Modeling potential environmental impact of new settlements on groundwater, Nile Delta, Egypt

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ABSTRACT
The Mobarak Industrial Area in Quessna City, Egypt, covers an area of the Nile Delta quaternary aquifer that is highly vulnerable due to the local absence of a clay cap. 3D finite difference numerical modeling was used to represent groundwater flow and assess potential contaminant transport that could be related to industrial sewage water infiltration. Groundwater flow was found to be largely influenced by irrigation and Nile River water infiltration. Transport simulations indicated the possibility for groundwater quality deterioration from two potential pollution sources, which is supported by groundwater chemical analyses.

RÉSUMÉ
La Zone Industrielle Mobarak à Quessna City, Égypte, couvre une partie très vulnérable de l'aquifère quaternaire du Delta du Nile où la couverture argileuse est localement absente. Un modèle 3D en différences finies a permis de représenter l'écoulement et d'évaluer le transport de contaminants potentiels qui pourraient provenir de l'infiltration d'eaux usées industrielles. L'écoulement s'est avéré très influencé par l'infiltration des eaux d'irrigation et du Nile. Les simulations du transport ont indiqué la possibilité de détérioration de la qualité de l'eau souterraine à partir de deux sources potentielles de pollution, ce qui est supporté par les analyses chimiques de l'eau souterraine.

1 INTRODUCTION

The study area is Quessna City, which belongs to the Menoufia governorate in the middle Nile Delta region, Egypt (Figure 1).

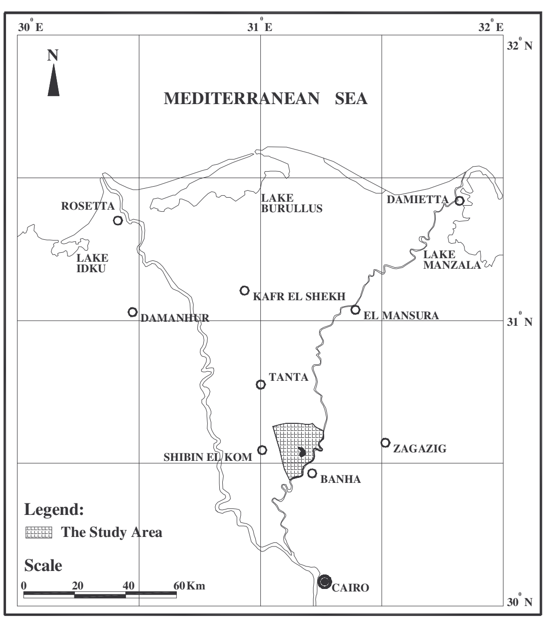

Figure 1. Location of the study area in the Nile Delta

Topography is almost flat and ranges between 9 m to 14 m above mean sea level (amsl) from north to south (Figure 2). In the study area is found a “turtle back”, which is an area standing above this low relief at about 22 m amsl. Land use is mostly agricultural with small urban centers. An extensive network of canals and drains serve agricultural irrigation. Wells are used to supply drinking water and serve irrigation and industrial purposes.

The land use map shows that various potential pollution sources are present within the area: domestic, agricultural and industrial (Figure 2). Groundwater could thus be impacted by these potential sources. However, as described in Section 2, the Nile Delta quaternary aquifer is generally well protected from pollution by thick low-permeability clay over most of its surface. This protective cover is however absent over the turtle back, where the aquifer sand outcrops at the surface. Concerns over potential groundwater pollution thus focus on this area.

Located over the turtle back, the Mobarak Industrial Area is located about 60 km from Cairo City and initiated its activities in 1995. Over the turtle back, where the underlying aquifer is vulnerable to surface contamination, numerous potential pollution sources could cause deterioration in groundwater quality: factories illegal sewage disposal wells, dump disposal sites and various leakages (sewage pipes, sewage storage tanks, El Khadrawya Drain). The El Khadrawya Drain is known to be quite polluted because it receives the Mobarak Industrial area sewage water disposal in two ways: a) Mobarak Industrial area effluent sewage pipe, and b) sewage disposal trucks.

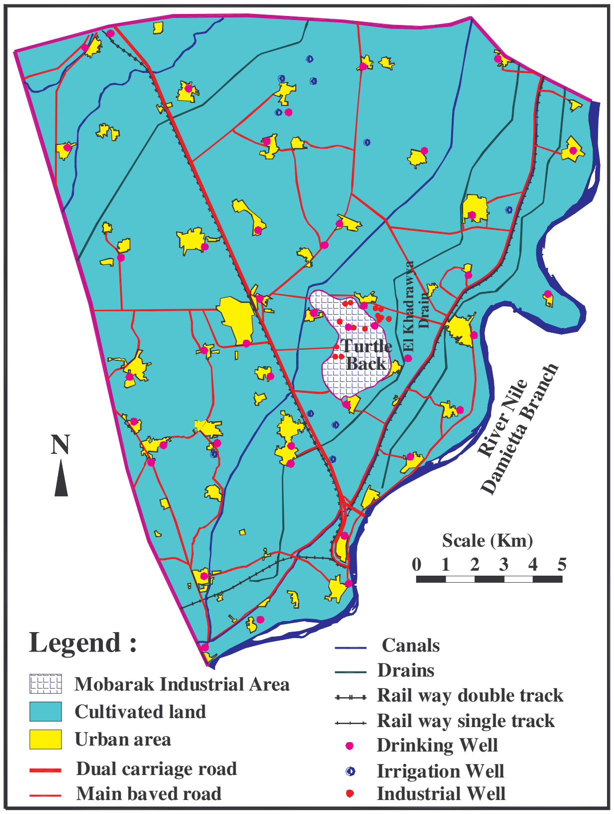

Figure 2. Land use map of the study area

Our study aimed at evaluating the potential impact on groundwater quality related to the new settlements of the Mobarak Industrial Area. This paper presents a 3D groundwater flow and transport model developed in order to better understand the groundwater flow system and to predict the potential migration of pollution plumes.

2 CONCEPTUAL MODEL

Figure 3 shows the geological and hydrogeological contexts, and potential contamination sources for the study area. Geologically (Fig. 3a), the base of the aquifer system is the Lower Pliocene clay, which forms an impermeable boundary for groundwater flow and contaminant transport (Said 1991). The aquifer itself is made up of quaternary sediments that lie uncomfortably over the Pliocene clay (Awad 1999). The aquifer comprises two units: an upper Pleistocene graded sand with intercalated clay lenses with an average thickness of 40 m, and a lower part of sandy gravel with an average thickness of 300 m. The aquifer is covered by a clay cap, except in the industrial area over the turtle back where the aquifer sand outcrops. The clay cap aquitard has an average thickness of 10 m, but vanishes towards the sandy turtle back.

Hydrogeologically (Fig. 3b), the aquifer system is mainly recharged by the River Nile, by irrigation excess water infiltration and by infiltration from the main canals. Four types of production groundwater wells exploit the aquifer: drinking water wells, governmental irrigation wells, private irrigation wells and industrial wells. These wells have different ranges of withdrawal depths (Fig. 3b).

There is a general deterioration in groundwater quality in all production wells inside or close to the industrial area, especially for TDS, Fe, and Al (El Araby 2007). This could be related to various potential groundwater contamination sources present over the area (Fig. 3c). Industrial sewage water is considered the main potential pollution source that could contaminate the aquifer through two pathways: 1) leakage of the El Khadrawya Drain that would represent a line pollution source, or 2) leakage from sewage dumps, factories sewage pipe, and illegal disposal wells that would constitute a diffuse pollution source over the northern part of the turtle back where most industries are located.

3 NUMERICAL MODEL

Objectives of the model were to better understand the flow system and to support the evaluation of the environmental risk for the water supply wells related to potential contamination sources found in the area.

Thus, a numerical model of the flow system was developed using Visual Modflow v.4.2: a) ModFlow-2000 to simulate steady-state groundwater flow, b) ModPath to simulate 3D particle tracking within the simulated flow field, and c) MT3D v.1.5 to simulate 3D transient contaminant transport, including advection and dispersion of contaminants in the groundwater flow system, but without considering chemical reactions.

3.1 Model Layers

The aquifer is vertically divided into 8 modeling layers assigned to four hydraulic units (Table 1 and Fig. 4).

Table 1. Initial and calibrated hydraulic parameters

Hydraulic Units	Layers No.	K_h (m/s)	K_v (m/s)	S_s (m^{-1})
Clay	1	$2.89x10^{-6}$	$2.89x10^{-7}$	$1.0x10^{-7}$
Sand with clay lenses	2, 3, 4	$6.37x10^{-4}$	$6.37x10^{-5}$	$2.7x10^{-6}$
Sand and Gravel	5, 6, 7, 8	$6.95x10^{-4}$	$6.95x10^{-5}$	$2.7x10^{-6}$
Hydraulic Units	S_y	n_e	n_t	Net Recharge (mm/year)
Clay	0.1	55%	55%	150
Sand with clay lenses	0.2	20%	35%	----
Sand and Gravel	0.2	20%	35%	----

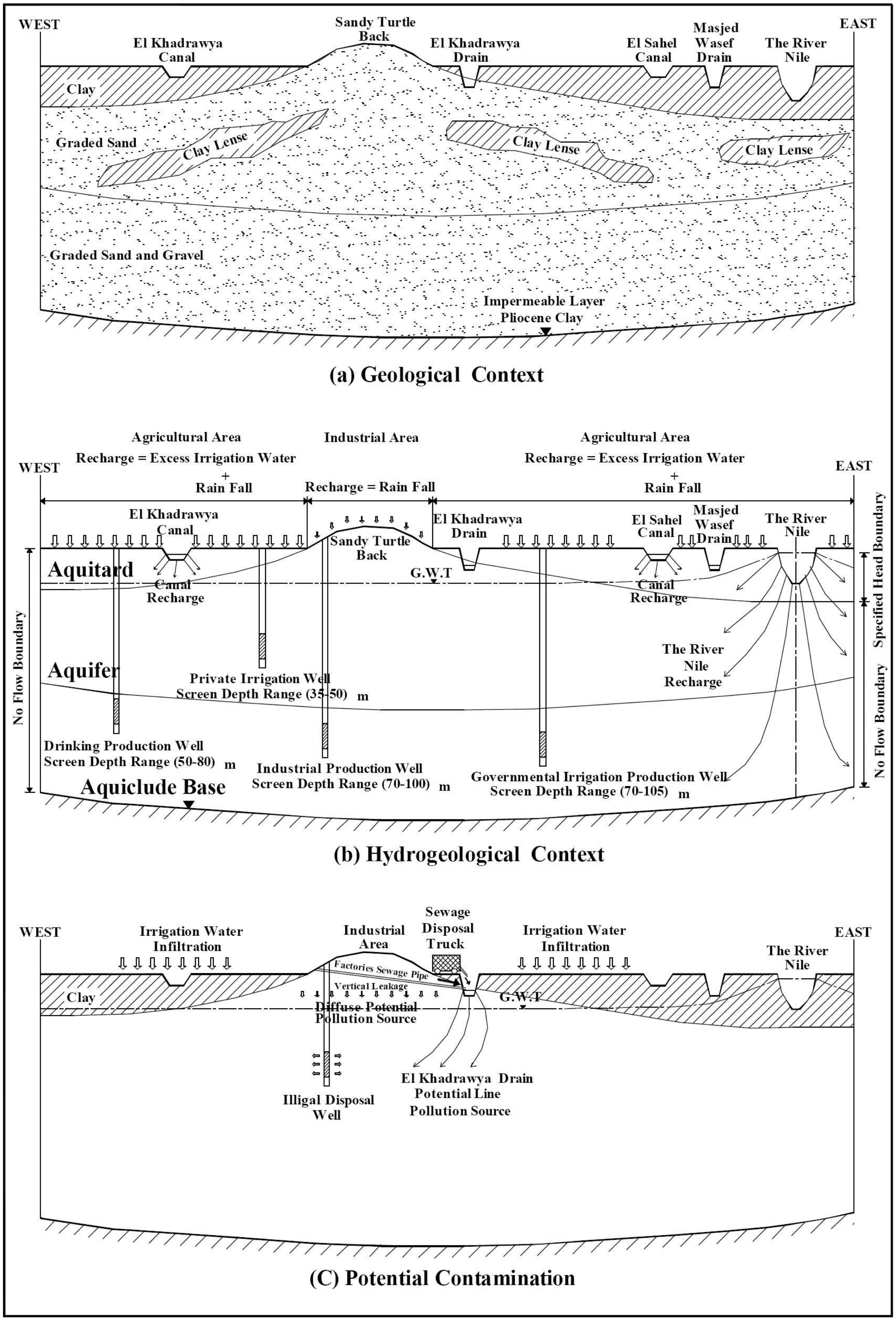

Figure 3. Conceptual models of the study area: (a) geological context, (b) hydrogeological context, and (c) potential groundwater contamination sources

Layering is defined to simulate representative potential plumes migration and considers well depths.

(a) The unit made up of the saturated part of the silty clay cap is represented as Layer 1 with a mean thickness of 10 m vanishing towards the turtle back.

(b) The quaternary sandy unit with intercalated clay lenses is simulated as three layers. Layers 2 and 3 have a constant thickness of 10 m, and Layer 4 has a constant thickness of 20 m. This unit is in the abstraction depth range for private irrigation wells between 35 to 50 m.

(c) The quaternary sand and gravel unit represents the abstraction depth range of production drinking wells (50 m to 80 m) and of production governmental irrigation wells (70 m to 105 m). It is represented by two layers: Layers 5 and 6 each having a constant thickness of 30 m.

(d) The last unit is made up of the lower part of the quaternary aquifer, which is simulated as two layers: Layer 7 has a constant thickness of 100 m, and Layer 8 with a varying thickness that is 150 m on average.

3.2 Model Grid and Boundary Conditions

Model dimensions in the study area are 22 060 m by 24 430 m (about 540 km^2), and with a grid element size of 100 m by 100 m, the number of rows and columns are 243 and 219, respectively. The number of elements is thus 53 217 for each layer and, for 8 layers, the total number is 425 736.

Boundary conditions are based on the hydraulic head map and on hydrogeological conditions (Figure 4):

(a) The northern limit of the model is represented as a constant head boundary of 7 m amsl. This head is assigned to the eight layers of the model to represent a constant head outflow boundary.

(b) The eastern limit of the model is a specified head boundary to represent the River Nile average water levels, which range from 9.84 m to 9.18 m amsl. Within the study area, the River Nile levels are higher than groundwater levels due to the Zifta Barrages north of the study area. This difference in water levels makes the River Nile act as a recharging water divide boundary. This condition is only assigned to the first clay layer taking into consideration the difference in hydraulic properties between the clay cap and the River Nile bed. However, a no flow boundary is assigned to the seven underlying layers since downward flow is presumed under the Nile.

(c) North eastern and western limits are represented as no flow boundaries corresponding to flow lines.

Groundwater recharge in the River Nile delta aquifer is dominated by contributions from leakages of irrigation canals. A representative average recharge of 0.60 mm/d for the study area was based on analogy with previous studies (Warner et al. 1991; Shamrukh et al. 2001). In the model, major canals were specifically represented as well as large flow rate production drinking wells and governmental irrigation wells. However, the numerous minor canals and private irrigation wells could not be specifically considered in the model. A net recharge was calculated by subtracting from the average recharge the pumping of private irrigation wells and the recharge induced in the model by main canals (based on simulations without and with canals). The resulting net recharge of 0.40 mm/d (150 mm/y) was applied over model Layer 1 (details are provided by El Araby 2007).

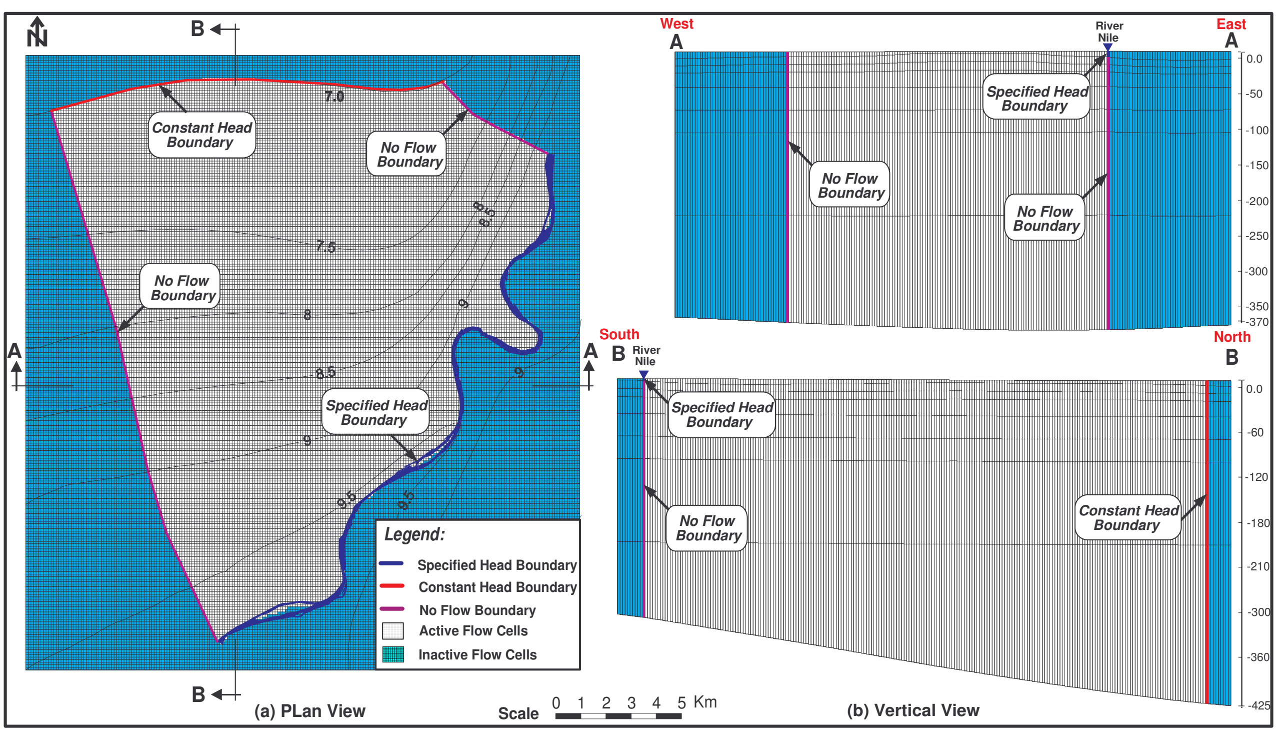

Figure 4. Numerical grid and boundary conditions shown (a) in plan view and (b) along two vertical cross-sections

3.3 Calibration and Sensitivity Analysis

A pre-calibration step was done to identify the main parameters that control the aquifer flow system. The calibration target of the model is 10% of the difference between the maximum and minimum head values (9.8 – 7.0 = 2.8 m), so about 0.3 m. The calibration process was carried out through several trials by adjusting hydraulic parameters and recharge. Complete sensitivity analyses were carried out (El Araby 2007). Results showed that the initial hydraulic parameters are actually the most realistic case and provide acceptable errors (mean error = 0.02 m, mean absolute error = 1.65 m, RMS = 0.22 m, which is the minimum value obtained for the sensitivity analysis).

4 GROUNDWATER FLOW CONDITIONS

4.1 Simulated Flow Pattern and Mass Balance

As shown in Figure 5, the main flow direction is towards the north-west and the main sources of aquifer recharge are the River Nile and the recharge form excess irrigation water and main canals infiltration (Table 2).

A forward particle tracking scenario (a) was made to show water pathlines originating from the River Nile and extending through the aquifer system, using a time step of 100 years (Figure 5). Tracking time steps ticks indicate that total transit time to reach the outflow constant head boundary for water originating from the River Nile is in the order of 1 750 years. This corresponds to an average groundwater flow velocity in the order of 14 m/year.

A backward particle tracking scenario (b) was done from 3 selected groundwater drinking production wells (D0, D15, and D18), again with a time step of 100 years, to better understand the origin of groundwater supply in the study area. This scenario shows that production wells in the study area have two abstraction directions. (a) First, a “direct supply component” from surface recharge through the upper aquifer layers with an average groundwater age of 100 years. (b) Second, a “long term supply component” from lower aquifer layers originating from the River Nile recharge and adjacent aquifer layers with an average groundwater age of about 500 years. Mixing of these two supply components is likely to reduce the risk related to pollution as the second component is too ancient to have been affected by modern pollution.

A backward particle tracking scenario (c) was made using one particle on each layer on the location illustrated in figure 5. This scenario shows the important vertical flow component in the system that can be related to the large values of groundwater recharge resulting from agricultural irrigation. The accumulation of newly recharged water along a flow path forces groundwater to sink lower in the flow system as it gets farther from its origin.

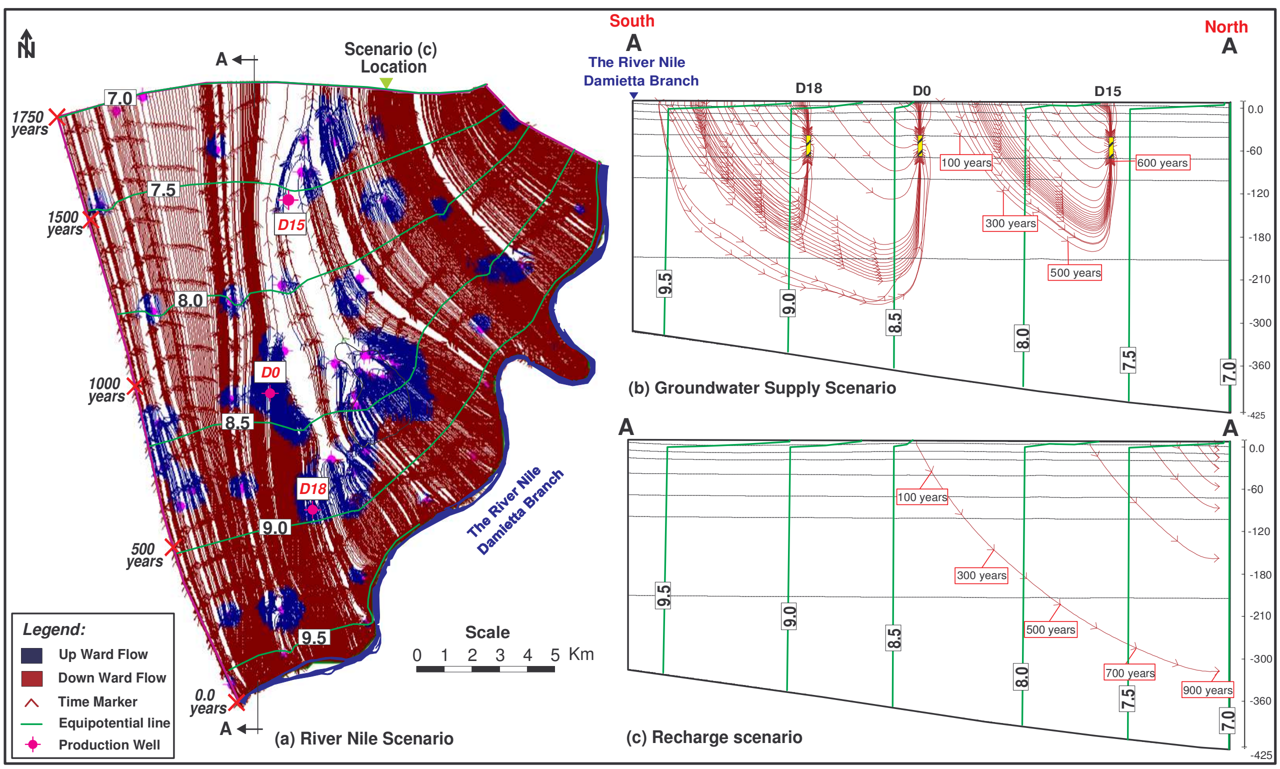

Figure 5. Particle tracking illustrating simulated groundwater flow patterns. (a) Plan view of forward particle tracking from River Nile. Vertical cross-sections showing backward particle tracking (b) from three drinking production wells, and (c) from each layer at the imposed head model outflow boundary.

Table 2 shows the calibrated model mass balance components. Recharge in the system almost equals production wells abstraction, so that the River Nile inflow is almost the same as out flow through the constant head boundary. Mass balance is 0.2% of inflow.

Table 2. Calibrated model mass balance components

Mass Balance Component	Inflow (+) m^3/day	Outflow(-) m^3/day	Inflow – Outflow m^3/day
Constant head	84 361	78 284	6 077
Wells	----	115 162	-115 162
Recharge	109 427	----	109 427
Total	193 788	193 446	342

5 GROUNDWATER PROTECTION

To study groundwater protection implications of simulated flow conditions, two main scenarios were assumed for potential pollution sources: (A) diffuse pollution source on the industrial area, and (B) line pollution source on the polluted reach of El Khadrawya Drain.

Two cases were simulated for the 2nd scenario: (1) applying the drain pollution source directly above the sandy Layer 2 (worst case), and (2) applying the drain pollution source above the clay Layer 1. The 2nd case represents a lower risk since the clay layer could reduce pollution flux and increase the transit time to the aquifer. The two scenarios (A) and (B) were studied using both particle tracking and solute transport (transport parameters summarized in Table 3).

5.1 Particle Tracking

As shown in Figure (6a), for scenario A particles are applied on Layer 1 over the industrial area. A potential pollution plume could migrate in two main directions: (a) northward along the main flow direction, from Layer 1 to 7, and then upward to Layer 5 to reach a well field after a transport time of 600 years; and (b) downward towards the sandy area production drinking and industrial wells, which would be reached after about 150 years.

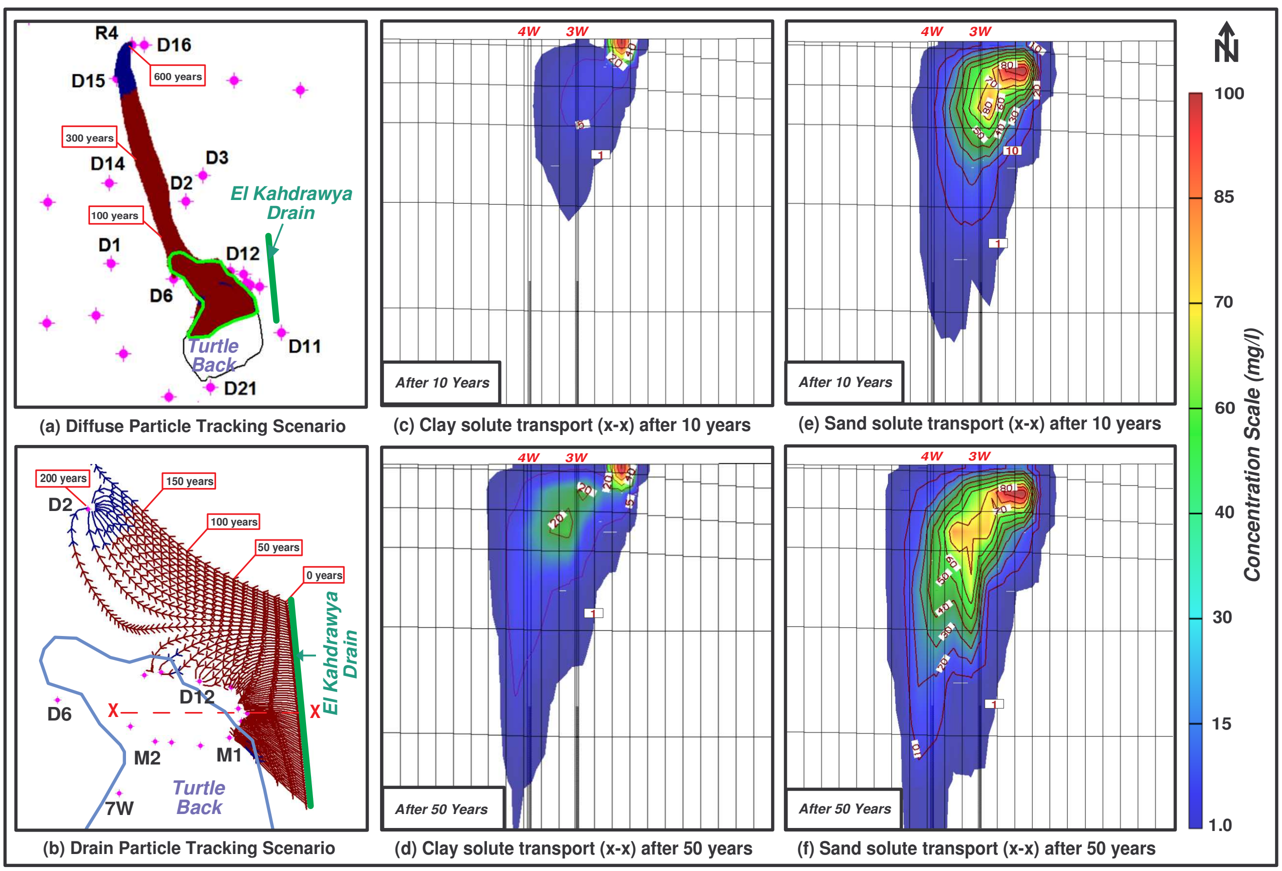

Figure 6. Simulations related to 2 potential pollution sources: infiltration from diffuse source over Turtle Back and from the El Kahdrawya Drain. Particle tracking shows groundwater flow patterns from the potential sources (a and b). Results from solute transport simulations after 10 and 50 years are shown in cross-sections for a case considering transport through the clay cap (c and d) and without a clay cap, for which contamination directly reaches the aquifer (d and f)

Table 3. Mass transport simulation parameters

Parameters	Value
Initial reference concentration (C_i, mg/l)	0
Applied constant concentration (C_o, mg/l)	100
Longitudinal dispersivity (α_L, m)[a]	10
Horizontal dispersivity (α_h, m) = 0.1 × (α_L)	1
Vertical dispersivity (α_v, m) = 0.01 × (α_L)	0.1
Diffusion coefficient (D*, m^2/d)[b]	10^{-4}

Sources. a: Gelhar et al. (1992), b: Charbeneau (2000).

The area at risk, where particle tracks are present, is narrow due to the small recharge on the potential impact area (sandy area) compared to the large recharge found outside. The very long travel time of the potential pollution plume prior to its interception by wells favors its attenuation.

As shown in Figure 6b, for scenario B involving a line pollution source, forward particle tracking was done by releasing particles on the polluted part of El Khadrawya Drain. Results show that migration from this potential pollution source would occur in two main directions: (a) a westward migration would be intercepted locally in the industrial area, very close to the drain, after about 20-40 years of advective migration; (b) a northwestward migration, along the main flow direction, from Layer 1 to 6, and then upward to Layer 5, to reach a well field after about 200 years.

5.2 Solute Transport

Figures 6c and 6d show simulated concentrations after 10 and 50 years for transport simulations related to scenario B, in the case where solute is applied to Layer 1 (clay). Two production wells are present on this section (X-X), and they eventually intercept the simulated plume with a concentration of 2 mg/l after 20 years. The concentration increases to 5 mg/l after 70 years (not shown).

Similarly, figures 6e and 6f show simulated concentrations after 10 and 50 years for scenario B transport simulations, this time for the case where solute is directly applied to the sand aquifer (Layer 2). In this case, the potential pollution plume would reach well screens after 10 years at 2 mg/l, whereas a steady state concentration of 15 mg/l would be captured by the wells after about 20 years.

Comparison between figures 6c/6d and 6e/6f shows the importance of the upper clay layer in reducing the risk related to potential contamination. This layer increases the time required for potential plumes to reach production wells, reduces the initial concentrations reaching the wells and significantly delays the time at which the steady state maximum plume concentrations would reach the wells.

6 CONCLUSIONS AND RECOMMENDATIONS

There is a general deterioration in the groundwater quality in all production wells located inside or close to the industrial area (El Araby 2007). This deterioration in groundwater quality could be due to various sources related industrial activities.

Visual ModFlow Pro.V.4.2 was used to simulate the flow system of the study area. The model was then used to do particle tracking and solute transport scenarios to better evaluate the risk related to potential industrial pollution. The model first provided a better understanding of the hydrogeological system: it highlights the important role of the River Nile to recharge the aquifer, in addition to important recharge from surface water due to irrigation and leakage from main canals. The model mass balance shows that surface recharge is almost equal to the production wells abstraction and that inflow from the River Nile is equivalent to outflow through the model exit boundary. This implies that current groundwater pumping rates from the aquifer are sustainable.

Two particle tracking and solute transport scenarios were done to study the potential migration of pollution plumes that could be related to the Mobarak Industrial area. Results show a high possibility for potential pollution released from the industrial area to cause deterioration of groundwater quality, especially under and near the industrial area itself. The clay cap aquitard was shown to be very important in protecting the aquifer system from potentially polluting activities. However, the portion of the aquifer underlying the Quessna area is considered highly vulnerable due to the absence of the clay cap.

The following recommendations aim to improve the environmental management of the study area and to protect groundwater quality:

(a) Design and implement a groundwater monitoring system and program down gradient of the El Khadrawya Drain to monitor and characterize suspected groundwater pollution from the drain;

(b) Implement appropriate treatment of effluents from the Mobarak Industrial area factories before their release to drains, and select adequate and suitable locations for liquid and solid waste disposal;

(c) Do regular checks on the pressure of transportation pipes and storage tanks and inspect the lining of ditches and ponds for industrial liquids, including wastewater;

(d) The El Khadrawya drain bed should be lined with clay or appropriate synthetic impermeable liners to reduce the potential release of pollutants from the drain due to leakage to the aquifer;

(e) Monitor production wells found at risk for drinking groundwater quality, especially wells D12, M1, and M2 located in the industrial area, and well D17 located west of the study area;

(f) Identify alternative sources of groundwater supply for the wells found at risk, in case they would become unsuitable for consumption. In the cases of wells M1 and M2, it is recommended to change their location up gradient from potential pollution, i.e. south of the industrial sandy area or east of the El Khadrawya Drain;

(g) Shallow groundwater from the top of the aquifer should generally not be used for drinking purposes, especially close to the sandy areas near a large number of potential pollution sources. These potential pollution sources should also be regularly investigated.

7 ACKNOWLEDGEMENTS

The numerical modelling work presented in this paper was carried out during a training period of M. El Araby at INRS in early 2007. That training was supported by the National Water Quality and Availability Management Project, funded by the Canadian International Development Agency. R.L. acknowledges support from a NSERC Discovery Grant that supported this publication.

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9 SYMBOLS AND UNITS

Symbol	Units	Description
K_h	m/s	Horizontal hydraulic conductivity
K_v	m/s	Vertical hydraulic conductivity
S_s	m^{-1}	Specific storage
S_y	-	Specific yield
n_e	-	Effective porosity
n_t	-	Total porosity

Only symbols not explained in the text are listed.