This paper presents an overview for the seawater intrusion problem in the Nile Delta aquifer. The causes and consequences of the problem are discussed. Two different numerical models have been employed to simulate the problem. A two-dimensional finite-element model (2D-FED) was employed to simulate the problem in the vertical cross section. The variable density approach was considered in the vertical simulation. For the horizontal simulation, SUTRA, a USGS finite-element model, was used to simulate the problem. The results of the numerical simulations were compared with field measurements. The effect of pumping activities and land use with specific reference of rice cultivation are investigated. Different scenarios of pumping and land use are considered for management and mitigation of additional seawater intrusion. It is concluded that seawater intrusion can be controlled if appropriate pumping and land use policies are adopted.

Key Words
Seawater intrusion, groundwater, coastal aquifers, management, numerical simulation, Nile Delta.

INTRODUCTION
Seawater intrusion phenomena are of main concern in almost all coastal aquifers around the globe. The problem is more severe in arid and semi-arid regions where the groundwater constitutes the main freshwater resource. A 3% mixing of seawater with the freshwater in a coastal aquifer would render the freshwater resource unsuitable for human consumption. Therefore, groundwater resources in coastal aquifers should be carefully studied to maintain the dynamic balance between the fresh and saline water bodies.

The shape and degree of the seawater intrusion in a coastal aquifer depend on several factors. Some of these factors are natural and cannot be controlled while others are manmade and could, thus, be managed. These factors, include among others, the type of the coastal aquifer (confined, phreatic, leaky, or multi-layer) and its geology and geometry, water table and/or piezometric head, seawater concentration and density, natural rate of flow, capacity and duration of water withdrawal or recharge, rainfall intensities and frequencies, evaporation rates, physical and geometric characteristics of the porous media, geometric and hydraulic boundaries, tidal effects, variations in barometric pressure, earth tides, earthquakes and other vibrational effects, water wave actions, and chemical changes. The depth of the aquifer at the seaside through which the seawater intrudes inland and pumping and recharge rates and locations are the most critical factors to be considered, Sherif and Singh (2003).

THE NILE DELTA AQUIFER
Layout and previous studies
The Nile Delta and its fringes occupy a total area of 22000 km² (figure 1). The level of the delta land ranges between +17m above the sea level at the south boundary to less than one meter at the north boundary (Farid, 1985).

Figure 1. A layout for the Nile Delta and its fringes.

The Nile Delta aquifer is naturally bounded northward by the Mediterranean Sea and eastward by the Suez Canal. The western boundary extends well into the desert. At the south, the aquifer demises and seems to be isolated from the aquifer of Upper Egypt by an aquiclude approaching the clay cap near Cairo. Many
Hydraulic parameters and pumping activities

Field and laboratory experiments were carried out to determine the hydraulic parameters for the Nile Delta aquifer. Based on field data, an isotropic hydraulic conductivity of 100.0 m/day and a storativity of about $10^{-4}$ to $10^{-3}$ were considered representative of the regional values of the 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 to represent the aquifer medium.

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 that acts as an aquitard, about 20 m thick. The second layer is the lower clayey sand layer, a few meters in thickness, with a higher permeability than the former. The thicknesses of the upper clay cap (aquitard) and the clayey sand layer are well defined at many locations in the Delta. 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.

The vertical movement of water through the upper semipervious layer affects the water balance of the system. The downward movement of water 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 defined by the seepage velocity and can be evaluated from Darcy’s law. The vertical hydraulic conductivity, $K_{sv}$, for the clay layer in the Nile Delta has an average value of $2.5 \text{ mm/day}$. Based on similar studies, the longitudinal dispersivity, $\alpha_L$, and lateral dispersivity, $\alpha_T$, for the Nile Delta aquifer are set equal to 100 m and 10 m, respectively. The free water table is measured at various locations, however, when missing it is generally assumed to be 1.0 m below the ground surface. The piezometric head is measured periodically through an intensive-monitoring network. Records for water levels and piezometric heads are available in the database of the Groundwater Research Institute (GWRI), National Water Research Center (NWRC), Egypt. Pumping activities from different governorates are monitored by the GWRI in Egypt. The total pumping from the Nile Delta is estimated at 2.3 billion m$^3$/year.

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 stations it is assumed linear.

The domain was subdivided into five subdomains; each subdomain was divided into a number of triangular 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 section (A-A) given in figure 2.

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 3a. Equiconcentration line 1.0 intruded the aquifer to a dis-
tance 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 3a). Unfortunately, due to the deep and wide opening of the Nile Delta aquifer to the Mediterranean sea, the sea-water 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 3b) that the depth of the window at the seaside was about 350.0m. 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 sections 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 quadrilateral 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 geometric 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 seawater 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 conditions 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 4 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 $31^\circ 00'$, 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. 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 seawater concentration.

**Figure 4.** Resulted equiconcentration lines in the areal view (current conditions).

**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 4). The simulation is performed via SUTRA to 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-1:** 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 calculated 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 pumping 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 5a - 5f present a comparison between equi-concentration lines 3.5 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 5a & 5b 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 (figure 5d) although the pumping from the entire Delta was doubled yet less intrusion was found in the middle Delta. On the other hand, equi-concentration 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 5f. 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 seawater 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 cultivation and/or reducing rates of water application in the north would help mitigate the seawater 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.

**CONCLUSIONS**

The Nile Delta aquifer is severely subject to the problem of saltwater intrusion from the Mediterranean Sea.
causing serious environmental impacts. Groundwater resources should thus be managed carefully and developed. 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.

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.

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REFERENCES


