Predicting the Impact of Surface Wastewater on Groundwater Quality in Quesna Industrial Area

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Abstract: The prediction of the impact of surface wastewater on groundwater can be achieved through statistical analysis and groundwater modeling. The objectives of this paper are to follow up the quality of the groundwater in the middle Delta at Quesna district, and to check the impact of the surface activities in that area on the groundwater quality. The present research was applied based on statistical analysis. In addition to numerical Groundwater flow and quality model (MODFLOW) and solute transport model (MT3D) were employed to simulate the groundwater behavior and migration of pollution plume under the initiated industrial and agriculture activities. The potential pollution sources are diffusion from Mubarak industrial area and El Khadrawya drain. The results of TDS, NO_3 and some heavy metals are analyzed using fitting curve between the parameter measured in the surface wastewater and groundwater. The results indicated that TDS decreased in the study area which means that the salinity of the groundwater in those locations was diluted. Results of the trend analysis indicated that the relations between the parameters of the surface activities and those of the groundwater differed from linear, power and polynomial. The statistical correlation values of TDS, NO_3, Fe and Zn in sandy soil were greater than those in clay soil while statistical correlation values of Mn and Sr were grater in clay soils, which clarify the dangerous impact of surface activities on the groundwater particularly in the industrial area. The model results showed that, in that area (turtle back) allows high infiltration rate of existing oxidation ponds and surface wastewater. Also, high risk possibility of the migration of the pollution plume causing deterioration in the groundwater quality.

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1. Introduction

In recent years, the increasing threat to groundwater quality due to human activities has become a matter of great concern. A vast majority of groundwater quality problems are due to pollution or over-exploitation, and /or by a combination of both. Rapid urbanization and industrialization in Egypt have resulted in steep increase of generation of wastes. Due to the lack of adequate infrastructure and resources, the waste is not properly collected, treated and disposed; and sometime injected directly to groundwater.

Groundwater in Egypt has always been considered an important source of fresh water for both urban, industrial and irrigation; being also far from direct pollution. Groundwater quality depends on many factors; some are internal or original such as the quality of the carrier formation, while others are external such as the means of waste disposal (including agricultural, domestic and industrial). The problem is more severe in and around large cities where various clusters of industries exist. In many of these areas groundwater is only the source of drinking water, thus a large population is exposed to risk of consuming contaminated water.

The present paper discusses the prevailing hydrogeological conditions and assesses the pollution risk in the middle of Nile Delta region. Quessna City (Mubarak industrial area) was selected as an area subjected to high pollution risks area due to the high vulnerability of groundwater to pollution (absence of the clay cap covering the quaternary aquifer in the Nile delta). In this area (turtle back) allows high infiltration rates from existing oxidation ponds, seepage from polluted Khadrawya drain and infiltration from surface wastewater. The aquifer vulnerability enhances the migration of pollutants from the various mentioned sources. The study applies statistical analysis and modeling of groundwater flow and solute transport to investigate the impact of wastewater migration on the groundwater quality as a mean to evaluate its environmental negative impacts.

2. Methodology

To satisfy the research objectives, the following steps are followed:

- Statistical analysis of water samples to study the correlation and regression between groundwater quality parameters and those of surface wastewater in both sand and clay formations.
- Simulation of groundwater flow in the study area (Quessna District region).
- Simulation of solute transport for a specific type of pollutants (nitrate) to predict the migration of this element in groundwater at various time horizons.

- Evaluation of the results of statistical analysis and groundwater flow and solute transport to investigate the impact of the Mubarak industrial wastewater on groundwater.

Description of study area

The area concerned in this study covers Quessna District which lies between latitudes 30° 25 and 30° 38 N and between longitudes 31° 02 and 31° 16 E. It belongs to Menoufiya governorate in the middle Nile Delta region. It is bounded to the East by Damietta Branch, to the south by El Bagur and Benha Districts and to the west by Shibine el Kom and Berket el Saba as shown in figure (1). Quessna District occupies an area about 203 km^2. Most of Quessna District is occupied by old traditionally cultivated lands.

The aquifer system (alluvial plain) is formed of sand and gravel, overlain by a cap made-up of silt and clay. The average thickness of the silty-clay cap is about 10 m vanishing towards the sandy turtle back (study area) where newly constructed industrial sites exist. The young alluvial plains of the Nile cover Quessna locality except the portion cut by the turtle back (Awad, 1999). Turtle backs are landscape features formed due to outcropping of the Pleistocene ravine sands in the middle of the agricultural fields representing the higher parts of eroded surface of this complex (El-Seidy, 1995).

The main aquifer (Quaternary) is represented as two units; the upper Pliestocene graded sand, intercalated by clay lenses with an average thickness of 40 m; while to lower part constitutes of sandy gravel with an average thickness of 300 m (RIGW/IWACO, 1990). Nile water is dominantly used for irrigation while groundwater is used for drinking, irrigation and industrial activities.

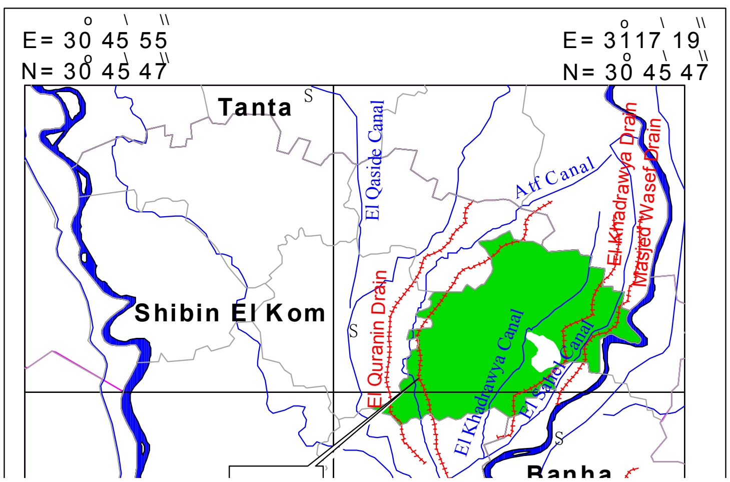


Figure (1). Location Map of the Study Area

Simulation

Statistical analysis

Fitting curves were used to investigate the preliminary relations between parameters of surface wastewater quality and those of groundwater and to select the most effective parameter which has high correlation coefficient that will be used in processing the model. The analysis was processed to create the equations which represent the relation between the studied components and to calculate the correlation factor R^2. Those curves were implemented to predict the correlation and regression coefficient of TDS, NO3, Fe, Mn, Sr and Zn between groundwater quality parameters and those of surface wastewater in both sand and clay soil. The present study is based on the data collected from Research Institute for Groundwater (RIGW) and by El Araby (2007). Numerical Groundwater flow and quality model (MODFLOW) and solute transport model (MT3D) were carried out depending on the results obtained from fitting curve to study the migration of the selected parameter in the study area.

Groundwater Flow Simulation

Simulation of the groundwater flow in the study area is carried out to understand the flow system prior to the evaluation of solute transport. The three dimensional groundwater model packages of Visual MODFLOW and solute transport MT3D are used to simulate the groundwater flow and pollution transport in the aquifer. The simulated region covers Quesna district (old land). Each model layers is discretized into 247 rows in the north south direction and 238 columns in the east west direction. A grid of rectangular cells is generated within the simulated area as shown in Figure (2).

The ground elevation of the study area between about 9m and 14m above mean sea level (+msl) from north to south respectively, except in the turtle back where it reaches about 22m (+msl) (RIGW/IWACO, 1990). Inputs to the groundwater flow model include also topography, aquifer thickness and basement.

Due to the variation of the aquifer profile, it has been distinguished into twelve layers to present the variation in Lithology, depth of pumping and the potential of plumes migration.

- The clay cap was simulated as layer 1 with an average thickness of 10 m vanishing towards the sandy turtle back (study area);
- Layers from 2 to 8 represent the abstraction depth for private irrigation, production drinking wells and governmental production irrigation wells with range from 10 to 100 m; and
- The lower part of the aquifer was simulated as four layers from layer 9 to 12

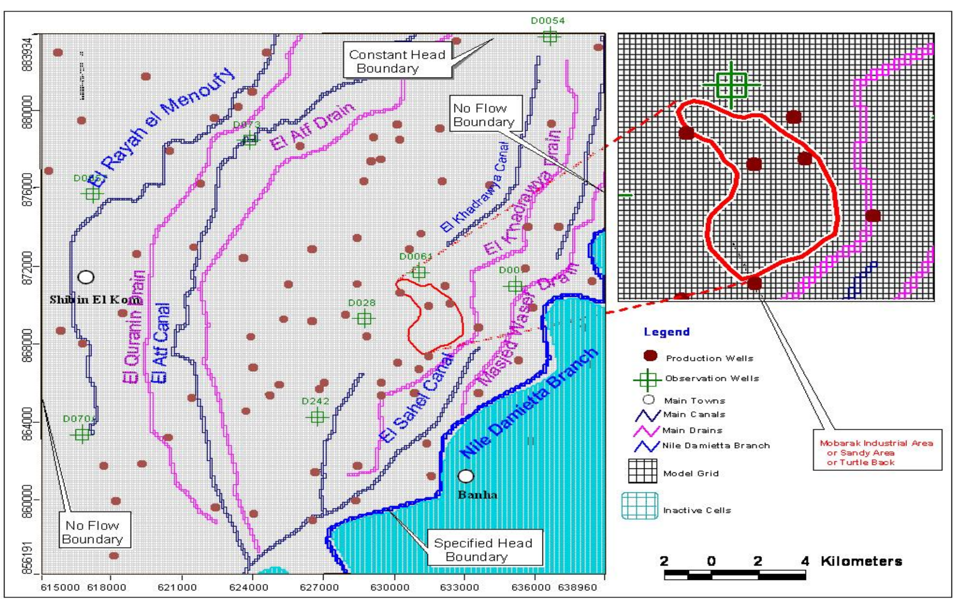


Figure (2). Grid Element and Boundary Conditions of the Study Area.

The boundaries of the modeled area are selected to coincide with the natural hydrogeological conditions, as shown in figure (2).

1) The North eastern and Western boundaries represented as a no-flow boundary corresponding to flow lines which are perpendicular to the equipotential lines.
2) The South eastern boundary coincides with the River Nile, being a specified head boundary to simulate the River Nile average water levels, which range between 8.8 m (+msl) to 10.2 m (+msl).

3) The Southern boundary is considered a specified head boundary; being far from the effect of flow in the studied area, with a head ranging from 8.15 m to 10 m (+msl).
4) The Northern boundary was considered as constant head boundary of 5 m (+msl).

Those boundary conditions were assigned to the layers of the model. The initial input hydraulic parameters are based on previous studies and current aquifer pumping tests which were done by RIGW.

Groundwater recharge in the study area is taking place from rainfall, downward leakage and seepage from surface sources and inter-aquifer flow.

1) Recharge from rainfall to the aquifer takes place only during the winter period with an average intensity of 25 mm/year.
2) Recharge through downward leakage is due to irrigation excess water, depending on the soil type, irrigation and drainage practices (**RIGW, 1992**), and is estimated to range between 0.25 and 0.8 mm/day.
3) Seepage from River Nile and canals. Water level in the River Nile levels is higher than the groundwater heads due to the back water curve upstream of Zifta Barrage located to the north of the study area. This difference levels makes the River Nile act as a recharging water divide boundary.

The calibration process is carried out through several trials by adjusting the hydraulic parameters and recharge rate. The calibration was done against the current piezometric heads in 2010. The calibrated hydraulic parameters for the model area are summarized in table (1).

Table (1). Calibrated Hydrogeologic Parameters for the Model Area.

Main Hydraulic units	Layers No.	K_h (m/day)	K_V (m/day)	S_s (1/m)	S_y	Eff. Por. %
Clay	1	0.1- 0.25	0.01-0.025	10^{-7}	0.1	50-60
Fine sand with clay	2 to 5	5-20	0.5-2	5×10^{-3}	0.15	30
Course sand (Quaternary)	6 to 8	20-55	2-7.5	2.35×10^{-3}	0.18	25
Graded sand and gravel	9 to 12	55-80	7.5-150	5×10^{-4}	0.2	20

K_h and K_V are the horizontal and vertical hydraulic conductivity, respectively;
S_s and S_y are the storativity and specific yield, respectively

Figure (3) shows a plan view of the calibrated piezometric contour map of study area and the velocity vectors of model output. The main groundwater flow direction is north-west.

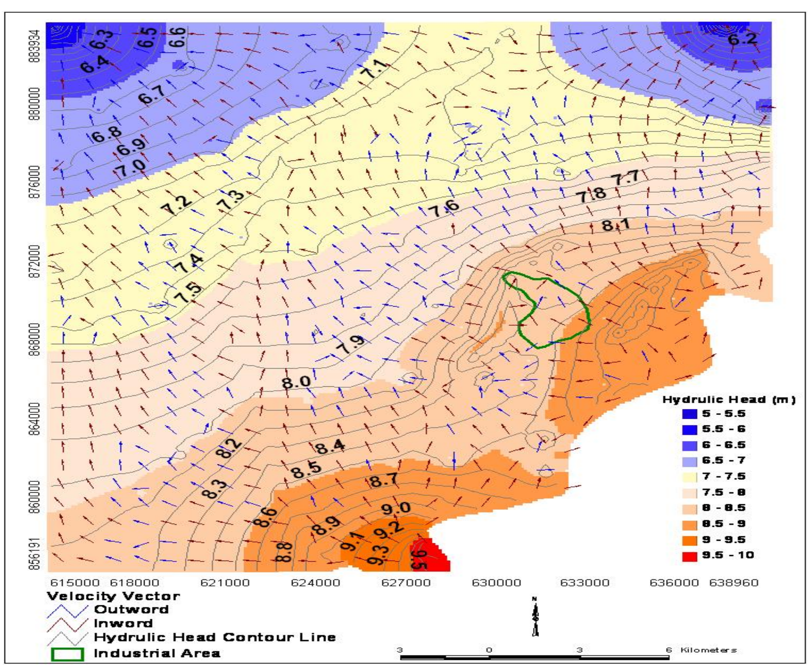


Figure (3). Calibrated Piezometric Contour Map and the Velocity Vectors.

Figure (4) shows the components of the water balance for the calibrated model. The water balance of the groundwater system comprises several components including constant head, artificial wells, drains, recharge, river interaction and aquifer storage.

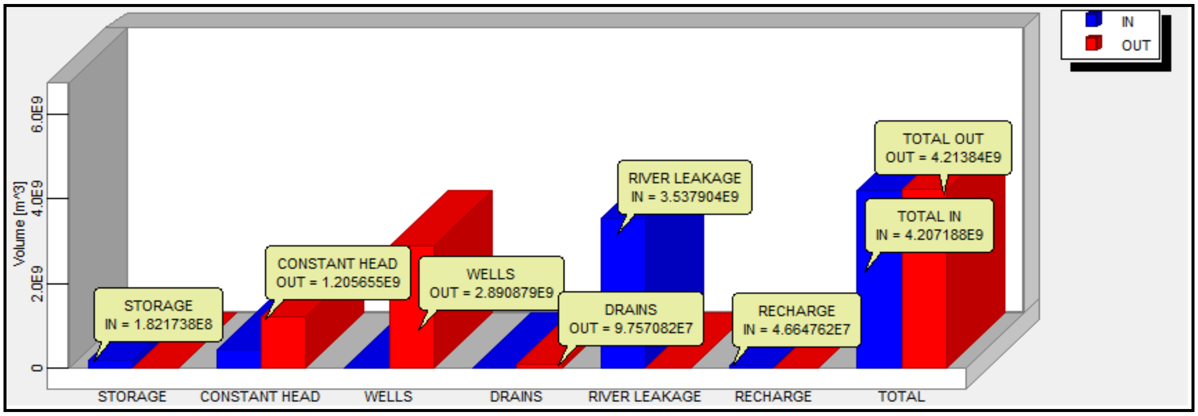


Figure (4). Components of the Calibrated Water Balance.

Groundwater Quality Simulation

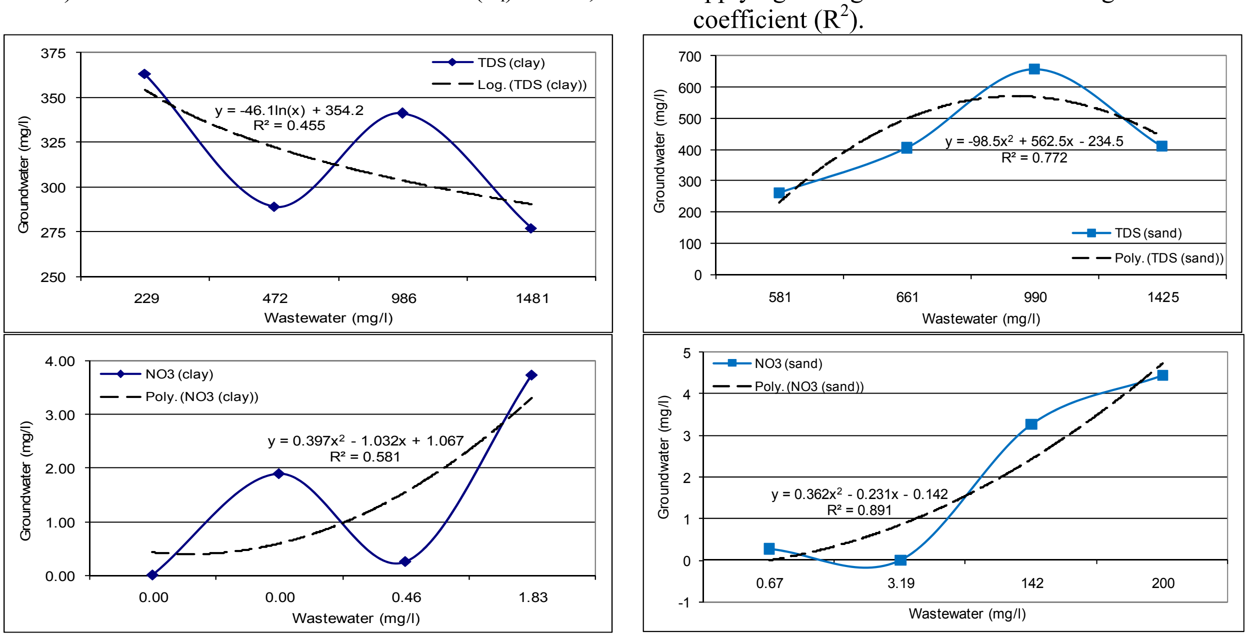
Industrial wastewater is considered the main potential pollution source which contaminates the groundwater. Leakage from El Khadrawya Drain, sewage damps, factories sewage pipe, and illegal disposal wells are considered diffuse pollution sources. In order to assess their impacts on groundwater quality in the study area due to changes in groundwater stresses, MT3D numerical solute transport model is used. Groundwater quality diffuse pollution sources on the industrial area are used to predict the migration of pollution originating from the high-risk zone and their trend with time. The change in concentration is investigated under the effect of advection and dispersion. Input parameters for the solute transport part are considered as follows:

1) The initial reference concentration (C_i) = zero,
2) The applied constant concentration (C_o) = 100 mg/l,
3) The longitudinal dispersivity (α_l)=13m (**Gelhar *et al.*, 1992**), based on the prevailing hydrogeological situation,
4) The transversal dispersivity (α_T)=0.1*(α_l) =1.3m,
5) The vertical dispersivity (α_v)=0.01(α_l)=0.13m, and
6) The diffusion coefficient D*=10^{-4} m^2/day (**Charbeneau, 2000**).

3 Results and Discussion

Statistical analysis Results

Table (2) and figure (5) present the results of the statistical analysis which has been carried out by applying fitting curve and calculating the correlation coefficient (R^2).



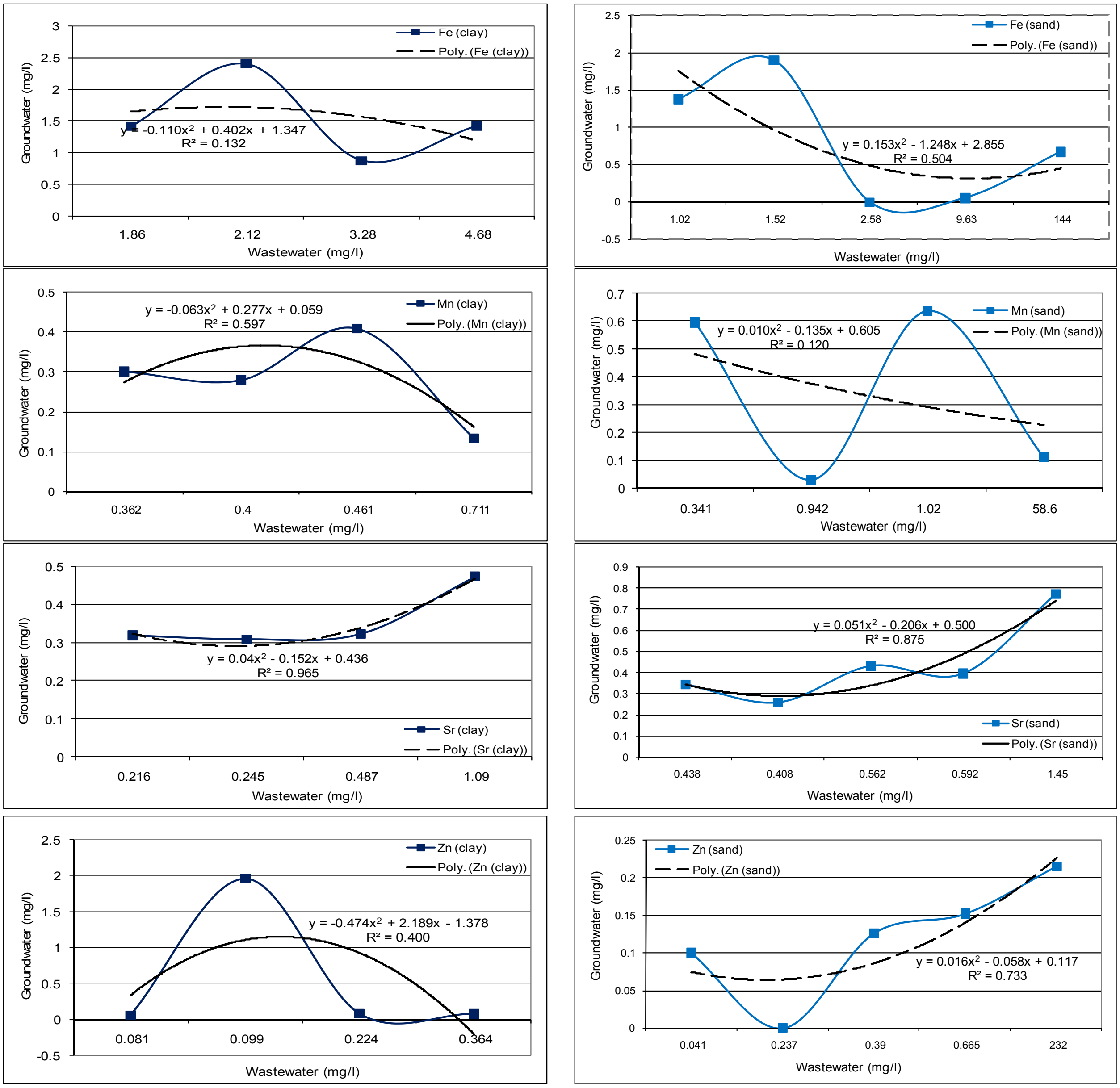


Figure (5): Regression and Correlation Coefficients Hydrographs

Table (2) Regression and Correlation Coefficients of some Parameters between Wastewater and Groundwater for clay and sandy soils

Parameter	Clay Soil		Sand Soil	
	R^2	Equation	R^2	Equation
TDS	0.4558	$y = -46.192Ln(x) + 354.2$	0.7729	$y = -98.5x^2 + 562.5x – 234.5$
NO_3	0.5812	$y = 0.3975x^2 – 1.0325x + 1.0675$	0.8915	$y = 0.3625x^2 – 0.2315x – 0.1425$
Fe	0.1324	$y = -0.1105x^2 + 0.4027x + 1.3475$	0.5048	$y = 0.1538x^2 – 1.2484x + 2.8554$
Mn	0.5977	$y = -0.063x^2 + 0.2778x + 0.0595$	0.1207	$y = 0.0103x^2 – 0.136x + 0.6058$
Sr	0.9658	$y = 0.04x^2 – 0.1524x + 0.436$	0.8751	$y = 0.0511x^2 – 0.2069x + 0.5008$
Zn	0.4005	$y = -0.4743x^2 + 2.1894x – 1.3788$	0.7333	$y = 0.0161x^2 – 0.0587x + 0.117$

TDS: total dissolved salts (mg/l) NO_3: nitrate Fe: iron
Mn: Manganese Sr: Strantium Zn: Zinc
R^2: correlation coefficient X: represents surface sewage water Y: represents groundwater

1) The relation between the TDS of the surface wastewater and that of the groundwater in both clay and sandy soils follows a logarithmic relation according to the equation y=- 46lin(x) +384.2 in clay soil; while in the sandy soil, the relation follows a polynomial regression with equation $y= -98.5x^2$ 562.5x-234.5. The correlation coefficient (R^2) for the both relations is 0.455 and 0.772 for the clay and sandy soils respectively. This means that the relation between TDS of surface wastewater and that of groundwater is more significant in sandy soil.
2) The relation between NO_3 of surface wastewater and that of groundwater in clay and sandy soil in the studied area follows a polynomial regression for both studied soils with equations $y=0.397x^2-1.032x+1.067$ and $y=0.362x^2-0.231x-0.142$ for clay and sandy soils respectively. The correlation coefficient values (R^2) for both studied soils is 0.581 and 0.891 which means that the relation between NO_3 of the surface wastewater and that of groundwater in sandy soil is more than that in clay soil.
3) The relation between Fe of the surface wastewater and that of the groundwater in both studied soils follows the same trend for both soils; with a correlation $y=-0.11x^2+0.402x+1.347$ and $y = 0.153x^2-1.248x+2.855$ for clay and sandy soil respectively. This means that the relation between Fe of surface wastewater and that of groundwater is significant in sandy soil and was not significant in clay soils. (R^2) for clay differs from that of sand; being 0.132 and 0.504 for clay and sandy soils respectively.
4) The relation between Mn of the surface wastewater and that of groundwater differs from clay to sand; following in both cases a polynomial trend. The equation that presents the relation between Mn in surface sewage water and that of groundwater for clay soil is $y= -0.063x^2+0.277x+0.059$; while that for sandy soil is $y= 0.010x^2-0.135x+0.605$. The correlation coefficients for the previous equations are 0.597 and 0.120 for clay and sandy soil respectively, which means that the relation between Mn of surface wastewater and that of groundwater is more significant in clay soil than in sandy soils.
5) The relation between the Sr of the surface sewage water and that of the groundwater in both clay and sandy soils in the studied follows a polynomial regression with equation $y=0.04x^2+0.152x+0.436$ and $y=0.051x^2-0.206x+0.50$ for clay and sandy soil respectively. The correlation coefficient values for the both derived equations are 0.965 and 0.875 for clay and sandy soils respectively.
6) The relation between Zn of the surface sewage water and that of the groundwater in both clay and sandy soils follows a polynomial regression where the (R^2) values are 0.40 and 0.733 for clay and sandy soils respectively. This means that the relation is significant in sandy soil while it was not significant in clay soils.

The correlation coefficient of NO_3 and Sr is significant in both studied soils. This means that those two elements can be considered in the application of the mathematical model MODFLOW to predict the impact of the surface sewage water quality on the groundwater. However, due to the low concentration of Sr, it may be more representative to study the behavior of NO_3 in the model application.

High concentrations of nitrate in groundwater are usually due to human activities. However, some nitrate may naturally occur in arid soils **(Graham *et al.*, 2008).** Also, nitrate is an indicator for both domestic and agricultural pollution (**El Arabi, 1999**) Therefore, the nitrate was chosen as an indicator for the spread of the pollution plume using the simulation model.

Comparison between the correlation factor (R^2) in clay and sand soil is shown in figure (6).

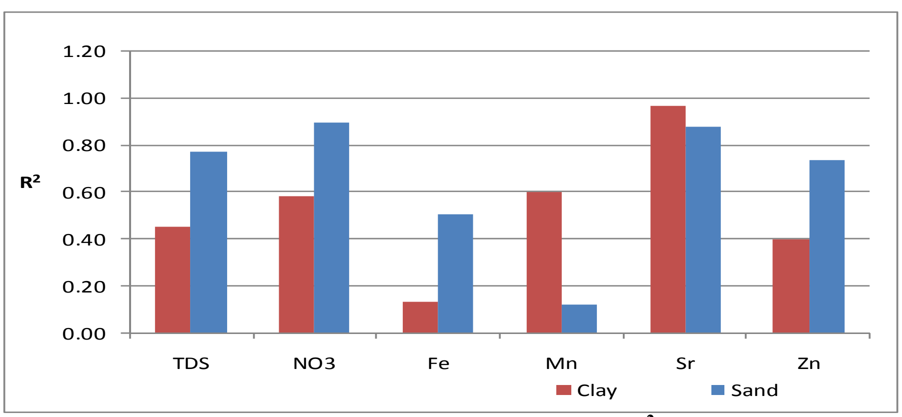


Figure (6). Comparison between Correlation Factors (R^2) in Clay and Sand Soil

Results of the Numerical Simulation

Figure (7) shows a plan view of nitrate concentration of 9 mg/l diffuse pollution source at different time steps (year 2010, 2060 and 2110) using the output concerning the velocity distribution from flow model; while Figure (8) presents an overlay image of land use of the Quessna district including the industrial area and the nitrate concentration diffuse pollution source after 50 years. The results indicate that:

1. The contamination plume moves 1300 m to the North West in the direction of the main flow direction and 850 m to the west direction.
2. Near and around the pumping wells, the plume is reduced due to pumping and the concentration of the two production drinking wells (M1 and M2) reaches about 9mg/l in the industrial area.
3. The concentration is faded out (concentration is equal 0.1 mg/l) under the effect of dispersion and advection after 1500 m in the lateral direction and 2800 m in the transverse direction from the industrial area.

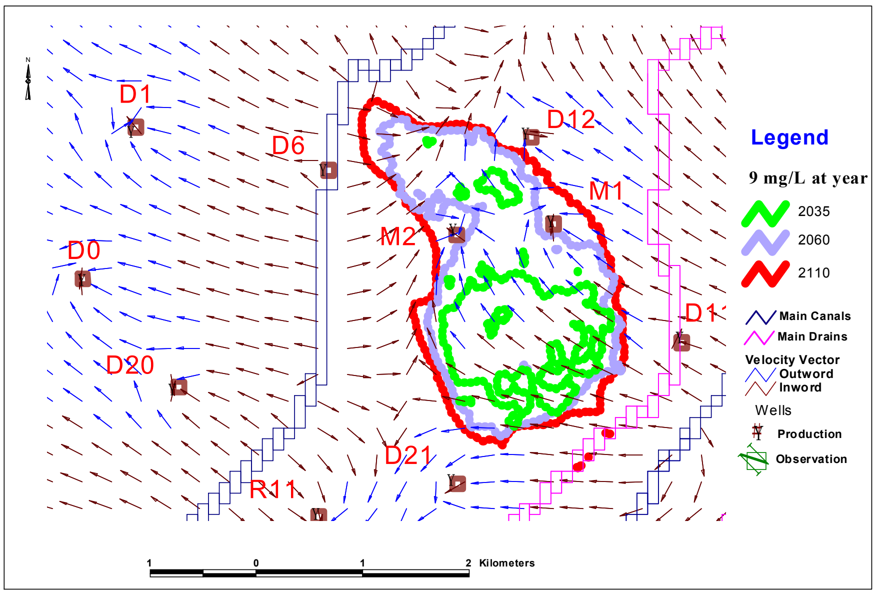


Figure (7). Nitrate Concentration of 9 mg/l at Different times.

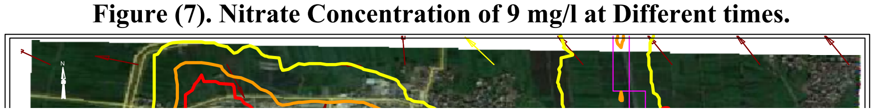


Figure (8). Plan View of Nitrate Concentration after 50 years

To determine the potential pollution plume migration of the nitrate element diffuse pollution source in the vertical direction, a vertical cross section (X-X) is used which includes two production drinking wells (M1 and M2), as illustrated in Figure (9), which also shows a plan view at layer (2). From the figure, it can be concluded that:

1) The plume penetrates to layer 10 after 100 year and will reach the production drinking wells screen with a concentration of about 9 mg/l. This can be attributed to recharge the sandy layer and around it.
2) The plume concentration is much higher in the top layer of the diffused potential polluted area than in the lower layers which may be due to the movement of pollutants by advection from top to down with the main flow direction.
3) From the vertical migration of the potential pollution plume, it is clear that the pollution plume is wide because of the close distance between wells screens which result in a wide downward flow.
4) Increasing pumping and recharge in the industrial area accelerating the travel time of the pollutants to reach more depths.

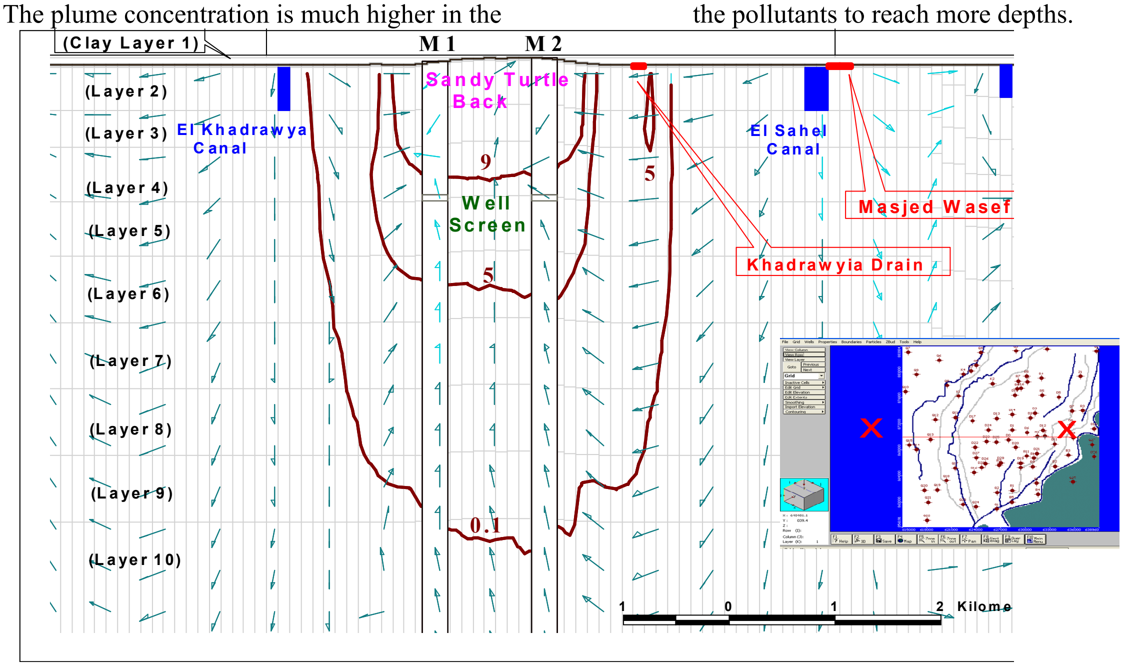


Figure (9). Cross Section (X-X) and the Velocity Vectors.

Time series for nitrate concentration in different wells are shown in figure (10); indicating that the concentration increases with time for most wells and the concentration reaches about 10mg/l after 100 year, which is standard for Egyptian drinking water according to **Ministry of Health Hrinking Water, 1995**. However, any increase in industrial and domestic activities would result in increasing the nitrate concentration after a short period time.

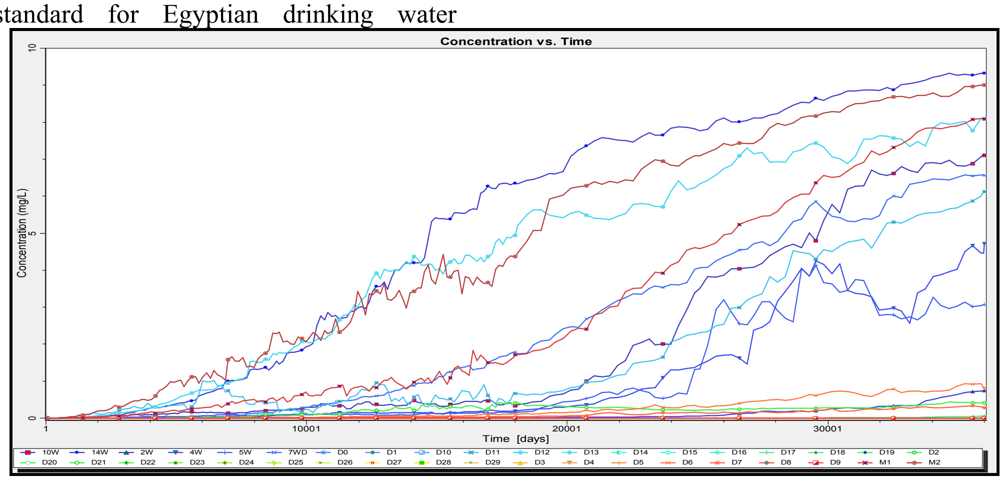


Figure (10). Time Series for Nitrate Concentration.

Conclusions

From the results of the statistical analysis and solute transport model application the following can be concluded:

1. Statistical fitting curves can be used as a tool to investigate the preliminary relation between pollutants in surface wastewater and those in groundwater as a tool to select the main parameters to be used in the model.
2. Results of the study indicate that:

a) The correlation coefficient (R^2) values of the relations between the TDS, NO_3 and Sr for surface sewage water and those for groundwater are higher in sandy soil than those in clay soils. This means that the TDS, NO_3 and Sr can migrate from the surface wastewater to the groundwater.

b) Although the correlation coefficient R^2 values of the relations between Fe and Mn in clay soil were higher than those of sandy soils, it is possible to relate the presence of Fe and Mn in groundwater in both studied soils due to the chemical composition of the carrier layers.

c) The correlation coefficient factor (R^2) is higher in the sandy soil (turtle back) than that in the clay soil, which indicates the important role of the clay cap layer in decreasing and delaying the pollutants migration to the aquifer.

- The original groundwater vulnerability to pollution plays an important role in the protection of groundwater from surface pollution. This is clear in the area where the turtle back predominates as the original vulnerability of groundwater to pollution is higher than the rest of the area.
- Migration of pollutants is increased with the continuous exploitation of groundwater due to the increase in migration.

Recommendations

1. Consideration of groundwater vulnerability to pollution is an important factor in the design of land activities.
2. Treatment of industrial and domestic wastewater is highly recommended before disposal.
3. Reuse of drainage water in irrigation should be restricted as much as possible in regions with high groundwater vulnerability to pollution.

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