INVESTIGATION OF SOME POTENTIAL PARAMETERS AND ITS IMPACTS ON SALTWATER INTRUSION IN NILE DELTA AQUIFER

Ismail M. Abdelaty 1, *, Hany F. Abd-Elhamid 2, Maha R. Fahmy 3 and Gamal M. Abdelaal 4

1, 2, 3, 4 Staff in Department of Water and Water Structures Engineering, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt

Received 18 May 2014; Revised 8 June 2014; accepted 18 June 2014

ABSTRACT

Coastal aquifers represent an important source of freshwater in arid and semi-arid regions. The increased extraction from coastal aquifers decreases the freshwater spilled out to the sea. Consequently, seawater intrusion increases inland and wells become contaminated. Nile delta aquifer in Egypt is one of these aquifers which subject to sever seawater intrusion from Mediterranean Sea. Saltwater intrusion is considered one of the main processes that degrade water-quality by raising salinity. It may occur due to human activities and/or by natural events. Over-pumping is considered the main cause of saltwater intrusion. Moreover, sea level rise accelerates saltwater intrusion. Due to climate change, it is expected a rise in temperature which would lead to an increase in the rates of evaporation and this will be accompanied by decrease in water level of the Nile, also this change would lead to sea level rise (SLR). A result to rise in population intensity and expected shortage in surface water would lead to an increase of extraction rate from groundwater. In this paper 3-D model (SEAWAT) is used to study seawater intrusion in Nile delta aquifer considering different scenarios, the first scenario is the increase of sea level by 25, 50 and 100 cm, the second is to decrease the surface water system by 25, 50 and 100 cm, the third is to increase the extraction rate by 25, 50 and 100% and fourth scenario is a combination of while the three scenarios. The results show that saltwater intrusion in East Nile delta reach 76.25 km from shore line for base case, but reaches to 79.25 km, 79 km, 82 km and 83 km for Equiconcentration line 35 and reaches to 92.25 km, 92 km, 91.75 km and 92.75 km for scenarios1, 2, 3 and 4 respectively after 100 year for Equiconcentration line 1.00. It is also observed that saltwater intrusion in the Middle reaches to 63.75 km from shore line for base case, but reaches to 67.25 km, 67.25 km, 65.75 km and 67.50 km for Equiconcentration line 35 and reaches to 97 km, 97.50 km, 107.75 km and 110 km for scenarios1, 2, 3 and 4 respectively after 100 year for Equiconcentration line 1.00. It is clear that saltwater intrusion in the West reaches to 48.00 km from shore line for base case, but reaches to 49.00 km, 48.75 km, 45.50 km and 47.75 km for Equiconcentration line 35 and reaches to 73.75 km, 74 km, 79.50 km and 79.50 km for scenarios1, 2, 3 and 4 respectively after 100 year for Equiconcentration line 1.00. Finally increasing SLR or decreasing recharge from

* Corresponding author.

Email address: Eng_abdelaty2006@yahoo.com
Ismail M. Abdelaty et al., Investigation of some potential parameters and its impacts on surface water or increasing extraction rate from wells increases saltwater intrusion in land direction but applying combination of these scenarios will damage large quantity of fresh water in the aquifer.

Keywords: Saltwater Intrusion, Climate Change, Sea Level Rise, Over-Pumping, SEAWAT, Nile Delta aquifer.

1. Introduction

Saltwater intrusion is a natural process that occurs in virtually all coastal aquifers connected to the sea as a consequence of the greater density of the seawater relative to the water in the aquifer, saltwater intrusion is a phenomenon with a long history of study as shown in Fig.1 [8]. Saltwater intrusion has a direct impact on groundwater resources, soil salinity, agricultural productivity and quality in the coastal zone [11].

Saltwater intrusion or encroachment is shoreward movement of saltwater from ocean into coastal aquifers due to the over pumping of groundwater, and it is a dynamic equilibrium of groundwater movement, consequently leading to the possibility of polluting the groundwater and corroding subsurface structures [13]. When the groundwater is pumped from aquifers which are in hydraulic connection with the sea, the gradients that are set up may induce a flow of seawater from the sea toward the well [14]. The main causes of saltwater intrusion include over-abstraction of the aquifers, Seasonal changes in natural groundwater flow, Tidal effects, Barometric pressure, Seismic waves, Dispersion and Climate change – global warming and associated sea level rise. Different measures have been presented to control saltwater intrusion in coastal aquifers [6]. The intrusion controlled by Physical model includes fresh water injection, saltwater extraction, and subsurface barrier. The fresh water injection rate of about 10% of the usage rate can effectively push the interface toward the shoreline, and keeping the pumping well free of salinity [38].

Different methods of preventing saltwater from contaminating groundwater sources including reduction of pumping rates, relocation of pumping wells use of subsurface barriers natural recharge artificial recharge abstraction of saline water combination techniques [37]. Coastal aquifers are affected by the rise in the sea level due to climate change and global warming. The rise in sea level will shift the saltwater interface further inland. As a result, the extraction wells that were originally in fresh groundwater may then be located in brackish water or saline water and upconing may occur [1]. Nile Delta aquifer is among the largest groundwater reservoirs in the world, due to the excessive pumping over the last few decades, the groundwater quality in the northern parts of the Delta has been deteriorated considerably, any additional pumping should be practiced in the middle Delta and pumping from the eastern and western parts.
should be reduced [33]. Abd-Elhamid and Javadi [2] developed a numerical model for simulating solute transport through saturated and unsaturated soils with the application to predict saltwater intrusion in coastal aquifers, the model includes coupling of transient water flow, air flow, heat transfer and solute transport, the model results showed that the developed of numerical model is capable of simulating saltwater intrusion into coastal aquifers with a good accuracy. Javadi et. al. [19] carried out a new methodology to control seawater intrusion in coastal aquifers using artificial surface recharge, this proposed method is based on a combination of abstraction of saline water near shoreline and recharge of aquifer using surface ponds, numerical model SUTRA is used to simulate this aquifer system in both 2D and 3D under steady state conditions, the model results show that the proposed system performs significantly better than using abstraction alone as it gives the least cost and least salinity in the aquifer. There are two type of interface first is sharp interface can solve by Analytical or numerical models and the second is diffuse interface can solve by numerical models.

Future sea-level rise is expected to occur at a rate greatly exceeding that of the recent past; the predicted increase in the sea level rise is in the range of 20-88 cm within the next 100 years. Numbers of studies have been carried out to estimate the future sea level changes based on past sea level changes due to thermal expansion, glaciers and ice caps and Greenland and Antarctic ice sheets melting. **Fig. 2** shows the estimated global average sea level rise from 1990 to 2100 [17].

![Fig. 2. SLR According to Global Climate of the 21st Century (IPPC, 2001) [17.]](image-url)

The main transport processes of concern in groundwater include physical Transport Processes as advection, diffusion and dispersion, geochemical transport process as adsorption, biodegradation and chemical reactions. **Advection** describes the movement of groundwater under hydraulic or pressure gradient. The rate of advective transport is described by a modified version of Darcy’s Law [9]. **Molecular diffusion** is the process describes the spread of particles through random motion from regions of higher concentration to regions of lower [4]. **Dispersion** is Spreading of pollutants due to heterogeneity of flow field (small scale dispersion, macro dispersion). There are two Kinds of Dispersion micro dispersion and macro dispersion (Small scale or large scale [26]. **Mechanical dispersion** is mixing caused by velocity variations around a mean flow velocity; it is expected to increase with increasing flow velocity. The groundwater models used to the simulation of groundwater flow and transport of pollutants in groundwater and can be classified as physical (e.g. a sand tank) or mathematical [5]. **Mathematical** models
including analytical models and numerical models, like finite difference, finite element models [25]. Analytical equations that deal solely with the effects of changes in hydraulic head or gradient are gross simplifications of the real situation, and also cannot be expected to accurately predict the position of the saltwater interference. According to the Ghyben-Herzberg’s Equation, the depth to the fresh water/sea water interface equals 40 times the freshwater hydraulic head or water level above sea level [24].

The available numerical models to estimate the variable density and concentration effects of the sea-water/fresh water groundwater interface (e.g. SHARP, SUTRA, HST3D and the SEAWAT program of MODFLOW) [24]. Several numerical methods are available to solve the advection-dispersion equation for solute transport [23] such as Eulerian method, Lagrangian method Mixed Eulerian-Lagrangian method. SEAWAT is selected in this study to simulate saltwater intrusion in Nile delta one of the strong programs in simulate saltwater intrusion. A number of pervious researchers studied the effect of SLR and increasing extraction rate from groundwater in two-dimensional but the study of decreasing surface water changes due to climatic change in River Nile and combination of these scenarios did not study yet in three-dimensional in Nile delta aquifer so this research aimed to study these scenarios.

2. Study area

Study area is Nile delta which located on Northern Egypt. The area is bounded by River Nile in South, Ismailia canal in East, Mediterranean Sea in North and Nubaria canal in West. It located between Latitudes 30˚ 00’ and 31˚ 45’N, and longitudes 29˚ 30’ and 32˚ 30’E. Its area of about 25,000 km² with about 200 km from South to North, and the coastline is about 300 km long. [21].

2.1. Geological properties

Nile Delta is mostly occupied by the Tertiary and Quaternary deposits, Tertiary aquifers are including the Eocene, Oligocene, Miocene rocks and Pliocene Rocks. Quaternary aquifers cover the greater part of the Nile Delta and are particularly developed in the northern portion and are dominant in the Nile Delta. The sediments constitute variable proportions of sands, clays and gravels with lateral variation and variable thicknesses [30]. Quaternary aquifers are including Holocene deposits with maximum thickness of about 77 m and Pleistocene deposits composed of coarse-grained Quartzizitic sands and gravels with discontinuous occasional clay lenses with an average thickness of 700 m [15].

2.2. Hydraulic parameters of the Aquifer

The Nile is completely controlled by the High Aswan Dam and a series of barrages along its course to the Mediterranean Sea. Water released from the dam is distributed among the whole country through a network of major and branch canals, lateral and distribution canals and field channels [21]. The Nile Delta Quaternary aquifer is considered as a semi-confined aquifer. It covers the whole Nile Delta. Its thickness varies from 200 m in the Southern parts to 1000 m in the Northern parts. [28]. Figure 3 shows the depth to the groundwater table in this aquifer ranges between 1–2 m in the North, 3 – 4 m in the Middle and 5 m in the South. Different estimated depths to groundwater table that have been reported by RIGW (2002) [29] and (Morsy, 2009) [22]. According to RIGW database the distribution of groundwater salinity as iso-salinity 1000 PPM comparison from period 1960, 1980, 1992 and 2008 as shown in Fig.4.
The most important parameter for controlling flow characteristic is the hydraulic prosperities such vertical and horizontal hydraulic conductivity, Specific yield, storage coefficient, transmissivity and porosity as show in Table.1. Recharge by the downward leakage due to irrigation excess water and canals infiltration towards the aquifer ranges between 0.25 and 0.80 mm/day also recharge by rainfall to the study area aquifer takes place only during the winter months with average rainfall of 25mm/year (RIGW, 1980) [27]. Abstraction well inventory for Nile delta region has been carried out by RIGW in 1992, 1995, 1997 and 2002 and new functionality is added to it in 2008. Values of extraction rate in Nile delta region for different governate and for tow period 1992 reach 3.30 Mm³/year and 4.90 Mm³/year 2008.

Table. 1.
Hydraulic Properties of Quaternary Aquifer in Nile Delta

<table>
<thead>
<tr>
<th>Main hydraulic units</th>
<th>Hydraulic Conductivity</th>
<th>Transmissivity</th>
<th>Storage Coefficient</th>
<th>Specific yield</th>
<th>Proosity</th>
<th>Effective Proosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K (m/day)</td>
<td>T (m³/day)</td>
<td>S (m³/day)</td>
<td>Ss (L/m)</td>
<td>n (%)</td>
<td>n₁eff (%)</td>
</tr>
<tr>
<td>RIGW(1992)[28]</td>
<td>75</td>
<td>15000-75000</td>
<td>10⁻⁴ - 10⁻³</td>
<td>........</td>
<td>25 - 40</td>
<td>........</td>
</tr>
<tr>
<td>Farid(1980)[12]</td>
<td>112</td>
<td>........</td>
<td>2.35*10⁻³</td>
<td>........</td>
<td>40</td>
<td>37.35</td>
</tr>
<tr>
<td>Zaghloul(1958)[39]</td>
<td>119</td>
<td>........</td>
<td>10⁻¹ - 10⁻³</td>
<td>0.15</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Shahin(1981)[31]</td>
<td>50</td>
<td>2500-25900</td>
<td>10⁻³ - 10⁻⁴</td>
<td>0.2</td>
<td>25</td>
<td>23.25</td>
</tr>
<tr>
<td>Bahr(1995)[7]</td>
<td>75</td>
<td>........</td>
<td>1.1*10⁻³</td>
<td>........</td>
<td>25</td>
<td>18</td>
</tr>
</tbody>
</table>
2.3. Meteorological aspects and climatic changes

Egypt’s climate is hot, dry, deserted and is getting warmer. During the winter season (December– February), Lower Egypt’s climate is mild with some rain, primarily over the coastal areas, while Upper Egypt’s climate is practically rainless with warm sunny days and cool nights. During the summer season (June- August), the climate is hot and dry all over Egypt. Summer temperatures are extremely high, reaching 38°C to 43°C with extremes of 49°C in the southern and western deserts. The northern areas on the Mediterranean coast are much cooler, with a maximum of about 32°C [21]. The climate system is a complex, interactive system consisting of the atmosphere, land surface, snow and ice, oceans and other bodies of water, and living things. There are three fundamental ways to change the radiation balance of the Earth as changing the incoming solar radiation, changing the fraction of solar and by altering the long wave radiation from Earth back towards space [16]. The global warming due to increasing concentrations of greenhouse gases in the atmosphere is estimated at 0.13 degree per decade [18] and is expected to have a full range of temperature projection of 1.1 degree to 6.4 degree by the end of this century. This range of temperature rise is expected to lead to melting of polar caps and expansion of water in deep oceans with a corresponding increase of sea level.

The Nile Delta shoreline extends from Alexandria to the west to Port-Said to the east with total length of about 240 km and is typically a smooth wide coast. The Nile Delta region is presently subject to changes, including shoreline changes, due to erosion and accretion, subsidence and sea level rise due to climate changes [3]. The Nile Delta coastal zone is highly vulnerable to the impacts of sea level rise through direct inundation and salt water intrusion.

Fig. 5. (a, b, c) Satellite Maps of Nile Delta, Showing the Potential Impact of SLR with a- the Occurring Status in 2002 and the Coastal Inundation with a 0.5 and 1m SLR[35].
3. Numerical model

SEAWAT-2000 is the latest release of SEAWAT computer program for simulation of three-dimensional, variable-density, transient ground-water flow in porous media. SEAWAT-2000 was designed by combining a modified version of MODFLOW-2000 and MT3DMS into a single computer program. SEAWAT-2000 contains all of the processes distributed with MODFLOW-2000 and also includes the Variable-Density Flow Process (as an alternative to the constant-density Ground-Water Flow Process) and the Integrated MT3DMS Transport Process [36]. The partial-differential equation of solute transport of contaminant in ground-water flow used in SEAWAT is [40]:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial X_i} \left( D_{ij} \frac{\partial C}{\partial X_j} \right) + \frac{\partial}{\partial X_i} \left( V_i \ast C \right) + \frac{q_s \ast C_s}{\Theta} + \sum_{k=1}^{k=n} R_k \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \li
Ismail M. Abdelaty et al., Investigation of some potential parameters and its impacts on…………

Fig. 7. Vertical Section in (a) X direction from East to West and (b) Y direction from North to South

The model bounded by constant head as 16.96 m above mean sea level at South and by constant head as zero value along shore line at North. South East bounded by Ismailia canal as water level in field start by 16.17 m from South to 7.01 m at East. South West bounded by El Rayah El Behery and Nubaria canal as water level in field start by 16.00 m from South to 0.50 m North above mean sea level and East boundary leave as free as shown in Fig.8-a. A concentration of 35000 mg/l (seawater TDS) is applied along the coastal zone where an inland flow from the sea occurs, the initial concentration of the groundwater was set to 0 mg/l as shown in Fig.8-b [34].

Fig. 8. Model Boundary Condition for (a) Head (b) Concentration

3.2. Model hydraulic parameters

Hydraulic parameters for each layer in model as hydraulic conductivity ($K$), specific storage ($S_s$), specific yield ($S_y$) and total porosity are shown in Table.2. Recharge depend on the excess water from irrigation process and water seepage from canal plus and rainfall value this values was conducted by (RIGW, 1980) [27] as shown in Fig.9 location map of wells distribution as shown in Fig.10 based on the data collected by (RIGW) with total abstraction equal 2.78*10^9 m^3/year in 2008. The values of scale dependent as Longitudinal dispersivity ($\alpha_L$) equal 100 m, Lateral dispersivity ($\alpha_T$) equal 10 m, vertical ($\alpha_V$) dispersivity equal 1.00 and the value of diffusion coefficient equal 10^-4 m^2/day [32].

Table 2.
Values of Hydraulic Properties in Nile Delta (El Arabi, 2007) [10].

<table>
<thead>
<tr>
<th>Main Hydraulic Units</th>
<th>Layer No</th>
<th>Hydraulic Conductivity</th>
<th>Hydrollic Conductivity</th>
<th>Storage Coefficient</th>
<th>Specific Yield</th>
<th>Effective Prosiy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$K_h$</td>
<td>$K_v$</td>
<td>$S_s$</td>
<td>$S_y$</td>
<td>$n$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m/day</td>
<td>(m^2/day)</td>
<td>(m/day)</td>
<td>(1/m)</td>
<td>%</td>
</tr>
<tr>
<td>Clay</td>
<td>1</td>
<td>0.10 --- 0.25</td>
<td>0.01 --- 0.025</td>
<td>10^-3</td>
<td>0.10</td>
<td>50 - 60</td>
</tr>
<tr>
<td>Fine Sand with LenSesof Clay</td>
<td>2,3,4 and 5</td>
<td>5 --- 20</td>
<td>0.5 --- 2</td>
<td>5*10^-3</td>
<td>0.15</td>
<td>30</td>
</tr>
<tr>
<td>Course Sand Quaternary</td>
<td>6,7,8 and 9</td>
<td>20 --- 75</td>
<td>2 --- 7.50</td>
<td>2.50*10^-3</td>
<td>0.18</td>
<td>25</td>
</tr>
<tr>
<td>Graded Sand and Gravel</td>
<td>10 and 11</td>
<td>75 --- 100</td>
<td>7.50 --- 10</td>
<td>5*10^-4</td>
<td>0.20</td>
<td>20</td>
</tr>
</tbody>
</table>
4. Model output and calibration

Distributions of Saltwater intrusion in Nile delta aquifer are the main output of transport model based on available data in 2008 compared with the values as shown in Fig.4. **Figure 11-a** shows distribution of TDS at layer 3 with average thickness 225 m in North and 50 m at south, at layer 6 with average thickness 450 m in North and 100 m at south as shown in **Fig.11-b**, at layer 9 with average thickness 675 m at North and 150 m at south as shown in **Fig.11-c** and bottom of Aquifer with average depth 900 m in North (at sea) and 200 m at south as shown in **Fig.11-d**.
Calibration is a process that shows the difference between calculated salt concentration from model and salt concentration in observation well at field based on available data from (RIGW) at 2008 as shown in Fig.4. Number of transport model such as SEAWAT need period of time to reach steady state, this period depend on software type as 2D or 3D and aquifer geometry such as area or depth, when the concentration keep to constant with time at this time the model reach to steady state. This model took about 730000 day to reach steady state condition. After this time the different scenarios applied to the model. On the other hand, Fig.12- a shows the mass balance of salts entering and leaving the system through all sources and all sinks at start of simulation, it is also the total mass of salts remain in the system at the end of each stress period and salt balance take place when the input salt equal output salt as shown in Fig.12-b.

5. Results and Discussions

The model run and calibrated under available data in 2008 this case consider base case, the values of head and concentration as mentioned before which considered the base case. Three typical cross section applied in Nile delta, the first (Sec I) in West delta, Second in (Sec II) Middle delta, third (Sec III) in East Nile delta as shown in Fig.13.
5.1. Base Case

Distribution of saltwater intrusion as TDS in Nile delta aquifer Equiconcentration line 35 and 1 is shown in Fig. 11. According to Sec I in the West the line 35.0 moved inland by a distance of 48.00 km from shore line and Equi-line 1 moved inland by a distance of 72.50 km from shore line so the transition zone equal 24.50 km as shown in Fig. 14-a. It is also clear that at Sec II in the Middle the Equi-line 35 moved inland by a distance of 63.75 km from shore line and Equi-line 1 moved inland by a distance of 93.75 km from shore line so the transition zone equal 30.00 km as shown in Fig. 14-b. It is also observed that at Sec III in the East the Equi-line 35 moved inland by a distance of 76.25 km from shore line and Equi-line 1 moved inland by a distance of 90.75 km from shore line so the transition zone equals to 14.50 km as shown in Fig. 14-c.
5.2 Impact of sea Level rise (SLR) on saltwater intrusion (SWI) (scenario-1)

The results of increasing SLR by 25 cm, 50 cm and by 100 cm are shown as in Fig (15-a, b and c) respectively. The Figure prevailed that, increasing SLR increases saltwater intrusion in the aquifer from North to South. Increasing SLR by 25 cm, 50 cm and 100 cm at Sec I is shown in Fig.16. The results show that SWI reaches to 78.75 km, 79.00 km and 79.25 km from shore line for Equiconcentration line 35.00 and reach 91.50 km, 91.75 km and 92.25 km for Equi-concentration line 1.00 respectively. The results also show at Sec II as shown in Fig.17, SWI reaches to 66.75 km, 67.00 km and 67.75 km from shore line for Equi-line 35.00 and reaches to 95.75 km, 96.25 km and 97.00 km for Equi-line 1.00 respectively. Figure.18 indicates the results at Sec III; the SWI reaches to 48.50 km, 48.75 km and 49.00 km from shore line for Equi-line 35.00 and reaches to 73.00 km, 73.25 km and 73.75 km for line 1.00 respectively.

**Fig. 15.** Areal Distribution of TDS at Increasing SLR by (a) 25 cm, (b) 50 cm and (c) 100 cm
**Fig. 16.** Vertical Distribution of TDS in Nile delta Aquifer at SLR by (a) 25 cm, (b) 50 cm and (c) 100 cm at **Sec I**

**Fig. 17.** Vertical Distribution of TDS in Nile delta Aquifer at SLR by (a) 25 cm, (b) 50 cm and (c) 100 cm at **Sec II**
5.3. Impact of surface water level change on swi (scenario-2)

The results of decreasing surface water level by 25 cm, 50 cm and 100 cm are shown as in Fig. 19-a, b and c respectively. The Figures show that decreasing of surface water level will increase saltwater intrusion in aquifer from shore line to South. The results at Sec I as shown in Fig. 20, SWI reaches 78.50 km, 78.75 km and 79.00 km from shore line for line 35.00 and reaches 91.25 km, 91.75 km and 92.00 km for Equi-line 1.00 respectively. The results show also at Sec II as shown in Fig. 21, SWI reaches 78.50 km, 78.75 km and 79.00 km from shore line for Equi-line 35.00 and reaches 91.25 km, 91.75 km and 92.00 km for Equi-line 1.00 respectively. The results at Sec III, as shown in Fig. 22 show that SWI reaches 78.50 km, 78.75 km and 79.00 km from shore line for Equi-line 35.00 and reaches 91.25 km, 91.75 km and 92.00 km for Equi-line

**Fig. 18.** Vertical Distribution of TDS in Nile delta Aquifer at SLR by (a) 25 cm, (b) 50 cm and (c) 100 cm at Sec III

**Fig. 19.** Areal Distribution of TDS at Decrease Surface Water by (a) 25 cm, (b) 50 cm and (c) 100 cm
Fig. 20. Vertical Distribution of TDS in Nile delta Aquifer at Decrease Surface Water by (a) 25 cm, (b) 50 cm and (c) 100 cm at Sec I

Fig. 21. Vertical Distribution of TDS in Nile delta Aquifer at Decrease Surface Water by (a) 25 cm, (b) 50 cm and (c) 100 cm at Sec II
5.4 Impact of increasing extraction wells change on swi (scenario-3)

The results of increasing extraction rate by 25 %, 50 % and 100 % are shown as in Fig.23a, b and c. The Figures indicate that the increase of extraction rate increases SWI in aquifer from shore line to South. Increasing extraction rates by 25 %, 50 % and 100 % on SWI at Sec I, as shown in Fig.24 causes the SWI reaches 48.25 km, 47.50 km and 45.50 km from shore line for Equi-line 35.00 and to 73.00 km, 74.00 km and 79.50 km for Equi-line 1.00 respectively. The results show also at Sec II as shown in Fig.25, the SWI reaches 63.75 km, 66.50 km and 65.75 km from shore line for Equi-line 35.00 and reaches 98.25 km, 101.25 km and 107.75 km for Equi-line 1.00 respectively. Again the results at Sec III as shown in Fig.26 show that the SWI length reaches 80.50 km, 81.50 km and 82.00 km from shore line for Equi-line 35.00 and reaches to 91.00 km, 91.50 km and 91.75 km for Equi-line 1.00 respectively.
Fig. 23. Areal Distribution of TDS Increasing Extraction Wells by (a) 25 %, (b) 50 % and (c) 100 %.

Fig. 24. Vertical Distribution of TDS in Nile delta Aquifer for Increasing Extraction Wells by (a) 25 %, (b) 50 % and (c) 100 % at Sec I
Fig. 25. Vertical Distribution of TDS in Nile delta Aquifer for Increasing Extraction Wells by (a) 25 %, (b) 50 % and (c) 100 % at Sec II

Fig. 26. Vertical Distribution of TDS in Nile delta Aquifer for Increasing Extraction Wells by (a) 25 %, (b) 50 % and (c) 100 % at Sec III
5.5 Impact of three combination scenario change on SWI (scenario-4)

The results of increasing SLR by 25 cm, 50 cm and 100 cm, decreasing surface water system by 25 cm, 50 cm and 100 cm and increasing extraction rates by 25% 50% and 100% are shown as in Fig. 27-a, b and c show the increase of SWI in aquifer from shore line to South. The results at Sec I as shown in Fig. 28 the SWI reaches 48.75 km, 48.50 km and 47.75 km from shore line for Equi-line 35.00 and reaches 73.50 km, 76.25 km and 79.50 km for Equi-line 1.00 respectively. Also The results at Sec II as shown in Fig. 29 concluded that SWI reaches 66.75 km, 67.25 km and 67.50 km from shore line for Equi-line 35.00 and reaches 99.25 km, 103.25 km and 110.00 km for Equi-line 1.00 respectively. The Combination of three Scenarios results that, at Sec III as shown in Fig. 30 the SWI reaches 80.50 km, 82.00 km and 83.00 km from shore line for line 35.00 and reaches 91.50 km, 91.75 km and 92.75 km for Equi-line 1.00 respectively.

![Fig. 27. Areal Distribution of TDS for Combination of Three Scenarios Change by (a) 25 %, (b) 50 % and (c) 100 %.]
Fig. 28. Vertical Distribution of TDS in Nile delta Aquifer for Combination of Three Scenarios Change by (a) 25 %, (b) 50 % and (c) 100 % at Sec I

Fig. 29. Vertical Distribution of TDS in Nile delta Aquifer for Combination of Three Scenarios Change by (a) 25 %, (b) 50 % and (c) 100 % at Sec II
**Fig. 30.** Vertical Distribution of TDS in Nile delta Aquifer for Combination of Three Scenarios Change by (a) 25 %, (b) 50 % and (c) 100 % at Sec III

**6. Conclusions**

The main objective of this research was to study the effect of SLR, decreasing surface water level, increasing extraction and combination of this scenarios on saltwater intrusion in Nile delta aquifer. The results of show that:

1. **Increasing** SLR by 25 cm, 50 cm and 100 cm (Scenario-1) leads to an increase in SWI to reach 73, 73.25 and 73.75 km in the West, at the Middle the SWI reach 95.75 km, 96.25 km and 97 km, also at the East the SWI reach 91.50, 91.75 and 92.25 km respectively for Equi-line 1.00.

2. **Decreasing** surface water level by 25 cm, 50 cm and 100 cm (Scenario-2) increases SWI to reach 73.25 km, 73.75 km and 74 km at the West, at the Middle the SWI reach 96 km, 96.50 km and 97.50 km, also at the East the SWI reach 91.25 km, 91.75 km and 92 km for Equi-line 1.00.

3. **Increasing** extraction rates by 25%, 50% and 100% (Scenario-3) leads to an increase in SWI to reach 73 km, 74 km and 79.50 km at the West, at the Middle the SWI reach 98.25 km, 101.25 km and 107.75 km, also at the East the SWI reaches 91 km, 91.50 km and 91.75 km for Equi-line 1.00.

4. The most **effective** scenarios is the combination of increasing extraction rates, increasing SLR and decreasing surface water system (Scenario-4) causes the SWI
intrusion reach to 73.50, 76.25 and 79.50 km at the West, at the Middle the SWI reach 99.25 km, 103.25 km and 110 km, also at the East the SWI reach 91.50 km, 91.75 km and 92.75 km for Equi-line 1.00. Combinations of three Scenarios have strong effect on SWI.

6. Recommendations

It could be recommended to study different scenarios to control of saltwater intrusion considering climatic change in Nile delta aquifer to protect groundwater.

REFERENCES


Intrusion and Coastal Aquifers. Monitoring, Modeling, and Management”, Essaouira, Morocco, April 23.25.


دراسة تأثير التغيرات المناخية لتدخّل المياه المالحة على خزان الدلتا بمصر

الملخص العربي

تتعدد ظاهرة تدخّل المياه المالحة داخل الخزانات الجوفية الساحلية من أخطر الظواهر الطبيعية التي تهدد نوعية المياه العذبة بالخزانات الجوفية الساحلية. حيث قام جابين هيرمانج بدراسة تلك الظاهرة عام 1860 ولكن لاتزال هذه الظاهرة تعتقد وتشكل أذى للعلماء في كيفية التحكم في تلك الظاهرة. وفي هذا البحث تم الدراسة لتغيرات التغيرات المناخية على الخزان الجوفي بدلالة شروط، وذلك بدراسة تأثير ارتفاع منسوب مياه البحر وكذلك انخفاض منسوب المياه السطحية وأيضاً تأثير زيادة معدلات السحب من المياه الجوفية. بعد تطبيق الدراسة على الخزان الجوفي بالدلتا، توصلت الدراسة إلى:

1- من خلال تطبيق النموذج على خزان الدلتا، يتضح أن التدخّل يصل إلى 90.75 كلم في شرق الدلتا ونحو 93.75 كلم في غرب الدلتا وتقريباً 72.50 كلم في غرب الدلتا بالنسبة لخط تركز الملوحة.

2- ارتفاع منسوب مياه البحر (سيناريو 1) بمقدار 25 سم و50 سم سوق يؤدي إلى زيادة تدخّل المياه المالحة داخل الخزانات تصل إلى 91.50 كم و91.75 كم في شرق الدلتا ونحو 96.25 كم و97.00 كم في غرب الدلتا في غرب الدلتا وتفصل التدخّل تقريباً إلى 73.00 كم و73.25 كم في شرق الدلتا.

3- انخفاض منسوب مياه السطحية (سيناريو 2) بمقدار 25 سم و50 سم سوق يؤدي إلى زيادة تدخّل المياه المالحة داخل الخزانات تصل إلى 91.25 كم و91.75 كم في شرق الدلتا ونحو 96.50 كم و97.50 كم في غرب الدلتا وتفصل التدخّل تقريباً إلى 73.25 كم و73.75 كم في شرق الدلتا.

4- زيادة معدل السحب من المياه الجوفية (سيناريو 3) بمقدار 25% و50% و100% سوق يؤدي إلى زيادة تدخّل المياه المالحة داخل الخزانات تصل إلى 91.00 كم 91.50 كم و91.75 كم في شرق الدلتا ونحو 98.25 كم و101.25 كم في غرب الدلتا ونحو 79.50 كم و74.00 كم في شرق الدلتا ونحو 73.00 كم و74.00 كم في غرب الدلتا.

5- يعتبر أكثر النتائج السابقة تأثيراً على تدخّل المياه المالحة هو زيادة معدل السحب من الخزان من (سيناريو 3) ثم ارتفاع منسوب مياه البحر (سيناريو 4) وبعد ذلك تقليل منسوب المياه السطحية داخل حدود الخزان (سيناريو 2) ولكن بالجسر بين النتائج المختلفة السابقة من ارتفاع منسوب مياه البحر وانخفاض منسوب المياه السطحية وزيادة معدل السحب من المياه الجوفية (سيناريو 4) بمقدار 25% و50% و100% سوق يؤدي إلى زيادة تدخّل المياه المالحة داخل الخزانات تصل إلى 91.50 كم و92.75 كم و95.25 كم و103.25 كم في غرب الدلتا ونحو 79.50 كم و77.25 كم في شرق الدلتا.

الناتج الإجمالي من الدراسة يظهر أن تأثير التغيرات المناخية على موارد المياه في الدلتا بمصر يلزم الاهتمام بدراسة وتوجيهات سيناريوهات سطحية ومائية تساهم في حماية موارد المياه في الخزانات الجوفية.