Modeling the impact of nitrate fertilizers on groundwater quality in the southern part of the Nile Delta, Egypt

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ABSTRACT

The use of fertilizers in agriculture in Egypt, especially nitrogen, has increased significantly in the last decade, resulting in nonpoint contamination of the groundwater resources. This study investigated the effect of using nitrogen fertilizer on groundwater contamination with nitrate in the central southern part of the Nile Delta. NO$_3$ concentrations in shallow groundwater were assessed based on the applied urea dose (the common nitrogen fertilizer used) in year 2014. A groundwater modeling system (GMS) comprising MODFLOW and MT3D was used to simulate the three-dimensional groundwater flow and NO$_3$ transportation processes in El-Menoufiya Governorate, located in the central region of the Nile Delta aquifer. Calibration for MODFLOW was conducted to match known head configurations to minimize the water balance differences. Calibration of MT3D was accomplished by fitting the model to the measured NO$_3$ concentrations during the year 2014. The results highlighted areas of groundwater contamination by NO$_3$, which occurred at shallow depths (40 m) due to the significant loads of nitrogen fertilizer application and the flood irrigation method. While the results suggested one approach was to avoid using contaminated shallow groundwater as a water source, a more sustainable approach would be to implement best management practices to reduce and control the amount of nitrate leaching into the shallow groundwater system in the future.

Key words | groundwater contamination, MODFLOW, Nile Delta aquifer, NO$_3$ fertilizers, numerical modeling

INTRODUCTION

The Nile Delta is a vast leaky aquifer that directly connects with the Nile River and is bounded by its two branches (Mabrouk et al. 2013). Consequently, the groundwater quality in the Nile Delta is strongly affected by the changes in the Nile River flows (Dawoud 2004). The horizontal expansion of lands under reclamation for increasing the agricultural area in Nile Delta, with extensive groundwater extraction, has resulted in the increasing pollution and deterioration of groundwater resources (Abdel-Shafy & Aly 2002). The use of fertilizers is now becoming a common practice in agriculture in Egypt, while both consumption and application rates have been increased significantly (FAO 2009). Excessive use of nitrogen fertilizers is likely to be responsible for increasing nitrate concentrations in the shallow groundwater system. Thus, appropriate water and nutrient management is required to minimize groundwater pollution and to maximize nutrient use efficiency (Shekofteh et al. 2013). Groundwater contamination under agricultural catchments occurs when nitrogen rich fertilizer application as urea exceeds the plant demand.
and the denitrification capacity of the soil, leading to nitrogen leaching to the groundwater system, usually in the form of nitrate, which is highly mobile with little sorption (Birkinshaw & Ewen 2000).

The Nile Delta and Valley aquifers have been studied by RIGW/IWACO (1999) and results showed that Egypt faces imminent threats in addition to the urgent need for a comprehensive management plan for drought mitigation, based on limiting extraction rates. The annual extraction rates that were reported as follows; $3.02 \times 10^9$ m$^3$ yr$^{-1}$, $3.5 \times 10^9$ m$^3$ yr$^{-1}$, and $4.6 \times 10^9$ m$^3$ yr$^{-1}$ in years 2000, 2003, and 2010 respectively (RIGW 2010). The highest ion concentrations that have been detected in a groundwater aquifer in the Nile Delta were NO$_3^-$, SO$_4^{2-}$, K$^+$, and PO$_4^{3-}$ (Al-Agha et al. 2015). In addition, the vulnerability of water resources to pollution was mainly related to the excess use of fertilizers in agricultural activities. Therefore, it is important to carry out the groundwater vulnerability evaluation for the management of groundwater resources (Bai et al. 2013, 2016). On the other hand, the impact of local hydrogeological conditions and human activity on water resources in the south east of the Nile Delta has been studied by El-Fakharany & Mansour (2009), it was found that groundwater quality issues are related to these activities.

Agriculture is the main activity in the study area, and the land under cultivation is in increase that equals 326,260 feddans, which is estimated at about 70% of the total Governorate area (Mohamed 2004). Therefore, the problem of increasing nitrogen fertilizer application is becoming worse as more nitrate is leached to the groundwater table, causing the deterioration of the Nile Delta aquifer. The objective of this study is to investigate the effect of using urea fertilizer in agricultural lands in El-Menoufia Governorate on the groundwater contamination with nitrate for the central southern part of the Nile Delta. The groundwater modeling system (GMS) package, including MODFLOW and MT3D, was used in the model simulations for groundwater flow and nitrate transportation respectively. The model calibration for the groundwater heads and observed nitrate concentrations at 40 m depth in year 2014 was performed. Then, the current fertigation strategy which applied with the flood irrigation method was assessed for better groundwater management in the aquifer.

**STUDY AREA**

El-Menoufia Governorate is located in the central southern part of the Nile Delta of Egypt. It extends between latitude $30^\circ - 20^\circ - 30^\circ$ 40’ N and longitude $30^\circ$ 50’-31 15’E. The governorate, whose total area is about 2,543.82 km$^2$, is bounded on the east by Damietta branch and on the west by Rosetta branch. The governorate extends to El-Gharbiya in the north and Cairo in the south. The governorate consists of nine administrative districts, all of them are cultivated land and densely populated, covered by an extensive irrigation network consisting of canals and drains. The average ground elevation slope is 10 cm/km, and gradually decreases from 12 m to 10 m above mean sea level (MSL) from south to north.

**Geologic and hydrogeological setting**

The Quaternary and Pliocene deposits that constitute the main water-bearing formations of the Nile Delta in the study area comprise the aquifer system, which is intercalated by semi-pervious clay and silty layers. The Nile silt aquitard, which belongs to the Holocene age, caps the main aquifer that belongs to the Pleistocene, which consists of sand, gravel and rock fragments representing the groundwater aquifer itself. The formations are underlain by an impermeable base of Pliocene clay deposits that act as an aquiclude (Schlumberger 1984).

Figure 1(a) shows the hydrogeological section of the Nile Delta aquifer after (Elewa 2010), while Figure 1(b) shows the key map for the area. It can be noticed that the average thickness of the aquifer in the study area is about 200 m, underlain by the Pliocene clay, while the hydraulic conductivity ranges from 50 m/day to 120 m/day. The transmissivity of the Nile Delta aquifer in El-Menoufia ranges from 2,000 to 3,000 m$^2$/day, effective porosity ranges from 12% to 19%, and total porosity ranges from 25% to 40% (Ebraheem et al. 1997). The average depth of the groundwater table is generally 3–5 m, (Morsy 2009) (see Figure 2), while the water level ranges between 12 m and 9 m above MSL. The constant head boundary of the Nile Delta (see Figure 3) was identified by RIGW (1990), where the direction of the groundwater flow is from south east to north west. Therefore, most of irrigation canals are recharged from Damietta branch and run towards the Rosetta branch.
Agricultural activities

In El-Menoufi, the agricultural practices are the main activity of the people. Crops are cultivated in a mixed pattern following two or three crop rotations per year. The main crops consist of wheat and clover in the winter, starting from October to November, and maize and cotton in the summer starting from May to June (Bader 2004). Irrigation is mainly by the traditional flooding method, 0.25 m submergence of agricultural land by irrigation water, which occurs frequently, three and two times per month in the summer and winter, respectively (Krueman & Vullings 2007).

The nitrogen fertilizer is the major chemical used in the study area, where urea is the most common type, which is supplied to farmers through the Agriculture Directorate, El-Menoufi, Ministry of Agricultural and Land Reclamation. The application rate of nitrogen fertilizer is recorded by Agricultural cooperative societies, and from field data as follows: 270 Kg/ha and 187 Kg/ha in summer and winter respectively (Mohamed 2004). The time and method of urea application depends on the crop type (see for instance FAO 2005).

MODELING FRAMEWORK

The GMS was chosen to build the required simulation models used in this study. MODFLOW is a modular, three dimensional, finite difference groundwater flow model...
which was coupled with the MT3D model for nitrate transport simulation. GMS integrates these two models by coupling, conceptualizing, running the simulation codes, and visualizing the simulation results.

**Theoretical approach**

Groundwater flow within the aquifer was simulated in MODFLOW, which numerically solves the governing flow equation based on water balance (Wang & Anderson 1982; Wang et al. 2005), which is written as follows:

\[
\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right)
= S_{ss} \frac{\partial h}{\partial t} + R
\]

where \(K_{xx}, K_{yy},\) and \(K_{zz}\) are hydraulic conductivities along the \(x, y,\) and \(z\) directions (m/d) respectively, \(h\) is the piezometric head (m), \(R\) is the volumetric flux per unit volume representing the source/sink terms (m³/d), and \(S_{ss}\) is the specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material (dimensionless), and \(t\) is time (day).

The nitrate transport process was then modelled in MT3D, which employs a mixed Eulerian-Lagrangian approach to solve the advection-dispersion-reaction equation, Zheng (1990) as:

\[
\frac{\partial C}{\partial t} + \Delta_1[D \Delta C] - \Delta_1[\nu C] + \frac{\partial}{\partial t} \left( \rho_p \frac{\partial C}{\partial t} \right) - \lambda \left( C + \frac{\rho_p}{\theta} C \right)
\]

where \(C\) is the solute concentration, \(D\) is the dispersion tensor, \(\nu\) is pore water velocity, \(q_s\) is the volumetric flux per unit aquifer volume, \(\theta\) is the porosity, \(C_s\) is the concentration of the source/sink water, \(\rho_p\) is the bulk density of the porous medium, and \(\lambda\) is rate constant of first-order reactions.

**Design of the conceptual model**

Due to the presence of the lower Pliocene clay layer, which represents the impermeable boundary of the aquifer, only the upper 200 m portion was modelled, as shown in the hydrogeological section in Figure 1(a). The upper layer belongs to the Holocene and consists of silt and clay with variable thickness from 5 m to 20 m (Fadlelmawla & Dawoud 2006). The conceptual model approach was used to construct the MODFLOW simulation, then layers parameters were defined as coverage. Subsequently, the conceptual model is converted to the grid model with elevation data interpolation to MODFLOW and MT3D.

The aquifer is dominated by unconsolidated coarse sand and gravel with occasional clay lenses. Therefore, the aquifer is subdivided in the vertical direction into four layers: the upper is a silty clay cap with a thickness varying between 5 m to 20 m; the second is fine sand with a depth ranging from 10 m to 25 m; the third is a coarse sand layer with an average thickness of 30 m; and the fourth layer is sand and gravel, which is assumed to be deeply extended to the impermeable layer. For the boundary condition, the two branches of the River Nile were assigned as constant heads. The irrigation network was assigned using river and drain packages, where the infiltration of the groundwater is controlled by the bed conductance. The southern boundary of the study area is parallel to the head gradient of the groundwater; therefore, it was set as a flux boundary with a variable inflow rate.

**Modeling groundwater flow**

After hydrological data collection, building the 3D stratigraphic model is performed using the solids module in GMS, which was subsequently exported to MODFLOW and MT3D as shown in Figure 4. The groundwater system in the Nile Delta aquifer is in a steady state equilibrium with negligible change in storage, especially after construction of the Aswan High Dam (Warner et al. 1991). Therefore, the steady state case in MODFLOW was adopted to simulate the groundwater flow in the study area. The aquifer is continuously recharged by the infiltration of excess irrigation water from agricultural fields according to the estimated recharge rate from traditional agriculture, which is around 0.0005 m/day. In addition, there is seepage from the main irrigation canals and directly from Damietta branch. While Ju et al. (2015) concluded that the high intensity rainfall and its temporal distribution play an important role.
role in soil water changes, rainfall in the Nile Delta is extremely low (around \( \sim 20 \) mm/year) so it is not a significant source. The discharge of the aquifer takes place from direct extraction by wells either for drinking or irrigation, and seepage to drains and the Rosetta branch.

The values of horizontal hydraulic conductivities for the silt clay, fine sand, coarse sand, and sand and gravel are 0.20 m/d, 10 m/d, 85 m/d, and 100 m/d, (RIGW 1990). The values of vertical conductivity were set as 10% of the horizontal conductivities. Fifty-five pumping wells located in the study area were included in the simulations. The screen depths of these wells vary from 30 m to 50 m for drinking water wells, and from 60 m to 70 m for irrigation wells (see Figure 5). The pumping rates were collected from the municipalities of the governorate, where the most frequent ranges were identified as 500–1,000 m³/day (Fadlelmawla & Dawoud 2006). Wells are defined as point sink and presented in the model as nodes. Also, the cell refinement was performed around these nodes because of the rapid change in the head gradient using the Thiem
equation (Anderson & Woessner 1992). The storage coefficient, $S$, and specific yield, $S_y$, were assigned from the estimated values (after RIGW 1990) as $10^{-4}$, $-10^{-3}$ and 0.15–0.20 respectively.

**Modeling NO$_3^-$ transportation processes**

The same grid configuration used in MODFLOW was also used in the nitrate transport modeling (MT3D). The calibration of the MT3D model parameters was accomplished by matching the measured nitrate concentrations at a level 40 m below the ground surface with those calculated at the end of the calibration period from 1990 to 2014. The longitudinal dispersivity was assigned a constant value of 120 m, and the ratios of transverse and vertical to longitudinal dispersivity adopted were 0.05 and 0.005 respectively.

The molecular diffusion, $D_0$, for nitrate was adopted after (Daniel & Shackelford 1988), equal $1.6416 \times 10^{-10}$ m$^2$/d.

After urea application, many biological and chemical transformations occur in both the root and vadose zones. The leaching amount of nitrate is equal to the amount applied at the surface minus crop uptake, taking into consideration the transformations of nutrients in the vadose zone. The main reactions that influence the nitrate movement are mineralization, nitrification, and denitrification (see Figure 6). At the first step, when applying urea fertilizer, the mineralization, which is the formation of ammonium during microbial decomposition of organic N, occurs. Then, the nitrification of ammonium to nitrite and further to nitrate takes place, which is considered the key reaction in relation to nitrogen losses from the root zone. Finally, the denitrification process occurs, in which microorganisms transform nitrate to nitrous and/or nitrogen gas under anaerobic conditions.

According to Lowrance (1992), more than 95% of the leached amount of nitrogen from the root zone is assumed to be transformed to the NO$_3^-$ form at the water table, with low concentrations of nitrite and ammonium. Goderya et al. (1996) reported that approximately 30% to 50% of this transformed amount of NO$_3^-$ leaches to the groundwater. From the applied dose of urea and the estimated plant uptake, which equals 142 and 146 kg N/ha in summer and winter, the calculated NO$_3^-$N loadings to groundwater were 128 and 41 kg N/ha in summer and winter respectively, which equals about 35% of the annual NO$_3^-$ fertilizer application.

**Model calibration and validation**

A preliminary sensitivity analysis, as an inherent part of model calibration, was carried out to identify the most sensitive parameters that affect model results. Then, MODFLOW steady state calibration for the hydraulic conductivities, recharge rates, and the conductance was performed based on the groundwater spatial distribution map after RIGW (1990). The correlation–based measures including the correlation coefficient ($r$), coefficient of efficiency ($E$), and index of agreement ($d$), besides the error–based measures, including the root mean squared error, the mean absolute error, and the mean relative error, have been used to evaluate the goodness-of-fit of the model.

In our study, the nitrate concentrations in recharge water were estimated from dividing the leaching mass by the recharge volume during the fertilizer application period. Nitrate losses by denitrification in the unsaturated zone are about 6 to 9 kg/ha annually (Lowrance 1992), which is considered relatively small compared to the microbiological denitrification that affects nitrate movement in the saturated layer under the anaerobic conditions. MT3D calibration began with the average initial concentration in the Nile Delta aquifer, which in 1990 was 0.4 mg/l. Besides, the denitrification was represented as a first order reaction with a rate constant $\lambda$ that was firstly estimated using the half life time of NO$_3^-$, which was assumed to be equal to 2.5 years (Korom 1992). The field measured concentrations at 40 m depth from the ground surface have been obtained.

![Figure 6](https://iwaponline.com/ws/article-pdf/17/2/561/409897/ws017020561.pdf)
from eight observation wells (as shown in Table 1) after RIGW records in 2014.

RESULTS AND DISCUSSION

The central southern part of the Nile Delta aquifer was modelled after steady state calibration with the observed groundwater heads. The contour map of the groundwater head distribution in the year 2014 is shown in Figure 7. It can be noticed that groundwater levels matched well with those from RIGW. Results also confirm that the direction of groundwater flow is from south east to north west, where the aquifer is in dynamic steady state equilibrium. The explanation for that is the direct hydraulic connection between the Damietta and Rosetta branches and the aquifer, which means that any changes in the water levels of either branch will affect groundwater levels. The infiltration from and/or to distributed canals and drains is small compared with the Damietta and Rosetta branches because they pass through the top clay layer of low vertical permeability. On the other hand, the maximum difference between the measured and the observed groundwater heads does not exceed 40 cm. The relation between them is shown in Figure 8 with the statistical parameters’ calculations.

It can be seen from Figure 8 that all points are within the ±5% error bounds, and the $R^2$ indicates a good agreement between the MODFLOW results and the groundwater levels presented in the hydrogeological map (Figure 3). From the primary sensitivity analysis, it was concluded that any change in the recharge rate either from the two branches of the Nile or the excessive irrigation water will significantly affect the model results rather than hydraulic conductivity or the bed conductance of irrigation canals and drains.

For nitrate concentrations, the field measurements of the groundwater samples from the monitoring network all over the Nile Delta were analyzed by the Research Institute of Groundwater. Concentrations in the year 2014 were calculated and the interpolation between them was performed, then the spatial distribution map of NO$_3$ was

<table>
<thead>
<tr>
<th>Sample code</th>
<th>X (Deg. E)</th>
<th>Y (Deg. N)</th>
<th>pH</th>
<th>TDS</th>
<th>NO$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30° 54' 03&quot;</td>
<td>30° 22' 53&quot;</td>
<td>7.78</td>
<td>376</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>30° 54' 38&quot;</td>
<td>30° 24' 50&quot;</td>
<td>7.52</td>
<td>406</td>
<td>2.7</td>
</tr>
<tr>
<td>3</td>
<td>31° 01' 90&quot;</td>
<td>30° 24' 89&quot;</td>
<td>7.73</td>
<td>537</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>31° 07' 58&quot;</td>
<td>30° 29' 36&quot;</td>
<td>7.41</td>
<td>1,895</td>
<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>31° 09' 55&quot;</td>
<td>30° 33' 18&quot;</td>
<td>7.64</td>
<td>453</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>31° 01' 18&quot;</td>
<td>30° 35' 28&quot;</td>
<td>7.43</td>
<td>471</td>
<td>0.9</td>
</tr>
<tr>
<td>7</td>
<td>30° 55' 74&quot;</td>
<td>30° 36' 04&quot;</td>
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<tr>
<td>8</td>
<td>31° 01' 34&quot;</td>
<td>30° 44' 40&quot;</td>
<td>7.60</td>
<td>342</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Figure 7 | Contour map of the calculated groundwater level (m) for the central southern part of the Nile Delta in 2014.

Figure 8 | Scatterplot of the observed versus calculated groundwater heads in year 2014 at the steady state calibration receptors. The solid line represents the 45° line, while the others represent the ±5% and ±10% error bounds.
generated (see Figure 9). The calibration of the MT3D model was accomplished by matching the measured nitrate concentrations at 40 m depth from the ground surface with those calculated at the end of the calibration period from 1990 to 2014. No calibration was carried out for the porosity and dispersivity, while it was only for $\lambda$. The calibrated half-lives of $\text{NO}_3^-$ for the silty clay cap and the sand gravel layer were 3.5 and 4 years, respectively (smaller than the values obtained from Frind et al. (1990)). These small values of $\lambda$ may be attributed to the limited amount of organic matters, and the variation between the values of the two layers may be due to the difference in heterotrophic and autotrophic denitrification rates.

Nitrate concentrations at 40 m depth were calculated and are shown in Figure 10, which obtained to be less than the maximum contamination level of 45 mg $\text{NO}_3^-$/$L$ for drinking water purposes (WHO 2011). Despite the fact that there are many unofficial hand pumping wells that are drilled at lower depths, these wells are not included in the model simulation. Results showed that $\text{NO}_3^-$ concentrations are related to the discharge rates from the production wells. That means when hand pumping wells are included, higher extraction rates will occur, leading to higher concentrations at shallow depths.

The comparison between nitrate concentration in the eight observation wells and the calculated values in the year 2014 is shown in Figure 11. The maximum deviation in nitrate concentration between the observed and simulated concentrations was around 0.22 mg/l at well No. 6, while the other deviations at other wells ranged between...
0 mg/l and 0.21 mg/l. The history matching and the validation between the simulated and observed values of NO\textsubscript{3}/C\textsubscript{0} is shown in Figure 12, with a value of $R^2$ equal to 0.98.

CONCLUSIONS AND RECOMMENDATIONS

The groundwater in the Nile Delta aquifer is in steady state equilibrium, flowing towards the northwest. The most significant recharge of the aquifer is the Damietta Branch, then the main irrigation canals and excessive irrigation water from the agriculture fields. The vulnerability of groundwater in aquifer depends on the existence or absence of the silty-clay layer and, where applicable, on its thickness. In addition, the change of discharge rates and operation strategies for production wells affect the nitrate distributions and concentrations in the aquifer. The excessive practices of the unofficial extraction from the groundwater aquifer by the hand pumps at lower elevations increase the susceptibility of the aquifer to the higher degree of pollution and deterioration. In order to maintain the acceptable range of nitrate concentrations, it is recommended that the existing wells operate according to regulated pumping rates and discharge. The adjustment of the applied urea dose according to plant requirements for higher crop productions for the minimum leaching amount to the water table is highly recommended. Finally, chemical analyses of groundwater samples should be taken periodically, including the analysis of NO\textsubscript{3}, K\textsubscript{2}SO\textsubscript{4}, (NH\textsubscript{4})\textsubscript{3}PO\textsubscript{4}, and total dissolved solids (TDS) in particular for agricultural lands.

ACKNOWLEDGEMENTS

The first author would like to thank the Egyptian Ministry of Higher Education (MOHE) for providing him with the financial support (PhD scholarship) for this research, also the Egypt-Japan University of Science and Technology (E-JUST) and JICA for offering the facilities and tools needed to conduct this, as well as the Tokyo Institute of Technology.

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First received 9 January 2016; accepted in revised form 12 September 2016. Available online 27 September 2016