

Using Modflow and MT3D Groundwater Flow and Transport Models as a Management Tool for the Quaternary aquifer,

East Nile Delta, Egypt

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Abstract

The area under investigation lies in the southeastern part of the Nile Delta. It is bounded by longitudes 31° 00', 31° 45' E and latitudes 30° 00', 30° 45' N. The water resources in the study area are both surface water (canals and drains) and groundwater withdrawn from the Quaternary aquifer, which represent one of the most important groundwater resources for domestic and agricultural purposes in Egypt.

The main objective of the present study is to predict the future changes in groundwater levels and quality of the southeastern part of the Nile Delta aquifer. Three suggested scenarios of pumping with different abstraction rates for years 2000 through 2030 have been explored by Visual MODFLOW (version 3.0) and MT3D models. These scenarios include: first, maintaining the current pumping rate increasing by 10% from the period 2000 to 2030; second, increasing the pumping rate by 50%; third, increasing the pumping rate by 100%. Results indicate that the first and second scenarios have little effect on drawdown reaches to 0.5m and 1.8m, respectively. The third scenario gives the worst drawdown reaches to 14m and should be avoided. Mass transport of total dissolved solids, SO₄, Na, Cl, Fe, Mn, Al and NO₃ have been investigated using MT3D. Simulation results indicate that the concentrations of TDS and different elements increases with time and move with groundwater flow direction.

Keywords: Modflow - Groundwater management - East Nile delta

1. Introduction

The area under investigation lies in the southeastern part of the Nile Delta. It is bounded by longitudes 31°00', 31°45' E and latitudes 30° 00', 30° 45' N (Fig. 1). The study area is characterized by low relief topography with a gentle slope towards the north, while the elevations ranging from 20m (A.M.S.L.) at the southeastern part to 5m (A.M.S.L.) at the northern portions.

During the last years, intensive pumping from the Quaternary aquifer has been arisen to cover the increased water demand due mainly to the explosive population growth in the study area. Furthermore, private wells increased dramatically; these wells are not even authorized. The total pumping from the basin

was estimated to reach 220,000m³/day in the year 2000. Absence of full control on private wells and its pumping rates in addition to pumping from the water authority well fields resulted in Overexploitation of water storage and deterioration of groundwater quality in some parts of the aquifer. Due to general lack of data about the aquifer system for example, only five observation wells do exist in the study area, the study presented herein use Processing Modflow (version 3.0) and the solute transport code (MT3D) to construct a groundwater flow model and to model contaminant transport in the basin. These models were then used as a management tool for assessing the current situation and forecasting future responses to assumed coming events. Groundwater modeling plays an extremely important role in the management of water resources. Groundwater flow models solve for the distribution of heads, whereas solute transport models solve for concentration of solute as affected by advection, dispersion and chemical reactions. Mathematical models simulate groundwater flow indirectly by means of a governing equation though to represent the physical processes that occur in the system, together with equations that heads or flows along the boundaries of the model (1).

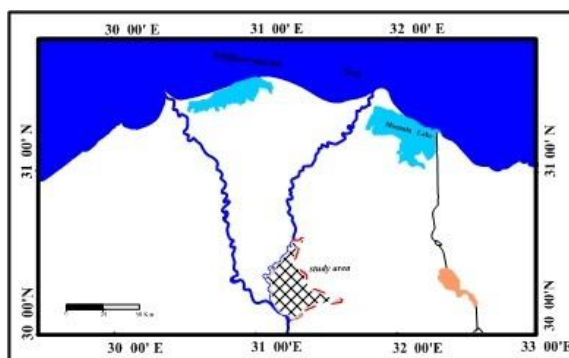


Fig. (1) location map of the study area

2- Aim and methods of study

The present work aims to predict the future changes in groundwater levels and quality with time and has been used herein as a management tool for the southeastern part of the Nile Delta aquifer. To achieve this purpose, field and laboratory measurements carried out for the collected groundwater samples. Besides, three suggested scenarios of pumping with different abstraction rates for years 2000 through 2030 have been explored by Visual MODFLOW (version 3.0) and MT3D models. These scenarios include: first, maintaining the current pumping rate increasing by 10% from the period 2000 to 2030; second, increasing the pumping rate by 50%; third, increasing the pumping rate by 100%.

3-Geologic and hydrogeologic setting

According to (2), (3), (4), (5) and (6), the area east of the Nile Delta is essentially occupied by rock units belonging to the Tertiary and Quaternary. Basaltic rocks belonging to Upper Oligocene age are exposed at Abu Zaabal Quarries, while Miocene and Pliocene sediments outcrops at the eastern portions (Fig.2). The Pliocene clay is overlain by the Quaternary deposits in the Nile Delta flood plain with a thickness of about 200m. The Quaternary deposits covers the majority of the area, it is classified into two rock units; the upper unit is the Holocene Nile silt and clay, while the lower one is the Pleistocene sand and gravel intercalated with clay lenses that exposed at the eastern parts of the studied area. These sediments rest uncomfortably on the older rock units (7).

The Nile Delta (Quaternary) aquifer is one of the most important water resources in Egypt. It forms an immense and complex groundwater system. (8), (9), (10), (11), (12) have discussed in detail the hydrogeology of eastern Nile delta. The study area is mainly occupied by the Quaternary aquifer which discriminated into to hydrogeologic units; the upper unit is the Holocene aquitard and the lower one is the Pleistocene aquifer. The Pleistocene aquifer system consists of sand and gravel with clay lenses, which overlain by a semi pervious Holocene aquitard (clay cap) and underlain by an impermeable Pliocene aquiclude. The thickness of the Holocene aquitard ranges between 0 m at the eastern portions to 20m at the

southwestern part of the investigated area (Fig. 3). The Pleistocene aquifer has a variable thickness, at the eastern parts, the thickness ranges from 0 to nearly 50m, while at the northwestern part of the investigated area, they may reach 400m (Figs. 2). In the study area, the Quaternary aquifer is mainly recharged from the Nile River, subsurface flow from Damietta branch, Ismailia Canal and leakage from the net of irrigation canals and drains, as well as the minimal infiltration of the occasional rainfall. The discharge takes place by pumping wells for the irrigation and domestic uses. The groundwater levels in the Quaternary aquifer slope generally from south to north (Fig.2). Tracer experiments on direction of groundwater flow system approaches steady state conditions and direction from SW toward the NE of the study area (13).

4-Hydrogeochemistry

4.1 Major elements

The major constituents of dissolved solids in groundwater samples are the following cations; calcium, magnesium, sodium, and potassium and the following anions; chloride, sulfate and bicarbonates. The average ions contents (ppm) in groundwater listed in table (1). Ions contents of shallow groundwater are higher than the deeper one.

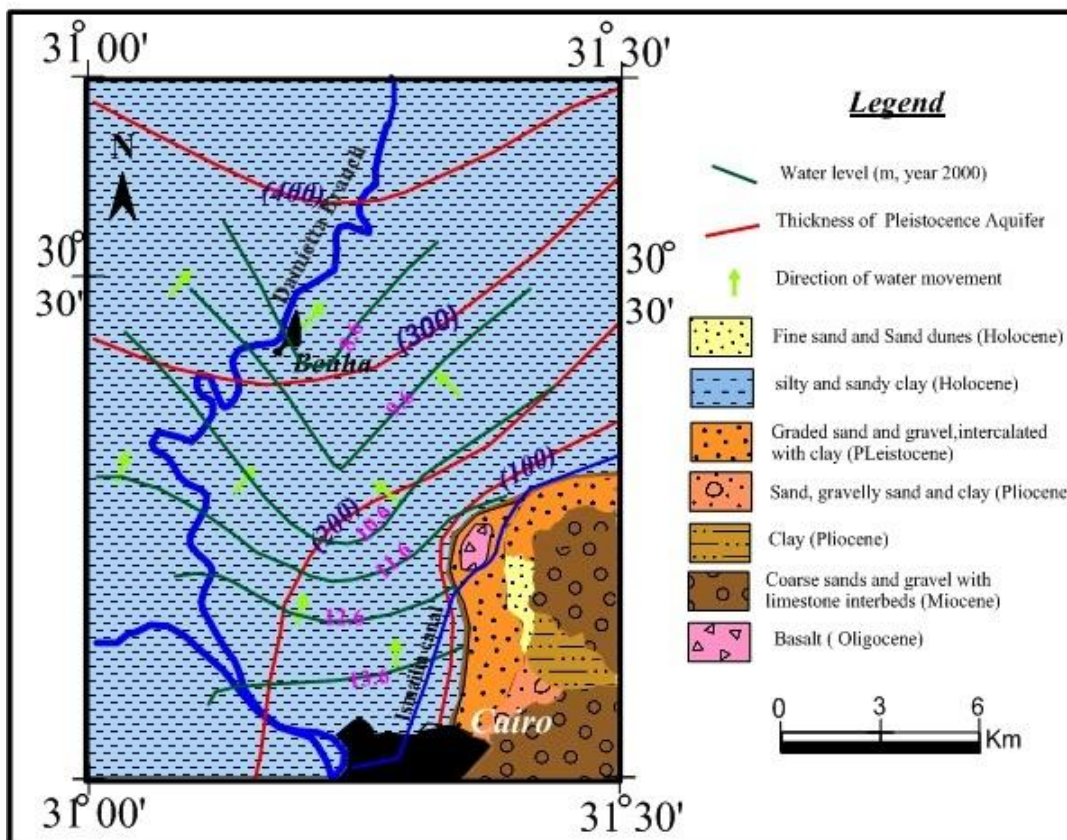


Fig. (2) Hydrogeologic map of the study area
(modified after RIGW,1992)

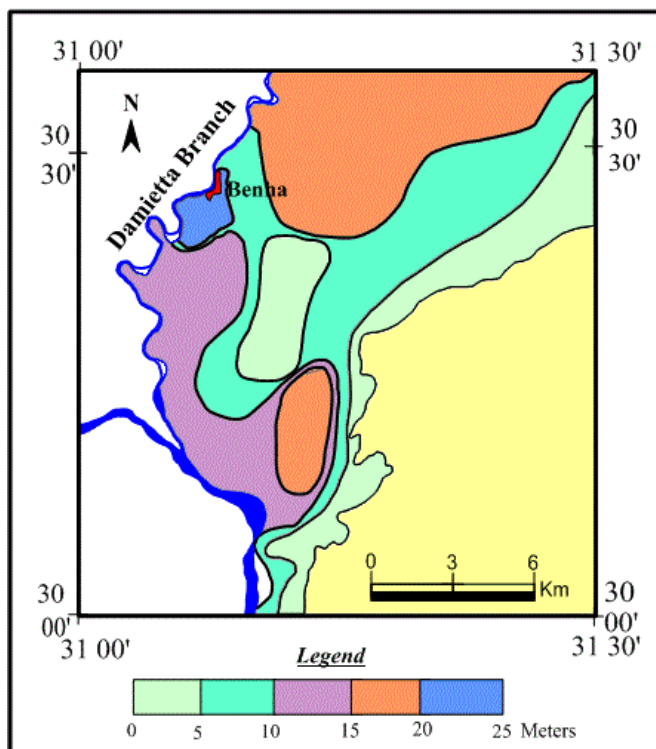


Fig. (3) Isothickness map of the Holocene aquitard in the study area (after RIGW, 1989)

Table (1) Average salinity and ions contents (ppm) in groundwater (2010)

TDS and Ions		shallow well	deep wells	WHO (2004)	
				Permissible (mg/l)	Acceptable (mg/l)
	TDS	243 - 2711	228.5 - 874.54	500	1000
	Total hardness	138 - 922	196 - 440	250	500
Major elements	Chloride	21 - 615	16 - 205	250	600
	Sulfate	34.5 - 868.79	43.35 - 334.1	250	500
	Bicarbonate	57.34 - 494.1	65.88 - 273.28	-	-
	Sodium	26 - 650	20 - 185	-	200
	Potassium	1 - 79	1.7 - 21	-	-
	Magnesium	2.88 - 109.92	5.76 - 68.64	50	150
	calcium	12 - 142.4	5.6 - 100	75	200

Trace elements

The inspection of chemical analyses of trace element (Table 2) indicate that most of trace element concentrations are below the standards limits of drinking water, except aluminum, iron and manganese, which were given by (14) in the following table.

Table (2) Average concentrations of different pollutants in groundwater

Pollutants		Shallow water	Deep water	WHO(2004)	
				Permissible (mg/l)	Acceptable (mg/l)
Nutrients	Nitrate	0.3-210	0.2-10	10	
	Phosphate	< 0.2	< 0.2	1	
Trace elements	Iron	0.102 - 3.614	0.099-16.3	0.3	1
	Manganese	0.006-1.313	0.012-1.481	0.1	0.4
	Copper	0.001-0.205	0.005-0.761		2
	Vanadium	0.005 -0.14	0.005-0.3		0.1
	Chromium	0.001-0.063	0.001-0.089		0.05
	Lead	0.001-0.045	0.001- 0.066		0.01
	Arsenic	<0.001	<0.001		0.01
	Nickel	0.001-0.041	0.001-0.564		0.02
	Aluminum	0.005-1.329	0.005-2.382		0.2
	Barium	0.037-0.98	0.035-0.18		0.7
	Zinc	0.001-2.437	0.001-0.252	5	15
	Cadmium	0.001-0.065	0.001-0.065		0.003
	Strontium	0.22-3.555	0.154-1.718	-	-
	Selenium	<0.001	<0.001		0.01
	Antimony	<0.001	<0.001		0.02
Tin	<0.001	<0.005		0.01(2003)	

Conceptual model and input data

The conceptual model for eastern Nile Delta adapted by this study consists of two hydrogeological units; the upper unit is Holocene aquitard and lower one is the Pleistocene aquifer. The conceptual model is a simplified representation of the features governing groundwater flow for the main aquifer (Quaternary aquifer). Such as the aquifer geometry, hydraulic properties, permeability, recharge and discharge of irrigated area. In addition to, simulate the hydraulic parameters of the main river and canals, and the groundwater extraction in the study area. The model data entry was based on hydrogeological maps of the study area (15).

Flow and transport governing equation

The partial different equation of groundwater flow used in modflow is (16)

$$\partial/\partial x(K_{xx}\partial h/\partial x)+\partial/\partial y(k_{yy}\partial h/\partial y)+\partial/\partial z(k_{zz}\partial h/\partial z)+W=S_s\partial h/\partial t$$

Where:

$-K_{xx}$, K_{yy} and K_{zz} are values of hydraulic conductivity along the x,y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T), h is the potentiometric head (L), W is a volumetric flux per unit volume representing sources and/or sinks of water, with $w<0.0$ for flow out of the groundwater system, $w>0.0$ for flow (T⁻¹), S_s is the specific storage of the porous material (L⁻¹), t is time (T)

When the groundwater flow equation is combined with boundary and initial conditions, describes transient three dimensional groundwater flows in a heterogeneous and anisotropic medium, provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions.

The groundwater flow process solves the groundwater flow equation using the finite difference method in which the groundwater flow system is divided into a grid of cells, for each cell, there is a single point, called a node, at which head is calculated. (16). MT3D is a transport model that can be used to simulate changes in concentration of single species miscible contaminants in groundwater considering advection, dispersion and some simple chemical reactions, with various types of boundary conditions and

external sources or sinks. The chemical reactions included in the model are equilibrium controlled linear or non linear sorption and first order irreversible decay or biodegradation. The MT3D transport model is intended to be used in conjunction with any block centered finite difference flow model such as modflow and is based on the assumption that changes in the concentration field will not affect the flow field measurably. This allows the user to construct and calibrate a flow model independently. MT3D retrieves the hydraulic heads and the various flow and sink/source terms saved by the flow model, automatically incorporating the specified hydrologic boundary conditions.

Governing equation (groundwater transport model)

The partial differential equation describing three dimensional transport of contaminants in groundwater can be written as follows (17):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_j} v_{ic} + \frac{q_s}{\theta} C_s + \sum_{k=1}^N R_k$$

Where

C: is the concentration of contaminants dissolved in groundwater ML^{-3} , T: is time, T; X: is the distance along the respective Cartesian coordinate axis. D_{ij} : is the hydrodynamic dispersion or linear coefficient, L^2T^{-1} , V_i = the seepage or linear pore water velocity; Q_s = the volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative). T^{-1} ; C_s : is the concentration of the sources or sinks, ML^{-3} . θ =the porosity of the porous medium dimensionless; $\sum_{k=1}^N R_k$: is a chemical reaction term, $ML^{-3}T^{-1}$.

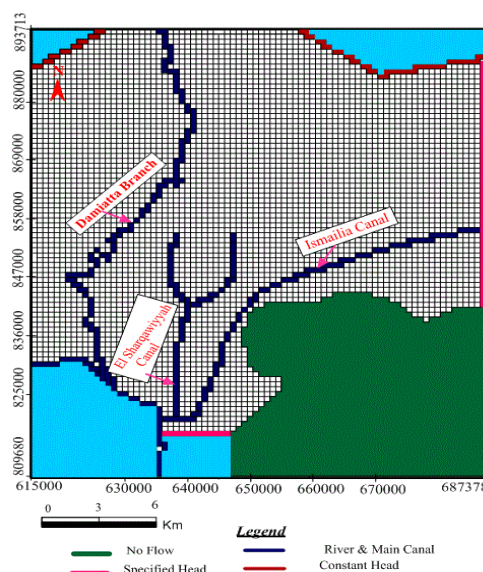


Figure (4) the conceptual of regional model grid and Boundary Conditions

Model grid geometry

The designing of the Quaternary aquifer model include the following steps; a grid of 7200 cell (80 column and 90 rows) is constructed to cover the study area, (Fig. 4).

Boundary conditions

Boundary conditions are mathematical statements specifying the head or fluxes off the problem domain (1). Correct selection of the boundary conditions is a critical step in the model design. The eastern boundary was selected along the physical boundary of Miocene rock and this boundary was represented by "a no flow boundary". The inflow of groundwater from or outflow of groundwater to adjacent formation

was neglected. The western boundary was selected along Damietta branch of River Nile and this boundary is represented by "river boundary". The piezometric heads were defined according to the observed piezometric heads and this boundary was represented by "a constant piezometric head" and this boundary is selected as constant head+6m. It is considered far enough from the any development area. The boundaries were selected as "specified piezometric head" in each boundary grid point. These boundaries are far enough and outside the model area to avoid any mutual influence between the devolvement areas.

Calibration procedure

The objective of the model calibration is to generate piezometric levels, which are in agreement with historical level in the different situation. The calibration process is distinguished in to three phases:

The first phase: steady state condition for regional model for the year 2000 (from observed piezometric head and field investigations which were given in the following table.

Well No.	Observed Head	Calculated Head
27	7.33	7.59
283	8.2	8.42
344	10.2	9.5
35	9.56	10.05
201	11.25	11.47
281	12.9	12.03
37	13.5	13.48
44	14.5	14.41

***The second phase:** unsteady state condition for regional model during the period from 2000 to 2030, where the amount of groundwater extraction increasing by 10% rate of pumping.

***The third phase:** unsteady state condition for regional model during the period from 2000 to 2030, Where the amount of groundwater extraction increasing by 50% pumping rate after 5 years.

***The fourth phase:** unsteady state condition for regional model during the period from 2000 to 2030, Where the amount of groundwater extraction increasing by 100% pumping rate after 5 years.

Model calibration

Steady state calibration for the flow model was achieved by comparing the hydraulic heads obtained from available groundwater level contour maps of the model layer and the calculated hydraulic heads of the Modflow simulation in order to simulate the flow lines of the layer. During calibration, horizontal and vertical hydraulic conductivities were adjusted in sequential model runs to match the simulated heads and measured head. The comparison between measured and simulated levels for the aquifer is shown in figure (5).

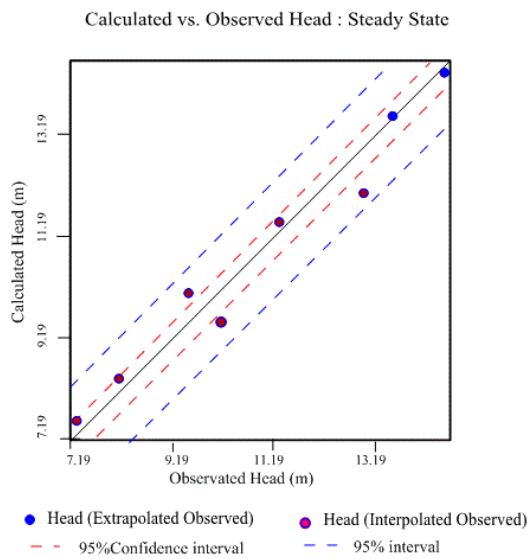


Fig.(5) Comparison between the observed and calculated groundwater levels (calibrated,2000)

Model results were used during the calibration phase in order to regress between the calculated data and those observed in groundwater monitoring wells. Based on these results, standards error of the estimation (SEE) was 0.169m. A root mean squared (RMS) value of 0.45m was achieved during calibration. The normalized RMS for the model was 6.3%.

Transient calibration

The results of the groundwater simulations under human pressure of the investigation area are shown in figures (6, 7 and 8). The fluctuation of hydraulic heads in the area influenced by pumping of groundwater. The first phase was assumed to increase the current pumping rate by 10%. The simulate

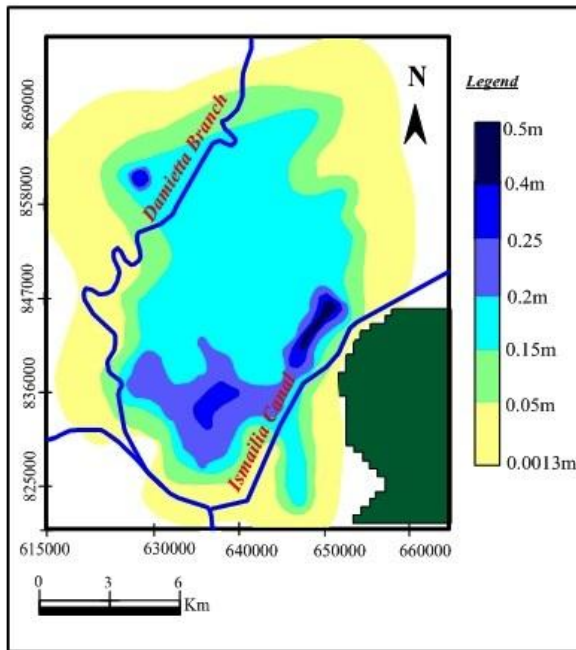


Fig.(6) The difference of groundwater levels contour map from year 2000 to 2030 (The first scenario)

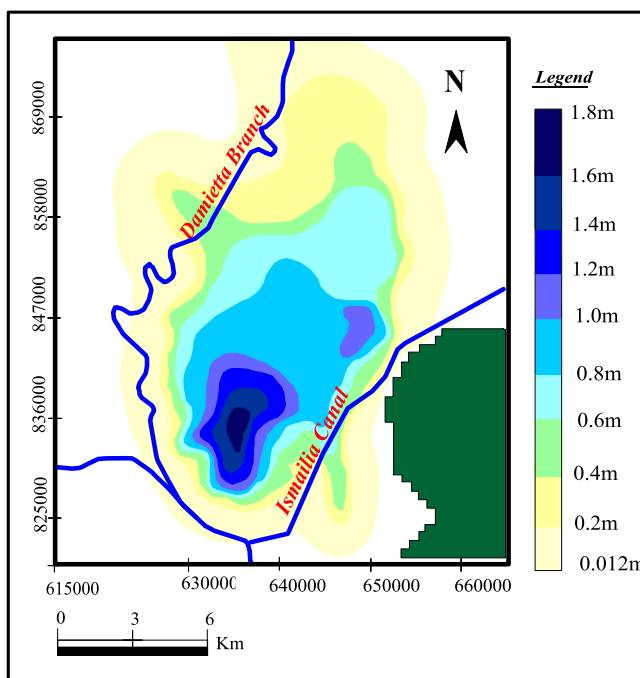


Fig.(7) The difference of groundwater levels contour map from year 2000 to 2030 (The Second scenario)

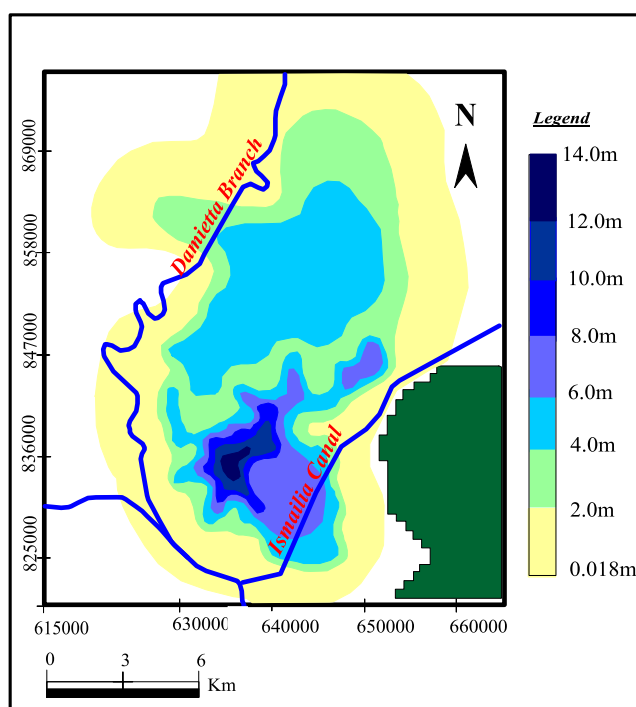


Fig.(8) The difference of groundwater levels contour m:
from year 2000 to 2030 (The Third scenario)

values of hydraulic heads were from the follow figures. It can be noticed that lowering in hydraulic heads ranges between 0.05 to 0.5m, which all of the study area the lowering in heads 0.2m except the south and east of the investigation area reached to 0.5m, which this area nearly to the end of the aquifer. The second phase was assumed to increase the current pumping rate by 50% in order to meet increasing in population. The lowering in water level of groundwater reached to 1.8m in the end of 2030, this drawdown in water level recorded in south of the study area. The third phase was assumed to increase the current pumping rate by 100% in order to meet increasing in population and usage groundwater in irrigation. The lowering in water level reached to 14m in south of investigation area

Solute transport model

Due to the environmental impact on the existing groundwater, continuous decline in water level accompanied with changes in water quality is developed. Accordingly, it was very necessary to study the impact of this development on groundwater quality by applying solute transport Model (visual model MT3D) which simulates a final calibration for the same period of groundwater flow model. Mass transport of total dissolved solids, SO_4 , Na, Cl, Fe, Mn, al and NO_3 have been investigated by using MT3D, which is a computer model for simulation of advection, dispersion and chemical reactions of soluble contaminants in three dimensional groundwater flow systems. Different parameters including TDS, concentration of major and trace elements, model boundary, particles tracking algorithm and advection parameters and methods were adjusted to run the model by using methods of characteristic (MOD).

Initial concentration:

The initial concentration of the measured TDS (shallow wells) has been simulated using the salinity contour map of 2010. Both the time and the stress period were divided into several steps. The first step started from the beginning of the 2010 and end to 2030. This represents the steady state period where there was no significant change in TDS concentration. Simulation results using indicate that the concentrations of TDS and different elements increases with time and move with groundwater flow direction toward the north west and north east (Fig. 10- 24, inclusive).

CONCLUSION

The visual Modflow and MT3D model used in the study area; provide an effective tool for managing the southeastern part of the Nile Delta aquifer through different scenarios during the period from years 2000 to 2030. Results indicate that increasing the current pumping rates by 10% and 50% caused the lowest drawdown values reaches to 0.5m and 1.8m, respectively. Increasing the current pumping rates by 100% gives the worst drawdown reaches to 14m and should be avoided. Simulation results using MT3D indicate that the concentrations of TDS and different elements increases with time and move with groundwater flow direction.

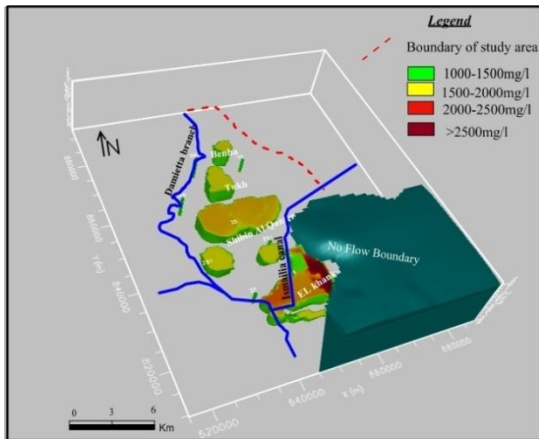


Fig. (9) Show distribution of salinity in the study area in the steady state

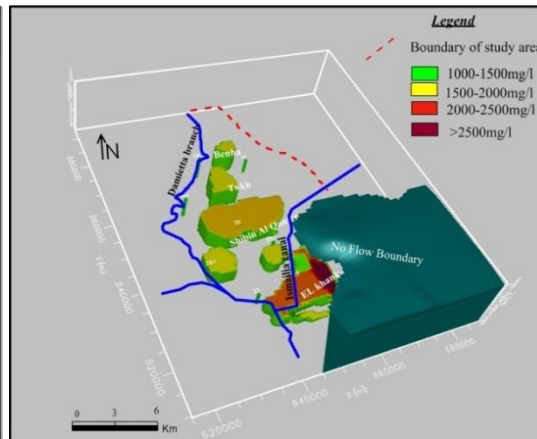


Fig. (10) Show distribution of salinity in the study area after 20 years

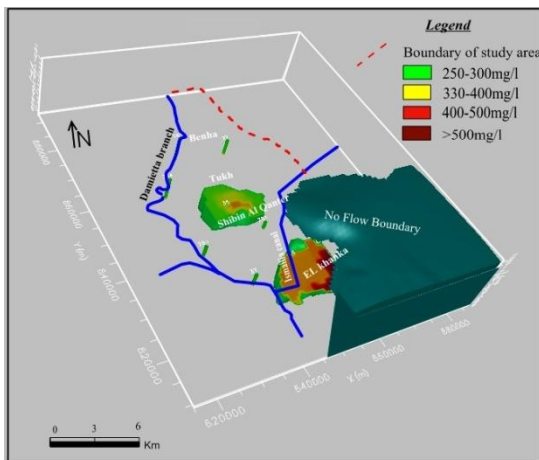


Fig. (11) Show distribution of Sodium in the study area in the steady state

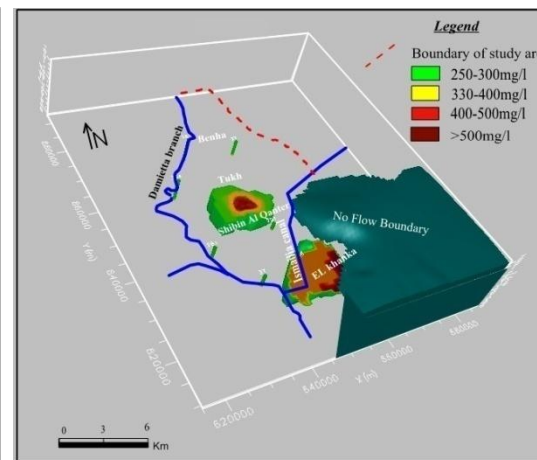


Fig. (12) Show distribution of Sodium in the study area after 20 years

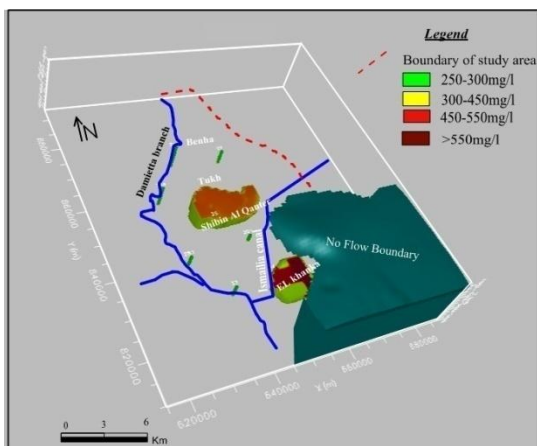


Fig. (13) Show distribution of Chloride in the study area in the steady state

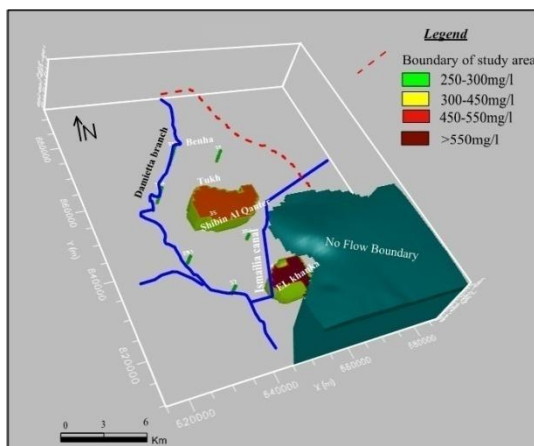


Fig. (14) Show distribution of Chloride in the study area after 20 years

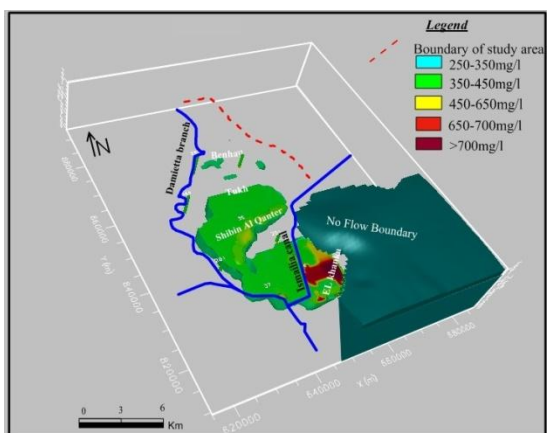


Fig. (15) Show distribution of Sulfate in the study area in the steady state

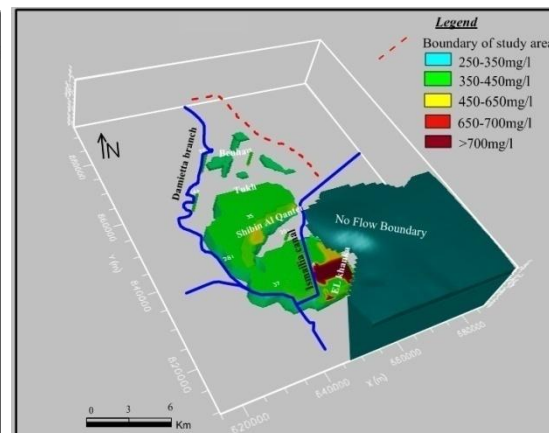


Fig. (16) Show distribution of Sulfate in the study area after 20 years

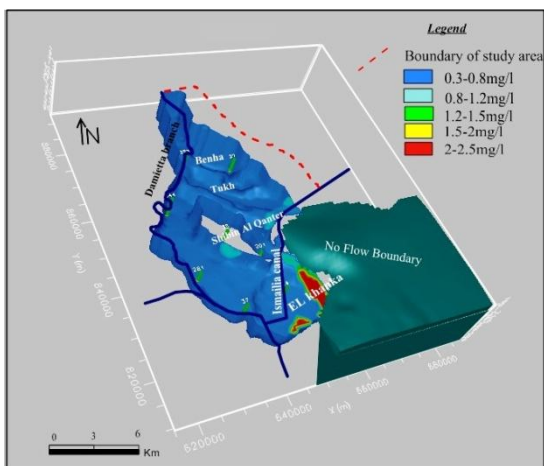


Fig. (17) Show distribution of Iron in the study area in the steady state

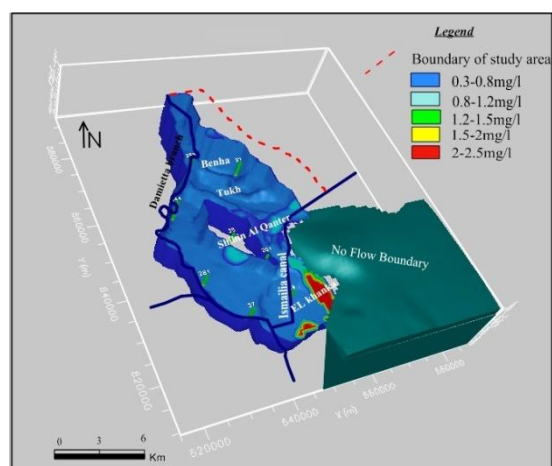


Fig. (18) Show distribution of Iron in the study area after 20 years

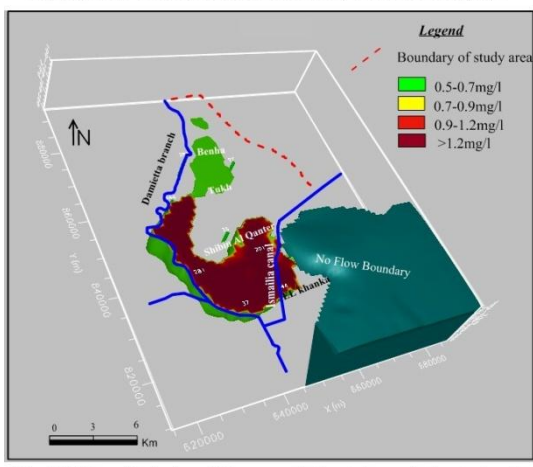


Fig. (19) Show distribution of Manganese in the study area in the steady state

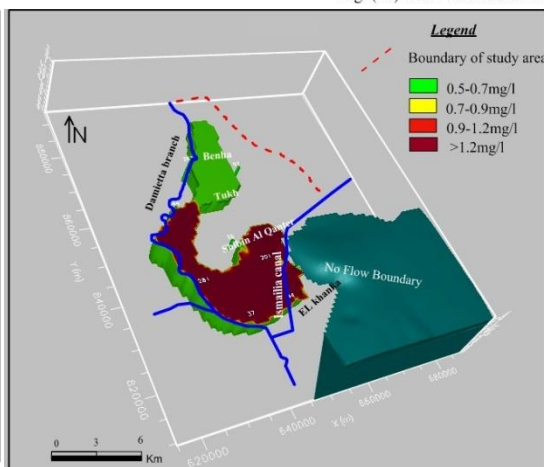


Fig. (20) Show distribution of Manganese in the study area after 20 years

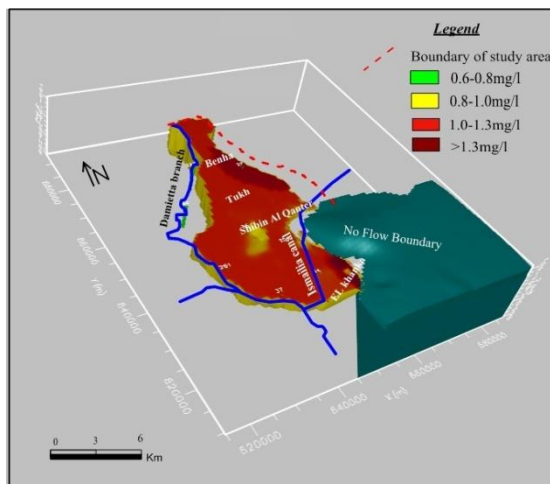


Fig. (21) Show distribution of Aluminum in the study area in the steady state

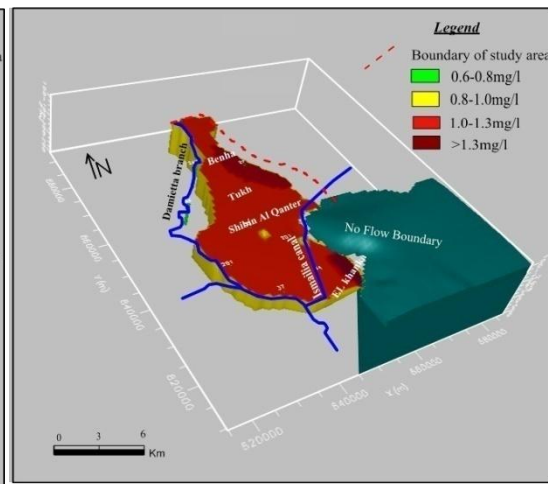


Fig. (22) Show distribution of Aluminum in the study area after 20 years

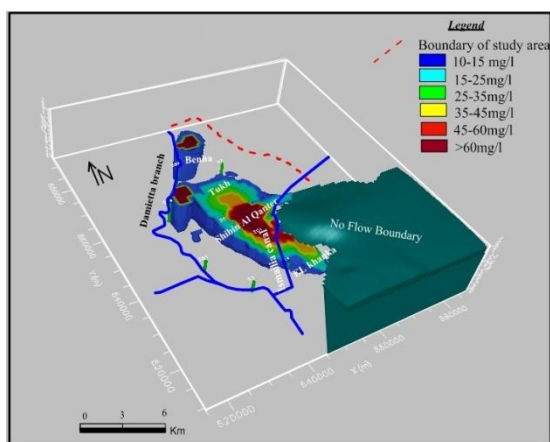


Fig. (23) Show distribution of Nitrate in the study area in the steady state

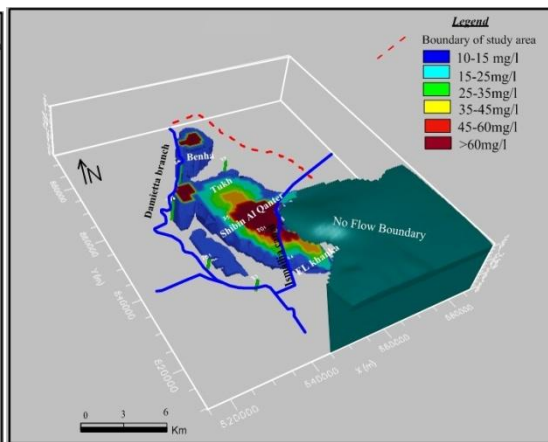


Fig. (24) Show distribution of Nitrate in the study area after 20 years

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