WATER AND SALT MANAGEMENT STRATEGIES IN A CLOSED DRAINAGE BASIN

by

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ABSTRACT

The Fayoum basin of Egypt is a closed basin with a lack of natural drainage outlets. The saline drainage water disposed of and impounded into Lake Qaroun is subject to evapoconcentration. As a result of these physical and environmental constraints, water and salt management are generally hampered, and salt accumulation in the lake can reach hazardous levels. In order to assess alternative water and salt managment scenarios, mathematical models of lake evaporation, as well as lake routing and basin water balance were developed and tested.

Findings from model simulations showed that the most suitable scenario for reducing salinity in Lake Qaroun was to divide the lake into two compartments. The smaller compartment, located at the east end of Lake Qaroun, will have relatively fresh water with a salinity level of 13.3 dS/m, and a water level of -43.79 m MSL. The other compartment, located at the west end of Lake Qaroun, will have saline water (72.2 dS/m). Evaporation ponds of 6 km^2 are required to evacuate the salt load of 620,000 tonnes/year.

Based on water balance simulations, it was recommended that the water level of Upper Wadi Rayan Lake be -8.7 m MSL, and total inflows into Lake Qaroun and the basin be 417 MCM/year, and 2430 MCM/year, respectively. It was further concluded that increasing the reuse of drainage water can conflict

with expansion of the irrigated area. Therefore, it is recommended that the potential for drainage water reuse be limited to a maximum of 275 MCM/year, which allows for a high overall irrigation efficiency of 70%, and a reclamation of 2,226 ha.

Further water balance simulations showed that without increasing the total irrigation intake amount, water shortages can be avoided by improving the match between supply and crop water demand. With an overall irrigation efficiency of 70%, and expansion of irrigated land of 2,226 ha, the drainage water reuse is a maximum of 195 MCM/year.

RESUME

Le bassin versant Fayoum en Egypte est un bassin fermé n'ayant aucun drainage naturel. Des eaux de drainage salées sont evacueés et entreposées dans le lac Qaroun, où elles deviennent sujet à la concentration par évaporation. Suite à ces contraintes physiques et environnementales, la gestion d'eau et de sel y est généralement difficile. L'accumulation de sels dans le lac peut atteindre des niveaux dangeureux. Afin d'évaluer différentes alternatives de gestion eau / sel, des modèles mathématiques portant sur l'évaporation lacustre, l'acheminement des eaux, et l'équilibre en eau du bassin versant, furent développés et mis à l'épreuve.

Les résultats des modèles de simulation ont indiqué que la division du lac en deux compartiments serait le scénario qui conviendrait le mieux afin de réduire la salinité du lac Qaroun. Le plus petit compartiment, situé à l'extremité est du lac Qaroun, contiendrait une eau relativement douce, avec une salinité de 13.3 dS/m et un niveau de -43.79 m NMS. L'autre compartiment, à l'extremité ouest du lac, contiendrait une eau salée (72.2 dS/m). Des étangs d' évaporation d'une superficie de 6 km^2 seraient necessires pour disposer de la charge en sels de 620,000 t/an.

Selon la simulation d'équilibre en eau, il fut recommandé que le niveau du lac le plus en amont (lac Wadi Rayan) soit à -8.7m NMS, et que l'influx total

atteignant le lac Qaroun et le bassin Fayoum soit de 4.17 x 10^8 m^3/an et 2.43 x 10^9 m^3/an respectivement. De plus il fut démontré qu'augmenter la réutilisation d'eau de drainage pourrait nuire à l'expansion de l'aire irriguée. Il fut donc recommandé que le nireau potentiel de réutilisation d'eau de drainage soit limité à 2.75 x 10^8 m^3/an, ce qui permettrait terant une hausse globale en irrigation de 70% et la mise en valeur de 2,226 ha.

Une autre simulation d'équilibre en eau montre que sans augmenter l'apport total d'irrigation, le manque d'eau pourait être évité en faisant que la provision et la demande en eau de la culture soient semblables. Avec une efficacité d'irrigation d'ensemble de 70% et une expansion de l'aire irriguée de 2,226 ha, la réutilisation d'eau de drainage serait limitée à un maximum de 1.95 x 10^8 m^3/an.

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CONTRIBUTIONS TO KNOWLEDGE

In this thesis, water and salt management strategies for Egypt's Fayoum drainage basin were studied. Based on the results of this research, this thesis provides the following contributions to knowledge:

1. An energy budget model was developed to estimate monthly and annual lake evaporation. The model is applicable to shallow lakes such as Lake Qaroun.
2. The model represents an improvement over other evaporation models in that a modification was made to the energy equation to calculate evaporation from saline lakes.
3. A lake routing model was developed to predict water and salinity levels in Lake Qaroun. The model can assess the effects of various drainage water disposal options.
4. The model incorporates a new feature of considering Lake Qaroun as a series of compartments. This research developed new solutions for the salinity problems in Lake Qaroun. By dividing the lake into two compartments, the salinity level in the fresh water zone will be 81.5% less than the saline portion.
5. By developing a basin-scale water balance model, this research answered some questions concerning irrigation water management under present conditions in the Fayoum basin. The model simulations clarified that although

the increased drainage water reuse could conflict with expansion of the irrigated area, this limitation could be overcome with a higher overall irrigation efficiency. The model simulations also showed that improving the match between water supply and crop water demand in time can significantly reduce water shortages.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	area emitting radiation
A_i	surface area of each lake compartment
A_s	Lake Qaroun surface area
AD	average absolute deviation
AM	average mean of difference
BCM	billion m^3
b	weir width
C	coefficient of the saline solution with certain ionic composition
C_{clouds}	cloudiness correction
C_m	concentration of the substance in the volume (m)
C_{ni}	concentration of the adjacent volume (ni)
C_{pda}	specific heat at completely dry air
C_{pm}	specific heat at moist ambient air
CD	coefficient of determination
CF	transfer coefficient over the water body
CI	salinity of the lake inflow
CO	salinity of the lake outflow
COMP	compartment
CRM	coefficient of residual mass
CV	lake salinity
^oC	degree celsius
cm	centimetres
co	salinity of the flow transferred (co = cv)
cv	salinity of the compartment
D	Julian or calander day
DRI	Drainage Research Institute
d	actual distance between the earth and the sun
dS/m	decisiemen per metre
d'	average distance from the earth to the sun
E	evaporation from water surface
E_f	evaporation rate from a freshwater body
E_n	evaporation rate from pan n
E_{ss}	evaporation rate from the saline water surface
E_v	lake evaporation
E_1	evaporation rate from pan 1
EF	modeling efficiency
E'	bulk diffusion coefficient
e_a	actual vapor pressure in the air
e^o	saturation vapor pressure,kPa
e^o_{db}	saturation vapor pressure at the dew point temperature,
e^o_{so}	saturation vapor pressure at 0°C
e_s	saturation vapor pressure at the temperature of the water surface

$e_s(T_{ss})$	saturation water vapor pressure over the saline water
FDA	Fayoum Irrigation Department
FID	Fayoum Irrigation Department
fed	feddan
feddan	feddan (fed)=0.42 hectare
$f(N,u)_f$	transfer coefficient over the freshwater
$f(N,u)_{ss}$	transfer coefficient over the saline water body
HAD	High Aswan Dam
H	depth of flow over the weir
ha	hectares
I	rate of the saline drainage disposal into the lake
J	Joule
K	coefficient that depends on a number of factors including temperature and chemical characteristics of the reacting substances
K	kelvin
kg	kilogram
kJ	kilojoule
km	kilometre
kpa	kilopascal
k	decay rate of the compartment
L	latitude in degree
L	long wave radiation
L	lake water level
L or l	litre
MCM	million m^3
ME	maximum error
MJ	megajoule
MPWWR	Ministry of Public Works and Water Resources
m	metre
mg	milligram
m MSL	elevation expressed in metre above mean sea level
mm	millimetre
NA	not available
N	mass transfer coefficients for the entire lake
N	possible hours of sunshine
n	measured hours of sunshine
O	rate of outflow from the lake
P	atmospheric pressure
P_r	precipitation directly on the water body
ppm	parts per million
Q	flow transferred from one compartment to another (over the weir)
Q_a	incoming long-wave radiation
Q_{ar}	reflected incoming long-wave radiation
Q_{bs}	long-wave radiation emitted by body of water

Q_e	energy used for evaporation
Q_h	sensible-heat transfer (conduction) to the atmosphere
Q_{in}	saline drainage water entering the lake
Q_m	rate at which water flows through the volume (m)
Q_{ni}	rate at which water flows from the adjacent volume (ni)
Q_r	reflected global radiation
Q_s	incoming global radiation
Q_v	advected energy
$Q\theta$	increase in energy stored in the water body
q	specific humidity, a dimensionless ratio
RH	relative humidity as a decimal
R(S)	net outgoing long wave radiation
RMSE	root mean square error
R_a	extraterrestrial solar radiation
R_n	net (all-wave) radiation absorbed by the water body
R_s	solar radiation
R_{nl}	net outgoing long wave radiation
R_{ns}	net short wave radiation
S	sunshine ratio
S	salinity at the water surface
S	short wave radiation
SC	solar constant
SD	standard deviation of differences
SE	standard error
T	air temperature
T_a	temperature in air
T_s	temperature at the evaporating surface
T_k	average daily air temperature
t	time
u	representative mean wind speed
V	Lake Qaroun volume
v_i	volume of each lake compartment
z	elevation above sea level
W	net mass load
α_R	albedo
α	reduction in evaporation due to salinity
δ	declination of the sun
Δ	slope of vapor pressure
ΔE	decrease in evaporation rate caused by the salt water
Δe_s	decrease in the saturation vapor pressure
ΔS	change in Lake Qaroun storage
Δt	time increment
ΔWL	change in water levels every January
ε	ratio of the mole weight of water to air
ε'	emissivity

ε'_{bulk}	combined air and earth emissivity
$\varepsilon_{surface}$	emissivity of the water
ε_{sky}	emissivity of the sky
γ	psychrometric constant
λ	latent heat of vaporization
Θ	zenith angle of the sun
ω	hour angle
Ψ	relative humidity
ρ	density of moist air
ρ_v	density of water vapor in the air
σ	Stefan-Boltzmann constant
$\sum A_n$	total surface area of the all compartments
$\sum v_n$	total volume of all the lake compartments

AUTHORSHIP AND MANUSCRIPT

Traditional and Manuscript-based Thesis. The doctoral dissertation can consist of either a single thesis or a collection of papers that have a cohesive, unitary character that allows them to be considered as a single programmatic research product. If the manuscript-based structure for the thesis is chosen by the candidate, the following provisions are applicable. **The text of the following paragraphs below must be reproduced in full in the preface of the thesis** (in order to inform the external examiner of faculty regulations):

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2. If this option is chosen, **connecting texts that provide logical bridges between the different papers are mandatory**. The thesis must be written in such a ways that it is more than a mere collection of manuscripts, in other words, results of a series of papers must be integrated.
3. The thesis must still conform to all other requirements of the "Guidelines for Thesis Preparations". **The thesis must include**: A table of Contents, an abstract in English and French, an introduction which clearly states the rationale and objective of the study, a comprehensive review of the literature, a final conclusion and summary and a thorough reference list.
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CHAPTER ONE

INTRODUCTION

Agriculture in Egypt is almost entirely dependent on irrigation; the country has no effective rainfall except for a narrow band along the northern coastal areas, while the main source of water is the Nile River. Irrigation agriculture in Egypt is considered a major economic sector that has a significant social dimension. The Egyptian irrigation and drainage network is one of the oldest in the world, having evolved over centuries. Operation of the system by both operators and farmers has been very efficient for decades. Nevertheless, as population increases the pressing water requirements created force water policy makers to search for possibilities for conserving and saving Nile River irrigation water.

1.1 Background

The Nile River provides Egypt with 85% of its annual water requirements for Agricultural purposes. The High Aswan Dam (HAD) is the major control structure on the river in Egypt, controlling releases from Lake Nasser to serve irrigation and other water requirements according to monthly schedules of demand. Water is diverted and supplied to the inhabited areas by means of control structures and man-made network of canals. Water is collected and disposed of by a system of artificial drains.

The drainage system has a hierarchical structure consisting of field drains, predominantly of the subsurface type performing the dewatering function, and a main system of open channels for collecting and disposing drainage water. Following the shift of seasonal flooding to perennial irrigation, drainage of agricultural land in the Nile Delta and Valley became necessary in order to check waterlogging and reduce soil salinity. This shift occurred after the completion of the High Aswan Dam in 1968.

Most of the drainage water from the valley (Upper Egypt) flows back to the Nile as return flow. The drainage water of the Nile Delta is disposed into northern lakes or the Mediterranean Sea. The Fayoum region is characterized by a deep depression that forms a closed basin. The region's drainage water is disposed into its lowest point that forms Lake Qaroun, and into a nearby depression that forms the Wadi Rayan Lakes.

Water losses from the irrigation distribution system include both fresh water and drain water disposed of in the Mediterranean sea or lakes, evaporation from the surface of the Nile channel and the distribution network of canals and drains, and water losses to deep groundwater aquifers.

1.2 Fresh and Drainage Water Disposal

In the following sections, the types of water losses incurred at three operational levels are discussed:

i. macro level (the overall irrigation and drainage system);

ii. directorate level (the main or branch canal system);

iii. field level (the mesqa, tertiary distibutaries, system).

Fresh water flowing directly to the sea, canal disposal into the drainage system, and drainage water of good quality lost to the sea are the main losses presented.

1.2.1 Macro Level Disposal

(i.) Fresh water disposal:

The water released from the HAD during the low requirement season that flows directly to the sea may be considered as the first form of fresh water spilled from the system at the macro level. The average annual quantity of fresh water drained into the Mediterranean is approximately 6.7 BCM (from 1974/75 to 1983/84), and 2.3 BCM (from 1984/85 to to 1993/94). During 1993/94, it reached its minimum of 1.15 BCM. This reduction in the quantity of disposed water may have occurred for two reasons: firstly, the horizontal expansion of irrigated agricultural land from about 6 million feddans (feddan=0.42 hectare) in 1975 to 7.7 million feddans in 1993, and secondly, the shortage in the Nile River yield due to the period of drought experienced by Nile Basin countries may have led to extensive use and reuse of Nile River water before it reached the Mediterranean.

The second form of water disposal at the macro level is drainage water collected from the Delta area and pumped into the northern lakes and the Mediterranean. Over the period 1984/85-1994/1995, this volume of water varied between 11.5 BCM (1988/89), and 13.7 BCM (1984/85) (DRI, 1993b and Abdel-Dayem, 1997b).

(ii.) Drainage water reuse:

As water shortages are experienced in many locations at the tail-ends of canals, drainage water, if available, is used either officially, by pumping it into canals, or unofficially through diesel pumps used by farmers. The extent of drainage water use for irrigation is dependent on its salinity level, which may harm crop yield or adversely affect the soil. Previous studies carried out by the National Water Research Center (NWRC) have suggested that if the salinity of drainage water is less than 1.56 dS/m, then this water can be used to irrigate agricultural land without mixing with fresh water, and without threat of damage or adverse effects to crop yield (DRI, 1993a and Abdel-Dayem, 1994). If the salinity level is between 1.56 dS/m and 3.13 dS/m, it is recommended that drainage water be mixed with canal water at a ratio of 1:1 to obtain an acceptable quality of irrigation water. If the drainage water salinity exceeds 3.13 dS/m, it is recommended that this water not be used for irrigation, and that it be removed from the system and discharged to the sea. In 1994/1995, the total drainage water reused was estimated at 3.4 BCM.

1.2.2 Main Canal or Distributary Disposal

Disposals at this level are from the tail-ends of main canals, branch canals, as well as distributaries into the drainage system, and cannot be recovered or reused. For the irrigated area located in Upper and Middle Egypt, the drainage system carries the flow back to the main Nile channel, while in the Delta, the drains discharge water into the Mediterranean sea. Disposal may occur during the night when farmers do not irrigate, and when there is water in the distributary canals or the mesqas, according to a particular schedule for plantation.

Drainage water is reused for irrigation at this level as a compensation for less water delivered to the directorates than target requirements. Reuse of drainage water at the directorate level is dependent on the availability of appropriate quality drainage water in the drains within the borders of the directorate.

1.2.3 Mesqa and Field Disposal

If water in the mesqa is not used, it flows into the drains and may not be recovered. This type of disposal may occur only for a few days within the year, and the water lost to the drainage system may be used by farmers at the tail-end of other mesqas. District engineers operating the mesqa gates try not to allow any fresh water spillage into the drainage system as they are always faced with water shortages at tail-ends of branch canals and distributaries. The main contributor or source of drainage water is deep percolation from the root zone in excess of crop consumptive use, and surface runoff from fields. Surface runoff from fields may occur because of the change in the on-farm irrigation practice from the saqia (water wheel) system to the pumping system, which conveys more water to the fields.

1.3 The Nature of the Problem

The natural drainage system of the Fayoum basin discharges surface runoff and subsurface drainage into Lake Qaroun, which is situated in the lowest part of this closed basin. The lake has no outlet and the drainwater impounded is subject to evapoconcentration.

The disposal of saline drainage water into the lake has a deteriorating effect on lake water quality. Over the period 1980-1996, the annual average inflow was 445×10^6 m^3, with a salt load of 540×10^6 kg/year. The average annual lake level (1995) was - 43.68 m MSL, with a lake surface area of 241 km^2 and lake volume of 1087×10^6 m^3. The average salt concentration over the period (1990-1995) was 45 dS/m with a total salt load of 51000×10^6 kg. The potential problem of drainage water disposal is the accumulation of salt in lake Qaroun to hazardous levels harmful to fish, wildlife, tourism and ultimate disposal. The lake water quality tends to deteriorate with time as evaporation leads to increasing levels of salinity from the inflow of (saline) drainage water.

1.3.1 Desired Lake Users

Lake Qaroun is principally used as a drainage sump for the irrigated area in the Fayoum basin. In addition, Lake Qaroun is an important recreational resource, used for boating and swimming, and providing tourists with a setting of solitude and relaxation. The lake is also a place rich in wildlife and a valuable source of fish. Consequently, Lake Qaroun has an annual commercial value, in terms of food supply and tourism, of many millions of dollars. Lake Qaroun therefore demonstrates a delicate and difficult balance between utilisation and carrying capacity. Before undertaking a management strategy to find a solution, these varied usages and their limitations need to be defined.

(i.) Agricultural considerations:

When the lake level falls below -43.80 m MSL, almost all of the drainage water can be evacuated by gravity. When the lake level rises above -43.20 m MSL, drainage water from 20,000 feddans is evacuated by pumping (DRI,1993b). Therefore, it is assumed provisionally that drainage interests require maintaining a lake level that permits gravity drainage of most of the lands bordering the lake. Lake Qaroun should be kept at the prescribed levels (e.g., average -43.80 m MSL; minimum -44.10 m MSL; maximum -43.5 m MSL).

(ii.) Fish and wildlife considerations:

The deterioration of the lake's water quality is rapidly changing the ecosystem and creating a situation that will eventually lead to the complete loss of flora or fauna near the shores and within the lake. One particular example is the large number of migratory birds that winter in, or pass through, this area. If the ecological deterioration is not halted and improvements initiated, these extensive and varied flocks will vanish entirely (Haas, 1990).

Commercial fish species show a severe decline when the salinity of the lake water exceeds 37 dS/m (Euroconsult, 1992). Since the lake's salinity is currently about 51 dS/m and continuously increasing, the commercial and subsistence fisheries will, within the next two decades, entirely disappear. The interest of the fisheries are, therfore, to maintain a suitable lake salinity (between 19 and 35 dS/m) (Euroconsult, 1992).

(iii.) Tourism and infrastructure considerations:

Lake Qaroun and its shores are an important tourism resource. It is the closest recreational region to Cairo and features long beaches and a variety of hotels. Consequently, Lake Qaroun plays a vital role in the province's tourism sector, providing fishing, boating, swimming and general leisure activities. The beaches themselves are mainly mud flats, occasionally improved by spreading a layer of sand. At lower lake levels, the beaches could potentially be extended (Euroconsult, 1992). Rising water levels, however, endanger the infrastructure and tourist facilities built near the lake. As a result, tourism interests dictate both a maximum permissible water level with only minor seasonal variations and control of salinity levels.

1.3.1.1 User Conflicts

User conflicts arise from limitation in the salinity and water levels suitable for respective activities. Decreasing Lake Qaroun's water level will increase its salinity and vice versa. The interest of tourism and agriculture can be accommodated by a water management policy that ensures a stable lake level with narrow margins of fluctuation. A proposed average lake level is -43.80 m MSL with fluctuations of approximately $\pm$ 0.25 m. To maintain a suitable water salinity for fisheries and wildlife, Lake Qaroun requires a gradual increase in volume which conflicts with the other parties interests. It is suggested that the average lake salinity should be kept around 20 dS/m. Such conflict must therefore be factored into lake management based on criteria acceptable to interest groups. An important goal of this study, therefore, is to develop a compatible lake management plan with environmentally acceptable solutions.

1.4 Study Objectives

The overall objective of this thesis is to study water and salt management strategies in the closed drainage basin represented by Egypt's Fayoum drainage basin. The specific objectives are to:

i. develop an evaporation model to estimate the evaporation rates from Lake Qaroun as influenced by lake salinity;

ii. develop a lake routing model for water and salt control in Lake Qaroun (the model can assess the effect of various drainage water disposal options);

iii. develop a basin water balance model to study the irrigation management strategies in the Fayoum basin;

iv. use the collected information from the study area and the models' simulations to assess various salt and water management options for lake salinity control and for basin irrigation water strategies, and formulate the acceptable scenarios.

1.5 Thesis Presentation

The structure of the present thesis is as follows. In the literature review (Chapter 2), a total of five cases, discussing the disposal of saline water, are brought together from different parts of the world. The description of the Fayoum basin is reviewed in Chapter 3. It includes the description of the area, soils, agriculture, irrigation and drainage system, as well as projects for the reuse of drainage water, and structure of the Fayoum Irrigation Department.

Chapter 4 presents a study on the evaporation of Lake Qaroun as influenced by lake salinity. A model for estimating monthly and annual Lake evaporation is developed using energy budgets for Lake Qaroun. A modification is made to the energy equation to allow the calculation of evaporation from saline lakes by analysing data from four evaporation pans with different salinities.

Chapters 5 and 6 present a study on Lake Qaroun management for salinity control. The serious constraint of salt and water disposal which is making it difficult to control salinity is presesented. To assess various water and salt management strategies for salinity control, a computer simulation model, simulating the interrelated processes and interventions in space and time, is developed. The different management options presented in Chapter 6 deal mainly with the following strategies: (i.) constructing regional evaporation ponds, and (ii.) dividing Lake Qaroun into a series of compartments separated by dams.

Chapters 7 and 8 present a study on the water management in the irrigated land in the Fayoum basin. The constraints which hamper water management in the basin are discussed. In order to assess alternative water management scenarios, a mathematical model is developed and tested, simulating water balances in the Fayoum basin and Lake Qaroun under present conditions. Chapter 8 answers several questions, such as the determination of the actual demand, the effects of drainage water reuse, fluctuations in water level of Lake Qaroun, and the water balances for other proposed horizontal expansion.

The general conclusions of the study and recommendations for future research work are included in Chapters 9 and 10, respectively.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background

The outlet of a drainage basin is normally a convenient low point on a component of the hydrological system suitable to act as a recipient for drainage water. In drainage basins, saline drainage water is disposed of either by discharging into another body of water, such as a river or lake, or into a nearby depression. Drainage water can be disposed of without seriously affecting the water quality of the receiving water body. However, in some cases, the resulting mixture is unsatisfactory for future use. In these cases, solutions or other means of disposal must be adopted.

In the natural world, without the interference of mankind, rivers play the role of drains; oceans and seas play the role of salt sinks. Salt is generated by the continuous weathering of soil minerals. Depending upon the particular river, these salts are carried in differing degree of natural concentration. Irrigation projects turn waters of low salt concentration, introduced into the basin, into waters of reduced volumes and higher salt concentrations. In many arid regions, where rivers both supply irrigation water and carry drainage water, a river's water volume, after receiving the saline drainage water disposal, will have a higher salt concentration.

This is due to the fact that the same river will transport a diminished volume of water with the same, or larger quantities of salt (Willardson, 1993).

In Egypt, the disposal of saline drainage water takes different forms. Disposal into the Mediterranean sea and coastal lakes occurs from main drains in the Nile Delta. In 1996, the disposal of saline drainage water was estimated to be 1242 MCM. With the exception of the Fayoum region, all drainage water produced in the Nile Valley until the south of Cairo returns to the river's main course. In the Fayoum region, the saline drainage water is disposed into Lake Qaroun and the Wadi Rayan depression. In 1996, the total disposal volume was estimated to be 650 MCM (Ali and Madramootoo, 1996).

The Dead Sea (401 metres below sea level), the Great Salt Lake (1200 metres above sea level), and the Aral Sea (41 metres above sea level) are examples of areas where large scale disposal of drainage water by evaporation occurs. Where large quantities of fresh water (containing some salt at relatively low concentration) are brought into an irrigated basin with a limited natural drainage capacity, the imported salts will accumulate in the soil, in the groundwater and in the surface water. An example is the Salton Sea in the Imperial Valley of California, created and maintained by surface runoff, subsurface seepage and drainage from imported irrigation water. The Salton Sea, which appeared in 1902 when fresh water first ran into a geological depression, is now more salty than sea water and is accumulating salt at a rate of 9000 tons per day (Willardson, 1993).

2.2 Case Histories on the Disposal of Saline Water

A total of five case histories on the disposal of saline water are brought together from different parts of the world. They represents the following contributions:

I. Salinity in the River Murrary in South Australia;

II. Disposal of saline drainage water in India;

III. Left bank outfall drain in Pakistan;

IV. Agriculture return flow management in Tulare Lake;

V. A disposal of saline water in the Mexicali Valley irrigation district.

2.2.1 Salinity in the River Murrary in South Australia (Noora Drainage Disposal Scheme)

Approximately 1.3 million tonnes of salt enters the river Murray each year. Thirty six per cent of this total 470,000 tonnes enters the River in South Australia (Smith, 1987). Figure 2.1 shows the River Murray Catchment.

In 1968, following a period of low river flows and consequent high salinities, the River Murray Commission (RMC) started to investigate the salinity problem. RMC (1970) reported tentative proposals for salinity investigation. Its report stimulated the three States which are party to the River Murray Waters agreement (the Governments of South Australia, Victoria, New South Wales and the Commonwealth) to undertake further investigations and develop detailed control proposals. In South Australia, the result was an Engineering and Water

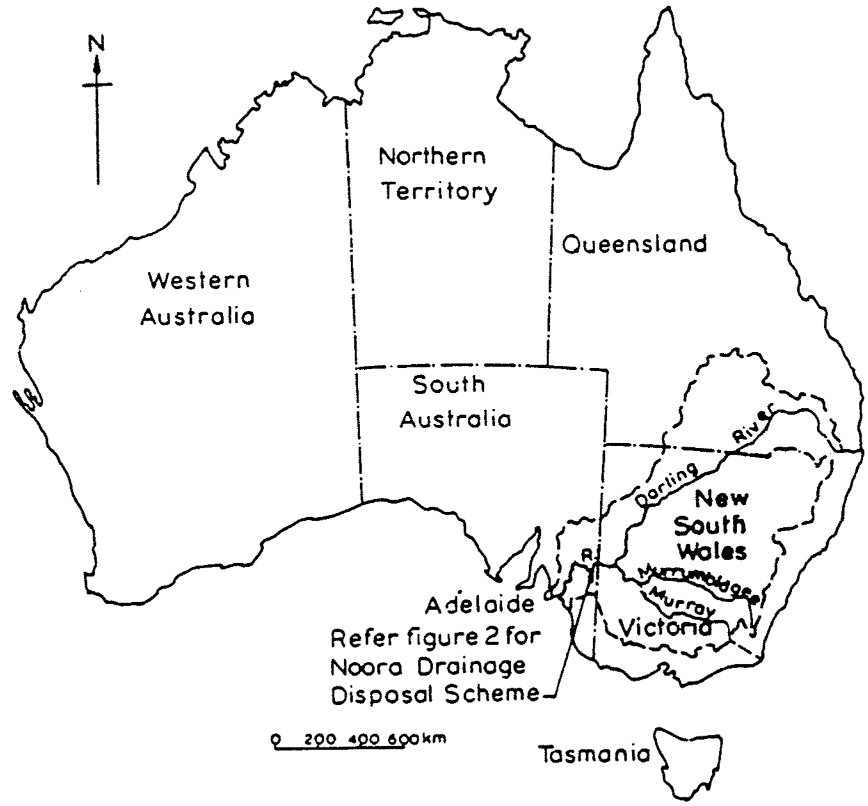


Figure 2.1 River Murray catchment

Supply Department report (EWSD, 1978). The main proposal, in terms of both cost and contribution to salinity reduction, was the Noora Drainage Disposal Scheme, involving the pumping of saline drainage water from the riverside evaporation basins (Berri, Dishers Creek and Bulyong Island), which serve the Berri and Renmark irrigation areas, to a new evaporation basin at Noora, a natural depression 20 km east of Loxton (Figure 2.2).

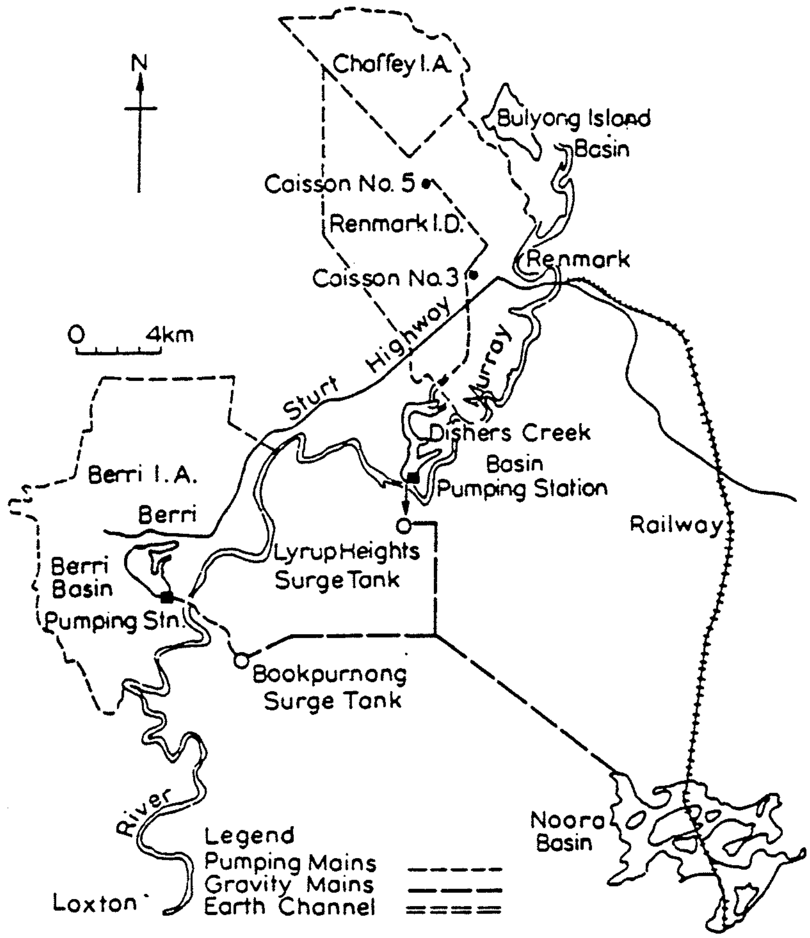


Figure 2.2 Noora drainage disposal scheme

The significance of the evaporation basins in contributing to salinity was highlighted in the 1978 report, which estimated that about 100,000 tonnes of salt entered the Murray River in South Australia annually because evaporation basins were held at a higher level than the river, thereby inducing seepage of saline water into the river. This amount of salt inflow could increase by nearly 70 per cent by the year 2010.

Project construction of the Scheme began in April 1980, and its first stage was commissioned in October, 1982. This stage involved the construction of a pumping station at the Berri Evaporation Basin (capacity 0.336 m^3/s at 72 m head), a 4.4 km, 550 mm diameter mild steel concrete lined rising main (including two river/creek crossings), a gravity main comprising 20.3 km of 600 mm, 675 mm, and 750 mm diameter asbestos-cement and reinforced concrete pipeline, and construction at the Noora Basin, including railway and road realignment.

The project's second stage was commissioned in February, 1983 and included a pumping station at Dishers Creek Evaporation Basin (capacity 0.302 m^3/s at 55 m head), a 1.5 km, 550 mm diameter mild steel concrete lined rising main (including two river/creek crossings), and a gravity main comprising 6.5 km of 600 mm, and 675 mm diameter asbestos-cement and reinforced concrete pipeline.

The third stage of the scheme involved the construction of a 6.0 km, 450 mm diameter asbestos-cement rising main from Drainage Caisson No. 5 to Caisson No. 3, and a rearrangement of the pumping plant at Caisson No. 5 so that drainage water could be discharged to the south-east through the new main to Caisson No. 3, and thence to Dishers Creek Evaporation Basin, instead of north-east to the Bulyong Island Evaporation Basin, which was abandoned. The third stage was commissioned in July, 1984.

2.2.2 Disposal of Saline Drainage Water in India

In India large areas of land lie either uncultivated, or produce very low crop yields because of soil salinity, or alkalinity, or both. It is estimated that about 7 million hectares of land have been affected. The areas under saline and alkaline soils in Uttar Pradesh, Gujarat and West Bengal are 1,295,000, 1,214,000, and 850,000 hectares (Joshi, 1987).

Apart from coastal areas, the worst affected areas are in the Indo-gangetic plains of Punjab, Haryana and Uttar Pradesh, where about one third of the canal irrigation areas have been rendered unproductive due to this problem.

Apart from inherent characteristics of soils, the problem of salinity in most areas is due to inadequate drainage. Adverse effects of inadequate drainage due to salinity can be categorized in two groups:

- accumulation and evaporation of saline runoff water as experienced in North-Western Parts of Gujarat;
- accumulation of runoff water on soils having salty bed rock materials, which accelerate salt concentration in surface runoff and deposit salts upon evaporation, as is experienced in the Bhal traject of Gujarat.

According to Abrol and Thakur (1981), subsurface drainage works were conducted for the reclamation of saline soils of Bidaj farm of the National Dairy Development Board. These soils are in the heavy textured clay loams that have ground waters of medium to high salinity. Two main open drains and several lateral drains, at 200 m spacing, were constructed. Land Development Works built irrigation channels at the head, and field drains at the tail end of each plot. This work was coupled with the adoption of suitable cropping patterns in reclaimed areas for the leaching of the salts. The experiment began in June 1978, and indicated that due to severe salinity, no crop could be raised. The drains were meant to keep the water table sufficiently low and leach salts from the soil profile. Closely spaced horizontal drains at 15-25 m were found to accelerate desalinization in several problem areas. However, within about 4 to 5 years, the general drainage system provided for the entire farm was able to improve the land with respect to salinity and waterlogging.

A drainage system with proper periodic maintenance, should be adequate to ensure a favorable water and salt balance in such problem areas. Shallow open ditches in waterlogged soils ensure quick removal of stagnant water after heavy rainfall. They will also flush away the salts present. Effectiveness of these ditches (1 m deep and 32 m apart) at IARI, New Delhi was observed in the yields of sorghum and wheat, which were consistently higher under drained conditions during 1969 and 1970 (Joshi, 1987). The research findings on different aspects of the alkali soils were investigated at the Institute for the reclamation of alkali soils in the States of Punjab, Haryana and Uttar Pradesh. The technology development package included chemical measures, as well as agronomic and cultural practices.

The quality of some drainage waters was studied by Sharma and Abrol (1973) for agricultural purposes. Data on the chemical composition of drain water were collected. Results showed that the salt concentration in drain water was within safe limits for irrigation purposes, and therefore warranted that every effort be made to reutilize this water for irrigation purposes.

2.2.3 Left Bank Outfall Drain in Pakistan

Irrigation in the Sind Province of Pakistan (Figure 2.3) has a history of several thousands years. In 1932, barrage commanded irrigation was introduced with the construction of the Sukkur Barrage system, supplying a gross area of some three million hectares on the left and right banks of the River Indus (Figure 2.4). It is the left bank of Sukkur Barrage with which the left bank Drain Project is concerned. It was known in 1932 that the command would eventually require drainage, but with deep water tables prevailing at that time, this was not initially needed. As part of the Lower Indus Project (LIP), the Left Bank Outfall Drain (LBOD) (Figure 2.5) was first proposed in 1966 (McCready. 1987) . The project recommended that the drain be aligned from the Rann of Kutch and taken north through the command area as far as the Khairpur Project, which was then under construction and was proposed to discharge saline drainage water to the Rohri canal. It was suggested that the drain could, if necessary, be extended into the Gudu command.

Meanwhile, in 1974, the Government of Pakistan had approved Phase I of the project as proposed in the second Project Planning report, produced in 1972, and construction was started in 1975. By 1982, some 150 km of the spinal drain had been constructed including the outfall. In mid 1986, the total planned length of 240 km was completed.

Figure 2.3 Sind irrigation area

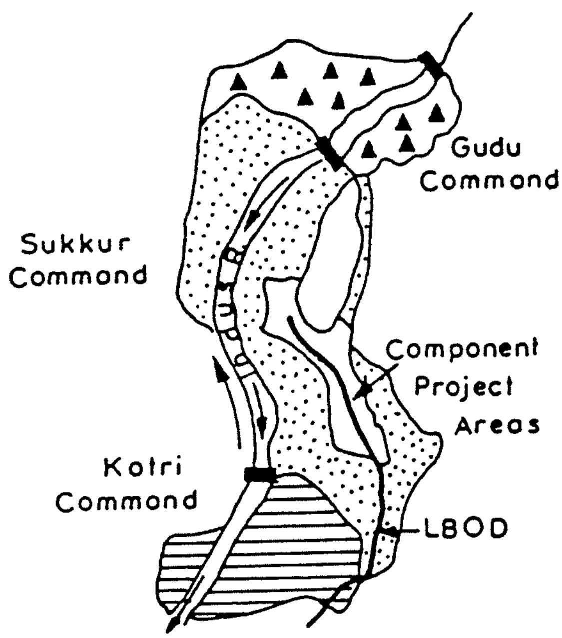


Figure 2.4 Sind irrigation commands

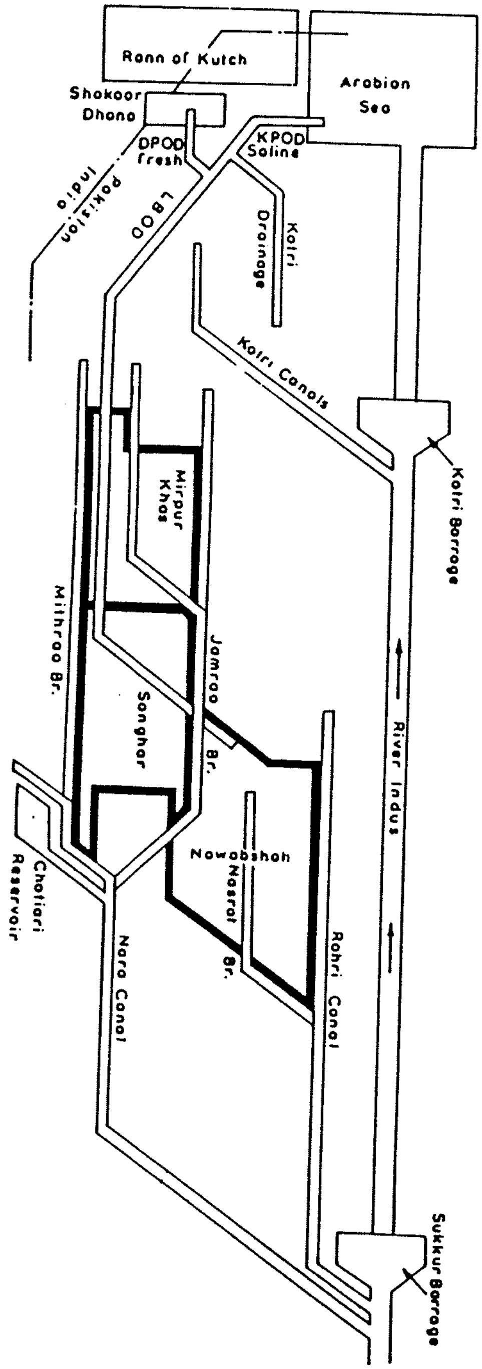


Figure 2.5 Left bank outfall drain (LBOD) schematic arrangement

Problems and Solutions (McCready, 1987):

The general rise of the water table and the accompanying salinisation of land was evidence for the need for drainage in Sind. Added to that were the thousands of hectares of cotton that died in the summer of 1983 after a storm in August that flooded large areas and brought the water table instantly to the surface in areas where it was already high.

The water to be drained had undoubtedly been saline; effluent salt concentrations from tile drainage varied from 4.7 to about 12.5 dS/m, and that from tubewells was twice as saline. The problem concern was how to remove the water without affecting good agricultural land. Salinity effects of conveying water from tubewells to an outfall can be minimized by careful design. However, the problem of disposal was difficult, the choices being the Thar Desert, the River Indus, the Rann of Kutch, or the Arabian Sea. Disposal into the first two were not considered due to cost, as well as hydraulic and environmental considerations. Outfall into the Rann of Kutch or Arabian Sea was technically feasible but, since the latter had the more satisfactory hydraulic performance, it was adopted as the outfall for the Left Bank Outfall Drain (LBOD). In addition to this advantage, this outfall would isolate the discharge from Indian territory.

To control the watertable, there were choices: open drains, tile drains or tubewells. Open drains are very expensive, take up too much land and present the farmer with an unacceptable maintenance problem. Tiles are also expensive, slow to install, and, in relatively flat land, require numerous small pumping stations. However, little maintenance is required, and, over a period of time, the water quality from tile drains does improve and the water may then be reusable. Tile drains become proportionately more expensive the deeper the desired level of water table control. Tubewells are cheap, quick to install, can control the watertable at virtually any required depth, require little maintenance, but can only be used where aquifer conditions are suitable. Large capacity wells are the cheapest and have been used where possible.

The depth at which the watertable is to be established is inevitably a compromise between what is desirable and what is essential. The deeper it is, the better the drainage, the better the ability to cope with normal fluctuations, and the storage is available to accommodate monsoon rainfall. Also, deeper rooting crops like cotton need about 2 m of unsaturated soil for full root development. Finally, the salinisation of soils through evaporation from the capillary fringe is substantially less at greater watertable depths. Virtually the only negative aspect is the fact that some crops draw on the capillary fringe under conditions of water supply shortage.

LBOD Stage I has provided surface drainage and priority subsurface drainage for 0.5 million ha in Sukkur Left Bank, along with additional irrigation supplies, to halt the present deterioration and allow a progressive and permanent increase in annual cropping intensities from 86 to 120 percent.

The scheme has covered the Nawabshah, Sanghar and Mirpurkhas areas (Figure 2.5) and the components are: SPINAL DRAIN to provide outfalls for the safe and acceptable disposal of saline effluent and stormwater runoff, and the provision of maintenance equipment and workshops. The project scheme also includes 760 km of interceptor drains, which will provide additional irrigation water, 4,200 kilometres of 11 kV electric distribution, as well as on farm water management and maintenance facilities.

2.2.4 Agriculture Return Flow Management in Tulare Lake

According to Summers (1987), the management of Tulare Lake represents the implementation of a program to alleviate a severe drainage problem in a large irrigated area of California's San Joaquin Valley. The Tulare Lake Drainage District, organized in 1966, encompasses a gross area of 93,450 hectares. The area within the District (Figure 2.6), was once part of a large fresh water lake. The area has been reclaimed for agricultural use by a system of levees and channels and the construction in the Sierra Nevada, of multi-purpose projects on the four principal rivers that are tributary to the lands. The fertile lands within the District are confronted with a serious drainage problem. The lands are part of a closed basin with no natural outlets to facilitate the removal of salt laden agricultural waste waters. Vertical movement of water through the soil profile is retarded by stratified clays. As a result of these conditions, a salt balance is generally lacking throughout the District, and a major portion of the area has a high water table laden with sodium. Operators within the District have been able to sustain the productivity of the lands by careful water application and proper agricultural practices. Cognizant of the serious problem with which they

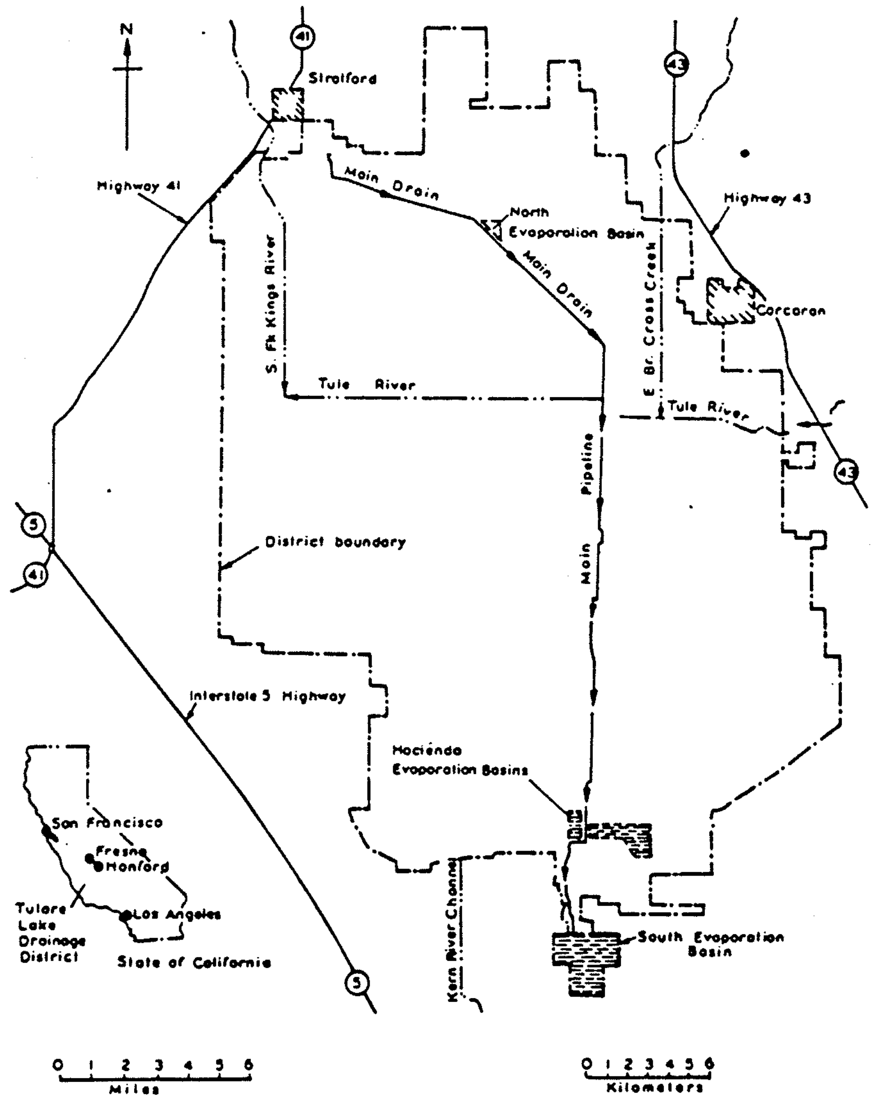


Figure 2.6 Tulare Lake drainage district, Corcoran, California

were confronted, these farmers have instituted a program of return flow management. The total water supply available to lands within the District together and the corresponding salt load are 491 MCM and 71,700 tonnes, respectively. The current crops such as grain, cotton and alfalfa are relatively salt tolerant, which, because of the drainage problems, is essential.

Collecting Facilities and Disposal (Summers, 1987):

The collection system consists of approximately 23 km of concrete pipe and 27 km of open drains, 11 pumping plants and appurtenant structures. The alignment of the collection system was established so that facilities would be available in the vicinity of outlets from existing drainage works, return pumps and contemplated improvements. Disposal of the return flows from the development is accomplished by evaporation basins.

A field reconnaissance was conducted to determine suitable sites for evaporation basins. A comprehensive geological investigation was performed and an analysis of the soil profile indicated there were at least three dense clay layers, relatively shallow, which would impede downward movement of the waste water. Permeability studies were conducted using infiltrometers and ponds. A percolation pond was developed within the basin, and water necessary for the study was imported from a nearby channel. A temporary weather station was established adjacent to the site to monitor evaporation, rainfall and temperature. The pond, with a surface area of 0.19 ha was surveyed to determine the wetted perimeter and volume of water. The water level was held nearly constant so that any effect from change in depth would be eliminated. The test was conducted over an 83-day period and indicated an infiltration rate of 1.35×10^{-6} cm/sec. With such a low rate, it was concluded that with proper design there should be no serious problems with this type of waste water disposal system.

The rate of evaporation was established to determine the area required for disposal. U.S. Weather Bureau studies indicated approximately 279 cm of pan evaporation could be assumed near the disposal sites. Applying a pan coefficient of 0.74, this would give an annual lake evaporation of 206 cm. A design value of 137 cm was concluded to be reasonable when consideration is given for precipitation on the basin and lower than normal evaporation during a particular season. Consideration was given to the reduction in evaporation rate as a result of the increased salinity of the water. It was concluded that such a reduction would be insignificant, at least up to sea water concentration (43.7 dS/m).

The configuration of the evaporation basins was dictated by the topography, prevailing winds and permeability characteristics of the soils, etc. (Figure 2.7). The drainage water is pumped into the basin and flows through the various ponds along a path which provides the greatest exposure. The normal water depth of the ponds is less than 1.2 m. When the salt built up in the lowest pond or crystallization area retards the rate of evaporation the material is removed and delivered to a suitable disposal area. The evaporation basin is surrounded by an interceptor drain to recover any water moving laterally out of the basin. This recovered water is likewise reintroduced into the ponds. At the delivery points, each pump is equipped with a flow meter and a conductivity cell to continuously record the salt load. With this data, management is able to evaluate the tonnage of salt removed from the lands and compare it to that which is introduced annually with the irrigation supply. Some of the evaporation ponds have been in operation for 10 years, and aside from the normal operation and maintenance, they have operated as designed.

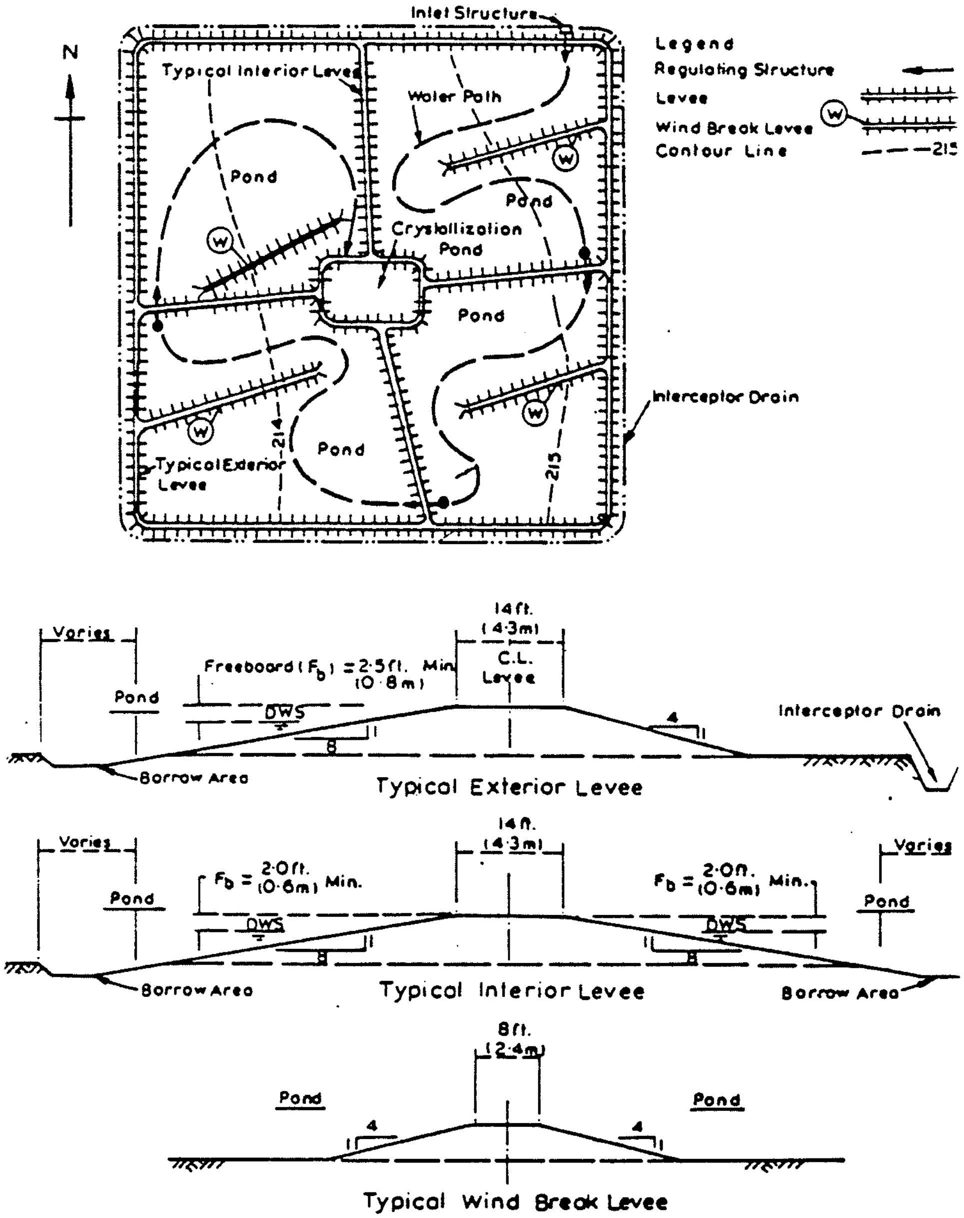


Figure 2.7 Typical evaporation basin

2.2.5 Disposal of Saline Water in the Mexicali Valley Irrigation District

Because of its size, gross farm income and special location, the Mexicali Valley Irrigation District (MID) is one of the four most important irrigation districts in Mexico. It is located in the northern part of Baja California Norte (BCN) and Sonora States, bordering with California and Arizona in the United States (Figure 2.8). The main source of irrigation water is the Colorado River, which flows into the Gulf of California.

Salinity Problems in the Mexicali irrigation District (Tabor, 1973):

The annual rainfall in the irrigation District averages only 58 mm, while the potential evaporation reaches 2,240 mm, causing a natural tendency toward salinization. This tendency is increased by the deteriorating quality of the irrigation water along the Colorado River, where the MID is the last user of its waters. This situation has been getting worse with time, due to the more intensive use of water along the river. The salt content at Imperial Dam was estimated at 1.08 dS/m, and 1.4 dS/m, in 1945, and 1970, respectively.

Salinity problems arise in those parts of the irrigation district with heavy water losses through seepage in earth canals and ditches, as well as deep percolation in the irrigated plots lacking field drainage. The water losses on the irrigated plots are motivated, at least partially, by the low cost of water. In 1980, one thousand m^3 of water cost about US $1.42, while in the Imperial Valley, the cost was US $ 4.58. Presently, the cost of water in the MID is about 6 times less than in the Imperial Valley. Another reason may be the lack of experienced labor

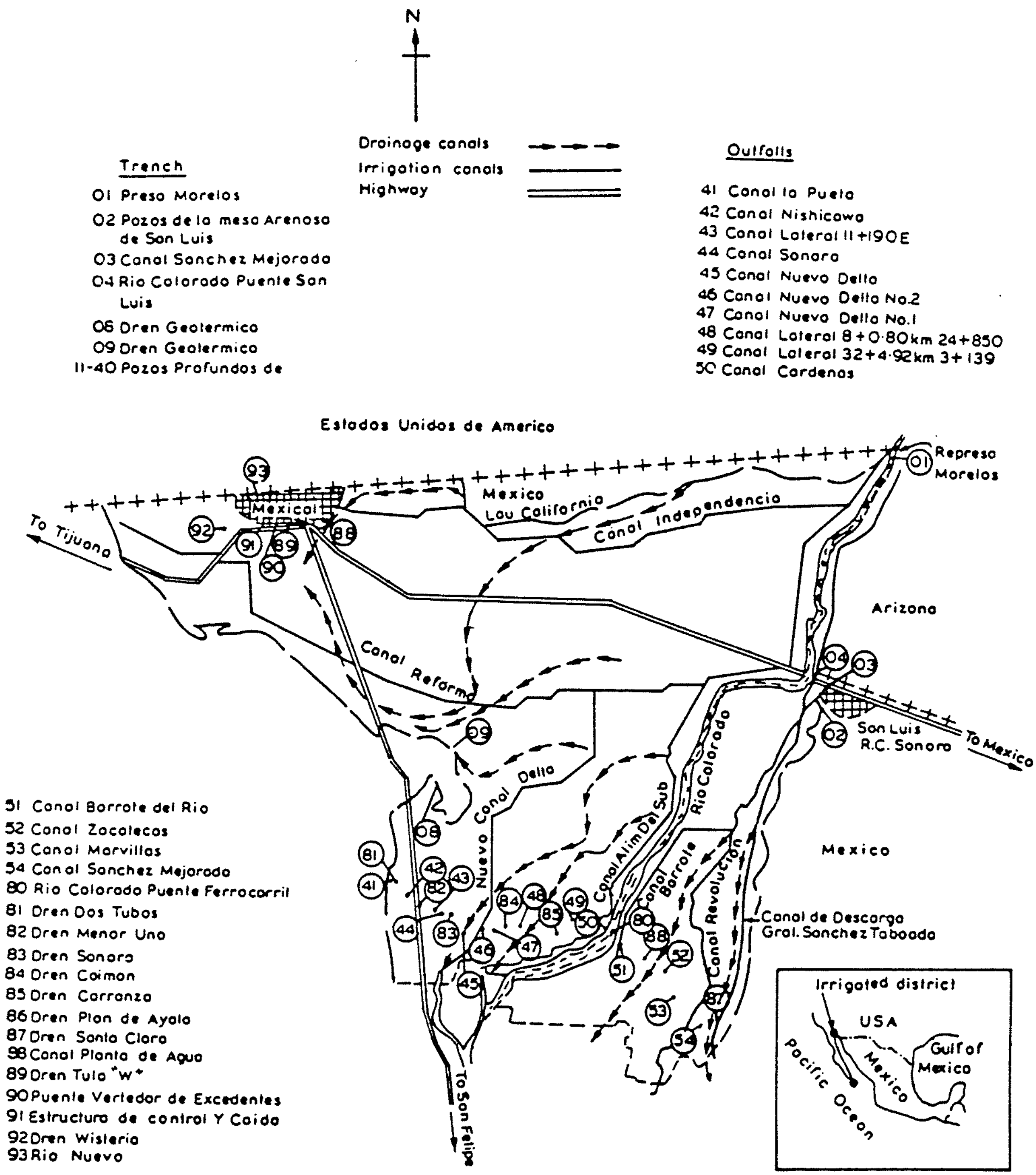


Figure 2.8 Location of the main control points at the inlets and outfalls of water in the irrigation District no.014, Colorado River, Mexico

to manage water during irrigation times. From 1961 to 1976, the salinity problems were aggravated by the release into the Colorado River, upstream from the Morelos Dam, of highly saline drainage waters from the Wellton-Mohawk Irrigation Project in Arizona. These waters were pumped from the gravel aquifer that underlies the Gila River and that serves as an underground reservoir that collects percolated irrigation water. The drainage water was allowed to flow into the old canal of the Gila River and then into the Colorado River. The first effluent came out of this canal on February 10, 1961.

In the beginning the salt content of these waters was 8.1 dS/m, with an average discharge rate of about 8.5 m^3/s. The salt content decreased on an average of 0.35 dS/m per year.

Up to November, 1965, the MID was forced to use all the drainage water, mixed with waters from the Colorado River, which raised the salt content from a range of 1.4 -1.64 dS/m, up to 2.03 - 3.90 dS/m, depending on the volume required at different times of the year.

Unfortunately, this situation coincided with a decrease in the volume furnished to Mexico, down to the quantity established in the 1944 treaty. All these circumstances motivated an estimated 30,000 ha reduction of the irrigated area, as well as a reduction in the proportion of the area dedicated to the cultivation of cotton, the crop with the greatest water requirements.

According to a provisional 5-year agreement (November, 1965), the U.S. constructed a 32 km long concrete lined canal, with a discharge capacity of 10 m^3/s, from a point in the Gila Valley to the Morelos Dam. This canal had a bifurcation feature, so that all or part of the canal flow could be diverted into the Colorado River above the Morelos Dam, or the flow could be by-passed. Additionally, selective pumping started in the Wellton Mohawk project, so that the better water quality drainage wells were pumped from February to September, when MID requirements were such that there was sufficient Colorado River water to dilute the drainage water, and the lesser water quality wells were pumped from October to January, when the drainage effluent could be by-passed.

In this way, the salt content was kept about 1.95 dS/m all of the time, at the price of sacrifying 130 X 106 m^3 of water annually, of which half was charged to the Mexican quota and half to the U.S. From 1965 up to 1972, this situation improved somewhat, because only 65 X 10^6 m^3 of water coming from the Wellton-Mohawk drainage system was discharged and used by Mexico. In June, 1972, Mexico unilaterally decided to by-pass all the drainage water. Finally, in August 1973 an agreement was reached through which, among other measures, an extension of the drainage canal from the Morelos Dam up to the Santa Clara Slough near the California Gulf was to be constructed at the expense of the U.S. The U.S. also agreed to furnish Mexico water at the Northern Boundary (north of the Morelos Dam) with a salt concentration not greater than 0.226 dS/m, as compared to the water quality at Imperial Dam.

This 55 km long concrete lined canal, called "Canal de Descar General Sanchez Taboada", with a discharge capacity of 10 m^3/s was completed in June 1977, and with it, the Wellton-Mohawk problem was solved.

2.3 Evaporation from Water Surface

The change of liquid water to the vapor state occurs when some molecules in the water mass attain enough kinetic energy to eject from the surface. The motion of escaping molecules produces a partial pressure of aqueous vapor called vapor pressure. As a stabilizing effect, some of the molecules colliding with those in the air drop back into the water mass. At saturation, the continuous processes of evaporation and condensation are in equilibrium. The net loss depends on the difference between vapor pressures of the liquid and overlying air. As stated by Dalton's law, the rate of evaporation is proportional to the deficit in vapor pressure.

$$E = CF\,(e_s - e_a) \tag{2.1}$$

where

E is the evaporation;

CF is a transfer coefficient over the water body which is a function of wind speed, surface roughness, and atmospheric stability within the atmospheric surface layer;

e_s is the saturation vapor pressure at the temperature of the water surface;

e_a is the actual vapor pressure in the air.

Evaporation is controlled by several factors that change the vapor pressure of a body of water or the air above: temperatures of water and air, wind, atmospheric pressure, salt content of the water, and nature of the evaporating surface. Temperature is the primary factor correlating directly with rate of evaporation. By providing energy, solar radiation increases the temperature and vapor pressure of the water; conversion from liquid to the vapor state requires approximately 2500 joules for each gram of water.

The four generally accepted methods for computing lake evaporation are water budget, energy budget, mass transfer, and lake-to-pan relations. For a water budget determination, inflow, outflow, precipitation, and seepage data are balanced to yield the unmeasured evaporation loss. Application of these calculations rarely produces reliable results, since small errors in volume of inflow and outflow can result in large deviations of computed evaporation. The energy-budget technique, which involves measuring solar radiation and other heat transfers, requires elaborate instrumentation and is only feasible for special investigations. Mass-transfer procedures are based on observations of surface water temperatures, dew point, and wind movements that are available for only a few lakes.

Evaporation from lakes:

Dealing with the evaporation from lakes, different methods for both direct and indirect evaluation are available. The direct method consists of applying the eddy correlation flux theory (ECS), which enables a determination of atmospheric turbulent heat fluxes by measuring fluctuations of vertical wind speed, air temperature, and specific humidity. The indirect methods consist of empirical formulas that address some of the physical aspects of the transfer of both mass and heat across the air-water interface. Among theses, the energy budget method (EBM) " is considered by many to be the most accurate method available for periods of a month or less" (Rosenberry et al., 1993). The Penman method is considered to be a satisfactory technique for evaporation estimation (Penman, 1948; Jensen, 1974; Doorenbos and Pruitt, 1977; Burman and Pochop, 1994).

Energy budget estimates of lake evaporation were made during the well known Lake Mead studies (U.S. Geological Survey, 1958). Other application of the energy budget are Lake Colorado City (Harbeck et al., 1959), Hungry Horse reservoir (Simons and Rorabaugh, 1971), and Lake Kinnerest, Israel (Assouline, 1996). The evaporation of Lake Nasser was estimated by Omar and El-Bakry (1970) using a synthesis of the conventional Dalton, Penman, McIlroy, and Class A evaporation pan approaches.

Great Lakes evaporation studies typically used mass transfer formulations from the classic Lake Hefner study (U.S. Geological Survey, 1954, 1958). Phillips (1978) and Quinn (1979) included atmospheric stability effects on Great Lakes evaporation bulk transfer coefficients; the latter approach is used presently by both Canadian and U.S. agencies applied to monthly data for surface temperature, wind speed, humidity, and air temperature (Derecki, 1981; Quinn and Kelley, 1983; Atmospheric Environment Service (AES), 1988).

Mean annual evaporation estimates were determined for 30 lakes by use of a numerical model (Morton, 1979) and by use of an evaporation map prepared by the U.S. Weather Service (Kohler et al., 1959). The numerical model can provide monthly estimates for shallow lakes and is based on monthly observations of temperature, humidity, and sunshine duration. Evaporation of Utah's Great Salt Lake and Lake Okeechobee, U.S.A, were estimated by heat capacity mapping mission (HCMM) derived thermal data and using NOAA polar-orbit satelite APT data, repectively (Xin et al., 1991).

Practical estimates of lake evaporation must rely on data that can be observed in the land environment. This has been attempted with the well known pan evaporation, potential evaporation and mass transfer techniques. However, as has been documented elsewhere (Morton, 1983a), these techniques have serious conceptual and empirical failings, the most important of which is that they do not take into account the changes in temperature and humidity that occur when the air passes from land over a lake. Therefore, Morton (1983b) provides the basis for a CRAE (complementary relationship areal evapotranspiration) model. The model was tested against 143 comparable water-budget estimates for river basins in Canada, the United States, Ireland, Austrakia, New Zealand and several countries in Africa, and significant of such estimates to the science and practice of hydrology are discussed in detailed by (Morton, 1983b). A few minor changes (Morton, 1983a, 1983c) convert the CRAE model to a CRWE (complementary relationship wet-surface evaporation) model which can provides estimates of Lake-size wet surface evaporation. This potential is demonstrated by comparing model estimates with published water budget estimates for 16 lakes (such as Lake Victoria in East Africa, Great Salt Lake in Utah and Dauphin Lake in Manitoba) (Morton, 1986).

The direct and indirect methods rely on on-site measured values of the relevant microclimatic variables appearing in the respective equations. In practice, the number of stations providing the appropriate data is restricted. In the case of shallow lakes, it is possible to locate a station at the center of the lake (Stannard and Rosenberry, 1991, Rosenberry et al., 1993). In the case of small lakes, a land station close to the shore and raft station in the lake can br used, but theses generally provides complementary rather than comparative data (Sturrock et al., 1992). In the case of large and deep lakes, the stations are generally restricted to shoreline locations (bolsenga, 1975; Derecki, 1981).

Rosenberry et al. (1993) evaluated the effect of using microclimate data from a land station located 100 m from the northern shore of Williams Lake, Minnesota. The differences have been monitored between the western and eastern shores of Lake Kinneret, Israel, in terms of wind speed, relative humidity, and pan evaporation data (Stanhill and Neuman 1978), Mahrer and Assouline (1993) used the two dimensional version of a numerical mesoscale model to evaluate the horizontal distribution of the evaporation rate over the lake. An experimental evaluation of the spatial and temporal variability in Microclimate and evaporation over Lake Kinneret was performed by Assouline (1996).

Lake Coefficient By Calibration:

Lakes and other bodies of finite extent rarely satisfy the fetch requirement. In such situations, the bulk transfer coefficients, derived for a uniform surface, are often not applicable and it may be necessary to give consideration to the effects of local advection. In practice, no general strategy has evolved thus far, but there are several ways of coping with this difficulty.

A lake has its own particular exchange characteristics with the environment, on account of its geometry, topography, land use and surroundings climate. In addition, the meteorological data must often be recorded at some site which may have its own features. This means that it is very difficult to develop expressions for the water vapour or heat transfer coefficients, which are valid for any lake under different conditions. For this reason, the most accurate application of the bulk-transfer approach is by means of a coefficient obtained by calibration for the lake under study. In its simplest form, the calibration consists of establishing a relationship between u and $E/(e_s - -e_a)$ as follows :

$$E = N \times u \times (e_s - e_a) \qquad (2.2)$$

where

E is the evaporation averaged over the entire lake surface;

e_s is the saturation vapor pressure corresponding to the mean lake surface; temperature or to some representative water surface temperature;

e_a is the vapor pressure of the air measured at a nearby reference location;

u is the representative mean wind speed;

N is the mass transfer coefficients for the entire lake.

The values of E needed in this correlation are obtained by some other independent method such as the energy budget method, more detailed profile measurements, eddy correlation measurements over the lake surface, or a detailed water budget. Clearly, the value of N depends on the location where u and e_a are measured, and on other factors such as wind direction, nature and length of fetch, and the stability of the air. However, for long-term calculations, the effect of the latter three is usually neglected. This procedure can also be used with other equations. Many investigators prefer Stelling's equation where the rate of evaporation is expressed as a linear function of the mean wind speed. Others have attempted to improve on equation 2.2 by taking u to some power other than unity. However, these different forms do not appear to change the accuracy of the method very much, so that the simple form of equation 2.2 is usually considered to be adequate. Examples of the application of this method have been published by Harbeck and Meyers (1970) and Hoy and Stephens (1979). In these studies E, for the calibration was determined by the energy budget method.

2.3.1 Energy-Budget Detrmination of Lake Evaporation

The energy-budget approach, like water budget, employs a continuity equation and solves for evaporation as the residual required to maintain a balance. Although application of the energy budget had been attempted by numerous investigators, with cases selected to minimize the effect of terms that could not be evaluated, the Lake Hefner, U.S.A experiment is believed to constitute the first test of the method with adequate control. The energy-budget approach is receiving increasing application to special studies.

The energy budget for a lake is expressed as

$$Q_s - Q_r + Q_a - Q_{bs} - Q_h - Q_e - Q_\theta + Q_v = 0 \qquad (2.3)$$

where

Q_s is the incoming global radiation;

Q_r is the reflected global radiation;

Q_a is the incoming long-wave radiation;

Q_{ar} is the reflected incoming long-wave radiation;

Q_{bs} is the long-wave radiation emitted by body of water;

Q_h is the sensible-heat transfer (conduction) to the atmosphere;

Q_e is the energy used for evaporation;

Q_θ is the increase in energy stored in the water body;

Q_v is the advected energy (net energy content of inflow and outflow elements).

All of the above terms are expressed in equivalent energy units per unit surface area.

A thorough understanding of the factors controlling the energy balance of a water body enables making accurate estimates or predictions of lake evaporation. Therefore, it facilitates more effective quantity routing for the lake. Computation of energy budget parameters is explained in the following sections.

2.3.1.1 Thermodynamic Parameters

The thermodynamic parameters used in predicting evaporation include, but may not be limited to, atmospheric pressure, air density, specific heat at constant pressure, and latent heat of vaporization. Other required parameters that may be considered to be thermodynamic parameters include the psychrometric constant and the vapor pressure-temperature relationship. Standard S.I. units wiil be followed.

Atmospheric Pressure:

An equation was developed by Burman (Jensen, 1974), by plotting values of atmospheric pressure against elevation taken from the Smithsonian Meteorological Tables (List, 1984). The plot yielded a straight line relationship with minimal deviations. The slope was determined graphically and the zero elevation intercept was set to a pressure of 101.3 kPa. This expression is estimated as follows:

$$P = 101.3 - 0.01055\,.\,z \qquad (2.4)$$

where

P is atmospheric pressure, kPa;

z is elevation above sea level, m.

Vapor pressure:

Much of the interest in developing alternate models for estimating vapor pressure in the atmosphere was generated by a need to have models that could be used repeatedly in calculations with a minimum of computer time as part of large atmospheric models used for weather prediction. Burman et al. (1987) and Weiss (1977) showed that any one of several methods of estimating vapor pressure can be used for the estimation of evaporation from the standpoint of accuracy. In this study, the model shows that a form of Tetens' equation credited to Murray (1967) is satisfactory for estimating vapor pressure. Weiss (1977) presents this equation as:.

$$e^{o} = e^{\theta}_{so} \exp[\frac{17.27T}{T+237.3}] \tag{2.5}$$

where

e^{o}	is the saturation vapor pressure,kPa;
e^{o}_{so}	is the saturation vapor pressure at 0°C, kPa;
T	is the air temperature,°C.

For the units used in this study, $e^{o}_{so} = 0.6108$ kPa. The equation is very satisfactory up to an air temperature of about 100 °C.

Slope of vapor pressure:

For all versions of the combination (Penman) equations and some of the methods of estimating evaporation using a form of solar energy, numerical values of the slope of vapor pressure, Δ_{vp}, need to be calculated. Any satisfactory relationship used to estimate vapor pressure may be differentiated with respect to temperature to obtain an algorithm for the estimation of Δ_{vp}. Differentiation of the form of the Tetens' equation shown in the previous section results in the following equation:

$$\Delta_{vp} = \frac{2503}{(T+237.3)^2} \exp[\frac{17.27T}{(T+273.3)}] \tag{2.6}$$

Where

Δ_{vp} is the slope of vapor pressure, kPa $^{o}C^{-1}$.

Actual vapor pressure:

The actual vapor pressure of air, e_a, is determined by the use of the following expression:

$$e_a = RH \, . \, e^o_{db} \tag{2.7}$$

where

e_a is the actual vapor pressure of the air, KPa;

e^o_{db} is the saturation vapor pressure at the dew point temperature, kPa

RH is the relative humidity as a decimal.

Specific humidity:

Specific humidity is estimated as follows:

$$q = \frac{\rho_v}{\rho} = 0.622 \frac{e_a}{P - 0.378 e_a} \tag{2.8}$$

where

ρ_v is the density of water vapor in the air, kg m^{-3};

ρ is the density of moist air, kg m^{-3};

e_a is the vapor pressure of the air, kPa;

P is the total atmospheric pressure, kPa.

Specific heat at constant pressure:

Specific heat at constant pressure, C_p, for dry air is commonly used with a value of 1.004 kJ kg^{-1} K^{-1} at standard sea level conditions. This value varies slightly in the fourth significant digit, depending on the reference used. Brutsaert (1982) recommended the following method of estimating the weighted specific heat for moist ambient air.

$$C_{pm} = (1 + 0.84q)C_{pda} \tag{2.9}$$

where

C_{pm} is the specific heat at moist ambient air, kJ kg^{-1} K^{-1} ;

C_{pda} is the specific heat at completely dry air, kJ kg^{-1} K^{-1};

q is specific humidity, a dimensionless ratio.

The use of an average value of C_p for moist air is justified because C_p varies only slightly, and evaporation estimates are not sensitive to changes in C_p. To be correct theoretically, a value of C_p for moist air should be used. Jensen et al. (1990) recommended a value of 1.013 kJ kg^{-1} K^{-1}.

Latent heat of vaporization:

Latent heat of vaporization, λ, may be estimated using the following linear regression equation based on thermodynamic steam tables (Harrison, 1963):

$$\lambda = 2501 - 2.3602.T \qquad (2.10)$$

where

λ is the latent hat of vaporization, kJ kg^{-1};

T is the air temperature, °C.

Burman et al. (1987) recommended that T be used as the average daily air temperature in normal evaporation calculations.

Psychrometric coefficient:

Most references define gamma, γ, as the psychrometric constant. In the present study, it is defined as the psychrometric coefficient to reinforce the conclusion that is not a constant in reality. Gamma is actually strongly dependent on elevation, and weakly dependent on temperature:

$$\gamma = C_{pm} P / \varepsilon\lambda \qquad (2.11)$$

where

C_{pm} is specific heat at constant pressure for naturally occurring moist air, kJ kg^{-l} K^{-l};

P is total atmospheric pressure, kPa;

λ is the latent heat of vaporization, kJ kg^{-l};

ε is the ratio of the mole weight of water to air and has a value of 0.622.

2.3.1.2 Radiation

Heat is transferred by conduction, convection, and radiation. Radiant heat transfer is very important in ET because the source of energy for ET comes from the sun. A knowledge of radiant heat transfer and the ability to estimate solar and net radiation is vital for the prediction of ET.

Radiation transfers energy by means of electromagnetic waves characterized by wavelength or wave-number. Wein's Displacement Law shows that the wavelength of maximum intensity is an inverse function of temperature (Welty et al., 1976). For this reason, radiation from the sun, which is at a much higher temperature than the earth, has a much shorter wavelength or maximum intensity than radiation from the earth.

Solar radiation occurs in the so-called short wavelengths of about 0.15 to 4μ with a maximum intensity near 0.5μ. Radiation from the earth and atmosphere, that is terrestrial radiation, is referred to as long wave radiation and is mainly in the 4 to 50μ wavelengths (Gates, 1962). There is very little overlap in wavelengths between solar and terrestrial radiation. Solar radiation reaching the earth's surface is limited essentially to wavelengths above 0.3 μ because the shorter ultraviolet wavelengths are screened out by the ozone layer of the atmosphere. Solar radiation includes the visible spectrum of approximately 0.4 to 0.74 μ.

The rate of radiant heat emission is given by the Stefan-Boltzmann equation, or simply Stefan's equation.

$$\frac{q}{A} = \varepsilon' \sigma T^{-4} \tag{2.12}$$

where

q is heat transfer in energy units MJ day $^{-1}$;

ε' is the emissivity, the ratio of the radiation from the surface;

A is the area emitting radiation, m^2;

T is absolute temperature, and

σ is known as the Stefan-Boltzmann constant which in this case has a value of 4.90 10^{-9} MJ day $^{-1}$ m^{-2} K^{-4}.

Solar radiation:

Solar radiation can be estimated from measured data using an appropriate model. Discussion here is limited to daily or monthly estimates of solar radiation and to the method which is useful on a practical level.

Solar constant (SC):

Solar radiation at the top of the earth's atmosphere on a surface perpendicular to the sun's rays varies with time, but is constant enough for many applications to justify use of the term solar constant. This term is quite useful in estimating both extraterrestrial solar radiation, R_a, and clear day solar radiation, R_{so}. The value of the solar constant, SC, has been estimated, on the basis of high altitude measurements, to be from 1353 to 1396 W m^{-2}. According to Frohlich, 1982, a recent SC value of 1367 W m^{-2} is recommended. The value of 1367 W m^{-2} is equal to 118.1 MJ m^{-2} day^{-1}. From a practical standpoint, minor variations are not significant in estimating evaporation.

Albedo:

Albedo, is the ratio of electromagnetic radiation reflected from a soil and crop (plant) surface to that incident upon it, as defined by ASCE (Jensen et al., 1990). Albedo primarily refers to a somewhat narrow definition of a portion of the range of fractional reflectance of radiation. Albedo has been described as referring to visible or solar radiation. In this study, albedo relates to the total reflectance of solar radiation, both diffuse and direct (Pielke, 1984). Albedo varies with the kind of surface, and is highly dependent upon the angle of incidence. Albedo is used in calculating energy balance quantities, and, in particular, it is used in this thesis to predict net radiation from the following equation:

$$\alpha_R = 0.127 \exp(-0.00108 * R_S) \tag{2.13}$$

where

α_R is the Albdo;

R_s is the solar radiation, MJ m^{-2} day^{-1}.

Sun-earrth geometric relationship:

The need for expressions to estimate various components of both short wave radiation and terrestrial radiation has been stated. Because the ultimate source of energy for ET is the sun, many of the calculations utilize trigonometric functions. These trigonometric functions are based on geometric relationships involving the earth and sun.

Two geometric expressions that are used in models useful in predicting ET are the relationships that define the zenith angle, Θ_z, of the sun and the relationship for the hour angle, ω_h. Garg (1982) discussed these terms. The zenith angle, Θ_z, is defined as:

$$\cos\Theta_z = \sin L \sin\delta + \cos L \cos\delta \cos\omega_h \tag{2.14}$$

A general expression for the hour angle ω_h is:

$$\cos\omega_h = \sin[\frac{\cos\Theta_z}{\cos\delta\cos L}] - \tan\delta\tan L \tag{2.15}$$

where

Θ_z is the zenith angle of the sun in degree;

δ is the declination of the sun in degree;

L is the latitude in degree.

Because the $\cos\Theta_z$ is zero at sunset or sunrise, the hour angle at sunrise and sunset reduces to the following:

$$\cos\omega_{hs} = -\tan\delta\tan L \tag{2.16}$$

where

ω_h is known as the sunset hour angle. The hour angle is then the angle between the sun at solar noon and the sun at sunrise or sunset and is in degree.

Declination of the sun:

Numerical values of declination of the sun, δ, are required to estimate day length and radiation parameters such as extraterrestrial radiation. While precise values of δ are required for procedures such as surveying, the small yearly variations are not of practical significance in applications such as the estimation of evaporation. At least three algorithms exist for estimating δ for any desired calendar day of the year. One of them is the model of Burman and Jacquot which is satisfactory for routine use in estimating ET because yearly variations of δ are small.

Burman-Jacquot declination model:

A procedure developed by Jacquot and Porter (1989) for the Fourier analysis of periodic functions was issued to develop a cosine series to predict δ. The two terms shown below are recommended because they give satisfactory accuracy (United States Naval Observatory, 1988). The first two terms of the series are:

$$\delta = 0.3931 + 23.2577\cos(0.9861D - 170.7) + 0.3906\cos(1.9154D - 174.4) \qquad (2.17)$$

where

δ is the declination of the sun in degree;

D is the calendar day number of the year.

Variations in the sun-earth distance:

The distance between the sun and the earth, $[\frac{d'}{d}]^2$, is known to vary slightly during the passage of a year. The earth-sun relative distance is also shown in astronomical tables for individual years. For many common purposes such as estimating evaporation, variations between years is not significant. For this reason simple algorithms have been developed. Based on convenience and performance, the Duffie-Beckman model is recommended (Burman and Pochop, 1994).

Duffie-beckman sun-earth distance correction:

A simple periodic function credited to Duffie and Beckman (1980) follows. Corrections are usually of the form $[\frac{d'}{d}]^2$ because the intensity of radiation is known to be inversely related to the square of the distance between radiating bodies.

$$[\frac{d'}{d}]^2 = 1 + 0.034\cos[\frac{360D}{365*25}] \tag{2.18}$$

where

D is the calendar day number of the day;

d' is the average distance from the earth to the sun;

d is the actual distance between the earth and the sun.

Extraterrestrial radiation:

Extraterrestrial radiation, R_a is the solar radiation received on a horizontal surface above the earth's atmosphere and is very useful in predicting ground level solar radiation perpendicular to the sun's rays. Extraterrestrial radiation, R_a, is a function of latitude and date only if radiation from the sun perpendicular to the sun's rays is assumed to be constant. Because the earth' s axis is tilted and the distance from the sun to the earth varies with season, the geometry involved is complex, but merely represents an integration of the functional relationship between the zenith angle of the sun with an empirical distance correction.

$$R_a = \frac{SC}{\Pi}[\frac{d'}{d}]^2 \int_{sunrise}^{sunset} \cos\Theta_z dt \tag{2.19}$$

Using equation 2.19, Sellers (1965) has a detailed derivation of the following equation:

$$R_a = \frac{SC}{\Pi}[\frac{d'}{d}]^2 [\omega_h \{\frac{\pi}{180}\} \sin L \sin\delta + \cos L \cos\delta \sin\omega_h] \tag{2.20}$$

where

R_a is extraterrestrial solar radiation, MJ m^{-2} day^{-1};

d is the distance to the sun at any time;

d' is the yearly average distance between the sun and the earth;

SC is the solar constant, MJ m^{-2} day^{-1}.

2.3.1.3 Solar Radiation

Solar radiation striking the earth's surface is obviously attenuated by atmospheric constituents, especially by clouds. Estimation methods of solar radiation at the earth's surface have been based upon either extraterrestrial solar radiation, or clear day solar radiation and some indication of cloud cover.

Penman (1948) suggested estimating ground level solar radiation using sunshine and extraterrestrial radiation R_a data as:

$$R_s = R_a(a + b.S) \tag{2.21}$$

where

- R_s is the solar radiation, diffuse and direct, received at the earth's surface on a horizontal surface, MJ m^{-2} day^{-1};
- R_a is the extraterrestrial radiation, MJ m^{-2} day^{-1};
- S is the ratio of hours of actual bright sunshine to the possible hours of bright sunshine. It is estimated by using the following equation:

$$S = \frac{n}{N} \tag{2.22}$$

where

- n is the measured number of hours of bright sunshine;
- N is the possible number of hours of bright sunshine at a location and time.

For general use, Doorenobs and Pruitt (1977) recommended values of a=0.25 and b=0.5 for the regression constants of equation 2.21. They also show an extensive table of values for more specific locations and uses. Note that (a+b) is always less than 1.0 because less than 100% of the extraterrestrial solar radiation is expected to be received at the earth's surface over a daily or monthly period.

2.3.2 Methods Based on Penman's Combination Approach

Most of the methods which have been developed to estimate evaporation from free water services are based upon Penman's combination approach (Penman, 1948). Penman's equation described evaporation as the combination of water loss due to radiation energy input and an aerodynamic term accounting for the removal of water vapor from a saturated surface. Penman's equation requires temperature, radiation, humidity, and wind data.

Several modifications of Penman's equation have appeared. Because of the general scarcity of data for some of the meteorological parameters, a few of the modifications have been proposed to permit estimation of evaporation using more commonly available data. Others have been proposed to provide what are termed improved estimates of evaporation, but generally these methods have even greater data requirements. Examples of these Modifications include: Kohler-Nordenson-Fox (1955), Kohler-Parmele (1967), Linacre (l967), Priestley-Taylor (1972), Stewart-Rouse (1976), and deBruin (1978).

The data requirements of the various evaporation formulas are analogous to those of the various ET formulas. For example, the Linacre formula requires only temperature data; the Stewart-Rouse and Priestley-Taylor equations require temperature and radiation data; the deBruin equation requires temperature, humidity, and wind data; and the Kohler-Nordenson-Fox and Kohler-Parmele equations require temperature, humidity, wind, and radiation data. The recommended applications of these equations are generally similar to those of the ET formulas, with the equations using more data recommended for estimates as short term as daily, and those using limited data recommended for longer term estimates.

Although all the equations to be discussed have been developed to estimate free-water evaporation, their applications differ greatly, depending on the equation, development and calibration have been for Class A pan evaporation, shallow lakes, free water surfaces, etc. Extreme care should be taken to observe the conditions to which each equation applies.

Kohler-Nordenson-Fox equation:

The Kohler-Nordenson-Fox equation (Kohler et al., I 955) is perhaps the model which has been most widely used for estimating evaporation. The model was an adaptation of the Penman equation for estimating Class A pan evaporation and is given as:

$$E_p = \frac{\Delta_{vp} R_n + \gamma_p E_a}{\Delta_{vp} + \gamma_p} \tag{2.23}$$

where

E_p is pan evaporation, mm day $^{-1}$;

R_n is net radiation of equivalent depth of water, mm day $^{-1}$;

Δ_{vp} is the slope of the saturation vapor-pressure versus temperature curve at the air temperature, kPa $^{o}C^{-1}$;

γ_p is the psychrometric coefficient, kPa $^{o}C^{-1}$;

E_a is an aerodynamic function, mm day^{-1}.

An adjustment was made in the psychrometric coefficient to account for the sensible heat conducted through the sides and bottom of the pan. Based on studies from Lake Hefner, OK, the psychrometric coefficient was found to be 0.001568P in units of kPa per ^{o}C where P is atmospheric pressure in kPa. Kohler-Nordenson-Fox actually recommended a constant value of 0.152 for the psychrometric coefficient up to the elevation of Lake Hefner, OK, of 1525 meters. These values exceed the theoretical values for the psychrometric coefficient as calculated using the equation given in section 2.3.11.

$$\gamma_p = 0.001568\, P \tag{2.24}$$

The aerodynamic function E_a was evaluated using pan data from four locations scattered across the US.

$$E_a = 25.4\,[\,0.296\,\{(e_a - e_d)^{0.88}\}\,(0.37 + 0.00255\,u_p)] \tag{2.25}$$

where

u_p is wind speed at 0.152 m above the rim of a class A pan, km day^{-1};

e_s is the saturation vapor pressure at the air temperature, kPa;

e_d is the saturation vapor pressure at the dew point temperature, kPa;

The effective net radiation for a Class A pan accounting for the effects of sensible heat transfer through the sides and bottom of the pan was determined by rearranging the pan evaporation equation to solve for R_n (Kohler et al., l955; Lamoreux, 1962; and Jensen, 1974).

$$R_n \Delta_{vp} = 154.4 \exp[(1.8 T_a - 180)(0.1024 - 0.01066 \ln(0.239 R_s)) - 0.01544] \quad (2.26)$$

where

T_a is air temperature, °C;

R_s is solar radiaion, J cm^{-2} day^{-1};

Kohler et al. (1955) assumed that so long as air and pan water temperatures are equal, lake evaporation is 70% of that from a Class A pan. The only other change in calculating evaporation for a lake is that the value of the psychrometric coefficient, as defined by the Bowen ratio, is used in place of the value determined for a Class A pan, which becomes

$$\gamma_p = 0.000661 P \quad (2.27)$$

Thus, lake evaporation is estimated by

$$E_l = 0.7 \frac{(\Delta_{vp} R_n + \gamma_p E_a)}{\Delta_{vp} + \gamma_p} \quad (2.28)$$

Kohler-Parmele equation :

Kohler-Parmele (1967) reexamined the assumptions of the Penman (1948) and Kohler-Nordenson-Fox (1955) equations. Assumptions involving the water and air temperatures being equal, sensible heat transfer through the sides and bottom of a Class A pan, net radiation calculations, the wind function, E_a, advected energy, and the slope of the saturated vapor pressure versus temperature curve were all considered to have potential to contribute to errors.

Kohler-Parmele (1967) reasoned that although the Penman equation adjusts for the difference in air and surface temperatures in the aerodynamic portion of the equation, adjustments are not made to account for this difference in the energy term. Thus, they modified the original Penman type equation to account for the difference between air and water temperatures in calculating emitted radiation from the water surface. Their expression for evaporation from free water surfaces is:

$$E = \{\Delta_{vp}\,(R_{ir} - \varepsilon\sigma T_a^4) + E_a\,[\gamma + \frac{4\varepsilon\sigma T_a^3}{f(u)}]\} / \{\Delta_{vp} + \gamma + \frac{4\varepsilon\sigma T_a^3}{f(u)}\} \qquad (2.29)$$

where

E is the evaporation, mm cm^{-2} day^{-1};

R_{ir} is the dfference between incident and reflected all-wave radiation, mm cm^{-2} day^{-1};

ε is the emissivity ratio of the water surface;

σ is the Stefan-Boltzmann coefficient, 7.81 x 10^{-11}mm cm^{-2} k^{-4} day^{-1};

T_a is the mean air temperature, K;

E_a and f(u) are related by:

$$E_a = (e_s - e_a)\,f(u) \qquad (2.30)$$

where

E_a is expressed in mm cm^{-2} day^{-1};

e_s is the saturation vapor pressure at the air temperature, kPa;

e_d is the saturation vapor pressure at the dew point temperature, kPa;

f(u) is:

$$f(u) = 1.361 + 0.01102\, u_4 \tag{2.31}$$

where

$f(u)$ is expressed in mm cm^{-2} kPa^{-1} day^{-1};

u_4 is wind run at 4 meters height, km day^{-1}.

Energy storage and advection were accounted for Kohler and Parmele (1967) in estimating lake evaporation as:

$$E_L = E + \alpha\,[\,Q_i - Q_o - (S_2 - S_1)\,] \tag{2.32}$$

where

E_L is estimated lake evaporation, mm cm^{-2} day^{-1};

E is the computed free-water evaporation, mm cm^{-2} day^{-1};

Q_i is the energy content of inflow to the lake, mm cm^{-2} day^{-1};

Q_o is the energy content of ouflow to the lake, mm cm^{-2} day^{-1};

S_2 is the energy storage at the begining of the period, mm cm^{-2} day^{-1};

S_2 is the energy storage at the end of the period, mm cm^{-2} day^{-1};

α is expressed as:

$$\alpha = \Delta_{vp} / \{ \Delta_{vp} + \gamma + \frac{4 \varepsilon \sigma T_a^3}{f(u)} \} \tag{2.33}$$

The ratio α is considered to be somewhat similar to the Bowen ratio. It should be used with wind measured directly above the surface, although Kohler and Parmele (1967) recommended that wind data from the 4 meter height was satisfactory.

The major difficulty in computing lake evaporation is in obtaining data for the advection, energy storage, and water temperature terms. Kohler and Parmele (1967) state that generally the affected energy is relatively small and that the energy storage may be neglected in computing mean annual evaporation. When calculating daily evaporation, daily changes in energy storage usually cannot be determined with sufficient accuracy. Thus, the equation for generalized free-water evaporation remains the most useful as a evaporation reference. Estimating specific lake evaporation is difficult, and the effect of lake size is not accounted for anyway.

Priestley-Taylor equation:

Priestley and Taylor (1972) attempted to describe evaporation using the concept of equilibrium conditions, i.e. when the air in contact with a wet surface is vapor saturated. Under these conditions, radiant energy dictates the evaporation rate, and the aerodynamic term in the Penman combination equation becomes zero with the equation reducing to the energy term. However, since actual atmospheric conditions can only approach equilibrium conditions, Priestley and Taylor introduced an empirical coefficient that is defined as the ratio of evaporation from a wet surface when conditions of minimal advection exist to evaporation under equilibrium conditions. The Priestley-Taylor equation became:

$$E = \alpha_1 \frac{\Delta_{vp}}{\Delta + \gamma} (R_n + G) \tag{2.34}$$

where

E is evaporation from a uniformly saturated surface, mm cm^{-2} day^{-1};

R_n is the net radiation;

G is subsurface heat flow, mm cm^{-2} day^{-1};

α_1 is the empirical coefficient.

Using several sets of data from various surfaces having unlimited water supplies, Priestley and Taylor (1972) found an average of rage of *al* = 1.26.

The Difficulty with the Priestley-Taylor equation is the lack of data for R_n and G. especially G. Some users have elected to ignore G and calculate evaporation using estimated net radiation. If this is the case, then only temperature and radiation data are required. Estimates of lake evaporation using Priestley-Taylor equation require inclusion of the G term. The Priestley-Taylor equation has been applied to ET as well.

2.4 Irrigation Management

2.4.1 The Potential of Using Saline Water in Irrigation

Although the number of documented reports on successfully using brackish water for irrigation is relatively limited, enough exist to support the premise that water, more saline than conventional water classification schemes allow, can be used for irrigation. Recent research development on plant breeding and selection, soil crop and water management, irrigation and drainage technologies enhance and facilitate the use of saline water for irrigated crop production with minimum adverse impacts on the soil productivity and the environment. Several extensive reviews of the world literature had been conducted on this topic, including those of Bressler (1979), Gupta (1979) and Gupta and Pahawa (1981).

Rhoades (1977) concluded that the bulk of drainage waters in the US (presumably in the world as well) have potential value for irrigation. Use of such water would not only permits the expansion of irrigated agricultural, but could also reduce drainage disposal and pollution problems as well.

In the United States, extensive areas (about 200.000 acres) of alfalfa, grain sorghum, sugarbeets and wheat are irrigated (by gravity and furrow methods) in the Arkansas Valley of Colorado with water containing less than 2.3 dS/m and up to 7 dS/m (Miles, 1977).

In the Pecos Valley of West Texas (United States), groundwater averaging about 3.9 dS/m, but ranging far higher, has been successfully used for irrigation of about 200.000 acres of land for three decades (Moore and HeLner, 1976).

Jurey et al. (1978) grew wheat in lysimeters with water up to 7.1 dS/m without deleterious effects on yield. Paliwal (1972) carried out several experiments in India, continuously irrigating with relatively high salinity water. Shalhevet and Kamburov (1976) suggested that water with up to 7.5 dS/m were often classed as acceptable and indeed used. Frenkel and Shainberg (1975) and Keren and Shainberg (1978) reported that cotton could be grown commercially in Israel with water having an electrical conductivity of 4.6 dS/m. Several workers, after testing water of salt concentration level between 4 dS/m and 15 dS/m concluded that such water could be used for certain crops without drastic yield reduction (Harden, 1976; Bressler, 1979).

Other evidence of the potential to use saline water for irrigation successfully under hot dry (arid) climate was demonstrated by Ayers and Westcott (1985) and Rhoades (1988). The experience of Israel of sixteen years of research carried out in the fields of Ranat Negev experimental stanon (Pasternak et al., 1984), evidently support the potentiality of using relatively high saline water for irrigation under arid conditions even under the harch desert conditions of Israel for variable crops that could be grown commercially such as: wheat, sorghum, sweet corn, sugarbeets, cotton, tomato, asparagus, broccoli, beets, celery, melons and lettuce.

O'Leary (1984) has shown that several halophytes have potential use as crop plants and can be grown under field irrigation with very saline water. Yields have been achieved under high salinity conditions which exceed the average yield of crops, like alfalfa, irrigated with fresh water. The most productive halophytes yielded the equivalent of 8 to 17 times of dry matter per hectare. These yields amounted to 0.6 to 2.6 times of protein per hectare, which also compared to that of alfalfa with fresh water irrigation. These crops yield even more when grown with water of lower salinity. For example, about double the above yields are obtained using water of 12.5 dS/m for irrigation. The use of drainage waters for the growth of such crops would facilitate the disposal of drainage waters as proposed by Van Schilfgaarde and Rhoades (1984).

Several examples can be found on the successful use of saline water in Middle East and Northern Africa. The saline Medjerda river water of Tunisia (annual average EC of 3.0 dS/m) has been used to irrigate date palm, sorghum, barley, alfalfa, rye grass and artichoke. With properly timed irrigation and the selection of appropriate crops, this saline water is being used successfully to irrigate even relatively impervious soils (Van's Level and Haddad, 1968, Van Hoorn, 1971). According to Arar (1975), salt tolerant cereal crops, vegetables, alfalfa and date palms are being successfully irrigated with water of 3.1 dS/m in Bahrain, 3.7 to 7.5 dS/m in Kuwait and 2.3 dS/m in the Tagoru area of the Libyan coastal plain. Forest plantations have been established in the United Arab Emirates using groundwater with up to 1.5 dS/m. In Egypt the total amount of drainage water discharged annually varies between 14 billion m^3 in 1984 to 12 billion m^3 in 1989.The EC value of the drainage water around the year is of an average 4.6 dS/m. The amounts of drainage water presently used in irrigation is 4.7 billion m^3 annually, which is expected to be increased gradually and reach 7.0 billion m^3 by the year 2000 (Abu-Zeid, 1991).

2.4.2 Leaching Management for Salinity Control

Leaching is the key factor by which soil salinity can be maintained at acceptable levels without undue damage to crops. Thus appropriate natural or installed drainage and disposal systems are essential.

Soil salinity control becomes more difficult as water quality decreases. Greater care must be taken to leach salts out of the root-zone before they reach levels that might affect yields. Alternatively, steps must be taken to plant crops tolerant to the expected root-zone salinity. The frequence and amount of leaching depend on water quality, climate, soil and crop sensitivity to salinity.

With efficient leaching management, it is questionably desirable to use extra water to every watering to leach the soil, at the same time increasing the peak requirements of an irrigated area or, on the contrary, to apply less water and to apply less leaching complements when more water is available. This will greatly depend on the salt distribution, which is related to the growing season.

Leaching efficiency can be defined as the amount of salt removed from the root-zone by drainage water at a given fraction of the irrigation water. This efficiency depends on salt content and distribution in soil, on solute composition, and on irrigation method and management.

Increase efficiency or reducing leaching under the proper circumstances, it can lead to more effective water use in the first instance, a reduction in the salt load needing disposal and a substantial reduction in the volume of drainage water. This will greatly help in solving the drainage water disposal problems as well as creating a more favourable environmental conditions.

To effect high efficiencies requires a high level of management skills coupled with the use of modern technology. In the typical surface irrigation system, there tends to be an unavoidably large difference in water stored in the soil across a field because of a difference in opportunity time, length of time the water stands on the surface and a difference in infiltration rate. These inefficiencies can often be reduced, but not eliminated by modern laser-assisting grading techniques, so-called "dead-level" basin, or surge irrigation. Solid set or movable sprinkler lines have similar problems. Linear move or pivot sprinklers are better adapted for achieving high level of efficiency, while poorly designed and managed drip system can indeed come close to perfect uniformity.

The settlement of an efficient and a proper leaching management, the frequency and amount of water for leaching should be evaluated in view of the irrigation water quality, climate, soil and crop sensitivity to salinity, the crop season and period as well as the accumulated salts in soils.

The point which still under discussion is the leaching scheduling (amounts and intervals) allowing to have an efficient and effective leaching management In this regard, numerous field leaching trials have been conducted (Shalhavet, 1984; Bernstein and Francois, 1973; Francois, 1981; Meiri and Shalhavet, 1973; Mieri et al., 1986; Hamdy, 1990 and Hamdy, 1994)

The findings by those authors wae contradictory; a part of the results fully support the idea that leaching should be done at every irrigation, whereas the others were in favour of periodical leaching when salt accumulation in soils becomes excessive.

The adoption of LR as excess water at every irrigation, its indirect benefit is a maintenance of a higher soil water content in comparison with water application without leaching, for a significant time after each irrigation. The effect is most significant under frequent irrigations. Under such conditions the positive crop response to leaching can be due to both higher soil moisture and reduced soil salinity (Bressler and Hoffman, 1986; Meiri and Plaut, 1985).

The adoption of LR as excess water at every irrigation is most undesirable when saline water is added to a field having a lower salinity level than the acceptable maximum for the crop and salinity build-up occurs. The additional saline water may aggravate the salinity stress as it enhances the salinization for a short season crop it may also result in a higher EC values of extracted soil solution.

Leaching at every irrigation may be accompanied with large unintended errors. Since LR is usually a small fraction of irrigation dose, a small error in the estimate of ET may introduce a considerable error or in the intended L.R and as a result an over leaching practices.

Irrigation tests in Tunisia (Van Hoorn, 1991) have shown that leaching during the period of peak demand can quite well be reduced or postponed. This also follows from salt balance calculations. Leaching during a period of peak consumptive use means that not only are greater amounts of water applied but also that greater amounts of salt are brought into the soil. So, this surplus amount of salt counterbalances to a certain extant the advantage of more leaching water. The author also revealed that, as permanent leaching means greater water applications, there is greater risk of water stagnation and suffocation of the crops. On the other hand, seasonal leaching during a period of low consumptive use can also draw advantage from rainfall, at least in the Mediterranean area and the Middle East where rainfall occurs during the winter.

The findings of Bernstein and Francois (1973b), Francois (1981) and Hamdy (1990) support the idea that applying the required leaching when salt accumulation becomes excessive -periodically rather than at every irrigation- is a better strategy for short-season crops.

CHAPTER THREE

THE STUDY AREA

3.1 Background

3.1.1 Physiography and Soils

The Fayoum basin is a kidney-shaped depression, about 45 km in diameter, in the western Egyptian desert (Figure 3.1). Its gross area is 428,000 feddans (feddan=0.42 hectare), of which 364,000 feddans are served by the irrigation system in the Fayoum basin. The area of arable land is 342,000 feddans. The basin is bounded in the north by Lake Qaroun, an inland basin of 59,000 feddans in the deepest part of the depression. The basin slopes from +25 m MSL at Lahoun (Figures 3.2 and 3.3), the inlet from the Nile Valley, to -43.7 m MSL at Lake Qaroun, situated 35 km from Lahoun. In the south-western part of the desert surrounding the Basin, the Wadi Rayan Depression (lowest point -64 m MSL) has, since 1973, served as a spillway for approximately 30% of the total basin drainage water previously discharged into Lake Qaroun.

The Fayoum basin has the land form of an alluvial fan, dissected by deep and narrow gullies. The soils are fluvial and lacustrine deposits of the Nile, overlying a formation of limestone and marls. The average thickness varies from 0.5 to 8.0 m. The shallowest soils occur in the southwest towards Wadi Rayan

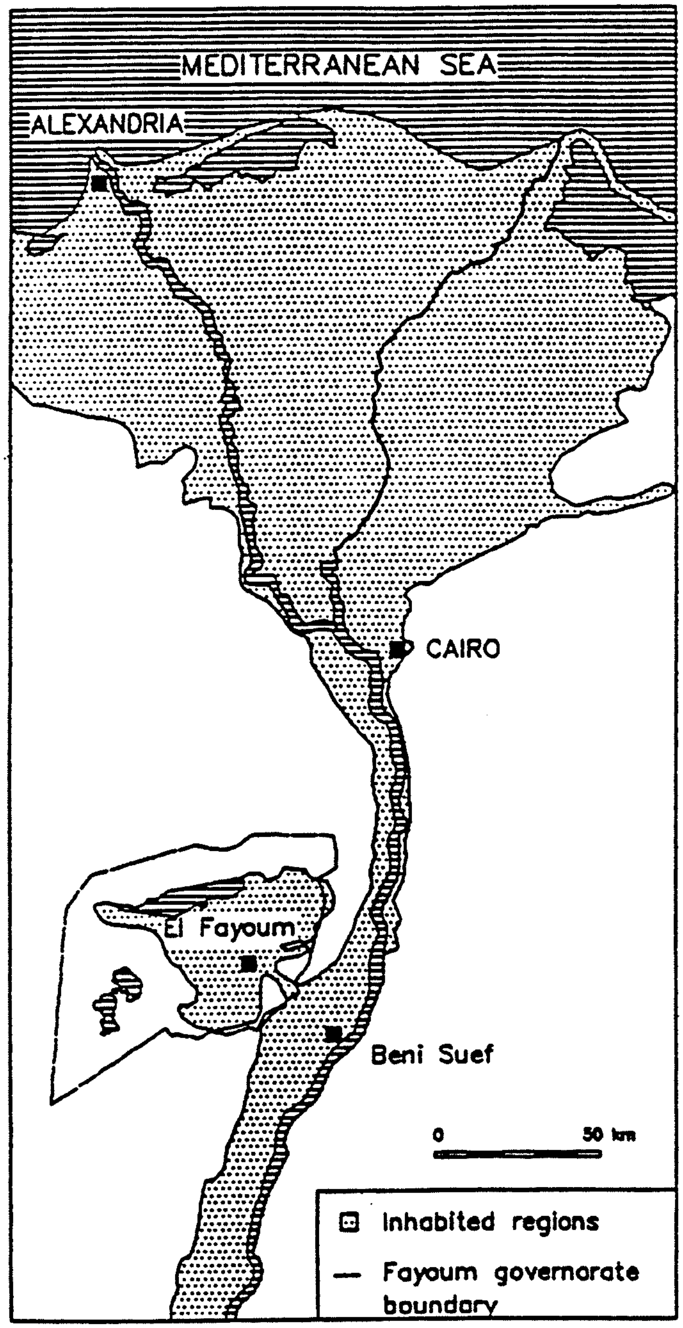


Figure 3.1 Location of the study area in Egypt

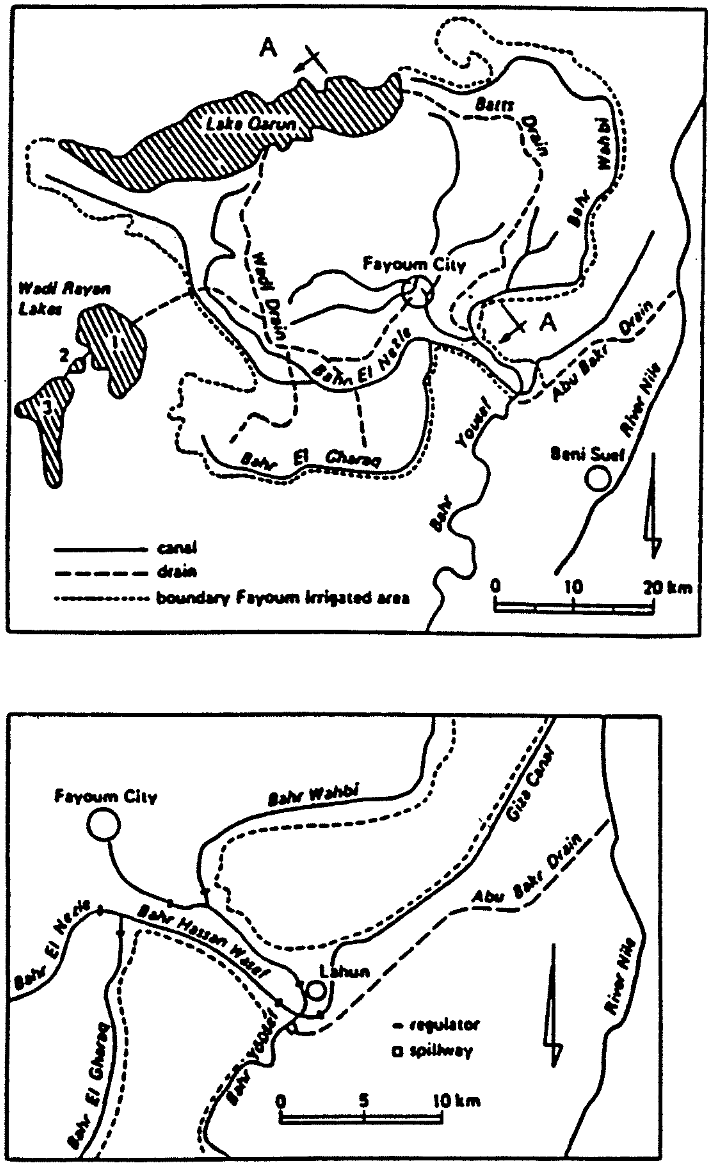


Figure 3.2 The Fayoum basin and the Hawara (Lahoun) gap

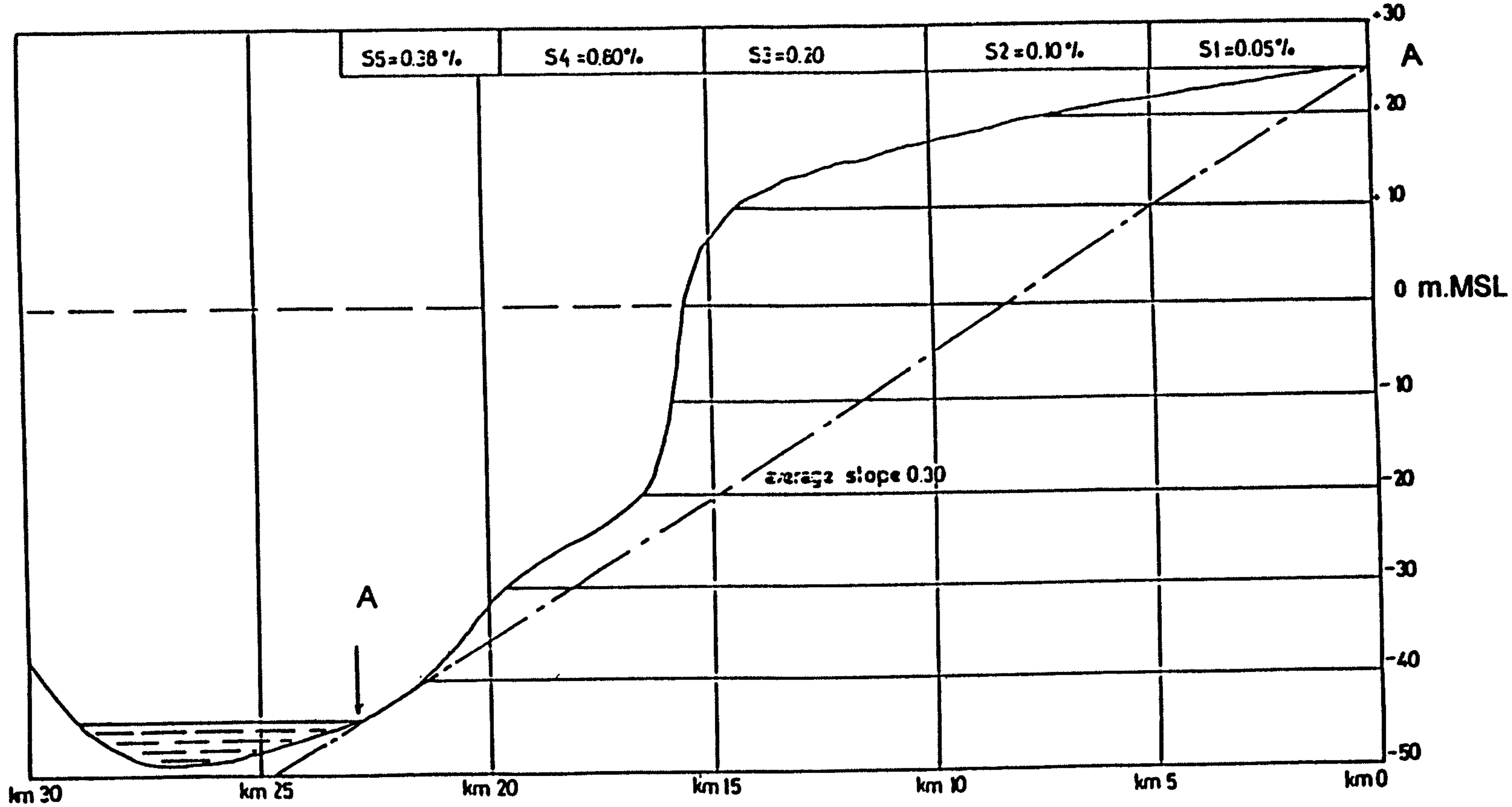


Figure 3.3 The Fayoum Depression (refer Figure 3.2 for section A-A)

and in some scattered patches in the south. Medium textured soils occur at the fringe of the alluvial fan, where it dips towards Lake Qaroun. These soils are midway between Fayoum town and Lake Qaroun, on the line Ibshawai-Sinnuris. The majority of the soils in Fayoum are heavy textured clays. Their locations are indicated in Figure 3.4.

The central part of the depression around Fayoum town, covering 40% of the depression, is non-saline or slightly saline. A band around the central part, covering another 40% of the depression, is medium saline. The remaining area is highly saline. The soil salinity map is shown in Figure 3.5.

In most places, the water table is deeper than 150 cm below surface. Water table depths of less than 150 cm are encountered near Lake Qaroun and south of the depression, in areas where deep percolation of irrigation water is hindered by rocky layers, found at different depths.

The Fayoum land capability map classifies 18% of the land as good; 45% as moderate; 26% as poor to very poor, due to salinity and impeded drainage, while 11% is uncultivable (Amer, 1992).

3.1.2 Agriculture

About 75% of the labor force in the Fayoum is engaged in agriculture. The average farm size is 2.5 to 3.0 feddans. Most farmers have 3 or more farm lots within different quarternary blocks of the same tertiary unit. Because water distribution within the unit is by rotation, farmers can irrigate their fields on different days and grow a variety of crops.

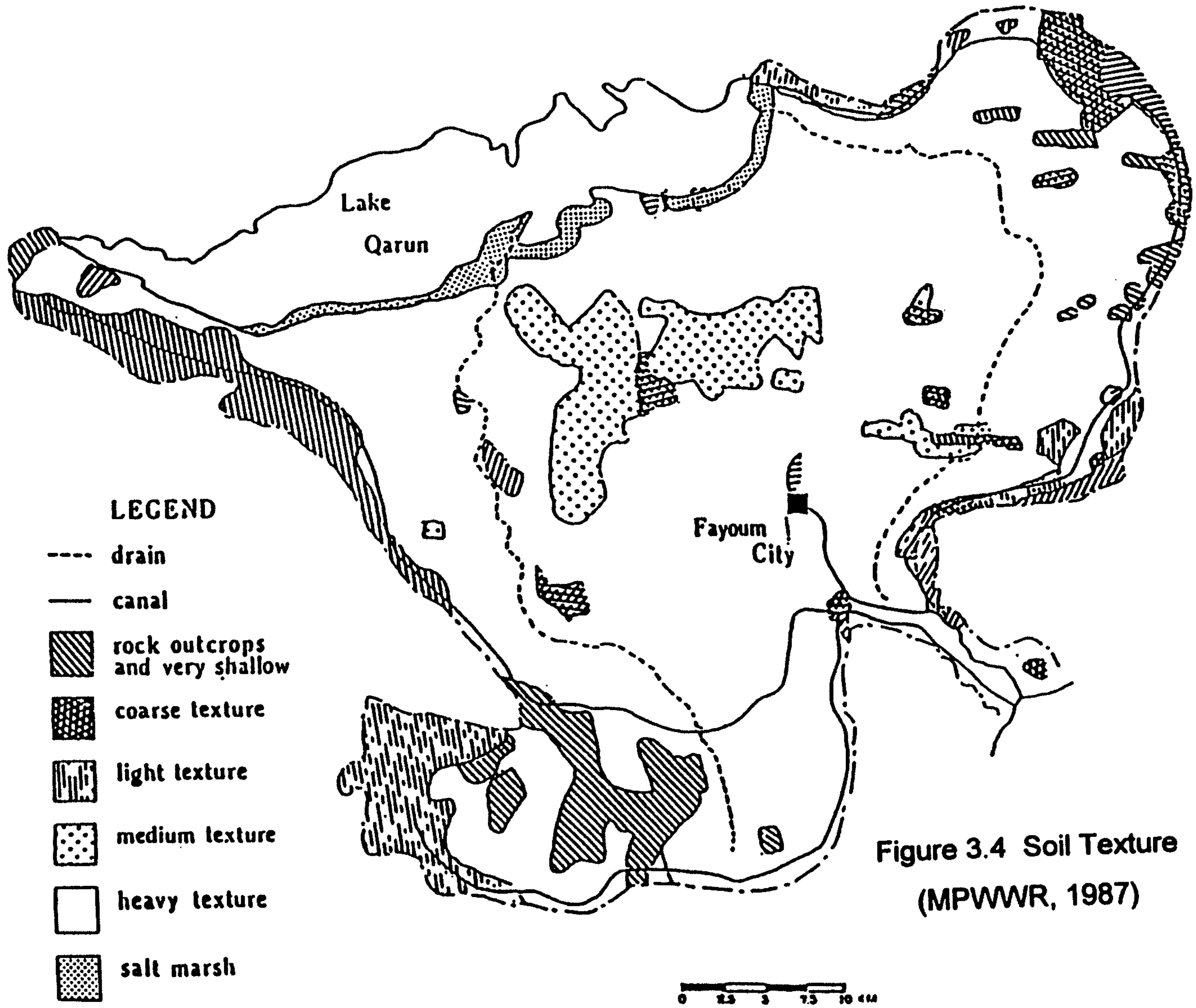


Figure 3.4 Soil Texture
(MPWWR, 1987)

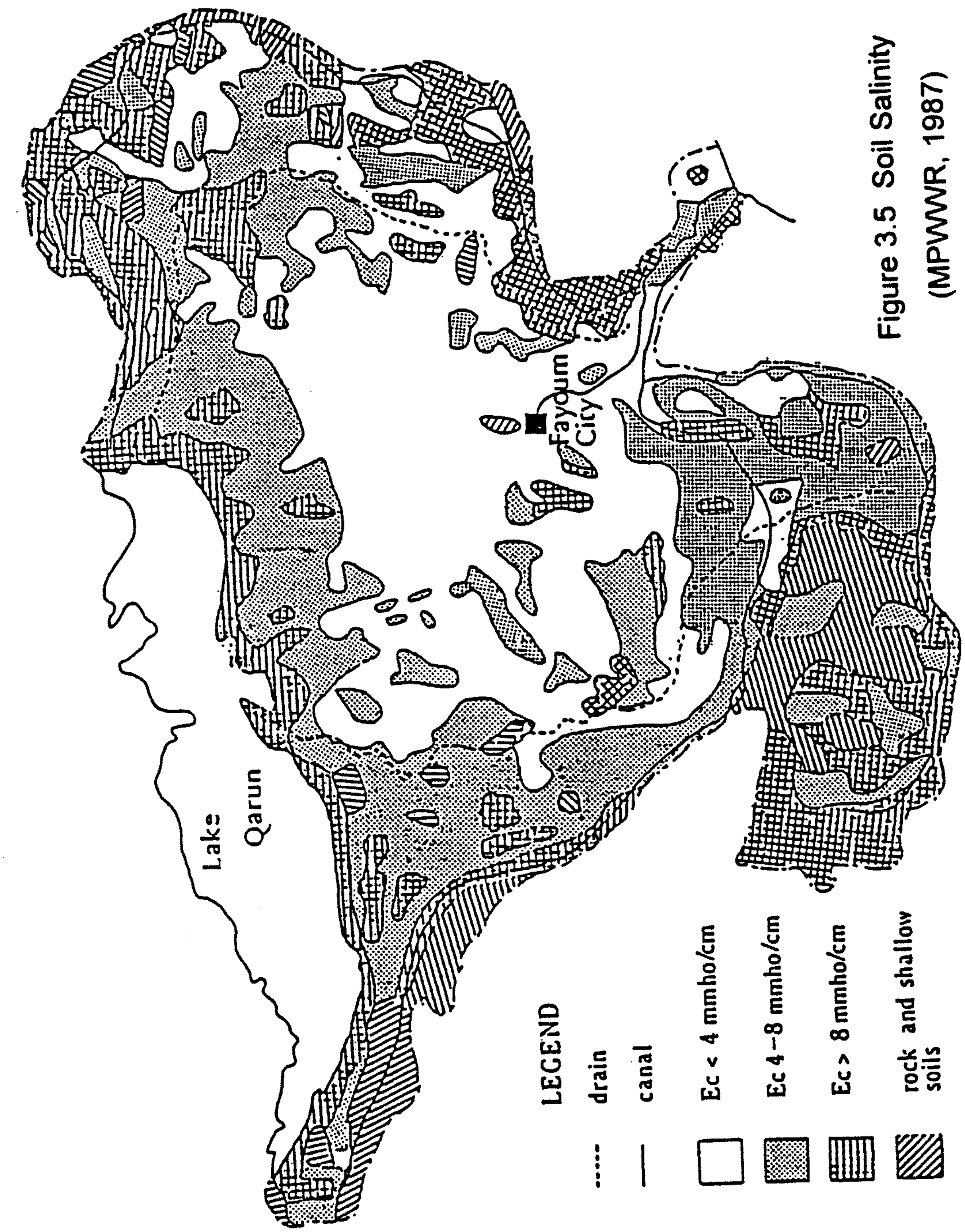


Figure 3.5 Soil Salinity
(MPWWR, 1987)

The Fayoum governorate is divided into five districts: Tamya, Senuris, Fayoum, Ibshway, Itsa. Within these districts, a wide variety of crops are grown over three cropping seasons, i.e., winter, summer and nili (Nile flood season). The major crops are as follows:

- winter season (October-April): wheat, berseem, beans, vegetables;
- summer season (March-October): sorghum, cotton, maize, rice;
- nili season-Nile flood season (July-December): maize, vegetables.

Beside the seasonal crops, about 7% of the cultivated land is planted with perennial crops such as citrus, date palm and other orchards.

There is overlap in cropping seasons (Table 3.1) which limits the choice of crops. A long duration summer crop can only be planted after a short duration winter crop. Nili crops can only be planted after a summer fallow and be succeeded by a late winter crop. The result is that out of a total area of 342,000 feddans, some 334,000 feddans can be cultivated, while 8000 feddans are seasonal fallow.

Table 3.1 The cropping calendar of the Fayoum

Month	1	2	3	4	5	6	7	8	9	10	11	12
Winter												
Summer												
Nili												
Perennial												

3.1.3 Climate

The Fayoum has an arid climate which is characterized by a high evaporative demand and very low rainfall. The main climatic factors are summarized in Table 3.2.

Table 3.2 The climate of Fayoum (Annual average values)

	Lake Qaroun	Fayoum town
Mean temperature	22.1 °C	22.0 °C
Max. Temperature	28.6 °C	26.5 °C
Min temperature	15.7 °C	14.5 °C
Mean relative humidity	61%	51%
Relative sunshine	82%	82%
Annual rainfall	9.2 mm	13.7 mm
Annual evaporation	1980 mm	2090 mm

3.1.4 Irrigation

The present irrigation system was constructed between 1900 to 1920 to be used for perennial irrigation. Irrigation water for the Fayoum is diverted from the Nile at the Assiut Barrage in Upper Egypt, and is conveyed along the fringe of the Nile Valley, first by the Ibrahimia canal to Dairut, and then by the ancient Bahr Yousef canal to Lahoun, for a total distance of 380 km. At Lahoun, three regulators divide the water over the following canals (Figure 3.2):

i. Lahoun regulator to Bahr Yousef, serving the central and NE parts of Fayoum;

ii. Lahoun regulator to Bahr Hassan Wasef, serving the southern and western parts of Fayoum;

iii. Giza regulator to Giza canal, serving part of the Nile Valley below Lahoun.

The distribution of water over the main and secondary canals is controlled by undershot gates. Downstream from these gates, daily discharge measurements are made by staff gauge readings. Water distribution over the tertiary command areas is regulated by groups of broad crested weirs. Such a cluster of diversion structures is named a "Nasbah", or a Fayoum Standard Weir (Amer, 1992). All the weir crests within a Nasbah have the same elevation and their width is proportional to the area served. The average land slope is 2 m/km, while the design gradient of the canals is 0.15 m/km. Many drop structures are required to reduce the natural gradient to the design gradient. The energy potential of these surface gradients has been occasionally tapped. Ancient waterwheels (Nuria's or Saqqias) lift water from canals into tertiary distributaries (mesqas). At locations where there are drops of more than 6 m, the installation of small hydroelectric power plants is permitted.

Apart from the Nuria's and a few diesel pumps, irrigation is impelled by gravity, and the supply is delivered to the rotational units. Within these units, water is applied to the field by the force of gravity, or lifted to the land by mule driven waterwheels (saqqia's). Since 1980, farmers have been gradually replacing their saqqia' s with diesel pumps.

The irrigation system is designed for a continuous supply of water (24 hours a day, 7 days a week) to the rotational units, which vary in size from about

20 to 500 feddans. The design maximum supply is 30 m^3/feddan/day (7.1 mm/day). The Fayoum Irrigation Department is responsible for the delivery of irrigation water to the rotational units. Within the units, the farmers rotate the water in a seven day rotation: every farmer officially receives water at the same time each week. An interesting description of the official 'munawaba' system is given by Mehanna et al. (1984). There is traditional commitment to share maintenance. The farmer owns the largest land on a mesqa usually leads the maintenance operation. In practice, each farmer is responsible for the maintenance of that portion of the canal that is adjacent to his field. The irrigation network in the Fayoum basin is shown in Figure 3.6.

3.1.5 Drainage

The natural drainage system discharges the drainage water into Lake Qaroun. These natural water courses are deeply incised into the alluvial fan. The main drains of the Fayoum are: the Batts in the eastern part, and the Wadi drain in the western part of the Fayoum. Together with several minor drains, these discharge into Lake Qaroun. The drainage network of the Fayoum basin is shown in Figure 3.7.

Since 1973, part of the water in the Wadi Drain is diverted to the wadi Rayan Depression through a tunnel in the limestone ridge between these two depressions (Figure 3.2). This represents about 30-40% of the total drainage water.

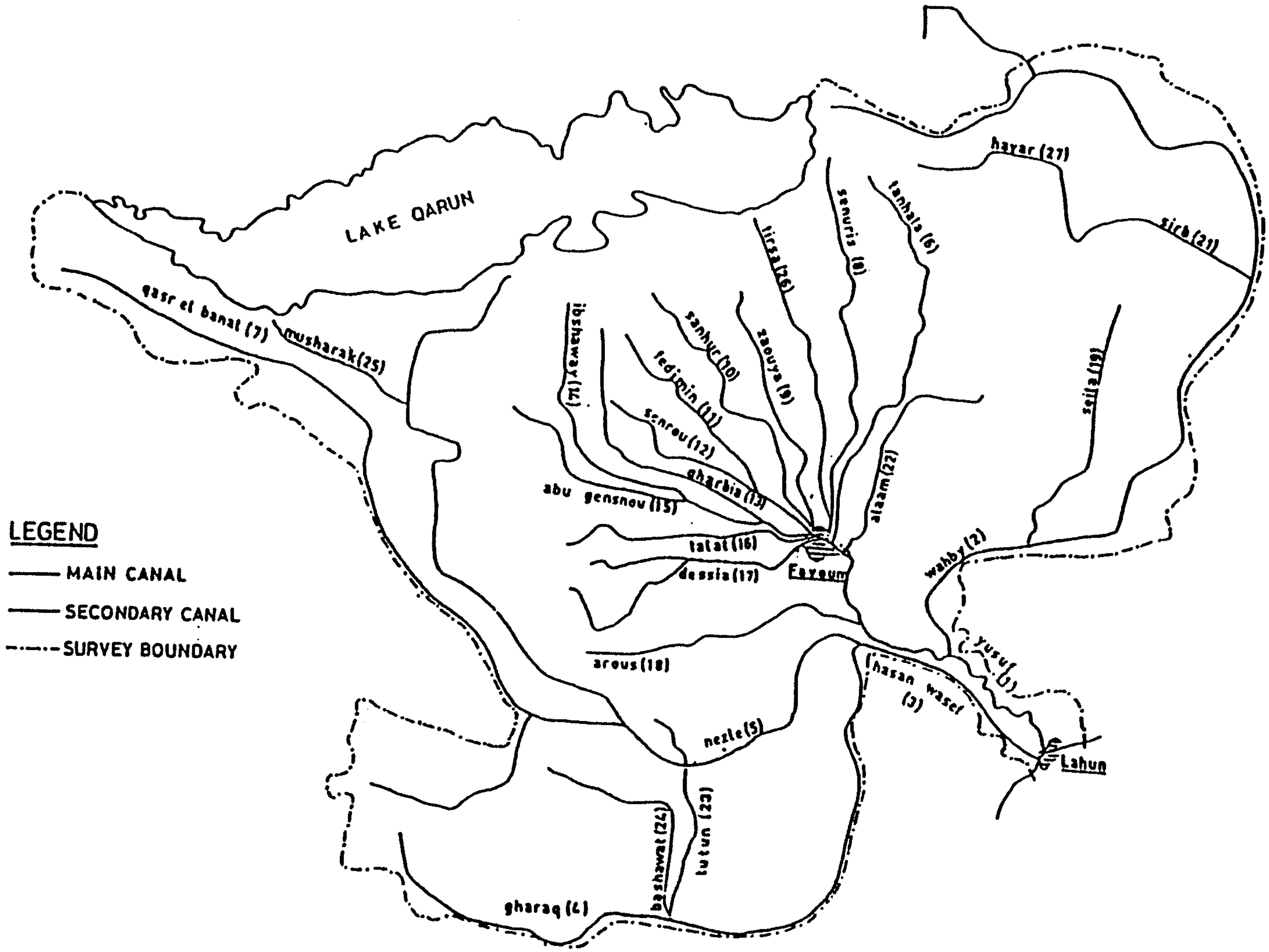


Figure 3.6 Irrigation Network (Amer, 1992)

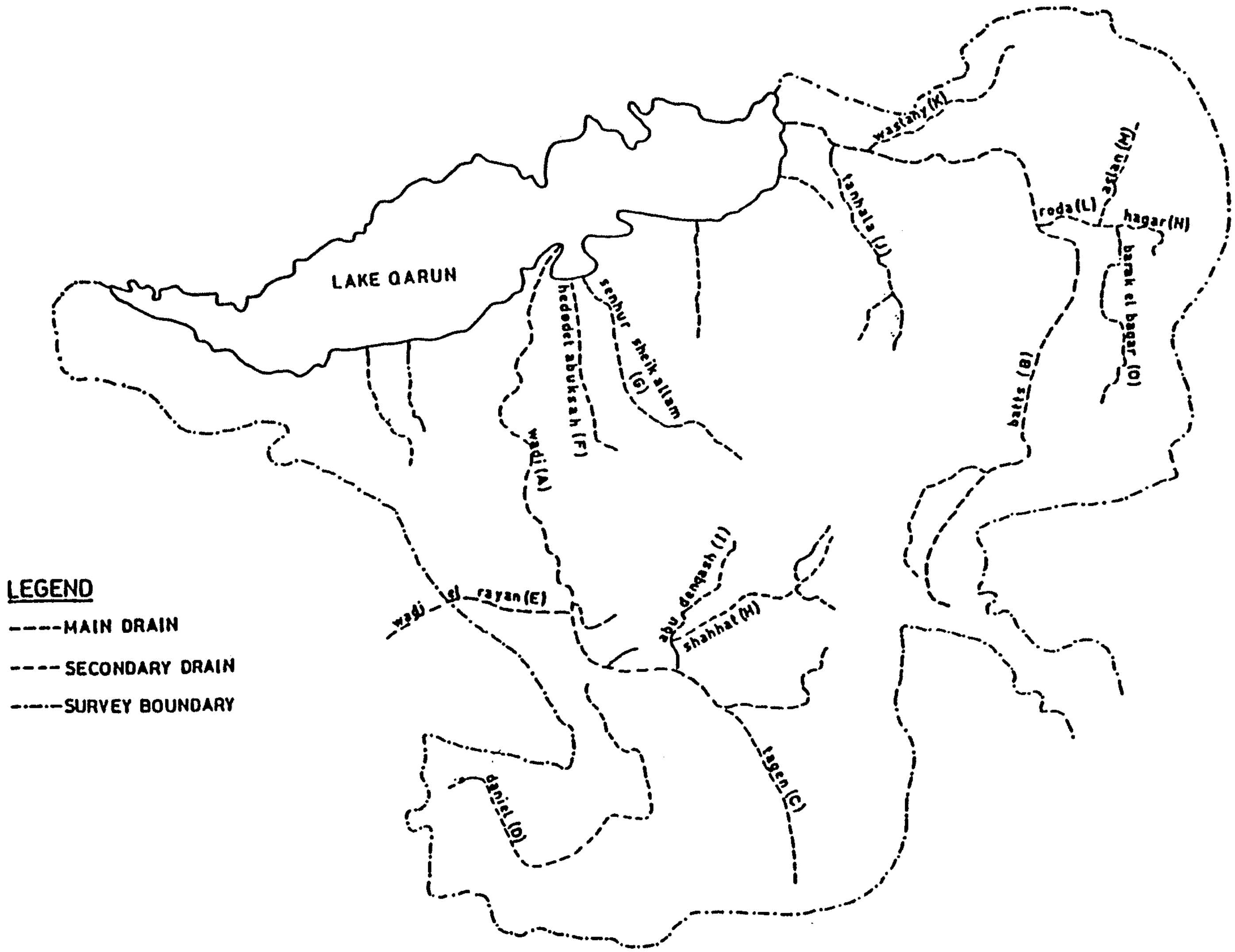


Figure 3.7 Drainage Network (Amer, 1992)

Drainage in the Fayoum works on a gravity system. The exception is a low lying area of some 12,000 feddans, bordering on Lake Qaroun, which requires pumped drainage.

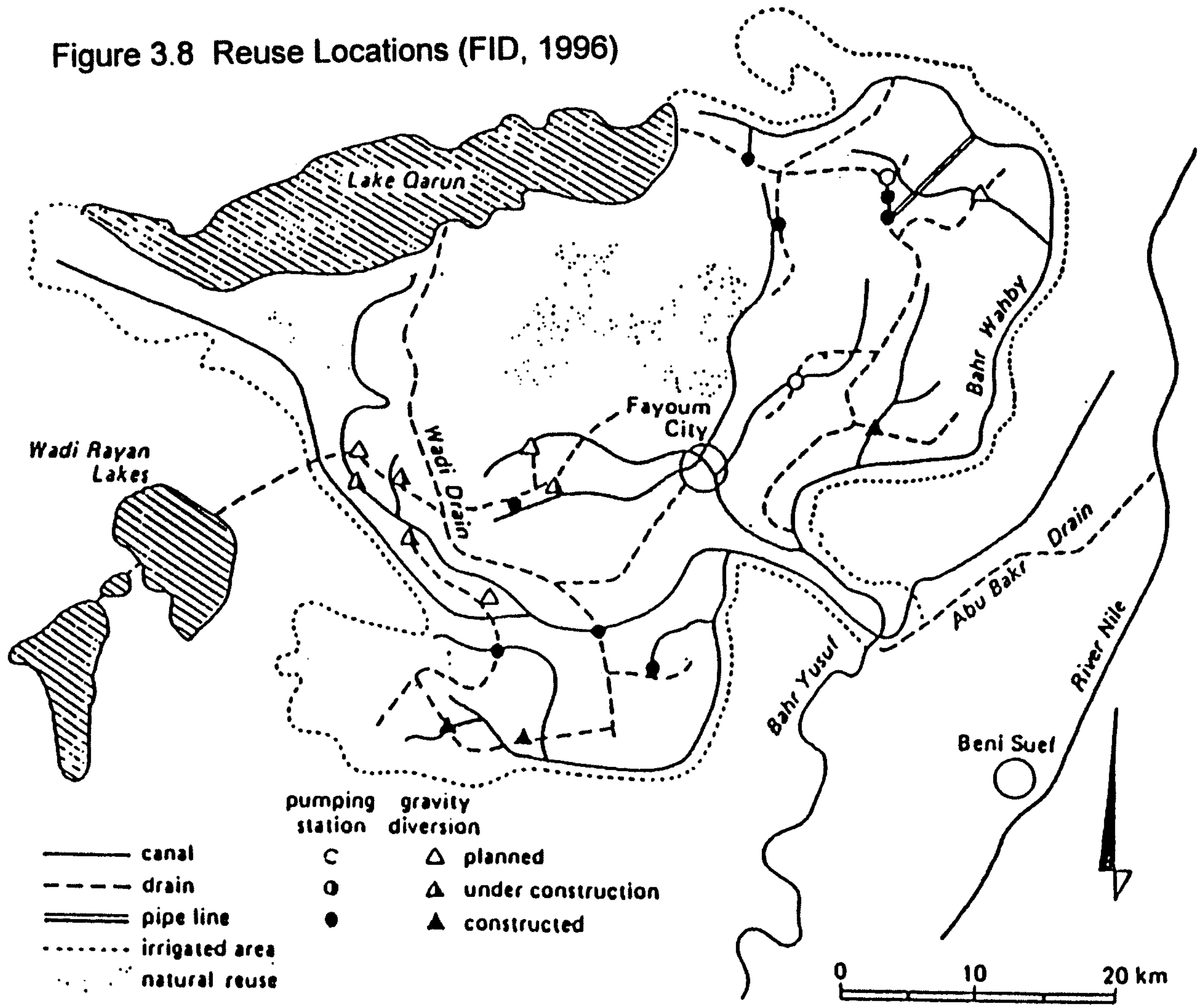
The reuse of drainage water increased over the past 14 years when the Fayoum irrigation Department started to construct a number of small pumping stations to mix drainage water with irrigation water. At some locations, the mixing can be achieved by gravity.

3.1.6 Reuse of Drainage Water and Reclamation Areas

The sloping lands in the Fayoum make reuse by gravity feasible. This feature was used in the original design of the present irrigation and drainage network. Natural watercourses, which were deeply scoured into the alluvial fan, acted as drains in the upstream sections and served as irrigation canals in the downstream sections. At other locations, small pumps were installed along the drains. Recently, large pumping stations have been constructed or are planned by the Fayoum Irrigation Department (Figure 3.8). These stations will deliver their discharge to existing irrigation canals. Through this mixing, water salinity can be kept within tolerable levels.

The estimated reuse of drainage water in 1988 was about 180 MCM/year by, lifting and 150 MCM/year by gravity. This explains the high irrigation system efficiency of 62%. Mixing drainage water with fresh irrigation water is required to ensure a good quality. In the Fayoum, a mixing ratio of 1:1 results in a salinity of around 1 dS/m (Alnagar and Amer, 1988).

Figure 3.8 Reuse Locations (FID, 1996)



Major reuse projects (DRI, 1993b):

- Tagen pump station

Of the present series of reuse pumping stations (Figures 3.8 and 3.9), the Tagen pump station was the first major reuse project. The pump station delivers drainage water at the intersection of Tagen drain with Bahr El Nezla. The amount of drainage water delivered from Tagen drain to Bahr El Nezle is 85 MCM/year. The drainage water will also serve to reclaim the new area at El-Gharaq and improve the conditions of the areas of Bahr El-Nezla downstream from the Tagen pumping station.

- Gharaq pump station

The mixing location is at the intersection of El Gharaq drain and Bahr El Bashawat. This project aims to improve the irrigation efficiency and contributes 39 MCM/year at the tail end of El Bashawat canal.

- Batts pump station

The major drainage water reuse project in Fayoum is the Batts pumping station, which was constructed in October, 1993 for lifting drainage water from Batts drain to Bahr Wahby near Kasr Rashawat (km 14.700) (Figures 3.8 and 3.9). The pumping station delivers drainage water with a maximum discharge of 180,000 m^3/day through a 6.5 km long pipeline where it meets Bahr Wahby in front of Abdel Hady weir (km 46.6). The purpose of reusing drainage water is to improve water delivery at the end of Bahr Wahby, and reclaim a new area of 15,000 feddans east of Bahr Wahby and north Komoshim. The total yearly estimated drainage water that can be used is 140 MCM/year.

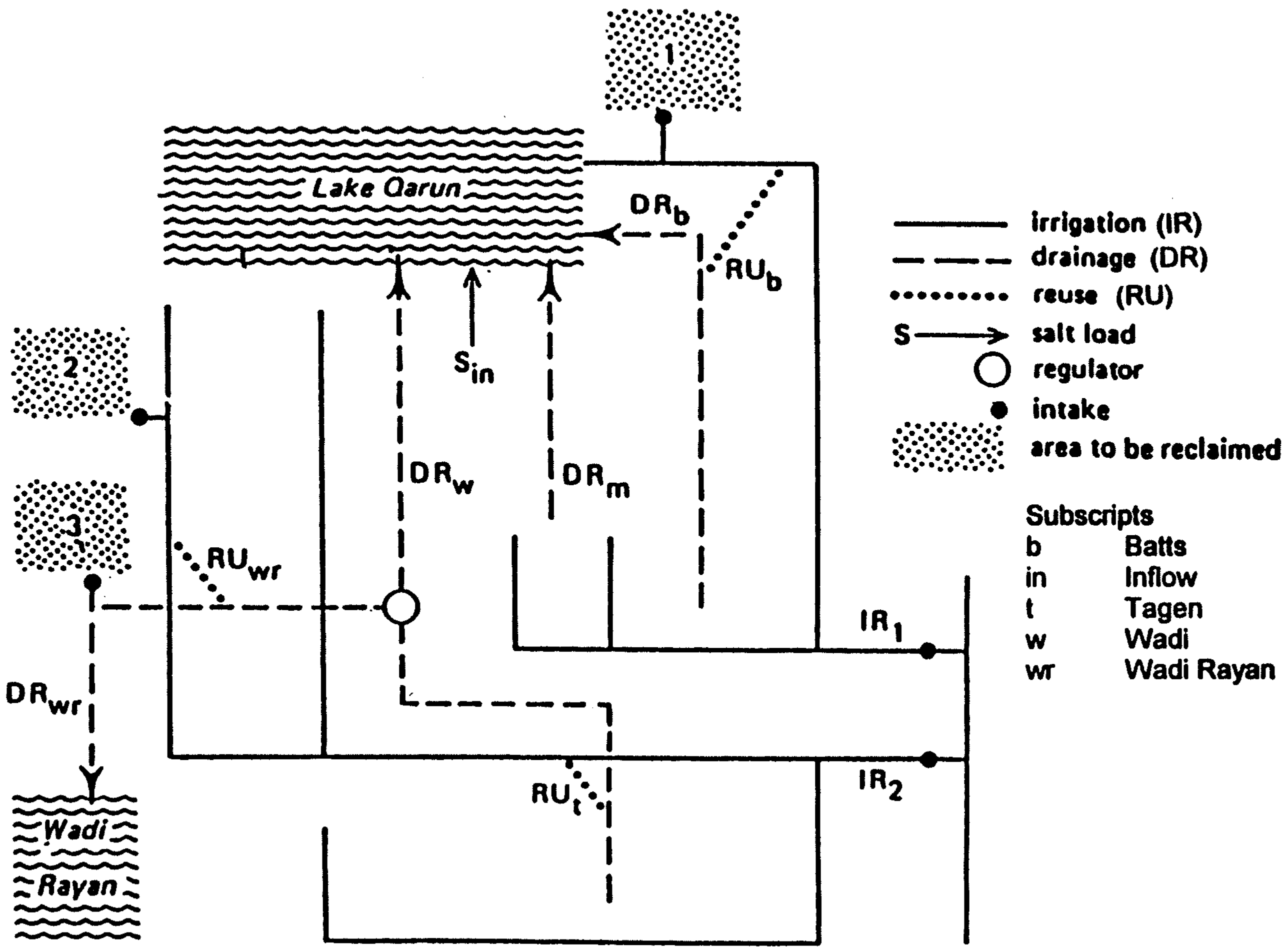


Figure 3.9 Major Reuse Projects and Reclamation Areas (FID, 1996)

New reuse pumping station (DRI,1993b):

The most promising locations of reuse pumping stations are the following (Figure 3.9):

i. Rayan-Nezle reuse pumping station (from Wadi Rayan feeder canal to Bahr Nezle):

the planned reuse station on Wadi Rayan drain will supply the lower Bahr nezle Command area, with an average discharge of 0.5 m^3/sec;

ii. Rayan-Banat reuse pumping station (from Wadi Rayan feeder to Bahr Qasr El-Banat):

the construction of a reuse pumping station in the Wadi Rayan feeder canal, downstream of the Rayan-Nezle pumping station, will require an average discharge of about 1.5 m^3/sec;

iii. Reuse pumping station from upper lake in Wadi Rayan (from the upper lake in Wadi Rayan depression to new expansion area):

the reuse pump station will be constructed and operated from the upper Rayan lake to a new expansion area; the operational design capacity is 2 m^3/sec.

Reclamation areas (DRI, 1993b):

Three desert land reclamation areas are currently being implemented to extend the agriculture perimeter of Fayoum. These are (Figure 3.9):

i. Bahr Gumhuriya expansion area (the areas of Kom Osheem and Bahr Gumhuriya):

the Bahr Gumhuriya reclamation area is supplied with irrigation water from the Kom Osheen and Gumhuriya canals that have their joint intake from Bahr Wahby; the drainage water flows to the Kom Osheem lakes and marshes, where it evaporates; It does not reach Lake Qaroun; the area that will be reclaimed is about 3200 feddans and has only limited scope for expansion;

ii. South Qaroun expansion area (the area south of Bahr Qaroun):

the reclamation area along Bahr Qaroun, known as the South Qaroun reclamation area is currently under implementation. The first phase of this project will comprise some 4000 feddans of cultivated land;

iii. Wadi Rayan expansion area (the area between the upper and lower Wadi Rayan lakes):

the reclamation area in the Wadi Rayan depression is the first phase of a plan to reclaim some 8000 feddans between both Wadi Rayan lakes; the area under implementation is 4000 feddans.

3.1.7 The Fayoum Irrigation Department (FID)

The Fayoum Irrigation Department (FID) operates under the responsibility of the Under-secretary of State for the Ministry of Public Works and Water Resources in the governorate. Figure 3.10 shows the organization diagram. The FID itself is headed by a Director General and two inspectors, for the east and west parts of Fayoum. The Director General and the two inspectors have a staff at their disposal consisting of several engineers. Each district is headed by a district engineer. The district staff further consists of some 2-6 technicians with supervision over the structures, and a large number of bahars.

The FID has two main tasks: (i) the planning of water supplies; and (ii) the daily operation of the system. The daily operational process is executed by the Director General and the two inspectors. They give orders to district engineers on the division of water over the main canals and the most important laterals. The district engineers supervise the water distribution within their district and also coordinate the daily monitoring of water levels. They are responsible for the maintenance of structures and canals, which is planned and executed in cooperation with the staff of the FID headoffice. Important elements in the district engineer's task are: (i) dealing with complaints of farmers; (ii) giving penalties where rules have been violated; and (iii) generally maintaining the discipline of water distribution. In case of problems, farmers can also complain at higher levels, to the inspectors, the Director General, the Under-secretary of State, or even to the Governor.

Data collection methods:

Most discharge measurements of the saline water disposal into Lake Qaroun were done with current meters. Measurements at Wadi drain were taken at the pump stations. Salinity measurements were carried out with the EC-meter, to study the quality of the irrigation water and the rate of reuse of drainage water for irrigation.

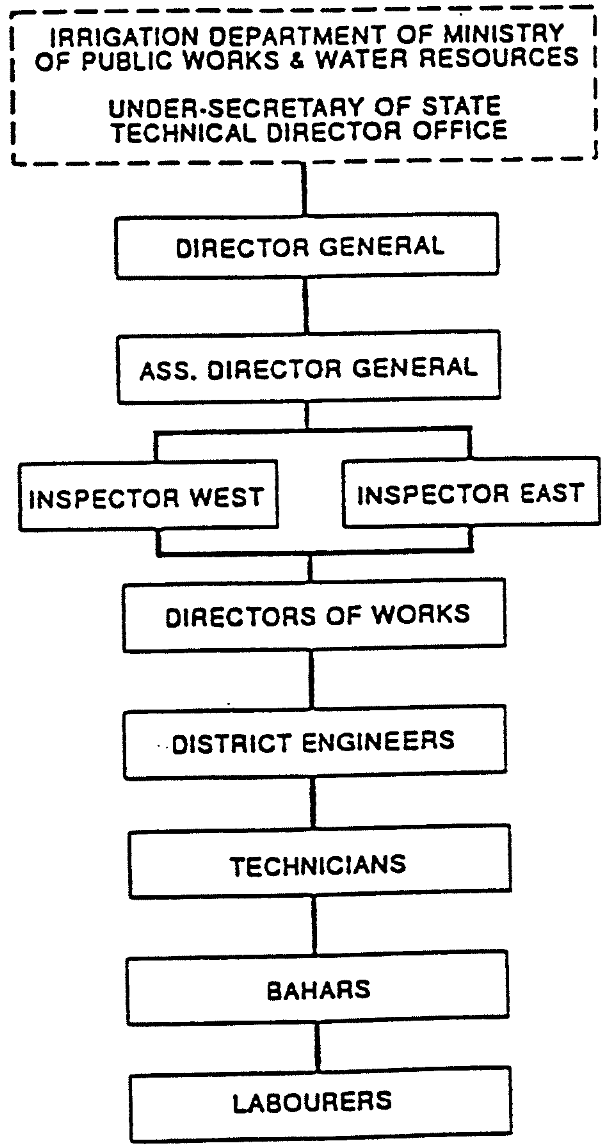


Figure 3.10 The Fayoum Irrigation Department (FID)

3.2 Field Data

3.2.1 Lake Qaroun Water Levels

Two main elements are included in the hydraulics of water levels of Lake Qaroun: the open water evaporation of the lake, and the inflow into the lake of drainage water from the irrigated lands of the Fayoum basin. Figure 3.11 shows the annual effect of these two parameters in decreasing the lake volume in 1995 (source: Fayoum Irrigation Department). The monthly effect of drainage inflow and evaporation on Lake Qaroun for 1995 is shown in Figure 3.12 (source: Fayoum Irrigation Department). The average monthly water levels of Lake Qaroun for the years 1984, 1987, 1990 and 1995 are shown in Figure 3.13 (source: Fayoum Irrigation Department). This typical fluctuation for each year shows that there is seasonal variation in water levels. Generally, the maximum level is reached in April and the minimum in October. In winter, the inflow exceeds evaporation; in summer, the evaporation is higher. The difference between the annual high water level in April and low in October is 40 to 60 cm.

In 1990, especially during autumn and winter, improper water management of Lake Qaroun resulted in rapidly increasing water levels. This resulted in 25 cm higher water level at the end of 1990 than at the begining of 1990 (Figure 3.13).

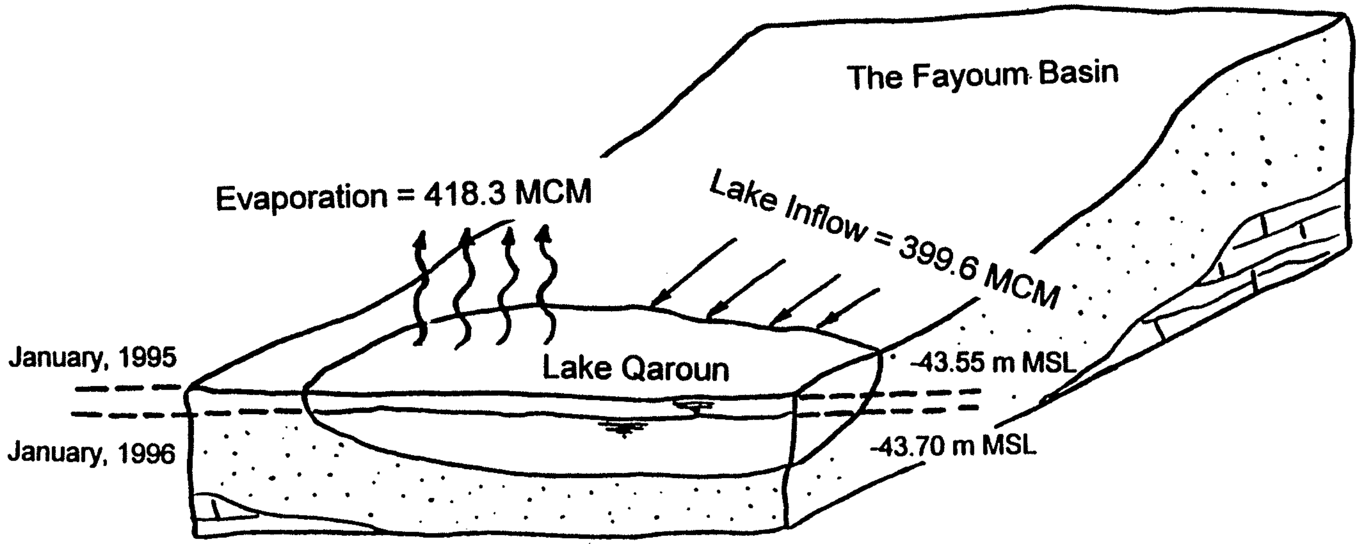


Figure 3.11 Annual combined effect of evaporation and saline disposal on Lake Qaroun water levels

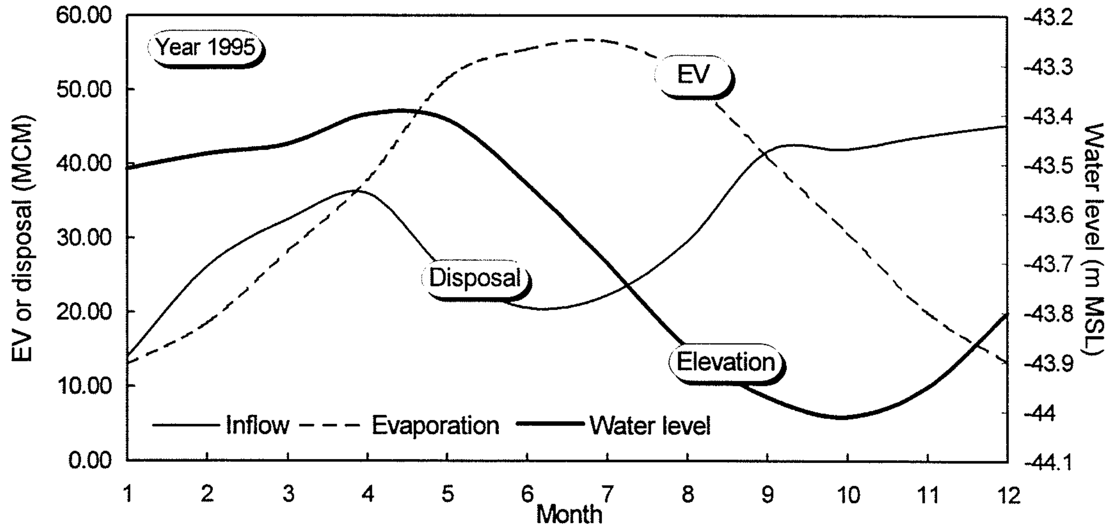


Figure 3.12 Monthly water levels, lake evaporation and drain inflows to Lake Qaroun water levels

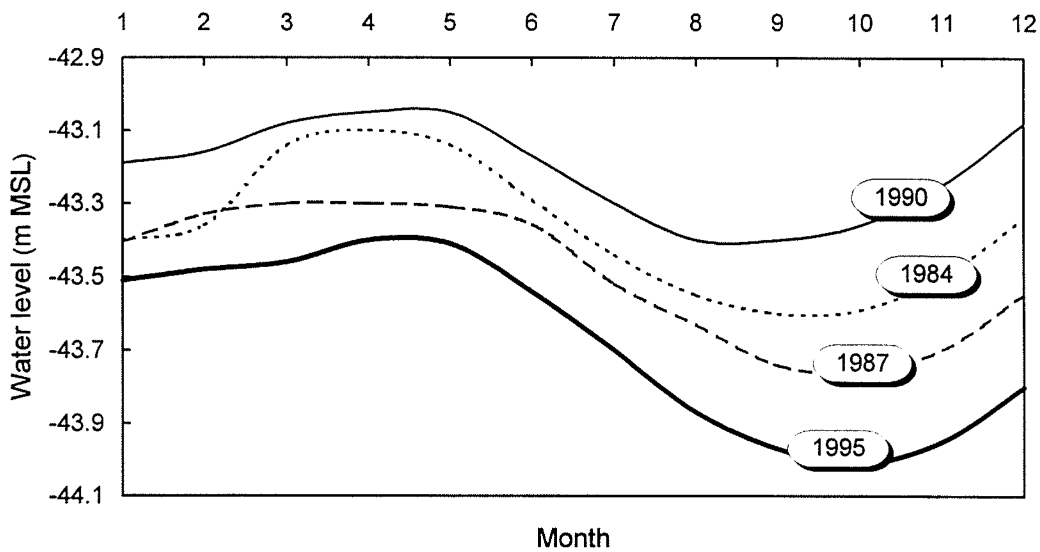


Figure 3.13 Average monthly water level of Lake Qaroun 1984,87,90,95

Annual changes in Lake Qaroun level (1980-1996) can be seen in Figure 3.14 (source: Fayoum Irrigation Department). Water levels increased from 1987 to 1991, but the most significant rise occured during the second half of 1990, when the 1990 minimum was almost 25 cm higher than the minimum of 1989. Together with continuous spilling until the closure period of 1991 (January/February) and heavy rainstorms (March), these factors resulted in the highest spring water levels (1991) since 1900, when water level recording first began.

The changes in lake water levels over this century are shown in Figure 3.15 (source: Fayoum Irrigation Department). With the intensification of cropping, started in 1953, and the related increase in water supply to Fayoum, the level of Lake Qaroun began to rise.

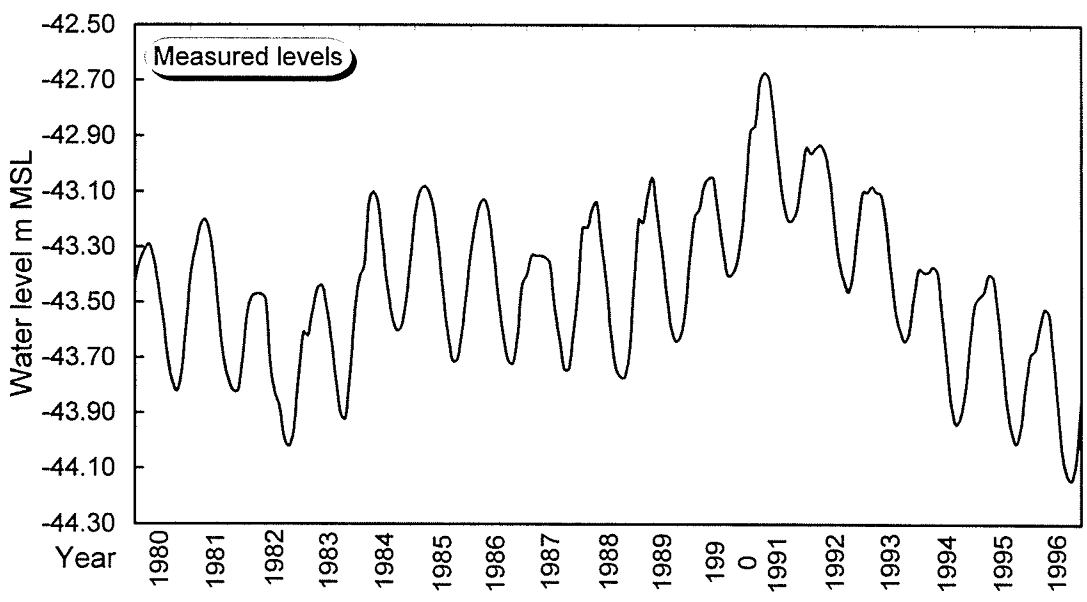


Figure 3.14 Averge monthly water levels of Lake Qaroun (1980-1996)

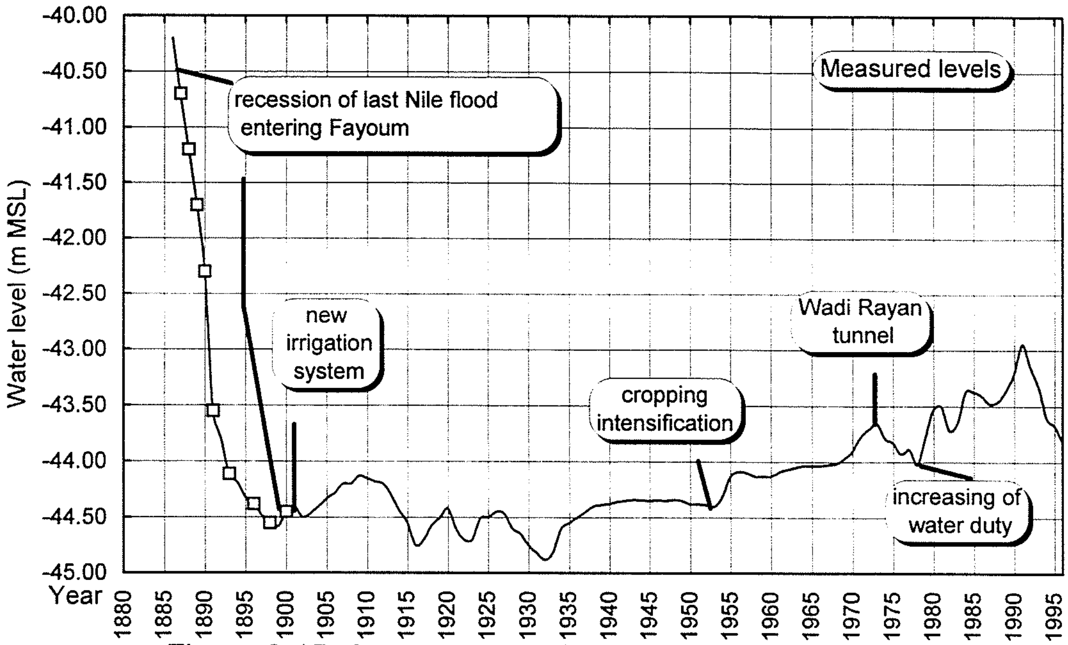


Figure 3.15 Average annual water levels of Lake Qaroun (1880-1996)

Since the lake has no natural outlet, a delicate balance exists between inflow and evaporation. Generally, the average annual intake of irrigation water for Fayoum amounts to about 2300 x 10^6 m^3. From this amount, some 700 MCM is evacuated as drainage water. Lake Qaroun has a capacity to evaporate some 425 MCM of drainage water per year, thus resulting in an average lake level of -43.80 m MSL. The remaining 275 MCM of drainage water must therefore be spilled. An inflow of 2.5 MCM of drainage water in excess of the equilibrium inflow will raise the level by 1 cm. In years with a lake inflow of more than 460 MCM, such as 1988, the result is a dramatic rise of the lake level, causing severe inundation and waterlogging of adjacent agricultural lands.

The change in lake storage and evaporation is a function of the surface area, and, consequently, the lake level. The annual changes in water levels (1990-1995) are presented in Table 3.3. According to observations from the Fayoum basin, the water balances (1990-1995) are shown in Table 3.4 (source: Fayoum Irrigation Department).

Table 3.3 The annual water level of Lake Qaroun (1990-1995)

Year	Average level m MSL	Minimum level m MSL	Maximum level m MSL	Level in January. m MSL
1990	-43.21	-43.40	-43.05	-43.26
1991	-42.94	-43.20	-42.67	-43.01
1992	-43.15	-43.46	-42.93	-42.97
1993	-43.33	-43.64	-43.08	-43.14
1994	-43.61	-43.94	-43.37	-43.40
1995	-43.68	-44.01	-43.40	-43.54

Table 3.4 The water balance of lake Qaroun (1990 -1995)

Year	Inflow (MCM)	Rainfall (MCM)	Evap[1] (MCM)	Extraction[2] (MCM)	ΔS[3] (MCM)	ΔWL[4] (cm)
1990	495.0	2.33	437.9	10.0	57.21	0.245
1991	447.7	14.32	446.3	11.2	10.1	0.044
1992	389.7	2.34	440.6	13.6	-39.5	-0.169
1993	362.1	2.31	433.28	13.9	-61.2	-0.265
1994	384.8	2.25	421.10	18.9	-32.6	-0.145
1995	379.6	2.24	418.30	17.1	-43.6	-0.155

[1]Evap = evaporation. [2]Extraction = salt factory extraction. [3]Δ **S**= change in Lake Qaroun storage every January. [4]Δ **WL**= change in water levels every January.

During 1994 and 1995, the average water level was around -43.6 m MSL. The water level at the beginning and the end of each year, with approximately 0.6 m fluctuation, was approximately the same. Generally, the maintenance of a stable lake level is necessary to prevent damage to adjacent agricultural lands, and to the villages and tourist infrastructure on the lake shore.

3.2.2 Lake Qaroun Water Salinity

Annually, drainage water carries roughly 500,000 tonnes of salt to Lake Qaroun. As no salt leaves the lake, the water quality is rapidly deteriorating. In July, 1995, the Nasr salt company measured the salinity of the lake water. The 650 samples taken showed an average salinty of 50 dS/m (FID, 1996). There is, however, no regular monitoring to accurately estimate the salt concentration in Lake Qaroun. Nevertheless, from these measurements (FID, 1996), it appears that the current annual salinity is about 50 dS/m. Figure 3.16 shows the annual changes in the lake water salinity over this century. Two main elements are included in the estimate of the salinity level of Lake Qaroun: the water level of the lake and the salt load (inflow) into the lake, which represents the drainage water from the irrigated lands of the Fayoum basin.

On a yearly basis, the increase in salinity is estimated to be 0.5 dS/m. Generally, about 60 tonnes of salt per hour enters Lake Qaroun. Therefore, it is expected that by the year 2020, Lake Qaroun will be hazardous because of high levels of salinity. That continous increase in lake water salinity will eventualy lead to a negative impact on fishing, recreaction, agriculture and tourism.

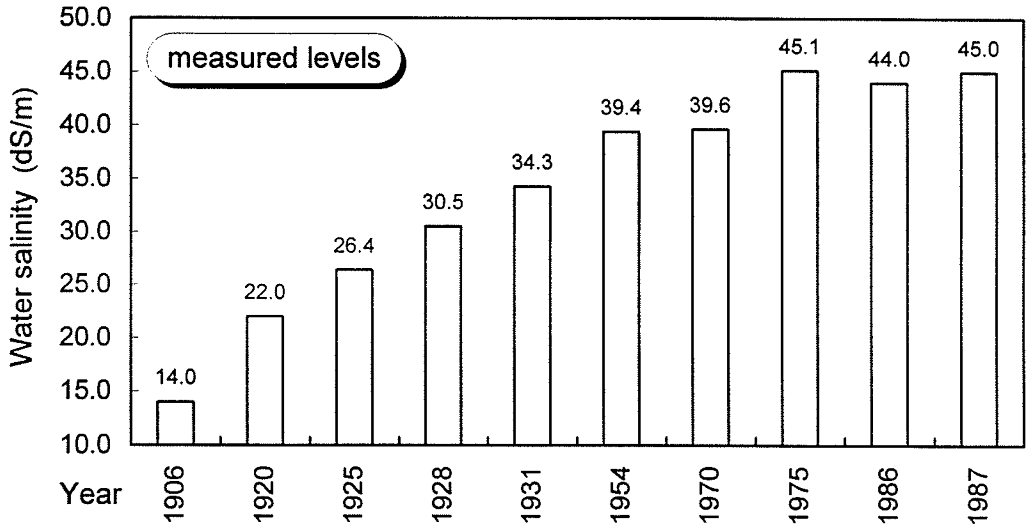


Figure 3.16 Average annual water salinity of Lake Qaroun (1906-1987) (Fayoum Irrigation Department)

3.2.3 Changes In Cropping Pattern

The cropping pattern for the Fayoum basin is established by the Fayoum Department of Agriculture. Cropping patterns are provided for each of the five districts: Fayoum, Tamiya, Senuis, Itsa and Ibshway. Three cropping patterns are issued every year:

i. winter season and some major summer crops (at the start of the year);

ii. summer and nili season;

iii. winter season (at the end of the year).

The total Fayoum basin crop patterns for 1980, 1990 and 1996 are shown in Table 3.5. From Table 3.5, it can be seen that nili maize planting completely stopped after 1990 and was replaced by summer sorghum. After

1991, summer sorghum planting was reduced by almost 35%. Apparently, the Fayoum department is altering the nili crop types. Starting from 1990, cotton was reduced almost by 36%, and maize increased by almost 120%, compared to the period 1980-1989. Over the study period 1980-1996, the area planted with wheat is considered the largest in comparison to the other planted areas. The total wheat cropped was estimated to be 80,000, 110,000 and 127,500 feddans for 1980, 1990 and 1996, respectively.

Looking at the large lists of crops cultivated every year, it seems that there are no large changes in the cropping pattern: the cultivated crops are still the same and the cultivated areas differ slightly from year to year. Looking at the total figures for the main cropping seasons, however, it seems that there are indeed some general trends that have evolved over the past 17 years. The crop intensity (1990) for the five districts: Fayoum, Tamiya, Senuis, Itsa and Ibshway are presented in Table 3.6. The summarized figures are given in Table 3.7 for the average situation during 1980-1985, 1986-1990 and 1991-1996.

The overall cropping intensity is now 183% compared to 176% in 1980. Itsa district has the greatest crop intensity. Table 3.7 shows that more crops are presently grown in the winter season (from October till April). Cropping intensity in the summer season (from May till August/September) has increased. However, the cropping intensity in the nili season (from July till December) has decreased.

Table 3.5 Average annual planned cropped pattern (in feddans) for years 1980, 1990 and 1996 (FDA, 1980; FDA, 1990; FDA, 1996)

Crops	1980	1990	1996
Wheat	80,000	110,000	127,500
Beans	18,000	25,000	15,000
Berseem	94,500	106,209	93,932
Vegetable winter	21,200	26,526	25,010
Others winter	25,800	20,758	22,419
Total winter	239,500	288,493	283,861
Cotton	54,500	35,450	35,000
Rice	24,300	12,500	13,630
Maize	25,500	55,000	57,000
Sorghum	45,400	46,847	62,977
Vegetables	21,800	29,100	34,000
Others summer	16,400	28,945	49,501
Total summer	187,900	207,842	252,108
Maize nili	75,100	50,000	0
Vegetables nili	22,200	37,170	67,755
Total nili	106,100	92,209	67,755
Trees	20,300	23,619	22,501

Table 3.6 Cropped area (%) and cropping intensity (%)* for 1990

Crops season	Fayoum	Senuris	Tamiya	Itsa	Ibshaway	Total
Winter	85.5	74.4	78.9	105.5	79.3	84.2
Summer	64.2	54.7	60.0	80.2	48.6	60.8
Nili	27.0	22.2	24.1	32.0	30.0	27.0
Trees	4.1	21.0	2.0	0.8	10.4	7.0
Total*	180.8	172.4	165.0	218.5	168.3	179.0

* Cropping intensity (%) is represented by the total

Table 3.7 cropped area (%) and Cropping intensity (%)* for 1980-1996

Crops season	1980-1985	1986-1990	1991-1996
Winter	78.7	82.4	83.5
Summer	59.9	62.3	73.9
Nili	33.4	28.0	18.5
Trees	6.7	6.9	6.6
Total*	178.7	179.6	182.5

* Cropping intensity (%) is represented by the total

Crop consumptive use:

The crop consumptive use for different regions in Egypt is determined by the Ministry of Public Works and Water Resources (MPWWR). The basis for the Ministry's estimate is the water duty table in m^3 per feddan per decade. It includes both the requirement of the crops and the cropping calendar. The consumptive use of 29 crops, represents a complete study performed all over Egypt, is estimated by MPWWR (MPWWR, 1990). Table 3.8 shows the water duty for every four months.

Table 3.8 Water duties for main crops (m^3/feddan/4 months)

Crops	January-April	May-August	September-December	Total
Wheat	1167.2	0.0	662.8	1830.0
Beans	909.0	0.0	550.4	1459.4
Barley	658.5	0.0	841.5	1500.0
Fenugreek	409.1	0.0	721.1	1130.2
Lupins	446.7	0.0	863.2	1309.9
Chick peas	446.7	0.0	863.2	1309.9
Lentils	441.2	0.0	773.9	1215.1
Berseem short	0.0	0.0	2250.1	2250.1
Berseem long	2458.4	254.3	857.1	3569.8
Flax	748.8	0.0	441.3	1190.1
Onion winter	1229.9	0.0	839.7	2069.6
Garlic winter	1058.1	0.0	722.3	1780.4
Vegetable winter	758.8	0.0	2301.1	3059.9
Others winter	2476.8	0.0	1123.2	3600.0
Cotton	962.5	3041.9	535.8	4540.2
Rice	0.0	7729.5	2200.5	9930.0
Maize summer	0.0	3100.0	0.0	3100.0
Sorghum summer	0.0	3000.0	0.0	3000
Soya beans	0.0	3600.0	0.0	3600
Sugar cane	1694.5	3740.1	435.2	9739.8
Sesame	0.0	3130.2	0.0	3130.2
Peanut	0.0	4600.0	0.0	4600.0
Onion summer	0.0	2200.0	0.0	2200
Vegetables Summer	1733.6	1626.3	0.0	3359.9
Other summer	0.0	3550.0	0.0	3550.0
Maize nili	0.0	1856.9	1243.0	3099.9
Sorghum nili	0.0	1797.0	1203.0	3000.0
Vegetables nili	0.0	971.0	2389.0	3360.0
Trees	678.8	1664.2	1326.8	3669.8

3.2.4 Actual Flows to the Fayoum Basin

Prior to the irrigation season, the cropping pattern is planned and decided upon by the Ministry of Agriculture. The Ministry of Public Works and Water Resources calculates the water requirements for a whole year in advance, and the Fayoum Irrigation Department, accordingly, demands the water it requires. The flows follow the requirements of the seasons: high in the summer and low in the winter. A perfect performance in time is an exact match of the flows diverted to Fayoum and the gross requirements during the year; i.e., requirements including a reasonable percentage for losses and drainage. The monthly flows distributed to the Fayoum, for 1980, 1988 and 1996, are compared in Figure 3.17. During 1980, considerably less water (2287.4 MCM) was diverted to the Fayoum basin than in 1996 (2428.4 MCM). The figures given in Table 3.9 summarize the average situation during 1980-1985, 1986-1990 and 1991-1996. Over the study period 1980-1996, the average annual inflow into the Fayoum basin was 2304 MCM, with a maximum of 2428.4 MCM (1996), and minimum of 2104.4 MCM (1992).

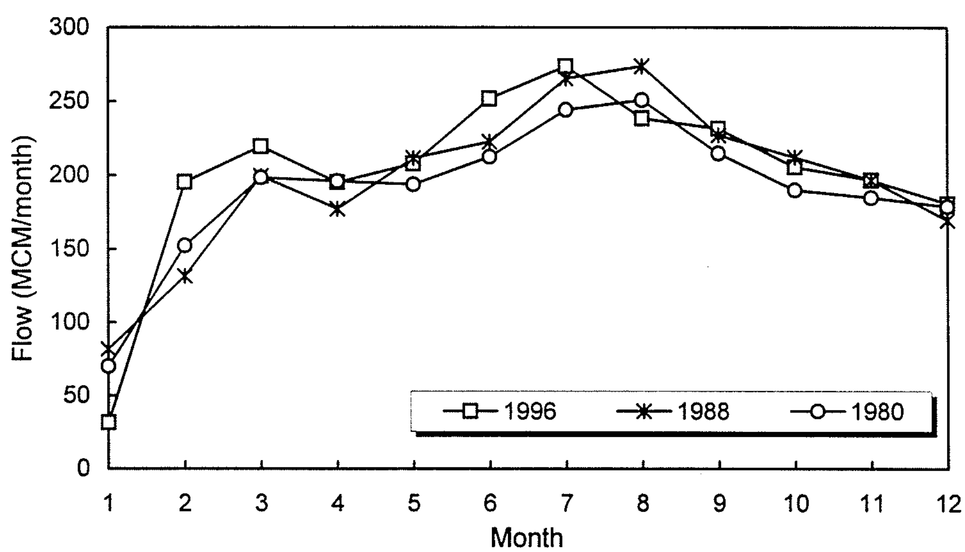


Figure 3.17 Monthly inflows into the Fayoum basin for 1980, 1988 and 1996

Table 3.9 The average annual inflow into the Fayoum basin (1980-1996)

Season	1980-1985 MCM	1986-1990 MCM	1991-1996 MCM
Winter	1163.5	1158.3	1137.3
Nili	1258.9	1310.6	1277.5
Summer	1115.5	1178.7	1164.3
Annual	2279.0	2337.0	2301.6

3.2.5 Drainage/Irrigation Ratio for the Fayoum Basin

The monthly fractions of irrigation water that were leached through the basin, drainage/irrigation ratios, for 1980, 1988 and 1996 are shown in Figure 3.18. During the period 1980-1996, the average monthly ratios are moderately high until April. During the closure period, the irrigation water supply to the Fayoum basin is at its lowest for the entire year. The highest ratio occurs in January when drainage flows lag and remain high. On the other hand, the lowest ratio monitored is during July when irrigation demand is high. The average annual ratios are estimated to be 30.4%, 34.8% and 27.0% for 1980, 1990 and 1996, respectively.

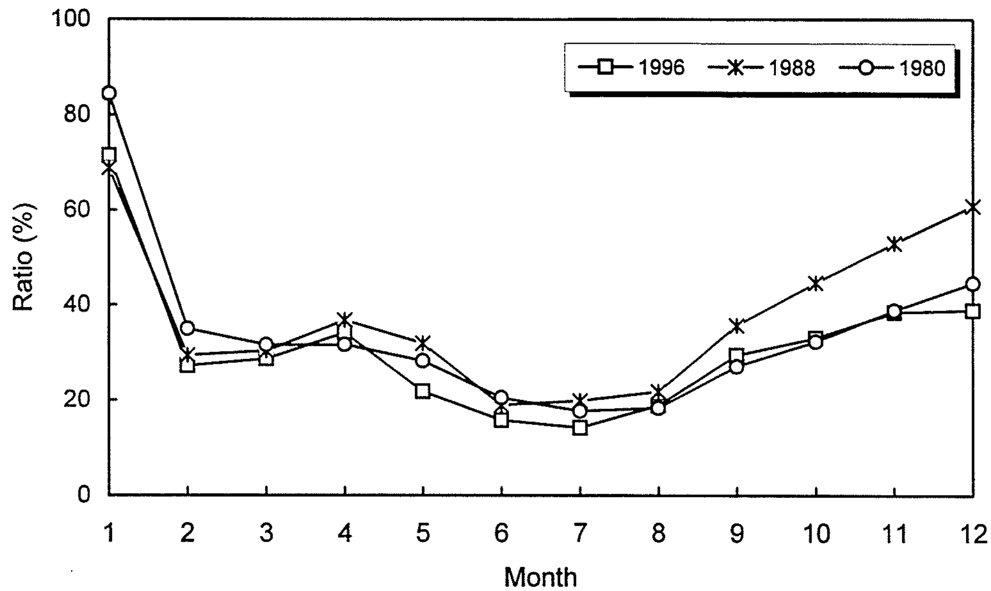


Figure 3.18 Monthly drainage/irrigation ratios for 1980, 1988 and 1996

The figures in Table 3.10 summarize the average situation during 1980-1985, 1986-1990 and 1991-1996. With respect to the last 17 years, the drainage/irrigation ratio is estimated to be 30 % with a maximum of 35 % (1988) and minimum of 25 % (1995). Considering the seasonal average (1991-1996), the ratio drops to 21.1% in the summer season, and increases in the winter to 38%. This tendency conforms with the general temporal performance of the Fayoum: water shortage in summer and an abundance in winter. The average annual inflow (irrigation water), outflow (drainage water) and drainage/irrigation ratios are shown in Figure 3.19.

Table 3.10 The average drainage/irrigation ratio for the Fayoum basin 1980-1996

Season	1980-1985	1986-1990	1991-1996
Winter	41.8	40.7	38.0
Autumn	30.7	33.1	29.7
Summer	22.6	24.9	21.1
Annual	30.4	32.1	27.9

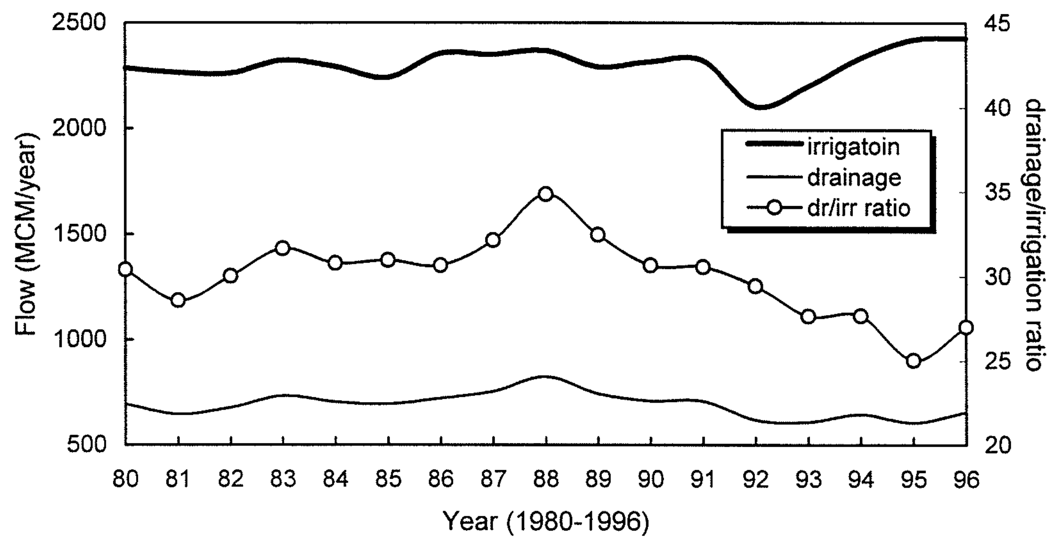


Figure 3.19 Annual actual flow and drainage/irrigation ratio for the study period 1980-1996

3.2.6 Water Balance of the Basin

Improved system performance in the Fayoum basin was begun in1991 by the Fayoum Irrigation Department. The cropped area in 1991 amounted to 282,324 feddans in the summer, and 356,350 feddans in the nili and winter seasons. The water duties supplied to the Fayoum amount to 28 m^3/feddan/day in summer, and 15.5 m^3/feddan/day in winter. The average annual requirement amounts to 7000 m^3/feddan: 4400 m^3/feddan in summer, and 2600 m^3/feddan in winter.

The composition of this gross water duty is presented in Table 3.11. The water balances for the summer and winter seasons are presented in Table 3.12. Table 3.12 reveals that during summer, a deficit in irrigation supply occurs, whilst during winter, an excess of irrigation supply results in a drainage flow that amounts to 2.62 times the volume required for leaching. Salinity measurements made in the drainage system confirm this conclusion: during summer, when very little water is available for leaching, the salinity of drainage water increases to 3.1 dS/m, whilst during winter, the salinity decreases to about 1.25 dS/m (DRI, 1993a). This seasonal variation in quantity and quality of drainage water is a limitation to the potential of drainage water reuse. During the winter, when the availability and quality of drainage water is at a maximum, the demand for supplementary water is at a minimum. During the summer, the reverse situation occurs.

Table 3.11 Composition of water duties for Fayoum crops

	Summer m^3/fed	**Winter** m^3/fed	**Year** m^3/fed
Crop evapotranspiration (75%)	3300	1950	5250
Leaching requirement (20%)	880	520	1400
Evaporation losses of open canals (5%)	220	130	350

Table 3.12 Water balance of Fayoum for 1991

	Summer MCM	Winter MCM	Total MCM
Demand			
Crop evapotranspiration	795.5	634.0	1429.5
Evaporation losses	53.0	42.3	95.3
Leaching requirement	212.1	169.1	381.2
Crop water requirement	1060.6	845.4	1906
Gross water requirement *	1293.9	1031.4	2325.3
Supply			
Actual supply	1170.1	1140.9	2319.0
Actual drainage	265.8	443.4	709.2
Available for the basin	904.3	697.5	1579.8

* Gross requirement includes non-agricultural water use. This is taken as 1.22 x crop water requirement

The average seasonal demand/supply for 1991 is estimated at 110.6% in summer and 90.4% in winter. Specifically, Bahr Yousef suffers from a shortage in supply during summer. In June, only 75% of the demand is supplied, while in April, 116% is supplied (Amer, 1992).

The Fayoum irrigation Department (FID) obtains data on cropped area, as well as planting and harvesting dates for the various crops, from the Department of Agriculture. Changes in cropped areas and the fact that farmers sometimes fail to report the exact cropping plan results in significant variance between planned cropped areas per crop and actual values. Consequently, the calculated crop water requirements no longer correspond with actual requirements. Since 1993, farmers are no longer obliged to grow prescribed crops. From a management point of view, this makes the management of irrigation water supply to satisfy crop water demand very difficult. The limited summer supply and uncontrolled crop cultivation are beyond the powers of the MPWWR/FID. The water users have been advised by MPWWR/FID to match demand with management strategies dealing with the pre-set supply of the water recommended for the basin (Euroconsult, 1992).

3.2.7 Reuse of Drainage Water and Tail End Losses

Due to its topography, the Fayoum irrigation system profits from the reuse of spillage at the tail escape of canals and mesqas (tertiary disributaries), and of runoff from irrigated fields. Despite this direct reuse, approximately 700 MCM per year of drainage water are annually discharged to Lake Qaroun and Wadi Rayan drain. This water presently has an average annual salinity of about 1.4 dS/m (FID, 1996). Assuming that under optimum management, drainage with a salinity of 2.34 dS/m can still be reused by mixing with irrigation water, then about 436 MCM of drainage water must be evacuated. A study sponsored by the planning sector, the water security project "Assessment of Drainage Water Quality and Allowable Reuse Limits" (DRI,1993a), shows that approximately 340 MCM of the drainage water can be reused. This reused drainage water would generate a leaching fraction of 70 MCM with a salinity of 2.34 dS/m. This implies that a total volume of 430 MCM has to be evacuated.

During the last six years, almost 50 % of that volume (340 MCM) has been used by the reuse pumping stations.

The improvement of equity in water supply and the seasonal match between supply and demand will result in a decrease of drainage flow. The seasonal match is the most important, since excessive drainage in winter cannot be used during that period, while storage to use it in summer is not a feasible drainage option.

For 1990, the volume of drainage water was 270 MCM in summer and 439.7 MCM in winter. Obviously, the need for additional water occurs in summer. The salinity of drainage water was estimated to be 1.59 dS/m in summer and 1.28 dS/m in winter (DRI, 1993b). After 1994, using the Charaq, Batts and Tagen Pump stations, the volume of reusable drainage water was decreased. Table 3.13 shows the scope of the additional reuse after 1994.

Table 3.13 Available drainage water in summer

	1990	**After1994**
Drainage volume (MCM)	270	270
Reuse from Batts drain (MCM)		30
Reuse from Wadi drain		60
Available drainage water	270	180
Salinity (dS/m)	1.59	1.59
Spill, (equivalent Nile water)	118.7	72.5

CHAPTER FOUR

EVAPORATION MODEL OF LAKE QAROUN AS INFLUENCED BY LAKE SALINITY

Abstract

A model for estimating monthly and annual Lake evaporation is developed using energy budgets of Lake Qaroun in Egypt. The evaporation is estimated from the amount of solar radiation, atmospheric long-wave radiation, back radiation, evaporative energy, and conducted energy from water mass as sensible heat. A modification is made to the energy equation to allow the calculation of evaporation from saline lakes by analysing data from four evaporation pans with different salinities.

The validity of the model is demonstrated by using published pond evaporation estimates for Lake Qaroun by Mankarous (1979). The monthly comparison shows that the model gives an acceptable accuracy. The model overestimates and underestimates evaporation by -12.38 % and 12.86%, respectively. The model produces reliable results in terms of annual prediction where the maximum error percentage is 2.97%, and the minimum is -2.68%. The standard deviation of differences, ranges from 0.08 to 2.22 cm, and indicates that

there is a good probability of obtaining simulated values within 2.22 cm of the actual values.

4.1 Introduction

Evaporation is the conversion of liquid phase to vapor phase. Evaporation from a free water surface depends on an energy supply, a difference in vapor pressure between the surface and atmosphere, and an exchange of surface air with surrounding atmospheric air. Evaporation prediction usually accounts for these factors through inclusion of temperature, radiation, humidity, and/or wind terms.

The ability to estimate evaporation from lakes is important for the management of water resources. Methods for estimating evaporation are similar to those used for estimating evapotranspiration and may be classified as:

i. empirical methods using meteorological parameters, and based, in general, on Dalton's law;
ii. water budget methods, which depend upon estimating water inflows and outflows;
iii. energy methods, which require defining all energy components contributing to the energy balance;
iv. mass transfer methods which attempt to identify the transfer rate of water vapor from the evaporating surface to the air (Gangopadhyaya, [1965], and Grando, [1973]).

4.2 Study Objectives

The overall objective of this study is to develop a model to estimate monthly and annual evaporation for Lake Qaroun. The model is based on the energy budget method. Specific objectives are to:

i. study the effect of salinity on open water evaporation and develop an approach for Lake Qaroun, based on the relationship between salinity and saturation vapor pressure;

ii. compute the components of the energy budget for Lake Qaroun, based on the available data from the study area;

iii. develop a mathematical model to estimate the evaporation rates from Lake Qaroun;

iv. validate the computer model by comparing model results with evaporation data from the study area.

4.3 Literature Review

A published study on Lake Qaroun done by Mankarous (1979) was used as a reference for estimating the evaporation from Lake Qaroun. To estimate evaporation from salt water of the Lake, Mankarous (1979), studied firstly the effect of salinity on the evaporation rate. A concurrent field experiment was conducted using evaporation pans at Shakshouk station.

Field experiment (I):

The experimental setup consisted of four rectangular evaporation pans located at Shakshouk station at the southern part of the Lake Qaroun. The experiment was performed by the National Water Research Center (Mankarous, 1979). The four pans were sunk in the ground and were 0.5 x 0.7 m in area, and about 0.35 m deep. At the experimental site, two square pans 1.5 x 1.5 x 0.7 m, and 1.0 x 1.0 x 0.7m, were filled with lake water. They were exposed to natural conditions. From time to time, salt water from the lake was added in order to increase the salinity of the water until the concentration reached about 112.94 dS/m. The four rectangular pans were filled by the saline water from the two square pans. Each pan was provided with thermometers to measure the temperature at the water surface and at various depths within the pans. Air temperature and relative humidity were also measured at the site. Since the four pans were identical in shape and size and were exposed to the same meteorological conditions, they could be used to study the effect of differences in salinity and chemical composition on the rate of evaporation.

At one day intervals, fresh water was added to each pan to compensate for the evaporative water loss and to maintain a constant salinity. The experiment was conducted during the period October 26-November 15, 1975. For each day, mean air temperature, humidity, water surface temperature and net evaporation were recorded (Mankarous, 1979). Table 4.1 lists the mean rate of evaporation for the four rectangular pans. Also, Table 4.1 shows the mean values of salinity in each pan for the whole period of the experiment for which complete data were available. Table 4.2 summarizes the measured water surface temperature and meteorological variables. Data taken from pan 1 represented the fresh water. Pans 2, 3 and 4 contained saline water from Lake Qaroun with different concentrations.

Mankarous (1979) used the ratio between the evaporation from fresh water and evaporation from salt water, as a function of water salinity, to reduce the evaporation rates obtained by Penman's equation for the period from 1969 to 1975. The results show that, for salt water, evaporation rates decreases at a rate 7%.

Field experiment (II):

A square masonry tank of an area 144.0 m^2 (12.0x12.0 m) and a depth of 1.7 m was built at Shakshouk station. The tank was made water-tight by insulating layers of asphalt sheets; it was surrounded by a pool of the lake water. Two points gauges were fixed in the direction of the prevailing wind for measuring the change in water levels. The tank was filled with lake water, which was kept at a constant level by the addition of more water every week. An automatic gauge recorder was used to measure the water level.

The pond conversion coefficient was adapted from the records 1969-1975 by applying the Penman's formula. Therefore, the measurements were reduced by a factor 0.9 (Mankarous, 1979).

Table 4.1 Mean rate of evaporation for four pans (Oct. 26, 1975 -Nov. 15, 1975)

Day no.	Date	Pan 1 *S= 0.61 ds/m*	Pan 2 *S=37.5 ds/m*	Pan 3 *S=74.1 ds/m*	Pan 4 *S=112.94 ds/m*
1	26-Oct-75	8.79	8.46	8.11	7.89
2	27-Oct-75	9.36	8.91	8.57	8.30
3	28-Oct-75	9.07	8.57	7.91	7.50
4	29-Oct-75	9.83	9.14	8.57	8.17
5	30-Oct-75	8.94	8.57	8.11	7.60
6	31-Oct-75	8.49	8.11	7.43	7.30
7	1-Nov-75	8.09	7.54	7.14	6.86
8	2-Nov-75	8.11	7.61	7.23	6.69
9	3-Nov-75	Na	Na	Na	Na
10	4-Nov-75	6.97	6.26	5.71	5.43
11	5-Nov-75	8.64	8.11	7.71	7.14
12	6-Nov-75	7.77	7.43	7.14	6.69
13	7-Nov-75	8.49	7.89	7.43	6.86
14	8-Nov-75	9.03	8.57	8.07	7.46
15	9-Nov-75	10.00	9.54	8.91	8.29
16	10-Nov-75	9.07	7.94	7.14	6.74
17	11-Nov-75	7.06	6.29	5.71	5.20
18	12-Nov-75	6.57	5.93	5.43	4.91
19	13-Nov-75	6.20	5.71	4.86	4.40
20	14-Nov-75	10.00	9.14	8.57	8.29
21	15-Nov-75	6.34	5.71	5.36	4.86
Average evaporation :		8.32	7.77	7.26	6.83

Rate of evaporation is given in millimeters per day. Na, not available.

S, mean values of salinity in each pan for the whole period of the experiment

Table 4.2 Measured water surface temperature and meteorological variables

Day no.	Air Temerature C	Relative Humidity %	Pan 1 S= 0.61 ds/m	Pan 2 S=37.5 ds/m	Pan 3 S=74.1 ds/m	Pan 4 S=112.94 ds/m
1	22.8	57.00	16.40	16.60	17.00	17.20
2	21.9	61.00	16.00	16.40	16.80	17.00
3	19	70.00	15.80	16.20	16.40	16.80
4	19.7	60.00	19.00	19.40	19.80	20.00
5	22.4	62.00	18.60	19.20	19.60	19.80
6	21.5	60.00	18.80	19.40	19.80	20.20
7	22.5	60.00	20.00	20.40	20.60	20.80
8	21.9	69.00	17.60	17.80	18.20	18.40
9	21.85	Na	Na	Na	Na	Na
10	21.8	66.00	18.40	18.80	19.20	19.60
11	21.9	68.00	18.80	19.00	19.40	19.60
12	21.4	64.00	17.80	18.20	18.40	18.60
13	20.7	69.00	17.60	18.00	18.00	18.20
14	20.7	66.00	18.00	18.40	18.60	19.00
15	20.9	67.00	18.40	18.60	18.80	19.20
16	21.6	63.00	18.20	18.40	18.40	19.00
17	20.5	62.00	17.00	17.20	17.40	17.40
18	19.7	64.00	16.20	16.60	16.80	16.80
19	20.8	60.00	16.40	17.00	17.20	17.20
20	19.8	59.00	16.40	16.80	17.00	17.20
21	17.9	64.00	15.20	15.60	15.80	17.00
Mean	21	64.05	17.50	18.63	18.10	18.39

Temperature is given in degrees Celsius. Na, not available

S, mean values of salinity in each pan for the whole period of the experiment

4.4 Lake Qaroun Evaporation Model

In the present study, a spreadsheet computer model (EVAPQ) was developed to estimate the monthly and annual evaporation rates from Lake Qaroun. The model is meant as a practical tool to assist the irrigation and agricultural specialists in the planning and management of Lake Qaroun. The model's basic mathematical principle is to modify the classical energy budget equation to study the effect of lake salinity on evaporation and apply it to Lake Qaroun. The required monthly climatological data such as average air temperature, humidity, and sunshine duration, as well as average of surface water temperature, and humidity were estimated from measurements taken from the meteorological station (Shakshouk).

4.4.1 Calculation Procedure of EVAPQ Model

The various equations used by the EVAPQ model were discussed in Chapter 2. The following illustrates the calculation procedure used in the model to estimate the evaporation rate from Lake Qaroun.

For the lake:

i. assemble input data:

- Latitude, degree;
- altitude above sea level, m.

ii. compute the atmospheric pressure, kPa (equation 2.4);

iii. estimate the declination of the sun, degree (equation 2.17).

For each month:

i. assemble input data:

- average air temperature, ^{o}C;
- average surface water temperature, ^{o}C;
- number of hours of actual bright sunshine;
- possible number of hours of bright sunshine;
- number of days in the month;
- relative humidity, decimal;
- water salinity, dS/m.

ii. calculate the sunset hour angle, degree (equation 2.16);

iii. calculate the distance between the sun and the earth, (equation 2.18);

iv. estimate the extraterrestrial radiation, MJ m^{-2} day^{-1} (equation 2.20);

v. estimate the radiation, MJ m^{-2} day^{-1} (equation 2.21).

Based on the latter two steps, the net radiation, and the estimate of model output (monthly evaporation rate) will be presented in the section covering the energy budget determination in the second part of the theoretical development (section 4.5.2). In the first part of the theoretical development (section 4.5.1), the study of Lake Qaroun salinity effects on evaporation rate will be discussed.

4.5 Theoretical Development

4.5.1 Salinity Effect on Evaporation

Evaporation rates from a freshwater body depend on the meteorological conditions of the surrounding terrain, as well as the characteristics of the water body in terms of its shape, depth, and turbidity. The evaporation rate from a freshwater body may be estimated using a Dalton-type equation (Brutsaert, 1982):

$$E_f = f(N,u)_f (e_s(T_f) - e_a) \qquad (4.1)$$

where

E_f is the evaporation rate from a freshwater body;

$f(N,u)_f$ is a transfer coefficient over the freshwater which is a function of wind speed, surface roughness, and atmospheric stability within the atmospheric surface layer;

e_s is the saturation water vapor pressure at water temperature (T_f);

e_a is the actual vapor pressure in the air at about 2 m.

The rate of evaporation from a fresh water surface may be expressed as

$$E_f = f(N,u)_f (e_s(T_f) - \Psi e_s(T_a)) \qquad (4.2)$$

where

Ψ is the relative humidity,

T_a is the temperature in air.

Due to the reduction of free energy of the water molecules, evaporation rates from a saline water body are consistently less than the corresponding value from a freshwater body under similar meteorological conditions (Bonython, 1959; Turk, 1970; Salhotra et al., 1985). Evaporation rates from a saline water body may be evaluated by the following equation:

$$E_{ss} = f(N,u)_{ss}(e_s(T_{ss}) - \Psi e_s(T_a)) + \Delta E \quad (4.3)$$

where

E_{ss} is the evaporation rate from the saline water surface;

$f(N,u)_{ss}$ is the transfer coefficient over the saline water body;

$e_s(T_{ss})$ is the saturation water vapor pressure over the saline water body at temperature(T_{ss});

ΔE is the decrease in evaporation rate caused by the salt water.

Hence, a change in evaporation rate occurs with a decrease in the saturation vapor pressure as a function of salinity:

$$\Delta E_s = f(N,u)_{ss}(\Delta e_s(T_{ss},S)) \quad (4.4)$$

where

Δe_s is the decrease in the saturation vapor pressure;

S is the salinity at the water surface.

As an approximation, it may be assumed that:

$$\Delta e_s(T_{ss},S) = R(S)\, e_s(T_{ss}) \quad (4.5)$$

where

$R(S)$ is a function of salinity.

Over limited ranges, the previous equation can be expressed as a linear function of salinity

$$\Delta e_s(T_{ss},S) = C \times S \times (e_s(T_{ss})) \quad (4.6)$$

where

C is a coefficient of the saline solution with certain ionic composition.

Using equations (4.4), (4.5) and (4.6), equation (4.3) is rewritten as :

$$E_{ss} = f(N,u)_{ss}[(e_s(T_{ss}) - \Psi e_s(T_a)) + C \times S \times e_s(T_{ss})] \tag{4.7}$$

The above approach of accounting for the effect of salinity on evaporation can be contrasted with the common approach based on an empirical ratio of salt water to fresh water evaporation (assuming similar meteorological conditions) embodied in:

$$E_s = \alpha E_f \tag{4.8}$$

where

α ($0 < \alpha < 1$) represents the reduction in evaporation due to salinity.

4.5.1.1 Data Analysis

Since each pan was subjected to identical meteorological conditions and was insulated, a heat budget would result in an inverse relationship between water surface temperature and evaporation rate. The lower vapor pressure over saline water permits less energy to escape as latent heat, thus causing an increase in temperature within the pan, and an increase in sensible heat loss and back radiation to the atmosphere. This conclusion is confirmed by comparing data in Tables 4.1 and 4.2, which present mean daily water temperature and evaporation rates for several typical days for pans 1, 2, 3 and 4. For each day, pan 4, with the lowest evaporation rate, has the highest water temperature; pan 1, with the highest evaporation rate, has the lowest temperature; pans 2 and 3, with an intermediate evaporation rate, have an intermediate water temperature.

Data from the four pans with complete meteorological measurements were used to determine the effect of salinity on saturation vapor pressure over the water surface. The transfer coefficient of pan 1 is considered constant and identical to those of pans 2, 3 and 4 under the same conditions.

$$f(N,u)_f = f(N,u)_{ss} = f(N,u) \tag{4.9}$$

From equation 4.2, the evaporation rate in pan 1 is expressed as:

$$E_1 = f(N,u)(e_s(T_f) - \psi e_s(T_a)) \tag{4.10}$$

From equation 4.7, the evaporation rate in pan n (2, 3, or 4) is expressed as:

$$E_n = f(N,u)\ [(e_s(T_{ss}) - \Psi e_s(T_a)) + C \times S \times e_s(T_{ss})] \tag{4.11}$$

Dividing equation 4.11 by 4.10, assuming identical f(N,u) for the two pans, and simplifying:

$$(e_s(T_{ss})(1 + C \times S) = \frac{E_n}{E_1}[e_s(T_f) - \Psi e_s(T_a)] + \Psi e_s(T_a) \tag{4.12}$$

The left hand side of equation 4.12 is considered to be the saturation vapor pressure over the saline surface water. Its value is determined from measurements of E_n, E_1, T_f, T_a and Ψ. Table 4.3 presents the values of saturation vapor pressure computed from equation 4.12 for the four pans based on meteorological conditions and surface water temperatures in Table 4.2. Table 4.4 lists the values of the saturation vapor pressure for each pan, divided by the

Table 4.3 Computed values of saturation vapor pressure for four pans

Day no.	Pan 1 S= 0.61 ds/m	Pan 2 S=37.5 ds/m	Pan 3 S=74.1 ds/m	Pan 4 S=112.94 ds/m
1	18.63	18.53	18.42	18.34
2	18.16	18.06	17.98	17.92
3	17.93	17.79	17.61	17.49
4	21.95	21.38	20.91	20.57
5	21.41	21.22	20.98	20.72
6	21.68	21.40	20.89	20.80
7	23.36	22.89	22.54	22.30
8	20.10	19.98	19.89	19.76
9	Na	Na	Na	Na
10	21.14	20.74	20.44	20.28
11	21.68	21.45	21.27	21.02
12	20.36	20.18	20.03	19.79
13	20.10	19.87	19.70	19.48
14	20.62	20.39	20.14	19.83
15	21.14	20.93	20.64	20.36
16	20.88	20.30	19.90	19.69
17	19.36	18.87	18.52	18.20
18	18.39	18.03	17.75	17.46
19	18.63	18.33	17.79	17.50
20	18.63	18.20	17.92	17.77
21	17.25	16.84	16.61	16.29

Vapor pressure is given in millibars. Na, not available

S, mean values of salinity in each pan for the whole period of the experiment

Table 4.4 Computed values of saturation vapor pressure normalized by saturation vapor pressure for fresh water at the same temperature

Day no.	Pan 1 *S= 0.61 ds/m*	Pan 2 *S=37.5 ds/m*	Pan 3 *S=74.1 ds/m*	Pan 4 *S=112.94 ds/m*
1	1.00	0.98	0.95	0.94
2	1.00	0.97	0.94	0.93
3	1.00	0.97	0.94	0.92
4	1.00	0.95	0.91	0.88
5	1.00	0.95	0.92	0.90
6	1.00	0.95	0.91	0.88
7	1.00	0.96	0.93	0.91
8	1.00	0.98	0.95	0.93
9	Na	Na	Na	Na
10	1.00	0.96	0.92	0.89
11	1.00	0.98	0.95	0.92
12	1.00	0.97	0.95	0.92
13	1.00	0.96	0.96	0.93
14	1.00	0.96	0.94	0.90
15	1.00	0.98	0.95	0.92
16	1.00	0.96	0.94	0.90
17	1.00	0.96	0.93	0.92
18	1.00	0.96	0.93	0.91
19	1.00	0.95	0.91	0.89
20	1.00	0.95	0.93	0.91
21	1.00	0.95	0.93	0.84
Mean	1.00	0.96	0.93	0.91
s.d.	0.00	0.01	0.02	0.02

s.d. = standard deviation   Na, not available   S, mean value pan for the whole period saturation vapor pressure for fresh water, computed at the same temperature. In addition to these values, the time weighted mean and standard deviations are presented. The effect of salinity on the saturation vapor pressure is also shown in Figure 4.1. This figure confirms the assumption made in equation 4.6, where the function R(S) is expressed as a linear function of salinity. As is expected, the maximum reduction in saturation vapor pressure (0.91) is for pan 4, which contained the highest concentration.

Based on values of (1 + C x S) and the average salinity reported in Table 4.2 for each pan, the reduction in saturation vapor pressure can be used to compute the coefficient C for each water salinity. The mean value of C for the Lake Qaroun water (pan 1) is 0.0, while pans 2, 3 and 4 have identical values of -0.0009. Thus, the reduction in saturation vapor pressure can be estimated by using (1-0.0009 x S).

Finally, Table 4.5 lists computed values of α for the four pans, i.e., evaporation from each pan normalized by evaporation from freshwater, computed as follows:

$$\alpha = \frac{E_n}{E_1} \tag{4.13}$$

Combining equations 4.11 and 4.12, equation 4.13 may be rewritten as:

$$\alpha = \frac{[e_s(T_{ss})[1 - 0.0009 \times S] - \Psi e_s(T_a)]}{[(e_s(T_{ss}) - \Psi e_s(T_a)]} \tag{4.14}$$

In addition to the ratios for each day, the time weighted means and standard deviation are included in Table 4.5 for each pan. The values of α are plotted as a

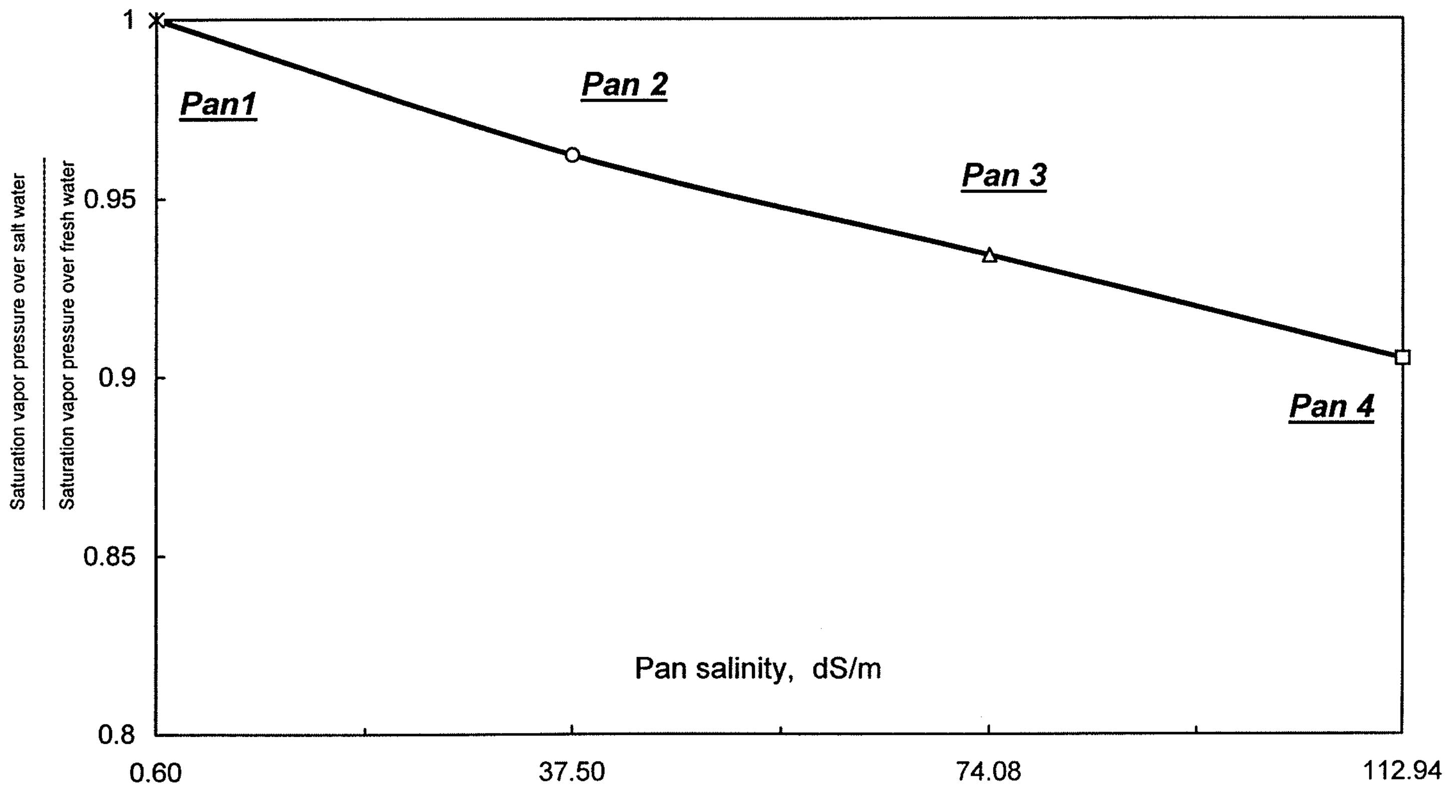


Figure 4.1 Estimate of the saturation vapor pressure ratio for four pans

Table 4.5 Computed values of α (ratio of evaporation from pans 1,2,3 and 4 normalized by evaporation from fresh water)

Day no.	Pan 1 *S= 0.61 ds/m*	Pan 2 *S=37.5 ds/m*	Pan 3 *S=74.1 ds/m*	Pan 4 *S=112.94 ds/m*
1	1.00	0.96	0.92	0.90
2	1.00	0.95	0.92	0.89
3	1.00	0.94	0.87	0.83
4	1.00	0.93	0.87	0.83
5	1.00	0.96	0.91	0.85
6	1.00	0.96	0.88	0.86
7	1.00	0.93	0.88	0.85
8	1.00	0.94	0.89	0.82
9	Na	0.93	0.89	0.82
10	1.00	0.90	0.82	0.78
11	1.00	0.94	0.89	0.83
12	1.00	0.96	0.92	0.86
13	1.00	0.93	0.88	0.81
14	1.00	0.95	0.89	0.83
15	1.00	0.95	0.89	0.83
16	1.00	0.88	0.79	0.74
17	1.00	0.89	0.81	0.74
18	1.00	0.90	0.83	0.75
19	1.00	0.92	0.78	0.71
20	1.00	0.91	0.86	0.83
21	1.00	0.93	0.84	0.77
Mean	1.00	0.93	0.87	0.81
s.d.	0.00	0.02	0.04	0.05

s.d. = standard deviation   Na, not available

S, mean values of salinity in each pan for the whole period of the experiment

function of salinity in Figure 4.2. Mankarous (1979) used values of α from Figure 4.2 to predict the evaporation from Lake Qaroun. For a given day, differences in evaporation rates among pans reflect effects of salinity. On the other hand, variation in the rate for a given pan for different days reflects varying meteorological conditions (equation 4.14).

By comparison of Figures 4.1 and 4.2, it is clear that variations for $\{\alpha\}$ are much larger than variations for {(1+C x S), C= -0.0009}. The two approaches to compute the evaporation rates are quite different. This is because α is a function of meteorological variables as well as salinity. Therefore, the commonly used α approach to account for salinity effects based on the ratio of salt water to fresh water evaporation rates (Figure 4.2) is hard to use accurately. A more accurate method is the {[1+C x S),C= -0.0009} approach, which is based on the effect of salinity on saturation vapor pressure (Figure 4.1).

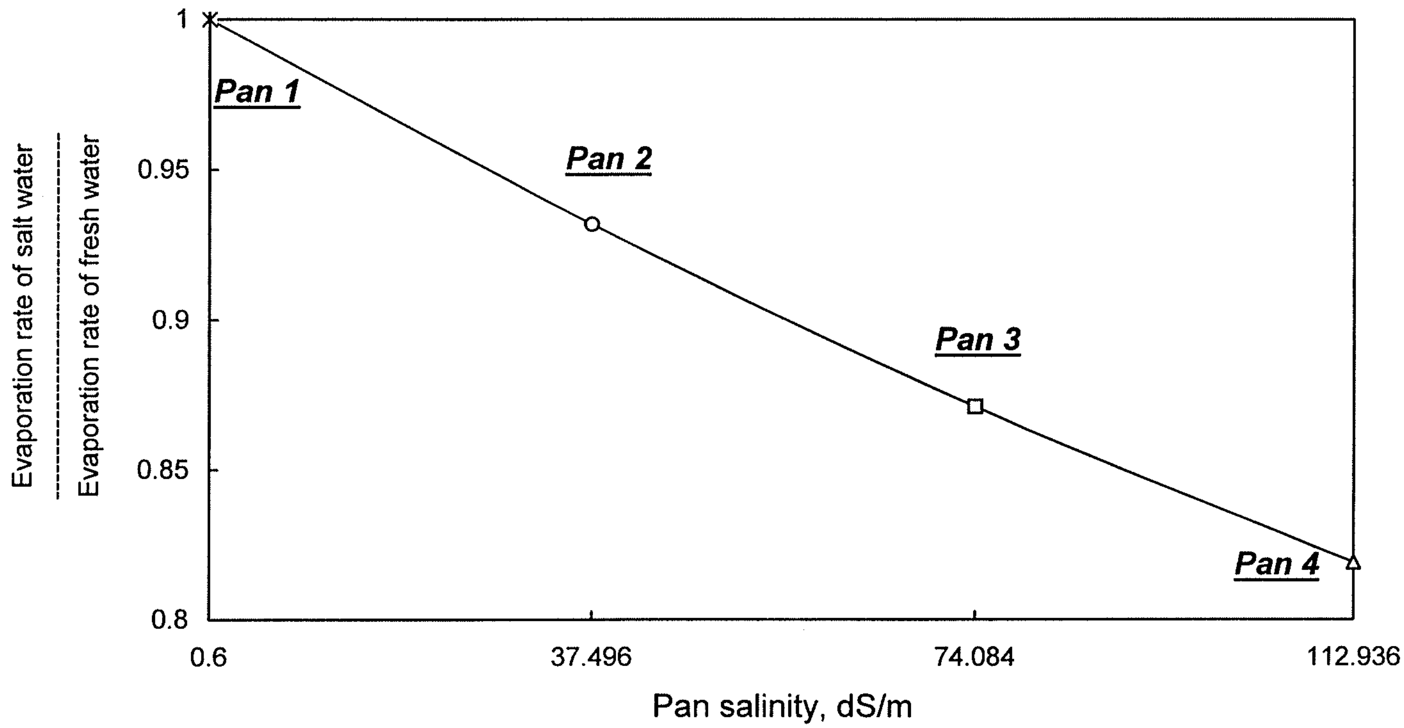


Figure 4.2 Estimate of the ratio of evaporation rates

4.5.2 Energy Budget Determination

The energy budget equation (equation 2.3) can be rewritten as follows :

$$R_n - Q_h - Q_e = Q_\theta - Q_v \tag{4.15}$$

where

R_n is the net (all-wave) radiation absorbed by the water body;

Q_h is the sensible-heat transfer (conduction) to the atmosphere;

Q_e is the energy used for evaporation;

Q_θ is the increase in energy stored in the water body;

Q_v is the advected energy (net energy content of inflow and outflow elements.

All of the above terms are expressed in equivalent energy units per unit of surface area.

The energy advection and storage terms (Q_v -Q_θ) of Equation 4.15 can be computed from an approximate water budget, and from temperatures of respective water volumes. In the present study, advected energy and change in energy storage tend to balance for Lake Qaroun, particularly over long periods of time, and are frequently assumed to be canceled when considering monthly or annual evaporation rates. Therefore, equation 4.15 is rewritten as follows :

$$R_n = Q_h + Q_e \tag{4.16}$$

Letting λ represent the latent heat of vaporization, and $R^\backslash$ the ratio of heat loss by conduction to heat loss by evaporation, equation (4.16) becomes:

$$E = \frac{R_n}{\rho\lambda(1 + R^{\backslash})} \tag{4.17}$$

Where

E is the evaporation of saline water body;

ρ is the density of water.

The ratio of conduction of sensible heat to evaporation is given by Bowen (1926) as:

$$R^{\backslash} = \gamma \frac{(T_s - T_a)}{(e_s - e_a)} \tag{4.18}$$

where

γ is the psychrometric coefficient;

T_s is the temperature at the evaporating surface;

T_a is the air temperature above the surface;

e_s is the saturated vapour pressure at the evaporating surface;

e_a is the prevailing saturated vapour pressure at the same height as T_a.

The problem that generally, the surface temperature, T_s, is unknown. Benman therefore introduced the additional equation (Burman and Pochop, 1994):

$$e_s - e_a = \Delta_{vp}^{\backslash} (T_s - T_a) \tag{4.19}$$

where the proportionality constant $\Delta_{vp}^{\backslash}$ is the first derivative of the function $e_s(T)$.

To introduce the effect of lake salinity on evaporation rates, equation 4.20 is introduced from Figure 4.1:

$$(e_s - e_a)_{saline\,water} = \alpha (e_s - e_a)_{fresh\,water} \tag{4.20}$$

Re-arranging gives

$$\Delta_{vp}^{\backslash} = \alpha\, \Delta_{vp} \tag{4.21}$$

where

Δ_{vp} is the slope of vapor pressure in the case of fresh water.

The classical energy budget equation for water bodies, as applied in the past to lakes, can then be modified by taking the effect of salinity as a function of vapor pressure reduction. Thus, equation 4.17 becomes:

$$E = \frac{\alpha\ \Delta_{vp}\ R_n}{\rho\lambda(\alpha\, \Delta_{vp} + \gamma)} \tag{4.22}$$

The theoretical development of the energy budget equation is integrated into a model for estimating monthly and annual evaporation from Lake Qaroun.

4.5.2.1 Net Radiation

In the present model, net radiation is estimated using one of several models based upon solar radiation, and parameters such as air temperature and humidity. Net radiation, R_n, is the difference between incoming and outgoing radiation of both short wavelengths from the sun , as well as long wavelengths from the earth, from clouds and other material in the sky:

$$R_n = S\downarrow - S\uparrow + L\downarrow - L\uparrow \tag{4.23}$$

where

$$S\downarrow - S\uparrow = R_s(1-\alpha_R) = R_{ns} \tag{4.24}$$

and

$$L\downarrow - L\uparrow = R_{nl} \tag{4.25}$$

Where S and L are, respectively, short and long wave radiation. Fluxes are defined as positive when they are toward the ground surface. The terms R_n, R_{nl}, L, and S are radiant energy in MJ m^{-2} day^{-1}, and α_R is the dimensionless ratio called albedo. R_{ns} is called net short wave radiation, and R_{nl} is a combined term known as net outgoing long wave radiation. The long wave radiation terms involving $L\uparrow$ and $L\downarrow$, as shown in the previous equations, are solved in a variety of ways. Weiss (1982) retained the identity of each term by using a sky radiation model developed by Brutsaert (1975), and incorporated a cloudiness correction of Linacre (1967) to estimate R_n.

The Stefan-Boltzmann equation for the determination of radiant heat transfer is used to determine the long wave radiation, R_{nl}. Two basic approaches are in common usage. The first, known as Brunt equation, uses ground level air temperatures and calculates a combined ε'_{bulk} for both the air and ground level surfaces. The second approach retains the identity of both the atmosphere and the ground level surfaces. This approach is called a component approach.

Net Long Wave Radiation Using Component Approach

When using the component equation to estimate R_{nl} (Weiss, 1982), T_{ka} is the average of the daily maximum and minimum temperatures, in K, for use in

Stefan's equation. The component procedure of estimating R_{nl} has the advantage of making it possible for the estimator to determine separate values of the emissivity ε for both the sky and the ground or water surface. This should make it possible to make allowances for different water and ground surface conditions. The procedure has two steps.

i. Estimate the long wave radiation components using Stefan's equation (see section 2.3.1.2). In contrast to the combined parameter approach, the component method uses the average daily air shelter temperature (Weiss, 1982).

- estimate the long wave radiation leaving the earth's surface. This radiation is received by the atmosphere or lost into space (equation 4.27).
- estimate the long wave radiation received at the ground surface from the sky. The long wave radiation from the sky is almost always much less than the long wave radiation leaving the earth's surface (equations 4.28, 4.29 and 4.30).

ii. Apply an empirical correction for cloudiness

Net long wave radiation is estimated as follows:

$$R_{nl} = C_{clouds}(L\downarrow + L\uparrow) \tag{4.26}$$

where

C_{clouds} is a dimensionless ratio (cloudiness correction).

The outward long wave radiation component is estimated using a simple direct application of Stefan's law, as follows:

$$L\uparrow = \varepsilon_{surface}\sigma T_k^4 \tag{4.27}$$

where

$\varepsilon_{surface}$ is the emissivity of the water;

σ is the Stefan-Boltzmann constant ;

T_k is the average daily air temperature, K.

The estimate of the term representing long wave radiation from the sky R_{nl} is difficult to calculate because the only data available for routine estimates of evaporation are shelter air temperature, and, perhaps, shelter vapor pressure. The temperature distribution of the atmosphere as well as the distribution of water and other constituents is unknown. Brutsaert (1975) proposed the following empirical function for the estimation of ε_{sky}:

$$L\downarrow = \varepsilon_{sky} \sigma T_k^4 \tag{4.28}$$

$$\varepsilon_{sky} = 1.24[10\frac{e_a}{T_k}]^{1/7} \tag{4.29}$$

$$if\ C_{clouds} \rangle 0.7 \quad \varepsilon_{sky} = 0.97\varepsilon_{sky} \tag{4.30}$$

where

e_a is average vapor pressure, kPa;

T_k is the average daily air temperature, K.

Weiss (1982) found the equations to be reliable and recommended them.

The cloudiness correction recommended by Weiss (1982) is an adaptation of one proposed by Linacre (1968). Weiss (1982) recommended different coefficients than Linacre (1968). The correction used by Weiss is:

$$C_{clouds} = (0.4 + 0.6 * R_s / R_{so}) \tag{4.31}$$

where

R_{so} is the clear day solar radiation received on horizontal surface.

4.6 Model Evaluation

The model was evaluated by plotting the measured and simulated values of evaporation rate against time. Additionally, the agreement between the model and observations was checked statistically by calculating the following parameters: the average mean of differences (AM), the average absolute deviation (AD), the standard error of estimate (SE) and the standard deviation of difference (SD). Statistically, the average mean of differences provides information on whether the model is under or over-estimating; the average absolute deviation and the standard error of estimate are indicative of the quantitative dispersion between the measured and simulated values; and the standard deviation of difference provides a measure of the range of errors in the probability distribution of error occurrences.

The average mean of difference (AM) is calculated as:

$$AM = \frac{\sum_{i=1}^{n} (O_i - S_i)}{N} \tag{4.32}$$

where

N is the number of years in the study period;

O_i is the measured water level (monthly average) of Lake Qaroun;

S_i is the predicted water level (monthly average) of Lake Qaroun.

The standard error is estimated by:

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{N}} \tag{4.33}$$

The average absolute deviation (AD) is also computed for each month as:

$$AD = \frac{\sum_{i=1}^{n}\left| O_i - S_i \right|}{N} \tag{4.34}$$

The standard deviation of differences was calculated from the following equation:

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2 - ((\sum_{i=1}^{n}(O_i - S_i))^2 / \mathrm{N})}{N-1}} \tag{4.35}$$

4.7 Results and Discussion

Measured and simulated levels of Lake Qaroun using the EVAPQ model were compared using data for the period 1969-1975. The comparison is presented by plotting the average monthly levels. Figures 4.3, 4.4 and 4.5 show the average monthly levels for the years 1970, 1971 and 1975, respectively. Over the study period 1969-1975, the monthly error percentage of the model estimates ranged from -12.38 % to 12.86%. Figure 4.6 shows the total annual evaporation rates of

Lake Qaroun calculated by both methods. The maximum annual error percentage of the model estimates is 2.97%, and the minimum is -2.68%. From the figures, it is clear that the trend between the measured and simulated data is similar.

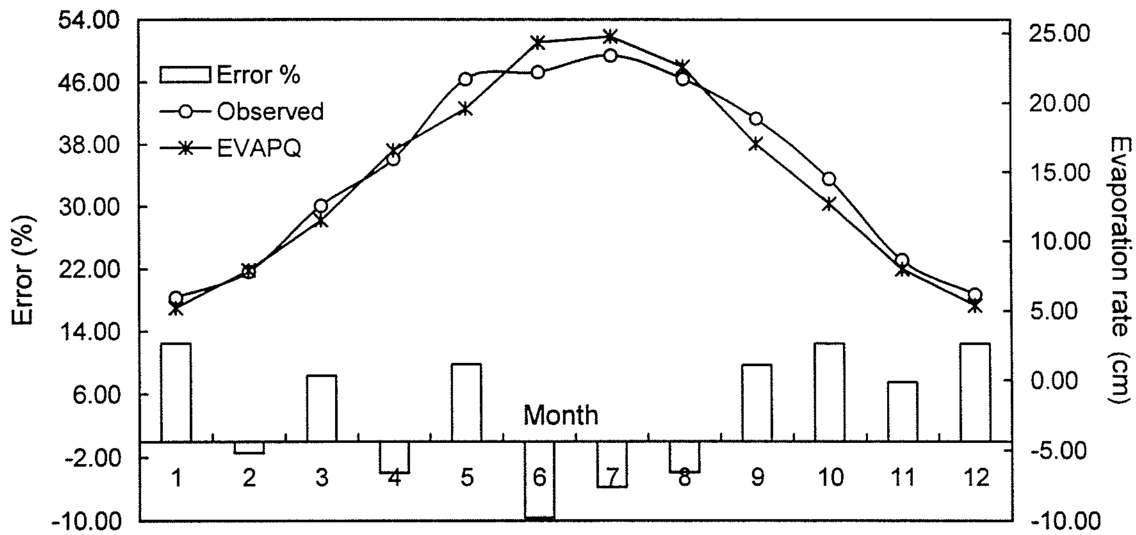


Figure 4.3 Monthly evaluation of EVAPQ model prediction (1970)

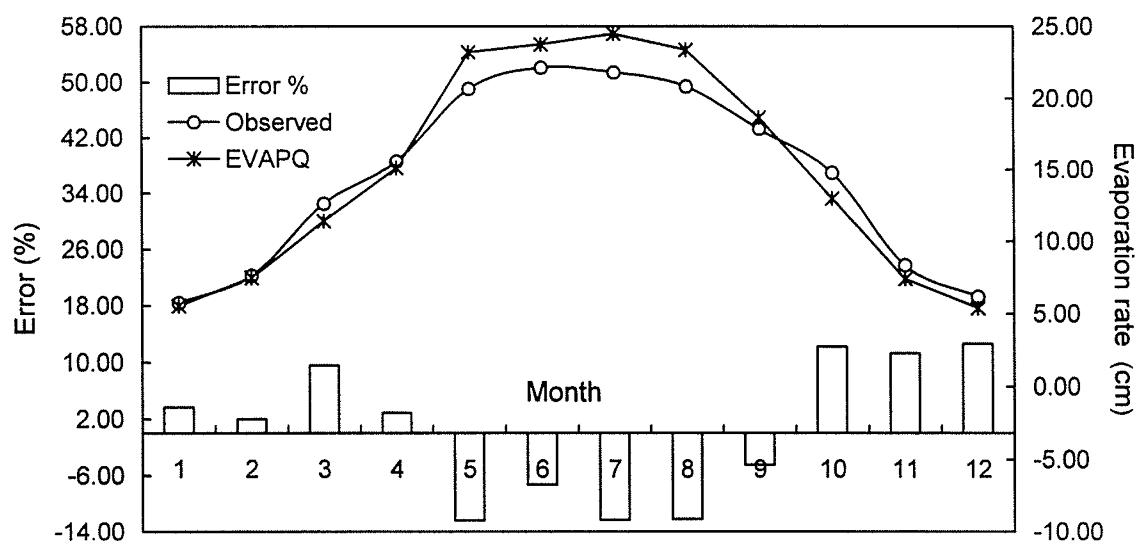


Figure 4.4 Monthly evaluation of EVAPQ model prediction (1971)

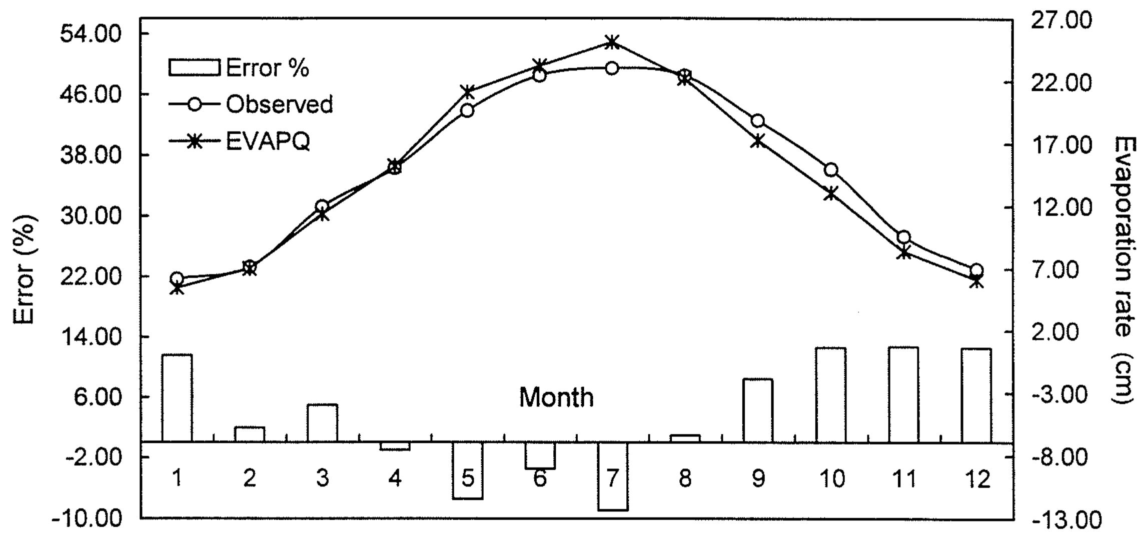


Figure 4.5 Monthly evaluation of EVAPQ model prediction (1975)

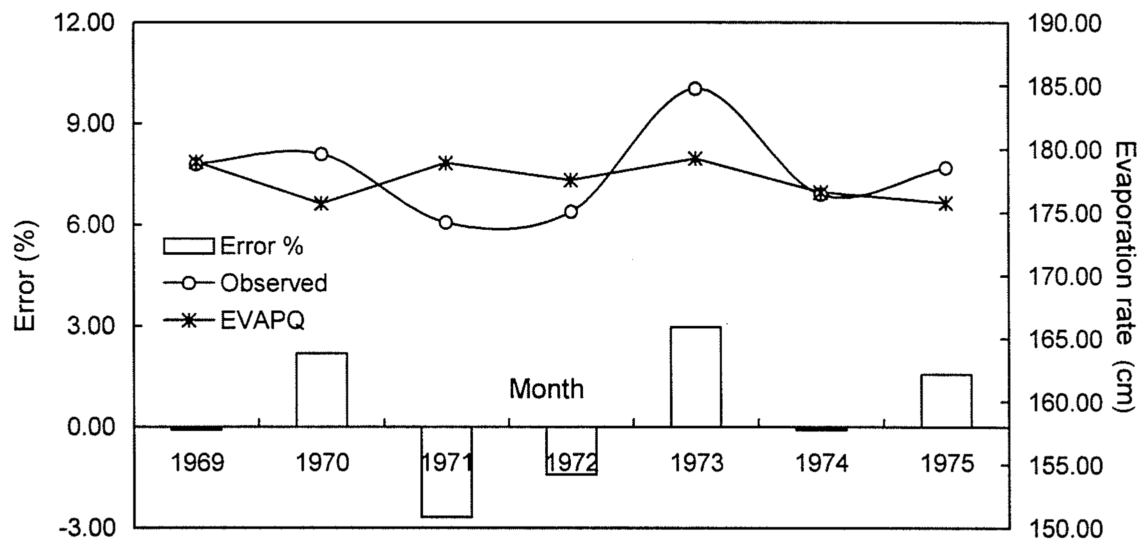


Figure 4.6 Annual evaluation of EVAPQ model prediction (1969-1975)

Table 4.6 shows the results of the statistical analysis of water levels for the EVAPQ model. It includes the calculated values of the average mean of differences (AM), the average absolute deviation (AD), standard error of estimate (SE), and the standard deviation of the differences (SD). The values of AM, SE, AD and SD for the EVAPQ model for the period 1969-1975 range from -2.04 to 1.65 cm, 0.46 to 2.26 cm, 0.43 to 2.25 cm and 0.08 to 2.22 cm, respectively. The average mean of the differences between simulated and measured values indicates whether the model is over or under-predicting. A negative value represents overestimation and a positive value represents underestimation. From Table 4.6, it is evident that EVAPQ underestimated lake evaporation rates from September until March, and overestimated levels for the remaining months (April-August). Results from the twelve month period indicates that the model achieved an acceptable level of accuracy; the average mean of the differences vary from -2.04 to 1.65 cm, with an annual average of -0.07 cm. The average absolute deviation and standard error are indicators of quantitative dispersion between the measured and simulated values. The average absolute deviation ranges from 0.43 to 2.25 cm. This indicates that, on average, the simulated results are different from the measured values by 0.43 to 2.25 cm on either side of the mean for the twelve months. The simulation and measurements are more or less equivalent when it comes to simulating levels at the beginning of the year. The standard error ranges from 0.46 to 2.26 cm for all months. The standard deviation of differences ranges from 0.08 to 2.22 cm, which indicates that there is a good probability of obtaining simulated values within 2.22 cm of the measured values.

Table 4.6 Average mean of differences (AM), average absolute deviation (AD), standard error of estimate (SE), and the standard deviation (SD) for measured vs. predicted lake Qaroun evaporation rate for EVAPQ model (1969-1975).

Month	AM (cm)	SE (cm)	AD (cm)	SD (cm)
January	0.45	0.56	0.45	0.38
February	0.12	0.55	0.43	0.62
March	0.44	0.90	0.83	0.91
April	-0.22	0.46	0.44	0.47
May	-1.18	2.26	2.25	2.22
June	-2.04	2.07	2.04	0.45
July	-1.51	1.94	1.72	1.40
August	-1.11	1.82	1.67	1.66
September	0.71	1.19	1.11	1.11
October	1.65	1.67	1.65	0.27
November	1.03	1.06	1.03	0.30
December	0.80	0.80	0.80	0.08
Annual	-0.07	0.27	0.23	0.31

Although model sensitivity analysis was not accomplished in this study, using water surface temperature measurements and not using wind speed variables can be a large source of error. The overestimation or underestimation presented in the graphical and statistical evaluations can be mainly attributed to the use of the annual evaporation pond conversion factor to provide a monthly evaporation rate. Monthly variations in the conversion factor are usually large enough to preclude the use of a constant value.

4.8 Summary and Conclusions

The dependence of evaporation on meteorological variables and salinity has been analyzed from evaporation pans located near Lake Qaroun. The commonly used approach to account for salinity effects based on ratios of salt water to fresh water evaporation rates (α approach; equation 4.13) is hard to use accurately since it is a function of salinity, ionic composition, and meteorological variables. A more accurate method is the (1+C x S) approach (equation 4.12) which is based on the effect of salinity on saturation vapor pressure. The latter approach is computed indirectly by field experiments using evaporation pans.

The evaporation model presented herein was formulated to provide estimates of monthly and annual evaporation from shallow lakes using routine climatological observations. The input requirements are monthly averages of air temperature, water temperature and sun duration. Also required is the latitude and salinity of the lake. Based on the approach mentioned above, a modification is made to the energy equation to allow the calculation of evaporation from saline lakes.

The validity of the model is demonstrated by using published evaporation pond estimates for Lake Qaroun by Mankarous (1979). The monthly comparison showed that the model is in acceptable agreement. Over the study period (1969-

1975), the monthly error percentage of the model estimates ranged from -12.38% to 12.86%. The model produced reliable results in terms of annual prediction, where the maximum error percentage of the model estimates is 2.97%, and the minimum is -2.68%. The standard deviation of differences ranges from 0.08 to 2.22 cm, and indicates that there is a good probability of obtaining simulated values within 2.22 cm of the measured values.

Based on the results of this study, it can be concluded that the EVAPQ model can be used to estimate the monthly and annual evaporation rates from Lake Qaroun.

CONNECTING TEXT

In the Fayoum drainage basin, there is difficulty in achieving lake salinity control where disposal of saline drainage water is physically constrained. A convenient solution is needed to allow the saline drainage water to be disposed of into a safe, environmentally acceptable outlet of sufficient capacity. Salt and water management options are difficult since many processes and many possible remedial interventions must be considered simultaneously in all their complex interrelationships. In this thesis, where appropriate solutions are required, lake salinity control and saline water disposal can be accomplished with the aid of a computer model which simulates these interrelated processes and interventions.

To achieve the latter objective, in the following Chapter, a lake routing model is developed in order to estimate the water and salinity levels of Lake Qaroun. The model is meant to function as a prediction tool for providing an understanding of the impact of various drainage water disposal systems on Lake Qaroun. The results from Chapter 4, the estimate of monthly evaporation rates from Lake Qaroun, are used as input for the lake routing model.

CHAPTER FIVE

LAKE QAROUN ROUTING MODEL

Abstract

The physical and environmental constraints of Egypt's Fayoum basin result in serious restrictions in the efficiency of basin outlets used for the disposal of saline drainage waters. Most of the drainage water is disposed of in Lake Qaroun, located in the lowest part of the Fayoum basin. The lake itself has no outlet and the drainwater impounded is subject to evapoconcentration. There are various potential problems in such a system, the most important being the accumulation of salt in the receiving system which can reach hazardous levels harmful to fish and wildlife. Such deterioration of lake quality can also negatively affect tourism, and ultimately lead to difficulty of disposal.

A model for estimating monthly and annual water and salinity level of Lake Qaroun (LQR) was developed using hydrologic routing techniques. The model can assess the effects of various drainage water disposal options. The water and salinity levels are estimated from drainage water disposal rates, drainage water salinities, as well as evaporation rates.

The model simulations were checked against the measured water and salinity levels from 1980-1996. In comparison with the values computed for five

statistical parameters, the predictions of water levels produced by the LQR model were in accord with measured values. The monthly modelling efficiency (EF) ranged from 0.58 to 0.93. On an annual basis, EF is estimated to 0.88. Compared with the available salinity measurements, the model produced reliable results in terms of annual prediction (EF=0.5). However, over monthly periods, the LQR model was not in good agreement with the field measurments (EF= from -8.2 to 0.53).

5.1 Introduction

Modelling of the drainage basin at the outlet level should simulate the effects of drainage water disposal on the receiving site or system. The latter would normally be a sea, a lake, a river system or an evaporation pond. Disposal of saline drainage water into a lake may have a deteriorating effect on lake water and its salinity. The effect can be simulated with observations from the study area. This approach, although sufficient for presenting the problem and suggesting management options, is inadequate for studying lake systems where more specific and effective solutions are required. This can be achieved with the aid of mathematical models where temporal variations in the salt concentration are required. Modelling becomes more complicated when lake hydrology is affected by other inflows and/or outflows. This situation may require considerable data collection, and may include modelling of the hydrology of other systems (Smedema, 1993).

5.2 Study Objectives

The objectives of this study are to:

i. develop a lake routing model for water and salinity control in constrained drainage basins; the model can assess the effects of various drainage water disposal options;

ii. validate the mathematical model for various options by comparing model results with field observations from the study area .

5.3 Lake Qaroun Routing Model

In the present study, a spreadsheet computer model (LQR) has been developed to estimate the monthly and annual water and salinity level of Lake Qaroun. The model is meant as a practical tool to assist water resources specialists in the planning and management of Lake Qaroun's salinity control. The model's basic mathematical principle is the hydrologic routing technique, used to study the effects of various water disposal options.

The input data required to run the LQR model are:

- monthly drainage water disposal rates;
- monthly drainage water salinities;
- monthly evaporation rates;
- initial storage of the lake at start of the simulation period;
- initial water salinity of the lake.

The output of the LQR model simulations are:

- monthly and annual water levels;
- monthly and annual water salinity.

The model is linked to the evaporation model (EVAPQ) developed in Chapter 4, which estimates the input data for evaporation rates. The validity of the model is demonstrated by using available data collected during the period 1980-1996.

In the next section, the development of a mathematical computer model will be presented. The model consists of two separate lake storage and salinity submodels. The lake storage model simulates Lake Qaroun's changes in water level and volume. These changes are provided as inputs to the lake salinity model, which analyzes changes in the lake system's salinity.

5.4 Theoretical Development

5.4.1 Lake Volume

The first step in lake modelling is the establishment of a water budget. Flows carry salt into and out of lakes, and water quality problems cannot be assessed without a quantitative understanding of lake hydrology. The basic water balance equation considers the following terms:

$$\begin{gathered} INFLOW + PRECIPITATION = \\ OUTFLOW + EVAPORATION \pm CHANGE\ IN\ \ STORAGE \end{gathered} \tag{5.1}$$

Data for inflow and outflow should be evaluated over annual or seasonal periods. Inflows may include tributary streams, point source discharges, runoff from shoreline areas and groundwater. Outflows may include the lake outlet, groundwater discharge, as well as withdrawals for water supply, irrigation, or other purposes. Precipitation and evaporation can be derived from regional climatologic data. The change in storage accounts for changes in surface elevation over the study period. This change is positive if lake volume increases, negative otherwise.

The water balance equation for Lake Qaroun is (Thomann and Mueller, 1989):

$$\frac{dV}{dt} = Q_{in} + P_r A_s - E_v A_s \tag{5.2}$$

where

V is Lake Qaroun volume;

A_s is Lake Qaroun surface area;

Q_{in} is the volume of saline drainage water entering the lake;

P_r is the precipitation falling directly on the water body;

E_v is the lake evaporation.

Routing techniques may be classified into two categories: hydraulic routing and hydrologic routing. Hydraulic routing uses both the equation of continuity and the equation of motion, customarily, the momentum equation. This particular form utilizes the partial differential equation for unsteady flow in open channels. Hydrologic routing, which will be considered here, employs the equation of continuity with either an analytic, or an assumed relationship between storage and discharge within the system (Maidment et al., 1993). The continuity equation (equation 5.2) can be rewritten in this general form:

$$I - O = \frac{dV}{dt} \tag{5.3}$$

where

I is the rate of saline drainage disposal into the lake;

O is the rate of outflow from the lake;

t is time.

Because I, O and V vary with time, it is possible to convert this equation to one involving finite differences, i.e:

$$\frac{(I_1 + I_2)}{2}\Delta t - \frac{(O_1 + O_2)}{2}\Delta t = V_2 - V_1 \tag{5.4}$$

where

Δt is the time increment between times indicated by subscripts I and 2.

The lake routing calculation is based on equation 5.4 with some rearrangement. All known variables are taken to the left-hand side of the equation, and unknown variables are brought to the right-hand side. Thus:

$$\frac{(I_1 + I_2)}{2}\Delta t - \frac{(O_1 + O_2)}{2}\Delta t + V_1 = V_2 \tag{5.5}$$

Full knowledge of the drainage disposal rates (inflows) and evaporation (outflows) is required. With a known initial lake water elevation, the initial storage volume in the lake is estimated. The solution is advanced in time increments of Δt, and the basic step is to use the above equation (5.5) to calculate values of V_2. These values represent storage at the end of the first time increment, and can therefore be used as initial values for calculations involving the second time increment, t_2 to t_3.

Assumptions:

Volume-elevation curve:

The overall physical relationships for a lake can be summarized in area-elevation and volume-elevation curves. A survey made of Lake Qaroun is shown in Figure 5.1. The relationships characterize the area and volume as a function of the elevation of the lake. This survey was performed by the Geological Survey Department (Amer, 1992). Within the elevation range -45.00 and -43.00 m MSL, the following equations are valid:

$$A_s = 1202 + 22\,L \tag{5.6}$$

$$V = 11570 + 240\,L \tag{5.7}$$

where

A_s is the surface area of the lake, km^2;

V is the volume of the lake, MCM;

L is the lake water level, m MSL;

At a lake level of -43.50 m MSL, the surface area is 245 km^2 and the volume is 1130 MCM. Between -43.00 and -45.00 m MSL, the surface area varies from 256 km^2 to 212 km^2, respectively.

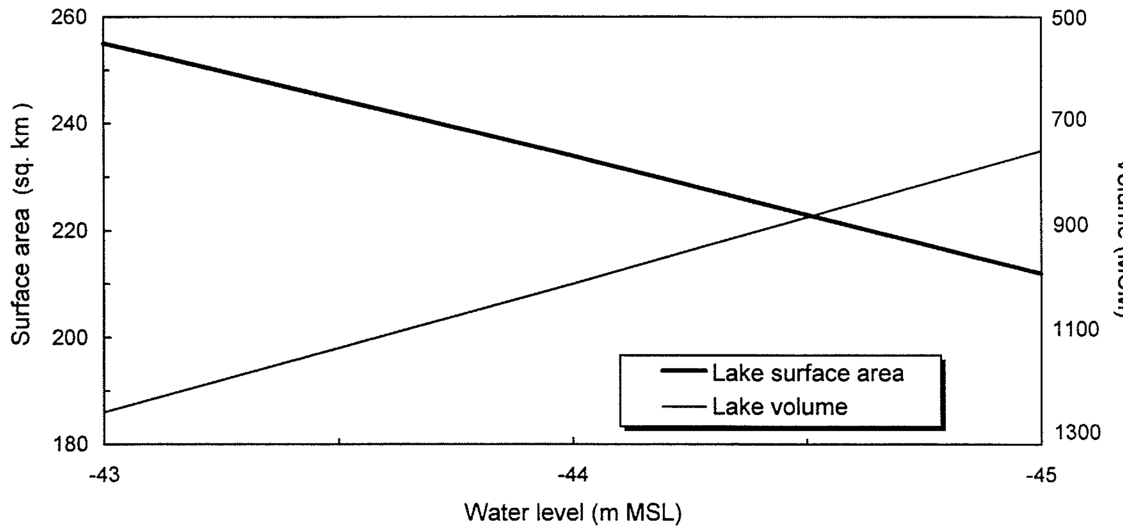


Figure 5.1 Elevation-area-volume characteristics of Lake Qaroun

5.4.2 Lake Salinity

The basic organisational principle of mechanistic water quality models is the conservation of mass within a finite volume of water. In quantitative terms, the principle is expressed as a mass balance equation that accounts for all transfers of matter across the system's boundaries and all transformations occurring within the system. For a finite period, it can be expressed as (Chapra and Reckhow, 1983):

$$[Accumulation]=[Loading]\pm[Transport]\pm[Reaction] \tag{5.8}$$

Transport is the movement of the matter through the volume, along with water flow. In addition to this flow, mass is gained or lost by transformations or reactions of substances within the volume. Reactions either add mass by changing another constituent into the substance being modelled, or remove mass by transforming the substance into another constituent. Finally, the substances can be increased by external loading. The mathematical expression of mass conservation provides a framework for calculating the response of a body of water to external influences. For more details on the levels of substances at various locations within the volume, the system can then be divided into subvolumes for which separate mass balance equations can be developed. Additional transport terms can be included to account for the mass transfer between subvolumes.

i. Mass Transport:

Numerous types of water motion transport matter in lake systems. Mass typically enters and leaves a lake via inlet and outlet streams. Within-lake motion can be divided into two general categories: advection and diffusion. The rate of movement of mass out of a volume of water via advection can be represented as:

$$[transport]_{advection\ out} = -\ Q_m\ C_m \tag{5.9}$$

where

Q_m is the rate at which water flows through the volume (m);

C_m is the concentration of the substance in the volume (m).

The negative sign denotes a loss of mass from the system. Likewise, movement of mass into the volume by advection from an adjacent volume can be expressed as:

$$[transport]_{advection\ into} = Q_{ni}\ C_{ni} \tag{5.10}$$

where

Q_{ni} is the rate at which water flows from the adjacent volume (ni);

C_{ni} is the concentration of the adjacent volume (ni).

A simple mathematical representation of the diffusion process is:

$$[transport]_{diffusion} = E'(C_{ni} - C_m) \tag{5.11}$$

where E' is the bulk diffusion coefficient, a parameter that reflects the magnitude of the mixing process between two volumes.

ii. Reaction Kinetics:

Just as mass is transported in space by water motion, it is moved between chemical forms by a variety of chemical and biochemical reactions. The kinetics of such reactions can be expressed quantitatively by the law of mass action. For a volume of water, the rate of mass exchange (i.e., of A and B to form C and D) can be generally expressed as:

$$[reaction] = K\,V\,C_A^w\;C_B^z \tag{5.12}$$

where

- K   is a coefficient that depends on a number of factors including temperature and chemical characteristics of the reacting substances;
- V   is the volume;
- C_A is the concentration of A (w is an empirically derived exponent);
- C_B is the concentration of B (z is an empirically derived exponent).

The lake salinity is dependent upon the lake routing explained above. By taking water salinity into consideration, the finite difference form of equation 5.5 can be rewritten as follows:

$$\frac{(I_1.CI_1 + I_2.CI_2)}{2}\left(\frac{\Delta t}{V_2}\right) - \frac{(O_1.CO_1 + O_2.CO_2)}{2}\left(\frac{\Delta t}{V_2}\right) + \frac{V_1}{V_2}.CV_1 = CV_2 \tag{5.13}$$

where

CI is the salinity of the lake inflow;

CO is the salinity of the lake outflow;

CV is the lake salinity.

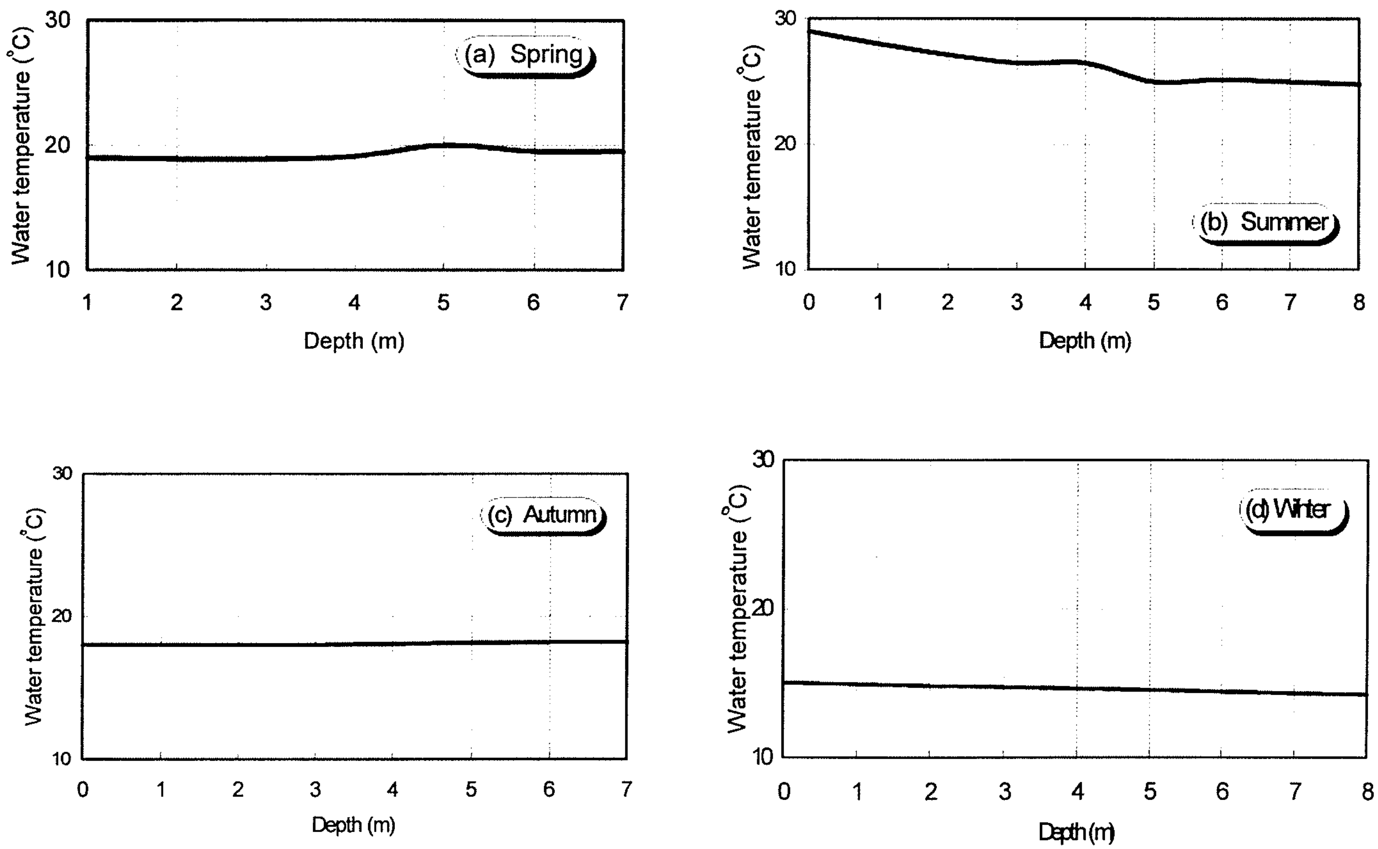
Assumptions:

i. Temperature stratification:

The vertical temperature profile at the end of winter for Lake Qaroun is shown in Figure 5.2a and is approximately homogenous from top to bottom. As spring warming begins, the surface layer begins to heat and to stratify (Figure 5.2b). By summer, a layered temperature stratification is formed. During fall, surface temperature begins to cool and fall mixing begins (Figure 5.2c). As surface temperatures continue to decline, a winter inversion develops, as shown in Figure 5.2d.

Except during summer, there is very little difference between surface temperature and temperature at 1m depth. Additionally, only during summer, there is a significant difference between surface water and bottom temperatures. During the other seasons, the temperature varies little with depth. Therefore, Lake Qaroun may be stratified into two layers. At other times, for example, winter, the lake can be considered isothermal and well mixed. As will be explained shortly, these considerations of temperature behavior in Lake Qaroun will not be incorporated into the lake model. This determination is justified on the basis of the shallowness of the lake, where the average depth is only 4.6 m.

Figure 5.2 Variation of water temperature with depth through the year (Kleijn, 1988).
(a) Spring. (b) Summer. (c)Autumn. (d) Winter



ii. Lake Mixing:

According to the overall objective of this study, it is useful to describe Lake Qaroun under the assumptions that the body of water is completely mixed horizontally and vertically. These assumptions can be justified on the basis of wind stresses on the water surface, which result in internal mixing.

iii. Conservative substance:

Generally, the nonconservative substance decays with time due perhaps to chemical reactions, bacterial degradation, radioactive decay, or perhaps settling of particulates out of the water column. For a conservative variable such as salinity, there is no loss due to decay rate. Therefore, the decay rate coefficient is not considered, i.e. K=0.

5.5 Model Evaluation

The model was evaluated by plotting the measured and simulated values against time. The agreement between the model and the observations was also checked statistically by calculating the following parameters: maximum error (ME), root mean square error (RMSE), coefficient of determination (CD), modeling efficiency (EF) and the coefficient of residual mass (CRM). The five criteria are explained as follows (Hack-ten Broke and Hegmans, 1996):

$$ME = Max_{i=1}^{n} \left| O_i - S_i \right| \tag{5.14}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{N}} * (\frac{100}{O_m}) \quad (5.15)$$

$$CD = \frac{\sum_{i=1}^{n}(O_i - O_m)^2}{\sum_{i=1}^{n}(S_i - O_m)^2} \quad (5.16)$$

$$EF = \frac{\sum_{i=1}^{n}(O_i - O_m)^2 - \sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O_m)^2} \quad (5.17)$$

$$CRM = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} O_i} \quad (5.18)$$

where

N is the number of years in the study period;

O_i is the measured water level (monthly average) of Lake Qaroun;

O_m is the mean of values of O_i ;

S_i is the predicted water level (monthly average) of Lake Qaroun.

5.6 Results and Discussion

Measured Lake Qaroun levels and levels simulated using the LQR model were compared using data for the period 1980-1996. The comparison is presented by plotting the average monthly levels. Figures 5.3, 5.4 and 5.5 show the average monthly levels for the years 1988, 1990 and 1995, respectively. Over the study period, the monthly error percentage of the model estimates range between -0.43% to 0.99%. Figure 5.6 shows the average annual water levels of Lake Qaroun calculated by both methods. The maximum annual error percentage of the model estimates is 0.44% and the minimum is -0.19%. From the figures, it is clear that the trend between the measured and simulated data is similar.

Table 5.1 shows the results of the five statistics used in the comparison. It contains the calculated values of the maximum error (ME), root mean square error (RMSE), coefficient of determination (CD), modeling efficiency (EF) and the coefficient of residual mass (CRM). The values of ME, RMSE, CD and EF for LQR model for the period 1980-1996 range from 0.134 m to 0.429m, 0.35% to 0.13%, 0.64 to 1.05, and 0.58 to 0.93, respectively. The ME values represent the worse case performance of the model, which is 4.3 cm. This value represents an error percentage of 1 % for the water level. The RMSE values show that the simulations overestimate or underestimate the measurements by 0.35% to 0.13% of the mean value of the measurements. The ratios between the scatter of simulated values and the scatter of measurements (CD) are comparable for the twelve months; the coefficient of determination ranges from 0.64 to 1.05 with an annual average of 0.895. The positive values of EF indicate that the simulated values provide a superior estimate to the average value of the measurements. The values which are close to 1 show that the model is in good agreement with the measured values. This conclusion can be confirmed by using the values of CRM, where error percentages range from -0.09% to 0.18%. The positive values reveal that there is a tendency for overestimation in the last five months.

Although sensitivity analysis was not accomplished in this study, the difference between model results and measurements can be mainly attributed to the parameter which was not taken into account (groundwater seepage). The underestimation of the results (from January to July) may stem from the seepage to Lake Qaroun that occurs when the water level is high. The overestimation of the results (from August to December) may have been caused by seepage to the surrounding land from Lake Qaroun that occurs when the water level is lower.

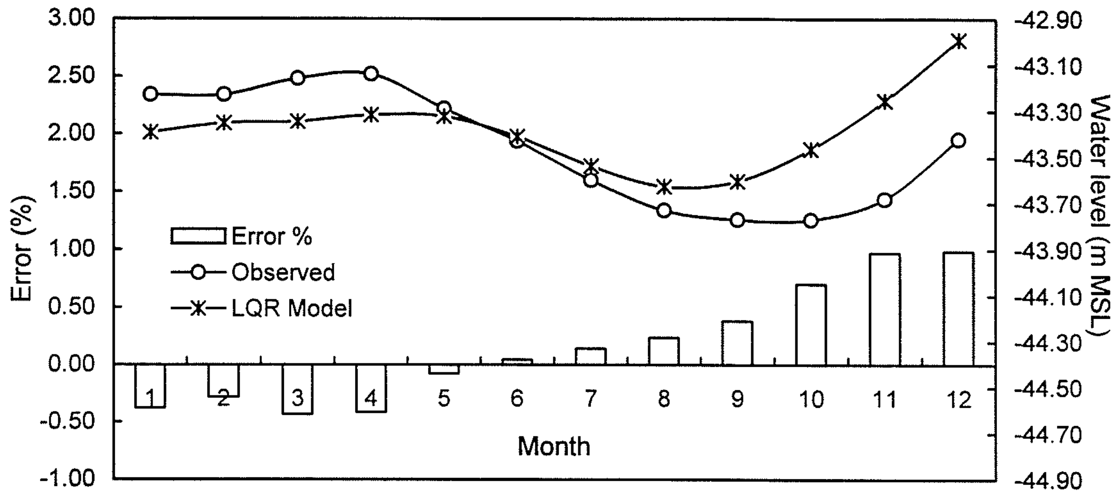


Figure 5.3 Monthly evaluation of LQR model-water level-prediction (1988)

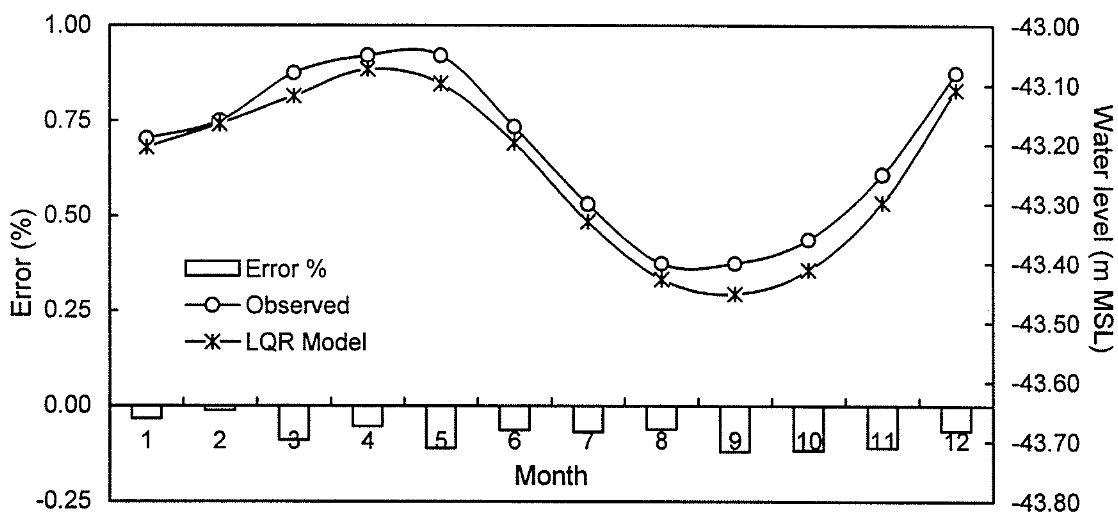


Figure 5.4 Monthly evaluation of LQR model-water level-prediction (1990)

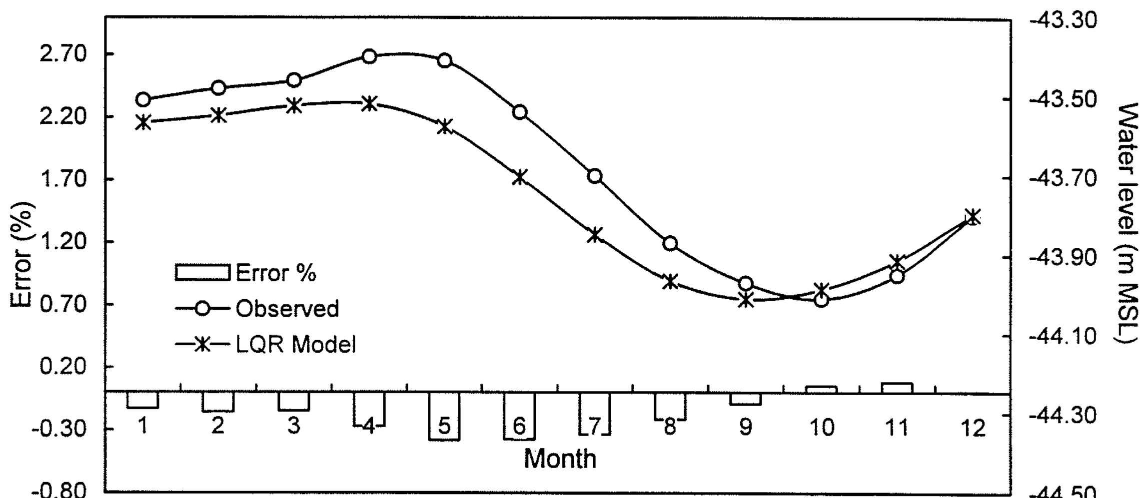


Figure 5.5 Monthly evaluation of LQR model-water level-prediction (1995)

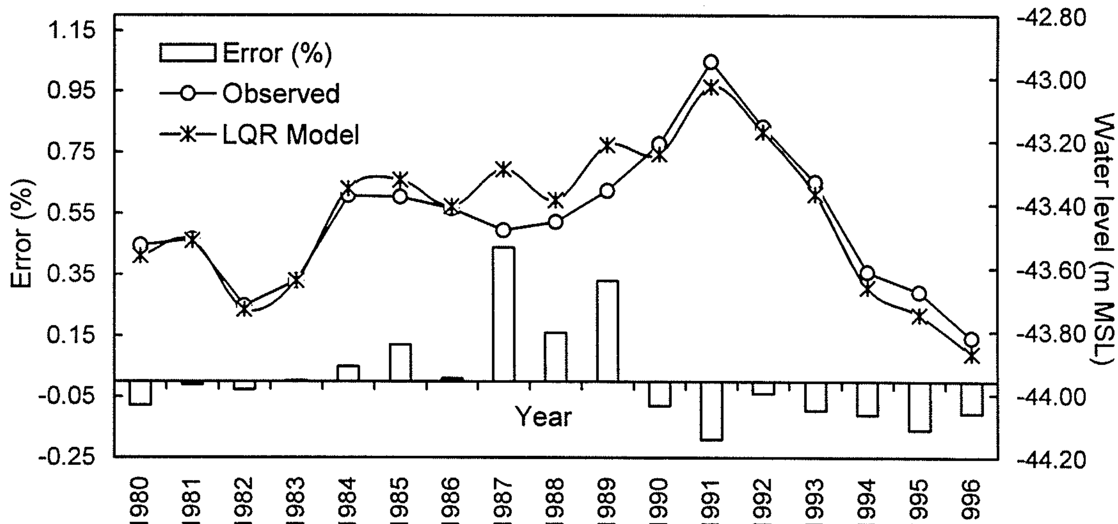


Figure 5.6 Annual evaluation of LQR model-water level-prediction (1980-1996)

Table 5.1 Maximum error (ME), root mean square error (RMSE), coefficient of determination (CD), modeling efficiency (EF) and the coefficient of residual mass (CRM) for measured vs. predicted water levels for LQR model (1980-1996).

Month	ME (m)	RMSE %	CD	EF	CRM
January	0.164	0.132	0.944	0.929	-0.0007
February	0.134	0.142	0.956	0.914	-0.0002
March	0.187	0.172	1.048	0.887	-0.0009
April	0.236	0.192	0.934	0.848	-0.0009
May	0.312	0.206	0.844	0.814	-0.0009
June	0.271	0.190	0.918	0.858	-0.0006
July	0.219	0.213	0.860	0.811	-0.0002
August	0.217	0.217	0.835	0.808	0.0002
September	0.288	0.259	0.850	0.754	0.0008
October	0.330	0.318	0.808	0.653	0.0016
November	0.426	0.349	0.746	0.587	0.0018
December	0.429	0.340	0.639	0.579	0.0015
Annual	**0.192**	**0.164**	**0.889**	**0.889**	**0.0001**

The LQR model was tested using available lake salinity data collected in 1980, 1981, 1986 and 1987. Comparison of model estimates to observations are performed by plotting monthly average water salinity figures such as Figure 5.7. Over the four years data available, the monthly percent error of the model estimates ranges between -16.7% to 15.3%. Figure 5.8 shows the average annual water salinity of Lake Qaroun calculated during these four years. The maximum annual percent error of the model estimates is 7.6%, and the minimum is -4.5%.

From the graphical presentation of the four year measurements, it is clear that the trend between measured and simulated data is differs.

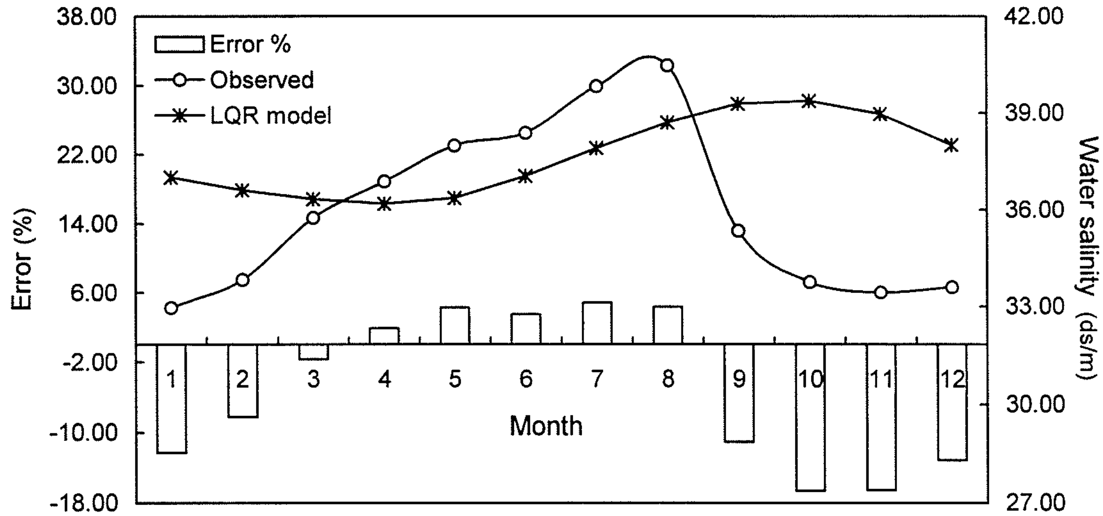


Figure 5.7 Monthly evaluation of LQR model-salinity-prediction (1986)

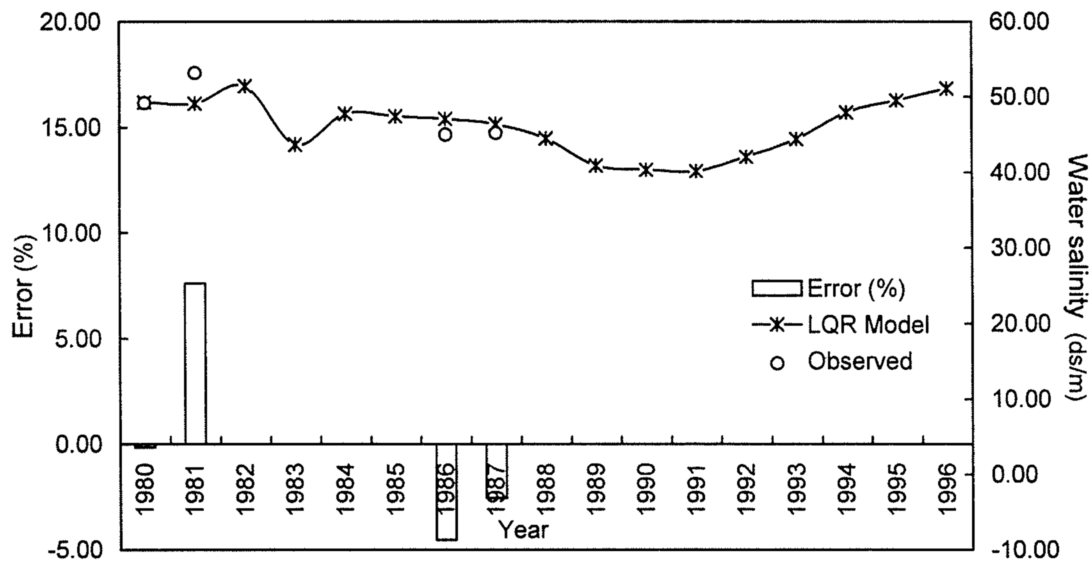


Figure 5.8 Annual evaluation of LQR model-salinity-prediction (1980-1996)

Table 5.2 shows results of the five statistics used in the comparison. It presents the calculated values of the maximum error (ME), root mean square error (RMSE), coefficient of determination (CD), modeling efficiency (EF) and the coefficient of residual mass (CRM). The values of ME, RMSE, CD, and EF for the LQR model for the years 1980, 1981, 1986 and 1987 range from 2.1 dS/m to 6.6 dS/m, 3.5% to 10.6%, 0.08 to 8.1, and -8.2 to 0.53, respectively. The (ME) values represent the worse case performance of the model, which is 6.6 dS/m. This value represents an percent error of 15.25 % for water salinity. The RMSE values show that the simulations overestimate or underestimate the measurements by 3.5% to 10.6% of the mean value of the measurements. The ratio between the scatter of simulated values and the scatter of measurements (CD) over the twelve months has a range of 0.08 to 8.1, with an annual average of 9.4. The values of EF, which are not close to 1 show that the model is not in good agreement with the measured values. The positive values of CRM demonstrate that there is a tendency for underestimation from March to August. Based on the monthly comparison, and given the fact that there is no agreement in trend between the four years of data, and between the model results and measurements, it can be concluded that the model simulations must be performed for more years.

Table 5.2 Maximum error (ME), root mean square error (RMSE), coefficient of determination (CD), modeling efficiency (EF) and the coefficient of residual mass (CRM) for measured vs. predicted water salinity for the LQR model (1980, 81, 86, 87)

	ME (dS/m)	RMSE (%)	CD	EF	CRM
January	4.24	10.59	2.77	-0.10	-0.0568
February	3.02	7.63	4.22	-0.03	-0.0336
March	3.90	5.38	8.12	0.06	0.0147
April	6.62	9.04	0.91	-1.00	0.0657
May	5.27	7.63	0.49	-1.64	0.0653
June	6.48	8.54	1.06	-0.63	0.0617
July	2.38	4.98	0.16	-3.86	0.0494
August	2.09	3.45	0.08	-8.20	0.0222
September	3.93	7.89	7.13	0.49	-0.0176
October	5.62	9.22	1.83	0.23	-0.0648
November	5.53	9.66	2.03	0.26	-0.0642
December	4.41	8.40	7.20	0.53	-0.018
Annual	**3.24**	**5.11**	**9.35**	**0.52**	**-0.0015**

5.7 Summary and Conclusions

The lake routing model presented herein was formulated to provide estimates of monthly and annual water and salinity levels for Lake Qaroun. The model was tested with measurements made in 1980-1996. Several statistical parameters were also computed. The comparison between results produced by the LQR model and the measured values are presented in Figures (5.3 to 5.8) and Tables (5.1 to 5.2).

In comparison with the water level measurements, the results produced by the LQR model were in accord with measured values. The monthly modelling efficiency (EF) ranged from 0.58 to 0.93. On annual basis, The model demonstrated good performance (EF=0.88). The LQR model revealed a tendency to overestimate water levels from August to December. Although model sensitivity analysis was not conducted in this study, the overestimation of the results can be mainly attributed to the seepage from Lake Qaroun.

Compared with the available salinity measurements, the model produced reliable results in terms of annual prediction (EF=0.5). However, over monthly periods, where EF ranged from -8.2 to 0.53, the LQR model was not in good agreement with field measurments. The LQR model underestimated lake water salinity from March to August. Based on the monthly comparison, and given the fact that there is no agreement in trend between the data collected for the four years of measurements, it is recommended that the model simulations be performed for more years.

On the whole, the model performed satisfactorily. Comparison between simulation and measurements demonstrates the capacity of the model to function as a useful tool for analysing salinity and water levels of the lake.

CONNECTING TEXT

In Chapter 5, the Lake Qaroun Routing model (LQR) was developed and tested in order to estimate the water and salinity levels of Lake Qaroun. Validated by comparing model results with field observations, the model can be used as a prediction tool for providing an understanding of the impact of various drainage water disposal system on Lake Qaroun.

In the next Chapter, the LQR model is extended to deal with various management options with the lake being divided into series of compartments. Evaporation ponds, as one of the more viable alternatives for reducing lake salinity, are used to evacuate the salt.

CHAPTER SIX

MANAGEMENT OF LAKE QAROUN FOR SALINITY CONTROL

Abstract

The serious constraint of salt and water disposal in Lake Qaroun results in tremendous difficulties in salinity control. To assess various water and salt management strategies for this salinity control, the lake routing model (LQR), simulating the interrelated processes and interventions in space and time, is extended. The model provides an understanding of both drainage water disposal in Lake Qaroun, and lake management options for salinity control.

The various management options presented in this Chapter deal mainly with dividing Lake Qaroun into a series of compartments separated by dams, as well as constructing regional evaporation ponds. The study used the information collected from the study area and the model simulations to analyse the prospects of lake management for salinity control, and to find environmentally acceptable solutions to the disposal problem. Using the LQR model, simulations evaluated the effect of the different options on the lake system.

It was concluded that the most suitable solution is to divide Lake Qaroun into two compartments (assumed to be 35% and 65% of the lake area) and considering a target time of ten years. The smaller compartment, located at the

east end of Lake Qaroun, has a relatively fresh water with a salinity level (13.3 dS/m) reduced by 74% of the original, and a recommended water level of -43.79 m MSL, with narrow fluctuations of $\pm$ 0.25 m. The other compartment, located at the west end of Lake Qaroun, has saline water. The salinity level (83.1 dS/m) is increased by 65% of the original level, though It has the lowest salt accumulation, which is effectively reduced by using the regional evaporation ponds north of the lake. It is estimated that annual salt load into the evaporation ponds is 620,000 tonnes. This will reduce the salinity level from 83.1 dS/m to 72.2 dS/m. An area of 6 km^2 is required to evacuate the salt.

6.1 Introduction

Failure to halt the salinization of Lake Qaroun will ultimately result in a sterile lake. Some plans (Figure 6.1) are required to control both the level and the salinity of the lake. After assessment of their technical feasibility, environmental impacts should be assessed by parties involved in and around the lake.

The simplest plan is to construct fish ponds, constantly refreshed by through-flow of drainage water, in the shallow part of the lake, near the outfalls of drains. However, only a small part of the lake is suitable for the implementation of this approach.

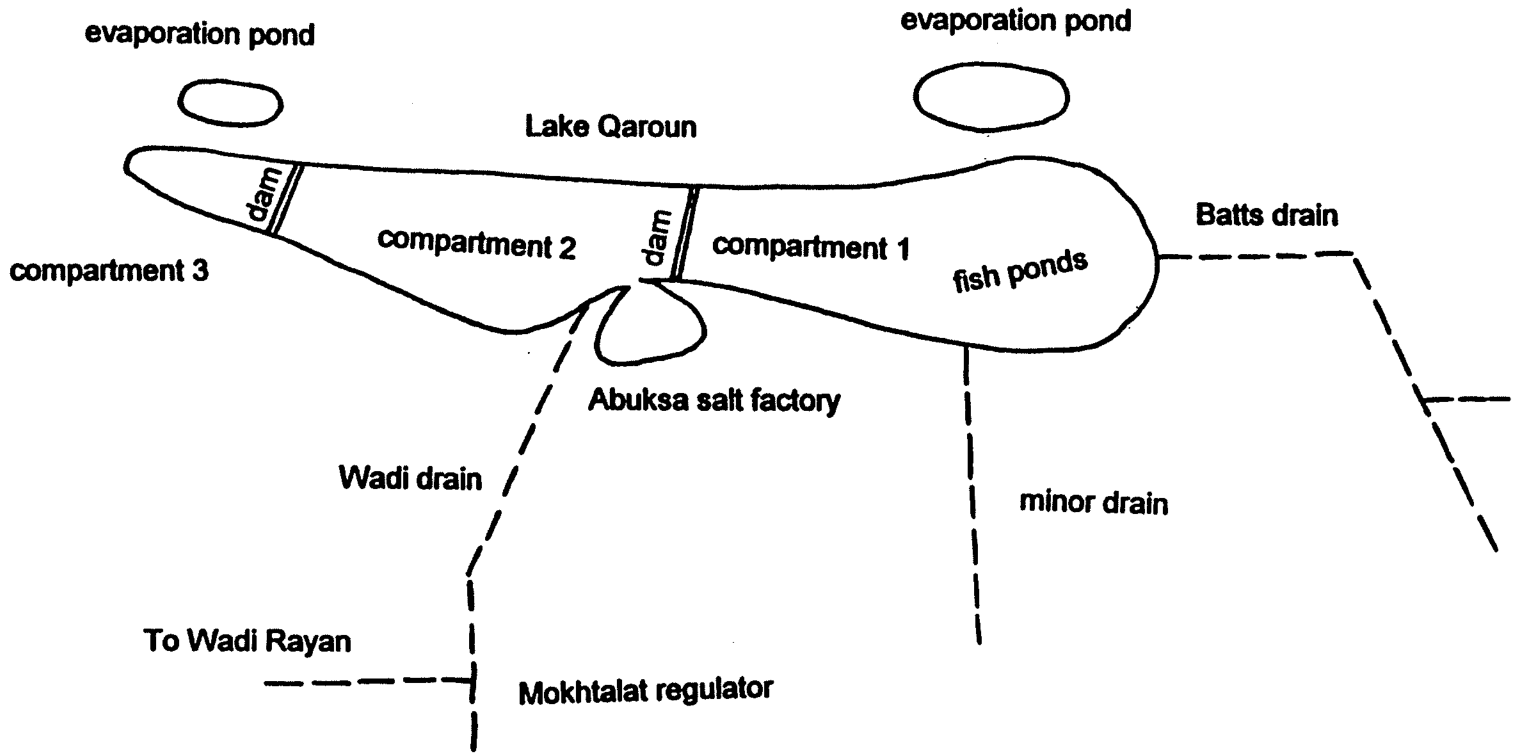


Figure 6.1 Some management concepts to control the water and salinity level of lake Qaroun

A second plan is to remove the salt from the lake by pumping the saline lake water into regional and/or on-farm evaporation ponds. Regional ponds could be constructed at the old lake bed north-east of Lake Qaroun. Once the water in this area becomes a brine, it can be lifted into salt pans. A huge ponded area is required to evacuate annually the salt from the lake, in addition to the salt extraction of the Abuksa salt factory at Shakshouk. The salt factory currently extracts 180,000 tonnes per year, of which only 60,000 tonnes of salt are presently processed, with the rest being stored. Plans exist to once again dispose of it in Lake Qaroun.

A third plan (Figure 6.1) is to divide the lake, by dams, into a series of compartments (Abdel-Dayem,1997a). The output from one compartment that receives an input of saline drainage water becomes, in turn, the input to a second compartment downstream. That compartment may also discharge to a third compartment. The salinity of the first compartment covering the eastern part of the lake, due to the transfer of salts to the second compartment and the low salinity of the inflowing drainage water, will decrease and stabilize at a low level. The salinity in the second compartment will increase to higher levels than those under current conditions. Some of the salt in this second compartment can thus be more efficiently extracted by the salt factory at Shakshouk. Also, an additional amount of salt might finally be extracted by means of a third compartment acting as a salt pan. In this way, the salinity level of the second compartment might even be kept at lower pre-set levels. This plan requires the construction of a long dam with hydraulic structures such as sluices or weirs. In order to control the water levels of the compartments (Figure 6.1), the regulator at Mokhtalat would be used to control flow of the Wadi drain to Lake Qaroun,

6.2 Study Objectives

The objectives of this study are to:

i. extend the LQR model for water and salinity control in constrained drainage basins; the model can asses the effects of various drainage water disposal options on the divided lake Qaroun;

ii. use the collected information from the study area and the model simulations to analyse the prospects for lake salinity control and find acceptable solutions with different management strategies.

6.3 Model Extension

In this study, it is proposed to divide Lake Qaroun by dams, into a series of compartments. The mathematical model (LQR), developed in Chapter 5, is extended in order to study the water salinity in these compartments. In addition, the use of regional evaporation ponds outside the lake will be taken into consideration. After performing the model simulation with different management options, the appropriate solution is discussed.

The input data required to run the model are the same as mentioned in section 5.3. In addition, the number and area of each compartment is required. The output of the model simulations are:

- monthly and annual water levels for each compartment;
- monthly and annual water salinity for each compartment.

6.4 Theoretical Development

If each pond is considered as a completely mixed body of water, a mass balance equation can be written for each compartment.

Following Figure 6.2 and equation 5.8, assuming temporally constant volume for each compartment, the equations for three compartments indicated by 1, 2 and 3 are:

$$\frac{d(v_1\, cv_1)}{dt} = W_1(t) - Q_{12}\, co_1 - v_1\, k_1\, cv_1 \tag{6.1}$$

$$\frac{d(v_2\, cv_2)}{dt} = W_2(t) + Q_{12}\, co_1 - Q_{23}\, co_2 - v_2\, k_2\, cv_2 \tag{6.2}$$

$$\frac{d(v_3\, cv_3)}{dt} = W_3(t) + Q_{23}\, co_2 - v_3\, k_3\, cv_3 \tag{6.3}$$

where

v is the compartment volume;

cv is the salinity of the compartment;

W is the net mass load;

Q is the flow transferred from one compartment to another;

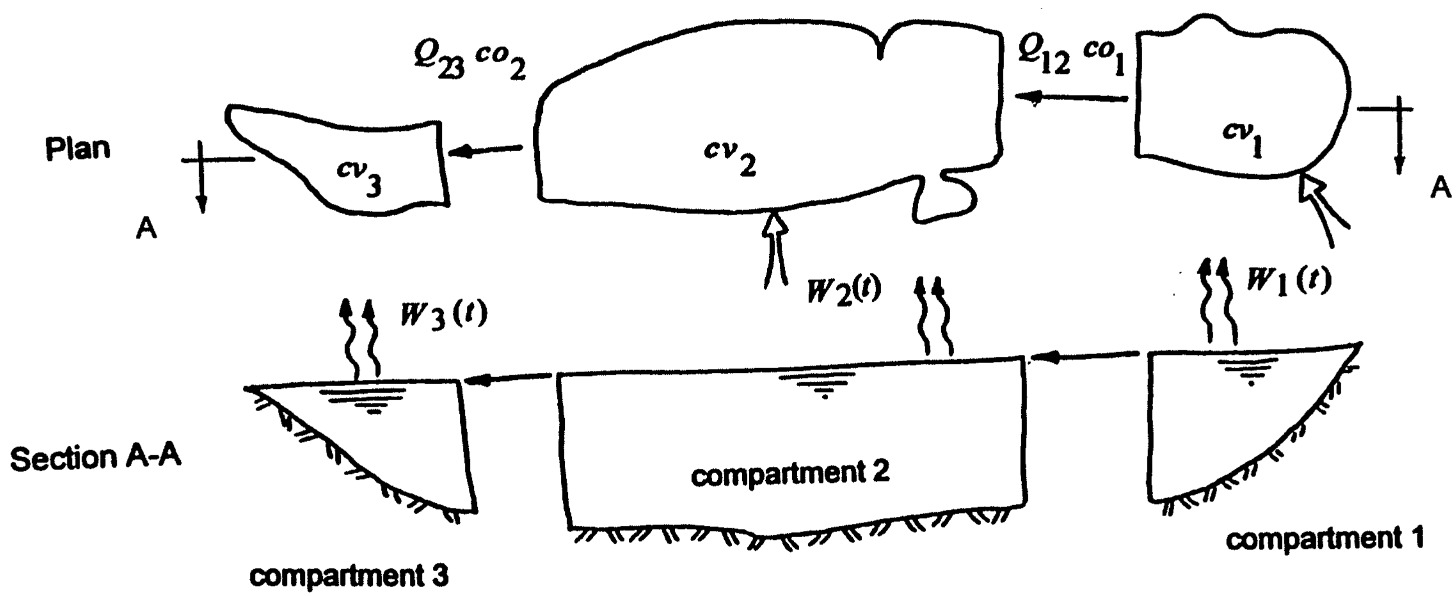


Figure 6.2 Illustration of three compartments in series

co is the salinity of the flow transferred (co = cv);

k is the decay rate of the compartment.

Temporally constant parameters are assumed, but the parameters may change from compartment to another. The output from one compartment that has received an input of water of variable quality becomes, in turn, the input to another compartment. Note that mass output of the first compartment, $Q_{12}\ co_1$, becomes an input to the second compartment in equation 6.2. Equations 6.1, 6.2 and 6.3 can be considered as a simple special case of the more general representation of lake routing used in Lake Qaroun, as in Equation 5.13.

Assumptions:

i. Physical features:

The principle physical feature of the divided Lake Qaroun:

Length: As will be shortly explained, the length of the lake in a compartment series differs according to the various options. Depth: the average depth of the divided Lake Qaroun is considered to be 4.6 m. Also, percolation or seepage is assumed negligible with respect to surface inflow and evaporation.

ii. Volume-area-elevation curve:

The overall physical relationships for the divided lake are based on the area-elevation and volume-elevation curves illustrated in section 5.4.1. These relationships characterize the area and volume as a function of the elevation of each lake division (compartment), and are calculated as a ratio of the total compartment areas. Therefore, the following equations are assumed:

$$A_i = \frac{A_i}{\sum_n A_n} \quad (1202 \quad + \quad 22\ L) \tag{6.4}$$

$$v_i = \frac{v_i}{\sum_n v_n} \quad (11570 \quad + \quad 240\ L) \tag{6.5}$$

where

A_i is the surface area of each lake compartment, km^2;

v_i is the volume of each lake compartment, MCM;

$\sum A_n$ is the total surface area of all the compartments, km^2;

$\sum v_n$ is the total volume of the divided lake into compartments, MCM;

L is the lake water level, m MSL.

iii. Evaporation :

Dividing Lake Qaroun creates a series of compartments with varying salinities. Assuming that the salts do not evaporate, an approach based on the effect of salinity on saturation vapor pressure has been used to estimate the evaporation from saline Lake Qaroun. A computer model for estimating monthly and annual saline water evaporation has been developed (Chapter 4).

iv. Temperature stratification:

The considerations of temperature changes in Lake Qaroun will not be incorporated into the divided lake. Therefore, there will be no temperature stratification. This assumption is justified on the basis of the shallowness of Lake Qaroun, where the average depth is 4.6 m.

v. Conservative substance:

Generally, the nonconservative substance decays with time due perhaps to chemical reactions, bacterial degradation, radioactive decay, or perhaps settling of particulates out of the water column. For a conservative variable such as salinity, there is no loss due to decay rate; therefore, there is no change in concentration between the different sections of the same compartment.

vi. Hydraulics of flow over the dam:

By dividing Lake Qaroun into a series of compartments, the transfer of flow from one division to another can be estimated by different hydraulic structures. In the present study, a rectangular weir will be considered. For a rectangular ("broad-crested") weir, with b defining the width (m) of the weir and H the depth of flow (m), the discharge of flow over the weir Q (m^3/s) is given by (Herschy, 1985):

$$Q = b\sqrt{g}\left(\frac{2}{3}H\right)^{3/2} \tag{6.6}$$

In SI units, this becomes

$$Q = 1.7\,b\,(H)^{3/2} \tag{6.7}$$

6.4.1 Dividing Lake Qaroun

As mentioned In section 6.1, this study presents a lake management strategy to halt the salt buildup in Lake Qaroun. This management strategy requires dividing Lake Qaroun into a series of compartments separated by dams. The dams will be used to set off a portion of the lake, which will serve as a drainage pool, allowing saline levels to drop in the other area of the lake. Dividing Lake Qaroun is evaluated by presenting four options. Figure 6.3 and Table 6.1 show the characteristics of these four management options, representing possibilities for dividing the lake into compartments with differing salinities - from relatively fresh to saline.

Assumptions

In the various options, three main assumptions are made in the lake division with respect to the project's commencement, the compartment areas, and the saline water receiving compartments.

Project's commencement:

The building of the proposed management project suggests completion by the end of year 2001, providing sufficient time for dam construction and for the lake to reach the recommended water level (section 1.3.1). In the final year before divisions are effected, the average annual water and salinity levels are predicted, by the LQR model, to be -43.83 m MSL and 50.1 dS/m, respectively.

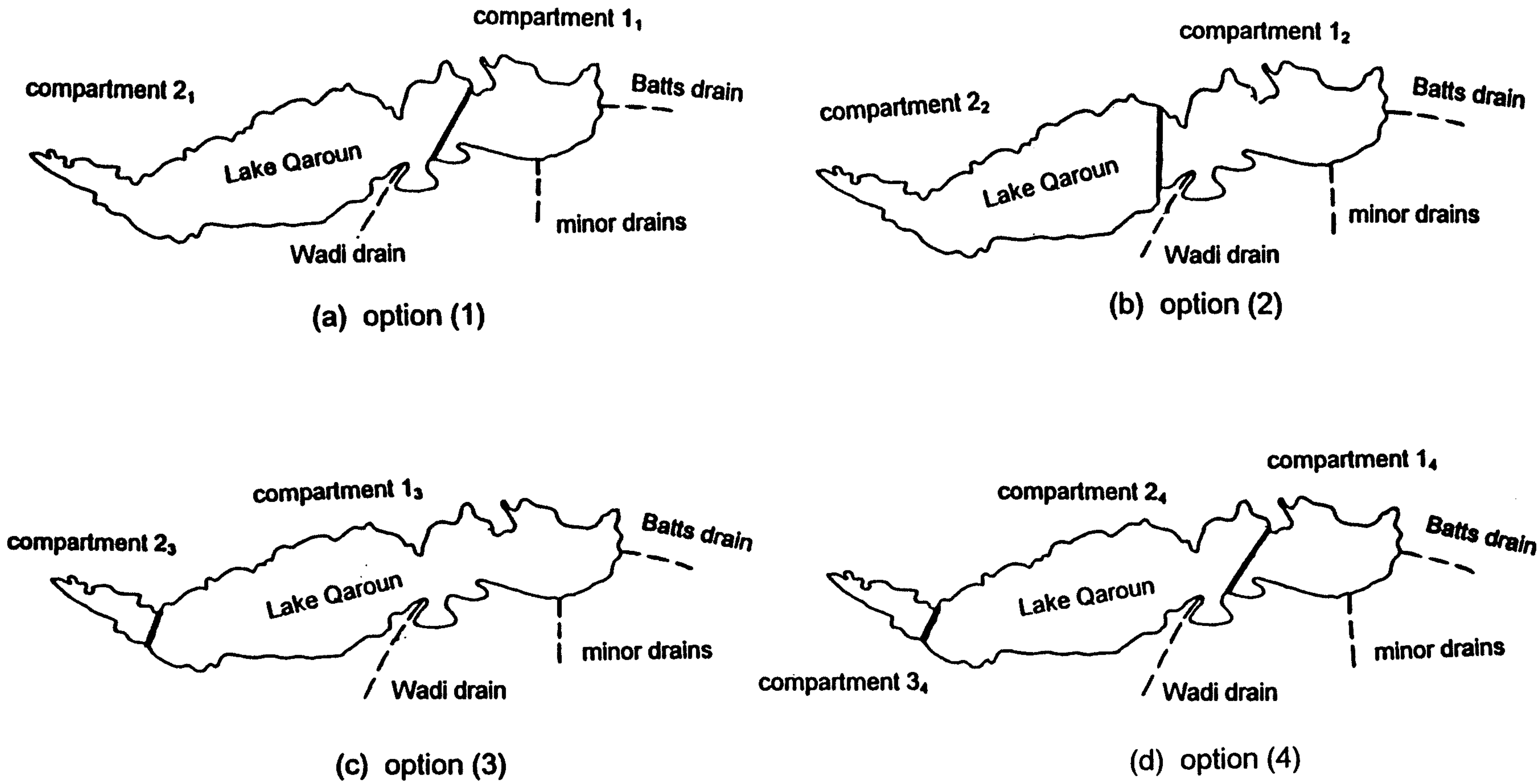


Figure 6.3 Characteristics of the four management options

Table 6.1 The alternative options for divided Lake Qaroun

Option	Compart-ments	No of Comp-artme-nts	Compar-ment** location	Comp-artment area*** %	Dam length km	Length of weirs m	Weir level m MSL
Option	$Comp1_1$	1	east	35	2.5	150	-43.82
(1)	$Comp2_1$*	1	west	65			
	$Comp3_1$	_	_	_	_		
Option	$Comp1_2$	1	east	53	2.1	150	-43.82
(2)	$Comp2_2$	1	west	47			
	$Comp3_2$	_	_	_	_		
Option	$Comp1_3$	1	east	85	1.5	30	-43.75
(3)	$Comp2_3$	1	west	15			
	$Comp3_3$	_	_	_	_		
Option	$Comp1_4$	1	east	35	2.5	150	-43.82
(4)	$Comp2_4$	1	middle	55			
	$Comp3_4$	1	west	10	1.5	75	-44.22

*$Comp2_1$ = compartment no 2 in option 1 **compartment location in Lake Qaroun

*** pond area as a percentage of the surface area of Lake Qaroun

Compartment areas:

Within the different options, the estimate of compartment areas is dependent upon two main factors: the area of the relatively fresh compartment, and the flushing of the receiving saline water disposal, to stop or reduce the salt buildup. Following Table 6.1, the area of the first and second compartments in option 1 are assumed to be 35% and 65% of Lake Qaroun, respectively. In the second option, the area of $comp1_2$ is 1.51 times greater than $comp1_1$ and comp 2_2 is 0.72 times less than $comp2_1$. In the third option, $comp1_3$ and comp 2_3 are assumed to be 85% and 15% of Lake Qaroun, respectively. In the last option, compared to the first option, $comp1_4$ has the same area as $comp1_1$, $comp2_1$ is 0.77 times less than $comp2_4$, and a third compartment, $comp3_4$, has been added.

The receiving saline water disposal:

The annual saline water disposed from the basin to the divided lake and its annual average salinity are assumed to be 417 MCM, and 1.32 dS/m, respectively. Following Table 6.1 and Figure 6.3, the management options and the assumed annual flow and its salinity are explained as follows :

<u>The first option with two compartments</u>:

- $Comp1_1$ receives the saline drainage water from Batts drain and minor drains (269 MCM, 1.3 dS/m);
- $Comp2_1$ receives the disposal from the basin only by Wadi drain (147 MCM, 1.36 dS/m) and the transferred saline water from $comp1_1$.

<u>The second option with two compartments</u>:

- $Comp1_2$ receives all the disposal drainage water from Batts drain, minor drains, and Wadi drain (417 MCM, 1.32 dS/m);
- $Comp2_2$ receives only the water transferred from $comp1_2$.

<u>The third option with two compartments:</u>

- $Comp1_3$ receives all the disposal from Batts drain, minor drains, and Wadi drain (417 MCM, 1.32 dS/m);
- $Comp2_3$ is working as a salt trap that receives the water transferred from $comp1_3$.

The fourth option with three compartments:

- $Comp1_4$ receives the disposal of Batts drain and minor drains (269 MCM, 1.3 dS/m);
- $Comp2_4$ receives the drainage water from Wadi drain (147 MCM, 1.36 dS/m) and the water transferred from $comp1_4$;
- $Comp3_4$ receives only the saline water transferred from comp 2_4.

6.5 Results and Discussion

Using the improved LQR model, simulations have been made to evaluate the effect of different options on the lake system, after its division into a series of compartments. The target time for all simulations is 10 years. The simulations are classified into 3 cases (A, B and C). Each case has a different target level of water salinity for the fresh compartment. These target values are assumed to be 5, 10, and 15 dS/m for cases A, B, and C, respectively. The first case, with four options, is summarized in Table 6.2. Figures 6.4 to 6.11 show in detail the model simulation for case A. The monthly average water and salinity levels for option 1 are shown in Figure 6.4. The annual average water level, after reaching the steady state, is shown in Figure 6.5(a). The annual average salinity levels are shown in Figure 6.5(b). With the same simulations, the other options (2, 3 and 4) for case A are illustrated in Figures 6.6 to 6.11.

Table 6.2 The LQR model simulation for case A.

Options	Inflow** %	Water level*** m MSL	Fluctuation m MSL	Water salinity dS/m after 5 year	Water salinity dS/m after10 year
Option (1)					
$Comp1_1$	0_{B+M}	-43.79_4	0.25	14.0	4.6
$Comp2_1$*	$+22_W$	-44.38_4	0.57	83.3	89.5
Option (2)					
$Comp1_2$	0_{B+M+W}	-43.78_4	0.26	10.9	3.8
$Comp2_2$	$+(16)_W$	-44.65_6	0.78	106.9	128.0
Option (3)					
$Comp1_3$	0_{B+M+W}	-43.80_4	0.41	46.3	41.2
$Comp2_3$	$+(27)_W$	-44.90_8	0.49	109.3	152.2
Option (4)					
$Comp1_4$	0_{B+M}	-43.79_4	0.25	14.0	4.6
$Comp2_4$	0_{B+M}	-44.40_4	0.59	81.3	89.3
$Comp3_4$	$+(15)_W$	-45.73_6	0.55	132.0	260.0

* $Comp2_1$ = compartment no. 2 in option (1).

** inflow % = the percentage change (increase = + or decrease = -) of the assumed inflow to each compartment. B = Batts drain, M = minor drains, W = Wadi drain. $+20_{B+M+W}$ means the inflow is increased by 20 % of the assumed inflow. $+(20)_W$ means the compartment received 20 % of the assumed inflow of Wadi drain. ( ) indicates the compartment does not have a direct outlet from Wadi drain. *** Water level = the annual average water level of each compartment upon reaching the steady state. Superscripts indicate the number of years to reach the steady state. -43.5_3 means the steady state water level (-43.5) reached after 3 years from the beginning of the project.

Case A:

Following Table 6.2 and Figures 6.4 and 6.5, the results of the LQR model for option (1) can be explained as follows: four years after the establishment of the lake divisions, the annual average water salinity of $comp1_1$ will be reduced to 54 % of the initial water salinity. After 10 years, the final salinity level will reach less than 5 dS/m, and 90 dS/m, for $comp1_1$, and $comp2_1$, respectively. By attaining these salinity levels, a fresh compartment can be created at the east of the lake, and a saline one at the west. This option offers the advantage of achieving levels of water and salinity for one part of Lake Qaroun ($comp1_1$), a result that is both safe and environmentally acceptable. The disadvantage is that $comp2_1$, also the larger of the two, is much more saline.

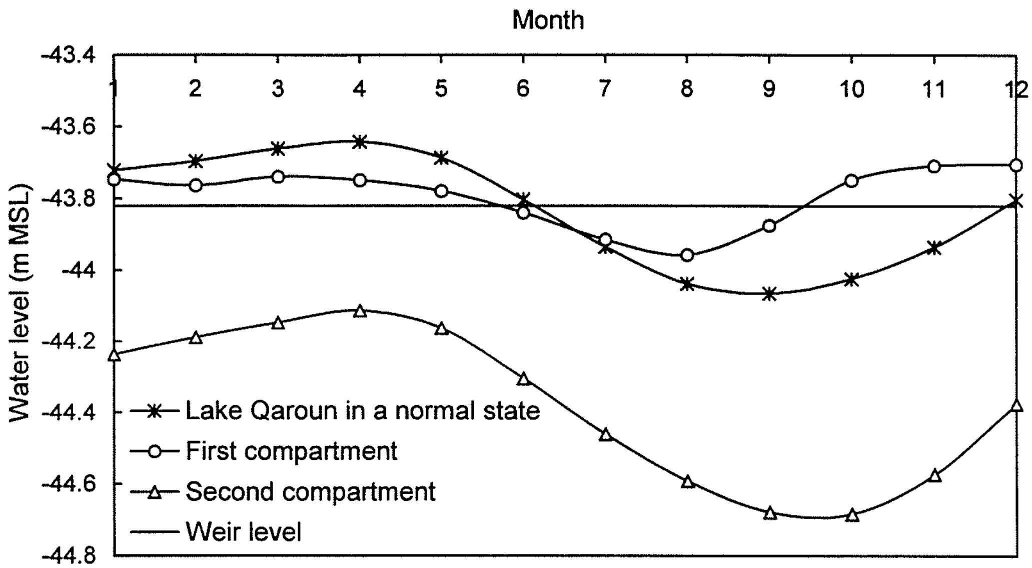
Option (2), represented by Table 6.2 and Figures 6.6 and 6.7, has a larger fresh compartment than option (1). Ten years after the establishment of the lake divisions, the annual average water salinity of $comp1_1$ will be reduced to 92 % of the initial salinity level. The annual average steady state water level is -43.78 m MSL, with narrow fluctuations of $\pm$ 0.26 m. The disadvantage of applying this option rests in the accumulation rate of salt in compartment 2_2, which is higher than that in the second compartment in option (1). The annual average water salinity after 10 years is estimated to be 128 dS/m.

In the case of option (3), the LQR model simulations are shown in Table 6.2 and Figures 6.8 to 6.9. Dividing the Lake into two compartments is not helpful in reaching the target salinity level after 10 years. The creation of a fresh compartment, therefore, has not been achieved. $Comp2_3$ shows a rapid rise in salinity, thereby becoming a hyper saline water body.

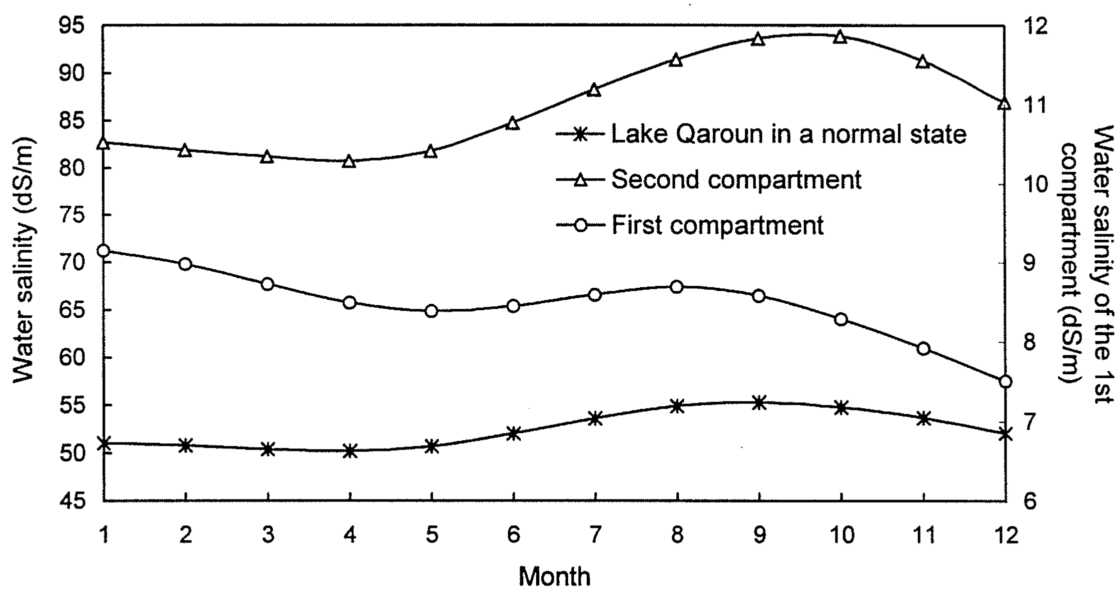
According to option (4) (Table 6.2 and Figures 6.10 and 6.11), fresh and saline compartments have been created. The target salinity level will be achieved in $comp1_4$. $Comp3_4$ becomes extremely saline within a few years.

According to the above simulations for the four options (case A), the potential problem is that the accumulation of salts is prevented in one compartment of the lake, though it shows up in another compartment. The only real solution is to remove the salt from the saline compartment in which it accumulates and ultimately discharge it in a selected desert area.

Comparing the above four options of case A, option (1) is clearly the most suitable solution. The compartment located at the east of Lake Qaroun achieves the recommended water level -43.79 m MSL with narrow fluctuations of $\pm$ 0.25 m. The saline level will reach the target level after ten years. The compartment, located at the west of Lake Qaroun will have the lowest salt accumulation rate, which can be effectively reduced by use of the regional evaporation ponds north of the lake.

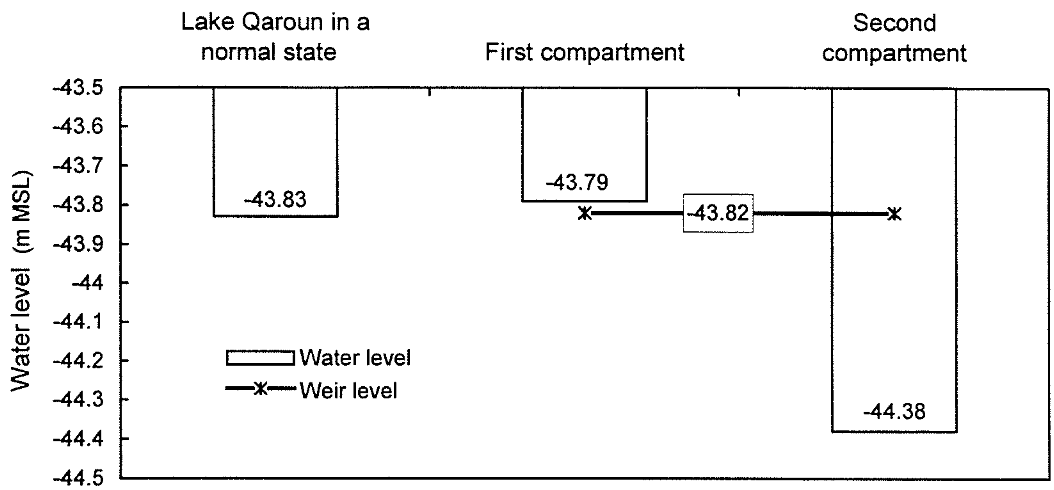


(a) Average monthly water levels of Lake Qaroun

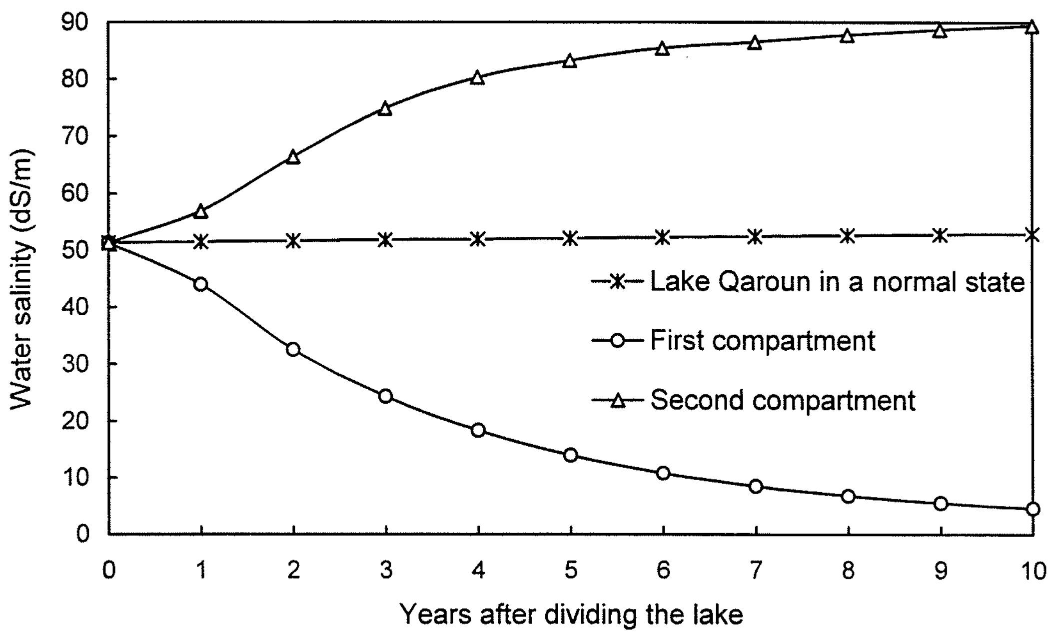


(b) Average monthly water salinity of Lake Qaroun

Figure 6.4 Monthly prediction of water and salinity level of Lake Qaroun using LQR model (option (1)-case A, 7 years after starting the project)



(a) Average annual water level of Lake Qaroun
(3 years after starting the project)



(b) Average annual water salinity of Lake Qaroun

Figure 6.5 Annual prediction of water and salinity level of Lake Qaroun using LQR model (option (1)-case A)

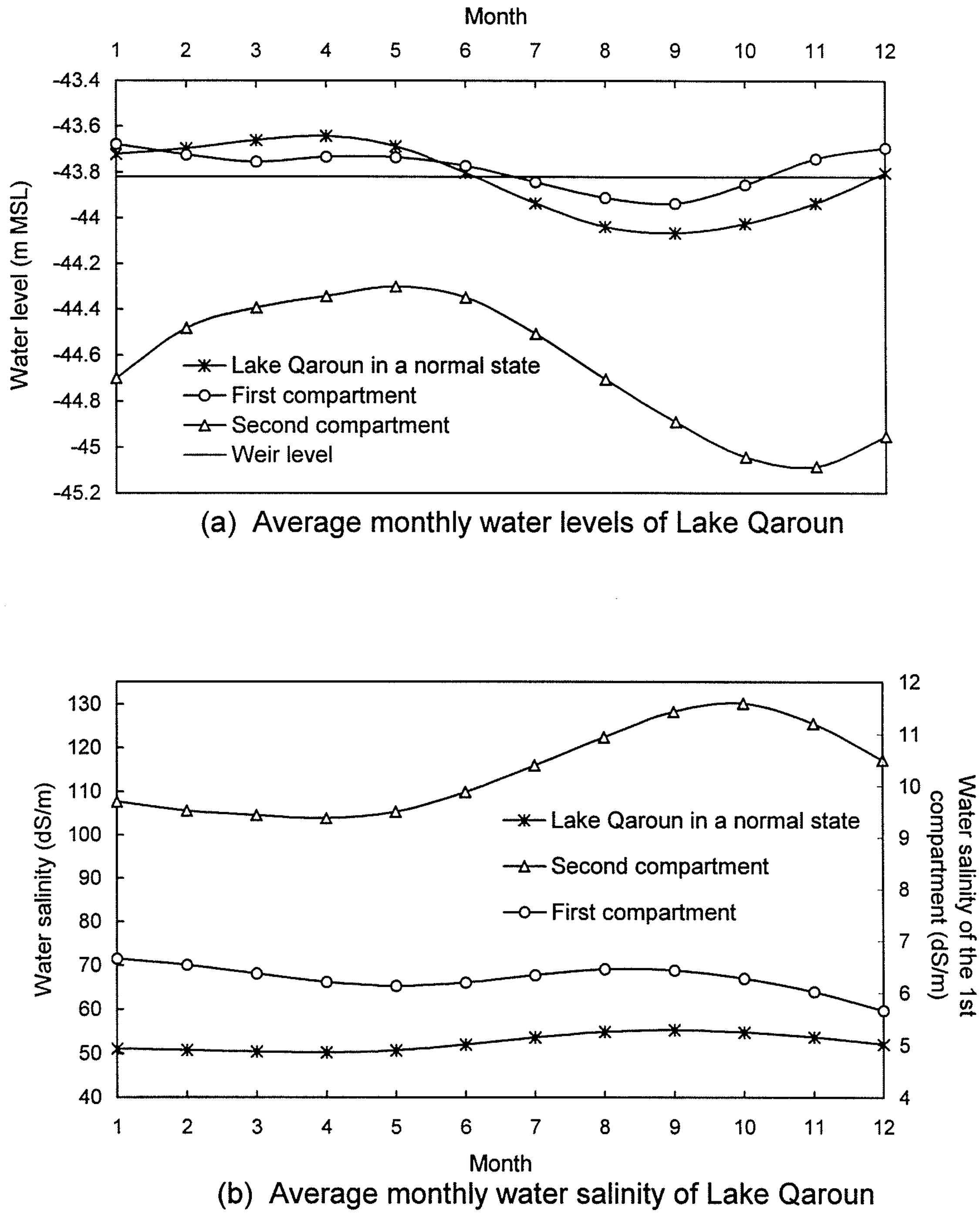
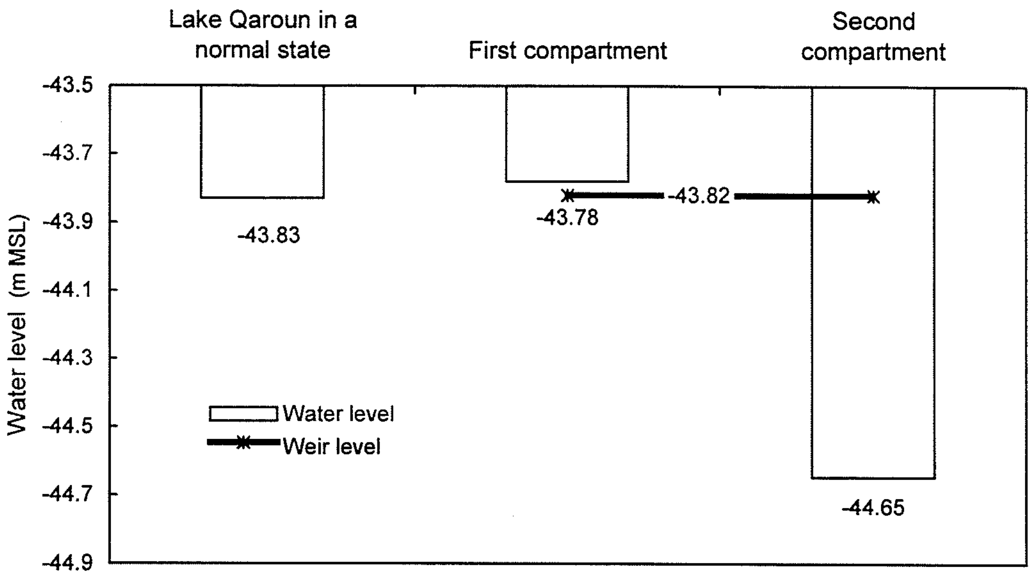
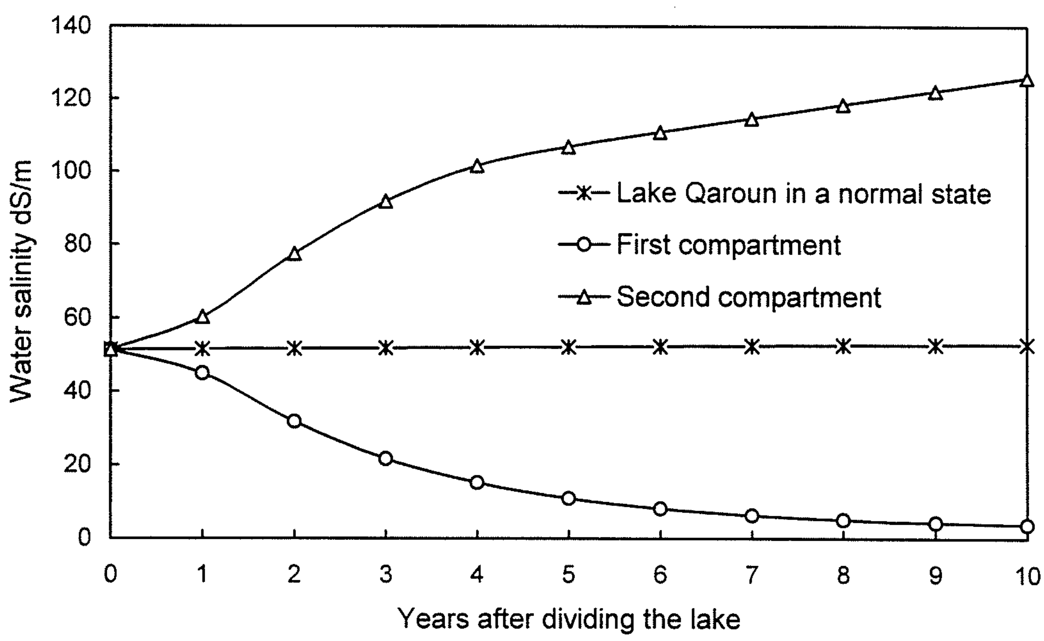


Figure 6.6 Monthly prediction of water and salinity level of Lake Qaroun using LQR model (option (2)-case A, 7 years after starting the project)

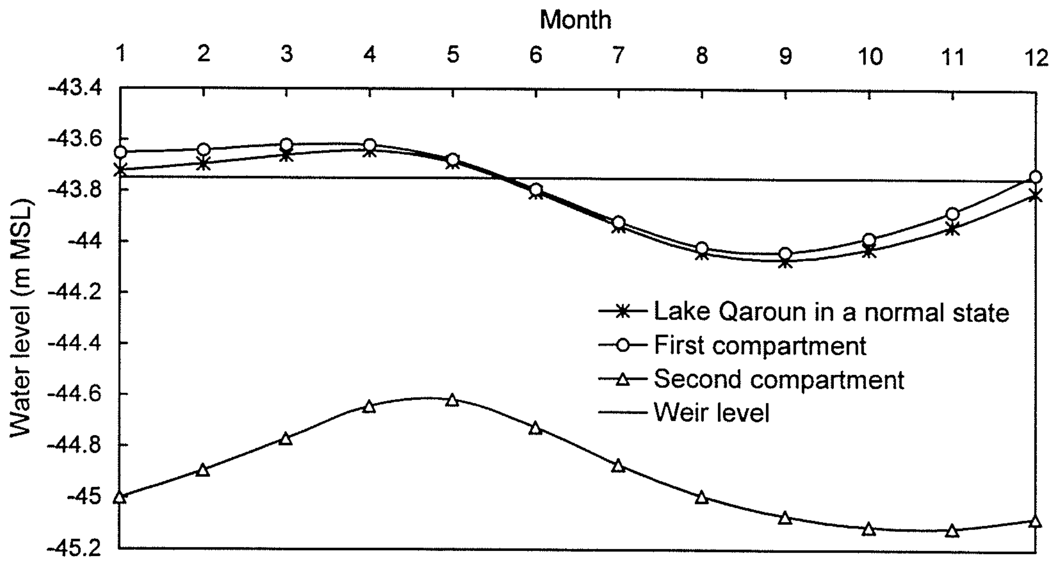


(a) Average annual water Level of Lake Qaroun
(3 years after starting the project)

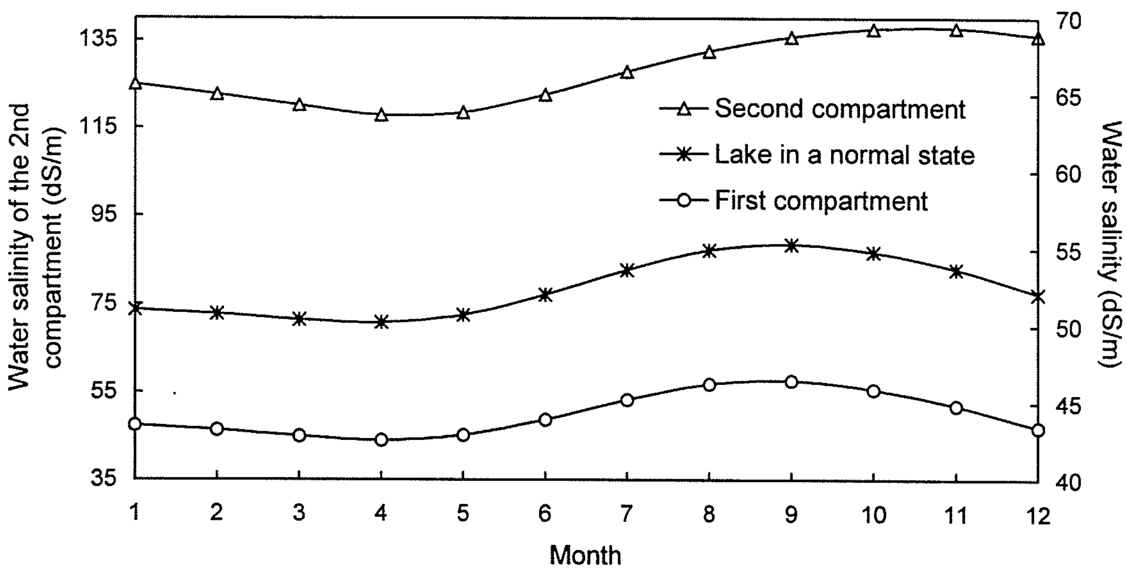


(b) Average annual water salinity of Lake Qaroun

Figure 6.7 Annual prediction of water and salinity level of Lake Qaroun using LQR model (option (2)-case A)

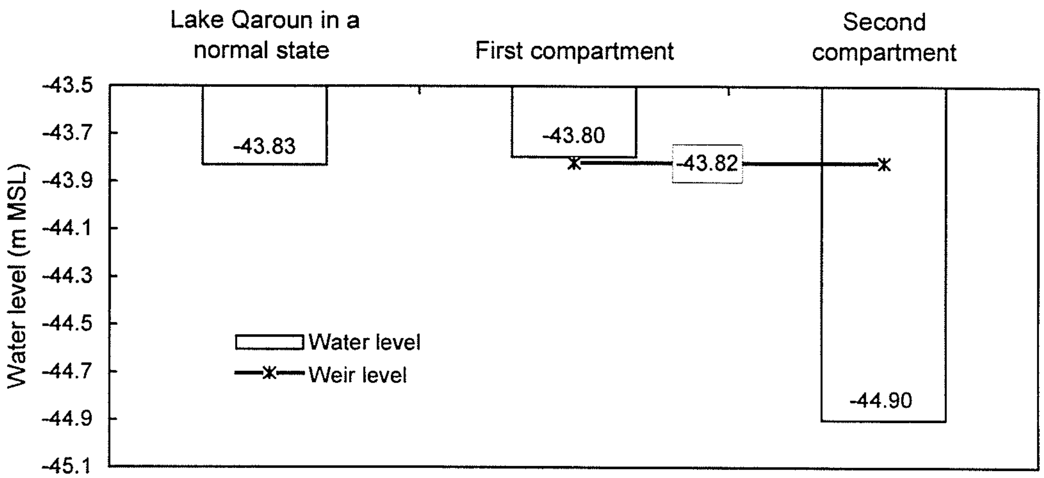


(a) Average monthly water levels of Lake Qaroun

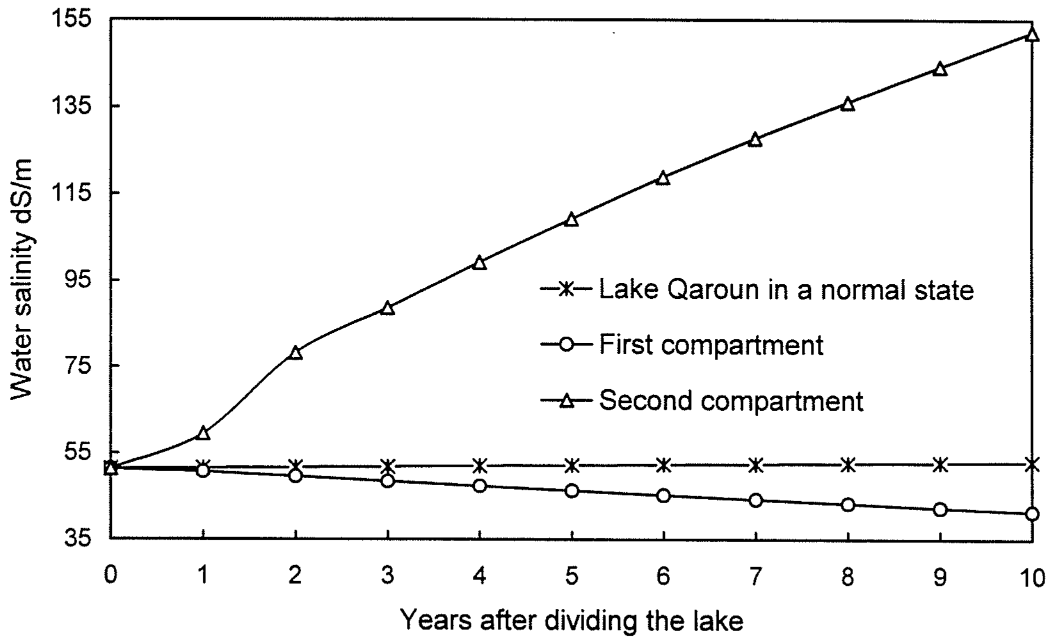


(b) Average monthly water salinity of Lake Qaroun

Figure 6.8 Monthly prediction of water and salinity level of Lake Qaroun using LQR model (option (3)-case A, 7 years after starting the project)

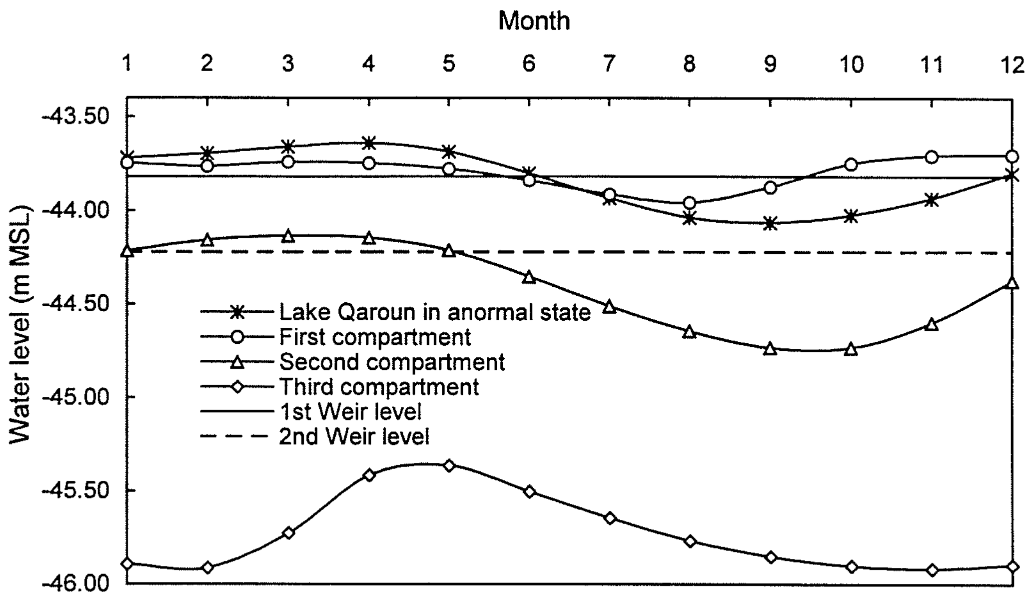


(a) Average annual water level of Lake Qaroun
(3 years after starting the project)

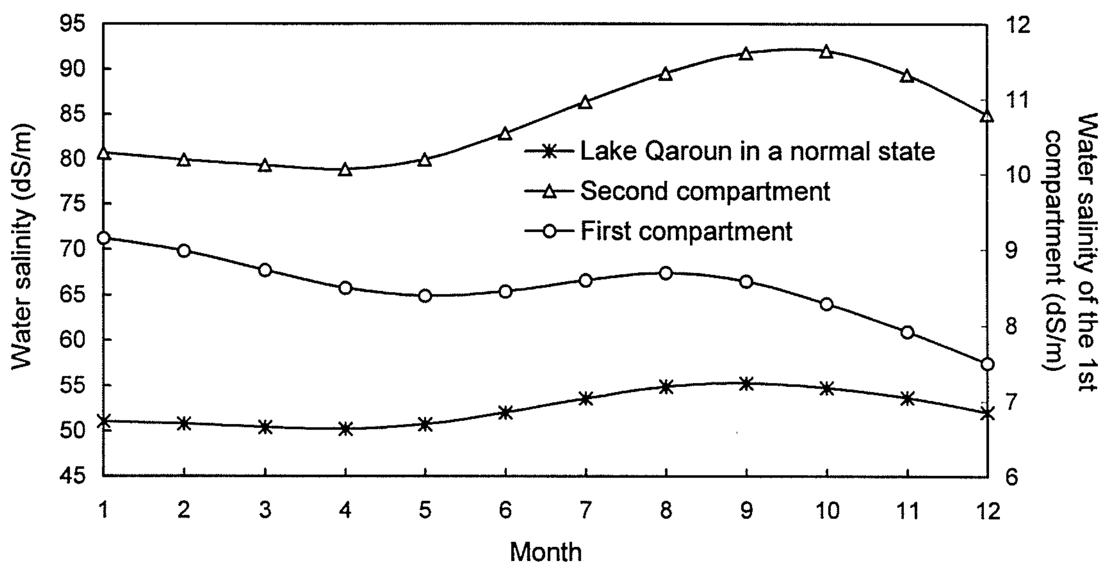


(b) Average annual water salinity of Lake Qaroun

Figure 6.9 Annual prediction of water and salinity level of Lake Qaroun using LQR model (option (3)-case A)

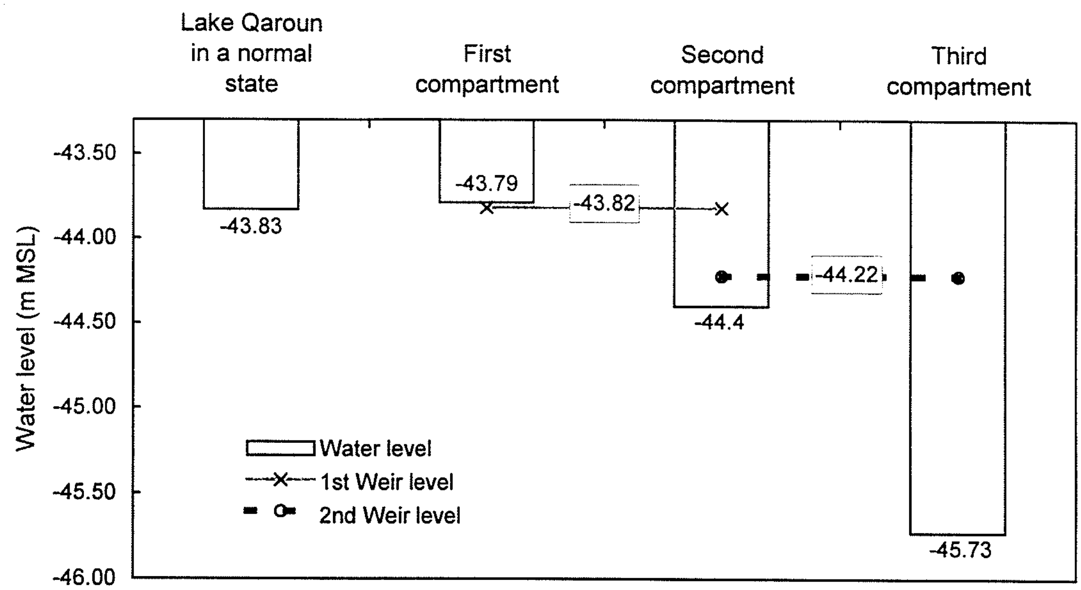


(a) Average monthly water levels of Lake Qaroun

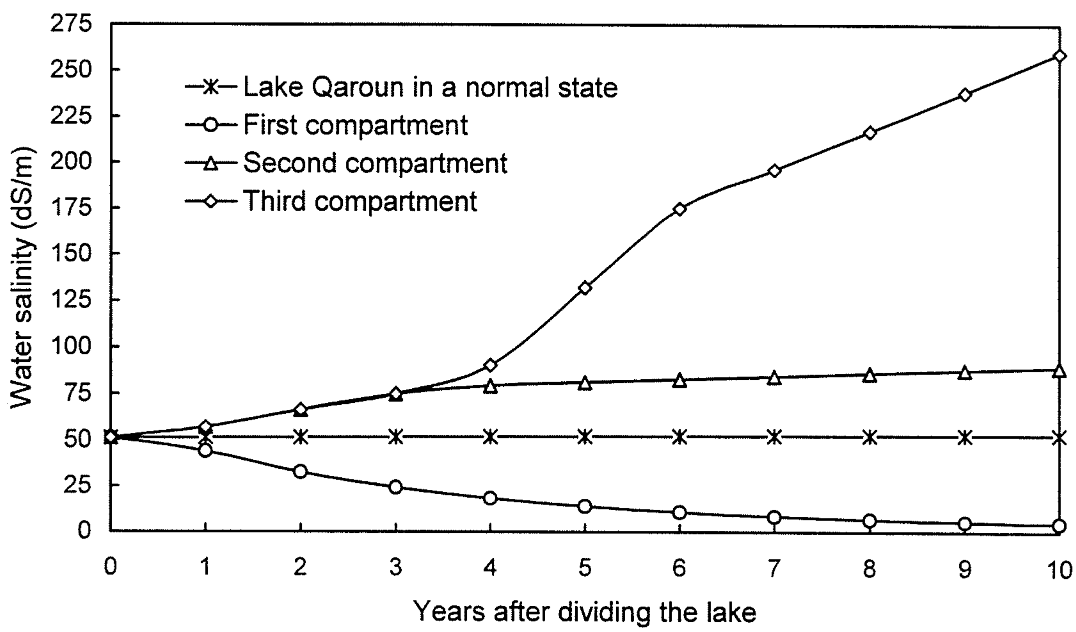


(b) Average monthly water salinity of Lake Qaroun

Figure 6.10 Monthly prediction of water and salinity level of Lake Qaroun using LQR model (option (4)-case A, 7 years after starting the project)



(a) Average annual water level of Lake Qaroun
(3 years after starting the project)



(b) Average annual water salinity of Lake Qaroun

Figure 6.11 Annual prediction of water and salinity level of Lake Qaroun using LQR model (option (4)-case A)

Case B & C :

After choosing option (1) as the most feasible, the model simulations were repeated, changing the target salinity from 5 dS/m (case A) to 8 dS/m (case B), and 14 dS/m (case B). Changing the target level is necessary in order to reduce the salt accumulation rate in the saline compartment; therefore, pumping the water (and salt) from the compartment will be more effective. Table 6.3 summarizes these simulations of option (1) in the three cases (A, B and C). The water levels of case A remained the same for the other two cases (B and C). Figure 6.12 shows the annual average water salinity for the three cases (A, B and C).

Table 6.3 The LQR model simulation of option (1) for cases A, B and C

Cases of Option (1)	Inflow** %	Water level*** m MSL	Fluctuation m MSL	Water salinity dS/m after 5 year	Water salinity dS/m after10 year
Case A					
$Comp1_1$*	0_{B+M}	-43.79_4	0.25	14.0	4.6
$Comp2_1$	$+22_W$	-44.38_4	0.57	83.3	89.5
Case B					
$Comp1_1$	0_{B+M}	-43.79_4	0.25	19.0	7.6
$Comp2_1$	$+27_W$	-44.38_4	0.57	78.2	85.2
Case C					
$Comp1_1$	0_{B+M}	-43.79_4	0.25	26.3	13.3
$Comp2_1$	$+30_W$	-44.38_4	0.57	74.7	83.1

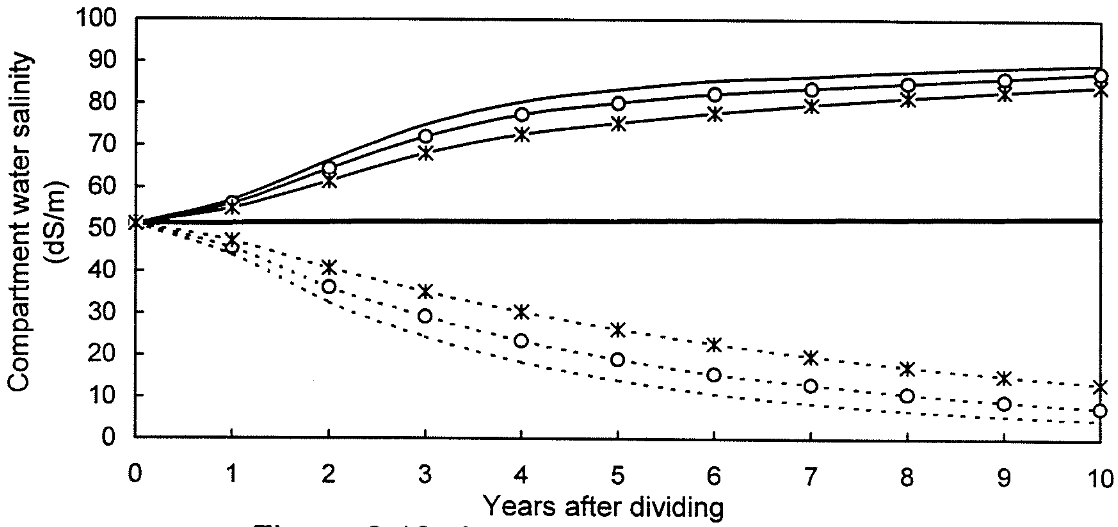


Figure 6.12 Average annual water salinity option (1) cases A, B & C

Comparing the above three cases (Table 6.3 and Figure 6.12), case (C) has the lowest salt accumulation, which can be effectively reduced by using the regional evaporation ponds north of the lake. Therefore, regional evaporation ponds can be used to keep the salinity levels of the saline compartment at reasonable levels. Figure 6.13 shows the effect of pumping saline water (11 MCM/year) from comp2_1 (case C). After 10 years, the annual average water salinity will be reduced by 13 %. The annual salt load into the regional pond is assumed to be 620,000 tonnes. An area of 6 km^2 is required to evacuate the salt.

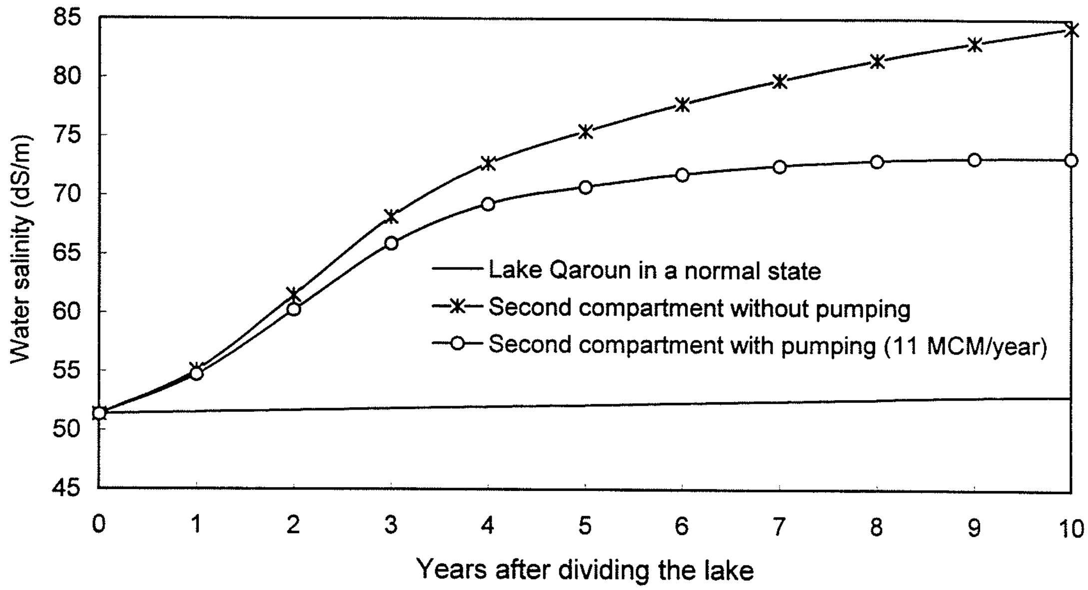


Figure 6.13 Average annual water salinity of the second compartment (Option 1) using regional evaporation ponds

6.6 Summary and Conclusions

The LQR model is extended to simulate flows, water levels and salt loads for Lake Qaroun management for salinity control. The management options involve dividing Lake Qaroun into a series of compartments. The main idea of lake division is to set aside a portion of the Lake which will serve as a drainage pool, allowing salinity levels to drop in the other area of the lake. The model shows its capability to evaluate various solutions, allowing saline drainage water to be disposed of in a safe, environmentally acceptable outlet of sufficient capacity.

Using the LQR model, simulations have evaluated the various cases of dividing Lake Qaroun. It was concluded that the most suitable solution is to divide Lake Qaroun into two compartments, and consider a target time of ten years. The first compartment is located east and assumed to occupy 35% of the lake area. The second is located west and assumed to cover 65% of the lake area. The first compartment has relatively fresh water with a salinity level (13.3 dS/m) reduced by 74% of the original, and a recommended water level of -43.79 m MSL with narrow fluctuations of ± 0.25 m. The second compartment has saline water. The salinity level (83.1 dS/m) is increased by 65% of the original level, though it has the lowest salt accumulation, which is effectively reduced by using the regional evaporation ponds north of the lake. It is estimated that annual salt load into the evaporation ponds is 620,000 tonnes. This will reduce the salinity level from 83.1 dS/m to 72.2 dS/m. An area of 6 km^2 is required to evacuate the salt.

CONNECTING TEXT

In Chapter 5, the lake routing model (LQR) was linked to the evaporation model (EVAPQ) which estimates the input data for evaporation rates from Lake Qaroun. The LQR model was formulated to provide estimates of monthly and annual water and salinity levels for Lake Qaroun. In Chapter 6, the LQR model was extended to provide the appropriate management strategy for reducing salinity in Lake Qaroun.

To achieve the latter solution, the disposal drainage water into lake Qaroun must be stablized at 417 MCM. Based on the latter condition, basin irrigation water management strategies are evaluted in Chapter 8. In the next Chapter, in order to assess alternative water managent scenarios, a basin-scale model is developed and tested, simulating water balances in the Fayoum basin and Lake Qaroun under present day conditions.

CHAPTER SEVEN

A BASIN-SCALE WATER BALANCE MODEL

Abstract

In order to assess alternative water management scenarios, a basin-scale model was developed and tested, simulating water balances in the Fayoum basin and Lake Qaroun under present day conditions. The model can simulate and evaluate the effect of some water managment options such as the increase in drainage water reuse and the improvement of water distribution with time.

The model results were evaluated with respect to measured Lake Qaroun water levels in 1980-1996. By comparing values computed for five statistical parameters, the predictions of the water levels produced by the model were deemed to be in accord with measured values. The monthly modelling efficiency (EF) ranged from 0.65 to 0.91. On an annual basis, EF was estimated to 0.89.

Based on the performance of the system during 1992-1996, it was concluded that, due to a mismatch between supply and demand either in time or in place, 12% of the intake water was not used effectively (for evapotranspiration and leaching) and was lost as surface runoff to the lower reaches of the system. The performance of the system could be improved by Increasing the volume of water pumped by reuse stations and/or Improving the water intake with time.

7.1 Introduction

The objectives of water management can be translated into a desired performance of the water system. To compare the actual performance with the desired one, various performance indicators are identified for each of the general objectives of water management in the Fayoum basin.

- Avoid stress conditions that reduce crop yield:

Stress conditions are avoided if, during the entire cultivated period, sufficient water of a suitable quality can be allocated to allow for potential evapotranspiration by crops. In addition to water required for crop evapotranspiration, water is also required for leaching, and preventing the accumulation of salts in the soil. The water demand is thus composed of crop water and leaching requirements. If the salinity of the irrigation water is below a certain level, the water demand is independent of water quality. If it is assumed that the quality of the irrigation water can be kept below this level, a simple parameter to indicate the occurrence of stress conditions is the demand/supply ratio.

- Increase cropping patterns:

If stress conditions can be avoided, the total cropped area is a good indicator of the agricultural production in the area. To account for the variability of the cropped area during different seasons, the cropped area should be expressed as the sum of the areas under cultivation in the respective seasons.

- Suitable cropping pattern:

Although the control of cropping patterns is a permanent concern of water management, it is not influenced by water management itself. Therefore, there is no need to relate a performance indicator to this aspect.

- Avoid spill:

As mentioned before, to avoid stress conditions, the salinity of the irrigation water should be below a certain acceptable level. The possibility of drainage water reuse for irrigation is thus constrained by the salinity of that drainage water. The value of 2.34 dS/m is used (DRI, 1993a) as a maximum salinity for reuse in the Fayoum basin. Water leaving the Fayoum depression with salinity of less than 2.34 dS/m can be considered as spill. The capacity of the drainage water to absorb additional salts is an indicator for spill and can be expressed in an equivalent quantity of Nile water. The quantity is defined as the volume of Nile water that would be required to absorb the same quantity of salts, assuming that the salinity is increased to 2.34 dS/m.

- Horizontal expansion:

The implementation of irrigation practices in newly reclaimed areas will be treated as a feature of a management option rather than a performance indicator. The total area of irrigation lands will be indicated, as mentioned before.

- Avoid degradation of soils:

One of the main limiting factors in irrigation is the risk of accumulation of salts in agricultural lands. Degradation of soils can be avoided by adequate flushing of salts that are added with the irrigation water. The annual salt balance is an indicator for salt accumulation. The management options should meet the condition that no salt is accumulating.

- Level of Lake Qaroun has to be stable:

To ensure stability in lake Qaroun, the average quantity of drainage water should be equal to the evaporation capacity of the lake. If the desired lake level is -43.8 m MSL, the evaporation capacity amounts to about 425 MCM/year (Chapter 5). All the water management options should be based on drainage to Lake Qaroun equal this quantity.

- Avoid environmental problems in the drains:

Environmental problems in the drains are mainly caused by the discharge of untreated sewage water into these drains. A simple measure to reduce these problems is to send more water to the drains for the purpose of flushing. In the comparison of different management options, the management of the system to ensure efficient operation for irrigation, implying minimal drain discharge, will play a dominant role. Therefore, this aspect will not be given attention in this thesis.

- Avoid environmental problems in Lake Qaroun:

Environmental problems in Lake Qaroun are caused by the discharge of salts and other constituents, such as pesticides and BOD, with the drainage water. Apart from measures aimed at the reduction of these emissions, the fluctuation of drainage water quantities over the year may be significant. As the average depth of lake Qaroun is only 4.6 metres, a reduction of the lake level by

1 meter means an increase in concentrations in the lake of 20% (Ali, 1995). A suitable indicator for this is the variation in the lake water levels (Chapter 5).

- Equity of water distribution:

It is possible that the total supply matches the total demand, while in some areas, the water is spilling, and in other areas, severe shortage occurs. To indicate the mismatch between demand and supply, the total deviation between demand and supply is computed, divided by the total demand. The latter performance can be used to indicate the equity of the water distribution over time.

7.2 Study Objectives

The objective of this study is to develop promising water management strategies that will improve the system performance in the Fayoum basin, taking into account the constraints imposed by the physical and managerial nature of the region. The proposed water management scenarios are evaluated with the aid of a basin-scale water management model, which uses system performance indicators throughout the study. Specific objectives are to:

i. develop a mathematical simulation model (water management model) in order to quantify the effects of the various water management strategies;

ii. validate the mathematical model for various water management options by comparing model results with field observations from the study area;

iii. use the collected information from the study area and the model simulations to evaluate and determine the impact of management measures.

7.3 Macro Level Modeling

In this study, a spreadsheet computer model (FWB) is presented to study the water balance of the closed basin. To study the management alternatives for the whole basin, at the basin level including the outlet level, the FWB model is linked to the Lake Qaroun Routing model (LQR) and the evaporation model (EVAPQ). The package of three models (EVAPQ, LQR and FWB) is called WM (Water Management) model. Therefore, the monthly and annual water levels of Lake Qaroun are estimated using the same input data required to run the FWB model. The validity of the WM model is demonstrated by using available data collected from the basin during the study period 1980-1996.

7.3.1 Fayoum Water Balance Model

The Fayoum Water Balance (FWB) model simulates and evaluates the water management of the Fayoum basin system. The model covers the total Fayoum scheme. More specifically, the model:

i. computes the net irrigation requirement in time for a specified cropping pattern;

ii. computes the outflow of the Fayoum basin;

iii. simulates the temporal water distribution at the macro scale and the effect of reuse stations;

iv. presents simulated performance of the system in diagnostic parameters.

The input data required to run the FWB model are:

- monthly water duties;
- monthly inflow into the basin (irrigation water);
- monthly drainage water reuse rates;
- monthly leaching ratios;
- crop pattern.

The output of the FWB model simulations are:

- the monthly and annual drainage water disposal rates;
- performance indicators.

7.4 Theoretical Development

7.4.1 Crop Water Requirement

The crop water requirement is the basis for irrigation water management. The model computes the net water demand of the Fayoum basin as follows:

i. The user can define a cropping pattern for the Fayoum basin. As stated in Chapter 3, the actual cropping pattern is not well known. In the absence of reliable data on the actual cropping pattern, the planned cropping pattern in Fayourn (source: Ministry of Agriculture) was used.

ii. Standard unit crop water requirements tables (Chapter 3) from the Ministry of Public Works and Water Resources (MPWWR) for Middle Egypt are used to convert the user defined cropping pattern into water demands in time.

The currently used water requirements are expressed in m^3/fed/day (1 mm/day equals 4.2 m^3/fed/day) and includes the following volumes:

- ETA_{crop} the actual crop evapotranspiration;
- LR the leaching requirement, which varies between about 15% of the actual crop evapotranspiration for irrigation water with a low salinity, and up to 35% for irrigation water with a salinity of around 2 dS/m;
- FL field losses, partly evaporation losses of canals and partly tail escape losses; surface runoff and percolation losses exceeding the leaching requirement.

7.4.2 Net Supply (Actual Net Irrigation)

The net supply calculation is based on:

i. Irrigation distribution efficiency. To compare the supply with the crop water requirement explained in the previous section, an efficiency of the water distribution system supplying water from the Nile river to individual fields is assumed. Over the study period 1980-1996, the efficiency is estimated to be 83.3%. The gross supply is multiplied by the value of this efficiency to calculate the net supply.

ii. Drinking, industrial and reuse water. The total supply is multiplied by a reduction factor, which is assumed to be 1.4% (Euroconsult, 1992).

7.4.3 Adjustment of the Net Irrigation Requirement

A correction factor is introduced here, based on experience during the year. In this way, adjusted requirements are created which are much more credible than requirements without correction. Taking 1991 as an example, Figure 7.1 shows the monthly values of the net requirements, together with the actual net supply to the Fayoum and the resulting total drainage discharge. The requirement curve does not reflect the actual situation. In April, the increase in requirements is steep. This results in a summer requirement approximately 125% higher than the actual flows diverted. The minimum in October is only 50% of the actual flow. The high peak in December is especially strange compared to the actual flow and the resulting drainage: actual flow decrease to a greater extent than the calculated requirements, yet the drainage discharge is still high.

A better estimate of the requirements is made after judging the actual irrigation and drainage flows. When both increase, it seems more appropriate to reduce the requirements. When drainage discharge reaches low rates, water shortage can be expected, and the requirements should be higher than the actual irrigation supply. In this way, correction factors have been estimated during the year. Table 7.1 shows the monthly correction factors for all the Fayoum basin during the study period (1980-1996). The adjusted requirements are the result of the multiplication of the original requirements by the correction factors. Figure 7.1 shows the monthly values of the adjusted requirements, the actual net supply to the Fayoum, and the resulting total drainage discharge. The figure shows reduced requirements in the spring due to the decrease in drainage discharge during this period. When the drainage tends to lessen, the adjusted requirements are increased. During autumn, the adjusted requirement is below the actual in order to suppress excess drainage. The peak in December is eliminated. Although this is an approximate method of calculating net irrigation requirements, it is a useful approach considering data availability.

7.4.4 Leaching Fraction

The leaching fraction is calculated from the estimates of both the net supply and total drainage water of the Fayoum basin (1980-1985). The average monthly values over the study period 1980-1996 are shown in Table 7.2.

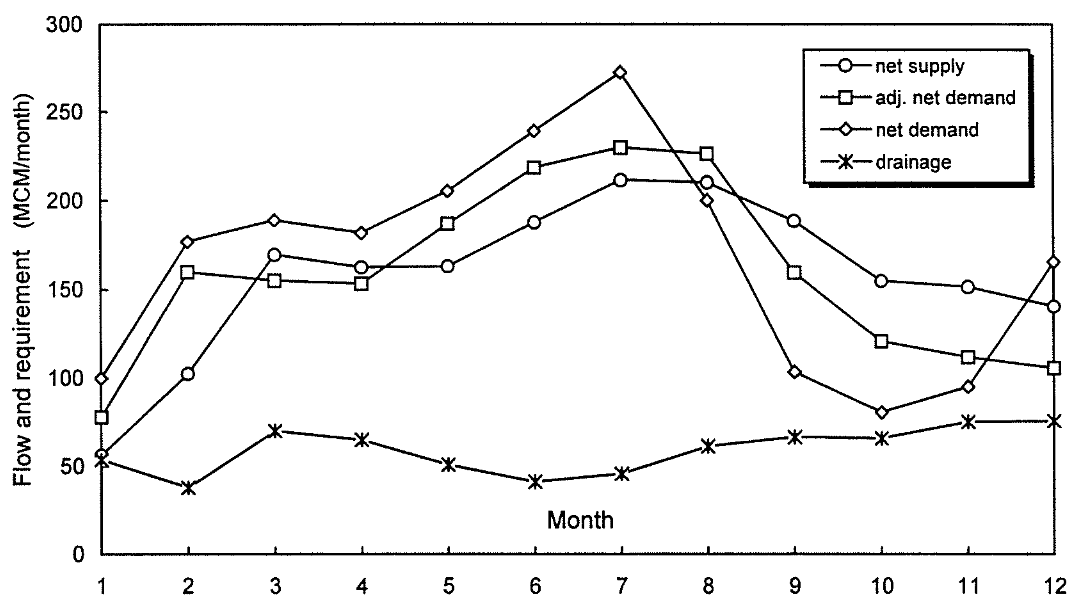


Figure 7.1 Monthly adjusment of the gross water requirements for 1991

Table 7.1 Adjustment for the crop water requirement for the Fayoum basin

Month	Correction factor (%)	Month	Correction factor (%)
January	78	July	85
February	90	August	113
March	83	September	153
April	85	October	146
May	91	November	120
June	91	December	65

Table 7.2 Average monthly leaching fractions for the Fayoum basin

Month	Leaching fraction (%)	Month	Leaching fraction (%)
January	73	July	25
February	45	August	27
March	36	September	31
April	37	October	36
May	36	November	45
June	23	December	53

7.4.5 Drainage Flows

The drainage flows from the Fayoum basin are estimated on the basis of the net supply and the net demand of the Fayoum basin. As long as the net supply does not exceed the net irrigation requirement, a fixed leaching percentage of the net supply is assumed to be drained. This percentage is taken as a constant for the whole Fayoum area and for all crops. The value can be changed by the user. If the net supply exceeds the net demand, the excess water plus the leaching requirement is considered to be drained. This can be explained follows:

case 1: The net supply < the net irrigation requirements

$$TD = S_n \ (LF); \tag{7.1}$$

case 2: the net supply > the net irrigation requirements

$$TD = IR_n \ (LF) + \Delta \ SR \tag{7.2}$$

where

TD is the drainage water from the whole Fayoum basin;

IR_n is the net irrigation requirement;

LF is the leaching ratio;

S_n is the net supply;

Δ SR the excess water supply.

7.4.6 Performance Indicators

For an overall evaluation and comparison of alternative water management strategies, a number of diagnostic performance parameters are required, to express the overall performance. The performance parameters used in the evaluation of a defined strategy, and computed by the model are:

- the overall irrigation efficiency;
- the effective supply ratio;
- the water levels of Lake Qaroun;
- the effectively irrigated area.

Eventually, the total effective irrigated cropped area is an important parameter. This effectively cultivated area is the potential cultivated area, based on: the total area, crop intensities, crop water demands, and match between demand and supply in time and place.

The effective cultivated area:

The effectively cultivated area (CA_{eff}) is calculated as follows:

$$CA_{ef} = \frac{A_T \, C_I \, S_{eff}}{D_T} \tag{7.3}$$

where

A_T is the total area cultivated;

C_I is the crop intensity;

D_T is the total demand;

S_{eff} is the effective supply, computed by adding the supplies to the whole basin for each month, whereby the maximum effective supply cannot exceed the demand. Hence, over-supply in the basin during a certain decade is not considered to be effective supply - contributing to S_{eff} as far as it exceeds the demand.

7.5 Model Evaluation

The model was evaluated by plotting the measured and simulated values against time. The agreement between the model and the observations was also checked statistically by using a set of statistical parameters used by Hack-ten Broke and Hegmans (1996). As stated in Chapter 5, this assessement comprises five criteria: maximum error (ME), root mean square error (RMSE), coefficient of determination (CD), modeling efficiency (EF) and the coefficient of residual mass (CRM).

Measured Lake Qaroun levels and levels simulated using the whole WM model were compared using data for the period 1980-1996. The comparison is presented by plotting the average monthly levels. Figures 7.2, 7.3 and 7.4 show the average monthly levels for years 1981, 1992 and 1996, respectively. Over the study period (1980-1996), the monthly percent error of the model estimates range between -0.55 % to 0.66 %. Figure 7.5 shows the average annual water levels of lake Qaroun calculated by both methods. The maximum annual percent error of the model estimates is 0.44 %, and the minimum is -0.33 %.

Table 7.3 shows the results of five other statistics used in the comparison. It contains the calculated values of the Maximum error (ME), root mean square error (RMSE), coefficient of determination (CD), modeling efficiency (EF) and the coefficient of residual mass (CRM). The values of ME, RMSE, CD, and EF for the WM model for the period 1980 -1996 range from 0.120 m to 0.287 m, 0.31 % to 0.14 %, 0.95 to 1.3, and 0.65 to 0.91, respectively. The (ME) values represent the worse case performance of the model, which is 2.9 cm. This value represents an percent error of 0.66 % for the water level. The RMSE values show that the simulations overestimate or underestimate the measurements by 0.31% to 0.14% of the mean value of the measurements. The ratio between the scatter of simulated values and the scatter of measurements (CD) over the twelve months indicates that the model performed satisfactority; the coefficient of determination ranged from 0.95 to 1.3 with an annaul average 1.16. The EF values, which are close to 1 show that the model is in good agreement with the measured values. This conclusion can be confirmed by considering the values of CRM where its percent error ranges from -0.09 % to 0.09 %. The positive values show that there is a tendency for overestimation in the last five months.

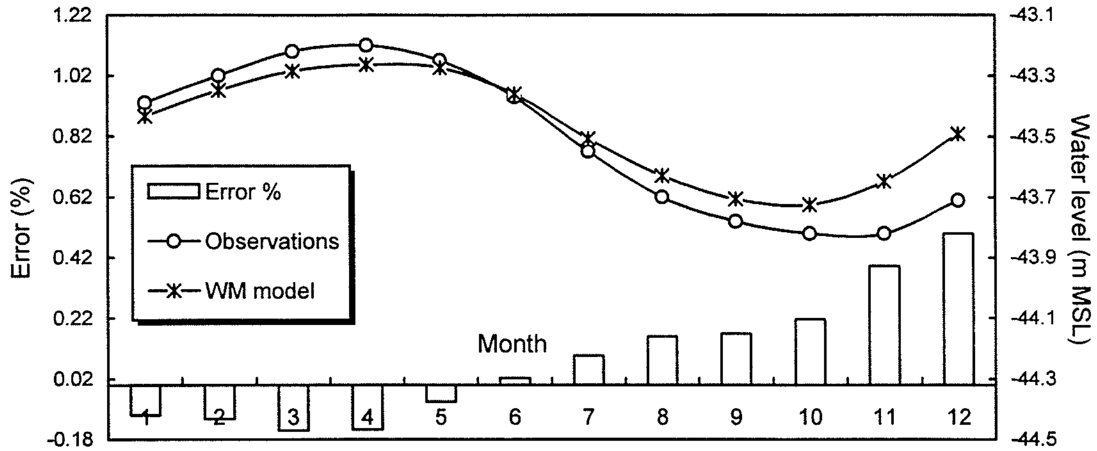


Figure 7.2 Monthly measured and predicted water level of Lake Qaroun for 1981

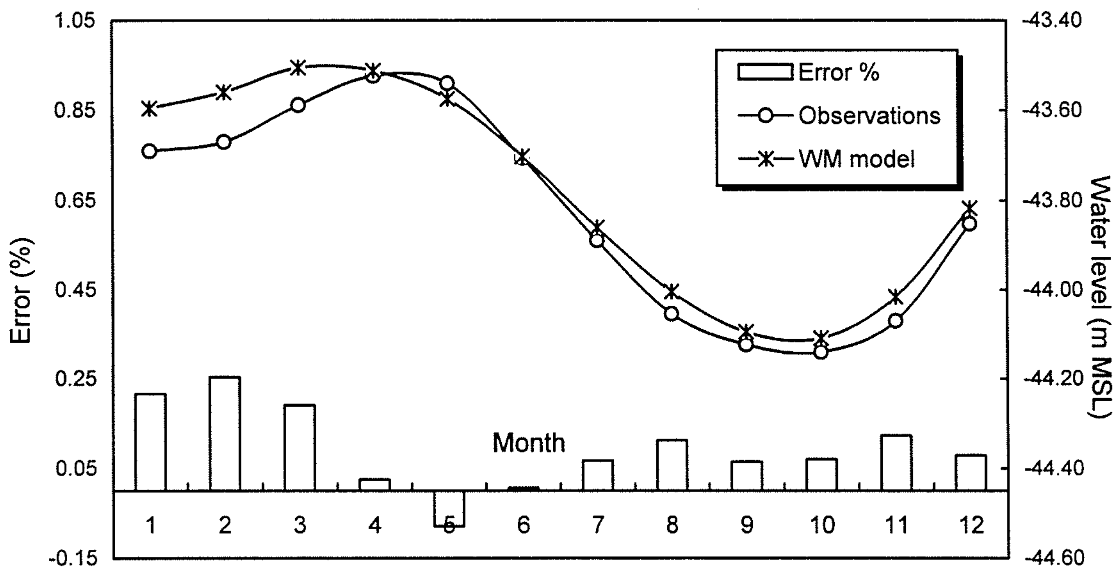


Figure 7.3 Monthly measured and predicted water level of Lake Qaroun for1996

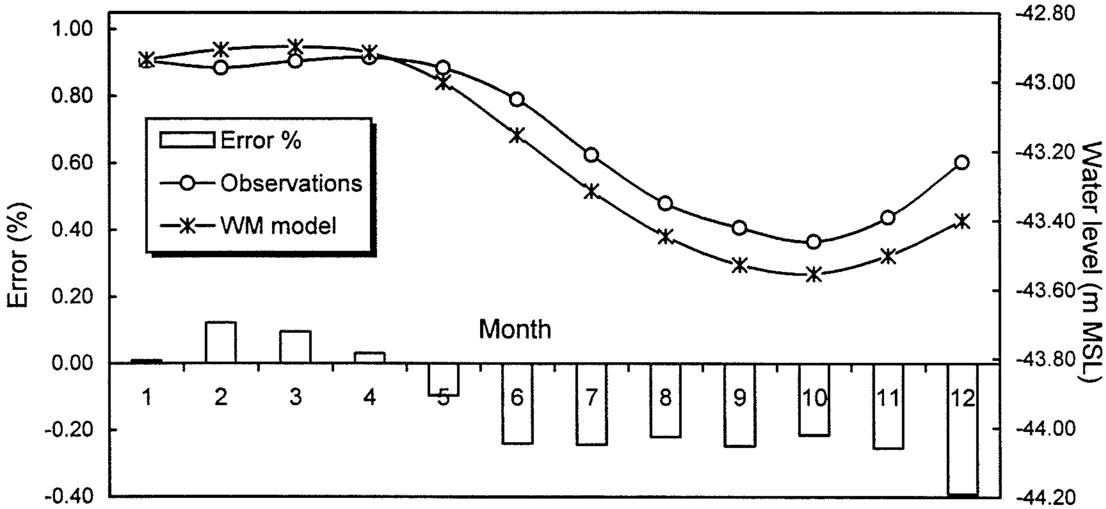


Figure 7.4 Monthly measured and predicted water level of Lake Qaroun for1992

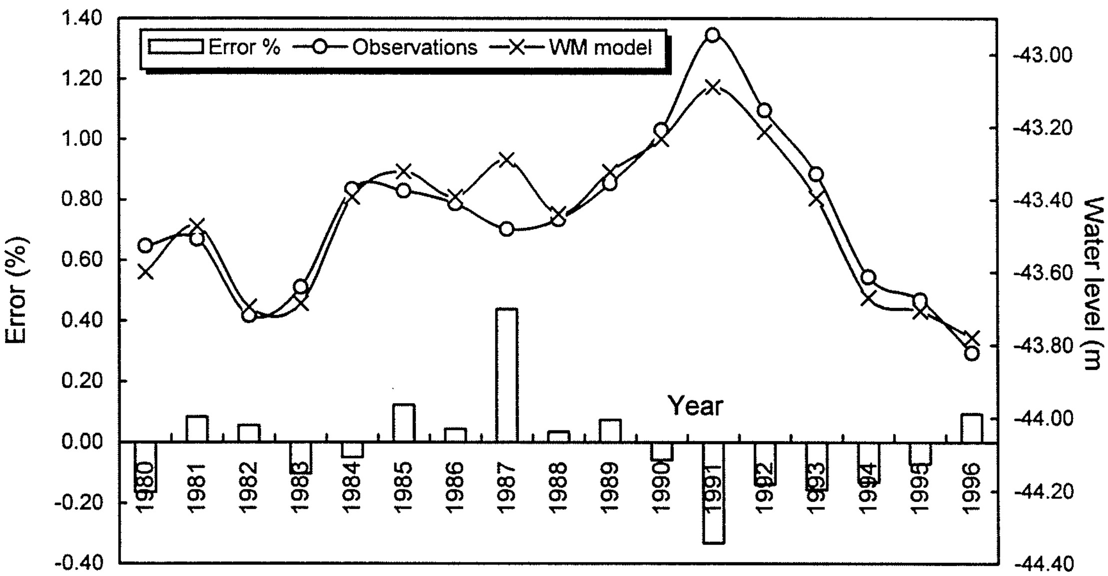


Figure 7.5 Annual measured and predicted water level of Lake Qaroun 1980-1996

Table 7.3 Maximum error (ME), root mean square error (RMSE), coefficient of determination (CD), modeling efficiency (EF) and the coefficient of residual mass (CRM) for measured vs. predicted water levels for WM model (1980-1996).

	ME (m)	RMSE (%)	CD	EF	CRM
January	0.174	0.155	1.043	0.902	-0.0007
February	0.120	0.142	1.091	0.914	-0.0003
March	0.166	0.186	1.300	0.867	-0.0007
April	0.200	0.212	1.192	0.815	-0.0009
May	0.227	0.205	1.117	0.815	-0.0009
June	0.234	0.209	1.276	0.828	-0.0006
July	0.227	0.231	1.171	0.778	-0.0003
August	0.217	0.227	1.136	0.79	0.0001
September	0.262	0.235	1.164	0.798	0.0004
October	0.287	0.253	1.072	0.781	0.0007
November	0.257	0.286	1.004	0.721	0.0009
December	0.257	0.309	0.95	0.652	0.0006
Annual	**0.191**	**0.163**	**1.164**	**0.889**	**-0.0001**

Inspection of the ME, RMSE, CD, EF and CRM values listed in Table 7.3 leads to the following comments:

- the statistics appear to be better for the early months; for example, ME values during the first four months do not exceed 0.2; the opposite can be noted after April ;
- the model overpredicts for the final five months; this observation can be seen by revewing the CRM values;
- the EF values indicate good performance.

Changes in crop pattern:

Simulations were made to test the effect of changes in crop pattern and crop evapotranspiration on the drainage outflow. The simulation during 1993 is used as a reference. The results are presented in Table 7.4. Four alternative crop patterns are evaluated. Their crop water use is compared with the corresponding value for the crop pattern of 1993. By using the same irrigation intake (2200 MCM) for these simulations, the resultant drainage flows can be compared. The major change in each crop pattern is reducing berseem by 10%, reducing cotton by10%, increasing berseem by 10%, and reducing rice by 4% in Patterns C1, C2, C3, and C4, respectively (Table 7.4). The effect on drainage outflow is minimal, resulting in deviation between 1.6% and 3.1%. Apparently, excess irrigation in winter and under - irrigation in summer are the dominant factors in the generation of drainage.

Table 7.4 Alternative crop patterns for Fayoum basin cropped area per crop in percent of cultivated area (341,055 feddans)

Crop	AC%	C1%	C2%	C3%	C4%
Wheat & Barley	40.6	48.0	40.6	40.6	40.6
Beans	4.4	5.2	4.4	4.4	4.4
Berseem	27.5	17.5	27.5	37.4	27.5
Vegetable winter	7.4	8.6	7.4	7.4	7.4
Other crops winter	3.1	3.7	3.1	3.2	3.1
Total winter	83.0	83.0	83.0	93.0	83.0
Cotton	10.3	10.3	0.0	10.4	10.2
Rice & Rush	4.0	4.0	4.0	4.0	0.0
Maize summer	16.7	16.7	16.7	16.7	16.7
Sorghum	18.4	18.4	18.4	18.4	18.4
Vegetable summer	10.0	10.0	10.0	10.0	10.0
Other crops summer	14.2	14.2	14.2	14.2	10.2
Sorghum	3.1	3.1	3.1	3.1	3.1
Vegetable nili	16.7	16.7	16.7	16.7	16.7
Trees	6.6	6.6	6.6	6.6	6.6
Total (summer + nili + permanent)	100.0	100.0	89.9	100.0	96.0
CWU 10^6 m3	1478.9	1438.2	1359.7	1570.1	1377.4
DR 10^6 m3	572.5	590.4	601.5	563.4	602.5
EF %	67.2	65.3	61.8	71.4	62.6

where: Ac = the crop pattern for 1993, C1, C2, C3 and C4 are the changed crop pattern, CWU is the consumptive water use, DR is the drainage outflow, EF is the irrigation system efficiency (CWU/Irrigation inflow)*100.

7.6 Model Simulations

The Fayoum irrigation system demonstrates many constraints that hamper water management. Nevertheless, within these constraints, it is possible to improve the water management without major infrastructural modifications. In this section, the impact of management measures are evaluated. The operation of the system during 1980-1996 is used as the study period. In other words, it is demonstrated how operations could have been improved under different management strategies during those years. Therefore, the following simulations have been made:

i. observed situation;

ii. increased use of reuse pumping stations;

iii. improved water distribution in time at Lahoun.

It should be noted that the total annual flow to Fayoum for all simulation has been kept at the observed total flow in each year.

7.7 Results and Discussion

7.7.1 Evaluation of the Observed Situation

The monitored intake supplies at Lahoun and Hassan Wasef were entered in the WM model. The effect of the reuse of drainage water was taken into consideration starting from 1991. Based on the planned cropping pattern and field experience, the water requirement for the Fayoum basin was defined. As explained in Chapter 3, no adequate data on the actual cropping pattern in

Fayoum could be obtained. Over the period 1980-1996, the cropping pattern resulted in an average annual water demand for Fayoum of 2650 million m^3. The average supply is only 87 % of the demand, whereby, it should be stressed that the water deficit in summer is significantly more serious. By adjusting the leaching fraction, which influences the amount of drainage water from the basin, the model was tested for the study period 1980-1996.

The system performance, as expressed by the indicators of Table 7.5, was reasonable, especially considering the limited water availability; 75.5% (1980 -1985), 77.2% (1986 -1990) and 86.5% (1991-1996) of the available water supplies for Fayoum were effectively supplied. In 1995 and 1996, the effective supply reached 89.5%, and 90.7% of the supply, respectively. Comparison of the inflow and effective supply in Table 7.5 also shows, however, that there is room for improvement. Around 10% of the available supply is lost by mismatching supply and demand, resulting in tail end losses. A perfect performance, assuming limited water availability, is reached when the effective supply equals the intake supply. The net drainage outflow cannot be considered as a loss since leaching is required to avoid salinity problems. The average yearly leaching requirement is approximately 20% of the intake (460 million m^3), assuming an intake salinity of 0.5 dS/m, and a desired drainage salinity of 2.5 dS/m.

Table 7.5 Performance indicators for years1980 -1996

Case	Inflow (Mm^3)	Reuse (Mm^3)	Net drainage[1] (Mm^3)	S_{eff}[2] (Mm^3)	CA_{eff}[3] (1000 fd)
'1980'	2287.4	-	728.4	1732.9	370.0
'1981'	2264.4	-	711.0	1720.2	369.1
'1982'	2262.2	-	718.2	1701.2	368.6
'1983'	2323.2	-	708.2	1756.7	382.3
'1984'	2294.4	-	698.1	1747.8	385.4
'1985'	2242.6	-	705.5	1669.7	354.3
Average	2279.0	-	711.6	1721.4	371.6
'1986'	2355.5	-	743.1	1783.2	386.5
'1987'	2350.7	-	731.2	1787.9	382.2
'1988'	2370.0	-	747.6	1789.9	383.2
'1989'	2293.0	-	669.9	1893.8	439.9
'1990'	2316.0	-	690.2	1760.1	420.0
Average	2337.0	-	716.4	1803.0	402.4
'1991'	2311.0	84.4	694.0	1771.4	453.3
'1992'	2104.3	84.4	558.1	1818.9	442.8
'1993'	2200.0	117.6	572.5	1928.0	461.1
'1994'	2233.7	178.6	588.4	2061.9	484.0
'1995'	2420.5	178.6	611.2	2167.0	504.4
'1996'	2428.4	178.6	619.9	2202.8	505.3
Average	2301.6	137.0	607.3	1991.7	475.2

[1] The net drainage is the total flow to lake Qaroun and Wadi Rayan drain

[2] S_{eff} is the effective supply (defined in section 7.4.6)

[3] CA_{eff} is the effectively cultivated area determined for the whole year, and therefore covers the winter, summer and nili season (defined in section 7.4.6)

7.7.2 Increased Use of Reuse Drainage Water

In 1993, the Batts pumping station, serving the tail end of Bahr Wahby, was only used from October onwards. To demonstrate the effect of increased usage of the reuse pumping station, the 1993 year was simulated. It should be noted that higher salinities are acceptable when soil leaching requirements are fulfilled. The results of the simulation with increased use of the Batts pumping station are summarized in Table 7.6.

Table 7.6 Performance indicators for 1993, with increased usage of Batts pumping station

Case	Inflow (Mm^3)	Reuse (Mm^3)	Net drainage (Mm^3)	S_{eff} (Mm^3)	CA_{eff} (1000 fd)
'Reuse'	2200.0	178.6	527.3	1988.9	483.6

In the 'Reuse' case, the additional supply available through an increased operation of the Batts pumping station, around 61 million m^3, is almost entirely allocated as the Wahby tail end showed serious water stress (Amer and De Ridder, 1989). As a result, the effectively cultivated area is increased by 23,000 feddans. The salinity of the irrigation water in Bahr Wahby, after mixing, is on the average of 1.6 dS/m, with higher values in summer, and lower values in winter (Amer, 1992). Although it is possible to irrigate with such saline water, the leaching percentage downstream of the pumping station outlet must be increased to avoid soil salinization problems. Increased leaching can be realized through an adequate subsurface drainage system and a higher irrigation frequency.

The simulated Batts pumping station operation reduces the amount of drainage water by 45 million m^3. To maintain a stable water level in Lake Qaroun, the reduced flow to Lake Qaroun must be compensated for with discharge diverted from the Wadi Rayan Feeder canal to the lower Wadi drain. This implies a reduction of the reuse potential of the Wadi Rayan drain.

7.7.3 Improved Water Intake at Headworks

As already stated, the supply to the Fayoum does not meet the crop water requirements in summer, and exceeds the crop water requirements in winter. The general over-supply in winter is required to fulfill the demands at the tail ends, but causes excessive oversupply at the head reaches. The performance of the system was evaluated by simulating (with the WM model) an improved match between supply and demand, and without changing the total intake supply (case 'Distribution' in Table 7.7). The results of the simulation are presented in Table 7.8.

Table 7.7 Water intake in million m^3 per month at head works for various model simulations

Case	Demand	'1993'	'Distribution'
January	147.0	73.0	70.0
February	190.9	138.1	145.0
March	201.1	184.2	180.0
April	197.8	182.0	170.0
May	228.3	179.0	170.0
June	263.5	224.5	220.0
July	276.9	251.0	250.0
August	318.1	253.7	265.0
September	259.5	210.6	240.0
October	198.9	183.1	185.0
November	176.9	178.0	152.0
December	159.7	142.9	153.0
Total	2618.5	2200.0	2200.0

The overall effect of improving the water intake in time is comparable with the increased use of reuse drainage water pumping stations. The total amount of intake water remaines fixed, but the effective supply is increased by 74 million m^3, resulting in an increase of the effective cultivated area of 18.900 feddans. The amount of drainage flow is reduced by 47.8 million m^3. Without ensuring sufficient winter supply for the tail reaches, this strategy is perhaps unrealistic. This could be achieved by using reuse stations or reducing the supply at the head reaches during winter. In the latter case, infrastructural measures are needed.

Table 7.8 Performance indicators for 1993, with improved water intake

Case	Inflow (Mm^3)	Reuse (Mm^3)	Net drainage (Mm^3)	S_{eff} (Mm^3)	CA_{eff} (1000 fd)
'Distribution'	2200.0	164.0	524.7	2002.0	480.0

7.8 Summary and Conclusions

The basin-scale water balance model presented herein was formulated in order to assess alternative water management scenarios. The model was tested with measurements made in 1980-1996. In comparison with the water level measurements, the results produced by WM model were in accord with measured values. The monthly modelling efficiency (EF) ranged from 0.65 to 0.91. On an annual basis; the model demonstrated good performance (EF=0.89).

Using the operation of the Fayoum system during 1993 as a reference, when the use of the Batts reuse station began, the effects of some water management options can be simulated and evaluated with the WM model. In Table 7.9, the simulation results (presented in sections 7.6.1, 7.6.2 and 7.6.3) are summarized.

Table 7.9 Comparing the different alternatives for 1993 year

Case	Inflow (Mm^3)	Reuse (Mm^3)	Net drainage (Mm^3)	S_{eff} (Mm^3)	CA_{eff} (1000 fd)
'1993'	2200.0	117.6	572.5	1928.0	461.1
'Resue'	2200.0	178.6	527.3	1988.9	483.6
'Disribution'	2200.0	164.0	524.7	2002.0	480.0

It was concluded that the performance of the system during 1993 was quite good. However, due to a mismatch between supply and demand either in time or in place, 12% of the intake water was not used effectively (for evapotranspiration and leaching) and was lost as surface runoff to the lower reaches of the system. The performance could be improved by:

- Increasing the operation of the reuse pump stations (case 'Reuse');
- Improving the water intake in time (case 'Distribution').

In practice, it is relatively easy to increase the use of reuse pumping stations. However, measures must be taken in the areas applying the reuse drainge water to cope with soil salinity effects of the more saline irrigation water. After 1993, Batts pumping station operated continuously with 2 pumps throughout the year. Adjusting the intake supply in time is possible without infrastructural changes in the system, and improves the overall performance of the system. However, measures must be taken to guarantee supply to the tail ends in winter. Improving the performance of the present system reduces the amount of drainage water, and thereby, the potential for sustainable irrigation supply from additional reuse stations, as well as new horizontal expansion areas.

Based on the results of this study, and given the fact that model calibration was not required, it can be concluded that the WM model can be used to evaluate and determine the effects of different management alternatives, and to formulate acceptable scenarios.

CONNECTING TEXT

In Chapter 7, the basin-scale model (WM) was developed, simulating water balances in the Fayoum basin and Lake Qaroun, to assess alternative water management scenarios under present day conditions. In Chapter 8, in order to develop promising water management strategies, the WM model is used under the present contraints. The model simulations provide answers to several questions, such as the development of reuse potential, and the conflict with the horizontal expansion.

CHAPTER EIGHT

BASIN IRRIGATION WATER MANAGEMENT STRATEGIES

Abstract

The Fayoum irrigation system features two main problems that hamper water management. The first problem is that the distribution of irrigation water over the year does not match the actual crop demand. The second problem is that reusable drainage water is spilling into the desert. The above mentioned problems are caused by a combination of constraints in the present water management system that are partly of a physical and managerial nature.

In order to develop promising water management strategies, the WM model was used, simulating water balances in the Fayoum basin and Lake Qaroun. The model answers several questions with respect to the effectively cultivated area, the development of reuse potential, and the conflict with horizontal expansion.

Based on the model simulations, it was recommended that the average annual water level of Upper Wadi Rayan Lake be -8.7 m MSL, and annual total inflows into Lake Qaroun and the basin be 417 MCM and 2430 MCM, respectively. The main finding that was drawn in this study shows that increasing the reuse of drainage water can be in conflict with horizontal expansion; it is

recommended that the potential of drainage water reuse be limited to a maximum of 275 MCM/year, which allows for a high overall efficiency of 70%, and a reclaimation of 5300 feddans.

8.1 Introduction

In the Fayoum basin, several projects are carried out to solve urgent problems: numerous poorly functioning structures are being repaired or replaced, various canal sections have been reshaped, and several reuse pumping stations have been constructed. At the same time there is constant pressure to increase the irrigated area. Within the Fayoum depression, farmers tend to augment the cultivated area by reducing the percentage of fallow land. Outside the Fayoum depression, a number of extension projects are under implementation; several others are being studied.

In this Chapter, water management strategies are developed giving specific attention to possible conflicts in water distribution that may rise in the near future. The objective of this Chapter is to develop water management strategies that will improve the distribution of irrigation and drainage water in order to fulfill the requirements of irrigated agriculture, and control the water level of Lake Qaroun. The consequences of measures and developments are determined, and strategies are identified for the irrigated area in Fayoum, as well as Lake Qaroun and the Wadi Rayan lakes.

8.2 Model Simulation

The alternatives for water management are determined by the WM model simulation where the best solution should agree with these conditions:

- adequate water supply in order to meet the crop water requirement;
- a high degree of overall system performance evaluated by the previously mentioned performance parameters in Chapter 7;
- system losses must be reused whenever the quality of the drainage water is suitable;
- a minimum drainage outflow to Lake Qaroun must be secured in order to maintain a permanent, safe, environmentally acceptable outlet condition;
- a minimum drainage outflow must be maintained to meet the leaching requirement for salinity control.

The procedure for simulation and evaluation of management options are as follows :

- determine the desired average water level of Lake Qaroun and its upper and lower limits; (respective levels of -43.8, -43.5 and -44.10 MSL were used in the analysis);
- calculate the corresponding inflow into Lake Qaroun necessary to maintain these levels;
- simulate drainage flows from the closed basin for a particular cropping pattern; and corresponding irrigation intake, and assumed reuse of drainage water at a varying number of mixing locations;

- determine the total drainage flows and their division over Lake Qaroun and Wadi Rayan;
- if the drainage flow to the lake system exceeds the desired flow, then the solution is rejected and the calculation is repeated with adjusted inputs.

As the physical characteristics and hydrology of the lake were studied (Chapter 5), alternative management procedures can be evaluated as a means of reducing contributions that are complicating the saline water disposal problems.

8.3 Results and Discussion

The results of different scenarios are presented in eight simulations (Tables 8.1 and 8.2). The results and corresponding conclusion are drawn as follows :

Cases (1), (2), (3) and (4) - Table 8.1:

- Case (1)

For the first case, the irrigation intake is assumed to be 2200.0 MCM/year. The cropping pattern remains under the present condition for 1996. The Wadi Rayan feeder canal and tunnel diverted large amounts (227 MCM/year) of good quality drainage water from the system towards the Wadi Rayan depression. Assuming that the output of the Batts pumping station is increased by an average of 30 MCM/year, the drainage flow to Lake Qaroun will decrease by 21 MCM/year. When, however, the level of Lake Qaroun must remain stable on a yearly basis, the decrease in drainage outflow from the Batts drain must be compensated for by diverting water from the Wadi Rayan feeder canal to the lower Wadi drain. To achieve this, 123 MCM/year must be diverted to the Wadi drain. This results in only 104 MCM/year remaining in the Wadi Rayan feeder canal. As mentioned in Chapter 3, three potential reuse pumping stations were considered for implementation along Wadi Rayan drain, and from the upper lake to a new expansion area at the Wadi Rayan depression. Operating the Rayan-Nezle and Rayan-Banat pumping stations simultaneously to satisfy peak demands during the summer will result in a drainage flow of around 57 MCM/year to the upper Wadi Rayan lake. Because the mean evaporation of the upper lake is almost 98 MCM/year, the water level of the upper lake is decreasing. Therefore, there will be insufficient flow to meet the pumping station requirements for the new expansion area between the two lakes of the Rayan depression. As a result, the lower lake may fall virtually dry and the quality of both lakes (upper and lower lakes of the Rayan depression) will deteriorate. This endangers the sustainability of the reclamation area in the Wadi Rayan depression.

The above short analysis leads to use the model to simulate three more cases, increasing the irrigation intake to 2430 MCM/year. Again the cropping pattern remained under the present condition for 1996. The differences between cases 2 through 4 are the volumes of reused drainage water applied by the present reuse pumping stations as mentioned in Chapter 3. The simulations and corresponding explanations are presented as follows:

- Case (2)

The first simulation of the increased intake shows that, after achieving the desired level for Lake Qaroun, the Wadi Rayan feeder canal and tunnel are diverting 313 MCM/year from the system towards the Wadi Rayan depression. Of all the water supplied to the system (2430 MCM/year), 30% ends up as drainage water (730 MCM/year). The overall efficiency is estimated to be 64%. This is considered high in comparison with a world-wide average of about 40% (Bos and Nugteren, 1990).

- Case (3)

To study the effect of reuse in the Fayoum, the Tagen and Gharaq stations are used. The used amount of reuse drainage water, the same as in 1993, is 83 MCM/year, and 17 MCM/year, for Tagen and Gharaq P.S, respectively. The calculated drainage outflow is 667 MCM/year with an overall efficiency of 66.6%.

- Case (4)

The additional supply available through increased use of the Gharaq pump station by 20 MCM/year, and use of the Batts pumping station (around 60 million m^3) is shown in case (4). By maintaining Lake Qaroun stable on a yearly basis, it is clear that the decrease in drainage outflow from the Batts and Wadi drains must be compensated for diverting water from the Wadi Ryan feeder canal to the lower Wadi drain. The irrigation/drainage ratio is estimated to be 25.4%, and the overall efficiency 68.6%.

The above three cases lead to use of the model to simulate four more cases with the same irrigation intake (2430 MCM/year). The differences between cases 5 through 8 are the volumes of reused drainage water applied by the new reuse pumping stations, and allocated for reclamation areas (10000 feddans) - see

Chapter 3. The simulations and corresponding explanations are presented as follows:

Cases (5), (6), (7) and (8) - Table 8.2:

- Case (5)

Assuming that the output of the Batts pumping station is increased by an average value of 30 MCM/year, and the planned reuse station (Rayan-Nezle) is in operation with 15 MCM/year, the total drainage water flow will decrease by 28 MCM/year. The overall irrigation efficiency increases to 69.7%.

- Case (6)

When the Rayan-Banat pumping station is fully operated, then 145 MCM/year remains in the Wadi Rayan feeder canal. An area of 3000 feddans can be reclaimed where the water requirement is 2 m^3/sec, corresponding to 36 m^3/fed/day. The evaporation of the upper Wadi Rayan lake is about 3.1 m^3/s on the average. The expected inflow to the lower lake is 47 MCM/year, which causes a decrease in the lake surface area, and the water quality to deteriorate.

- Case (7)

This case is as case (6), but with operation of the new expansion area in Wadi Rayan. An area of 4000 feddans can be reclaimed where 2 m^3/sec must be pumped (reuse Rayan) from the upper Wadi Rayan lake. Therefore, there will be insufficient inflow to the lower lake from the upper lake, then, a sharp drop in water level will be observed. This caused by the fact that the evaporation and the water supply to the new expansion area consumes all inflow. This endangers the sustainability of the reclamation area in the Wadi Rayan depression.

- Case (8)

This case is as case (7) with decreased use of reuse amounts from Batts, Nezle, Banat and Rayan reuse stations of 83.3%. About 167 MCM/year is left in the Wadi Rayan feeder canal. This implies that only a total area of 5300 feddans can be reclaimed. The expected inflow to the lower lake is 40 MCM/year which keeps the lower lake at a lesser surface area.

From the previous eight cases, the following observations can be drawn:

- There are related effects of reuse in the Fayoum: firstly, a high overall irrigation efficiency, and secondly, Fayoum lakes (Lake Qaroun and Wadi Rayan depression lakes) because of less inflow of drainage water from land drainage to the lake.
- The simulation of the above mentioned scenarios strongly suggest that with the recommended intake at Lahoun (2430 MCM/year), and by keeping Lake Qaroun stable, the limits of the reuse potential and land reclamation can be reached.
- The scenarios recommended by the previous simulations are case (6) or case (8). Both cases have approximatly the same overall efficiency and reclamation areas. Case (6) has been taken into account all the pumping stations, except the reuse pumping station from Upper Wadi Rayan Lake to a

new expansion area. Case (8) has taken into account all mentioned reuse stations of a lesser capacity.

Table 8.1 Results of simulation for different management cases (1) to (4)

Case no.*	(1)	(2)	(3)	(4)
Needed inflow into Lake Qaroun	417	417	417	417
Irrigation intake of the basin	2200	2430	2430	2430
Reuse Batts	60	-	-	60
Reuse Tagen	83	-	83	83
Reuse Gharag	37	-	17	37
Total reuse from Batts & Wadi drain	180	-	100	180
Reuse Nezle	-	-	-	-
Reuse Banat	-	-	-	-
Reuse Rayan	-	-	-	-
Total reuse from Wadi Rayan drain	-	-	-	-
Total reuse in the Fayoum basin	180	-	100	180
Reclamation of friges areas	-	-	-	-
Inflow to Lake Qaroun	315	451	415	388
Inflow to Wadi Rayan drain	227	279	252	230
Lake Qaroun level	-44.0	-43.79	-43.86	-43.92
Overall efficiency	69.4%	64%	66.6%	68.6%

Final Results				
Total outflow from the basin	542	730	667	618
Inflow to Lake Qaroun	417	417	417	417
Inflow to Wadi Rayan drain	125	313	250	201
Lake Qaroun level	-43.83	-43.83	-43.83	-43.83

* The units of Lake Qaroun water level in m MSL, drainage flow in million m^3 & reclamation area in feddans;

Table 8.2 Results of simulation for different management cases (5) to (8)

Case no.*	(5)	(6)	(7)	(8)
Needed inflow into Lake Qaroun	417	417	417	417
Irrigation intake of the basin	2430	2430	2430	2430
Reuse Batts	90	90	90	70
Reuse Tagen	83	83	83	83
Reuse Gharag	37	37	37	37
Total reuse from Batts & Wadi drain	210	210	210	190
Reuse Nezle	15	15	15	15
Reuse Banat	-	45	45	30
Reuse Rayan	-	-	60	40
Total reuse from Wadi Rayan drain	15	60	120	85
Total reuse in the Fayoum basin	225	270	330	275
Reclamation of friges areas	2000	5000	9000	5300
Inflow to Lake Qaroun	370	350	350	366
Inflow to Wadi Rayan drain	220	212	212	218
Lake Qaroun level	-43. 93	-43.97	-43.97	-43.94
Overall efficiency	69.7%	70.8%	70.8%	70.0%

Final Results				
Total outflow from the basin	590	562	562	584
Inflow to Lake Qaroun	417	417	417	417
Inflow to Wadi Rayan drain	173	145	145	167
Lake Qaroun level	-43.83	-43.83	-43.83	-43.83
Upper Wadi Rayan Lake	-8.7	-8.7	< -8.7	-8.7
Inflow to lower Wadi Rayan lake	75	47	18	40

* Case (5): as case (4), but with increased use of Batts pumping station; Case (6): as case (5), but with the Nezle and Banat pumping station operating at full capacity; Case (7): as case (6), but with operation of the new expansion in Wadi Rayan; Case (8): as case (7), but with less amount of reuse amount at (Nezle, Banat, Rayan).

As an expansion to the previous analysis, a second set of simulations were performed in order to improve the water distribution over time. The performance of the system was evaluated by simulating (with the EVAPQ-LQR-FWB models (WM model)) an improved match between supply and demand, without changing the total intake supply recommend by the previous simulation (2430 MCM/year). The results , as presented in Table 8.3, can be summarized as follows:

Cases (8), (9) and (10) - Table 8.3:

- Case (8)

This case, using the previous simulation (Table 8.2), represents option (8), is recommended due to the overall irrigation efficiency and the increased potential of drainage water reuse, which allows a reclaimation of 5300 feddans.

- Case (9)

Adjusting the intake supply in time is applied on case (8), with the same amount of reuse drainage water. This improves the overall performance of the system, whereby 95% of the total intake supply is effectively used. Compared to case (8), the effectively cultivated area increases by 2.7%. It should be noted that in this case, the annual flow to the Wadi Rayan lakes is reduced to 123 MCM since 417 MCM is required to maintain the level of Lake Qaroun. This will result in a sharp decrease of flow to the Wadi Rayan depression. As a result, there will be a sharp decrease in the water level of the upper Wadi Rayan lake. The lower lake could fall dry, and the quality of both lakes will deteriorate.

- Case (10)

Applying the same adjusment of irrigation intake and reducing the potentional use of drainage water reuse by 30 % results in case (10). The outflow and overall efficiency are almost the same as case (8), with increases in the effective supply, and the effective cultivated area, of 30 MCM, and 7000 feddans, respectively. The effect of water distribution in time is shown in Figure 8.1. It presents both the demand and the irrigation intakes for cases (8) and (10).

Adjusting the intake supply in time is possible without infrastructural changes in the system, and improves the overall performance of the system. The overall effect of improving the water intake in time is comparable to the increased use of reuse drainage water pumping stations. However, measures must be taken to guarantee supply to the tail ends in winter. Improving the performance of the presented system reduces the amount of drainage water, and thereby, the potential for sustainable irrigation supply from additional reuse stations, as well as to new horizontal expansion areas.

Table 8.3 Annual water balance for different irrigation alternatives. (Summer deficits and winter excess are minimized)

Case no.	**(8)**	**(9)**	**(10)**
Irrigation intake (MCM)	2430	2430	2430
Reuse (MCM)	275	275	195
Drainage outflow (MCM)	584	540	586
Overall efficiency (%)	70.0	71.8	69.9
Effective supply (MCM)	2250.0	2309	2280
Effectively cultivated area (fed)	516,000	530,000	523,000

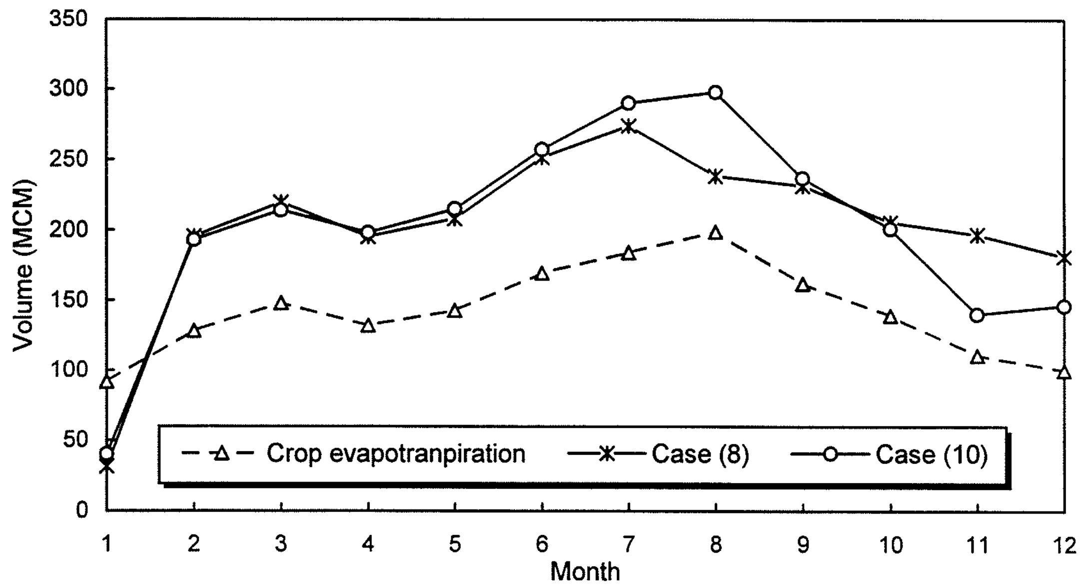


Figure 8.1 Present and proposed irrigation intake

8.4 Summary and Conclusions

The simulated water management scenarios using the WM model (EVAPQ-LQR-FWB models), showed clearly that there are related effects of drainage water reuse in the Fayoum: firstly, a high overall irrigation efficiency, and secondly, low water level of Fayoum lakes because of less inflow of drainage water from land drainage to Lake Qaroun and Wadi Rayan depression.

According to Tables 8.1 and 8.2, it was concluded that the various simulations strongly suggest that with the recommended intake at Lahoun (2430 MCM/year), and a stable drainage water disposal into Lake Qaroun of 417 MCM/year, the reuse potential is in conflict with horizontal expansion (new reclamation areas). The selected case (case 8, Table 8.1), as the most suitable strategy, estimates the maximum limits of drainage water reuse and horizontal land expansion of 275 MCM/year, and 5300 feddans, respectively. The calculated total draiange outflow is 584 MCM/year, with an overall efficiency of 70%. The water level of upper Wadi Rayan Lake, and the inflow to lower Wadi Rayan lake are assumed to be -8.7 m MSL, and 40 MCM/year, respectively. The comparison between the latter case and the condition of 1996 (case '1996', Table 7.5) shows that the effective supply is increased by 47 MCM, and the effectively cultivated area is increased by 11000 feddans.

However since the latter recommended case takes into account 40 MCM/year as a reuse of drainage water from the upper Wadi Rayan Lake to the new expansion area, it can be stated that the choice of developing an irrigation system in the Wadi Rayan is not rcommended. A significant amount of water is lost by evaporation in the upper Wadi Rayan lake before it reaches the intake of the pumping station, and the quality of irrigation water is relatively low. The latter implies that only specific crops can be grown effectively.

In the Fayoum, water, rather than availability of land, is obviously the limiting factor for agricultural development. The existing crop intensities in the Fayoum are, from a land availability point of view, far below their potential. In this respect, preference should be given to vertical expansion (crop intensification) rather than horizontal expansion. On-going horizontal expansion developments should be kept to a minimum: water can only be made available at the expense of existing lands inside the Fayoum.

The performance of the system could be improved by superior matching of supply and demand in time and in space. Nevertheless, the system will continue to show water shortages in tail-ends, where the main reclamation areas are also located. With respect to water distribution in time, it can be stated that the overall supply to Fayoum does not fulfill summer demands, while it exceeds those of winter. Applying the same adjusment of irrigation intake, and reducing the potentional use of drainage water reuse by 29 % results in case (10), Table 8.3. The basin outflow and overall efficiency are almost the same as case (8), with increase in the effective supply, and the effective cultivated area, of 30 MCM, and 7000 feddans, respectively. The comparison between case (10), and the condition in 1996 (case '1996', Table 7.5) shows that improved matching of supply and demand in time, without an increase of the total intake amount, will increase the effective supply by 77 MCM, and the effectively cultivated area by 18000 feddans. If it is not possible to increase the supply in the peak period, it is not advised to reduce the intake in winter. The extra amount of intake water during winter cannot be considered a loss since it is used to control soil salinity, and to stabilize the level of Lake Qaroun.

CHAPTER NINE

GENERAL CONCLUSIONS

Based on the work conducted in this study, the following conclusions were made:

1. The dependence of evaporation on meteorological variables and salinity has been analyzed from evaporation pans located near Lake Qaroun. The commonly used approach to account for salinity effects based on ratios of salt water to fresh water evaporation rates is hard to use accurately since it is a function of salinity, ionic composition, and meteorological variables. A more accurate method is an approach which is based on the effect of salinity on saturation vapor pressure. The latter approach shown in Chapter 4 is computed indirectly by field experiments using evaporation pans.

2. The evaporation model (EVAPQ) presented in Chapter 4 was formulated to provide estimates of monthly and annual evaporation from shallow lakes using routine climatological observations. The input requirements are monthly averages of air temperature, water temperature, and sunshine duration. Also required is the latitude and salinity of the lake. The simulations were checked against the measured lake evaporation rates in 1969-1975. The monthly comparison showed that the model is in acceptable agreement. The monthly percent error of the model

estimates ranged from -12.38 % to 12.86%. The model produced reliable results, in terms of annual prediction, where the maximum percent error of the model estimates is 2.97%, and the minimum is -2.68%. The standard deviation of differences range from 0.08 to 2.22 cm, and indicate that there is a good probability for obtaining simulated values within 2.22 cm of the actual values. The capability of the model to produce realistic estimates of monthly and annual lake evaporation from climatological observation was used as a tool for estimating evaporation rates from Lake Qaroun, and in the evaluation the water and salt management in Fayoum basin presented in Chapters 5 and 6.

3. The Lake Qaroun Routing model (LQR) presented in Chapter 5 demonstrated its value and effectiveness as a tool for the analysis of lake water and salinity levels. The model was tested with measurements made in 1980-1996. In comparison with the values computed for five statistical parameters, the predictions of water levels produced by the LQR model were in accord with measured values. The monthly modelling efficiency (EF) ranged from 0.58 to 0.93. On an annual basis, EF was estimated to be 0.88. Compared with the available salinity measurements, the model produced reliable results in terms of annual prediction (EF=0.5). However, over monthly periods, the LQR model was not in good agreement with field measurments (EF= from -8.2 to 0.53).

4. In Chapter 6, the LQR model was extended to simulate flows, water levels, and salt loads for Lake Qaroun management for salinity control. The various

management options presented dealt mainly with dividing Lake Qaroun into a series of compartments separated by dams, and constructing regional evaporation ponds. It was concluded that the most suitable scenario is to divide Lake Qaroun into two compartments, and consider a target time of ten years. The first compartment is located west and assumed to ocuppy 35% of the lake area. The second is located east and assumed to cover 65% of the lake area. The second compartment has relatively fresh water with a salinity level (13.3 dS/m) reduced by 74% of the original, and a recommended water level of -43.79 m MSL, with narrow fluctuations of $\pm$ 0.25 m. The first compartment has a saline water. The salinity level (83.1 dS/m) is increased by 65% of the original level, though It has the lowest salt accumulation, which is effectively reduced by using the regional evaporation ponds north of the lake. It is estimated that annual salt load into the evaporation ponds is 620,000 tonnes. That is reduce the salinity level from 83.1 dS/m to 72.2 dS/m. An area of 6 km^2 is required to evacuate the salt.

5. A basin-scale model (WM) was developed and tested, simulating water balances in the Fayoum basin and Lake Qaroun under present day conditions. In comparison with measurments made in 1980-1996, the predictions of the Lake Qaroun water levels produced by the WM model were in accord with measured values. The monthly modelling efficiency (EF) ranged from 0.58 to 0.93. On an annual basis, EF is estimated to be 0.88.

6. Based on the WM model simulations in Chapter 7, it was concluded that with the recommended intake at Lahoun (2430 MCM/year), and a stable drainage water disposal into Lake Qaroun of 417 MCM/year, the reuse potential is in conflict with horizontal expansion (new reclamation areas). The most suitable strategy estimates the maximum limits of drainage water reuse and horizontal land expansion to be 275 MCM/year, and 5300 feddans, respectively. The calculated total drainage outflow is 584 MCM/year, with an overall efficiency 70%. The water level of upper Wadi Rayan Lake, and the inflow to lower Wadi Rayan lake, are assumed to be -8.7 m MSL, and 40 MCM/year, respectively. The comparison between the latter case and the condition of 1996 shows that the effective supply is increased by 47 MCM, and the effectively cultivated area is increased by 11000 feddans.

However, since the latter recommended case took into account 40 MCM/year as a reuse of drainage water from the upper Wadi Rayan Lake to the new expansion area, it can be stated that the choice of developing an irrigation system in the Wadi Rayan is not recommended. A significant amount of water is lost by evaporation in the upper Wadi Rayan lake before it reaches the intake of the pumping station, and the quality of irrigation water is relatively low. The latter means that only specific crops can be grown effectively.

7. With respect to the basin water distribution in time, it can be stated that the overall supply to Fayoum does not fulfill summer demands, while it exceeds those in winter. Applying the same adjustment of irrigation intake to Lake Qaroun

as the latter conclusion, and reducing the potentional use of drainage water reuse by 29 %, results in a better managment strategy than the latter conclusion. The basin outflow and overall efficiency are almost the same, with increases in the effective supply, and the effective cultivated area, of 30 MCM, and 7000 feddans, respectively. The comparison between this scenario and the condition in 1996 shows that improved matching of supply and demand, in time without an increase of the total intake amount, will increase the effective supply by 77 MCM, and the effectively cultivated area by 18000 feddans. If it is not possible to increase the supply in the peak period, it is not advised to reduce the intake in winter. The extra amount of intake water during winter cannot be considered a loss since it is used to control soil salinity and to stabilize the level of Lake Qaroun.

CHAPTER TEN

RECOMMENDATIONS FOR FUTURE RESEARCH

The results from data analysis and computer simulation revealed the following areas for further investigation:

1. The evaporation model (EVAPQ) should be tested and verified by measuring the air temperature and other parameters for a greater number of years. Also, wind speed should be used to obtain better estimates of monthly and annual Lake evaporation. The predicted results should then be compared with field measurments.

2. Once the evaporation model is verified, it may be appropriate to extend this work to study the dependence of evaporation on the chemical composition of Lake Qaroun water.

3. The Lake Qaroun Routing (LQR) model should be tested and verified by measuring the lake salinity for a greater number of years. The predicted results should then be compared with the salinity measurments. That will give better estimates of monthly lake salinity.

4. Beside salt disposal, Lake Qaroun is receiving untreated sewage water through the drains, making it difficult to consider the lake an environmentally acceptable outlet in the future. It is recommended that the model be enhanced with some water quality parameters. This enhancement would be useful to simulating the quality of Lake Qaroun, and determining the needed environmental control.

5. The presented plan of dividing Lake Qaroun was conceived to control both the water and salinity level of the lake. After the assessment of its technical feasibility, a feasibility study and environmental impact assessment should be implemented to provide the decision makers with the necessary information.

6. The water managment (WM) model should be modified to study the salt balance in the Fayoum basin. Salinity measurments of the irrigation and drainage water should be made to estimate the salinity level of the water disposed into the lake. The predicted results should then be compared to Field measurments.

7. More effort should be taken to develop a model expansion, as part of the entire model package. It may then be regarded as a complete and intensive water and salt management model. That expansion can be achieved when the Fayoum area is schematised into catchments or sub-units. Inside each sub-unit, uniformity can be assumed by definition. The model can be also modified by calculating the performance for a specified year, using a time step of 10 days.

8. To improve crop water demands, an accurate survey is needed with respect to the actual cropping pattem. This type of data, however, can not be expected to become available in the short term. However, one might easily collect more reliable data about the percentages of fallow land, rice land, and dry crops, such as wheat, cotton and maize planted per month, through field visits. This would improve the input data significantly, and hence, the reliability of the model.

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