SEAWATER INTRUSION IN THE NILE DELTA AQUIFER: AN OVERVIEW

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ABSTRACT

The Nile Delta aquifer in Egypt is among the largest groundwater reservoirs in the world. The aquifer is subjected to a severe seawater intrusion problem from the Mediterranean Sea mainly due to its geometric and geological conditions, limited natural recharge and overexploitation of the aquifer. This chapter presents a comprehensive review of the aquifer system including its geometric, hydraulic and hydrogeological conditions. The seawater intrusion mechanisms and the boundary conditions are discussed. The impacts of pumping activities and land use are elaborated. Various numerical simulations for the seawater intrusion in the vertical and areal views are discussed and several scenarios for groundwater pumping and land use with specific reference to rice cultivation are presented. Recommendations are made for the mitigation of the seawater intrusion problem in the Nile Delta aquifer.

INTRODUCTION

Egypt lies between latitudes 22° and 32° North and longitudes 25° and 35° East. The North boundary of Egypt is the Mediterranean Sea, and the East is the Red sea. The South and West are political boundaries with Sudan and Libya, respectively. The total area of Egypt is equal to about one million km^2, 94% of which is desert. The population of the country is currently estimated as 67 million.

There are three dependent sources of water in Egypt: Nile water, groundwater, and drainage water. Rainfall is rare and does not contribute to the water resources of the country. The Nile water is the only source of the renewable water. The Egyptian share from the Nile water, according to the international agreements, is limited to 55.5 x 10^9 m^3 per year since 1959. The per capita share from the renewable water is 830 m^3/year. Currently, about 5.5 billion m3/year of groundwater are pumped from the different aquifers, 85% of which originates from the Nile water and the rest is fossil water. About 5 billion m^3/year of agriculture drainage water are being reused, while about 12 billion m^3 of low quality drainage water are expelled to the Mediterranean Sea and the northern lakes. Reuse of drainage water is not recommended because of its low quality and high contents of chemicals and pesticides.

The Nile Delta is one of the most fertile areas in Egypt. However, less than two-thirds of its area is under cultivation. The uncultivated lands are found along the sea to the north and the Delta fringes close to the desert. Irrigation is mostly practiced by surface water through an intensive network of canals branching out from the Nile River. The growth of population in the Nile Delta and hence, the increase in human activities, agricultural, and industrial has imposed an increasing demand for freshwater. This increase in demand in the Delta is covered by intensive pumping of fresh groundwater, causing subsequent lowering of the piezometric head and upsetting the dynamic balance between freshwater body and saline water body in the aquifer. Like any coastal aquifer, an extensive saltwater body has intruded the Nile Delta aquifer forming the major constraint against aquifer exploitation.

Many studies were conducted to simulate the seawater intrusion in the Nile delta aquifer using the numerical techniques. Most of which were based on the sharp interface approach, while few accounted for dispersion zone and density variation with water concentration. Examples of these studies include among others, Wilson et al. (1979), Amer et al. (1979), Farid (1980 and 1985), Sherif et al. (1988, 1990a and 1990b), Darwish (1994), Amer and Sherif (1995 and 1996), and Sherif and Singh (1997). Field investigations indicated that the width of the dispersion zone in the Nile Delta aquifer is quite large, hence, the sharp interface may not be a realistic assumption under such conditions.

PHYSICALAND GEOLOGICAL SETTING

The Nile Delta region lies within the temperature zone which is a part of the great Desert belt. It occupies a portion of the arid belt of the Southern Mediterranean region. The desert fringes on both sides of the Delta cause a rise in temperature and affect the changes in daily temperature. The average temperatures in January and July at Cairo are 12°C and 31°C, respectively. Minimum and maximum temperatures at Cairo are 3°C and 48°C, respectively. Rainfall over the Nile Delta is rare and occurs in winter. Maximum average rainfall along the shore of the Mediterranean Sea, where most of the rain occurs, is about 180 mm. This amount decreases very rapidly as one proceeds inland to about 26 mm at Cairo.

The Nile Delta aquifer is among the largest ground water reservoirs in the world and is a very important water resource for Egypt. The Nile Delta occupies an area of over six million acres with eastern boundaries near the Suez Canal and western boundaries well into the desert (figure 1). It fills a vast underground bowl situated between

Cairo and the Mediterranean Sea. If it were not for the presence of a saline body of seawater along the bottom of this bowl, the Nile Delta aquifer could be easily exploited to the best interests of Egypt. The threat of seawater intrusion has severely limited the exploitation of this aquifer.

Seepage out of the Nile River, canals and surplus of irrigation water percolating downward are the main fresh water sources recharging the aquifer. It may also be recharged, nominally, by northward flow from the Nile Valley aquifer. On the other hand, the aquifer loses some of its fresh water to the Mediterranean Sea and the drainage system in the northern part of the Delta.

The Nile Delta aquifer system forms an immense and complex groundwater system. It is a leaky pleistocene aquifer system overlain by a semipervious holocene aquitard (clay cap) and underlain by an impermeable miocene aquiclude. The clay cap (aquitard), being the main source through which aquifer recharge occurs, is of great importance. The aquifer status (phreatic, confined and leaky) is defined according its thickness and vertical permeability. On the contrary, the aquiclude has no hydrologic importance, except that it forms an impermeable bottom and defines the aquifer geometry.

The bulk of the Nile Delta aquifer consists of deltaic deposits 200-300 m thick in average. It is dominated by unconsolidated coarse sands and gravels with occasional clay lenses. The top boundary of the deltaic deposits, which acts as a cap for the aquifer is a semipervious clay and silt layers. The thickness of the clay cap increases uniformly in the seaward direction from about 5 m near Cairo and may reach 60 or 70 m at the Mediterranean coast. The clay cap is intermeshing with the aquifer near the shore. The base of the deltaic deposits rests on a thick clay section, which acts as an aquiclude.

Shata and Hefny (1995) indicated that in the delta area, as well as its fringes, the strata of hydrological importance belong essentially to the Quaternary and to the Tertiary. Of these strata, the deltaic deposits (200-500 m thick) which belong to the Pleistocene, constitute the bulk of the main aquifer. These are dominated by unconsolidated coarse sands and gravel (with occasional clay lenses). The top portion of such deposits changes in the seaward direction into impervious clays and silt.

Figure 1. Layout of the Nile Delta and its fringes.

Geometric aspects

The Nile Delta with its fringes (22000 km^2) lies between latitudes 30° 25´ and 31° 30´ North, and longitudes 29° 50´ and 32° 15´ East (figure 1). It is generally considered a leaky aquifer, however, phreatic conditions are encountered in some areas east and west of the Delta fringes, where the upper clay layer vanishes. A heavy clay layer of variable thickness covers most of the upper boundary of the aquifer. The bottom boundary is impermeable, in the sense that the aquifer does not gain or lose any water through this boundary.

The northern boundary of the Nile Delta aquifer is the Mediterranean Sea, where the aquifer depth varies and may reach a depth of 1000 m in some locations. Since the bottom impermeable layer approaches the upper clay layer near Cairo at El-Manawat (figure 2), the aquifer may be considered to be partly isolated from the Nile Valley aquifer to the south. The geometric dimensions of the aquifer have been investigated intensively since 1975.

Horizontal and vertical dimensions of the Nile Delta aquifer were obtained using deep oil borings and data from test bore holes (Farid

1980). The boundary between the pleistocene aquifer and the pliocene and/or miocene aquiclude was defined. Eight longitudinal and lateral cross sections were drawn, figures 2 and 3 present the vertical cross sections in the middle and east of the Nile Delta aquifer, figure 4 presents the contour lines of the aquifer thickness (Farid, 1980). The thickness of the pleistocene aquifer increases toward the Mediterranean Sea, and decreases southward, almost vanishing near El Manawat and partly separating the Nile Delta aquifer from the Nile Valley aquifer. South of Tanta in the transversal direction, the bottom boundary forms a concave shape. The aquifer thickness decreases eastward and southward with a maximum depth in the middle of the Delta. North of Tanta, the maximum thickness of the aquifer shifts toward the east.

Figure 2. Vertical cross section in the middle Delta.

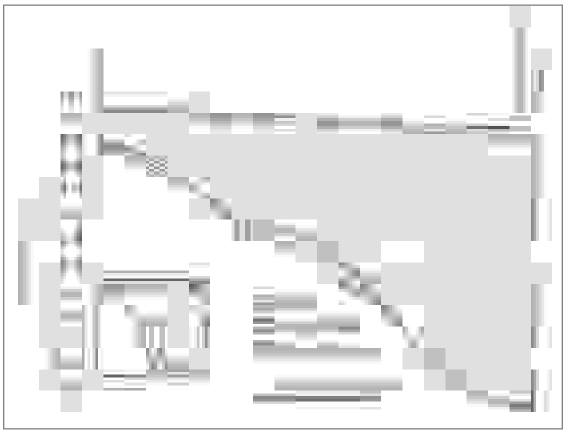

Figure 3. Vertical cross section in the eastern Delta.

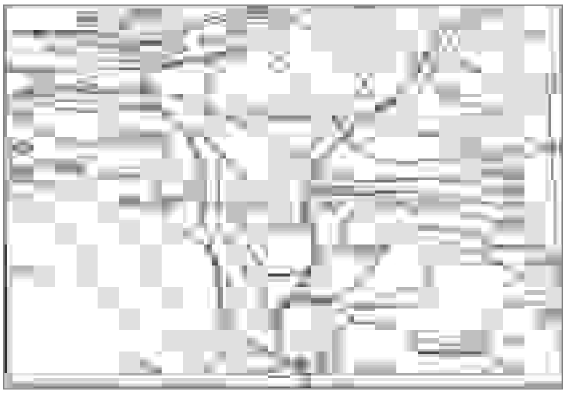

Figure 4. Contour lines for the aquifer thickness (Farid, 1980).

Upper clay layer

The clay cap takes different profiles along the shore of the Mediterranean Sea. Generally, it is divided into two layers. The first layer is the upper clay cap which acts as an aquitard, about 20 m thick, with a low permeability. The second layer is the lower clayey sand layer, a few meters thick, with a higher permeability. The thickness of the upper clay cap (aquitard) and the clayey sand layer are well defined at many locations in the Delta area. Their thicknesses are mostly less than 20 m and 15 m, respectively. Only along the Mediterranean shore, the thickness of the clay cap may reach 70 m. No clay cap exits at the Delta fringes. figure 5 presents the contour map for the combined clay layers in the Nile Delta which shows their sedimentation pattern.

This vertical water movement affects, to a great extent, the water balance of the system. Downward movement of water through the clay cap occurs in two different stages. The first is the downward infiltration of irrigation water from the ground surface to the subsoil water table through the unsaturated zone of the clay cap. The velocity of this movement is defined by the downward infiltration velocity. The second is the movement of the subsoil water from the water table to the groundwater in the aquifer through the saturated zone of the clay cap. The velocity of the flow in this zone is related to Darcy's law and is defined by seepage velocity. Values of the vertical hydraulic conductivity Kcv of the clay cap in the Nile Delta area are given in figure 6. It has an average value of to 2.5 mm/day.

Figure 5. Contour map for the thickness of combined clay layers in the Nile Delta.

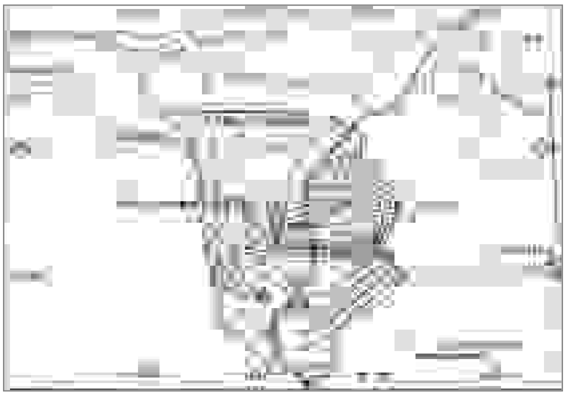

Figure 6. Vertical hydraulic conductivity of the upper clay cap in the Nile Delta.

Hydraulic parameters

Field experiments were carried out to determine the aquifer parameters. A hydraulic conductivity of 100.0 m/d and a storativity of about 10^{-4} to 10^{-3} are considered to represent the regional values for the Nile Delta aquifer. Farid (1980) reported different values for hydraulic conductivity and storativity at various locations. The hydraulic conductivity of the aquifer decreases toward the south and west. An effective porosity of 0.3 is considered representative for the aquifer medium.

The dispersivity of the Nile Delta aquifer has not yet been measured. It accounts for the lack of information about the pore velocity fluctuation when passing from the microscopic to the macroscopic configuration of the solid liquid interface. Values between 0.1 and 500 m can be found in the literature. Based on similar studies and on Sherif et al. (1988), the longitudinal dispersivity, α_L, and the lateral dispersivity, α_T, for the Nile Delta aquifer are set equal to 100 m and 10 m, respectively.

The free water table (if not measured) is generally assumed to be 1.0 m below the ground surface of the Delta. The piezometric head is monitored periodically by the Groundwater Research Institute (GWRI), National Water Research Center, Egypt.

Pumping activities

The pumping activities at each governorate are monitored by the GWRI in Egypt. According to the well inventory of 1992 the total pumping from the Nile Delta aquifer was estimated as 1.92 billion m^3/year (table 1). The current pumping is estimated at 2.3 billion m^3/year.

Governorate	No. of Well	Qx1000 m^3/year
Alexandria	18	813
El Beheira	40	109640
El Gharbia	3391	792851
Dakahlia	2	626
Sharkia	1953	404615
Ismaailia	396	62148
Menoufia	1719	549457
Total	7492	1920150

Table 1. Groundwater extractions in different governorates (GWRI, 1992).

THE ORIGIN OF THE BRACKISH WATER

To determine whether the brackish water in the Nile Delta aquifer with specific reference to the northern part is attributed to seawater intrusion or is it just a paleo-formation water, a hydrochemical study, (Farid 1980) was conducted to evaluate the Chloride-Biocarbonate $\{C1/(CO_3 + HCO_3)\}$ ratio for the groundwater in different locations of the Nile Delta aquifer. Revelle, (1941) concluded that this ratio could be used as a criterion for the recognition and evaluation of seawater intrusion in coastal aquifers. The ratio $C1/(CO_3 + HCO_3)$, in milligram equivalents per liter has been employed widely for the intrusion prediction via chemical methods.

Based on the Revelle ratio Farid (1980) indicated that the brackish water in the Nile Delta is of seawater origin. He also showed that the saline water wedge had retreated seaward by about 2.5 km during the years 1968 - 1978. This seaward movement was attributed to the continuous rise in piezometric heads during this specific period of time.

During the years 1958 - 1962, a number of wells were drilled by a Yugoslavian company in the Nile Delta aquifer (Sherif, 1987). Short and long normal resistivity curves, self potential and two microsonde curves were recorded in some bore holes. Water salinity in the permeable layers was calculated using the true resistivity and self potential methods. The salinity distribution with depth at different locations indicated a typical case for a seawater intrusion. Examples for such a distribution are provided in figure 7.

INTRUSION MECHANISM AND BOUNDARY CONDITIONS

Due to the direct hydraulic link between the freshwater in the Nile Delta aquifer and the saline water of the Mediterranean Sea, the saline water intrudes into aquifer from the sea boundary. Consider the vertical section in the middle of the Delta, Figure 8. The aquifer is recharged by freshwater entering from the landward boundary and by leakage through the upper semi-pervious layer in parts where the free water table is higher than the piezometric head. At the seaside boundary, there will be an influx of seawater into the system which because of its greater density, will migrate into the bottom of the aquifer and displace the freshwater. Upward leakage of mixed water will also take place through the upper semi pervious layer in parts where the free water table is lower than the piezometric head (near the sea boundary). The rest of the mixed water will find its way out of the system through the window at the seaside. This discharge through the window and the upward flux through the aquitard cause a loss of salt from the system which is replenished by new seawater moving in from the seaward boundary.

If the boundary conditions remain constant, a state of dynamic equilibrium will eventually be attained by the system. At equilibrium, the total fluid mass entering at both ends of the aquifer plus the leakage influx, will be balanced by the upward leakage through the aquitard plus the flux out through the window at the Mediterranean sea. Likewise, The salt mass entering at the seaward will be balanced by the salt mass swept out from

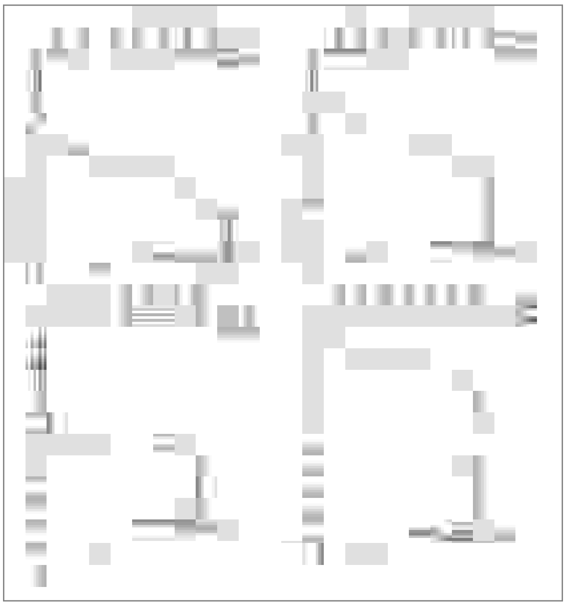

Figure 7. Variation of TDS with depth in the Nile Delta aquifer at: a- Abu-Kibir, b- Diyarb Nigm, c- Zifta, and d- Tanta.

Figure 8. Intrusion mechanism and boundary conditions.

the system with the mixed water through the upper semipervious layer and the window at the seaward boundary.

The lateral boundary (B1) at the landward side, figure 8, should be located at a point where either the concentration is constant and equal to the freshwater concentration Cf, or the change in concentration across the boundary is negligible, i.e., the concentration gradient is equal to zero. The former condition of prescribed concentration is preferable because it accelerates the convergence. The pressure at this boundary is hydrostatic and the freshwater flux through it is defined and can be calculated from Darcy's equation. The bottom of the aquifer (B2) is impermeable, i.e., the normal flux through the bed for both fluid and salt ions is equal to zero.

The seaward boundary (B3), where the aquifer is exposed to the open sea, is a very important boundary. It has been customary (Huyakorn *et al.*, 1987; Sherif *et al.*, 1988; Galeati *et al.*, 1992) to deal with the seaside boundary as prescribed concentration boundary when flow across it is directed inward, and as zero dispersive flux boundary when the flow direction is outward. Since conditions along this boundary vary with time, it may not be adequately prescribed on the basis of preliminary simulations as done by Huyakorn et al. (1987). We follow the approach utilized by Sherif et al. (1988) and Galeati et al. (1992). During each iteration the directions of velocities at all the nodal points on the boundary are checked, then assign the appropriate boundary condition accordingly, i.e., the boundary conditions at the sea side are updated after each iteration. The concentrations are prescribed and equal to seawater concentration Cs over the segment of inward flow. Over the window, (figure 8), where the flow is outward, the concentration gradient is equal to zero. The pressure is hydrostatic at this boundary and should also be updated after each iteration according to the new nodal concentration.

For the upper leaky boundary (B4), figure 8, in the segment where the free water table is higher than the aquifer piezometric head, i.e., there is a leakage of freshwater into the system, the concentration is known and equals to that of freshwater C_f. Otherwise, where the piezometric head is higher than the water table, the concentration along any vertical stream tube will be constant, that is, the concentration gradient is zero. The direction of flow through the boundary should be checked after each iteration and consequently updating the boundary conditions. The flux in the aquitard is vertical and is governed by Darcy's equation and may be downward or upward depending on whether the free water table is higher or lower than the piezometric head.

VERTICAL SIMULATION

Based on some field observations, it was assumed that seawater will not migrate inland up to Shatanuf, which is 150.0 km from the Mediterranean Sea (figure 2). Under this assumption a domain of 150.0 km in length was considered; the depth of the domain is varied from 680.0 m at the seaside to 240.0 m at the landside. The thickness of the upper confining semipervious layer was taken as 40.0 m from the sea boundary to Om-Sin which is about 17.0 km inland. From Om-Sin to Kafr-Elsheikh, 52.0 km from the sea, it is varied from 40.0 m to 15.0 m, after which the thickness of the semipervious layer is constant. The bottom boundary of the Nile Delta aquifer is impermeable. The piezometric head at the land boundary is 14.0 m above sea level. At the sea boundary the piezometric head is 0.60 m. The free water table level is given for some stations, and between these sta-tions it is assumed linear (Sherif et al. 1988).

The domain was subdivided into five subdomains; each subdomain was divided into a number of trian-gular elements with smaller areas in the regions where the variation in concentration gradient was relatively high. An intensive grid was also required near the shore boundary. The domain was finally represented by a nonuniform grid with 4020 nodes and 7600 triangular elements. The convergence criterion was set equal to 10^{-5}. A two-dimensional finite element model (2D-FED) was applied to identify the dispersion zone and the flow pattern in the Nile Delta aquifer using the density dependent approach. The model was applied to the longitudinal cross sec-tion (A-A) given in figure 2.

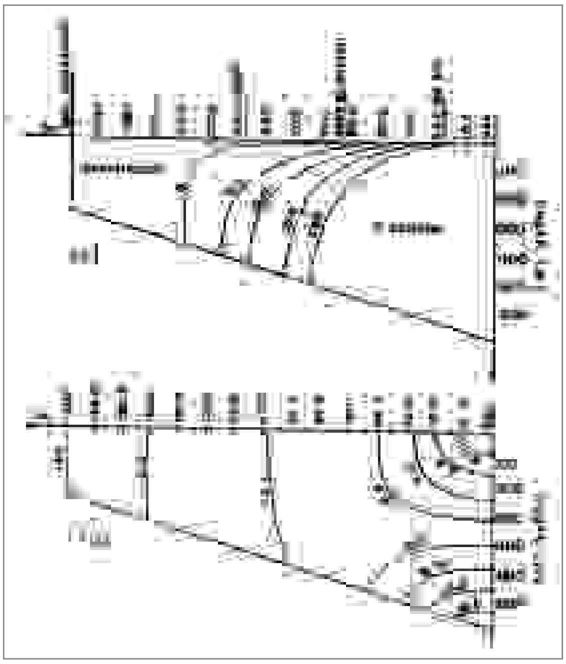

Figure 9. Results of the vertical simulation.

Equiconcentration line 35.0 (seawater) intruded the Nile Delta aquifer to a distance of 63.0 km from the seaside measured at the bottom boundary, figure 9a. Equiconcentration line 1.0 intruded the aquifer to a distance of about 108.0 km measured at the bottom boundary. The width of the dispersion zone is about 45.0 km, bigger than expected ever before, figure 9a. Unfortunately, due to the deep and wide opening a- Equiconcentarion lines, and b- Equipotential lines of the Nile Delta aquifer to the Mediterranean Sea, the seawater intruded the aquifer bottom under a high potential head, even more than that at the land side, and found its way back again to the sea through the window. At the last 22.0 km from the sea boundary, there was an upward flux of the mixed water through the upper semipervious layer. It can be concluded from the shape of the equipotential lines (figure 9b) that the depth of the window at the seaside was about 350.0 m. Strong cyclic flow at the sea boundary was detected. The agreement between the numerical results and field data available for the salinity distribution with depth at some selected sec-tions was good.

HORIZONTAL SIMULATION

Simulation of the current conditions

Sherif & Singh (1997) investigated the seawater in the Nile Delta aquifer in the areal view using SUTRA (Voss, 1984). The study domain was discretized into 998 quadratieral elements with 1084 nodal points. This discretization ensures the numerical stability and avoids improper dimensions of the elements throughout the domain. The cylinderness ratio of the various elements was kept less than 1:8. The geo-metric and hydraulic parameters were adopted for the database of the GWRI and the hydrological map of Egypt.

A specified head was considered below the two branches of the Nile river. The pressure at the

Mediterranean Sea was set equal to the atmospheric pressure. At the southern boundaries the pressure was defined from field measurements. Concentration along the Mediterranean Sea was set equal to sea-water concentration, C_s. The convergence criterion for both the concentration and the pressure was set equal to 10^{-3}. The boundary conditions and the pumping activities at the various nodes were introduced. For the initial conditions, a freshwater concentration and a hydrostatic pressure distribution between Cairo and the Mediterranean Sea were assumed throughout the entire domain.

The model was first run under transient condi-tions for both of water flow and salt transport. The time step was set equal to 3.65 days. Results of the concentration distribution and piezometric heads were stored after every 1000 time steps (10 years) and compared to each other after every 2000 steps.

Figure 10 presents the equiconcentration lines under the current pumping activities at the steady state conditions. Equiconcentration line 31.5 (31,500 ppm) intruded inland to a distance of 41.0 km along latitude 31° 00´, while equiconcentration line 17.5 intruded to a distance of 61.5 km along the same latitude measured from the sea side boundary. Equiconcentration line 3.5, representing 0.1 of the maximum concentration, intruded inland to a distance of 84 km measured from the same boundary along the same latitude.

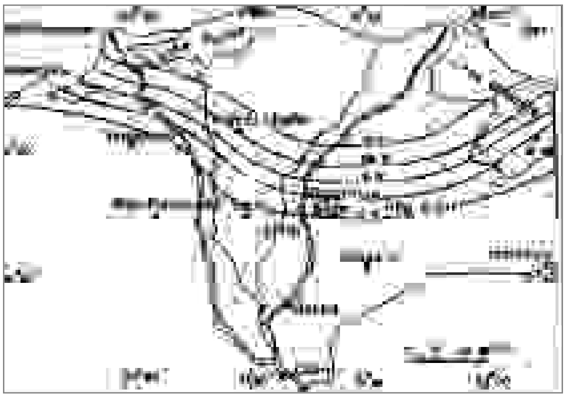

Figure 10. Resulted equiconcentration lines in the areal view (current conditions).

The verification of the resulted equiconcentration lines is not justified here. The salinity of any point in the areal view may vary in the vertical direction from fresh water concentration to sea-water concentration.

Selected pumping scenarios

To examine the response of the Nile Delta aquifer to pumping activities and define the best locations for additional groundwater pumping, six different scenarios of pumping were selected and the resulted equiconcentration lines were compared with the results of current pumping (Basic run, figure 10). The simulation is preformed via SUTRAto reflect the intrusion behavior in the areal view. These scenarios were chosen after many preliminary simulations with coarser grid systems. The Delta is divided into three main zones for pumping activities; the middle zone, the eastern zone, and the western zone. The following scenarios are thus considered:

- Scenario-l: The current pumping is redistributed in the eastern and western sides of the Delta without any pumping from the middle of the Delta. The 2.3 billion m^3/year are distributed among the nodal points in the eastern and western Delta only.
- *Scenario-2:* The 2.3 billion m^3/year are pumped from the middle Delta only without any pumping in the eastern and western sides.
- *Scenario-3:* In this scenario, the current pumping is doubled. 4.6 billion m^3/year are pumped from the same governorates. The share of each node, as calcu-lated in the basic run is thus doubled.
- *Scenario-4:* In this scenario, 4.6 billion m^3/year are pumped from the eastern and western sides of the Delta. No pumping takes place in the middle Delta.
- *Scenario-5:* The distribution of the current pumping (2.3 billion m^3/year) is maintained, while additional pumping of 1.5 billion m^3/year in the eastern Delta and 0.8 billion m^3/year in the western Delta are considered. The total pumping is thus equal to 4.6 billion m^3/year.

- *Scenario-6:* In this scenario, an additional pump-ing of 2.3 billion m^3/year is considered in the middle Delta only, while the distribution of the current pumping is maintained.

Results and discussions

The simulation was conducted under the steady state conditions. Figures 11a-f present a comparison between equiconcentration lines 31.5 and 3.5 of the various scenarios and same equiconcentration lines of the basic run (current pumping conditions). Scenarios 1 and 2, consider the current pumping but from different areas. In other words, the same pumping is redistributed. Figures 11a & 11b reveal that both of scenarios 1 and 2 are actually better than the current policy for groundwater pumping regarding seawater intrusion. Although the same amounts of water were pumped, yet less intrusion was encountered. Scenario-1 reduces the intrusion in the middle Delta considerably with slight inland intrusion in the east and west. Scenario-2 reduces the intrusion throughout the Nile Delta with specific reference to the eastern part of the Delta.

Scenarios 3, 4, 5 and 6 represent policies for pumping 4.6 billion m^3/year from the Nile Delta aquifer. Figures 5c through 5f reveal that scenarios 4 and 6 cause less impact than scenarios 3 and 5. In Scenario-4 (figures 11d) although the pumping from the entire Delta was doubled yet less intrusion was found in the middle Delta. On the other hand, equiconcentration line 3.5 advanced inland by a distance of about 21 km and 7.5 km in the western and eastern parts, respectively. Under Scenario-6, where an additional pumping of 2.3 billion m^3/year was considered from the middle Delta only, equiconcentration line 3.5 advanced inland by a limited distance in the middle and western Delta and retreated slightly in the eastern Delta as shown in figure 11f. Scenario-6 has the least impact under the condition of doubling the current pumping. Therefore, any additional pumping should be practiced in the middle of the Delta, while the pumping from the eastern and western sides should be reduced if possible. Pumping from the middle Delta is recovered through the leakage from the Nile River.

Effect of rice cultivation

To investigate the effect of land use on the sea-water intrusion problem additional scenarios for rice cultivation in the northern and southern parts of the Nile Delta were considered. First, an area of 1 million fed. of rice cultivation was considered in the northern part of the Delta with an average rate of water application of 8800 m^3/fed. Second, the same area of rice cultivation was moved to the southern part of the Delta assuming the same rate of water application. Evaporation and evapotranspiration were evaluated and the remaining water was assumed to recharge the groundwater system. Equiconcentration lines were presented for the two cases. In this exercise, the current pumping activities were maintained and the simulation was conducted under the transient conditions to assess the possible changes in the water quality due to the different scenarios of rice cultivation.

Results indicated that rice cultivation in the southern part of the Delta would contribute effectively to the mitigation of the seawater intrusion. The clay layer in the southern Delta is not only more permeable but also thinner. This will allow the excess irrigation water to percolate deep into the aquifer and recharge the groundwater system. Cultivation of rice in the southern Delta would maintain a steep hydraulic gradient toward the seaside.

It was also noted that reducing areas of rice culti-vation and/or reducing rates of water application in the north would help mitigate the sea-water intrusion. The effect of different scenarios of rice cultivation in the north would be momentous after several years. The average rate of the displacement of the equiconcentration lines is in the order of 50 m/year.

WATER/SALT BALANCE

The Nile Delta aquifer is mainly recharged by freshwater through irrigation practices and irrigation networks. In the southern parts of the aquifer the water table is higher than the aquifer piezometric head, considerable amounts of freshwater can percolate downward to the groundwater. In the northern parts, the aquifer piezometric head is higher than the free water table, hence the groundwater moves upward through the clay cap. This water in the clay cap, either evaporates or finds its way to the drainage system. The aquifer is also intruded through its open boundaries at the Mediterranean Sea with saline water. Due to its greater density seawater migrates into the aquifer. A one cubic meter of seawater contains about 35 kilograms of salts.

The out flux of salts in the Nile Delta aquifer is encountered through:

1- the water flowing back to the sea due to the rotational character of flow at the sea side boundary.

2- the upward flux of groundwater to the upper semi-pervious layer due to the difference between the aquifer piezometric head and the free water table in the clay cap. Salts will either transport with water to the drainage system or accumulate in the clay cap.

3- the water pumped from production wells. Generally small amounts of salts could be lost from the system through pumping activities. The pumped water is mostly fresh.

4- the water flowing out of the system through lateral boundaries.

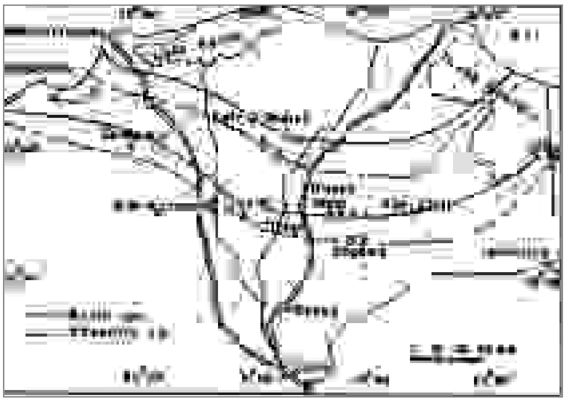

Figure 11c. Comparison between the results of scenario-3 and the basic run.

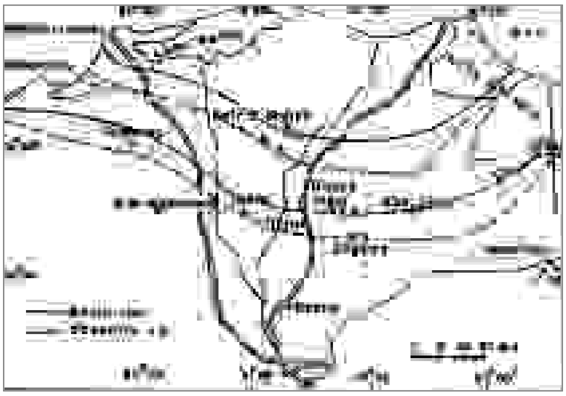

Figure 11e. Comparison between the results of scenario-5 and the basic run.

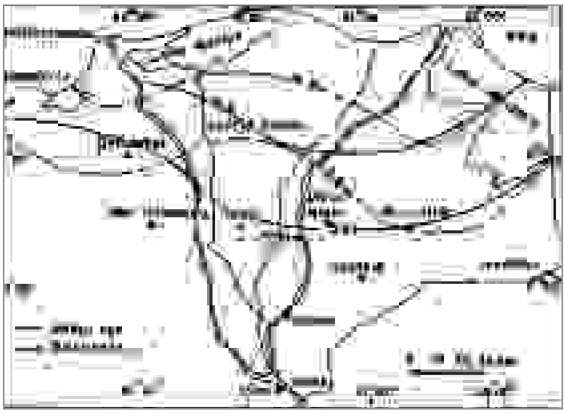

Figure 11a. Comparison between the results of scenario-1 and the basic run.

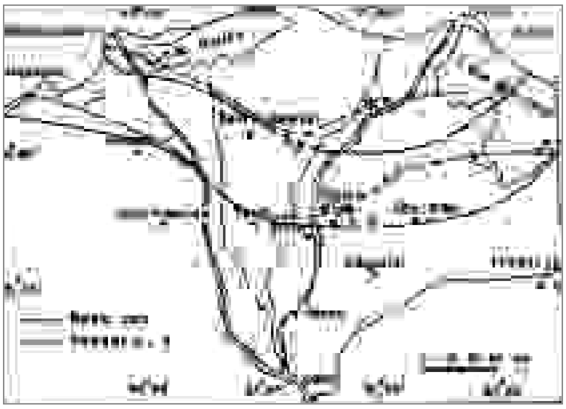

Figure 11b. Comparison between the results of scenario-2 and the basic run.

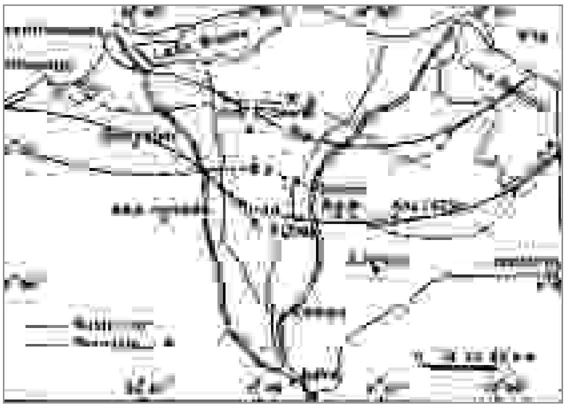

Figure 11d. Comparison between the results of scenario-4 and the basic run.

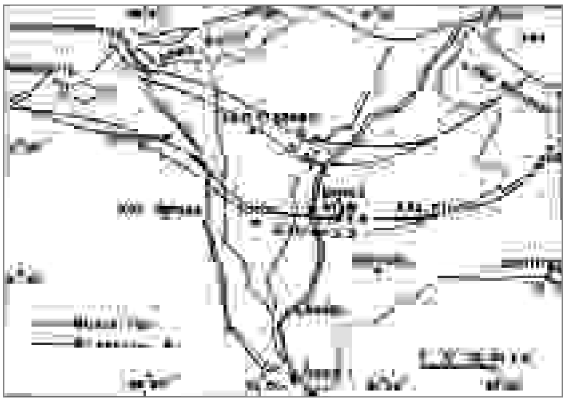

Figure 11f. Comparison between the results of scenario-6 and the basic run.

The mass budget provides information on the quantities of fluid mass and solute mass entering or leaving the simulated domain. It should be noted, however, that the balance calculation does not check the numerical accuracy, but rather aids in interpreting simulation results. Based on the study of Amer and Sherif (1997), 0.512 billion m^3 of brackish groundwater are lost to the Mediterranean Sea annually. The flux of ground-water to the upper clay layer is estimated at 0.895 billion m^3 per year, while the mass flux of salt ions to the clay cap is estimated at 9.77 million ton per year.

CONCLUSIONS

This chapter presents an over view of the geometric, hydraulic and hydrogeological parameters of the Nile Delta aquifer of Egypt. The aquifer is severely subjected to the seawater intrusion from the Mediterranean Sea causing serious environmental impacts. Groundwater resources should thus be developed and managed carefully to avoid any further deterioration in the water quality.

The vertical simulation of the seawater intrusion problem in the middle Delta revealed that the equiconcentration line 35, representing the seawater concentration has intruded inland to a distance of about 63.0 km measured along the bottom boundary from the seaside. A strong cyclic flow is observed near the shore boundary.

To examine the response of the Nile Delta aquifer under different pumping activities, six scenarios were considered and the resulted intrusion was compared to the original one under the current pumping conditions. Two alternatives for the amount of groundwater pumping were thus examined; 2.3 and 4.6 billion m^3/year. For the two alternatives different locations for pumping were checked and the resulted seawater intrusion was assessed for the different cases and compared with the intrusion under the current pumping conditions. For the first alternative, Scenario-2 is the best. All equiconcentration lines were retreated throughout the entire Delta with much more effect in its eastern and western parts. For the second alternative, where 4.6 billion m^3/year were pumped, Scenario-6 has the least impacts amongst the tested scenarios. All tested scenarios indicated that any additional pumping should be practiced from the middle Delta and minimized in the eastern and western parts of the Delta.

Land use with specific reference to the cultivation of rice would affect the seawater intrusion process in the Nile Delta aquifer. It is recommended to increase the area of rice cultivation in the southern parts of the Delta and reduce the rice cultivation in the northern parts. This will help mitigate the seawater intrusion on the long term.

The best way to control the intrusion migration in the Nile Delta aquifer is to maintain a steep slope for the piezometric head "as much as possible" towards the sea side. Therefore, different scenarios, either for the pumping activities or for the land use, should be examined and locations of pumping activities which may not cause more intrusion can be identified. Redistribution of the pumping fields and land use for agricultural practices (with specific reference to the crops of high water demands) may help mitigate the seawater intrusion. Other techniques such as the use of scavenger well, artificial recharge either through open basins or recharge wells and other can also be considered. The feasibility of such techniques should be examined.

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