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ArcGIS and Numerical Model for Studying Groundwater Pollutant Transport Problem in Sadat City in Egypt

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ملخص البحث :
تعتبر المياه الجوفية في مصر من المصادر التقليدية الرئيسية للمياه عند نقص المياه السطحية وخاصة في المناطق القاحلة كما هو الحال في معظم المدن الجديدة في الصحاري. ويمكن ان تتلوث المياه الجوفية من المناطق الصناعية أو الزراعية أو التسرب من محطات معالجة مياه الصرف الصحي أو شبكات الصرف الصحي. هذه المشكلة موجودة في مدينة السادات الصناعية في الصحراء الغربية في مصر. تم جمع البيانات الميدانية والسجلات السابقة لمصادر التلوث وبيانات الآبار الرسمية في المدينة. وقد تم استخدام برامج لعمل نموذج للابار وتحليل البيانات وذلك لمحاكاة منطقة الدراسة ودراسة معدلات نقل الملوثات والاتجاهات. وأظهر النموذج المفاهيمي أن التلوث ينتقل من المناطق الصناعية نحو المدينة الرئيسية التي تزود الآبار. ومع ذلك، فإن معدل نقل الملوثات بطيء جدا، والتي يمكن أن تعطي فرصة للرقابة قبل الوصول إلى حقل الآبار. وقد تم التوصل إلى مخرجات أخرى من معايرة النموذج واستهلاك المياه النموذجية التي توجد فيها آبار كثيرة غير مسجلة رسميا مما قد يتسبب أن يكون مضللا للحالة الفعلية في المدينة ويمكن أن يسرع في انتقال الملوثات للابار نتيجة زياده السحب.

Abstract:

Groundwater in Egypt, is considered one of the main traditional sources of water when there is a lack of surface water, especially in the arid regions like in most of the new cities in the deserts. Groundwater can be polluted from industrial or agricultural areas or leakage from wastewater treatment plants or sewer systems. This problem is existed in Sadat Industrial City in the western desert in Egypt. Field data and previous records have been collected for the sources of pollution and for the official supplying wells in the city. ArcGIS and Visual MODFLOW have been also used to simulate the study area and to study the pollutant transport rates and directions. The conceptual model showed that the pollution moves from the industrial areas towards the city main supplying wells. However, the rate of pollutant transport is too slow, which can give a chance to be controlled before reaching the wells field. Another output was concluded from the model calibration and the model water budget that there are many unregistered wells withdrawing transport. Which can be misleading to the actual situation in the city and can rapid the pollutants.

1. Introduction

Groundwater in Egypt is considered one of the important traditional sources of water in the arid or semi arid regions like in the industrial cities in the deserts. Water is used widely in various daily activities like domestic, agricultural and industrial purposes. Many regions in Egypt are suffering of groundwater pollution, because of leakage from sewer systems or seepage from agriculture areas. Although several aquifer systems exist in Egypt, the most important is the Nile aquifer system, which covers the Nile flood plain region and the desert fringes. Pollution is more severe on the edges and desert fringes of the Nile Valley and in the shallow portions of the aquifers underneath urban areas (domestic sewage). High concentrations of nutrients, E. coli, sulfur, heavy metals, etc. have been observed in the shallow groundwater, largely surpassing WHO standards for drinking water use. High concentrations of various metals are reported for the Rosetta Branch, the Alexandria region (coastal waters and Lake Maryut) and Lake Manzala. Measurements in the Rosetta Branch (near to the study area, Sadat City) show that cadmium, copper and zinc are above standards. As the heavy metals settle in sedimentation areas, they constitute a long-term threat for the environment. Although high numbers of water-borne diseases are reported, it is believed that many more people suffer from diseases because of water pollution and heavy metals in drinking water and food products which can affect human health adversely [1,3].EL Sadat City, the study area, is one of the largest industrial cities in Egypt. It is located in the Western Nile Delta region, on the way of Cairo-Alexandria Desert Road between km 95 and km 103 from Cairo city and administratively follows El Menoufia Governorate. The city is considered as one of the new communities, which has initiated in the mid seventeen's (1976) and considered as the first-generation cities by the New Urban Communities Authority. It covers areas about 500 km^2. Accordingly, many of activities have been established such as agriculture, various kinds of industries, residential and governmental district areas and other activities. As general, all the activities in the city area are mainly based on groundwater as the only water source. The residential area is divided into sub-areas planned to accommodate 500,000 capita by the year 2025. The agricultural area is located in the southern portion of the city, covering 2,000 feddans in addition to the green belt. The industrial area is located in the eastern portion of the city and consists of 144 factories with different kinds of industries, in addition to the Gas filling stations. The waste oxidation pond in Sadat city was implemented as treatment plant located at 11 km distance to the North East of the city on an area of approximately 72 feddans to receive all the wastewater treatment of all the city and reuse of the treated effluent for agriculture practices. Accordingly, such activities are polluting sources for the groundwater at present. A wide range of pollutant can be released from these sources, including biological, trace metals, nitrogen, phosphorous, and organic compounds; in addition to grease and gas. [1, 2].

2. Materials and Methods

2.1 Objectives: The main objective of this study is to predict the short and long-term impacts of moving pollutants to wells from the industrial activities which is the nearest source of pollution. The regional numerical model is designed mainly to study the pollutant transport rate and direction towards the city supplying wells to be monitored and controlled.

***2.2 The Study Area*:** El-Sadat City is located between 30° 21´ E and 30° 41´ E longitude and 30° 19´ N and 30° 34´ N Latitude and it lies at the kilometer 93 on Cairo–Alexandria highway north-west of Cairo (Figure 28), its total area is 523.5 km, the residential area is 100 km^2, divided into 12 blocks and the future extension of the city is 201km^2, while the industrial area covers 34 km^2 (8,000 Feddan) divided into 7 industrial zones and an agricultural area of 147 km^2 (35,000 feddan) [1,8]. **Figure 1**. Shows Sadat City area location and it is a relatively new industrial city in the western desert. **Figure 2** shows the Land use for study area and the groundwater different pollution sources. All the city activities are mainly depending on the groundwater most of the production (supplying) wells were constructed near to the residential parts of the city to cover the city needs for water, in addition to some other private wells which are used for irrigation purposes. The city treatment plants are existed in the north of the city and it applies tertiary treatment for the industrial and municipal waste water [4].Several studies have been done by The Research Institute of Groundwater in El Kanater-Egypt (RIGW) to find out the recharge distribution in the city, it was noticed that most of the city gets very little amount of water recharge or subsurface drainage which comes mainly from the green areas irrigation [1,6].The average recharge for the groundwater in the green areas is about 0.5 mm/day, [1,7].Groundwater in the study area is under phreatic conditions with the exception of some localities, which display a semi-confined condition. Depths to water and water levels were measured of some observation wells during 2002 to 2009, depth to water from the ground surface ranges from 15 to 25 m in the northern part and from 45 to 56 m at the southern part (reclaimed zone) and east to the Cairo–Alexandria Desert Road in the southern part. Groundwater levels are +5 to +4m (amsl) in the northern parts of the city and −4m and−5m (bmsl) at the southern parts. The low values of groundwater levels recorded at the southern part reflect impact of large scale groundwater extraction rates and limited groundwater recharge to these localities [1,2].

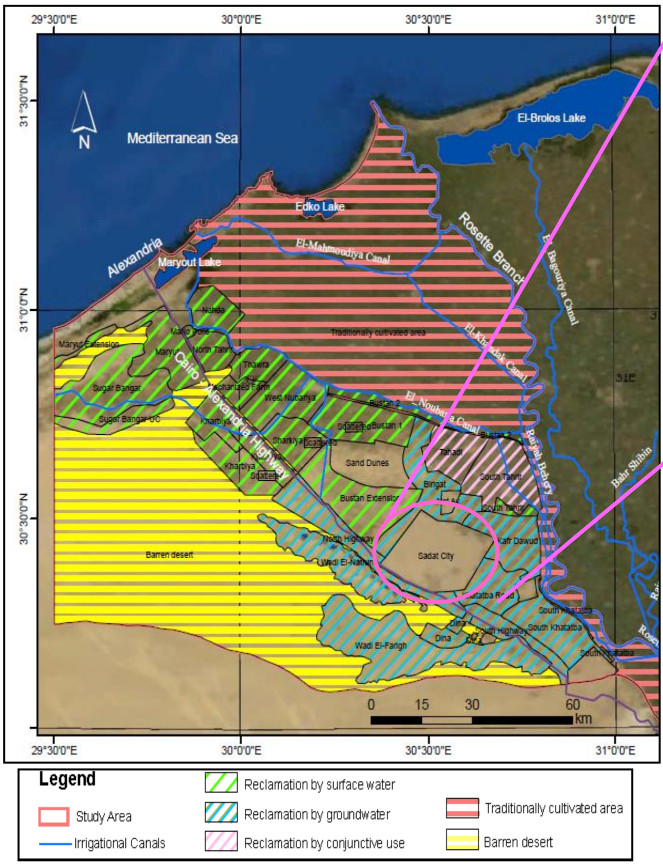

Figure 1: The study area location

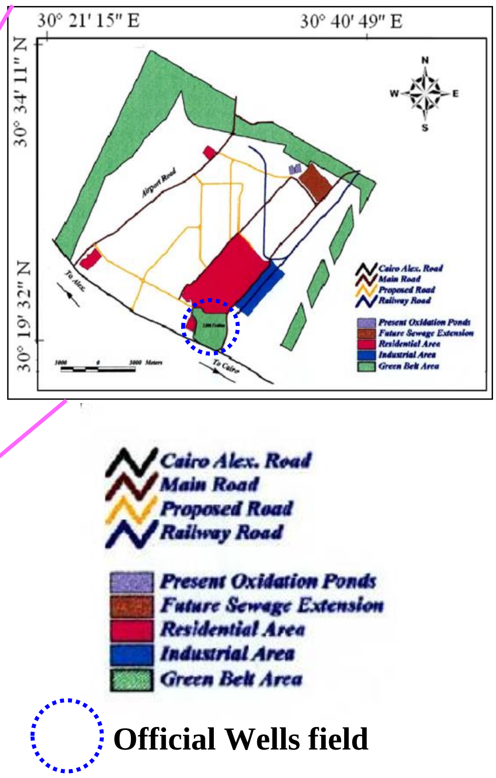

Figure 2: El-Sadat City Land use

2.3 Data collection and literature review: Several studies have been done on the groundwater quality in this region and showed its deterioration. One of them was done by others [5]. Groundwater samples were collected from 108 water wells in the western Nile Delta. The wells have depths varying from 27.0 to 120 m. Each well had a standard galvanized iron pipe that was enforced vertically into the ground. The groundwater samples were collected in two-liter polyethylene bottles during 2003. The analyzing processes had been done following the standard methods for the examination of water as described by the American Public Health Association (1989). The chemical analyses were carried out by the Research Institute for Groundwater (RIGW) laboratories. The main pollutants encountered in groundwater are:

•E. coli (>100 MPN/100 mL), found at shallow depths in regions with highly vulnerable groundwater.

•Nitrate (occasionally 70-100 mg/L and expected to increase with time) in regions with highly vulnerable groundwater and intensive fertilizer application.

•Organochlorine pesticides in highly vulnerable groundwater, also at greater depths.

•Organophosphorus and carbonate pesticides, especially in shallow groundwater.

•Iron and manganese and some other heavy metals have been detected.

2.4 Remote sensing and DEM maps: A digital elevation maps (DEM) from Shuttle Radar Topography Mission (SRTM) database for the satellite image (path/row177/39) were downloaded with *.tif.gz extensions for generating the topographic in ArcGIS. Digital images of 3 arc second scene were used (USGS,2006). These images were downloaded from the Earth Science Data Interface (ESDI) at the Global Land Cover Facility and opened on ERDAS Imagine 8.5 software and saved as one compiled imagine (*.img) file to be imported to ArcGIS platform and their data were exported to be ready for generating the topographic map. Figure 4 shows the imported image map on ArcGIS. The obtained topographic map from ArcGIS was compared with another topographic paper map from The Egyptian Survey Authority and so much agreement was found, so the topographic map from DEM data was used in this study as a good digital map. The obtained DEM was converted to UTM using 3DEM software system, to be used by MODFLOW 4.2 for aquifers and groundwater flow simulation. program. Figure 5 shows the imported image map on ArcGIS and the study area.

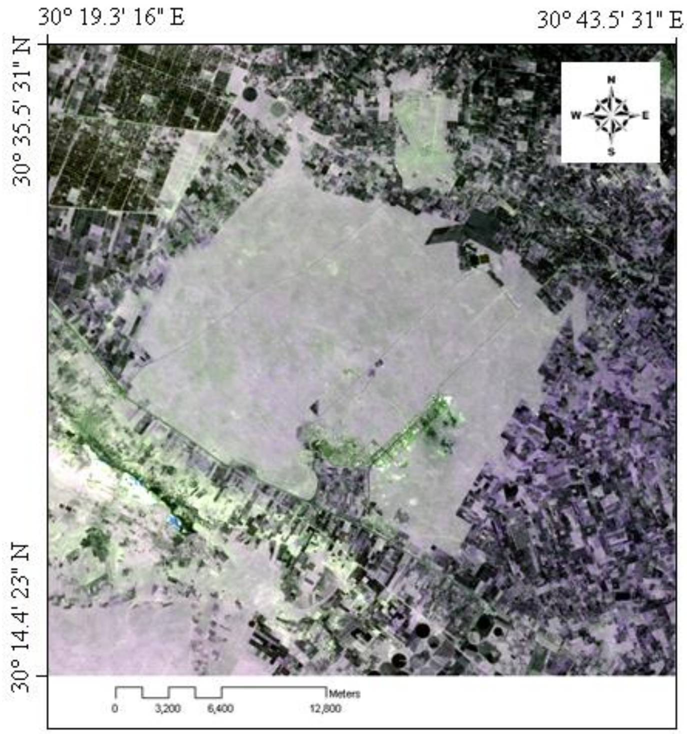

Figure. 4 The imported satellite image for the study area on ArcGIS.

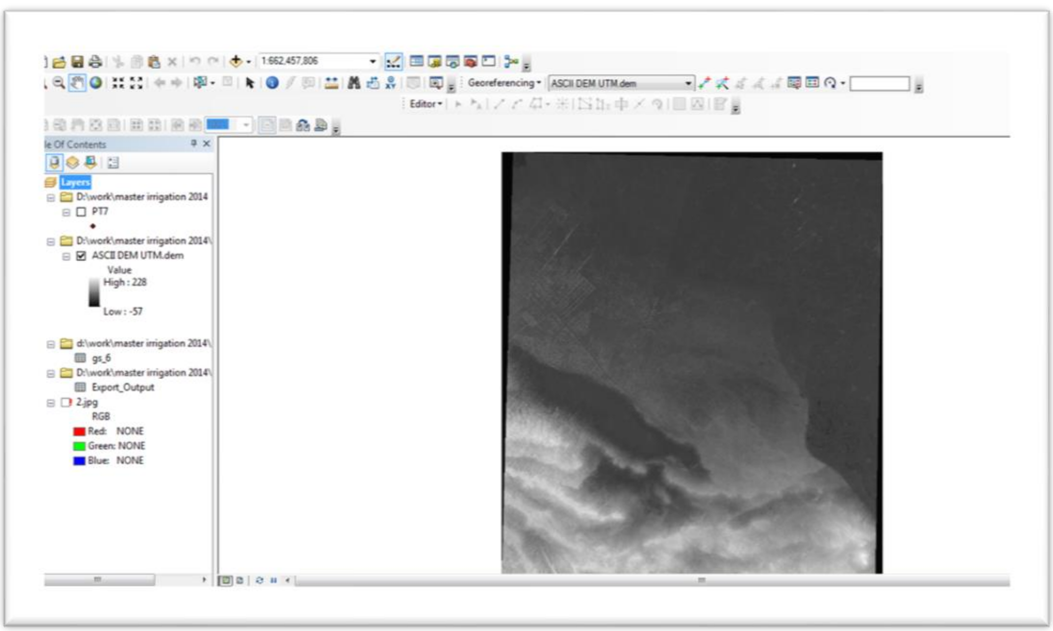

Figure.5: The imported image map on ArcGIS and the study area

2.5 The Numerical Model:

Visual MODFLOW 2000 (versions 4.2) is the selected to simulate the study area for practical application in groundwater flow and solute transport. MODFLOW is a multi-dimensional (2D and 3D), saturated groundwater flow code, it has agreat capability to use graphical modeling environment for professional 3-D groundwater flow and contaminant transport simulations [9]. MODFLOW model has been applied in many groundwater projects in Egypt and proved to be a powerful tool in groundwater researches, especially for quality and in simulating large areas like in the present study (≅523.5 km^2), moreover it is available as a full package at the research place MODFLOW version 4.2 was used in all the calibration and validation and the non-reactive transport models, while MODFLOW version 4.2 was used in the reactive transport models and its new tool pest was quite helpful for the calibration processes.
The solver which has been selected in MODFLOW 2000 is the Bi-Conjugate
Gradient Stabilized (WHS) as it has the ability to solve simultaneous equations in both linear-and non- linear systems (MODFLOW, 2002). WHS is the method for solving this large system of simultaneous linear equations by iterations. The advantage of the WHS solver is that it is very stable and generally converges to a solution.

2.6. Numerical Model Design

Model design represents the process of translating the conceptual model for groundwater flow in the aquifer into a numerical representation which is generally described as the model. Model design includes definition of the model grid, layer structure, the model boundary conditions and the model hydraulic parameters. Each of these elements and their implementation are described in this section. For the preliminary numerical model design, a number of requirements have been fulfilled;

1. A complete geometric configuration of number of layers and grid size in the x, y and z directions.
2. Information on heads required for model calibration in the steady-state (at boundaries).
3. Contour maps for: ground surface topography, piezometric water levels and the thickness of Quaternary aquifer layers.
4. Distribution of the soil permeability and porosity for different layers and zones obtained from geotechnical properties.
5. Head distribution at a number of piezometric wells to be used in the verification process. Loading the data of pumping wells in El- sadat city by using UTM coordinate with discharge data for every well in Visual Modflow 4.2 and entering DEM and pizometric maps.

Figure 6 shows DEM and pumping wells in study area in VMD (visual modflow) program.

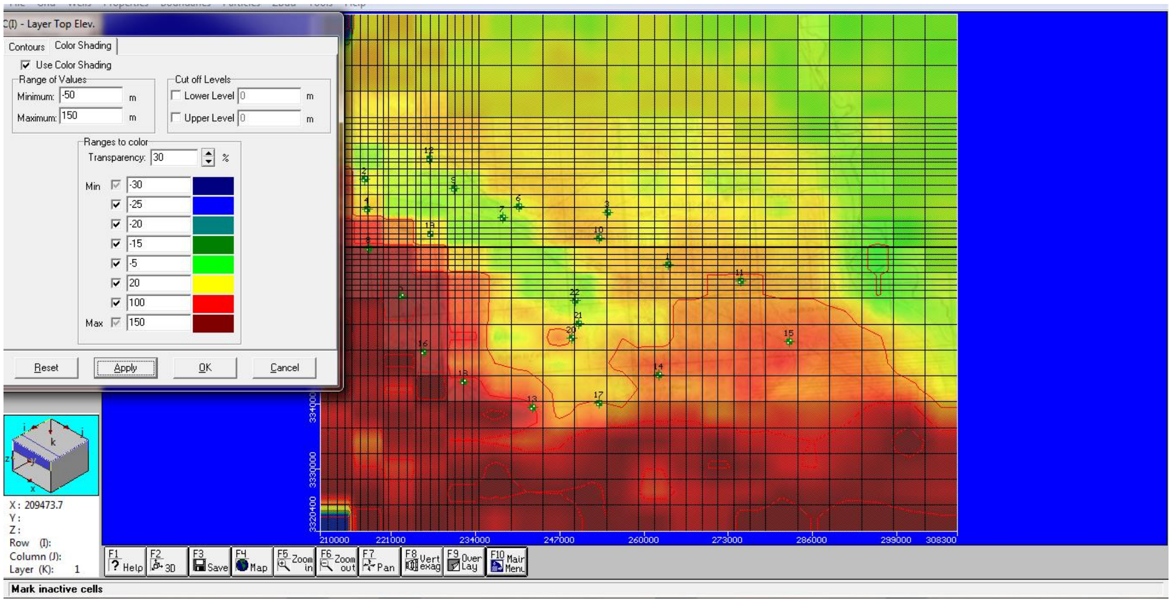

Figure. 6: Loading DEM and pumping wells in study area in VMD

Model Calibration:

Calibration is a trial-and-error adjustment of parameters until the model solution matches the field values. In general the model calibration aims to design a steady-state model for the head distributions to be used as an initial condition for a transient-state simulation after applying different scenarios on it. Model calibration consists of successive refinement of model input parameters from the initial estimates to improve the fit between observed and model-predicted results. The calibration procedure typically begins with selective definition of parameters/inputs based on available data and/or an initial conceptual model of the hydrogeologic system. Those parameters that are known or can be reasonably estimated are initially specified as part of the input data set. Calibration involved comparison of the model results and observed heads at 83 observation points from a piezometric head map as shown in Figure 3.The main parameters were chosen for the calibration process that greatly influence flow regime; soil permeability and recharge. Several runs, each involving adjustments of the calibration parameters, were made until a final calibration was achieved.

1. Results

3.1 Calibration Results:

Visual MODFLOW post-processing features allow for a graphical comparison of model-predicted and observed heads. The obtained calibration residual values are used to calculate statistics such as the standard error, root mean squared error and correlation coefficient. Figure (8) shows the calculated versus observed piezometric heads graph. From this figure it is clear that the dots are mostly lying within the 95 % confidence limits which mean a very good calibration result.

The model water budget is one of the important outputs from the calibration, which was achieved by a good agreement with the reference piezometric map and the model. It was found that the total pumped water from the model equals to 2346300 m^3/d which achieves the actual piezometric map, while the official value of the total discharge from the wells field is 22350 m^3/d. This means that there many unofficial pumping wells which can rapid the pollutant transport process in the groundwater. This result was confirmed by number of specialists at RIGW. Figure 8 shows the model calibration water budget.

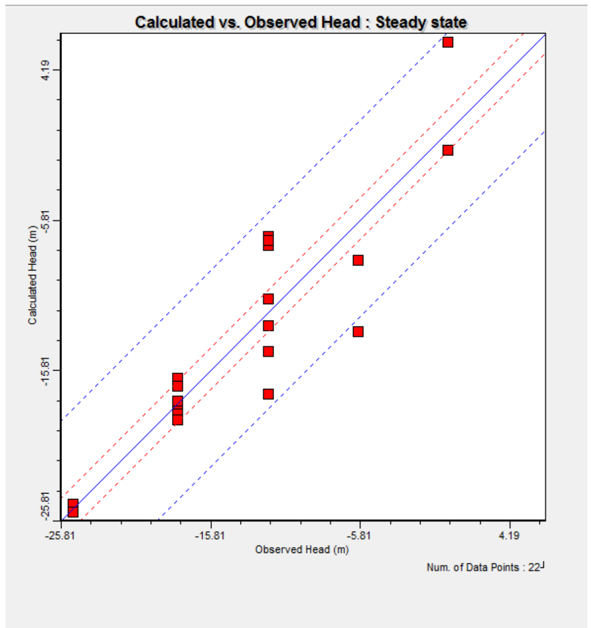

Figure (7): Calculated vs. observed piezometric levels results

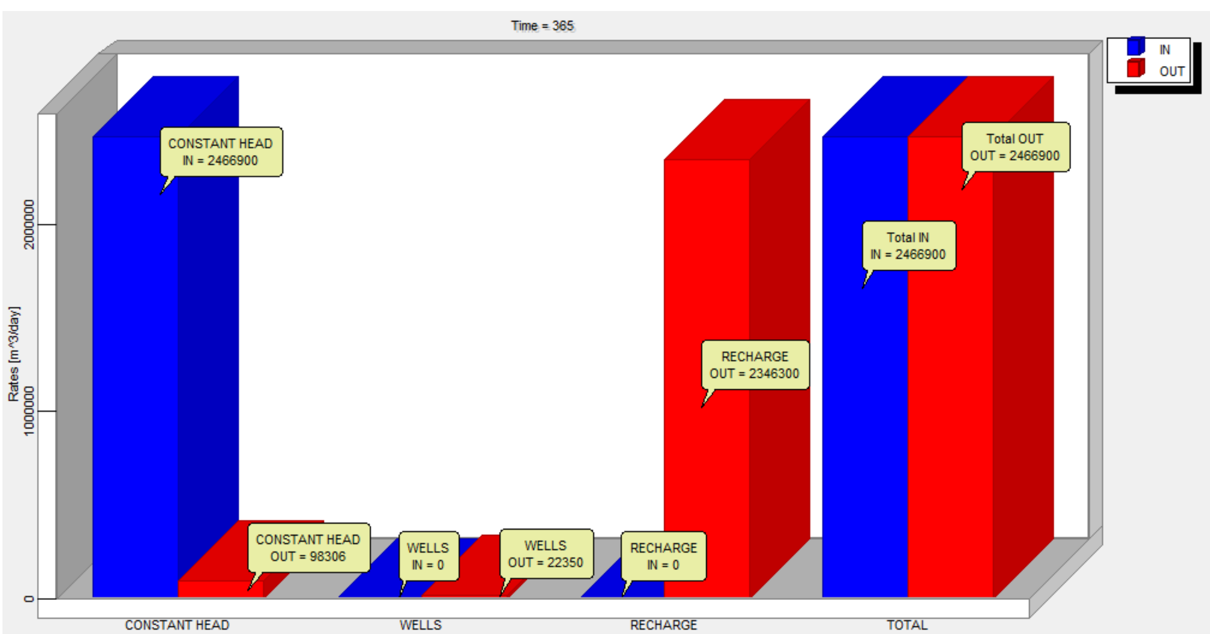

Figure 8: The water budget after model calibration and verification

3.2 Pollutant Transport Results

The groundwater movement was found to move from the industrial-Domestic and fuel areas towards the city wells field with velocities ranges 3.2e-6 m/s (0.28 m/d) and 1.4e-5 m/s (1.2 m/d), with average velocities = 0.74 m/d. An approximate distance between the center point of the pollution sources and the wells field = 32,800 m. The capture area for the wells field was determined by a rectangle (Y = 9155 m, X = 12000 m). This means that the number of days ´for pollutant transport ranges between 117000 and 27300 days (or average 72,000 days). This was checked through the model by applying number of particles around the wells field and studying its backward movement (to get the directions and time which move from), also some other particles were applied at the area of pollution source to study its forward movement.The introduction of particles at the point of water withdrawal wells and an analysis of the model for the study of backward movement punctuate the beginning of pollutants and the time of arrival of the places water withdrawal.Figure (9) shows Capture zone for 1000 days (particles circular path lines backward) and figure (10) shows Capture zone for 10,000 days.Figures A-1 to A-5 show the pollutant transport in a forward movement from the pollution source towards the wells field. The model showed a good agreement with the manual calculations of the reaching time. It showed that around 60,000 days the pollutant will approach to the city supplying wells.

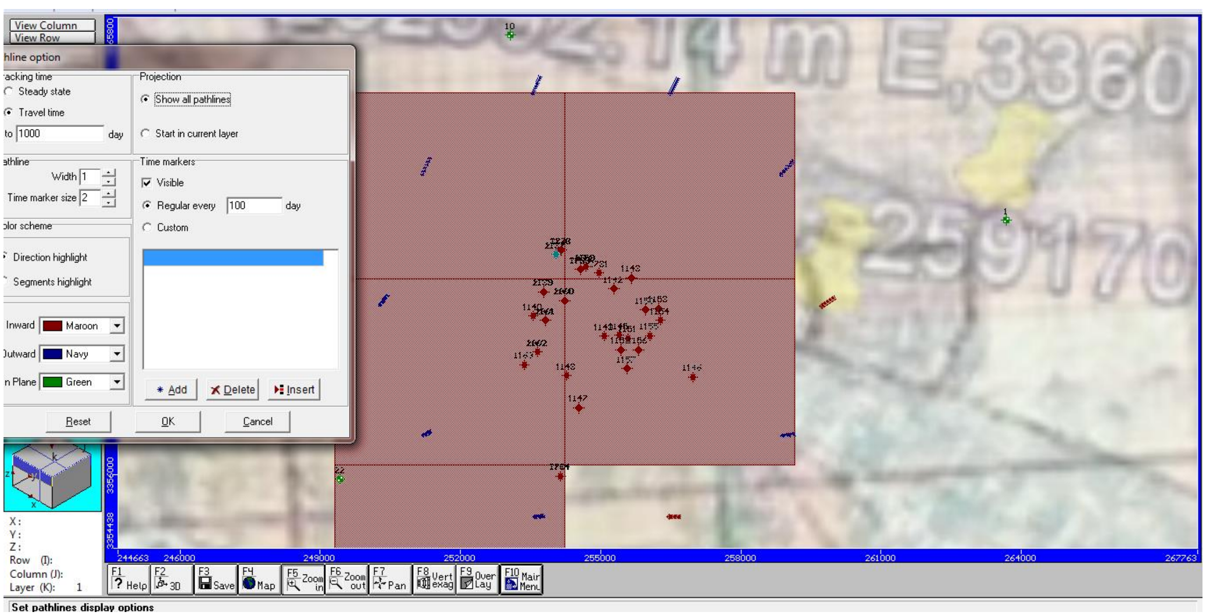

Figure (9): Capture zone for 1000 days (particles circular pathlines backward) –increment 100 days

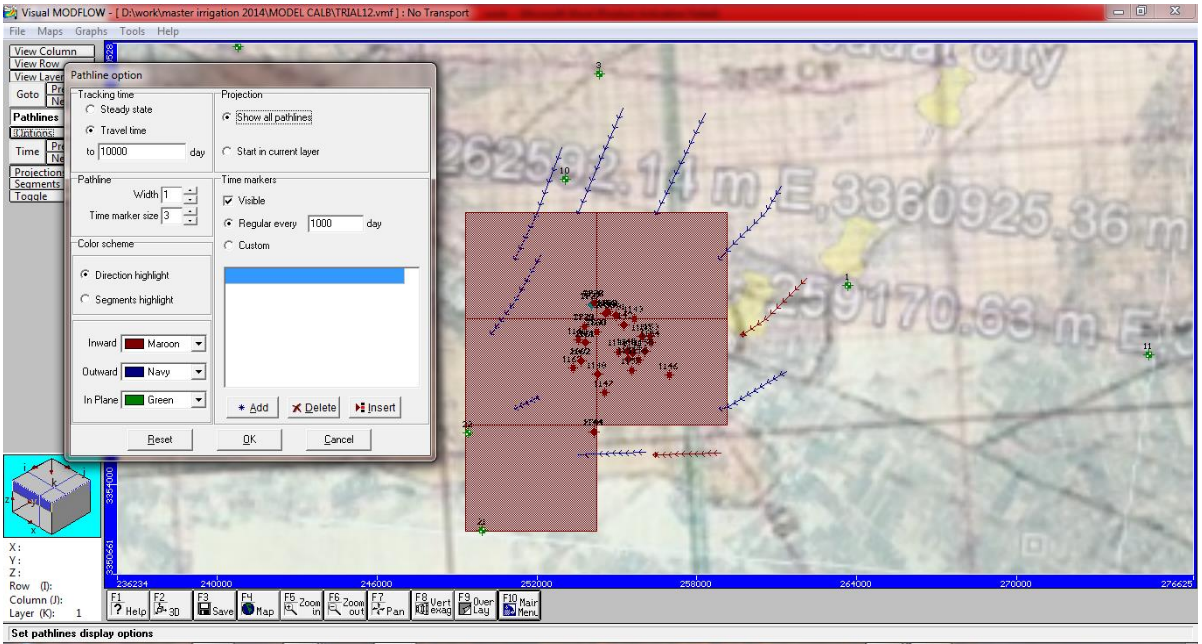

Figure (10): Capture zone for 10,000 days (particles circular path lines backward).

4. Discussion

4.1 Conclusions:

-The model showed that the groundwater flow moves from the pollution areas in the direction of the wells field with very small values of velocities, which takes a long time around 60,000 days. However there is population increase and uncontrolled activities for building up many new wells in the way from the pollution source and the wells field which will absolutely affect the public health adversely.

- A comparison between the results of the model calibration and the provided data by the Research Institute of Groundwater (RIGW) about the wells total production it was confirmed that there are many unregistered production wells with the government agencies and the model could estimate the actual daily discharge. The uncontrolled process of pumping wells can increase the pollutants transport velocities.

4.2Recommendations:

All unofficial pumping wells should be registered by the authorities and recording their data in order to control their rates and quality with respect to the transport of pollutants.

Observation and monitoring wells should be distributed around the city wells field and checked regularly.

All the leakage sources of the sewer systems in the industrial, domestic and fuel areas should be fixed.

A good management should be done to link between the city various activities such as industry, agriculture and water consumption.

Competing Interests The authors declare that they have no competing interests.

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Appendix: Figures of pollutant transport progress with time

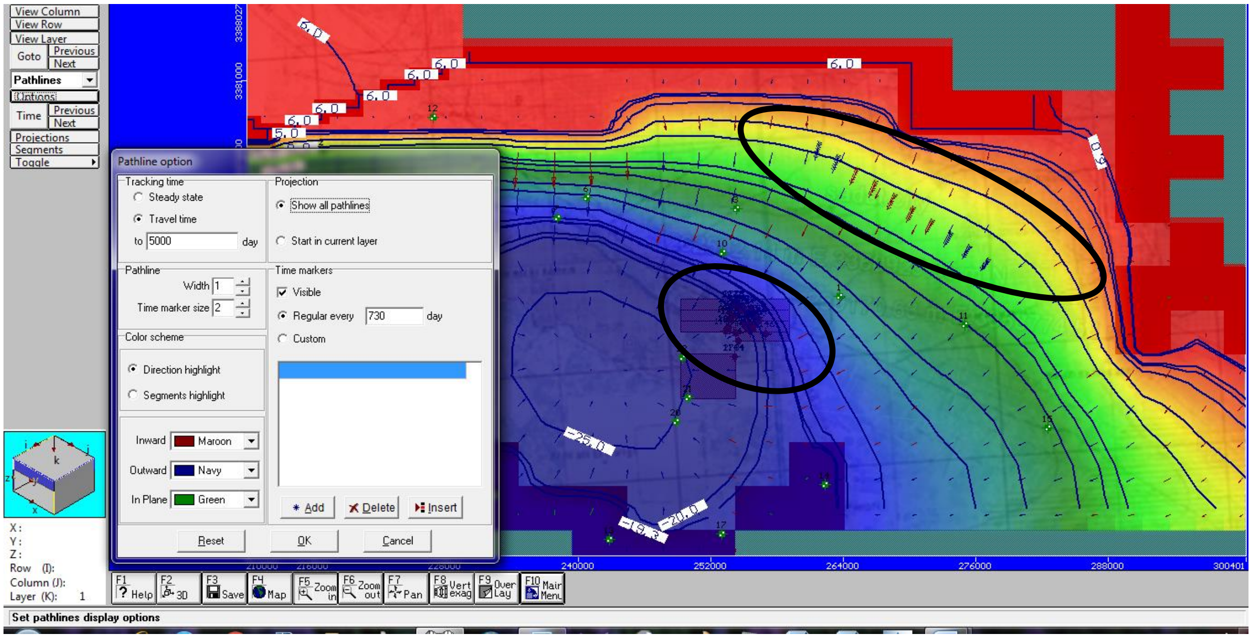

Figure A-1: forward movement after 5000 days, with time interval 730 days

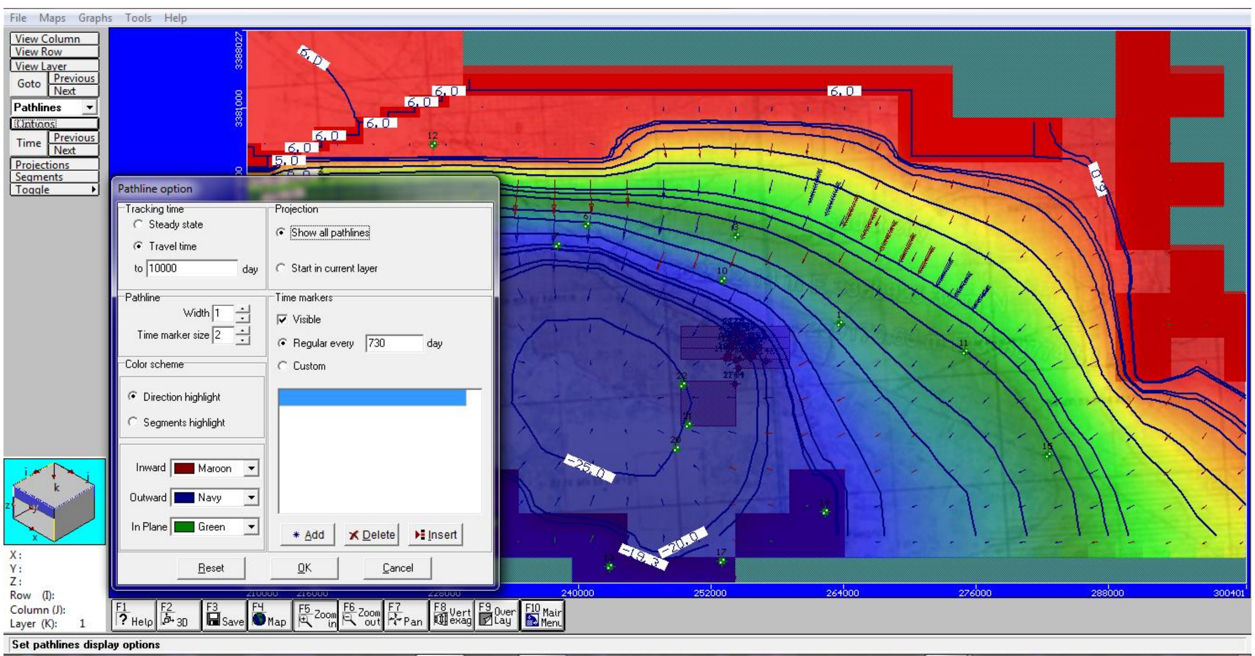

Figure A-2: forward movement after 10,000 days, with time interval 730 days

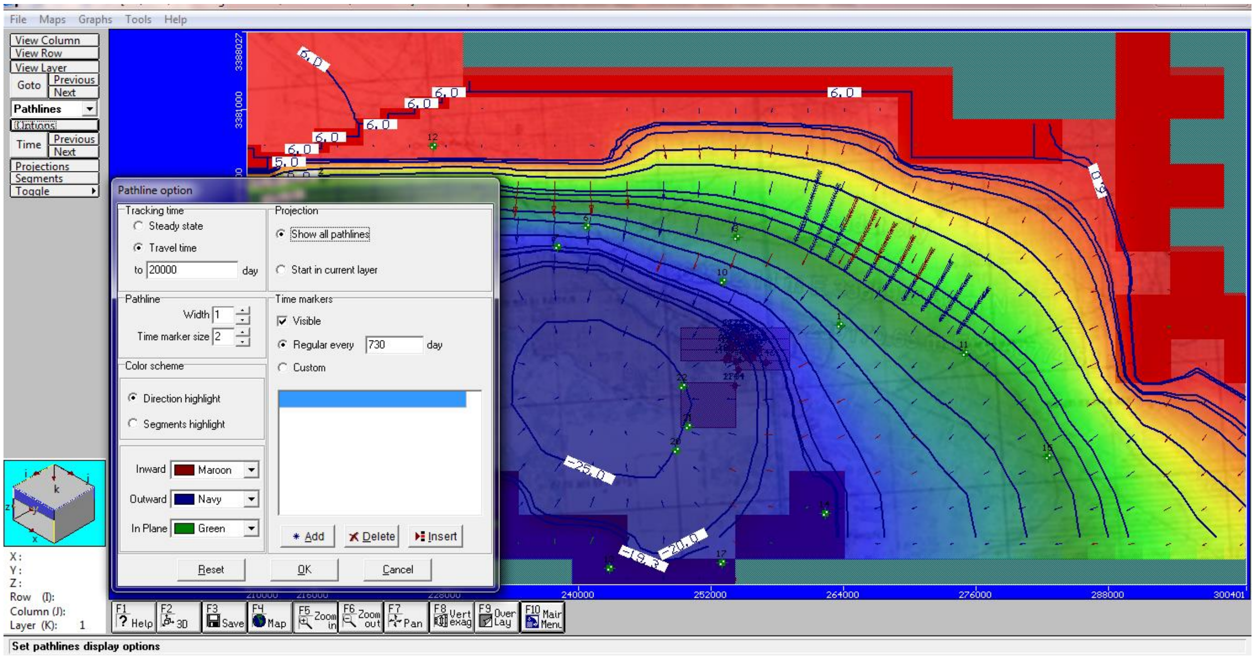

Figure A-3: forward movement after 20,000 days, with time interval 730 days

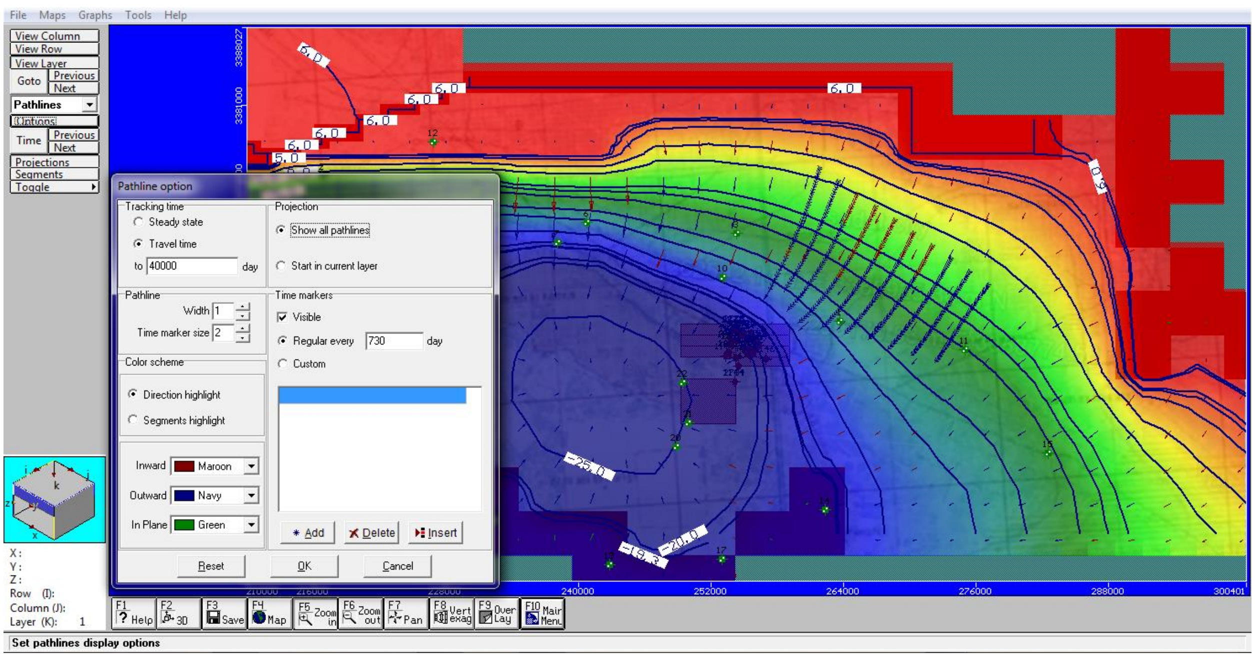

Figure A-4: forward movement after 40,000 days, with time interval 730 days

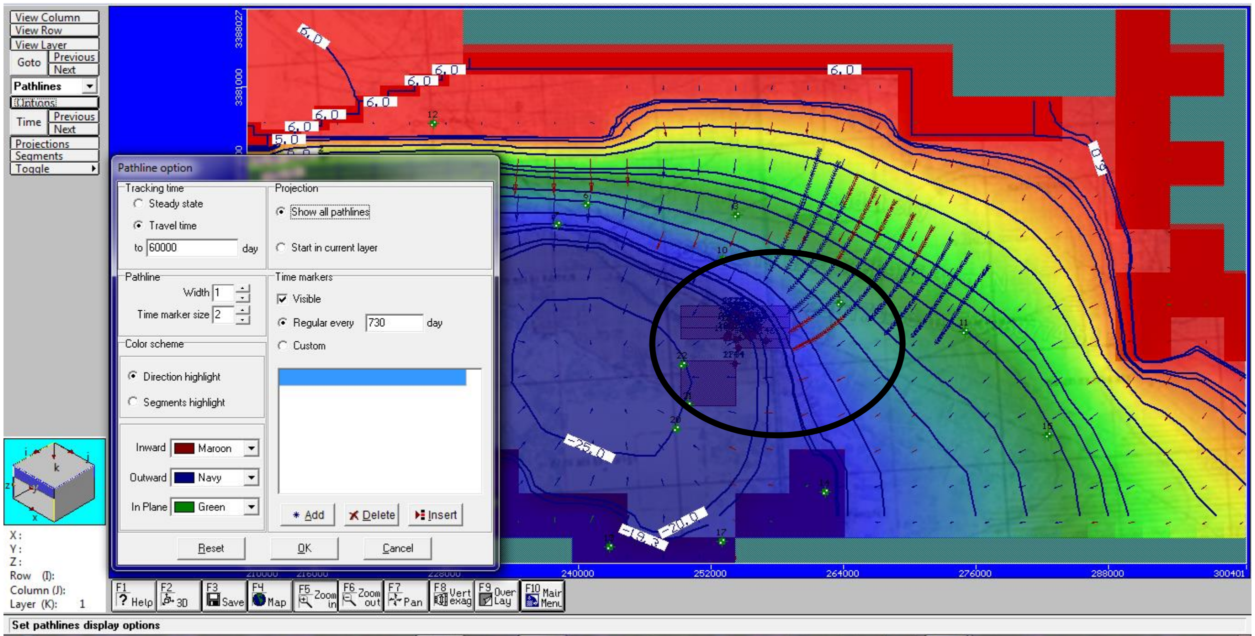

Figure A-5: forward movement after 60,000 days, with time interval 730 days