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ORIGINAL ARTICLE

Solute transport modeling of the groundwater for quaternary aquifer quality management in Middle Delta, Egypt

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Abstract Groundwater contamination is a major problem related strongly to both; protection of environment and the need of water. In the present study groundwater quality was investigated in the central part of the Nile Delta (El-Gharbiya Governorate). El-Gharbiya Governorate is an agricultural land and its densely populated area inhabited, includes small communities which totally not served by public sewers. Hydrochemical analyses were used to assess the quality of water in samples taken from the canals, drains and groundwater. A laboratory study and mathematical modeling works were presented. Two numerical computer models by the applying of finite difference method were adopted. Both models deal with the flow as a three-dimensional and unsteady. Results obtained include determining the levels of water and the values of solute concentration and distribution of it in the region at different times. The groundwater model MODFLOW was used to deal with the hydrodynamics of the flow through porous media. A solute transport model which can be communicated with MODFLOW through data files MT3DMS, was used to solve the problem of contaminants transport and the change of their concentrations with time. A proposed groundwater remediation scheme by using group of extraction wells was suggested at Birma region where the concentration values of ammonium contaminant are the up most according to hydrochemical analyses results. Proposed scenario for cleaning is to use a set of wells to pump contaminated groundwater extraction for treatment and reused to irrigation.

1. Introduction

Slow movement of water through the ground means that residence times in groundwater are generally longer than surface water. Once groundwater polluted, it can remain so for several decades, or even for hundreds of years until they can be cleaned if cleaning was actually possible. Sources of contamination of groundwater are numerous. Sources of pollution

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from human activities can be distinguished as domestic, agriculture and industrial.

1.1. Modeling of groundwater

Groundwater modeling consists of physical modeling and mathematical modeling. Physical modeling can be classified to Hele-shaw, sand tanks and electric analog models. Mathematical modeling can be classified to analytical and numerical models. Details of these models were presented by Harr [12]. The numerical techniques used the finite difference methods (FDMs), the finite element method (FEM) and boundary element method (BEM). Comprehensive treatments of the applications of these numerical methods to groundwater problems

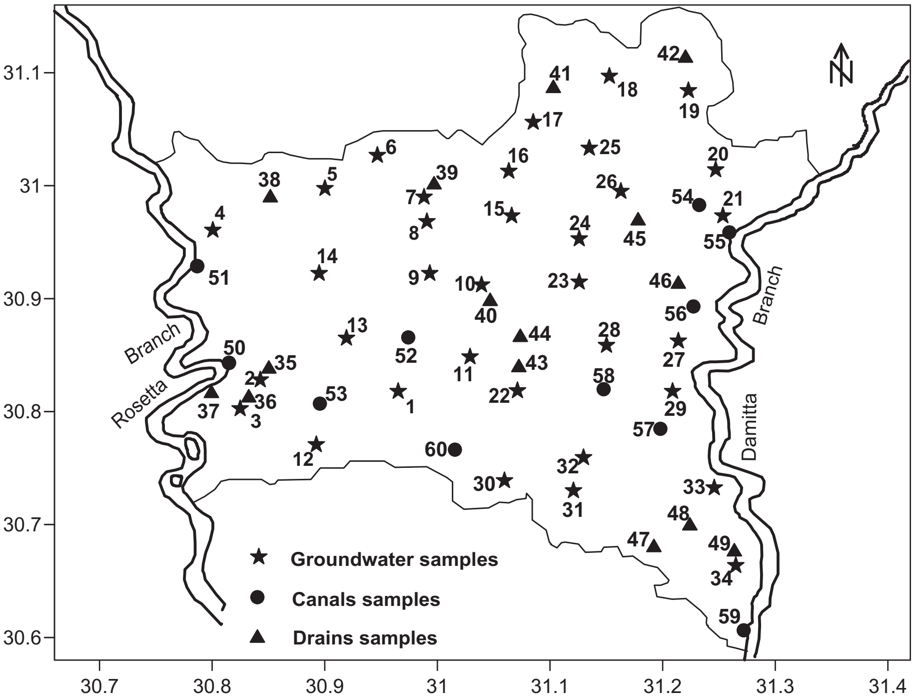


Figure 1 Locations of surface and groundwater samples.

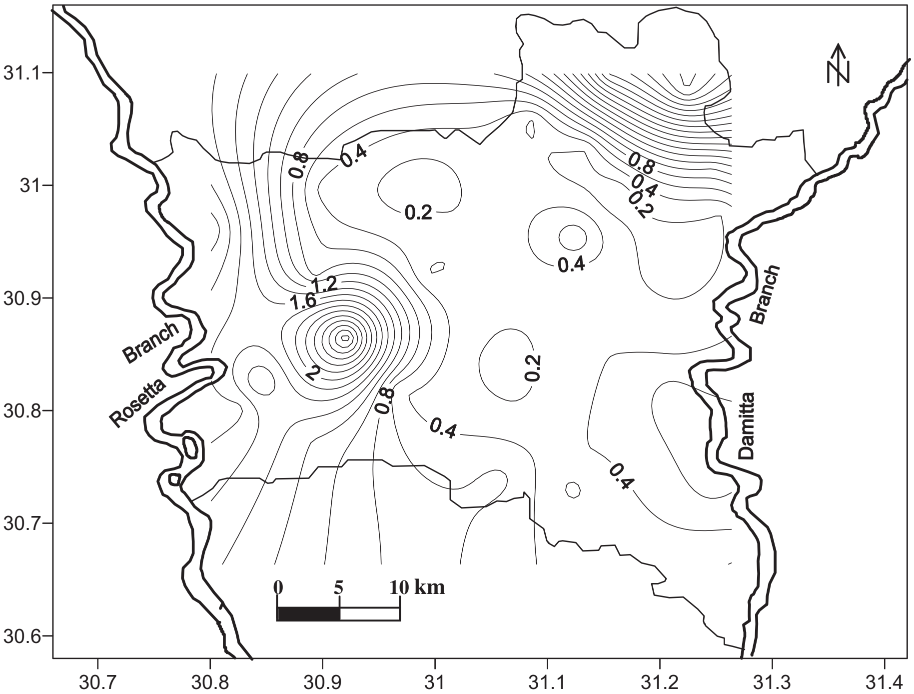


Figure 2 Iso-contour map of ammonium concentration in mg/L for groundwater samples.

were presented by Remson [18] and Wang and Anderson [26]. Based on the integrated finite difference method Nararimhan and Witherspoon [16] were developed a general model for both two and three dimensions groundwater flow. Shuluma [24] demonstrated applications for models in both two and three dimensions groundwater flow based on finite element method. Khalifa [13] used a three dimensions finite difference model (MODFLOW) in obtaining future piezometric head levels and the total volumetric water budget for Siwa Oasis. Bayer et al. [2] described how to source control with pumping wells located within the source zone. They concluded that down gradient plume control requires much lower pumping rates and is preferable for long-term control of a groundwater contamination. Bayer and Finkel [3] presented a comparison between pump-and treat and funnel-and-gate systems, as typical active and passive groundwater remediation technologies. Schalk et al. [21] proposed a modeling framework that takes advantage of the vast availability of measurement data in controlled water systems. The framework was successfully applied to improve a simulation model of the controlled water system of Rijnland, Netherlands. The suggestion water-system control model is more reliable for both design studies and operational decision support. Hamid et al. [11] presented a comprehensive evaluation of different finite difference schemes for the solution of head-based and mixed forms of the Richard's equation. He investigated the effects of various approximations of moisture capacity function, convergence criteria, and time stepping methods on the performance of the schemes. There results showed significant influences on mass balance, number of iterations, and convergence condition of the numerical schemes.

1.2. Modeling of contaminant transport in groundwater

The numerical methods commonly used to solve the problems of the transition can be classified as characteristics, random walk, Eulerian–Lagragian and adaptive grid methods. The suitability of a groundwater for irrigation is contingent upon the effects of the mineral constituents of the water on both the plant and the soil [29]. In specifying the quality characteristics of water, complete statement requires chemical, physical, sanitary and biological analysis [25]. Most drinking water

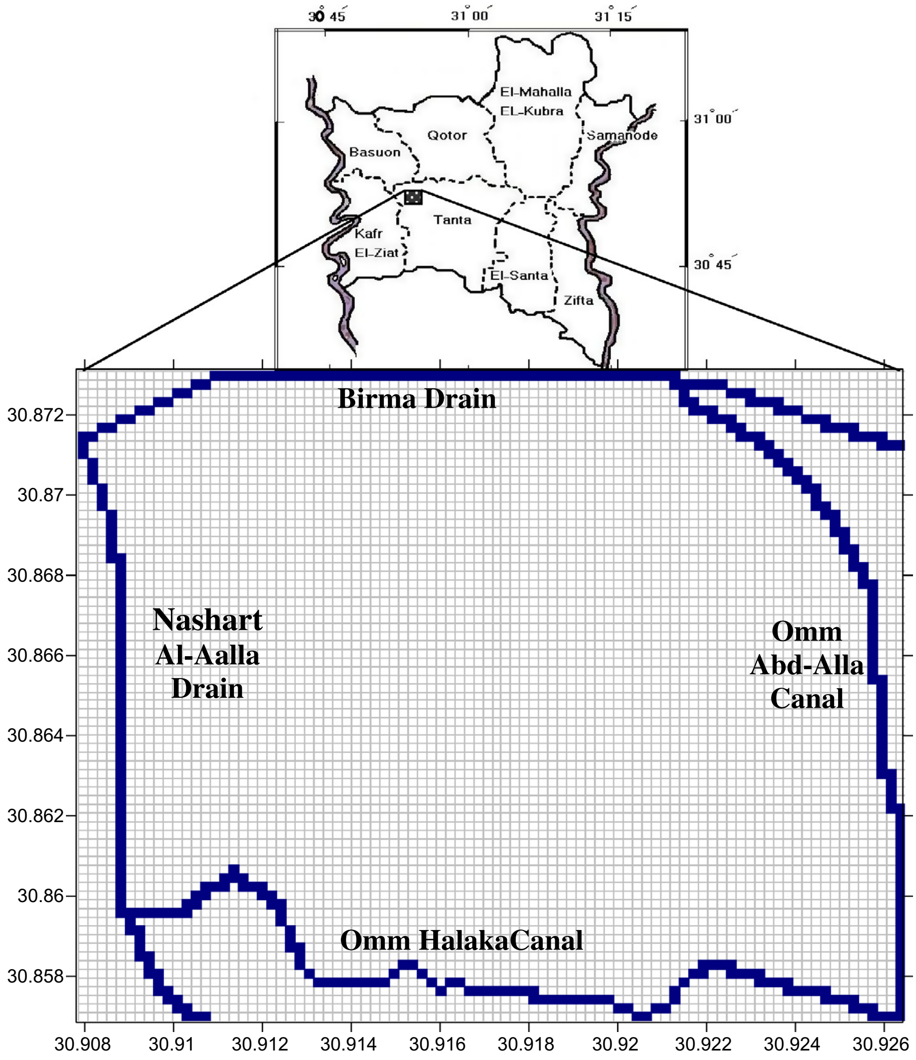


Figure 3 Location of Birma region and horizontal grid in the model.

supplies in accordance with the standard set by the World Health Organization [28].

Bear [4,5] used the basic equations of contaminant transport in groundwater. Abdel-Salam [1] was applied a finite element solute transport model (CSU/GWTRAN) to a vertical cross section in the Nile Valley of Egypt. Domenco and Schwartz [8] demonstrated the theoretical basis for the equation describing solute transport, which provide a conceptual framework for analyzing and modeling physical solute transport processes in groundwater. Shaltout (1999) studied the problem of contamination of groundwater by waste water. The study included a combination of field, laboratory and mathematical modeling works on a chosen area within Greater Cairo, Egypt. Kolditz et al. [14] examined variable density flow and corresponding solute transport in groundwater. Farid [9] presented study to provide guidelines to the Egyption government for improving environmental protection, concerning groundwater in the Tenth of Ramadan city. Dawoud [6] developed numerical simulation for transport of reactive multi-chemical components in groundwater. William [30] used GIS system to analyze, interpret and manage the quality of groundwater and characterize the most vulnerable locations for contamination along the groundwater flow path between the capital Amman and Zarqa area in Jordon. Wang et al. [27] presented numerical solution for governing equations describing advective–dispersive transport with multi rate mass transfer between mobile and immobile domains. Mohrlok et al. [15] made analysis of experimental tracer transport in three-dimensional flow field for groundwater and subsurface remediation at University of Stuttgart, Germany. A numerical model has been built up and simulation has been carried out for flow and transport processes. Experimental and simulated breakthrough curves were compared and the influence of aquifer heterogeneity on the transport has been brought out. Dilip et al. [7] obtained the Laplace transform technique and analytical solutions for two-dimensional advection–diffusion equations describing the dispersion of pulse-type point source along temporally and spatially dependent flow domains, respectively, through a semi-infinite horizontal isotropic medium. Sharief et al. [23] found that for remediation of dissolved phase contaminants in groundwater, a pump-and-treat method to be successful remediation technique. They concluded that, developing an efficient and robust design to solve groundwater pollution remediation problems using a pump-and-treat method is very important because of the large construction and operating costs involved. They made an attempt to develop a coupled simulation–optimization model based on the finite-element method and an evolutionary approach of an elitist genetic algorithm (EGA) for the optimal design of groundwater remediation by pump and treat. The simulation–optimization model was used to optimize the remediation of a large-field unconfined aquifer polluted with total dissolved solids (TDSs) to obtain optimal pumping rates.

The main objective of the present study is to investigate groundwater quality in the central part of the Nile Delta (El-Gharbiya Governorate). A combination study of laboratory and mathematical modeling works will be presented. The groundwater model MODFLOW will be used to deal with the hydrodynamics of the flow through porous media. A solute transport model which can be communicated with MODFLOW through data files MT3DMS, will be used to solve the problem of contaminants transport and the change of their concentration with time. Scenario proposed to clean up is to use a set of wells to pump contaminated groundwater extraction of groundwater for treatment.

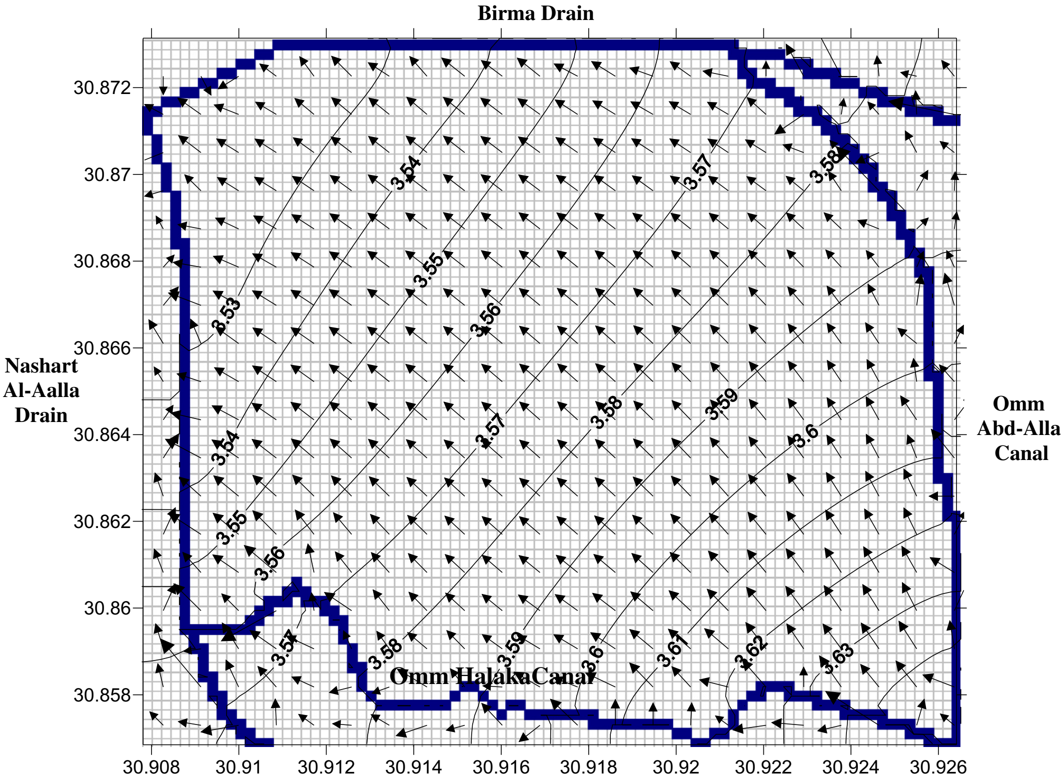


Figure 4 Calculated water levels and direction of groundwater flow in Birma region.

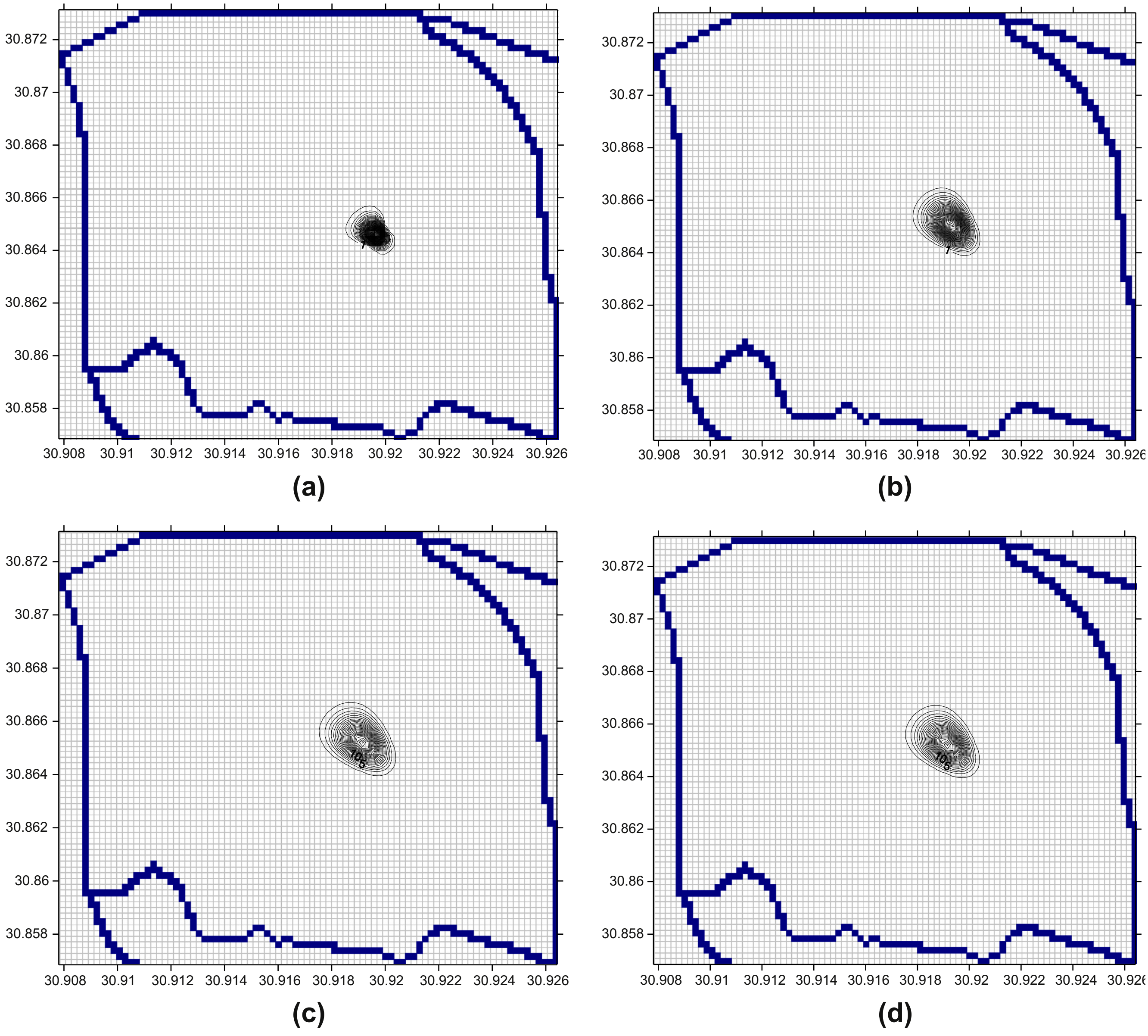
2. Description of the studied area

EL-Gharbiya Governorate is the central part of the Nile Delta of Egypt. It extends between latitudes 30°36′–31°09′N and longitude 30°45′–31°15′E. It includes more than 1943.51 km^2. The area is bounded on the west by "Rosetta Branch" and on the east by "Damietta Branch". The Governorate extends into Kafr El-Shiekh in the north and El-Menoufia Governorate in the south. The Governorate consists of eight centers, all of them are cultivated land and dense populated.

The area is dissected by an extensive network of irrigation canals and drains distribute the water on a rotation system. Topographical elevation slopes are gradually from south to north. It decreases from 8.5 m to 3.5 m above MSL (at the north portion). Generally, the average regional slope is 10 cm/km. The eastern portion of the studied area is slightly higher than the western portion. This explains the direction of the irrigation canals in the middle portion, where most of them are fed from Damietta branch and run towards the Rosetta branch.

2.1. Hydrogeological setting

The majority of the studied area is covered by the Quaternary deposits which are discriminated into two units. The upper unit belongs to the Holocene, which consists of silt and clay. Its thickness varies from 5 m to more than 20 m. The lower unit assigned to the Pleistocene that consists of sand and gravel with clay lenses. The thickness of this aquifer varies from 450 m to 600 m and underlined by the Pliocene clay. The transmissivity of the aquifer varies from 3000 to 5000 m^2/day. The hydraulic conductivity ranges among 50 and 100 m/day [20].



(a) (b)

(c) (d)

Figure 5 Simulated concentration at and round source (a) Simulated concentration after 5 years ((C/Co) max = 110 × E^{-3}), (b) after 10 years ((C/Co) max = 54 × E^{-3}), (c) after 15 years ((C/Co) max = 36 × E^{-3}), and (d) after 20 years ((C/Co) max = 27 × E^{-3}).

The effective porosity varies from 15% to 18% and the storage coefficient ranges among 0.01 and 0.001 [10].

The groundwater levels of the Pleistocene aquifer range between 8 m in the southern part of the Governorate and 2 m in the North. The direction of flow is from South East toward the North West. The aquifer is continuously recharged by infiltration of excess irrigation water in addition of seepage from the main network of canals and drains or directly from Damietta branch. The recharge from rainfall is very less (negligible). The discharge of the aquifer takes place through the natural outflow drains and Rosetta branch, outflow to adjacent aquifer and by groundwater extraction from existing wells for water supply and irrigation.

2.2. Hydrochemistry

Sixty groundwater samples from the Quaternary aquifer, canals and drains water were collected from the study area, Fig. 1. Groundwater samples were collected after wells had been pumped for at least 15 min. Electrical conductivity, bicarbonate, dissolved oxygen (DO) and pH was measured in the depth of these wells ranges between 13 m and 60 m. Water samples were filtered using 0.45 μm pore-size papers.

Major cations and anions were measured for the pre-filtered water samples by using U.V. spectrophotometer, flame photometer and titration methods. Vacuum Distillation method was used for determination of ammonia and nitrate in water.

All hydrochemical analyses were carried out in the Central Laboratory for Environmental Isotope Hydrology, National Center for Nuclear Safety and Radiation Control, Atomic Energy Authority, Cairo, Egypt. The iso-contour map of ammonium concentration of groundwater samples which range from 0.0 to 3.81 mg/l is shown in Fig. 2.

From Fig. 2, it can be seen that the concentration of ammonium have two high mount within the area. The first is located in the center of the Governorate at Birma Village and the second at the north eastern region with concentration gradient increases toward the north boundary outside the area of study. The low Nitrate of groundwater could be explained as denitrification process which can be strongly influenced by high Manganese and Iron concentrations at different regions of the studied area.

2.3. Birma village

The chosen area to conduct the numerical work as micro-scale study is Birma village, Fig. 3, where the concentration values of ammonium contaminant are the up most according to hydrochemical analysis. It lies at the central part of El-Gharbiya Governorate and belongs to Tanta center. The region to conduct the study looks almost like rectangular shape with length of 1.76 km and width of 1.5 km. It is surrounded by Birma Drain at north, Omm Halaka Canal at south, Omm Abd-Alla Canal at east and Nashart Al-Aalla Drain at west.

3. Methodology

Two software programs for solving the mathematical models numerically were used by applying the finite difference method. The first software program; "MODFLOW" was applied for the solution of groundwater movement problems. It is able to predict the future changes of heads and change in flow direction. The second software program; "MT3DMS" was applied for determination of contaminant transport movement and distribution. It communicates with MODFLOW program through data files. This should be linked to known groundwa-

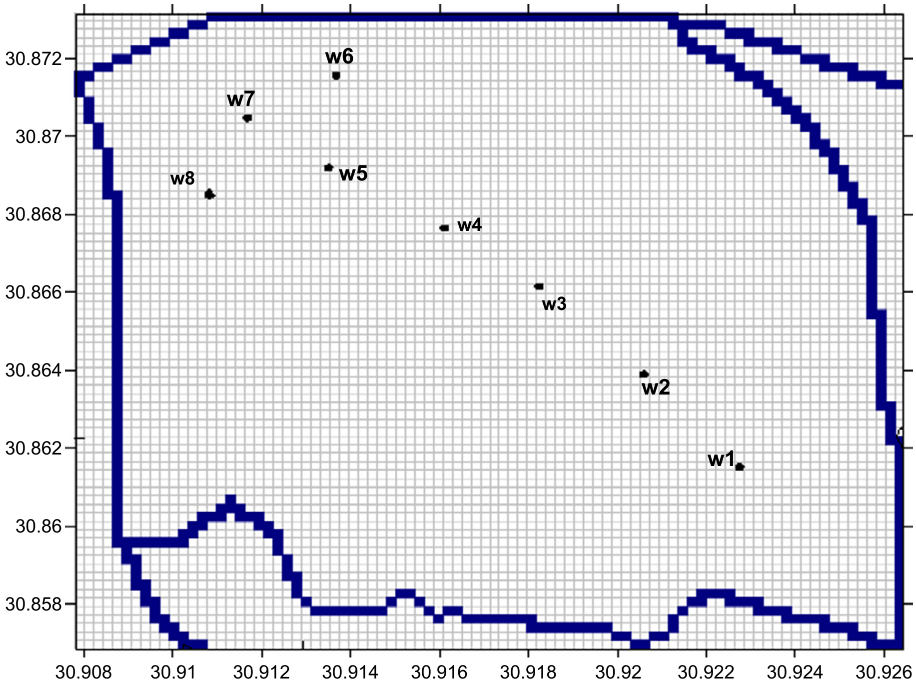


Figure 6 Locations of wells chosen as a diagonal toward the northern-west direction.

ter movement in order to determine the distribution and movement of contaminants in groundwater.

3.1. Verification of the MODFLOW model

The groundwater flow model was verified using two measured groundwater level contour maps of regions located in Egypt:

1. the Southern part of Cairo studied by Shaltout [22], and
2. the Central part of the Nile Delta aquifer (after RIGW [19].

The steady-state case in MODFLOW was adopted to simulate the flow in the study region. The hydraulic properties of the stratigraphic units have been taken from the previous works conducted by the Research Institute for Groundwater in Egypt [19] and the Geotechnical Encyclopedia of Egypt [10]. The horizontal hydraulic conductivity is assumed to be 10 m/day for the silt–clay cap and it ranges among 50 and 100 m/day for the sand-gravel stratigraphic units [20]. The vertical hydraulic conductivity is assumed to be 10% of the horizontal hydraulic conductivity [20]. The heads at the water boundaries have been based on the 1:100000 scale hydrogeological maps of Middle Delta region by RIGW [19] (West Tanta and East Tanta). The effective porosity is assumed as constant average value of 0.18 and the transmissivity is assumed as constant average value of 4000 m^2/day for the Pleistocene aquitard [10]. After complete entering of the data required for building the model, it was allowed to run. The calculated steady state groundwater levels and the direction of groundwater flow were verified with the previous data.

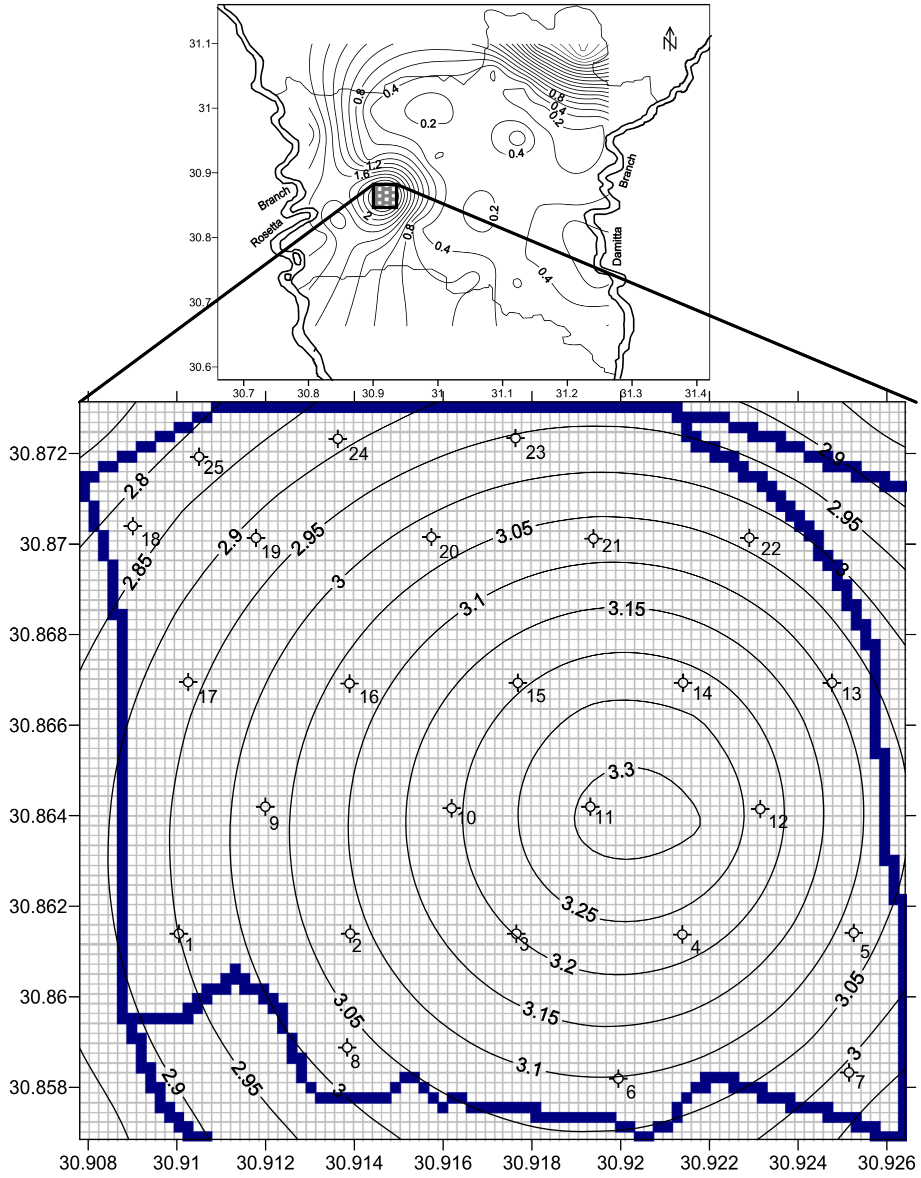


Figure 7 Iso-contour map of ammonium–nitrogen concentration in mg/L based on chemical analysis and position of boreholes to cover all Birma regions.

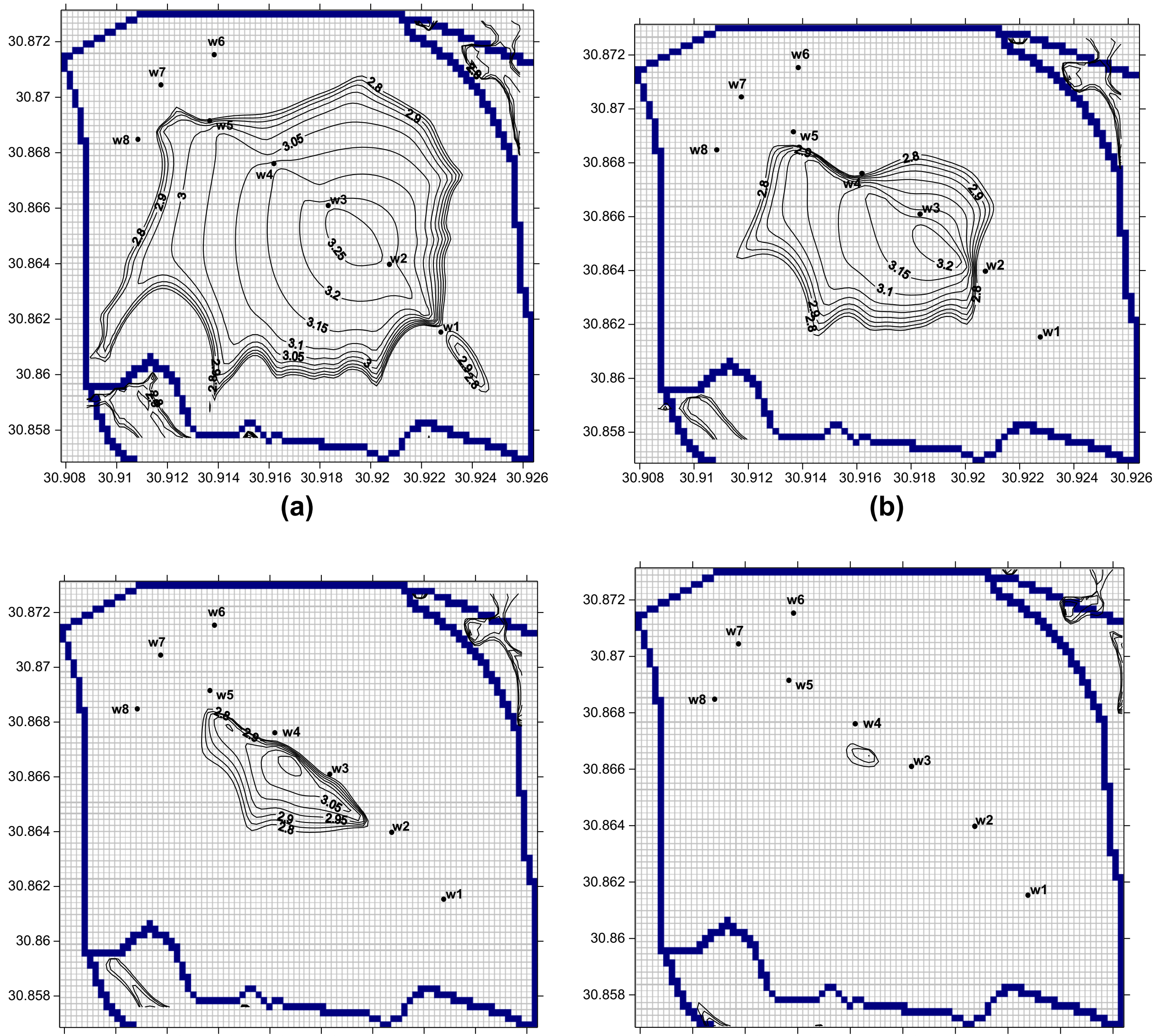
3.2. Verification of the MT3DMS model

In the present study, computer program MT3DMS was used to simulate ammonium contaminant variation at the study region. It can be used to simulate changes in concentrations of miscible contaminants in groundwater considering advection, dispersion, diffusion and some basic chemical reactions. A generalized partial differential equation describing the fate and transport of contaminants of species k in three-dimensional, transient groundwater flow systems can be formulated as follows:

$$\frac{\partial(nC^k)}{\partial t} = \frac{\partial}{\partial x_i}\left(nD_{ij}\frac{\partial C^k}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(nv_{si}C^k) + q_s C_s^k + \sum R_n \tag{1}$$

where C^k is the dissolved concentration of species k, n is the porosity of the subsurface medium, t is the time, x_i is the distance along the respective Cartesian coordinate axis, D_{ij} is the hydrodynamic dispersion coefficient tensor, v_{si} is the seepage or linear pore water velocity; it is related to the specific discharge or Darcy flux through the relationship, $v_{si} = q_i/n$, q_s is the volumetric flow rate per unit volume of aquifer representing fluid sources (positive) and sinks (negative), C_s^k is the concentration of the source or sink flux for species k and $\sum R_n$ is the chemical reaction.

The computer program MT3DMS paired with program MODFLOW were verified using one of the test cases that was proposed by Kolditz et al. [14] and Oldenburg and Pruess [17]. This test case is addressed to model groundwater flow over a hypothetical salt dome.



(a) (b)

(c) (d)

Figure 8 Iso-contour map of ammonium–nitrogen concentration in mg/L for groundwater (a) after 5 years, (b) after 10 years, (c) after 15 years, and (d) after 20 years.

3.3. Numerical solution

A three-dimensional grid was constructed to bound Birma sub-regional groundwater model. The grid cell size in the horizontal plane of the model is 20 m by 20 m, requiring the modeled area to be subdivided into 75 rows and 88 columns. Fig. 3 illustrates the location map of Birma region and the horizontal grid of the modeling area. The aquifer system has been subdivided into seven modeling layers in the vertical direction. Computer program MODFLOW was used the elevations of top and bottom of the aquifer layers to calculate the aquifer thickness for each cell node. The value of the first layer top has been changed according to the nature topography of the area by the grid SURFUR tool and saved as spreadsheet file accepted by MODFLOW package. The saturated part of the silt–clay cap layer was modeled as two layers of 7 m constant thickness. Layers 3 through 7 were assigned a constant thickness for each layer; 6, 6, 5, 5 and 4 m respectively. This vertical discretization was chosen according to the depth and screen length of the production wells that the groundwater samples were collected from. Lateral boundaries of the modeling area had been defined at constant-head boundary.

After complete entering of the data required for building the model, it was allowed to run. The calculated steady state groundwater levels are presented in Fig. 4. The directions of flow are illustrated in the same figure.

To investigate the direction of contaminant movement and its variation with time, unit rate of ammonium concentration is assumed to be applied from a point. The injection is assumed to start at $t = 0$ and continues indefinitely. The concentration of the contaminant at $t < 0$ is assumed to be zero in the whole region. The simulated contaminant concentrations for the 5, 10, 15 and 20 years after injection in the fifth layer were calculated for six observation boreholes in the North–South direction and other six boreholes in the East–West direction around the source, Fig. 5. The distance between the sources and the boreholes in each direction are 50, 100 and 150 m respectively. The calculated concentration in boreholes No. 1 and 10 which lie only 50 m west and north of the injection point increased to 7.66×10^{-3} and 7.07×10^{-3} respectively after 360 days, and reach the maximum relative concentration of 28×10^{-3} and 26.14×10^{-3} respectively after 2160 days (6 years). The analysis of the figures leads to the conclusion that most of the contaminant flows towards the northern-west direction. This results show that the hydraulic properties and gradient play the major role on the contaminant transport direction. In the meantime, the boundary conditions play a major role on the value of the concentration.

3.4. Suggested treatment

Management scenario is suggested to clean up the aquifer at Birma region from ammonium contamination. Proposed scenario for cleaning is to use a set of wells to pump contaminated groundwater extraction for treatment and reused in irrigation. The locations of wells were chosen as a diagonal shape toward the northern-west direction, as shown in Fig. 6, according to the flow direction of contaminant. The measured ammonium concentrations by hydrochemical analyses were used as the initial condition for the transport model. Prior to run the transport model, 25 observation boreholes were defined, for which the concentration–time relation can be calculated. The position of these boreholes was chosen irregularly to cover Birma region, Fig. 7. The proposed total extraction rate for the

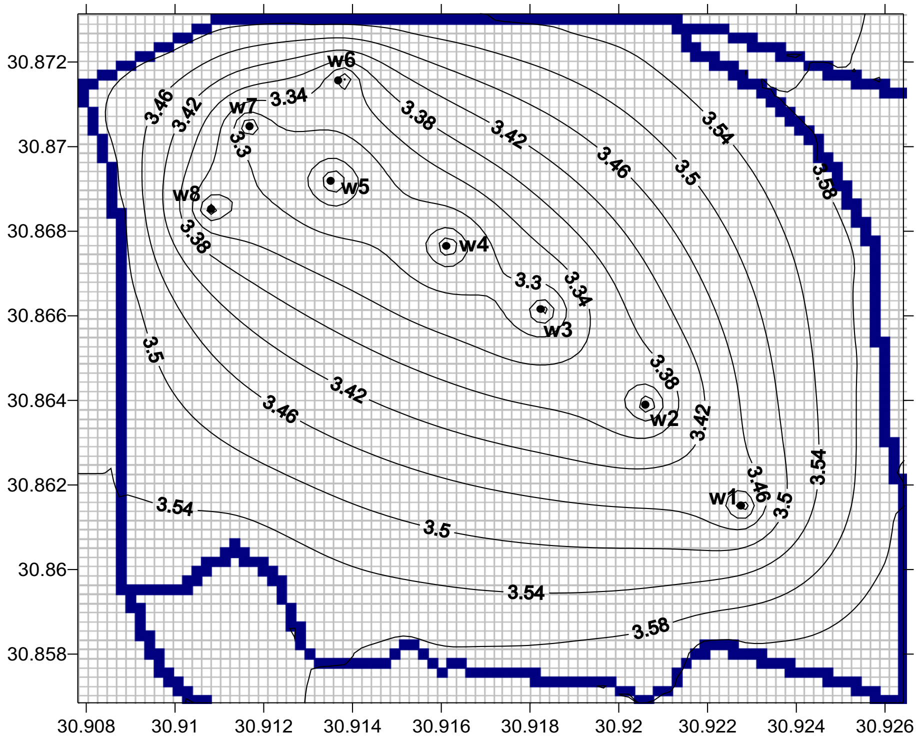


Figure 9 Calculated groundwater level contour maps in Birma region after 7220 days (20 years) of extraction.

eight wells is 800 m^3/day (100 m^3/day for each well), all from layer five.

The same grid configuration used in the flow modeling was used in the solute transport modeling. The considered boundary conditions in the transport model are surface and groundwater levels together with the other data and results of the flow model in addition to the resulted ammonium–nitrogen concentrations from chemical analysis. The value of bulk density for the entire domain was taken as 1.5 kg/m^3 and the distribution coefficient of the solute in the porous medium was assumed as 0.5 ml/g.

4. Results and analysis

After steady state run successfully the model becomes ready to run in the transient condition (time dependent conditions). The heads obtained from the steady state simulation were used as starting heads to the transient analysis. Time parameter was converted into transient. A simulation period of 7200 days (20 years) was applied. This simulation time was subdivided into four time intervals. Accordingly, heads and the contaminant concentrations could be obtained every 5 years (1800, 3600, 5400 and 7200 days). The transport model simulation results are presented in Fig. 8a–d, which illustrate the contour lines of ammonium concentrations obtained every 5 years through the simulation period of 20 years.

The final groundwater levels after the simulation period of 7200 days (20 years) are illustrated in Fig. 9.

5. Conclusions

The Quaternary aquifer in the studied area is quite vulnerable to pollution. Deterioration of groundwater indicates clearly that the human activities caused serious pollution problems. As results of chemical analysis, the nitrate concentrations have clear mount within the area except the north eastern part of the studied area. Ammonium concentrations of groundwater reached an alarming level and exceeded the drinking water standards (0.5 mg/L). The high concentrations are around Birma village at the central part of the studied area and at the north eastern region with concentration gradient increases toward the north boundary outside the area of study. The potential sources of nitrogen compound pollution are: water from sewage treatment plant used for irrigation, sludge and animal manure, septic tanks, soil nitrogen and artificial fertilizers.

Two software programs were used for solving numerically the three dimensional models by applying the finite difference method. A management scenario is suggested to clean up the Birma region. The remediation scheme assumes dewatering system through eight extraction wells to pump the contaminated groundwater out of the aquifer for treatment. The locations of wells were chosen toward the flow direction of contaminant. The scenario is successful application in the clean up the Birma region from contamination.

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