Adaptation to the Impact of Sea Level Rise in the Nile Delta Coastal zone, Egypt

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Abstract: The study area comprises a stretch between Ras El Bar and Gamasa along Egypt's northern coast with an average width of 15 Km from the shore line, in the north-south direction. The study area covers a reach of Damietta branch and a portion of Manzala Lake. A detailed hydrogeological data concerning groundwater flow and vertical distribution has been collected. In order to investigate the impact of saltwater/ freshwater interface behavior with different Sea Level Rise on groundwater aquifer system in Nile Delta Coastal zone, a numerical solute transport model was simulated, to provide a clear understanding of saltwater/ freshwater interface behavior. The results showed that the effect of sea level rise will affect the groundwater aquifer system to a certain limit. Taking into consideration that the applied mechanism used in assigning different sea level rise scenarios to the model was assigned as a vertical component only, due to the lack of data about the expected location of the new sea shore line related to the different sea level rise scenarios. The expected variation of heads due to sea level rise was a change in head ranging from 0.1 to 0.5 meters and the change in groundwater salinity marked only at a distance of 7 km from the sea (southwards). Several mitigation measures were proposed and evaluated using the model related to the three expected SLR scenarios. These mitigations include artificial recharge through injection wells, impervious barriers (slurry wall), constrains on groundwater extraction and implementation of local monitoring network.

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Key Words: Climate change, Groundwater Management, Sea water intrusion, Groundwater modeling, SEAWAT.

1. Introduction

Coastal areas are important for human settlement and development. It is estimated that more than half the world's population lives within 60 km of the shoreline, and this number could increase up to three quarters over a decade (UNCED, 1992). Over exploitation of groundwater in coastal aquifers may result in intrusion of saltwater. Contamination of coastal aquifers may lead to serious consequences on environment, ecology and economy of that region.

The saltwater intrusion in a coastal aquifer is a highly complex and nonlinear process. Management of coastal aquifers requires careful planning of withdrawal strategies for control and remediation of saltwater intrusion (Datta, 2009). Fresh water in coastal aquifers, supplied by rainfall, flows towards the sea floating above the heavier seawater. Under the fresh water a body of seawater exists often in the form of wedge. The dominant factors controlling seawater intrusion are the flow regime above the intruding wedge, the variable density of fluid and hydrodynamic dispersion (Kopsiaftis, 2009).

Density-dependent flow and transport processes, and saltwater intrusion in coastal aquifers, however, have been shown to be significantly affected by the common and random spatial variability of hydraulic properties in geologic formations (Dagan and Zeitoun, 1998; Simmons, 2001; Diersch and Kolditz, 2002; Prasad and Simmons, 2003 Prieto, 2006).

Egypt has a relatively long coast line, including (i) more than 950 km along the Mediterranean sea in the north; (ii) 300 km along the Gulf of Aqaba ;(iii)400 km along the Gulf Suez ;and (iv)1,200 km along the Red Sea, in the east . The coastal area of the Nile delta is one of the most populated regions in Egypt and is still attracting more population and variety of development activities. The coastal area of the Nile delta is very flat. One of the major constraints, facing the development, is the expected effect of sea level rise on the Nile delta aquifer system (RIGW/IWACO1998). Sea level rise will increase the intrusion of sea water causing the deterioration of groundwater quality. Consequently, the pumping rates from the Coastal Nile Delta Aquifer should be decreased affecting the development using groundwater in these areas. The goal of water resources planning and management is to meet the water demand of different uses, in the most effective manner with acceptable quality.

The purpose of this study is to investigate the impact of saltwater/ freshwater interface behavior with different Sea Level Rise on groundwater aquifer system in Nile Delta Coastal zone and test alternative mitigation options. A three dimensional, density dependent, finite difference based flow and transport simulation model (SEAWAT) through Visual MODFlow Pro. 4.2 package was selected to simulate the study area. The calibration analysis of the simulated seawater intrusion model is performed using actual data measured in the field including static groundwater head, electrical conductivity and total dissolved solids recorded in the year 2011.

2. Site description

Topographically, The Nile Delta region is almost flat with an average mild slope from Cairo to the Mediterranean Sea except some elevated sand dunes near the Mediterranean coast. Coastal deposits cover major part of the study area near Gamasa. The rest of the area is covered by sand dunes.

2.1. Physical settings of the study area

The study area comprises a stretch between Ras El Bar and Gamasa along Egypt's northern coast with an average width of 15 Km from the shore line, in the north south direction. The study area covers a reach of Damietta branch and a portion of Manzala Lake. The location of the study area is shown in Figure (1).

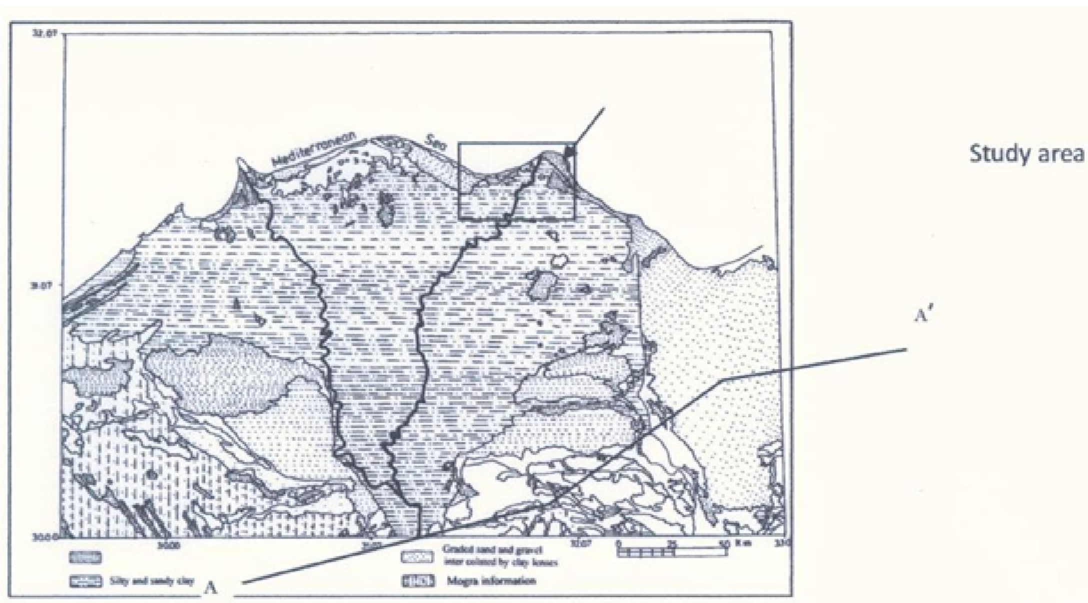

Figure (1) Local study area on the Nile Delta Region

2.2. Hydro geological characteristics of the study area

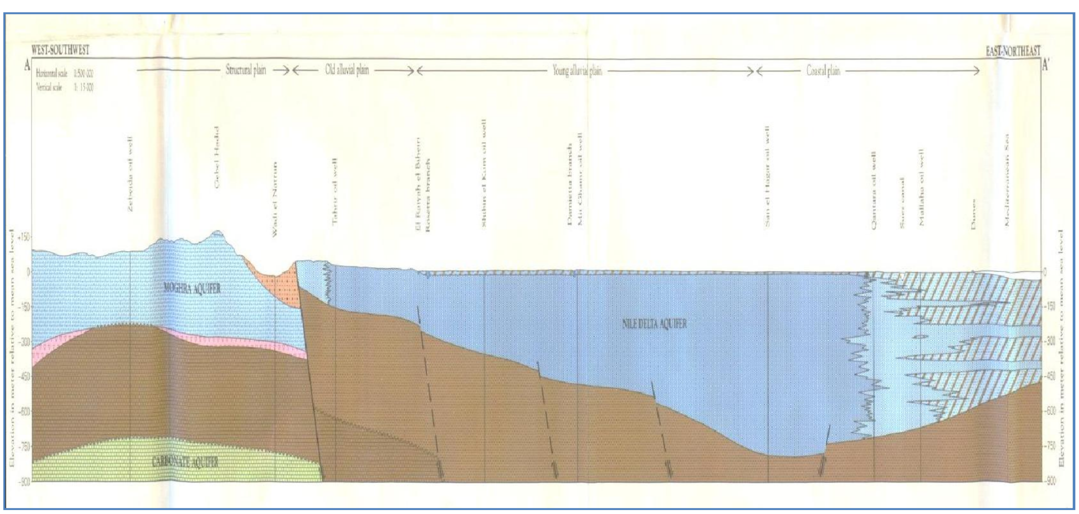

Figure (2) Regional hydrogeological cross section for the Nile Delta

The existing aquifer, in the study area, belongs to the main Nile Delta aquifer system. It is mainly formed of the Pleistocene graded sand and gravel, changing to fine sand intercalated with clay lenses. This aquifer is a semi-confined one. Thickness of the semi-confining layer is generally between 0 and 20m and increases near the study area reaching thickness of 70 m. Figure (2) shows a regional hydrogeological cross section in the Nile Delta. The saturated thickness of the aquifer ranges between 100 and more than 800 m reaching 1000m near the study area. The hydraulic conductivity ranges between 35 and 75m/day but decreases near the coastal line, due to the increase of the clay content. The transmissivity reaches 25000 m^2 /day in the apex of the Nile Delta (RIGW/IWACO, 1992).

The groundwater flow is directed from south to north where the piezometric head decreases gradually from more than 15 m + MSL in Cairo city to less than 1m + MSL near the coast, Figure (3).

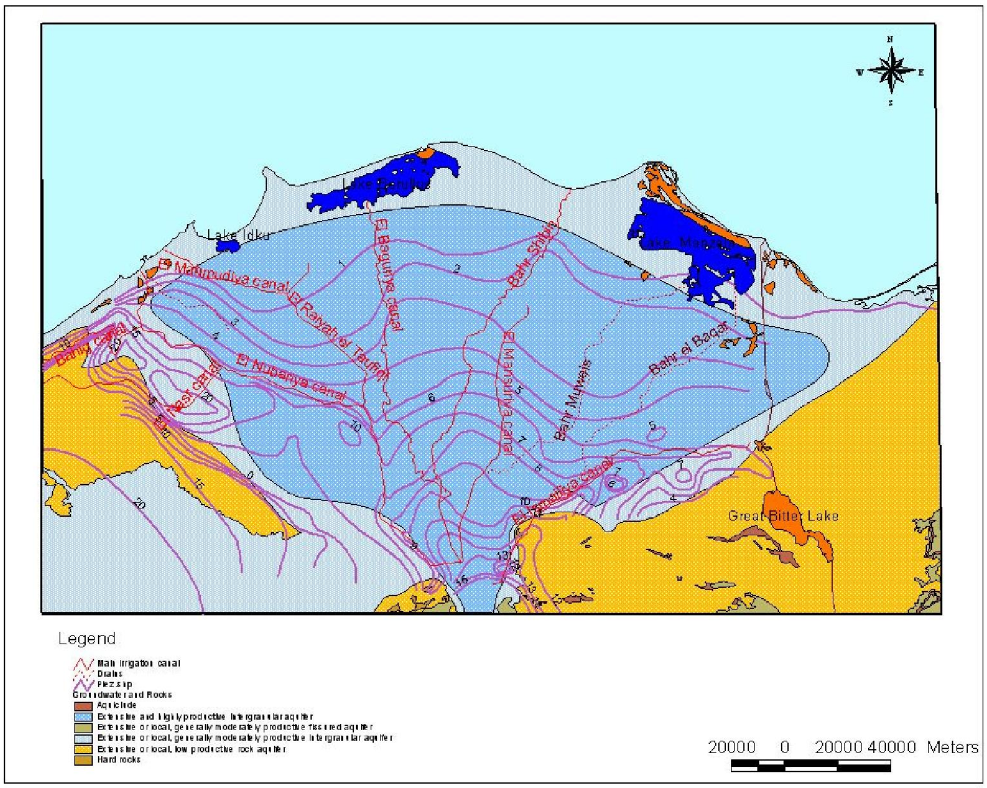

Figure (3) Regional groundwater contour map for the Nile Delta

2.3. Salinity distribution

Several authors indicated the presence of highly saline water in the north of Nile Delta (45000mg/l (Farid, 1985) and 120000mg/l (Saleh, 1980) which could be attributed to the subsurface intrusion of sea water (Laeven, 1991). Over the last decades, several attempts have been made to predict the salinity distribution within the Nile Delta aquifer using mathematical and numerical models. Early attempts were based on sharp-interface assumption in combination with the Ghyben-Herzberg relationship (Farid, 1980), or the variable-density flow models (Amer and Sherif, 1995). Some of these investigators defined that the actual fresh/ sea water interface is actively moving far inland where sea water intrusion reached Tanta, while others believe that the aquifer system and salt water intrusion are in a steady state (RIGW/IWACO, 1998).

RIGW (2002) prepared groundwater salinity contour maps for the years 1960 through to 2000. These maps concluded that the groundwater salinity in the Nile Delta aquifer has been affected by the development activities, in the Nile Delta region. The obvious effect is that groundwater salinity increased after the year 1980 and the iso-salinity line of 1000 ppm moved southward indicating more saline water intrusion as shown in map of the year 1990 (Figure (4).

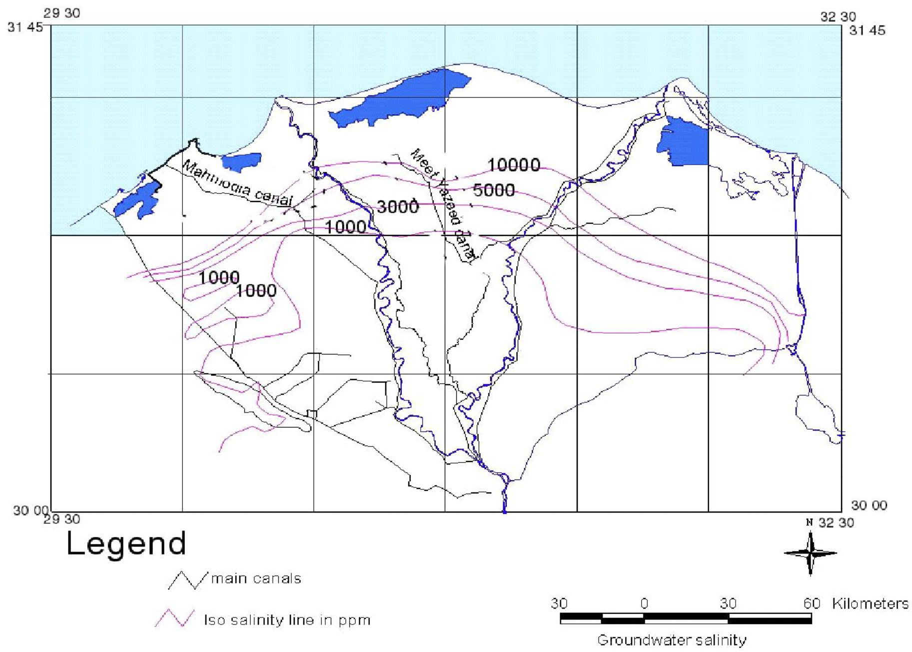

Figure (4) Distribution of Groundwater Salinity in Nile Delta in 1990

2.4. Field investigation and data collection

Due to the simulation of the groundwater model in this localized area, a specific hydrogeological data concerning the local groundwater flow and vertical distribution of salinity has been collected. A field campaign was implemented during the period of 4th to 7th July, 2011, where nine monitoring points related to RIGW were inventoried, the depths of these wells varies from 40 to 600 meters. A survey work was done for leveling of top casing of the wells and measuring the depth to groundwater, where the depth to groundwater varies from 0.2 to 19 meters. The groundwater salinity was measured in existing observation wells at depths that vary from 200 to 600 meter. The salinity values vary between 10,000 to 61,000 ppm, respectively. On the other hand, the salinity at shallow wells with depths from 40-70 meter amounts to 7,500 to 9,000 ppm, respectively. All the collected data were used to simulate the groundwater model.

3. Numerical simulation for the study area

Numerical models are, generally, required to solve complex geometry, boundary conditions and equations describing coupled and uncoupled processes in heterogeneous and anisotropic formations under various initial and boundary conditions. In most numerical models the governing equations are formulated to simultaneous equations relating unknown variables at discrete nodal and different times. Many powerful methods are available for this purpose. The various numerical models differ, mainly, in the method of numerically formulating the problem.

Various studies, including modeling of fresh and salt water movement has been carried out. These studies have been made to predict/ reproduce the salinity distribution within the Nile Delta region. Recently, Gaamea, 2000 investigated the geological evolution for the Nile Delta and its impact on the development of the salinity distribution on the transition zone using two mathematical Models (Metropol and Compaction Disequilibrium Model), and he concluded that the movement of the transition zone is decreasing with the increase of withdrawal of brackish water. The shape of the transition zone is, almost, stable.

The previous studies are, now, out of date and other factors have raised and needed to be put into consideration by using cutting edge software. Climate changes, all over the world, raised an extreme concern to investigate its impacts. Sea Level Rise is the main thread facing Egypt in the coming decades. This study will investigate the impact of SLR on the groundwater, in the studied area.

3.1. Visual MODFLOW with SEAWAT engine

Visual MODFLOW Pro.V.4.2 was selected to simulate the study area as the most complete and user friendly, modeling environment for practical applications in three-dimensional groundwater flow and contaminant transport simulation. This software was developed by Waterloo Hydrogeologic Inc. The SEAWAT engine is used to allow modeling of variable density flow such as seawater intrusion modeling problems. SEAWAT combines a flow code (MODFLOW) with a solute- transport code (MT3DMS) to form a single program that solves the coupled flow and solute-transport equations. It formulates flow equations using mass conservation instead of volume conservation.

3.2. Simulation of the studied area

3.2.1. Modeled area

The simulated area extends from Latitudes between 31° 21' 12" E and 32° 01' 30" E and Longitudes between 31° 00' 38" N and 31° 34' 08" N. Figure (5) shows the simulated area. The simulated modeled area is about 4000 Km^2. The general topography of the area is sloping from the south, at 1 m, towards the north at the sea level.

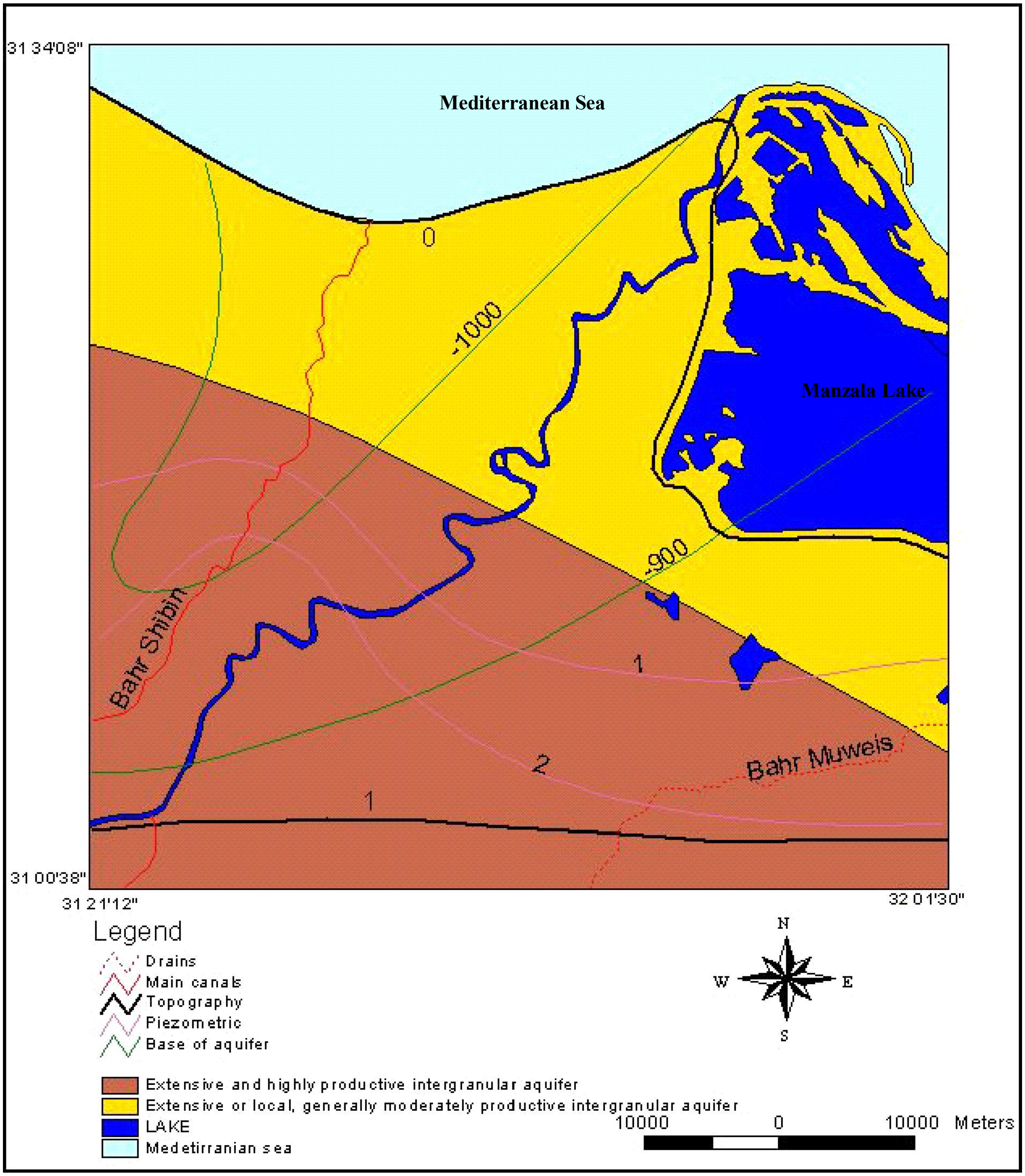

Figure (5) the modeled area

3.2.2. Model Grid

The simulated area is covered by a grid of 35 rows × 35 columns. Then, finer grid, at the coastal area, is used to increase the accuracy of simulated area near the shore. The total number of cells is to 9100 cells. Figure (6) shows the model 3-D grid. Different layers and position of the sea are visible in the figure.

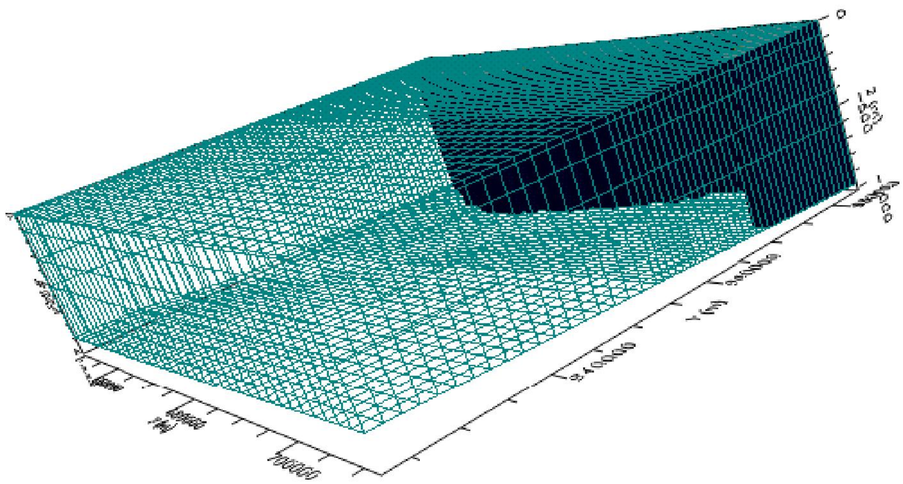

Figure (6) The model Grid

3.2.3. Boundary conditions:

3.2.3.1. Flow Boundary Conditions

The flow Boundary conditions assigned to the model, are shown in Figure (7), as follows:

- A zero specified head at the northern boundary of the model representing the Mediterranean Sea.
- A specified head of 2 meters at the southern boundary of the model, representing the piezometric head at that area.
- The Damietta branch was assigned to the model using the river package using all the geometry and water levels of the different reaches of the branch as well as the conductance values.
- Manzala Lake was also assigned as a water body using river package.

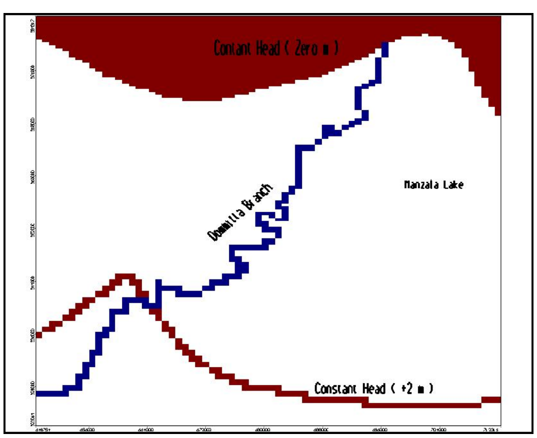

Figure (7) Flow boundary conditions

3.2.3.2. Concentration Boundary Condition:

The concentration boundary conditions were assigned to the model as follows:

- A constant concentration of 35,000 ppm for the sea water.
- Constant concentration value of the water in the Manzala lake
- Concentration value of the water in Damietta Branch

3.2.4. Hydraulic Conductivity and Dispersivity:

The hydraulic conductivities of different soil types were assigned to the model. The hydraulic values range from 50 m/d to 0.01 m/d (RIGW/IWACO, 1992). The dispersivity value was assigned to the model as one tenth the dimension of the studied area.

3.3. Calibration of the model

Before using the model in predicting the response of the system to any future activities, it must be calibrated. Calibration of the model refers to a demonstration that the model is capable of producing field measured heads, flow and concentrations, which are the calibrated values. The solute transport models are calibrated on two stages which are calibration of the flow and calibration of the concentration salinity (solute transport). The model calibration is performed through several trials by changing the hydraulic conductivity, the recharge and dispersivity values. The calibration target, of the model, is to minimize the difference between the calculated and the measured heads and concentrations.

3.3.1. Calibration of the flow

The model was calibrated for the flow and the output calibrated values for the hydraulic conductivity values are shown in Table (1).

Table (1) Hydraulic Conductivity of different soil layers

Type of soil	Hydraulic Conductivity (m/d)
Clay Cap	0.2 – 0.05
Quaternary aquifer (mostly Sand)	20 - 50
Clay lenses intercalated with sand	0.1
Deep Quaternary Aquifer (mostly sand)	40

The simulated heads for the shallow and the deep groundwater for the modeled area are as shown in Figures (8) through (10). Figure (8) shows the flow direction in shallow aquifer (layer 2) which is directed from South East to North West towards the Manzalla lake. The groundwater levels vary between 0 to 3 meters above MSL. In Figure (9) which presents the groundwater heads in the deep layer of the modeled area where it varies from -7.5 to -11 m related to MSL and the flow direction is northwards to the sea. Vertical cross sections were prepared to present the calculated heads at the present time in north south direction, Figure (10).

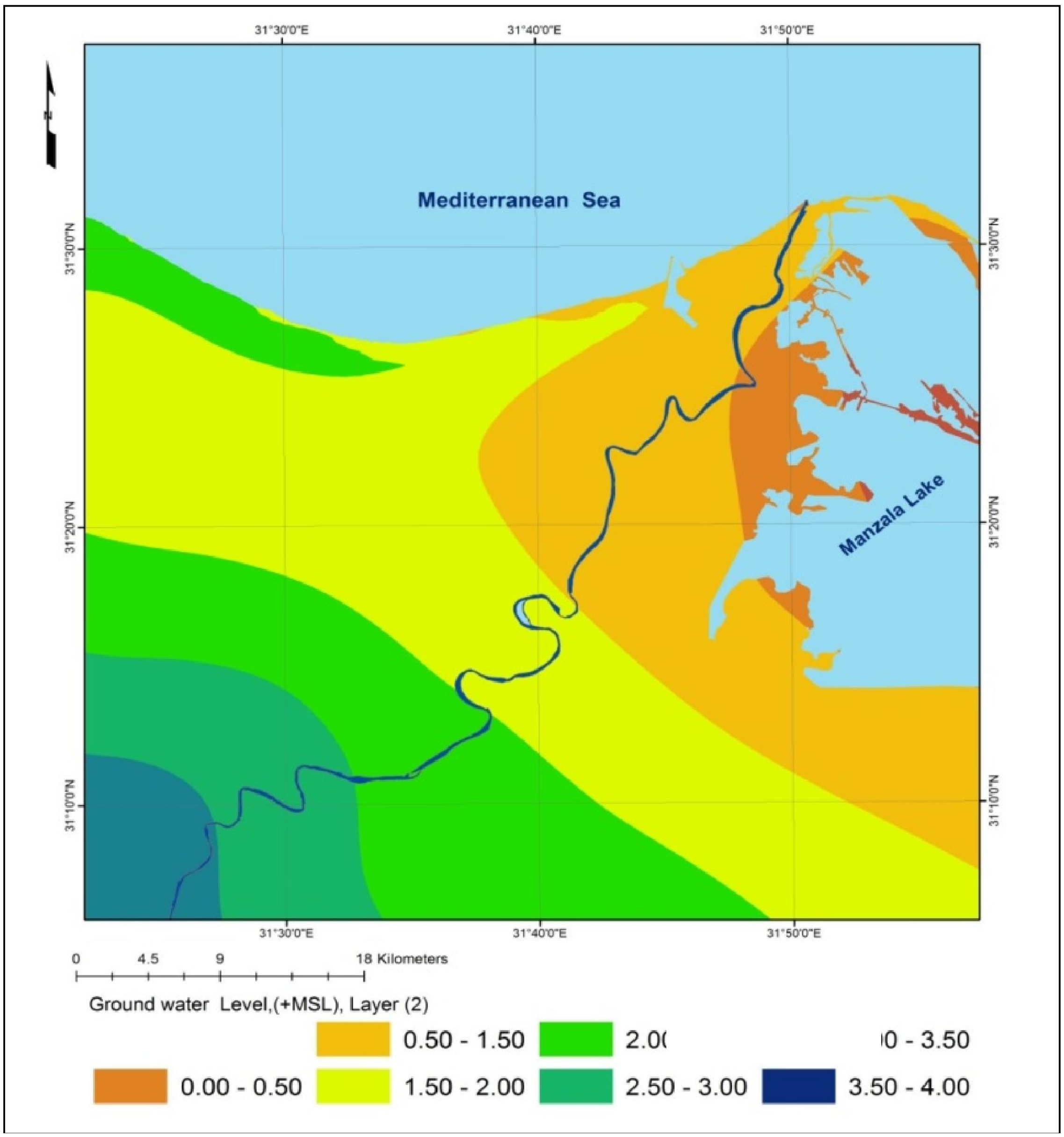

Figure (8) Calculated heads for shallow groundwater (2011)

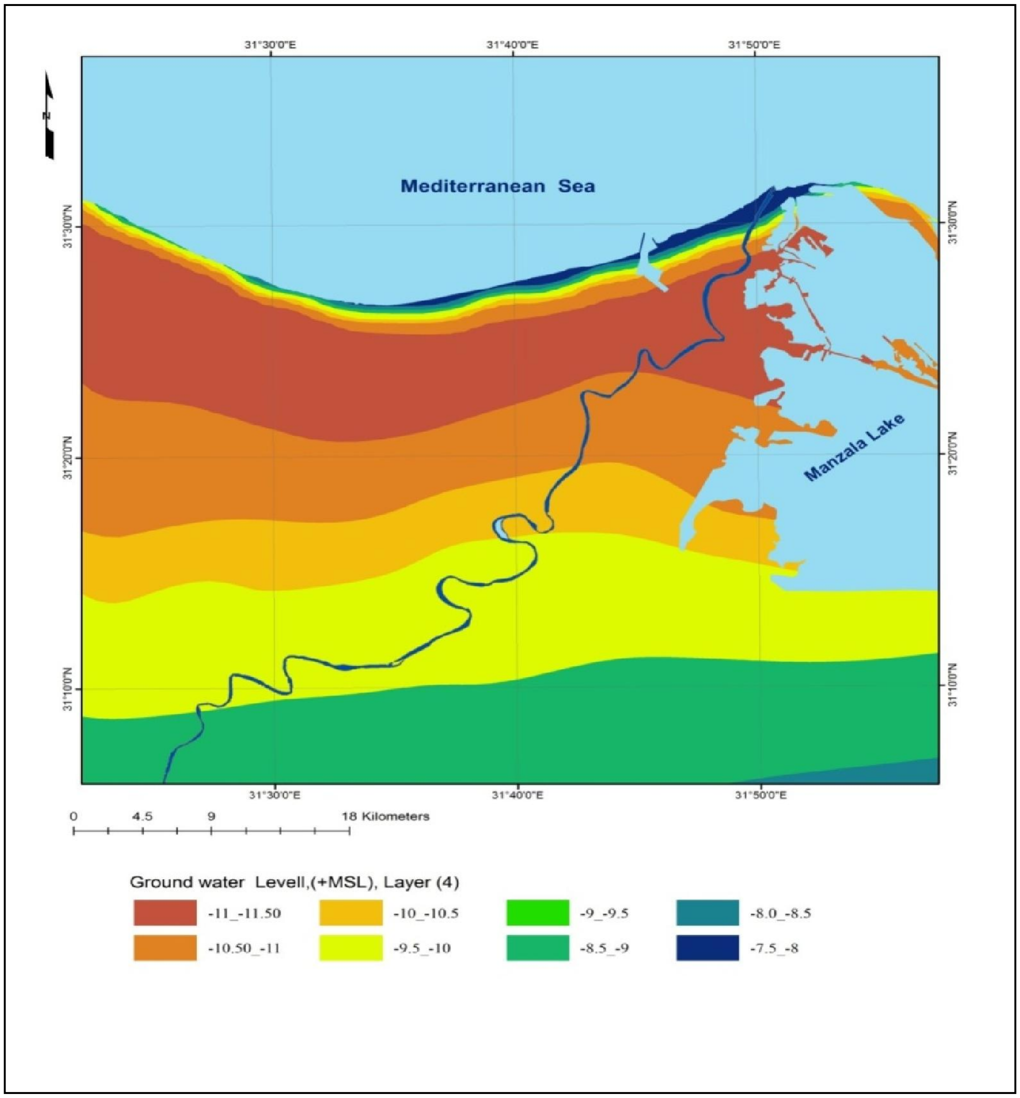

Figure (9) Calculated heads for deep groundwater (2011)

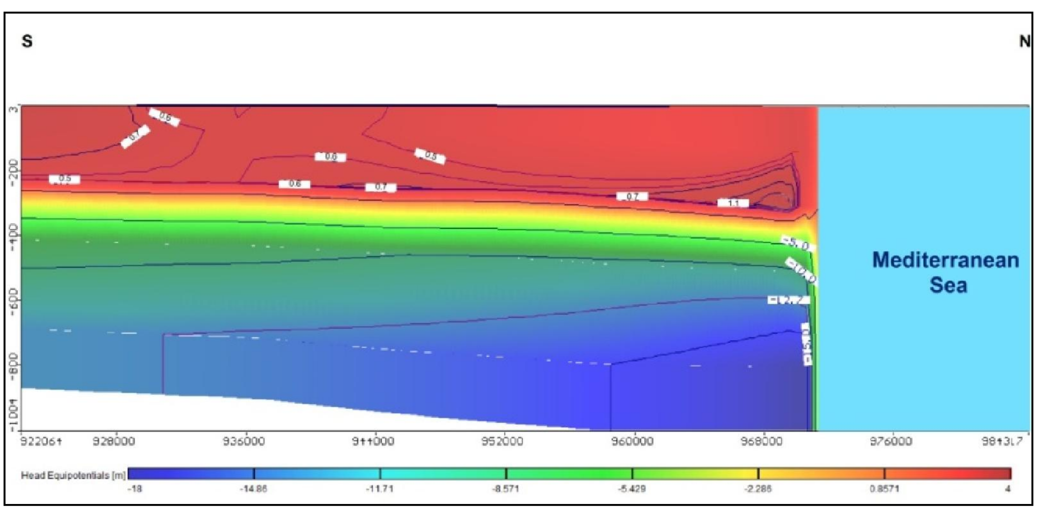

Figure (10) Cross section in the modeled area at present time.

3.3.2. Calibration of the concentration

The model was calibrated against the measured salinity values based on RIGW data bank and field survey for the multi depths groundwater quality monitoring wells. The calibration process for concentration (salinity) was conducted by trial and error changing the dispersivity value of the soil. The simulated concentrations of the salinity values for the different layers were calculated. The following Figures (11) and (12) show the concentration values (salinity) for shallow layer (layer 2) and deep layer (layer 4), in the modeled area, respectively. Figure (11) indicates that the shallow groundwater salinity varies from 5,000 to 35,000 ppm, the salinity increases northwards. Figure (12) indicates that the average deep groundwater salinity varies between 40,000 and 60,000 ppm. The low salinity exists in the northern part while the high salinity exists in the southern part of the modeled area. A vertical cross section was prepared to present the calculated vertical salinity at the present time in north-south direction, Figure (13).

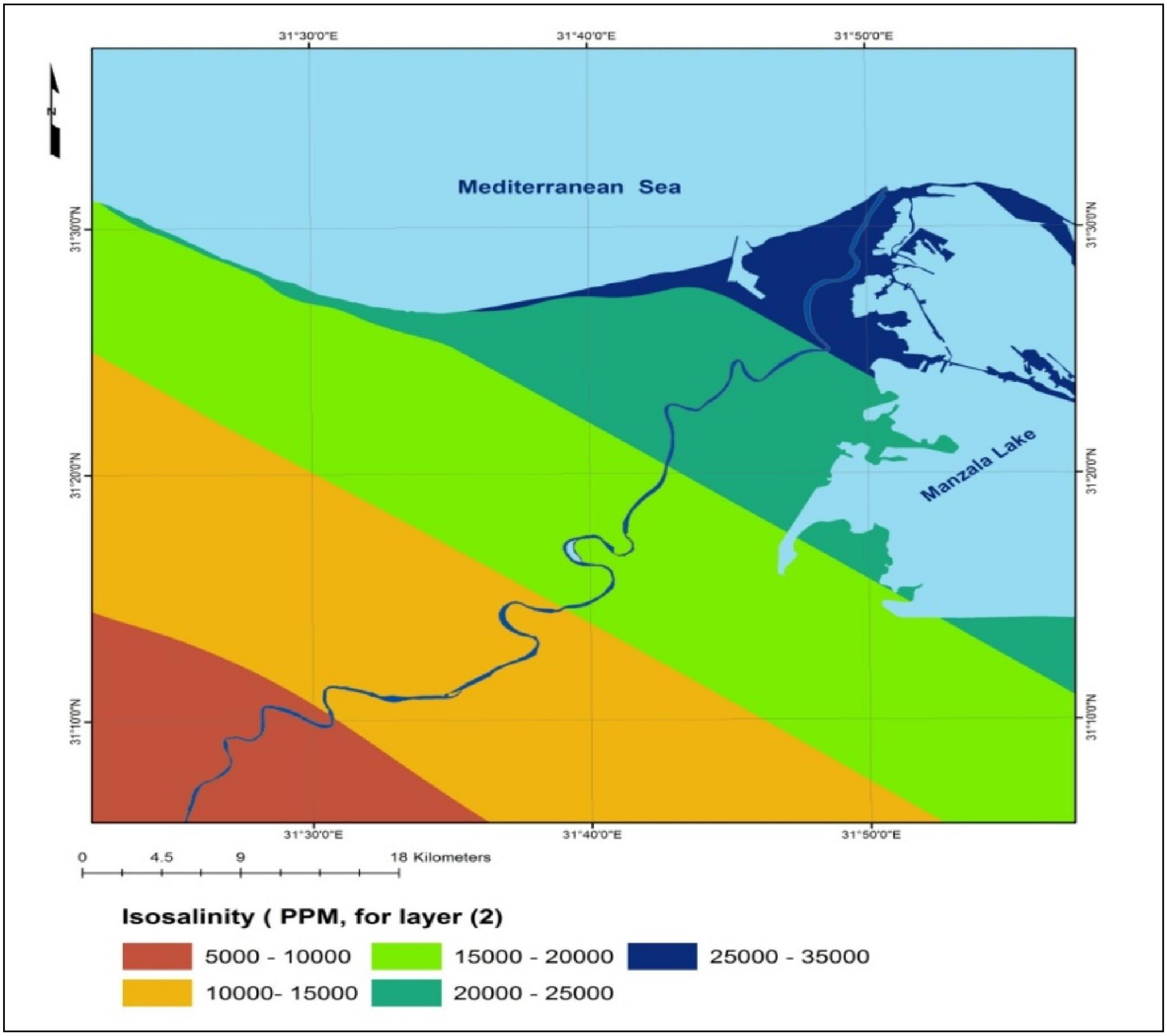

Figure (11) Calculated concentration of shallow groundwater (2011)

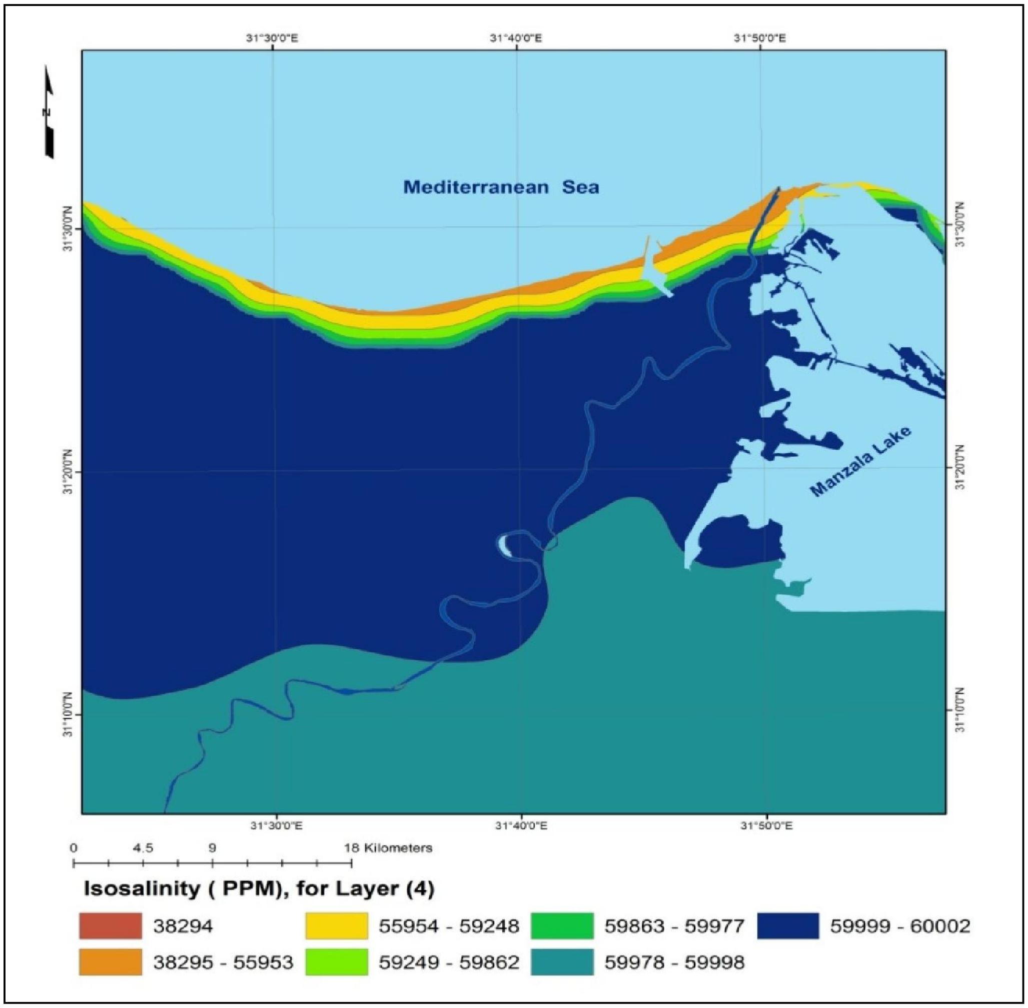

Figure (12) calculated concentration of deep groundwater (2011)

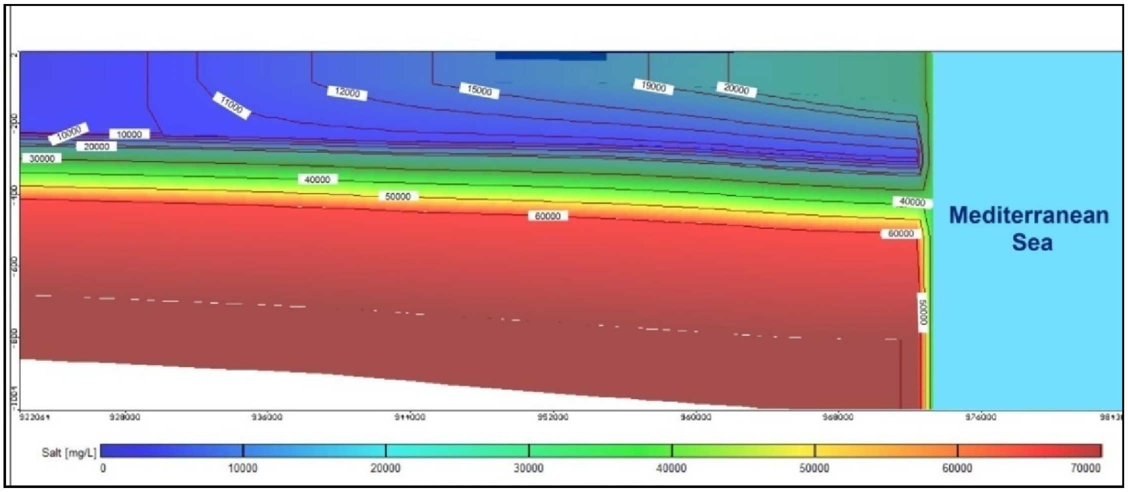

Figure (13) Cross section for calculated concentration (2011)

4. Evaluation of different Sea Level Rise Scenarios on groundwater aquifer system

Sea level rise (SLR) potentially impacts human populations (e.g., those living in coastal regions and on islands) and the natural environment (e.g., marine ecosystems). Global average sea level has risen with an average rate of about 1.8 mm per year over the years 1961 through to 2003 and at an average rate of about 3.1 mm per year during the years 1993 through to 2003. It is unclear whether or not the increased rate observed between 1993 and 2003 reflects an increase in the underlying long-term trend.

There are two main factors that have contributed to observed sea level rise. The first is thermal expansion: as ocean water warms, it expands. The second one is from the contribution of land-based ice due to increased melting process. The major storage of water, on earth, is found in glaciers and ice sheets.

4.1. Impacts of sea level rise on groundwater

It is expected the sea level rise will lead to increase the sea water intrusion southwards into fresh groundwater aquifers. One of the main objectives of the study is the detection of the fresh/ saline interface and its movement due to different expected increase in SLR. In order to study the predicted results of SLR on groundwater in the study area, several scenarios of SLR will be tested using the calibrated model to assess its impacts on groundwater status in the study area. Within this study, three options of SLR were evaluated. The effect of 0.25, 0.5 and 1.0 meter SLR was determined on groundwater heads and salinity after 30 years.

From the output results, it can be concluded that the effect of sea level rise will affect the groundwater aquifer system to a certain limit. The applied mechanism used in assigning different sea level rise scenarios to the model was assigned as a vertical component only, due to the lack of data about the expected location of the new sea shore line related to the different sea level rise scenarios. However this output is satisfying in the present time and can be taken as indication of the predicted effect of sea level rise on both quality and quantity groundwater system.

The expected variation in ground heads, after 30 years, due to sea level rise will lead to an increase in groundwater head ranging from 0.1 to 0.5 meters. The change in groundwater salinity will be marked only at a distance of 7 km from the sea (southwards).

5. Mitigation measures for salt water intrusion

From the above mentioned discussion about the expected effect of the sea level rise on groundwater system, several mitigation methods will be proposed and evaluated using the model. The main purpose of this mitigation will be alleviating the impacts of sea level rise on groundwater aquifer system in the Nile delta. The proposed mitigation measures are:

1. Artificial recharge of groundwater through injection wells using different sources of water (treated sewage water, excess surface water).
2. Building an impervious barrier (slurry wall) to prevent the salt water intrusion.
3. Propose some constrains for land-use and groundwater extraction within the highly affected zone (10 km southwards present sea line).
4. Implementation of local monitoring network with various depths to monitor any change in fresh / saline interface.

In the following, brief discussions will be given for each of the above mentioned mitigation measures.

5.1. Artificial recharge through injection wells

The study proposed injection of fresh water or tertiary treated sewage water into the aquifer along, the sea coast, through a group of wells. Different scenarios of injection rates and distribution schemes of the wells were studied and evaluated through the model. The most promising scheme was through proposing of 13 wells at a distance of 2.7 km southward the sea with distance about 3.6 km between the wells. The depth of the wells is about 300 m depth. The injection rate is 600 m^3/day for a period of 30 years. Figure (14) shows the proposed locations of the injection wells.

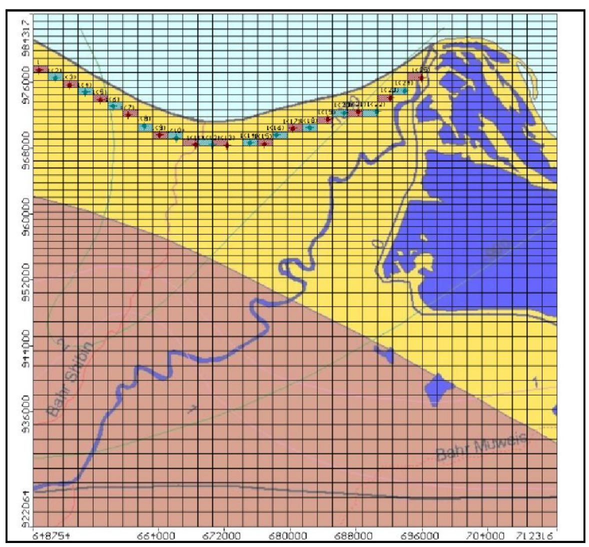

Figure (14) shows the proposed locations of the injection wells

The application of the proposed scenarios of injection wells simulating the three expected changes in sea level rise indicates that there is marked change in groundwater salinity and, consequently, retention of saline water interface. The salinity will be changed in average range of 10,000 to 30,000 ppm in the area of the injection zone. This result keeps the proposed scheme to be promising, especially, that treated sewage water that can be used in the injection.

5.2. Building an impervious barrier (slurry wall) to prevent the salt water intrusion

The effect of the subsurface barrier has been studied with different depths by the model in a hypothetical case. The subsurface impermeable barrier is proposed parallel to the sea at distance 100 meter. The analysis of the results showed that, increasing the barrier depth, delays the salt water intrusion in the coastal aquifer. But, after long term, the subsurface barrier is not effective whatever the barrier depth.

5.3. Constrains for land-use and groundwater extraction

Constrains for land-use and groundwater extraction is an option of mitigation measures used in the highly affected areas in the coastal zone. The highly affected areas were detected by the model to be of 10 km southwards the sea. These areas will be high vulnerable and will be affected by rising sea level and the consequence immersion of land by sea shore movement. This option will be regulating the land-use activities and prevent groundwater extraction in the highly deteriorated areas. Land-use applications directly affect the rate of recharge which reaches the shallow groundwater, especially when using this area in agricultural activities. For this reasons, some constrains have to be proposed in order to avoid waste of investments within these areas. Also, encouragement of using crops that result in high recharge rates to the shallow groundwater in these areas.

In addition to that, groundwater extractions from the highly effected zone will led to disturbance of hydraulic balance between fresh / saline interface and enhance the encroachment of saline water from the sea into the aquifer. Therefore it is important to prevent any groundwater extraction within the northern zone of the Nile Delta.

5.4. Implementation of local monitoring network

Groundwater monitoring is important within the highly vulnerable area. The distribution and design of the monitoring network is to be prepared in view of the output of the model as discussed previously. The study proposes three groups of monitoring wells (multi depths monitoring wells). Each group consists of three wells of depths 50, 150 400 meters. The collected data from these wells will be important and used for the recalibration of the solute transport model.

Conclusion

The main purpose of the study is to investigate the impact of saltwater/ freshwater interface behavior with different Sea Level Rise and set alternative mitigation options. In order to fulfill the requirements of the study, several activities has been established including collection of previous available hydrogeological studies, field investigations, well inventory and simulation of solute transport model. Visual MOD FlOW 4.2 software, SEAWAT, was used.

The model was calibrated with regional and local data concerning groundwater heads and vertical groundwater salinity distribution. Several scenarios were proposed for the expected sea level rise 0.25, 0.5, 1 meter. The output results indicate that the sea level rise will affect the groundwater aquifer system to a certain limit. The selected simulated time of the model, 30years, was chosen by trial and error methods until the model reached the steady state. The expected variation of heads after 30 years, due to sea level rise, will lead to change in head ranging from 0.1 to 0.5 meters. The change in groundwater salinity was marked only at a distance of 7 km from the sea (southwards).

Several remedies measures were proposed and evaluated using the model related to the three expected SLR scenarios. These mitigations include artificial recharge through injection wells, impervious barriers (slurry wall), constrains on land-use and groundwater extraction and implementation of local monitoring network.

Socio-economic impact, of the mitigation measures, on coastal settlements indicates that the injection wells contribute in retarding the seawater intrusion. But, the disadvantage will be that these injection wells will contribute in raising the groundwater level in the region. Increasing the barrier depth delays the salt water intrusion in the coastal aquifer. But, after long term, the subsurface barrier is not effective whatever the barrier depth. The conclusion is to block the entire thickness of the aquifer to prevent saltwater intrusion while this conclusion may not be practical or economical for thick aquifers like the Nile Delta aquifer.

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