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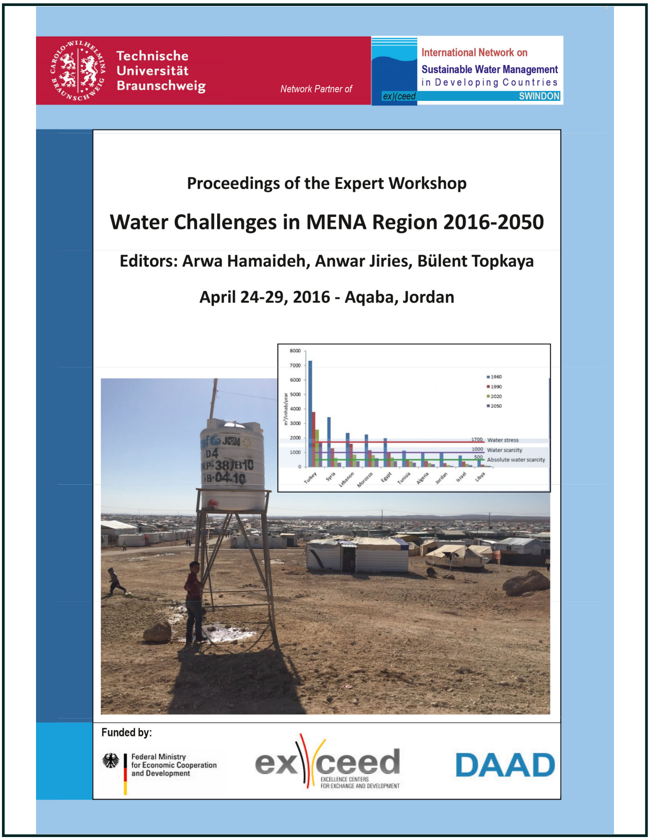

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IMPACT OF CLIMATE CHANGE AND SEA LEVEL RISE ON GROUNDWATER QUALITY AND QUANTITY IN COASTAL AQUIFERS

Hany F. Abd-Elhamid, **Ismail M. Abdelaty**

Department of Water and Water Structures Engineering, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt, hany_farhat2003@yahoo.com,

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Abstract

Climate change and sea level rise presents enormous challenges for water resources management in coastal areas. Sea level rise could have many effects on coastal areas in the long term, including increase of coastal erosion, submergence of shore cities which in turn would result in migration of people, saltwater intrusion, loss of agricultural land, and rise in coastal groundwater table. Increasing abstraction is considered the main cause of seawater intrusion. Also, the rise in sea level accelerates seawater intrusion. This paper presents a numerical study using SEAWAT code to investigate seawater intrusion in the Nile Delta aquifer under the effect of likely sea level rise. In this study, two scenarios of sea level rise are considered: 50 cm and 100 cm. The results showed that the rise of the sea level has a significant effect on the position of the transition zone. Sea level rise of100 cm gave extreme intrusion of saline water as equiconcentration line 35 and 1 reached 67.75 and 97 km. Compared to the current situation as equiconcentration line 35 and 1 reached 63.75 and 93.75 km. The transition zone moved inland 4.0 km. The Nile Delta aquifer is vulnerable to sea level rise and, therefore, protection from seawater intrusion is crucial.

1 Introduction

Climate change is a result of natural and/or man-made activities. Due to climate change, the seawater level will rise for several reasons, including oceans and seas thermal expansion, glaciers and ice caps melting, and Greenland and Antarctic ice sheets melting. Sea level rise has many effects on coastal regions on the long term such as increase in coastal erosion and seawater intrusion. Climate change has already caused changes in the sea level during the last decade. Global mean sea level rise has been ranged from (10-20 mm/yr) during the last century [1]. Future sea level rise due to climate change is expected to occur at a rate greatly exceeding that of the recent past. For example, during the next 100 years, sea levels are expected to rise at a rate between 20-88 mm/yr [2].Saltwater intrusion is a natural process that occurs in 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 has a direct impact on groundwater resources, soil salinity, agricultural productivity and quality in the coastal zone [3].The main causes of saltwater intrusion include over-abstraction, seasonal changes in natural groundwater flow, tidal effects, barometric pressure, seismic waves, dispersion, and climate change and associated sea level rise. Analytical and numerical models have been used to predict the location and movement of the saltwater/freshwater interface. The numerical models can be categorized as sharp interface models or diffusive (dispersive) interface models.

The first attempt to model seawater intrusion was introduced by Ghyben (1889) and Herzberg (1901) [4, 5]. This model is known as Ghyben-Herzberg model. Henry (1959) presented numerical solution of steady saltwater intrusion into coastal aquifer based on sharp interface assumption [6]. Henry (1964) also developed the first analytical solution including the effect of dispersion in confined aquifer under steady-state conditions [7].A number of mathematical models have been developed to simulate saltwater intrusion based on diffusive interface. Tasi and Kou (1998) developed a finite element mode, considering density-dependent flow and transport [8]. Cheng et al. (1998) developed a 2-D finite element model for density dependent flow and solute transport through saturated and unsaturated soils [9]. Abd-Elhamid and Javadi (2011) developed a coupled transient density-dependent finite element model to simulate seawater intrusion in coastal aquifers and investigated the effects of likely sea level rise due to climate change and over-pumping on seawater intrusion [10]. Abd-Elhamid et al. (2015) presented numerical simulation of seawater intrusion in Gaza aquifer using coupled transient finite element model considering different scenarios of sea level rise and over-pumping [11]. The results showed that Gaza aquifer is subjected to severe seawater intrusion from the Mediterranean Sea, and there is an urgent need to protect the aquifer from seawater intrusion.

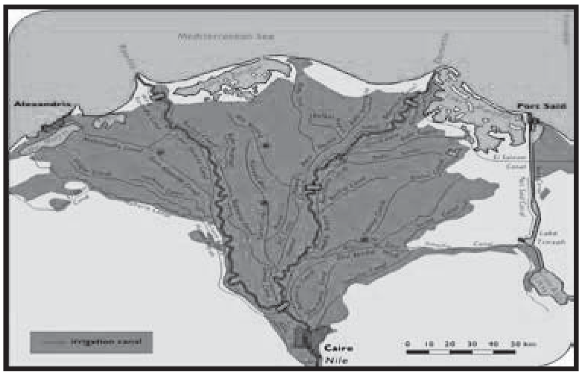


Figure 1: Location map of the Nile Delta aquifer, Egypt

The Nile Delta aquifer (Figure 1) is among the largest underground freshwater reservoirs in the world [12]. Previous investigations revealed that the aquifer is subject to sever seawater intrusion from the Mediterranean Sea. This has left only a small zone of fresh water in the aquifer. A number of studies have been conducted to simulate the seawater intrusion in the Nile Delta aquifer using different numerical techniques. Examples of these studies include, among others, [13-19]. Few studies addressed the possible impacts of climate change and sea level rise on the seawater intrusion in the Nile Delta aquifer [11, 20, 21]. Mohamed (2004) studied the global and local factors affecting the rise of sea level and its impact on coastal regions and specifically deltaic zones [23]. He assessed the impact of such factors on Northern coasts of Egypt extending from Alexandria to El-Arish for the year 2020 and 2050. Saleh (2009) developed a numerical model using MODFLOW and MT3D to quantitatively and qualitatively assess the possible impacts of the policies related to groundwater extraction and development activities in the Nile Delta region [24]. Freydoon and Abolghasemi (2014) investigated the impact of sea and groundwater level changes on seawater intrusion in an unconfined coastal aquifer using SEAWAT code [25].The results showed that increasing sea level will increase saltwater intrusion, as well.

In this study, 3-D coupled groundwater flow and solute transport model (SEAWAT) is used to investigate seawater intrusion in a large case study, which is suffering from severe seawater intrusion. This case is the Nile Delta aquifer. The model is applied to investigate the position and movement of the transition zone in response to sea level rise under the condition of climate change. Two scenarios of sea level rise have been considered: 50 cm and 100 cm. The impact of these scenarios on seawater intrusion is investigated and relation between sea level rise and intrusion length in the Nile Delta aquifer is developed.

2 Materials and Methods

2.1Case study

The Nile Delta aquifer is considered one of the largest aquifers in the world as it contains about 400 BCM of freshwater [26]. The aquifer supplies Egypt with 6.5 BCM/yr. It is bounded by Mediterranean Sea in the North, River Nile in the South, Ismailia Canal in the East and Nubaria Canal in the West as shown in Figure 1. The study area locates between Latitudes 30˚ 00` and 31˚ 45`N, and longitudes 29˚ 30`and 32˚ 30`E. The total area is 25,000 km^2 with 200 km length from South to North, and the coastline length is 300 km [26].The Nile Delta Quaternary aquifer is considered semi-confined aquifer. It covers the whole Nile Delta. The thickness varies from 200 m in the South to 1000 m in the North [28]. Recharge by downward leakage due to irrigation excess water and canals infiltration towards the aquifer ranges between 0.25 and 0.80 mm/d. Also recharge from rainfall to the study area takes place only during the winter with average 25 mm/yr [27]. Abstraction rate from the aquifer was 4.90 BCM/yr in 2008 [26].

2.2Numerical model

SEAWAT code is used in the current study. The code combines MODFLOW and MT3DMS into a single program that solves coupled groundwater flow and solute transport equations. SEAWAT has been tested and verified against benchmark problems involving variable density groundwater flow such as Henry problem, Elder problem and HYDROCOIN problem. The Variable Density Flow (VDF) process of SEAWAT uses the familiar and well-established MODFLOW methodology to solve the variable density groundwater flow equation [29]. The MT3DMS part of SEAWAT, referred to the Integrated MT3DMS Transport (IMT), process which solves the solute transport equation.

The VDF process solves the following variable density groundwater flow equation [29]:

$$\nabla\left[\rho * \frac{\mu_o}{\mu} * K_o\left(\nabla * h_0 + \frac{\rho - \rho_f}{\rho_f} * \nabla Z\right)\right] = \rho * S_{,s,0}\left(\frac{\partial h_O}{\partial t}\right) + \theta * \left(\frac{\partial \rho}{\partial C}\right)\left(\frac{\partial C}{\partial t}\right) - \rho_S * q^{\backslash}{}_S \ldots.(1)$$

The IMT process solves the following solute transport equation [29]:

$$\left(1 + \frac{\rho_b * K_d{}^k}{\theta}\right)\frac{\partial(\theta * C)}{\partial t} = \nabla\left(\theta D * \nabla C^k\right) - \nabla\left(q * C^k\right) - \left(q^{\backslash}{}_s * C_s{}^k\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2)$$

where $\boldsymbol{\rho_o}$ is the fluid density [ML^{-3}],$\boldsymbol{\rho}$ density of saline ground water [ML^{-3}], $\boldsymbol{\mu_o}$ dynamic viscosity of the fresh groundwater [$ML^{-1}T^{-1}$], $\boldsymbol{\mu}$ dynamic viscosity of saline ground water [$ML^{-1}\ T^{-1}$], $\mathbf{K_0}$ is the hydraulic conductivity [LT^{-1}],$\mathbf{h_0}$ is the hydraulic head [L], $\mathbf{S_{s,0}}$ the specific storage [L^{-1}], **t** time [T], $\boldsymbol{\theta}$ porosity [-], **C** salt concentration [ML^{-3}], $\mathbf{q'_s}$ a source or sink [T^{-1}] of fluid with density $\boldsymbol{\rho_s}$, $\boldsymbol{\rho_b}$ the bulk density (mass of the solids divided by the total volume) [ML^{-3}], $\mathbf{K_d^k}$ the distribution coefficient of species k [$L^3\ M^{-1}$],$\mathbf{C_k}$ the concentration of species k [ML^{-3}], **D** the hydrodynamic dispersion coefficient [L^2T^{-1}],**q** specific discharge [LT^{-1}], and $\mathbf{C_s^k}$ the source or sink concentration [ML^{-3}].

2.3 Boundary conditions and hydraulic parameters

The numerical model SEAWAT is used in this study for simulation of groundwater flow and seawater intrusion in the Nile Delta aquifer. The domain is divided into 194 rows and 260 columns with cell dimensions 1.00 km x 1.00 km with variable depth from 200m in South to 1000m at North as shown in Figure 2. The domain is divided into eleven layers: the first layer represents clay cap, other ten layers represent Quaternary aquifer and are of equal thickness. The first layer thickness varies from 20m in the South to 50m in the North. This clay cap keeps the Quaternary aquifer as semi-confined aquifer. Two sections are taken in X-direction and Y-direction as shown in Figure 3.

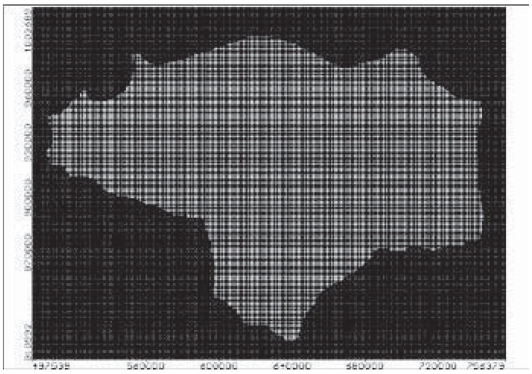
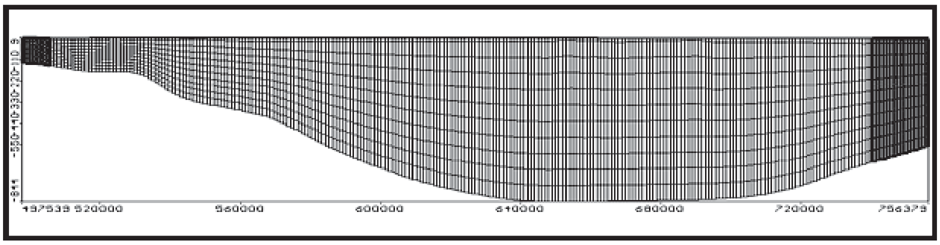
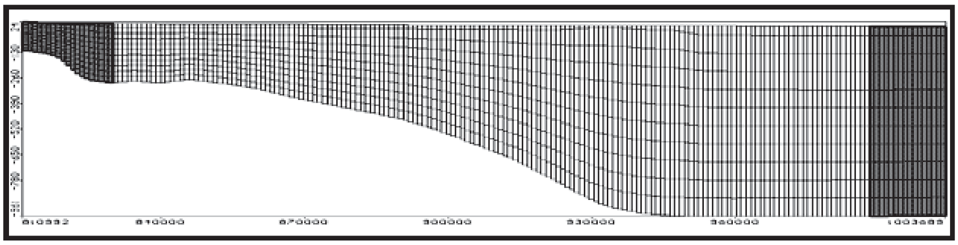


Figure 2: Model grid for the Nile Delta aquifer



(a) X- Direction



(b) Y- Direction

Figure 3: Vertical sections in X and Y directions in the Nile Delta aquifer

The boundaries used in this study represent head and concentration. The head boundary conditions were set in the model as zero at the North along the shore line. South East is bounded by Ismailia Canal, and water level starts at 16.17 m in South to 7.01 m in East. South West is bounded by Nubaria Canal, and water level starts at 16.00 m in South to 0.50 m in North, and East boundary was set free. A salt concentration of 35,000 mg/L is applied along the coastal zone, where an inland flow from the sea occurs. The initial salt concentration of the groundwater was set to 0 mg/L[18].The hydraulic parameters of the Nile Delta aquifer are presented in Table 1. The values of scale dependent were set as longitudinal dispersivity (α_L) equals 100 m, lateral dispersivity (α_T) equals 10 m, vertical (α_V) dispersivity equals 1.00, and the value of diffusion coefficient (D*) equals 10^{-4} m^2/d [16].The recharge to the Eastern Nile Delta aquifer ranges between 0.25 and 0.80 mm/d. The values or recharge was conducted by [27]. The abstraction rate equals to 3.48 x 109 m^3/yr in 2008, and the distribution of abstraction wells were assigned to the study area as collected by [27].

2.4 Model Calibration

Calibration is a process that shows the difference between calculated values from model versus the observed ones. A number of observation wells have been distributed in the study area based on the available data of piezometric head from RIGW in 2008. Figure 4 shows comparison between calculated versus observed heads in Nile Delta aquifer. The root mean square is 0.481 m and normalization root mean square is 3.702%. The model results for calculated heads values matches with the field data for piezometric heads. The results of the developed model were compared with those of [12] and [21], and a good agreement is observed in the middle cross section.

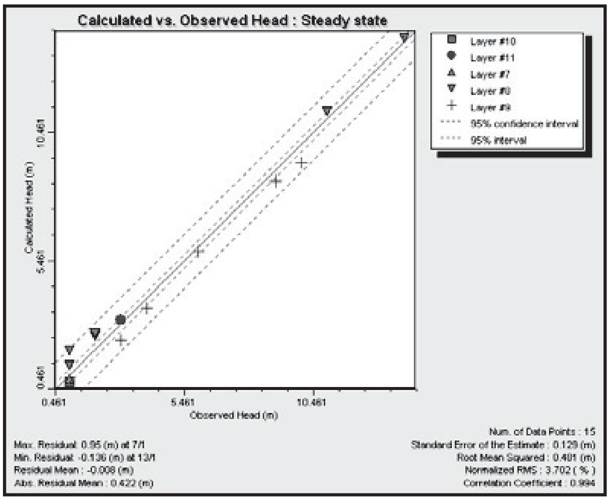


Figure 4: Observed groundwater head versus calculated ones in the Nile Delta aquifer

2.5Simulation of groundwater flow and seawater intrusion in the Nile Delta aquifer

SEAWAT model was employed to simulate groundwater flow and seawater intrusion in the Nile Delta aquifer. Figure 5 shows areal view of groundwater levels in the Nile Delta aquifer. The groundwater levels vary from 16.00 m in South to zero in North. The distribution of saltwater intrusion as total dissolved solids (TDS) in the Nile Delta aquifer is shown in Figure 6a and b. A vertical cross section is taken in the middle of the aquifer with length of 150 km and depth varies from 200 to 1000 m as shown in Figure 3-b. The vertical cross section (Figure 6b) showed that the intrusion length of equiconcentration line 35 reached 63.75 km from shore line. However, equiconcentration line 1 intruded to a distance of 93.75 km from shore line with transition zone of 30km.This is considered the ***base case*** for groundwater levels and distribution of saltwater intrusion as TDS in the Nile Delta aquifer

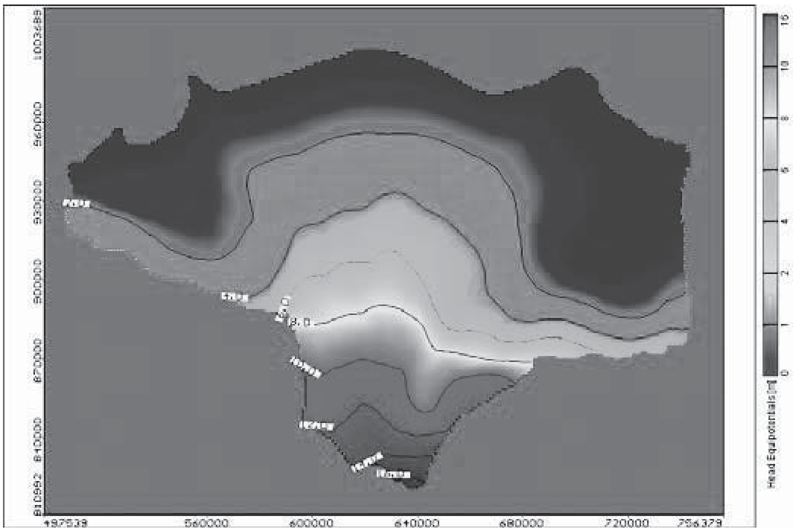


Figure 5: Areal view of groundwater levels in Nile Delta aquifer