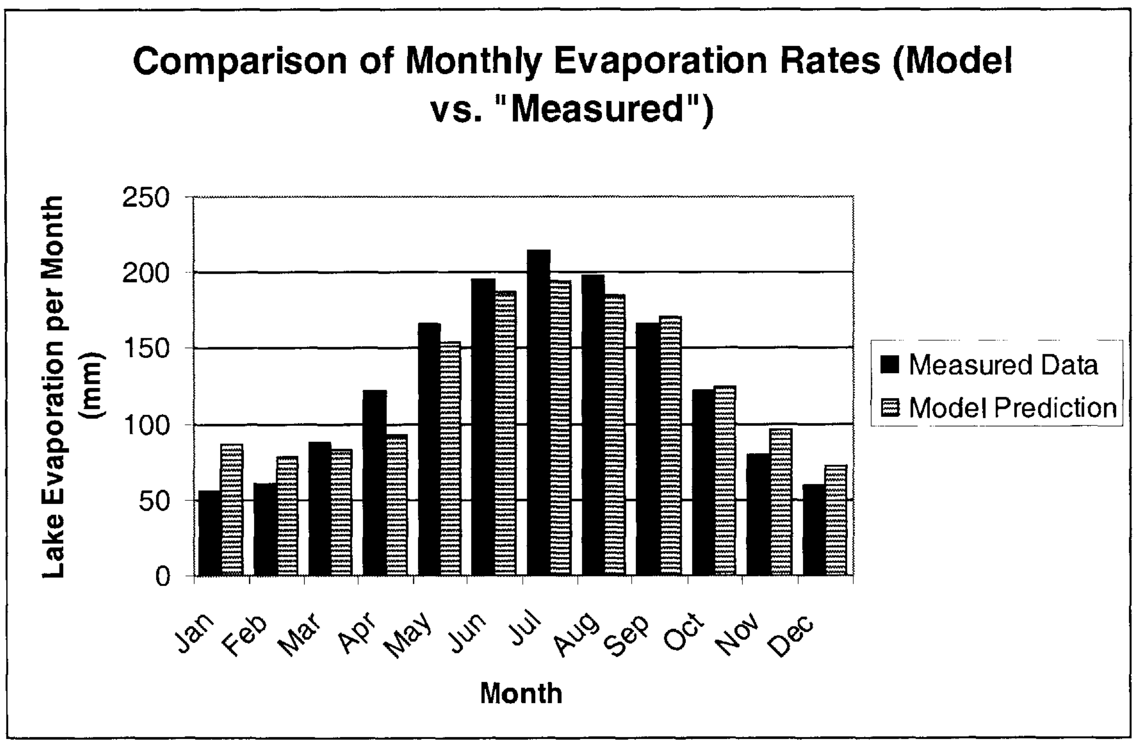


The evaporation rates for stratified and destratified conditions were then compared to determine how mixing the reservoir affects evaporation. Spreadsheets showing the reservoir state at each time step are contained in Appendix A.

7.5.2 Simplified Model Results

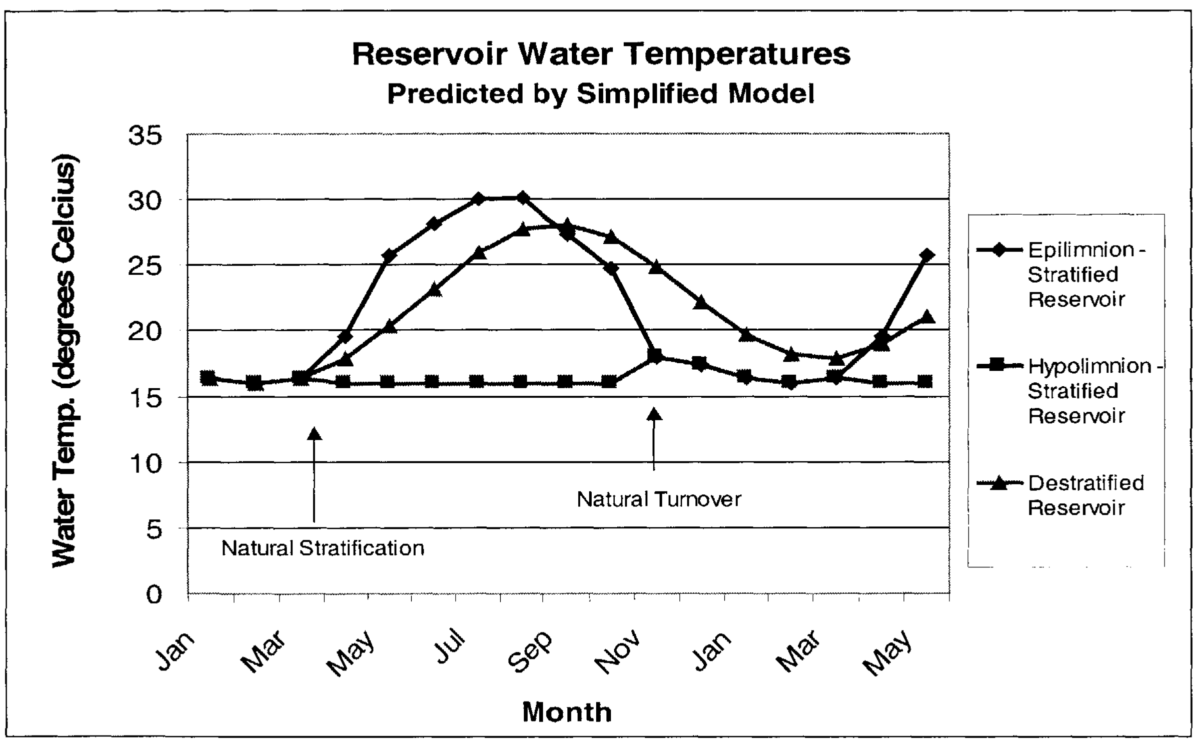
The simplified model does work reasonably well in predicting water temperatures and evaporation rates. The final correction factor applied to the evaporation rate predicted by the model was 0.62, meaning that the predicted average annual lake evaporation was 61% too high. The monthly averages still do not exactly correlate, even after the application of the correction factor. Predicted evaporation in the cold months is too high (31% too high in January) and too low in the spring and summer months (30% too low in April). Figure 7.5 displays monthly evaporation predicted by the model compared to evaporation rates from "measured" data using evaporation pans and a pan correction factor as described in Chapter 3.

FIGURE 7.5
EVAPORATION RATES PREDICTED BY MODEL FOR STRATIFIED RESERVOIR vs. "MEASURED" DATA



The source of the error in the predicted winter evaporation rates is unclear. It may be that the winter reservoir surface temperatures predicted by the model are too high, but data are not available for comparison. While there is uncertainty in the absolute magnitude of the predicted temperatures, the model reservoir does behave as expected in terms of change in temperature. Water temperatures of the stratified reservoir increase in the spring and summer and decrease in the fall and winter. The surface temperatures of the model reservoir are shown to increase more slowly after destratification. This is as expected, since the net positive energy flux must warm the entire reservoir and not just the epilimnion. The water temperature of the fully mixed reservoir does increase through the spring and mid-summer, but not as much. The fully mixed reservoir, however, begins to cool later in the year. The temperature response of the fully mixed reservoir lags the stratified reservoir by approximately a month. The lag is due to the larger thermal inertia of the well-mixed reservoir. Just over one year after mixing begins, the temperature response essentially repeats. Water temperatures predicted by the model are displayed in Figure 7.6.

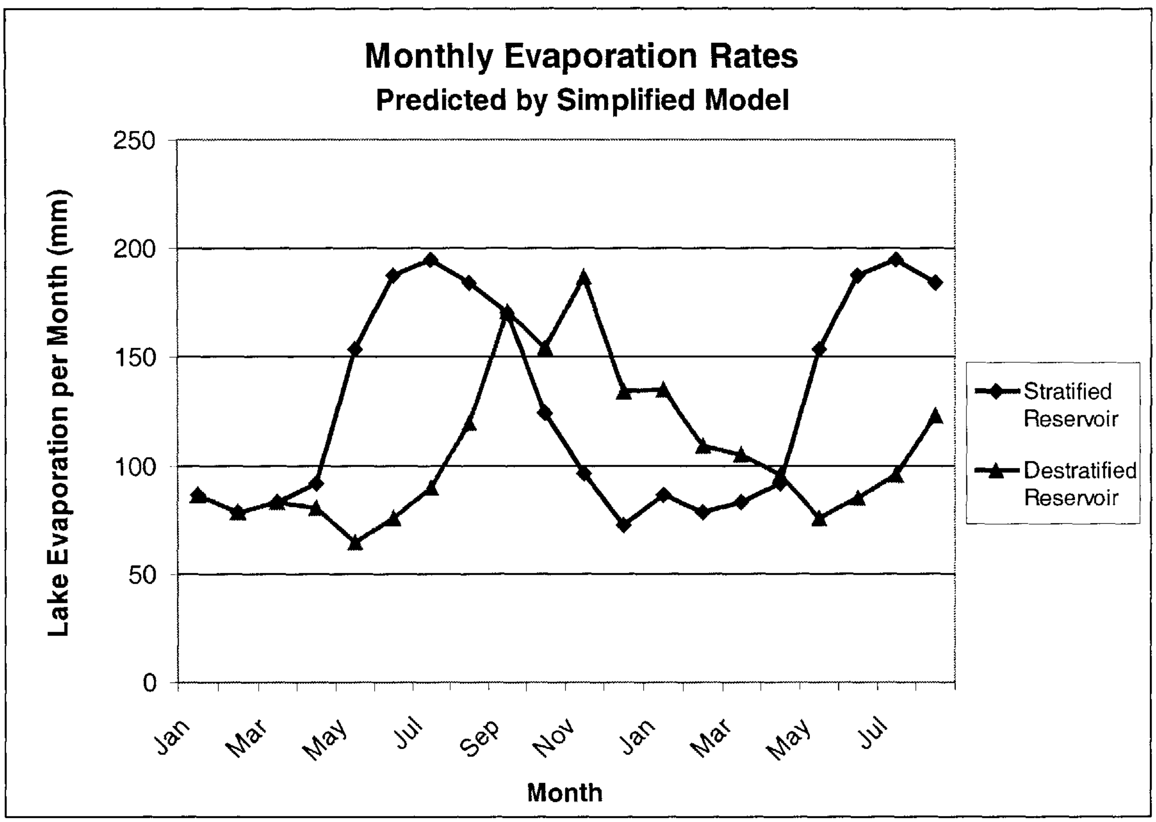
FIGURE 7.6
PREDICTED RESERVOIR WATER TEMPERATURES



Model Parameters:	Reservoir Depth	= 40 m
	Epilimnion Depth	= 5 m
	Hypolimnion Depth	= 35 m
	Surface Area	= 1 m^2

The model does show that net evaporation reduction may be expected due to artificial destratification of reservoirs in Cyprus. As would be expected from inspection of the reservoir surface temperatures, evaporation is reduced in the summer months (59% reduction in June) but increased in the winter months (49% increase in November). Evaporation rates are shown on Figure 7.7.

FIGURE 7.7
PREDICTED EVAPORATION RATES



The net effect of the change in the evaporation rates is an approximately 13% decrease in evaporation in the first year of destratification. But in the year after mixing began, the evaporation reduction rate fell to 3.1%. Table 7.1 lists the monthly evaporation rates over a three-year period: in year one, the reservoir is stratified, destratification begins in year two, and mixing continues in year three.

TABLE 7.1
PREDICTED MONTHLY EVAPORATION RATES

Month	Year 1 Stratified	Year 2 Well-mixed	Year 3 Well-mixed
	Monthly Evaporation (mm)		
Jan	86	86	135
Feb	79	79	109
Mar	83	83	105
Apr	92	80	96
May	153	65	76
Jun	187	76	85
Jul	195	90	96
Aug	184	119	123
Sep	170	171	173
Oct	125	154	155
Nov	96	187	188
Dec	72	134	134
TOTAL	1,523	1,324	1,476
REDUCTION	**0.0%**	**13.0%**	**3.1%**

7.5.3 Conclusions From Analysis of Simplified Model

The simplified model indicates that destratification does serve to decrease surface water temperatures in reservoirs and reduces net evaporation. The model also predicts, however, that the effects of destratification in suppressing evaporation may only last a single year, after which reduction efficiencies become minimal. It is possible that this effect is due to Cyprus's Mediterranean climate. The reservoirs studied by Cox (1992) exist in a temperate climate where temperatures may be lower than freezing in the winter. Substantial amounts of energy are therefore removed from the reservoirs in the winter by processes other than evaporation, and the reservoirs return to close to their initial temperatures by the spring. The simplified model of a reservoir in Cyprus shows that water temperatures in the well-mixed reservoir decrease slowly in the fall and winter, and evaporation rates remain correspondingly high.

It should be noted, however, that the model is very simplistic and many key variables have been assumed. The actual depth of the epilimnion is unknown and is also variable throughout the period of stratification. Monthly data have been used which may not offer enough resolution over a weekly time-step. The data are also from an airport station where wind speeds may be expected to be higher (due to a longer fetch) and humidity lower (no water surface) than at a location near a reservoir. The effects of withdrawls from the reservoir have been neglected. Inflows have also been ignored. Inflows may be very important because streamflows will almost certainly be cooler than the water already in the reservoir. Because the majority of inflows occur from November to January, when the increase in evaporation due to destratification is the greatest, inflows may serve to cool the reservoir and decrease evaporation differences. Other weaknesses of the model are its failure to account for changes in depth and thus surface area, and its assumption of a uniform temperature across the epilimnion. A more sophisticated model using more precise data is needed to better investigate the long-term effects of destratification on evaporation.

The model does validate the idea of destratification as a means of reducing evaporation during at least the first year of a drought. Even if reductions in subsequent years are not substantial, there may be value in the water savings gained in the first year alone. Once the reservoirs have re-filled and the drought is over, destratification systems could be shut down to save energy costs and allow the reservoirs to return to thermal equilibrium. Destratification could then begin again in the first year of the next drought.

7.6 Economic Analysis

Artificial destratification of the reservoirs of the SCP may lead to significant evaporation reductions, although there is a wide range of uncertainty. Assuming that mixing will reduce evaporation by 10% to 30%, a mean annual water saving of 0.6 MCM to 1.9 MCM over the whole SCP will result. This is by no means an enormous quantity of water (the existing desalination plant produces over 14 MCM per year), but the volume of water conserved does amount to between 1.2% to 3.9% of the current annual domestic demand in the SCP. Such a marginal increase is not insubstantial when supplies are extremely limited, such as during a drought. However, the utility of evaporation reduction does depend on the cost. If the unit cost of the water conserved is more than the cost of water from the next source to be developed, then there is no comparative benefit to reducing evaporation. The unit cost of conserving water through evaporation reduction is a function of the amount of water saved and the yearly cost of the system.

The cost of artificial destratification must include both the capital cost of the destratification system and the yearly operating cost. Both components of cost must be estimated and projected over the lifetime of the system in order to determine the cost of each unit of water saved. The cost of conserved water may then be compared to the current cost of surface water and the cost from the next viable source – desalination.

The cost of the destratification system hardware will depend on the type of system which is chosen for application. Regardless of which type of destratification system (air bubblers, pumps, or mechanical mixers) is chosen, it will have to mix the lake. Assuming that the efficiencies of all the systems are similar, it is a reasonable assumption that the energy costs of any system will be roughly equivalent, regardless of the manner of mixing. The capital costs may vary more, but will be assumed to be similar for the purposes of this analysis. Therefore, estimates of the operating costs and the capital costs of the destratification system will be developed without regard for the type of mixing system to be used.

As a first approximation of the possible costs of destratification systems for the reservoirs of the SCP, cost data from existing destratification projects will be examined. Case studies from destratification projects at six lakes or reservoirs are shown below in Table 7.2. Both capital costs and power costs are considered. The average power requirement given in Table 7.2 will be used to determine the amount of power required to destratify and continuously mix a reservoir based on reservoir capacity.

TABLE 7.2
DATA ON RESERVOIR DESTRATIFICATION COSTS

Dam or Reservoir Name	Capacity (MCM)	Capital Cost (CY£)	Capital Cost per Unit Capacity (CY£/m^3)	Power Requirement (kW)	Power Requirement per Unit Capacity (kW/m^3)	Power Cost (1) (CY£)
Ham's Lake	2.5	10,000	4,000	?	?	730
North Pine Dam (2)	200	600,000	3,000	?	?	?
Kouris Dam (3)	115	600,000	5,217	75	0.652	20,295
Baldeggersee (4)	173	1,730,000	10,000	84	0.486	22,730
Hallwilersee (4)	285	2,500,000	8,772	104	0.365	28,142
Sempachersee (4)	639	2,930,000	4,585	90	0.141	24,354
AVERAGES			**5,929**		**0.411**	

(1) Unit Power Costs taken as CY£ 0.041 / kWh (Electric Authority of Cyprus, 1998)

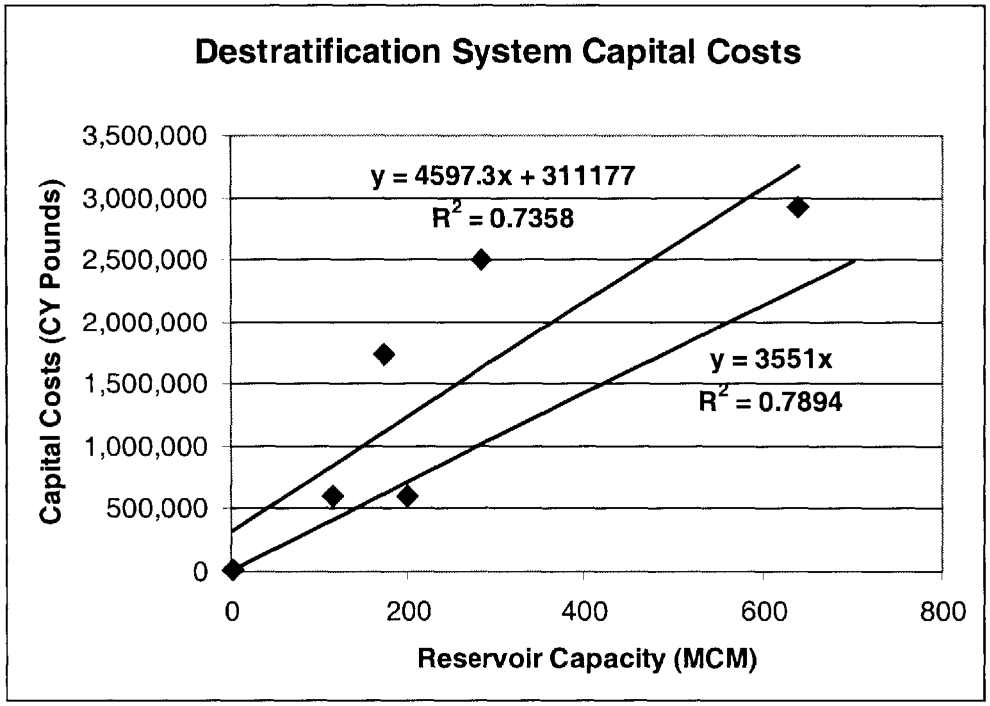
(2) Data From Jorg Imberger, May, 1999, Personal Communication

(3) Cost Estimate for Kouris Developed by Jungo Engineering Ltd based on actual reservoir geometry. Personal Communication with E. Jungo, May, 5/4/99.

(4) Lakes located in Switzerland, (Wehrli and Wüest, 1996)

The capital costs of the six destratification systems are plotted in Figure 7.8. A trendline with an r-squared value of 0.74 has been fitted to the data. The trendline shows that a reasonable approximation of capital costs of a mixing system can be inferred if the capacity of the reservoir is known. The data on capital costs are, however, divided into two groups. The costs of the destratification systems which were installed in the Swiss lakes are substantially higher than the others. This may be due to the high costs of material and labor in Switzerland, currency conversion rates, or perhaps site specific conditions. If these three data points are ignored, a second trendline with an r-squared value of 0.79 may be fitted. This line will be used as a low-end estimate of destratification system capital costs.

FIGURE 7.8
DESTRATIFICATION CAPITAL COSTS vs. RESERVOIR CAPACITY



The costs per unit of reservoir capacity developed from the historic data can now be applied to Cyprus and specifically the SCP. The equations of the trendlines shown in Figure 7.8 will be used to estimate the capital cost of each destratification system. The design life of the destratification systems will be assumed to be 20 years. The cost data from the Swiss systems explicitly stated that amortization would occur over 20 years. The average power requirement per unit of capacity will be used to determine the electrical power input into each destratification system. Annual power costs will be estimated based on continuous mixing over a nine-month period. The system and power costs of destratifying the reservoir at Kouris estimated by Jungo Engineering will be used in the "High" cost estimate, but the trendline equation will be applied to Kouris costs in the "Low" estimate. Table 7.3 displays the high and low capital cost estimates for all reservoirs and the estimated power requirements.

TABLE 7.3
COSTS OF DESTRATIFICATION OF THE RESERVOIRS OF THE SOUTHERN CONVEYOR PROJECT

Serial No.	Name of Dam/Pond	District	Gross Reservoir Capacity ($x1,000m^3$)	Total Capital Cost **HIGH** (CY £)	Total Capital Cost **LOW** (CY £)	Power Require-ment (kW)	Total Yearly Operating Cost (CY £)
34	Kouris Dam	Limassol	115,000	600,000	408,250	75.0	20,295
58	Yermasoyia Dam	Limassol	13,600	92,560	48,280	5.6	1,513
17	Dhypotamos Dam	Larnaca	15,000	99,000	53,250	6.2	1,668
26	Kalavasos Dam	Larnaca	17,000	108,200	60,350	7.0	1,891
38	Lefkara Dam	Larnaca	13,850	93,710	49,168	5.7	1,540
	Totals		**174,450**	**993,470**	**619,298**	**99.4**	**26,907**

The yearly cost of destratification may now be computed by annualizing the capital costs over 20 years, assuming an interest rate of 6%, and adding this figure to the annual power costs. By then dividing the yearly destratification costs by the mean annual quantity of conserved water, the unit cost of evaporation reduction by artificial destratification may be found. Table 7.4 shows total annualized costs of destratification for the SCP. Table 7.5 displays the high estimates of unit cost of water conserved by evaporation reduction through destratification at various potential reduction efficiencies, assuming yearly operation. Table 7.6 shows the estimates of unit costs based on the lower estimates of system capital costs, again assuming yearly operation.

If the destratification system is not operated each year, or the evaporation reductions after the first year are significantly diminished (as predicted by the model), then the unit cost of destratification will increase. If the system is not active, though, then there are no operating costs, so if the capital costs are considered sunk, then the process is still economically viable.

TABLE 7.4
ANNUAL COSTS OF DESTRATIFICATION SYSTEMS IN THE RESERVOIRS OF THE SOUTHERN CONVEYOR PROJECT

Serial No.	Name of Dam/Pond	District	Yearly Operating Cost (CY£/yr)	Annualized Capital Costs **HIGH** (CY£/yr)	Total Yearly System Cost **HIGH** (CY£)	Annualized Capital Costs **LOW** (CY£/yr)	Total Yearly System Cost **LOW** (CY£)
34	Kouris Dam	Limassol	20,295	52,320	72,615	35,599	55,894
58	Yermasoyia Dam	Limassol	1,513	8,071	9,584	4,210	5,723
17	Dhypotamos Dam	Larnaca	1,668	8,633	10,301	4,643	6,312
26	Kalavasos Dam	Larnaca	1,891	9,435	11,326	5,263	7,153
38	Lefkara Dam	Larnaca	1,540	8,172	9,712	4,287	5,828
	Totals		**26,907**	**86,631**	**113,537**	**54,003**	**80,910**

TABLE 7.5
UNIT COSTS OF WATER CONSERVED BY EVAPORATION REDUCTION IN THE SOUTHERN CONVEYOR PROJECT
(<u>HIGH ESTIMATES</u>)

Serial No.	Name of Dam/Pond	District	Total Yearly System Cost (CY £)	**10% Reduction**		**20% Reduction**		**30% Reduction**	
				Total Quantity of Water Saved by Evap. Reduction (MCM)	Unit Cost of Water Saved by Evap. Reduction (CY£/m^3)	Total Quantity of Water Saved by Evap. Reduction (MCM)	Unit Cost of Water Saved by Evap. Reduction (CY£/m^3)	Total Quantity of Water Saved by Evap. Reduction (MCM)	Unit Cost of Water Saved by Evap. Reduction (CY£/m^3)
34	Kouris Dam	Limassol	72,615	0.40	0.184	0.184	0.085	1.25	0.058
58	Yermasoyia Dam	Limassol	9,584	0.05	0.205	0.205	0.095	0.15	0.065
17	Dhypotamos Dam	Larnaca	10,301	0.05	0.200	0.200	0.092	0.16	0.063
26	Kalavasos Dam	Larnaca	11,326	0.06	0.194	0.194	0.089	0.19	0.061
38	Lefkara Dam	Larnaca	9,712	0.05	0.204	0.204	0.094	0.15	0.064
	Totals		**113,537**	**0.60**	**0.19**	**0.19**	**0.09**	**1.90**	**0.06**

TABLE 7.6
UNIT COSTS OF WATER CONSERVED BY EVAPORATION REDUCTION IN THE SOUTHERN CONVEYOR PROJECT
(LOW ESTIMATES)

Serial No.	Name of Dam/Pond	District	Total Yearly System Cost (CY £)	10% Reduction		20% Reduction		30% Reduction	
				Total Quantity of Water Saved by Evap. Reduction (MCM)	Unit Cost of Water Saved by Evap. Reduction (CY£/m^3)	Total Quantity of Water Saved by Evap. Reduction (MCM)	Unit Cost of Water Saved by Evap. Reduction (CY£/m^3)	Total Quantity of Water Saved by Evap. Reduction (MCM)	Unit Cost of Water Saved by Evap. Reduction (CY£/m^3)
34	Kouris Dam	Limassol	55,894	0.40	0.141	0.184	0.065	1.25	0.045
58	Yermasoyia Dam	Limassol	5,723	0.05	0.122	0.205	0.056	0.15	0.039
17	Dhypotamos Dam	Larnaca	6,312	0.05	0.122	0.200	0.056	0.16	0.039
26	Kalavasos Dam	Larnaca	7,153	0.06	0.122	0.194	0.056	0.19	0.039
38	Lefkara Dam	Larnaca	5,828	0.05	0.122	0.204	0.056	0.15	0.039
	Totals		**80,910**	**0.60**	**0.14**	**0.19**	**0.06**	**1.90**	**0.04**

If the "High" and "Low" unit costs are averaged, then the cost of water saved by evaporation reduction when the reduction efficiency is 10% is approximately CY£ 0.17/m^3. At 20% efficiency, the average unit cost of water is CY£ 0.08/m^3. If evaporation reduction is as high as 30%, the cost of water conserved drops to CY£ 0.05/m^3. These prices compare very favorably with the costs of water from other sources. Table 7.7 lists the costs of producing water from other sources.

Water "produced" by evaporation reduction is raw water which may be withdrawn from a reservoir along with the rest of the yield. The full cost of untreated raw water currently is CY£ 0.18/m^3 (excludes the CY£ 0.02/m^3 average pumping costs). The government fully recovers this cost from domestic users but charges only CY£ 0.07/m^3 to agricultural users. A benefit / cost ratio for evaporation reduction through artificial destratification can be computed by considering these levels of cost recovery for water sales. Because of the water scarcity problems in Cyprus, it is assumed that all water conserved though evaporation reduction will be demanded by domestic users, and the additional supply will not have an effect on prices.

TABLE 7.7
COMPARISON OF WATER COSTS AND
BENEFIT / COST RATIOS FOR EVAPORATION REDUCTION

Evaporation Reduction Efficiency	Cost of Water From Evaporation Reduction (CY£ / m^3)	Cost of Ground-water (CY£ / m^3)	Cost of Surface Water (CY£ / m^3)	Cost of Desalinated Water (CY£ / m^3)	Benefit / Cost Ratio of Evaporation Reduction (CY£ / m^3)
10%	0.17	0.11	0.18	0.44	1.06
20%	0.08				2.25
30%	0.05				3.6

7.7 Conculsions

Evaporation reduction in Cyprus in through artificial destratification should be capable of reducing evaporation rates by at least 10% but possibly up to 30%. The cost of evaporation reduction through artificial destratification is very competitive when compared to the cost of water from other sources, even when evaporation reductions are small. Artificial destratification may not only be able to provide additional water through evaporation reduction, but may also do so at a low cost. If evaporation reduction is continuously viable, the installation of destratification systems to reservoirs in the SCP and other large reservoirs is clearly justifiable based on both engineering and economic criteria. If evaporation reduction efficiencies are significantly less after the first year of operation, then the use of artificial destratification may be harder to justify. However, it should be noted that when reservoirs are full, there is no need for evaporation reduction. It may still be practical and useful to only operate the destratification systems during droughts when extra water is needed the most.

Chapter 8 SUMMARY AND RECOMMENDATIONS

8.1 Summary

Water is a scarce resource in the Republic of Cyprus. Increasing demand and highly variable rainfall are causing empty reservoirs and deficits in supply. In the past few years, water rationing has become the norm for many cities in Cyprus. Most conventional water resources in Cyprus have already been developed. Numerous dams already exist, and the opportunities for constructing new ones are limited. Groundwater, which has been productively utilized for many years, is now overpumped. As a result, many aquifers are in danger of saltwater intrusion.

Since the majority of conventional surface and groundwater sources have already been exploited, the Government is turning to non-conventional sources of water to augment supplies. Some of these secondary sources rely on well-understood technologies and are already being implemented. Municipal wastewater is treated at a tertiary level and pumped to fields and orchards for use in irrigation. Desalination of seawater is now providing a significant fraction of water for domestic consumption, and several new plants are under contract or in development. Other alternative sources being considered by the government are more marginal. Artificial rainfall enhancement has been studied, and there have even been serious discussions of importing water from other countries.

Another of the non-conventional sources which the Government has considered is evaporation reduction. Because of the Mediterranean climate of Cyprus, evaporation rates are quite high and losses from surface water ponds and reservoirs can be quite significant. The goal of evaporation reduction is to suppress the loss of water out of reservoirs and thereby conserve water for beneficial uses. Evaporation reduction is not a widely applied process, but due to the severity of water scarcity in Cyprus, even marginal savings may be worthwhile.

Evaporation rates in Cyprus are quite high. Examination of data from the network of Class A pans reveals that the mean annual rate of lake evaporation in Cyprus is 1,173 mm per year. Evaporation rates are actually quite spatially variable, however. The lowest evaporation rates, approximately 700 mm per year, are found in the mountains, while on the southeast coast, rates of up to 1,525 mm per year are observed. As expected, evaporation rates also vary throughout the year. July has the highest monthly rate at 214 mm per month. The least evaporation, 55 mm per month, occurs in January.

Many of the larger reservoirs in Cyprus are located in the foothill of the Troodos Mountain range where evaporation rates are quite substantial. An estimate of the total average quantity of water lost to evaporation may be made by applying local evaporation rates across the normal surface area of all major ponds and reservoirs. Following this procedure, it has been estimated that an average of over 19 million cubic meters (MCM) of water is lost to evaporation each year. The value of this water, defined as the capital recovery cost of surface water, is over CY£ 3.4 million per year. Desalination is now the next viable source of water. The cost of replacing water that has evaporated with water from the desalination plant now being built is more than CY£ 8.0 million per year. This estimate of evaporation losses is somewhat crude, however, because it does not take into account variations in surface area. By modeling reservoir operation for the Southern Conveyor Project, annual evaporation can be based on variable surface area which is the result of variable storage. Using more than 80 years of historic rainfall data as input into a deterministic operations model, an average annual evaporation rate of 6.9 MCM per year was predicted from the five largest reservoirs of the SCP.

The amount of water lost to evaporation each year makes evaporation reduction an attractive option as a method of enhancing water supplies. If some significant percentage of the water now being evaporated could be conserved, then a useful quantity of water could be made available to productive uses. Many different methods have been suggested for reducing evaporation from surface water bodies. Some of the ways of potentially reducing evaporation include vegetation control, reservoir surface area reduction, radiation barriers, floating covers, and wind barriers. Unfortunately, none of these techniques are particularly applicable for use in large reservoirs. The evaporation reduction method which is currently favored by the Cypriot Water Development Department is the use of monomolecular films. These films make use of a thin layer of fatty alcohols to coat the surface of a reservoir and reduce the vapor pressure gradient. Monomolecular films have a very high theoretical evaporation reduction efficiency... up to 60%. Under field conditions, however, the effectiveness of these films can drop significantly. The film-producing material must be continuously applied because wind and biological action can cause degradation. Proper application and spreading can be problematic, and there are concerns about the effects of these compounds on water quality. Due to these potential problems, monomolecular films have not been widely used in the United States or elsewhere.

Another method of reducing evaporation is through artificial destratification, or mixing, of reservoirs. As a result of mixing reservoirs, water temperatures become relatively uniform across all depths, leading to lower surface temperatures and thus reduced evaporation. There are several methods by which reservoirs can be mixed for the purpose of destratification. These methods can be grouped under three general types of systems: (1) Air bubblers pump air through submerged perforated pipes and cause mixing by entraining water behind rising bubbles. (2) Pump systems extract water from a lake at one depth and then re-inject the water at a different depth. (3) Mechanical mixers use rotating impellers, usually mounted on floating rafts, to push water from one depth to another. Each of these systems have particular strengths and weaknesses, and overall destratification efficiencies can range from 1% to 12%. Destratification systems have been well studied for use in water quality improvement.

Field studies have found that destratification lowers surface water temperatures, and evaporation reductions have been documented. Computer models verify that evaporation reduction is a consequence of artificial destratification. Finite difference models of two reservoirs in the U.S. predicted evaporation reductions of between 7% and 30%. A simplified computer model of a hypothetical reservoir in Cyprus predicted a 13% reduction in evaporation in the first year of destratification, but only a 3% reduction in the years thereafter. The Mediterranean climate in Cyprus may account for this decline in effectiveness, but inaccuracies in the data or model may also play a part.

The cost of the water produced through the reduction of evaporation is a function of the amount of water saved and the cost of installing and running the destratification system. Based on an analysis of destratification systems which have been constructed elsewhere, correlations were developed which relate capital costs and operations cost to the capacity of the reservoir. Use of these relationships allowed the total yearly cost of destratification in the SCP to be estimated. The total annual cost of financing and operating five systems in the SCP was estimated at approximately CY£ 97,000 per year. The system at Kouris Dam accounted for over two-thirds of this total. If the destratification of the SCP reservoirs produces an evaporation reduction of 10%, then an average total of 0.6 MCM of water will be conserved, leading to a unit cost of approximately CY£ 0.17/m^3 and a benefit / cost ratio of 1.06. If 30% evaporation reduction is achieved, then 1.9 MCM may be conserved, the unit cost drops to CY£ 0.05/m^3, and the benefit / cost ratio increases to 3.6.

8.2 Recommendations

Evaporation reduction by means of artificial destratification has the potential for producing a substantial quantity of water at a low cost. The average annual quantity of water conserved through this technique is not enormous, but when the savings from the SCP are combined with those possible from the other large ponds and reservoirs in Cyprus, evaporation reduction can make a significant contribution to total supply levels. In view of the low predicted cost of evaporation reduction, the process is particularly attractive. Evaporation reduction should be implemented alongside other non-conventional sources as an important part of an overall water supply enhancement strategy.

A pilot project should be undertaken as the first phase of a program to reduce evaporation losses from surface reservoirs in Cyprus. Data need to be collected on thermal stratification in all major Cypriot ponds and reservoirs, and a more detailed model should be used, as in the paper by Cox (1992). Destratification systems should then be studied at a single sizable reservoir, such as Kalavasos or Lefkara. Such a study will allow the appropriate type of destratification technology to be determined and an overall efficiency of evaporation reduction to be evaluated. Once the process is proven, destratification systems should be installed in all the reservoirs of the Southern Conveyor Project and at least the five other largest reservoirs in Cyprus.

Evaporation reduction by artificial destratification provides Cyprus with the opportunity to enhance its water supply at a low cost. In addition, since this technique has not yet been widely studied or applied, Cyprus can take the lead in developing a water-saving technology for use in all the arid regions of an increasingly thirsty world.

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APPENDIX A

SIMPLIFIED MODEL OUTPUT

Date	Air Temp (C)	Dew Point Temp (C)	Wind Speed (m/s)	Solar Rad (Langleys / day)	Net Solar Radiation (W/m2)	f(Uw)	e(AIR) (mbar)	e(Sat) (mbar)	Atmospheric Longwave (Swinbank, 1963)	Long-wave Back-radiation	Sensible Heat	Evaporation (w/m2))	Evaporation Mass Loss (mm/time step)	Sum of Energy Fluxes (W/m2)	Total Energy	Res Depth (m)	Water Temp	Total Yearly Evap (mm)
Year 1 - Steady State with Stratified Conditions																		
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	19.46	284.74	389.10	27.69	85.43	**23**	-75	2,803,245,315	40.00	16.73	**23**
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	19.10	284.74	387.53	26.01	82.06	**22**	-68	2,758,551,364	40.00	16.46	**45**
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	18.78	284.74	386.10	24.47	79.02	**21**	-62	2,717,794,194	40.00	16.22	**66**
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	18.49	284.74	384.81	23.07	76.30	**20**	-57	2,680,599,151	40.00	15.99	**86**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	18.23	286.48	383.63	19.62	73.90	**20**	-7	2,675,972,370	40.00	15.97	**106**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	18.20	286.48	383.48	19.47	73.61	**20**	-6	2,671,738,019	40.00	15.94	**126**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	18.17	286.48	383.35	19.32	73.34	**20**	-6	2,667,862,526	40.00	15.92	**145**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	18.14	286.48	383.22	19.19	73.09	**20**	-5	2,664,315,238	40.00	15.90	**165**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	18.12	293.17	383.11	13.85	74.28	**20**	50	2,697,454,855	40.00	16.09	**185**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	18.35	293.17	384.16	15.05	76.56	**20**	46	2,727,625,166	40.00	16.27	**205**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	18.56	293.17	385.12	16.13	78.65	**21**	42	2,755,076,523	40.00	16.44	**226**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	18.75	293.17	385.99	17.12	80.57	**22**	38	2,780,040,857	40.00	16.59	**248**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	18.93	316.41	386.79	-4.02	65.65	**18**	141	2,872,932,882	40.00	17.14	**265**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	19.61	316.41	389.76	-0.74	72.21	**19**	129	2,957,407,461	40.00	17.65	**284**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	20.25	316.41	392.47	2.24	78.36	**21**	117	446,369,306	5.00	21.31	**305**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	25.42	316.41	412.62	23.88	128.49	**34**	25	462,670,960	5.00	22.08	**340**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	26.66	338.15	417.00	9.34	96.25	**26**	109	534,522,323	5.00	25.51	**365**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	32.76	338.15	436.73	29.56	155.23	**41**	10	541,378,042	5.00	25.84	**407**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	33.40	338.15	438.65	31.49	161.43	**43**	0	541,633,382	5.00	25.85	**450**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	33.43	338.15	438.72	31.56	161.66	**43**	0	541,641,479	5.00	25.85	**493**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	33.43	363.30	438.72	11.90	136.92	**37**	78	592,705,642	5.00	28.29	**530**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	38.56	363.30	453.21	27.80	191.85	**51**	-8	587,713,495	5.00	28.05	**581**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	38.03	363.30	451.78	26.25	186.17	**50**	1	588,412,643	5.00	28.09	**631**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	38.11	363.30	451.98	26.47	186.96	**50**	0	588,317,567	5.00	28.08	**681**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	38.09	380.36	451.95	11.57	146.40	**39**	68	633,205,368	5.00	30.22	**720**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	43.11	380.36	464.96	25.55	200.07	**53**	-12	625,100,850	5.00	29.84	**773**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	42.16	380.36	462.59	23.03	189.95	**51**	3	626,860,882	5.00	29.92	**824**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	42.37	380.36	463.10	23.58	192.13	**51**	-1	626,490,054	5.00	29.90	**875**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	42.33	384.11	462.99	18.84	169.16	**45**	7	630,770,880	5.00	30.11	**920**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	42.82	384.11	464.24	20.08	174.12	**47**	-1	630,152,701	5.00	30.08	**967**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	42.75	384.11	464.06	19.91	173.40	**46**	0	630,244,128	5.00	30.08	**1,013**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	42.76	384.11	464.09	19.93	173.51	**46**	0	630,230,652	5.00	30.08	**1,059**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	42.76	370.03	464.09	28.80	202.94	**54**	-89	571,676,033	5.00	27.29	**1,114**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	36.37	370.03	447.20	13.15	144.26	**39**	2	573,054,471	5.00	27.35	**1,152**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	36.51	370.03	447.59	13.52	145.54	**39**	0	573,086,799	5.00	27.35	**1,191**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	36.51	370.03	447.60	13.53	145.57	**39**	0	573,087,521	5.00	27.36	**1,230**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	36.51	349.58	447.60	22.78	143.51	**38**	-68	528,112,162	5.00	25.21	**1,268**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	32.17	349.58	434.94	13.42	112.47	**30**	-15	518,003,388	5.00	24.73	**1,298**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	31.26	349.58	432.14	11.32	105.95	**28**	-4	515,403,903	5.00	24.60	**1,327**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	31.03	349.58	431.42	10.78	104.30	**28**	-1	514,716,736	5.00	24.57	**1,354**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	30.97	317.74	431.23	37.80	158.17	**42**	-158	2,998,328,011	40.00	17.89	**1,397**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	20.56	317.74	393.79	2.24	67.32	**18**	5	3,001,854,665	40.00	17.91	**1,415**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	20.59	317.74	393.91	2.35	67.56	**18**	5	3,005,076,606	40.00	17.93	**1,433**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	20.61	317.74	394.01	2.45	67.78	**18**	4	3,008,019,991	40.00	17.95	**1,451**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	20.63	293.32	394.11	19.86	71.25	**19**	-65	2,965,057,992	40.00	17.69	**1,470**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	20.30	293.32	392.72	18.68	68.76	**18**	-60	2,925,416,070	40.00	17.45	**1,488**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	20.00	293.32	391.44	17.60	66.49	**18**	-56	2,888,815,140	40.00	17.24	**1,506**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	19.73	293.32	390.27	16.59	64.43	**17**	-51	2,855,002,929	40.00	17.03	**1,523**

Date	Air Temp (C)	Dew Point Temp (C)	Wind Speed (m/s)	Solar Rad (Langleys / day)	Net Solar Radiation (W/m2)	f(Uw)	e(AIR) (mbar)	e(Sat) (mbar)	Atmospheric Longwave (Swinbank, 1963)	Long-wave Back-radiation	Sensible Heat	Evaporation (w/m2))	Evaporation Mass Loss (mm/time step)	Sum of Energy Fluxes (W/m2)	Total Energy	Res Depth (m)	Water Temp	Total Yearly Evap (mm)
Year 2 - Destratification Initiated producing well-mixed conditions																		
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	19.48	284.74	389.18	27.79	85.62	**23**	-75	2,805,709,550	40.00	16.74	**23**
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	19.12	284.74	387.61	26.09	82.22	**22**	-68	2,760,797,604	40.00	16.47	**45**
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	18.80	284.74	386.18	24.55	79.18	**21**	-62	2,719,843,344	40.00	16.23	**66**
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	18.51	284.74	384.87	23.14	76.43	**20**	-57	2,682,469,839	40.00	16.01	**86**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	18.24	286.48	383.69	19.68	74.02	**20**	-7	2,677,684,298	40.00	15.98	**106**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	18.21	286.48	383.54	19.52	73.72	**20**	-7	2,673,304,784	40.00	15.95	**126**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	18.18	286.48	383.40	19.38	73.44	**20**	-6	2,669,296,541	40.00	15.93	**145**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	18.15	286.48	383.27	19.24	73.18	**20**	-6	2,665,627,837	40.00	15.90	**165**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	18.13	293.17	383.15	13.90	74.37	**20**	50	2,698,650,187	40.00	16.10	**185**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	18.36	293.17	384.20	15.09	76.64	**20**	46	2,728,713,059	40.00	16.28	**205**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	18.57	293.17	385.15	16.17	78.73	**21**	42	2,756,066,094	40.00	16.44	**226**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	18.76	293.17	386.02	17.16	80.64	**22**	38	2,780,940,542	40.00	16.59	**248**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	18.94	316.41	386.82	-3.98	65.71	**18**	141	2,873,751,729	40.00	17.15	**265**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	19.62	316.41	389.78	-0.71	72.27	**19**	128	2,958,151,465	40.00	17.65	**285**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	20.25	316.41	392.50	2.27	78.42	**21**	117	3,034,775,762	40.00	18.11	**306**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	20.84	316.41	394.97	4.97	84.15	**22**	106	3,104,234,407	40.00	18.52	**328**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	21.39	338.15	397.23	-11.66	45.37	**12**	201	3,236,306,002	40.00	19.31	**340**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	22.47	338.15	401.54	-7.02	55.79	**15**	182	3,355,644,093	40.00	20.02	**355**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	23.49	338.15	405.47	-2.82	65.60	**18**	164	3,463,198,710	40.00	20.66	**373**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	24.43	338.15	409.03	0.96	74.78	**20**	147	3,559,900,454	40.00	21.24	**393**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	25.32	363.30	412.25	-18.20	50.17	**13**	221	3,705,123,370	40.00	22.11	**406**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	26.69	363.30	417.13	-12.55	64.90	**17**	196	3,833,754,283	40.00	22.87	**423**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	27.97	363.30	421.49	-7.54	78.52	**21**	173	3,947,284,715	40.00	23.55	**444**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	29.13	363.30	425.36	-3.12	91.00	**24**	152	4,047,161,435	40.00	24.15	**469**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	30.20	380.36	428.79	-14.11	61.87	**17**	202	4,179,675,209	40.00	24.94	**485**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	31.66	380.36	433.37	-8.95	77.51	**21**	176	4,295,513,965	40.00	25.63	**506**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	32.98	380.36	437.41	-4.44	91.71	**24**	154	4,396,403,843	40.00	26.23	**530**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	34.18	380.36	440.94	-0.51	104.51	**28**	133	4,483,982,794	40.00	26.75	**558**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	35.25	384.11	444.03	-0.28	98.73	**26**	115	4,559,555,748	40.00	27.20	**585**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	36.19	384.11	446.71	2.46	108.13	**29**	100	4,625,391,806	40.00	27.60	**614**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	37.03	384.11	449.05	4.84	116.50	**31**	87	4,682,621,908	40.00	27.94	**645**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	37.78	384.11	451.10	6.92	123.92	**33**	76	4,732,276,001	40.00	28.24	**678**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	38.44	370.03	452.88	18.46	163.24	**44**	-28	4,713,967,600	40.00	28.13	**721**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	38.19	370.03	452.22	17.85	161.00	**43**	-24	4,697,960,533	40.00	28.03	**764**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	37.98	370.03	451.65	17.31	159.06	**42**	-21	4,683,958,507	40.00	27.95	**807**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	37.80	370.03	451.15	16.84	157.37	**42**	-19	4,671,705,020	40.00	27.87	**849**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	37.64	349.58	450.71	25.05	151.55	**40**	-82	4,617,925,802	40.00	27.55	**889**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	36.94	349.58	448.79	23.65	146.56	**39**	-74	4,569,606,077	40.00	27.26	**928**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	36.32	349.58	447.07	22.39	142.14	**38**	-66	4,526,142,876	40.00	27.01	**966**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	35.77	349.58	445.53	21.26	138.22	**37**	-60	4,487,009,124	40.00	26.77	**1,003**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	35.29	317.74	444.14	49.53	195.88	**52**	-221	4,341,923,831	40.00	25.91	**1,056**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	33.53	317.74	439.03	44.92	180.55	**48**	-196	4,213,293,090	40.00	25.14	**1,104**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	32.04	317.74	434.54	40.84	167.52	**45**	-174	4,098,858,341	40.00	24.46	**1,149**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	30.76	317.74	430.57	37.20	156.36	**42**	-155	3,996,752,590	40.00	23.85	**1,190**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	29.66	293.32	427.06	46.97	139.20	**37**	-193	3,869,688,324	40.00	23.09	**1,228**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	28.33	293.32	422.71	43.48	129.22	**35**	-176	3,754,322,888	40.00	22.40	**1,262**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	27.17	293.32	418.79	40.32	120.50	**32**	-160	3,649,337,399	40.00	21.77	**1,294**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	26.16	293.32	415.25	37.44	112.84	**30**	-146	3,553,603,624	40.00	21.20	**1,324**

EVAPORATION REDUCTION:	**13.05%**

Date	Air Temp (C)	Dew Point Temp (C)	Wind Speed (m/s)	Solar Rad (Langleys / day)	Net Solar Radiation (W/m2)	f(Uw)	e(AIR) (mbar)	e(Sat) (mbar)	Atmospheric Longwave (Swinbank, 1963)	Long-wave Back-radiation	Sensible Heat	Evaporation (w/m2))	Evaporation Mass Loss (mm/time step)	Sum of Energy Fluxes (W/m2)	Total Energy	Res Depth (m)	Water Temp	Total Yearly Evap (mm)
Year 3 - Destratification continues with well-mixed conditions																		
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	25.26	284.74	412.04	51.79	140.18	**37**	-176	3,437,672,801	40.00	20.51	**37**
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	24.21	284.74	408.18	47.81	130.25	**35**	-159	3,333,420,313	40.00	19.89	**72**
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	23.29	284.74	404.73	44.22	121.64	**32**	-143	3,239,450,364	40.00	19.33	**105**
Jan	12.21	7.51	4.06	350.00	142.82	15.23	10.41	22.50	284.74	401.64	41.00	114.11	**30**	-129	3,154,575,479	40.00	18.82	**135**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	21.80	286.48	398.87	35.50	106.73	**29**	-71	3,107,935,542	40.00	18.54	**164**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	21.42	286.48	397.35	33.94	103.27	**28**	-64	3,065,595,035	40.00	18.29	**191**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	21.08	286.48	395.97	32.52	100.17	**27**	-59	3,027,125,332	40.00	18.06	**218**
Feb	12.50	7.22	3.96	450.00	183.63	14.85	10.20	20.78	286.48	394.72	31.23	97.40	**26**	-53	2,992,146,210	40.00	17.85	**244**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	20.51	293.17	393.59	25.65	97.94	**26**	4	2,995,099,532	40.00	17.87	**270**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	20.53	293.17	393.69	25.76	98.17	**26**	4	2,997,772,481	40.00	17.89	**296**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	20.55	293.17	393.78	25.85	98.37	**26**	4	3,000,191,541	40.00	17.90	**323**
Mar	13.60	7.79	4.25	560.00	228.51	15.95	10.61	20.57	293.17	393.85	25.94	98.56	**26**	3	3,002,380,716	40.00	17.91	**349**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	20.59	316.41	393.92	3.83	81.71	**22**	110	3,074,881,350	40.00	18.35	**371**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	21.16	316.41	396.27	6.38	87.20	**23**	100	3,140,548,317	40.00	18.74	**394**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	21.68	316.41	398.41	8.70	92.29	**25**	90	3,199,944,969	40.00	19.09	**419**
Apr	17.27	9.81	4.17	670.00	273.40	15.63	12.16	22.17	316.41	400.35	10.79	96.99	**26**	82	3,253,602,768	40.00	19.41	**445**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	22.61	338.15	402.11	-6.41	57.19	**15**	179	3,371,249,516	40.00	20.11	**460**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	23.62	338.15	405.98	-2.27	66.91	**18**	161	3,477,243,311	40.00	20.75	**478**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	24.56	338.15	409.50	1.46	76.00	**20**	145	3,572,511,236	40.00	21.32	**498**
May	20.50	14.63	4.16	720.00	293.80	15.59	16.70	25.43	338.15	412.68	4.81	84.43	**23**	130	3,657,949,874	40.00	21.83	**521**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	26.24	363.30	415.54	-14.38	60.04	**16**	204	3,792,022,727	40.00	22.63	**537**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	27.55	363.30	420.07	-9.16	74.04	**20**	180	3,910,494,618	40.00	23.33	**556**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	28.75	363.30	424.10	-4.55	86.91	**23**	159	4,014,829,945	40.00	23.95	**580**
Jun	24.03	17.94	4.60	740.00	301.97	17.25	20.63	29.85	363.30	427.68	-0.49	98.65	**26**	139	4,106,434,523	40.00	24.50	**606**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	30.84	380.36	430.83	-11.81	68.78	**18**	190	4,231,544,883	40.00	25.25	**624**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	32.25	380.36	435.18	-6.93	83.81	**22**	166	4,340,733,494	40.00	25.90	**647**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	33.52	380.36	438.99	-2.68	97.40	**26**	145	4,435,691,296	40.00	26.47	**673**
Jul	26.31	20.65	4.60	730.00	297.89	17.26	24.41	34.66	380.36	442.33	1.02	109.60	**29**	125	4,518,011,944	40.00	26.96	**702**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	35.67	384.11	445.24	0.95	102.94	**27**	108	4,589,219,147	40.00	27.38	**730**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	36.57	384.11	447.77	3.53	111.88	**30**	94	4,651,192,030	40.00	27.75	**759**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	37.37	384.11	449.97	5.78	119.83	**32**	82	4,705,017,769	40.00	28.07	**791**
Aug	26.80	21.25	4.28	670.00	273.40	16.05	25.33	38.07	384.11	451.90	7.73	126.85	**34**	71	4,751,682,801	40.00	28.35	**825**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	38.70	370.03	453.57	19.11	165.62	**44**	-32	4,730,925,603	40.00	28.23	**870**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	38.42	370.03	452.83	18.41	163.07	**44**	-28	4,712,787,238	40.00	28.12	**913**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	38.18	370.03	452.18	17.81	160.86	**43**	-24	4,696,928,246	40.00	28.02	**956**
Sep	24.94	17.97	3.95	580.00	236.68	14.81	20.66	37.97	370.03	451.61	17.28	158.94	**42**	-21	4,683,055,300	40.00	27.94	**999**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	37.79	349.58	451.11	25.34	152.61	**41**	-84	4,628,116,467	40.00	27.61	**1,039**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	37.07	349.58	449.15	23.91	147.50	**39**	-75	4,578,766,628	40.00	27.32	**1,079**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	36.44	349.58	447.39	22.63	142.97	**38**	-68	4,534,386,235	40.00	27.05	**1,117**
Oct	22.13	14.38	3.07	480.00	195.87	11.53	16.44	35.88	349.58	445.82	21.48	138.96	**37**	-61	4,494,434,163	40.00	26.82	**1,154**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	35.38	317.74	444.40	49.77	196.68	**53**	-222	4,348,493,861	40.00	25.95	**1,206**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	33.61	317.74	439.26	45.13	181.23	**48**	-197	4,219,128,249	40.00	25.17	**1,255**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	32.10	317.74	434.74	41.02	168.10	**45**	-175	4,104,057,330	40.00	24.49	**1,300**
Nov	17.47	10.63	3.75	370.00	150.98	14.08	12.85	30.82	317.74	430.75	37.37	156.86	**42**	-156	4,001,397,461	40.00	23.87	**1,342**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	29.71	293.32	427.22	47.10	139.57	**37**	-194	3,873,900,143	40.00	23.11	**1,379**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	28.37	293.32	422.85	43.60	129.55	**35**	-176	3,758,151,441	40.00	22.42	**1,414**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	27.21	293.32	418.92	40.43	120.79	**32**	-160	3,652,825,100	40.00	21.79	**1,446**
Dec	13.63	8.56	3.24	310.00	126.50	12.15	11.18	26.19	293.32	415.37	37.54	113.09	**30**	-146	3,556,786,895	40.00	21.22	**1,476**

EVAPORATION REDUCTION:	**3.09%**