ASSESSMENT OF LEAD MIGRATION IN GROUNDWATER FROM AN INDUSTRIAL DEVELOPMENT AREA, EASTERN SIDE OF CAIRO, EGYPT

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Abstract: A number of chemical industries has been established during the mid of the 20th century in Shoubra El Khima, Mostorod and Abou Zaabal industrial development areas in the Eastern side of Cairo Egypt. The effluents of such industries, whether treated or untreated, are being discharged into the Ismailia Canal, one of the most important streams in Egypt. The analysis of water samples from the study area proved that the quality of both surface and groundwater has been negatively affected due to the effect of the industrial effluent discharge. Both surface and groundwater samples were found to be contaminated by lead, which has long been recognized as a harmful environmental pollutant. The average concentration of lead in the collected samples proved to be very high when compared to the WHO water quality standards for drinking water. Groundwater flow and mass transport models were prepared using MODFLOW and MT3D softwares to predict the direction of flow of lead and its dispersion in the groundwater system in the industrial area under study over a period of 5 years.

Keywords: chemical industries, contaminant migration, industrial pollution, mass transport modeling, stream-aquifer interaction, lead concentration.

1. Introduction

The Ismailia Canal is considered one of the most important water streams in Egypt. It is located in the Eastern Side of the Nile Delta. Its water is used in drinking, irrigation, navigation and for industrial purposes. The Ismailia Canal area is considered extremely promising for new communities. Such a development depends mainly on the optimum exploitation of all existing water sources among which is the groundwater [1].

The groundwater reservoir in the Eastern part of the Delta has been considered very important in recent years to cover water requirements and is considered the second main source of fresh water after the Nile water. Like any other water resource, it is not just of public health and economic value but also has an important ecological function. The survival of natural habitats as well as animal species depends on the availability of a sufficient quantity of good quality water [2].

A number of industries has been established during the mid of the 20th century in Shoubra El Khima, Mostorod and Abou Zaabal industrial development areas located in the eastern side of Cairo. Such industries discharge their effluents into the Ismailia Canal as shown in Figure (1). The contaminants from the Canal seep through the stream bed into the ground water regime contaminating it and resulting in substantial degradation of the groundwater quality.

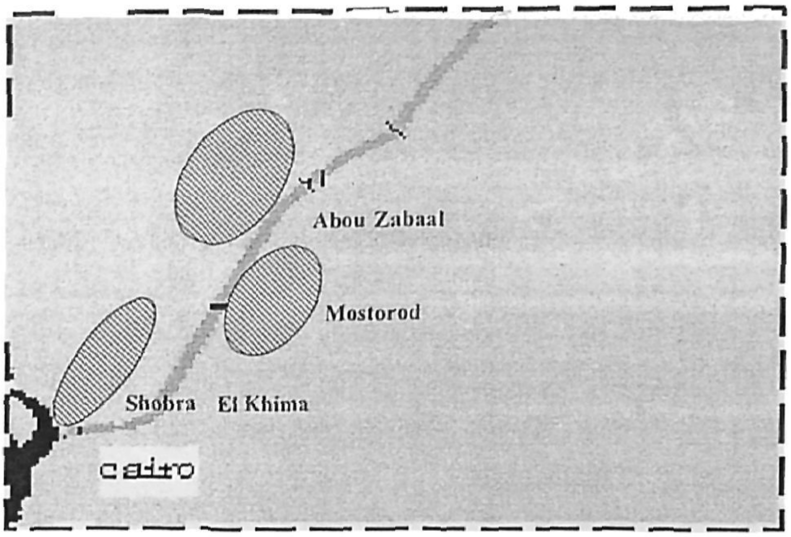

Figure (1): Industrial areas in the Eastern side of Cairo city

In the present work a comprehensive study was performed to determine whether lead (Pb) which has long been recognized as a harmful environmental pollutant has exceeded the acceptable levels in both, surface and groundwater.

Lead is known to affect practically all systems within the body. At high levels, lead can cause convulsions, coma and even death. Lower levels can cause adverse health effects on the central nervous system, kidneys and blood cells. The effects of lead exposure on fetuses and young children can be severe. They include delays in physical and mental development, lower IQ levels, shortened attention spans and increased behavioral problems [3, 4].

It is also well known that Oat, wheat and barley are extremely sensitive to lead. Some plants tend to accumulate lead and thus those plants should not be used as food for humans or animals which could succumb to lead poisoning.

In the present study a groundwater flow and mass transport model was prepared for quantitative assessment of the impact of Pb migration in the water shed and to predict the migration of Pb from the industrial area studied along a period of five years.

2. Field Sampling

Field sampling of both surface and groundwater was conducted in the study area in the month of May, 2004. A total of 30 points were sampled to represent the study area as shown in Figure (2).

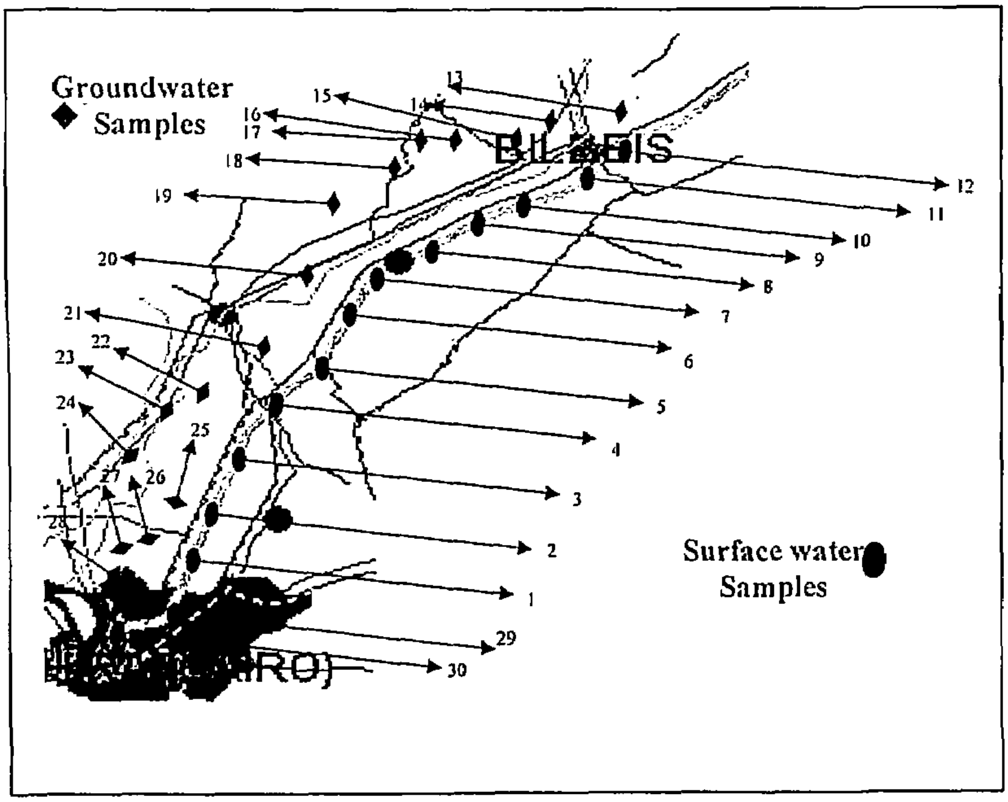

Figure (2) Sampling points in the study area

The Ismailia Canal Surface water was sampled from points 1-12, 29 and 30 while groundwater was sampled from points 13-28 through already existing wells.

3. Chemical Analysis

The chemical analysis of the water samples was carried out at the laboratory of the National Centre for Nuclear Safety and Radiation Control, Cairo, Egypt.

The Pb concentration in the samples was measured using Inductively Coupled Plasma Mass Spectrometer (ICP-MS) which is an analytical technique that performs elemental analysis with excellent sensitivity and high sample throughput. The ICP-MS employs plasma as the ionization source and a mass spectrometer analyzer to detect produced ions. The ICP-MS technique is generally used to measure a wide range of elements in concentration levels of ppb.

4. Computerized System Simulation for Studying Groundwater

In the present study both groundwater flow and mass transport modeling were performed in which the following were assumed:-

a. Darcy's law is valid and the hydraulic-head gradients are the only significant driving mechanism for fluid flow.
b. The hydraulic conductivity of the aquifer system is constant with time.
c. Gradients of fluid density, viscosity, and temperature do not affect the velocity distribution.
d. No chemical reactions occur that affect the fluid or aquifer properties.
e. The dispersivity coefficients are constant with time and the aquifer is isotropic with respect to longitudinal dispersion.

4.1. Groundwater Flow Modeling Using MODFLOW Software

The modular three-dimensional finite difference groundwater flow modeler, MODFLOW, which is used to illustrate the direction of flow of groundwater, is used. This software solves the groundwater flow equation and the solute-transport equation based on the method of characteristics, [5, 6]. Mathematical equations that describe groundwater flow and transport processes are developed from the fundamental principles of conservation of mass of fluid or of solute. Statements of conservation of mass (or continuity equation) combine with a mathematical description of the relevant process to obtain a differential equation describing flow or transport [7].

A general form of the ground flow equation describing the transient flow in a heterogeneous anisotropic aquifer may be derived by combining Darcy's law with the continuity equation and could be written in Cartesian tensor notation as shown in equation 1.

$$\frac{\partial}{\partial x_i}\left[Kij\frac{\partial h}{dx_i}\right]=S_s\frac{\partial h}{dt}+W \qquad (1)$$

Where: S_s is the specific storage of the porous material, $[L^{-1}]$;
K_{ij} is the hydraulic conductivity of the porous media, $[LT^{-1}]$;
h hydraulic head, [L];
t time, [T];
W the volumetric flux of water per unit volume of aquifer, $[T^{-1}]$;
x_i the distance along the respective Cartesian co-ordinate axis, [L].

The summation convention of Cartesian tensor analysis is implied in equation 1. It can generally be applied if isothermal conditions prevail, the porous medium deforms only vertically and the volume of industrial grains remain constant during deformation.

It is to be noted that although fluid sources and sinks may vary in space and time, they have been lumped in equation 1 in a single term, W, for convenience in notation.

If the principle axes of hydraulic conductivity tensor are aligned with the x-y-z coordinate axes, the cross product term of the hydraulic conductivity tensor is eliminated i.e. $K_{ij}=0$ where $i \neq j$.

The groundwater flow equation could then be written to include explicitly all the hydraulic conductivity terms as shown by equation 2, [8].

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{dx}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{dy}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{dz}\right]-W=S_s\frac{\partial h}{dt} \qquad (2)$$

Where: K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y and z coordinate axes respectively, $[LT^{-1}]$.

Under such assumptions, Darcy's law may be written as shown by equation 3.

$$\left.\begin{aligned} q_x &= -K_{xx}\frac{\partial h}{\partial x} \\ q_y &= -K_{yy}\frac{\partial h}{\partial y} \\ q_z &= -K_{zz}\frac{\partial h}{\partial z} \end{aligned}\right\} \tag{3}$$

Where: q is the specific discharge, $[LT^{-1}]$.

The velocity of the flowing groundwater will obviously affect the migration and mixing of chemicals dissolved in the groundwater. The specific discharge, q_i, calculated from equation 3 represents the volumetric flux per unit cross sectional area. Thus, to calculate the actual average interstitial velocity of groundwater, one must account for the actual cross sectional area through which flow is occurring which is usually calculated by equation 4.

$$v_i = \frac{q_i}{\varepsilon} \tag{4}$$

Where: v_i is the interstitial velocity, $[LT^{-1}]$;
ε is the effective porosity of the porous media, dimensionless.

Assuming the same grid alignment as that for equation 2 the interstitial velocity could be written in terms of Darcy's law as shown by equation 5.

$$v_i = \frac{K_{ii}}{\varepsilon}\frac{\partial h}{\partial x_i} \tag{5}$$

4.2. Mass Transport Modeling Using MT3D Software

Mass transport in three dimensions (MT3D) is a computer software for simulation of advection, dispersion and chemical reactions of contaminants in three-dimensional groundwater flow systems [9]. The model is used in conjunction with the blocked centered finite difference model MODFLOW.

Since the principle conservation of mass requires that the net mass of solute entering and leaving a specified volume of aquifer during a given time interval must equal the accumulation or loss of mass stored in that volume during the interval, the governing equation for solute transport in three dimensions in an incompressible fluid flow through a porous medium could be represented by the partial differential equation given by equation (6).

$$\frac{\partial(\varepsilon C)}{\partial t}+\frac{\partial \rho_b \overline{C}}{\partial t}-\frac{\partial}{\partial x_i}\left[\varepsilon D_{ij}\frac{\partial C}{\partial x_j}\right]+\frac{\partial}{\partial x_i}(\varepsilon v_i C)-\sum C'W+\lambda(\varepsilon C+\rho_b \overline{C})=0 \qquad (6)$$

Where: C is the volumetric concentration, [ML^{-3}];
ρ_b is the bulk density of the aquifer material, [ML^{-3}];
$\overline{C}$ is the mass concentration of solute sorbed or contained within the solid aquifer material, [MM^{-1}];
D is a second rank tensor of dispersion coefficient, [L^{2}T^{-1}];
C' is a volumetric concentration in the sink- source fluid, [ML^{-3}].
λ is the decay rate, [T^{-1}].

4.3. Numerical Solution of Governing Equations

The mathematical solution of the governing equations require the specification of certain initial and boundary conditions. Because the transport equation is always solved for transient conditions, the initial concentration must be specified throughout the domain within which solute transport occurs (which may be equal to or smaller than the domain in which the flow equation is applied and solved).

The specification of a constant-concentration boundary condition at one or more nodes for the transport equation would be analogous to the use of a constant-head boundary condition for the flow equation.

Although this is mathematically and numerically feasible, it is rare that a field environment would be consistent with such a constant-concentration condition. Therefore, we have not implemented the use of this type of boundary condition in this model. Instead, input concentrations must always be associated with a fluid flux.

Referring to the hydro geological data of the study area, it is noted that the aquifer system is with no flow in the North and East while the River

Nile and Ismailia Canal are the boundary sides on the West and South. Thus for the transport equation, two specified mass-flux boundary conditions are used in this model. At no-flow boundaries for the flow equation, the mass flux is also required to be zero. The second type of specified mass boundary condition is applied when the transport sub-domain is within a flow domain. That is, the boundaries of the transport sub domain do not coincide with the flow domain boundary. In this case, solute mass movement into and out of the transport sub-domain is assumed to be by advection only; no disperse solute flux can occur across a sub-domain boundary, which is mathematically equivalent to a zero gradient in concentration across the boundary.

The flow equation was first solved independently of the mass transport equation. Further, water level observations in the area indicate that hydraulic gradients do not change significantly with time. Thus groundwater flow was assumed to be in a steady state and groundwater heads were computed by visual MODFLOW using Successive Over Relaxation (SSOR) package, [10].

The chemical mass transport model, MT3D, was then solved in conjunction with mass flow model MODFLOW using first order Euler method for the partial tracking algorithm. It is worth mentioning that in doing so no additional recharge input from the Ismailia Canal is taken into consideration. In addition the chemical reaction was confined only to sorption and not to radioactive decay nor to biodegradation.

5. Hydro geological data

Referring to the hydro geological data of the area under study the following characteristics are noted [2]:-

- The study area is an aquifer system with no flow in the North and East with the River Nile and Ismailia Canal representing the boundary sides on the West and South.
- The system is unconfined and isotropic with horizontal hydraulic head of 4.629×10^{-4}m/s, vertical head of 10% of the hydraulic head and effective porosity of 0.25.
- The hydrodynamic model is applied to an area of 72km^2 with mesh characteristics 40 x 45 and with size 20 m.
- Steady state flow is applied.

6. Results and Discussion

6.1. Lead Concentration in Tested Samples

The Pb chemical analysis of both surface and groundwater samples are listed in Tables 1 and 2 respectively. The concentration of Pb is expressed in mg/l .

Table 1: Pb concentration in surface water samples

Sample No.	**Pb Concentration, mg/lit**	**Deviation from WHO standards**
6	11.66	+11.65
7	16.19	+16.18
11	11.66	+11.65
12	12.98	+12.97
29	11.72	+11.71
Average Conc.	**4.93**	**+4.92**

Table 2: Pb concentration in underground water samples

Sample No.	**Pb Concentration, mg/lit**	**Deviation from WHO standards**
20	11.54	+11.53
23	11.28	+11.27
24	11.35	+11.34
26	11.98	+11.97
27	11.28	+11.27
28	11.35	+11.34
Average Conc.	**6.25**	**+6.24**

Pb was detected in surface water samples number 6,7,11,12 and 29 and in groundwater samples number 20, 23, 24, 26, 27 and 28 while its concentration was less than the detection limit in the calibration curve for the rest of the samples.

For the samples where Pb was detected, its concentration was found to be extremely higher than the acceptable limits of the environmental standards for protection of human health for water pollution and standards for underground water pollution presented by the WHO which is 0.01 mg/lit, [2]. These high values of Pb are no doubt due to the high industrial activities in the study area.

It is clear that in the North part of the Canal Pb was detected only in some of the surface water samples collected while all groundwater samples were found to be free of Pb. This does not indicate the safety of the tested wells in this area as seepage from the Ismailia Canal is definitely going to contaminate the groundwater in the very near future.

6.2. Computer Modeling Results

6.2.1 MODFLOW Results

Figures 3 and 4 represent the results obtained from MODFLOW computer program which verifies the main sources of fresh water in the aquifer of the study area and the direction of flow of underground water. Both figures show that:-

- The seepage from Ismailia Canal is charging towards west and north of the study area.
- The seepage from the River Nile is charging towards the southwest part of the catchment's area.

The direction of flow shown in Figure 4 could be used to explain the fact that lead was detected only in sampling wells number 6,7,11,12 and 29 but was absent in the rest. The seepage from the Ismailia Canal is clear to push the contaminants towards the West and North of the study area away from the selected sampling points

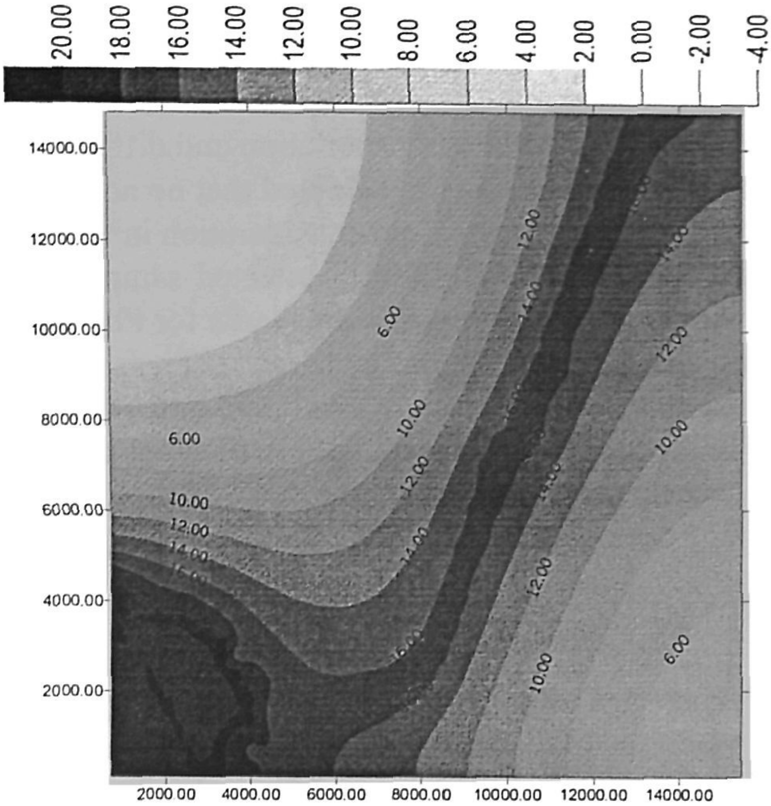

Figure 3 : Hydraulic head in the first ground layer around Ismailia Canal

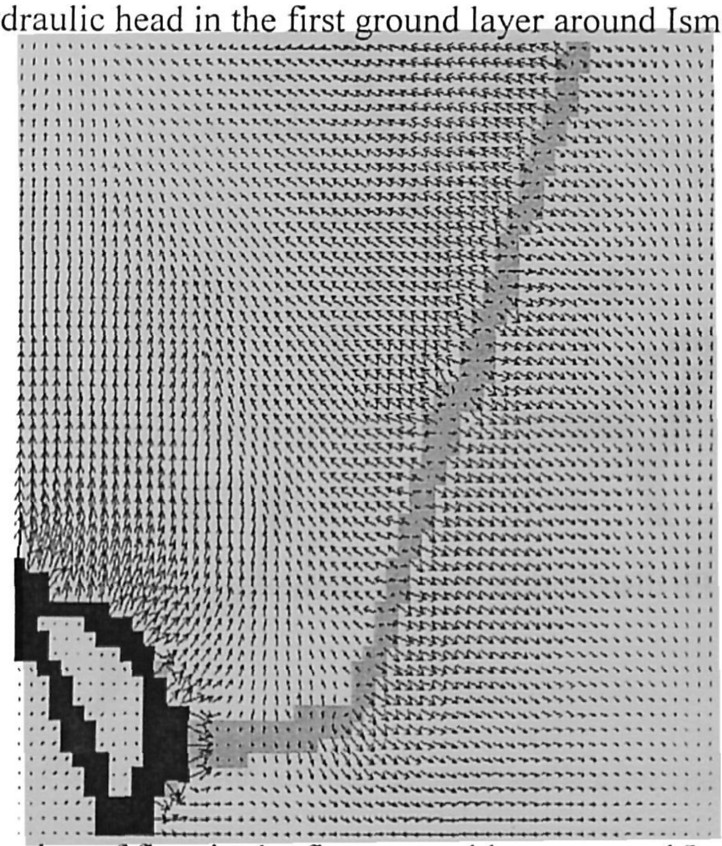

Figure 4: Direction of flow in the first ground layer around Ismailia Canal

6.2.2. MT3D Results

Figures 5, 6, 7 and 8 show the transportation and diffusion of Pb in the aquifer along a period of 3 years. It is to be noted that no additional recharge input from the Ismailia Canal is taken into consideration in the model.

After 5 years concentrations of Pb in infected sampling points were found to comply with the WHO acceptable standards for Pb concentration in underground water tested. Thus if input recharge of Pb from the industrial activities in the area under study is highly monitored and effectively stopped the ground water in the study area would be free of Pb as a life threatening pollutant within a period of 5 years.

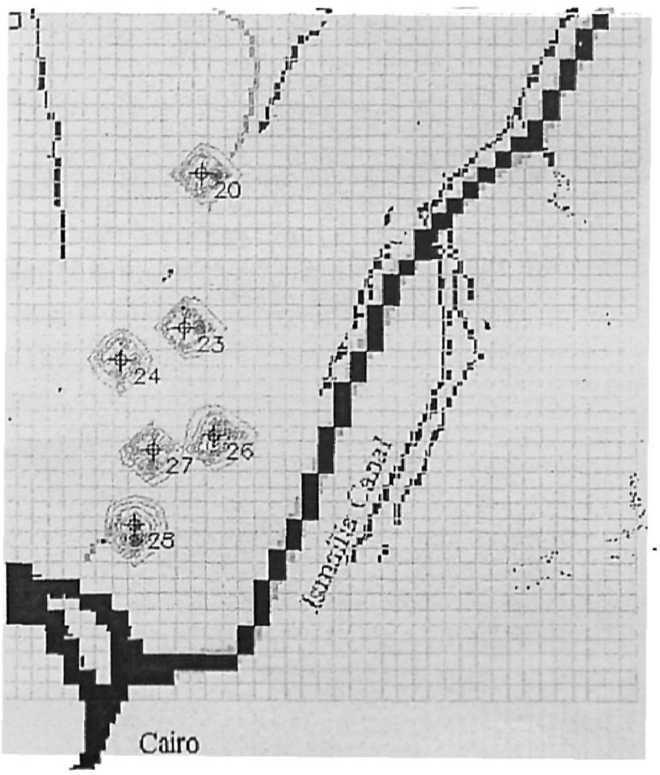

Figure 5: Pb distribution around ground wells after 30 days

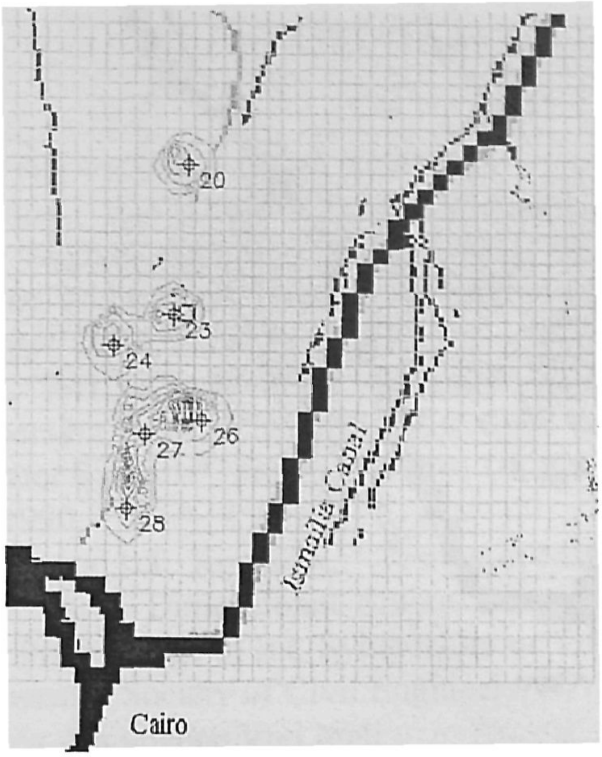

Figure 6: Pb distribution around ground wells after 6 months

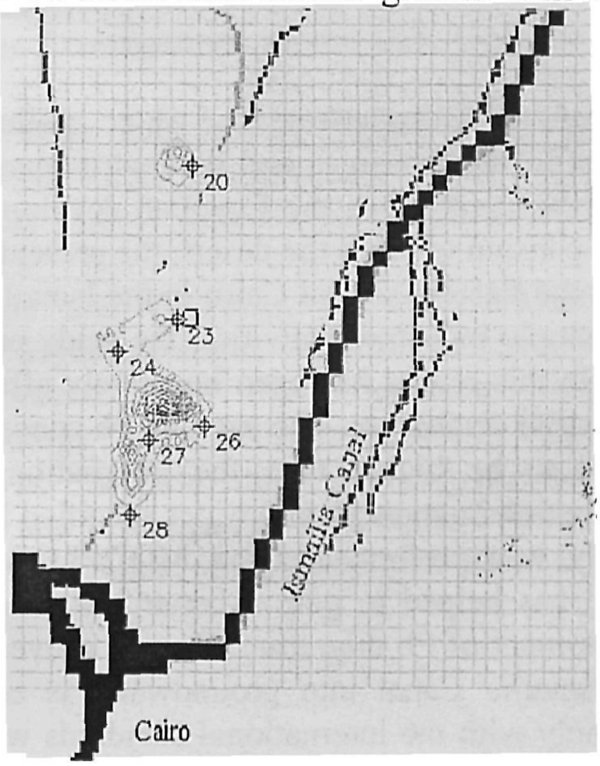

Figure 7: Pb distribution around ground wells after one year

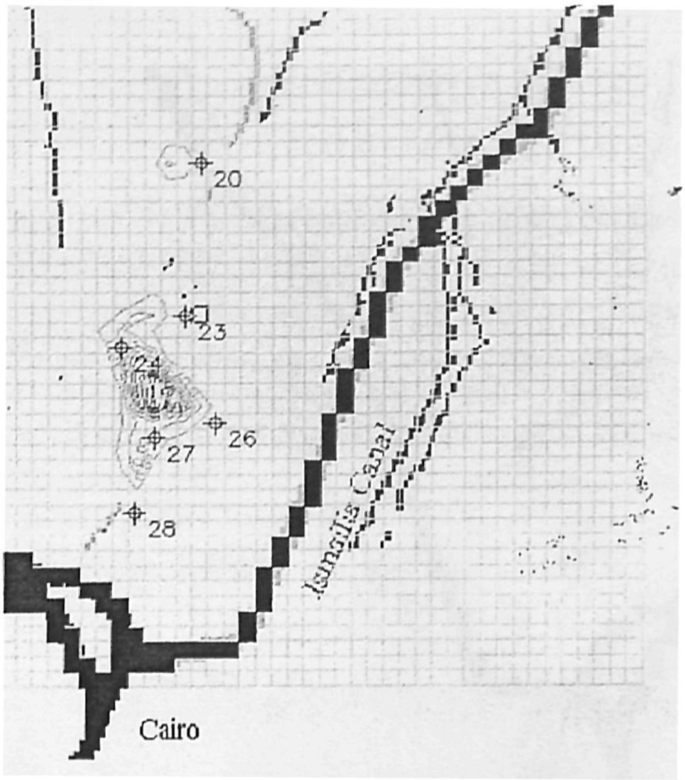

Figure 8: Pb distribution around ground wells after three years

7. Conclusion

A case study of groundwater/surface water pollution due to uncontrolled industrial effluent discharges and its environmental impact on groundwater regime is presented. Since the Egyptian development projects depend mainly on the expansion towards the desert, the present research was directed mainly towards the Eastern side of Cairo in the Ismailia Canal area. Due to the effects of multiple industrial activities, the study proved that the quality of groundwater in this region has been negatively affected with Pb due to the effect of industrial discharges. The average Pb concentration from sampling points proved to be higher than the internationally accepted standards for Pb concentration in underground water specified by the WHO.

A modeling study was performed using MODFLOW and MT3D computer softwares and has helped to gain a better insight for the hydro geologic setup and assessment of Pb migration. Results proved that if input recharge of Pb from Ismailia Canal into groundwater is controlled, the groundwater would comply with the international standards within a period of five years.

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