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# Modeling Groundwater Flow and Solute Transport at Azraq Basin Using ParFlow and Slim-Fast

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## ABSTRACT

Azraq basin, being one of the largest basins in Jordan and a viable drinking water resource, witnessed a dramatic increase in water demand over the past four decades. This led to an over-abstraction from this aquifer, which in turn resulted in deterioration of its water quality. To better manage and sustain this and other aquifers, new elaborate computer codes, called ParFlow and Slim-Fast, have been used to simulate groundwater flow and contaminants' transport at Azraq basin. ParFlow is a portable and parallel processing simulator, designed for modeling multi-phase fluid flow in 3D heterogeneous porous media. This code possesses a local mesh refinement capability, uses site topography and subterranean formations and offers a variety of numerical methods for various aspects of numerical simulation, while Slim-Fast uses the random walk method to solve sub-surface transport problems of multi-phase, multi-constituent contaminant mixture. Slim-Fast was written specifically to exploit a quasi-analytical formulation to find a rapid solution for the advection transport. These codes provided means to predict the hydraulic head in the upper and middle aquifers, simulate the movement of Total Dissolved Solids (TDSs) in the upper aquifer and estimate the age of groundwater. Results from groundwater model showed that steady state drawdown at points of observation may reach 28 m, which exceeds the 15.3 m drawdown previously predicted by other formal studies. Contaminant transport model results indicated that the concentration of total dissolved solids is expected to increase slowly in the basin due to the movement of high-salinity water toward the pumping wells used for domestic purposes. Estimated values of groundwater age varied between 3000 and more than 50,000 years based on the flow direction.

**KEYWORDS:** Groundwater flow, Over-abstraction, Hydrochemical modeling, Numerical modeling, Groundwater age, Azraq basin, ParFlow, Slim-Fast.

## INTRODUCTION

Azraq basin is one of twelve major groundwater basins in Jordan. It is an inland closed basin that has been used to supply the three major cities in Jordan; namely, Amman, Irbid and Zarqa, with potable water. Initially, groundwater extraction rates were just enough to supply the city of Irbid with drinking water. However, increased demand on water in Amman and Zarqa forced the official entity in charge of water resources (herein the Water Authority) to drill new wells and withdraw groundwater at high rates. Also, the number of private wells, both legal and illegal, increased dramatically in the past three decades. Absence of full control on drilling and pumping water from private wells in addition to the high pumping rate from the Water

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Authority well field resulted in overexploitation of water storage and deterioration of water quality in the form of salinization. The total abstraction from the basin in the year 2001 was estimated at 57.7 MCM/year, which is far beyond the safe yield of the basin that was determined to be 30 MCM/year (Al-Hadidi and Subah, 2001). As a result of overexploitation, aquifer depletion and change in the levels of Total Dissolved Solids (TDSs) became a major concern, since brackish water is adjacent to the Water Authority well field.

Concerns about increasing salinity in the basin began to rise since the mid 1980s due to the presence of salt playa and effect of water pumping. Several studies were conducted to assess the severity of the problem. The works of Worzyk (1987), Al-Waheidi (1990), Ayed (1996), Jordanian Consulting Engineering (1997), Bajjali and Al-Haddidi (2005), Abu-El-Sha'r and Hatamleh (2007), El-Naqa et al. (2007) and El-Naqa (2010) showed that the water quality in Azraq basin is deteriorating. However, change in the water quality in the basin is occurring slowly and the increase in salinity due to pumping water from the Water Authority well field during the period from 1980s until late 1990s was not considered threatening (Dottridge and Abu-Jaber, 1999). Later, El-Naqa (2010) showed that salty water was initially trapped in the Qa'a area, then it started to move toward the well field.

Although Azraq basin has been the center of great attention by different researchers for estimating the aquifer potential or assessing current situation and potential future scenarios (Parker, 1970; Barber and Carr, 1973; Barber, 1975; Arsalan, 1976; Agrar and Hydrotechnick, 1977; Howard Humphry and Sons, 1978; Howard Humphry and Sons, 1982; Rimawi, 1985; WAJ, 1989; Al-Kharabsheh, 1991; Al-Momani, 1993; Ayed, 1996; UNDP and Azraq Oasis Conservation Project, 1996; Jordanian Consulting Engineering, 1997; Abu-Jaber et al., 1998; Salameh, 1998; Al-Khatib, 1999; Abdullah et al., 2000; Al-Kharabsheh, 2000; Al-Hadidi and Subah, 2001; Abu-El-Sha'r and Hatamleh, 2007; Abu-El-Sha'r and Rihani, 2007), modeling groundwater flow for the entire basin was first introduced by Al-Hadidi and Subah (2001) using Modflow PM5. Later, Abu-El-Sha'r and Rihani (2007) introduced another study covering the entire basin using ParFlow simulator to model groundwater flow with the same grid and input data used in the previous study. Abu-El-Sha'r and Rihani (2007) predicted a higher maximum drawdown than the maximum drawdown of 15.3 m predicted by Al-Hadidi and Subah (2001). Difference between the two models is expected to be related to the way both codes used to solve the numerical problem.

Simulation of the solute transport and salinity problem in Azraq basin was conducted by several studies mainly using ModFlow and MT3D (Azraq Oasis Conservation Project, 1996; Jordanian Consulting Engineering, 1997; Abu-El-Sha'r and Hatamleh, 2007). However, these studies considered only the central section of the basin and an overall understanding of the entire basin quality and water movement is needed for managing and evaluating the water crisis in the basin and making appropriate decisions. In the work presented herein, groundwater flow and the movement of total dissolved solids for the entire upper aquifer at Azraq basin have been modeled using the high performance computing techniques employed by the computer codes ParFlow and Slim-Fast, respectively, with the input data and model grid provided by the Ministry of Water and Irrigation (MWI). Also, the water trip from source to sink and groundwater age have been investigated using the contaminant transport code Slim-Fast.

## Location and Topography

Azraq basin lies in the northeastern part of Jordan. It extends from 250 to 400 Palestinian Grid East and from 55 to 230 Palestinian Grid North (geological coordinate system used in Mandatory Palestine). Previous studies estimated its area as 12,710 km$^2$, while Al-Hadidi and Subah (2001) estimated it as 17,000 km$^2$. Most of this area lies within the Jordanian borders, about 5% of this area is located inside Syria and around 1% is inside Saudi Arabia. Figure 1 shows the location of the basin relative to Jordan and its aerial extent. Topography of the basin varies from 500 m above mean sea level (m.s.l.) at Azraq Qa'a, center of the basin, rising to 900 m (m.s.l.) in the south, east and west reaching 1550m (m.s.l.) in the north at Jebel Druze.

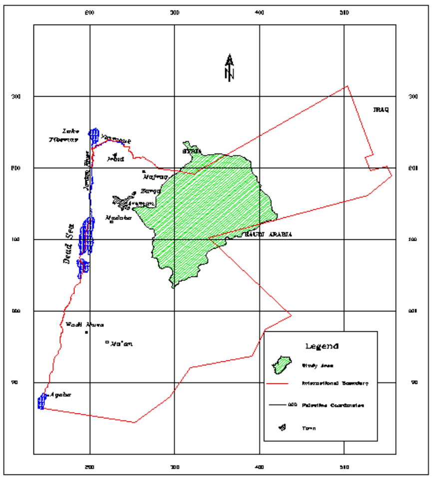


**Figure (1): Location of Azraq basin (Al-Hadidi and Subah, 2001)**

## Hydrogeology

Azraq basin consists of three overlain aquifers. First, the upper aquifer (B4/B5) is a chalky limestone with basaltic areas aquifer. It is an unconfined aquifer except at the middle (at Azraq Qa'a) and is considered the main source for drinking and irrigation water in the area. The upper aquifer is basically a closed basin system bounded by groundwater divides and a limit of saturation in the west. Second, the middle aquifer (A7/B2), which is a confined aquifer formed from limestone formations and separated from the upper aquifer by a bituminous marl aquiclude (B3). Third, the lower aquifer (K1/K2), which is also a confined aquifer formed from sandstone formations and separated from the middle aquifer by an aquitard (A1/A2) dominated by marl, limestone, dolomite and shale. Depth of the middle and lower aquifers varies between 400m and 3000m. Although a few wells have penetrated to the middle aquifer, these aquifers are still unexploited.

## Hydrochemistry

This study will focus on the geochemical characteristics of the groundwater in the upper aquifer as obtained from available historic records. Data for the middle and deep aquifers is scarce. Ayed (1996) studied water samples from Azraq basin and divided them into four main groups (I, II, III and IV) based on their composition. These groups were formed as a result of the interaction of precipitation with the soil matrix. Group I: this group covers the central part of the western half of the basin. Water in this area is characterized by low to medium salinity and moderate hardness; Group II: this group covers the northern part of the basin, mostly the basaltic formation. This area is characterized by low-salinity and moderately hard water. Group III was subdivided into III a, III b and IIIc. Group III a: this group covers the central part of the basin. This area is characterized by medium- to high-salinity and hard water. Chloride ions represent the major anion of the total anions, while sodium and potassium ions create the major cations; Groups III b and III c: these groups cover the southern part of the basin. This area is characterized by high-salinity and very hard water. Group IV: this group covers the area at the salt playa and its surrounding. Locations of these groups are shown in Figure 2.

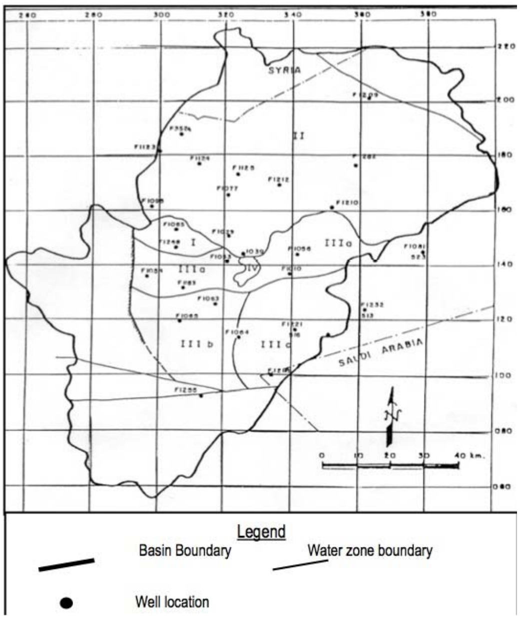


**Figure (2): Water group distribution in Azraq (Ayed, 1996)**

## Modeling

### Groundwater Flow Model

Data available about Azraq basin groundwater was limited to the upper and middle aquifers. Therefore, modeling herein is focused on the first two aquifers (the upper and middle aquifers). Accordingly, the domain representing the simulated area was divided into three overlain layers for groundwater flow: upper layer representing the B4/B5 formation (upper aquifer), middle layer representing the B3 formation (aquitard) and lower layer representing the B2/A7 formation (middle aquifer). These layers in addition to the surrounding boundaries (e.g. no-flow) are distinguished from each other by the hydraulic conductivity for each cell in its field. Hydraulic conductivity values for the layers are presented in Table 1. Water flow in the model starts from the domain boundaries and ends at the center of the domain, where springs and extraction wells are located.

**Table 1. Ranges of calibrated hydraulic conductivity**

| Formation | Hydraulic conductivity (m/day) |
|---|---|
| B4/B5 | 1.5-35 |
| B3 | 0.008 |
| B2/A7 | 0.09-2.0 |

The computer code used for simulating groundwater flow in Azraq basin is ParFlow. ParFlow is a new portable and parallel processing simulator, designed for modeling multi-phase fluid flow in 3D heterogeneous porous media. ParFlow operates in steady state saturated, variably saturated and watershed integrated modes. This code possesses a local mesh refinement capability, uses site topography and subterranean formations and offers a variety of numerical methods for various aspects of the numerical simulation (Ashby et al., 1994 and 1995). To reduce the complexity associated with communication routines needed to perform various iterative linear solver operations, ParFlow uses a multi-grid pre-conditioned conjugate gradient solver and a Newton-Krylov nonlinear solver. Therefore, ParFlow is considered suitable for modeling large-scale hydrological and hydrogeological problems on various computer platforms (Maxwell et al., 2016).

### Governing Equation

The mathematical background for the simulation in ParFlow is based primarily on the Richards equation with steady state groundwater flow in saturated porous media, described as follows (Maxwell et al., 2016):

$$S(p)S_s\frac{\partial p}{\partial t} - \frac{\partial(S(p)\rho(p)\varphi)}{\partial t} - \nabla.\big(K(p)\rho(p)(\nabla p - \rho(p)\vec{g})\big) = Q \qquad (1)$$

where:

p is the pressure-head of water [m], S is the water saturation, $S_s$ is the specific storage coefficient [$m^{-1}$], φ is the porosity of the medium, K(p) is the hydraulic conductivity tensor [m/d] and Q is the water source/sink term [$m^3$/d] (which includes wells and surface fluxes).

### Model Building and Calibration

The 3D grid of the domain for the simulation using ParFlow consisted of 75 columns, 85 rows and 100 layers to cover the entire domain, dividing it into uniform rectangular cells. Each cell has a dimension of 2000m, 2000m and 37.66m in the x, y and z coordinate, respectively. Figure 3 shows the top view of the grid system used and the active and inactive cells.

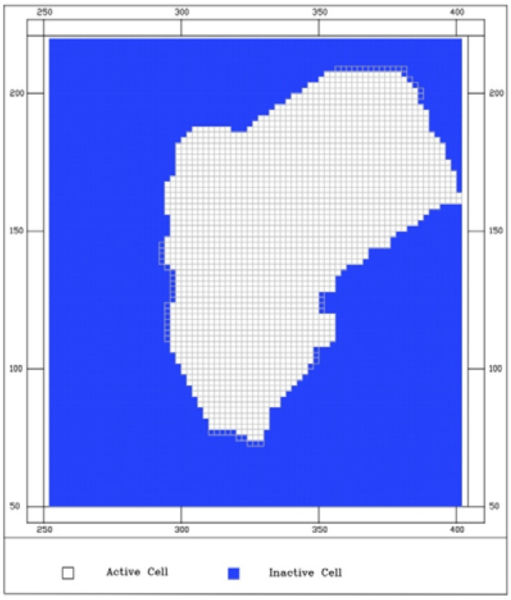


**Figure (3): Plan view of the grid system**

The three-dimensional shape of saturated zone in Azraq basin was sculptured within the domain geometry by defining areas with very low hydraulic conductivity ($10^{-6}$ m/day) that surround the active cells. Furthermore, different geological formation layers within the active cells (B4/B5, B3 and A7/B2) are specified using the topography and base contour maps.

Two types of boundary condition at the faces of the domain box have been used in the groundwater flow model: no-flow condition and constant head condition. These faces are referred to in ParFlow as *Patches*. Each patch is given a unique name in the model and for simplification, it is given a name according to its position to the viewer: front, back, right, left, top and bottom. Constant head pressure was assigned at the front (south) and back (north) patches with a value of 550 m and 590 m, respectively and no-flow condition was assigned to the remaining patches: right (west), left (east), top and bottom.

Recharge and discharge zones of the base flow have been specified by nine source/sink boxes, denoted as *Phase sources* in ParFlow code. Four of these phase sources were outflow, two are located in the middle of the basin representing Azraq Qa'a and the springs, while the other two stand for recharging Sirhan basin (south of the Azraq basin). The remaining phase sources stand for recharging the basin from north, northeast, west, southwest and south of the basin.

Through the years, more than 1,100 wells have been drilled in Azraq basin. By now, about 550 active wells are discharging water from the upper aquifer. Extraction of water from the remaining wells was stopped because of either damage which occurred to the pumping system or deterioration of groundwater quality in the well vicinity. Average pumping from the upper aquifer is estimated to be around 50 MCM/year. In this study, pumping from the wells is grouped into cell pumping wells according to their location in the grid system. Total pumping of each group is summed and set for the location of mid-point of the cell holding these wells.

Model calibration to match hydraulic head in the model with the actual hydraulic heads in the basin was primarily based on changing the hydraulic conductivity in the flow field. The used values of hydraulic conductivities were close to the existing conditions as provided by the soil drilling logs and geological formation maps. Results of calibrating hydraulic conductivity for the model are shown in Figure 4. Numerical values were also obtained for four observation wells located in the center of the basin and compared with their image location in the ParFlow model (Table 2). Calibrated heads from ParFlow for the upper and middle aquifers are shown in Figures 5a and 5b, respectively.

**Table 2. Observed head vs. calibrated head**

| Observation well | Observed head (m) | Calibrated head (m) | Difference (m) |
|---|---|---|---|
| F1022 | 507.0 | 507.84 | 0.48 |
| F1043 | 512.0 | 510.46 | 1.54 |
| F1060 | 512.0 | 511.43 | 0.57 |
| F1280 | 510.0 | 505.52 | 4.48 |

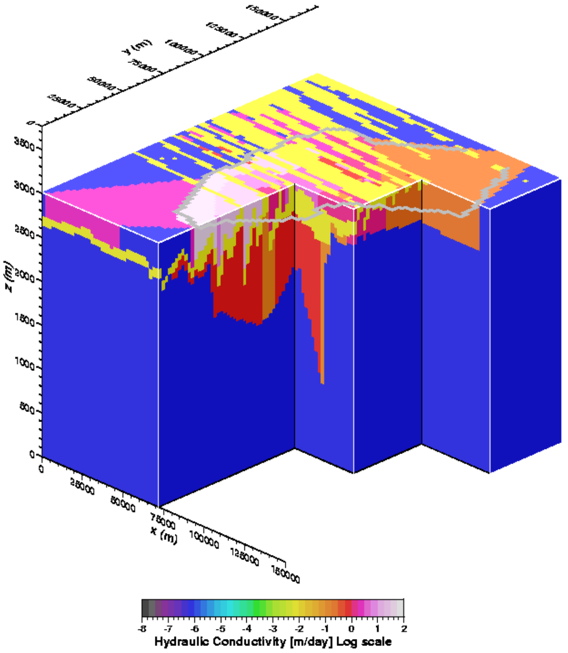


**Figure (4): 3D view of the hydraulic conductivity distribution**

## Flow Model Prediction

The calibrated model was used to estimate future drawdown in the water table. Predictions were made for the condition of maintaining a pumping rate of 50 MCM/year. Results obtained from ParFlow are presented in Table 3. An average value of 50 MCM/year was used as a continuous pumping rate for future conditions based on the official records of MWI. It is noted that the maximum drawdown in the upper aquifer may reach 28 m. Figures 6a and 6b show the predicted hydraulic heads for the upper and middle aquifers, respectively.

**Table 3. Estimated drawdown using calibrated model**

| Well ID | Simulated potential head before pumping (m) | Simulated potential head after pumping (m) | Expected drawdown (m) |
|---|---|---|---|
| F 1022 | 507.84 | 496.72 | 11.12 |
| F 1043 | 510.46 | 482.39 | 28.07 |
| F 1060 | 511.43 | 483.56 | 27.87 |
| F 1280 | 505.52 | 488.84 | 16.68 |

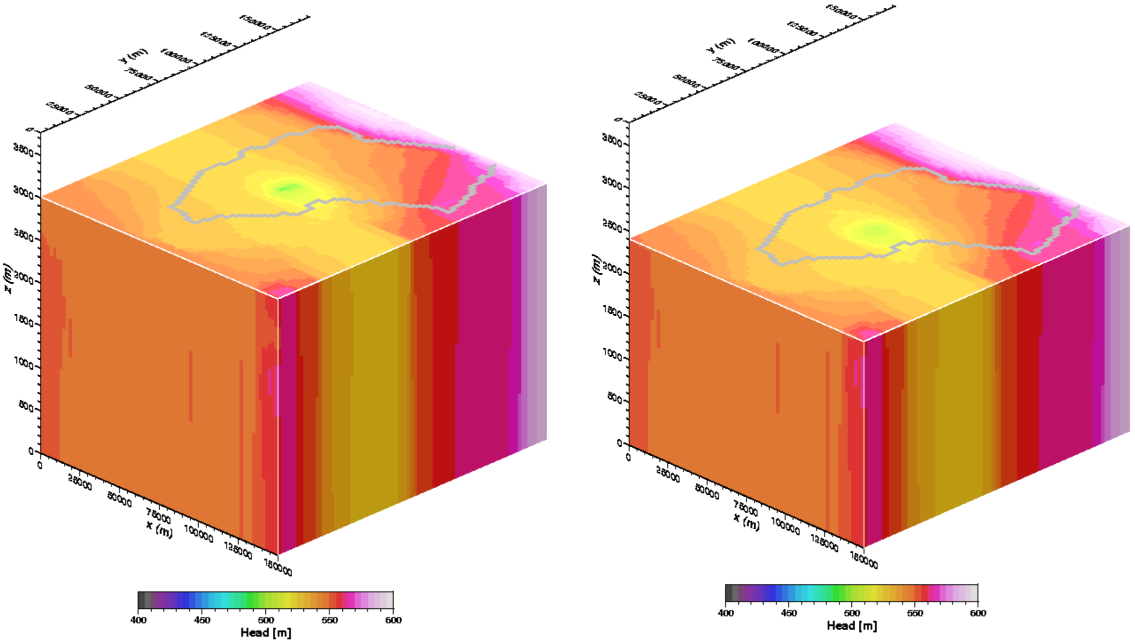
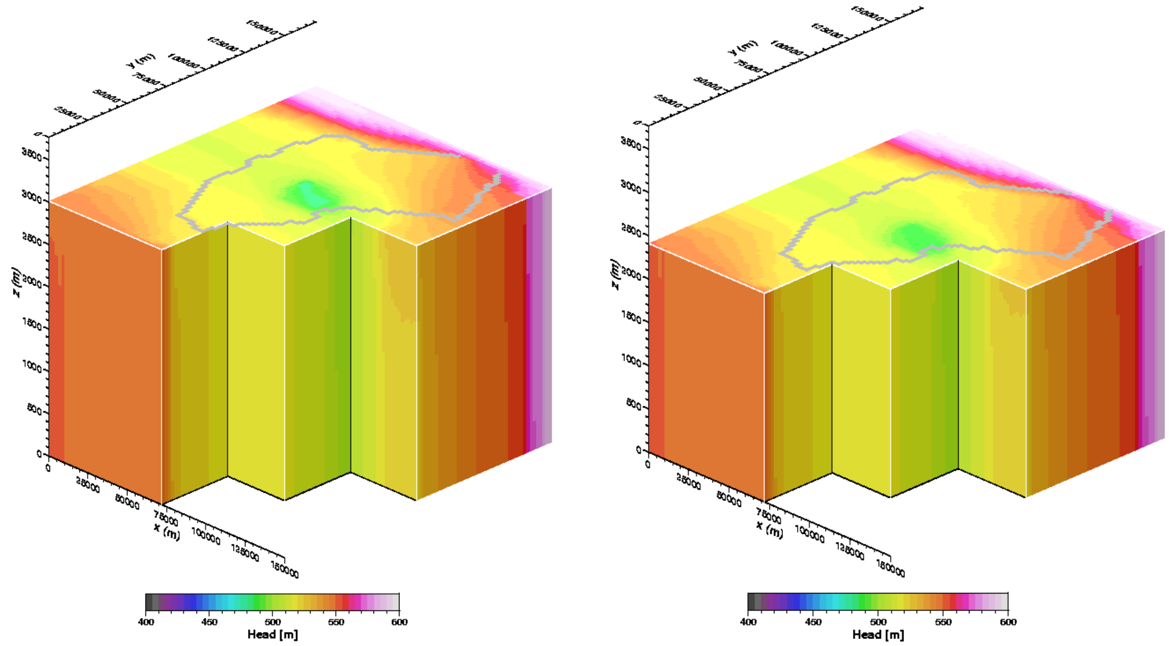


**Figure (5): ParFlow hydraulic head for: a) the upper aquifer and b) the middle aquifer**



(a) (b)

**Figure (6): ParFlow hydraulic head after pumping 50 MCM/yr: a) for the upper aquifer and b) for the middle aquifer**

## Transport Model

The transport model was made for two purposes: first, to simulate the movement of total dissolved solids (TDSs) in the basin by tracking it as a single constituent from its possible origin to its final destination; second, to estimate the time of travel of water from sources to sinks. In this study, transport modeling was applied to the upper aquifer, since the middle aquifer is still unutilized and a few wells actually penetrated the middle aquifer. However, the effect of the middle aquifer on groundwater quality of the upper aquifer was considered by assuming constant TDS concentration uniformly distributed over the middle aquifer.

Sources of TDS in the groundwater basin are considered to originate mainly from geological formations, salt evaporators or leakage from another aquifer. Sinks are the discharging zones in the aquifer (i.e., well field, springs). Therefore, TDS movement is simulated by assuming TDS as a mass of particles moving from point of formation and tracking its position within the porous media as it moves forward to the lower hydraulic head area. Since motion of particles in the porous medium is governed primarily by the hydraulic characteristics of the system, results of groundwater flow modeling obtained by ParFlow are used as input data for the transport model, Slim-Fast. Moreover, dispersion properties of the total dissolved solids, which are considered as an influential factor in particle movement beside the hydraulic head and flow velocities, are employed in the transport model.

Slim-Fast is an improved version of Lagrangian-based particle tracking code called SLIM that uses the random walk method to solve sub-surface transport problems of multi-phase, multi constituent contaminant mixture. Slim-Fast was written specifically to exploit a quasi-analytical formulation to find a rapid solution for the advection transport. This solution method uses linear velocity interpolation of boundary fluxes to solve for particle streamlines in each grid block. Dispersion phenomenon, however, is simulated using random walk method with bi-linear velocity interpolation as the most accurate method of solving for the advection-correction and random-walk dispersion (LaBolle et al., 1996). With this code, tracking TDS particles in the groundwater is like tracking a group of ping-pong balls in a river. Slim-Fast also permits "splitting" of the TDS particles, allowing researchers to track increasingly dilute TDS concentrations.

### Governing Equation

The transport model is based on single continuum conceptualization for chemical transport in saturated porous media. The mass balance equation for the chemical substance considers physical advection processes, dispersion and diffusion effects, recharge or extraction mechanisms, reactive transport in porous media and aqueous complexation. Slim-Fast uses a simplified version of the mass balance equation in the form (Maxwell, 2010):

$$\frac{\partial {c^T}_j}{\partial t} + \nabla.\left(\frac{v c_j^T}{R_j}\right) - \nabla.\left(\varphi D.\nabla \frac{{c^T}_j}{\varphi R_j}\right) = -\lambda_j c_j^T + \lambda_k c_k^T - R_j^{min} - s_j^{fm} - \frac{c_j^T}{\varphi R_j} \sum Q_j \delta(x - x_w)\delta(y - y_w)\delta(z - z_w) \tag{2}$$

where:

$c_j$ is the total concentration of species j, v is the groundwater velocity, φ is the porosity, D is the hydrodynamic dispersion tensor, $R_j$ is the retardation coefficient and partitioning among the mobile and immobile fractions of species j, $R^{min}{}_j$ is the rate of loss or gain of aqueous mass from mineral dissolution or precipitation reactions, $s^{fm}{}_j$ is the rate of loss or gain of aqueous mass in a fracture regime to and from the matrix regime, $\lambda_j$ is the radioactive decay rate of species j, $Q_w$ is the volumetric rate of pumping from well at location ($x_w$, $y_w$, $z_w$) and δ is a Dirac function.

Since Slim-Fast uses particle tracking to solve the mass balance equation, the total concentration is approximated by a finite system of N particles (Maxwell, 2010):

$$c_j^T(x,t) = \sum_{p=1}^{N_j} m_p \delta\left(x - X_p(t)\right) \tag{3}$$

where:

$m_p$ = mass and $X_p$ = particle location.

The movement of the particles is based on random-walk algorithm (Maxwell, 2010):

$$X_p(t + \Delta t) = X_p(t) + [v + \nabla.D' + D'.\nabla(ln\varphi_w)]\Delta t + B.Z\sqrt{\Delta t} \tag{4}$$

where:

Xp is particle location, Δt is a time step, B is a tensor defining the strength of dispersion and Z is a normally distributed random variable.

### Model Building and Calibration

The model domain and grid system used in the transport model are the same domain and grid used in the flow model. Therefore, the domain that covers the saturated area of the basin is estimated as 12,710 km$^2$. Grid system is also divided into 75 columns, 85 rows and 100 layers. Dimensions of the cells are 2000 m, 2000 m and 37.66 m, respectively. The physical characteristics of the flow model are employed by Slim-Fast just to calculate the flow velocity in the porous medium.

Addition of contaminants to the system in Slim-Fast is made in form of particles distributed over a specified volume or length. Each particle originating from the same source has the same amount of mass. Injection of particles is carried out by three types: well injection, box pulses and index files.

Release of total dissolved solids in the upper aquifer in Azraq basin is believed to originate from different sources: geological formation, salt playas and leakage from the middle aquifer. Sinks of the total dissolved solids are defined as the result of well discharge and springs. To cover all possible TDS sources in the upper aquifer of Azraq basin, TDS sources in Azraq basin were identified as six possible sources, which are presented in Table 4.

**Table 4. Possible TDS sources in the upper aquifer**

| Symbol | Source |
|---|---|
| A | Geological formations containing groups IIIb & IIIc |
| B | Geological formations containing group IIIa |
| C | Geological formations containing group II |
| D | Geological formations containing group I |
| E | Salt playa (Sabkha) |
| F | Leakage from the middle aquifer |

Groundwater within the geological formations which existed in the upper aquifer has been recognized to have different contents of total dissolved solids depending on the chemical composition of each formation. Basalt formation that covers the northern part of the aquifer contains groundwater with low salinity. The values of salinity ranged between 350 and 700 mg/L in 1982 (Humphreys, 1982) and from 515 to 946 mg/L in 1996 (Ayed, 1996). On the other hand, the B4/B5 formation, which is a combination of chalky limestone deposits covering the center and southern part of the basin, contains groundwater with medium to high salinity depending on the prevailing formation. Overall salinity ranged between 350 and 5,000 mg/L in 1982 (Humphreys, 1982) and from 787 to 2075 mg/L in 1996 (Ayed, 1996).

Salt playa, which is produced at the bottom of the basin as a result of the evaporation of collected runoff water and rising groundwater, has a great impact on the quality of groundwater. Although the thickness of these areas does not exceed a few meters (usually 2m), its influence is mediated by the infiltrated water and water circulation, as it carries large TDS amounts in its way down. Consequently, a massive increase in TDS concentration occurs in the upper aquifer depending primarily on the flow velocity.

Movement of groundwater between the middle aquifer and the upper aquifer is still undefined in terms of quantities and locations. However, different studies presented estimations of the leakage quantities based on the results of flow models used. In this study, an aquitard layer between the upper aquifer and the middle aquifer is assumed without cracks. Movement of groundwater and TDS migration through this layer depend on layer thickness, hydraulic conductivity of the layer and the potential head across the layer thickness. Although Jordanian Consulting Engineers (1997) reported a TDS concentration range between 4,300 and 36,500 mg/L with an average of 16,000 mg/L, distribution of TDS concentration in the middle aquifer is unknown, because a few wells have actually penetrated to the middle aquifer. Therefore, a constant concentration of 16,000 mg/L uniformly distributed over the middle aquifer has been assumed.

Abstraction wells distributed over the entire basin act as a TDS sink in the sense that they remove part of the TDS mass outside the system. However, they can affect the salinity fronts, causing retreat or advance in these fronts depending on the pumping rate and location relative to the formed fronts.

Calibration of the transport model was based on seven points in Azraq basin that represent existing wells by comparing the historical records for total dissolved solids in these wells with TDS values in their corresponding locations in the model. Accessible data for these wells covered the period until the year 2003. Figure 7 shows the location of wells used for transport model calibration.

Elements considered as the main parameters in the calibration phase are longitudinal and transversal dispersivity, initial concentration, loading of mass per grid block per time, time steps and number of particles per grid block. Results of calibration process are presented in Table 5 and Figures 8a, 8b and 8c. Following the transport model, the upper aquifer can be divided into five areas (A, B, C, D and E) according to the contents of total dissolved solids amounting to: 1300, 1050, 750, 330 and 3000 mg/L, respectively. The five areas and the corresponding TDS values obtained using this model were comparable to the measured values reported by Ayed (1996).

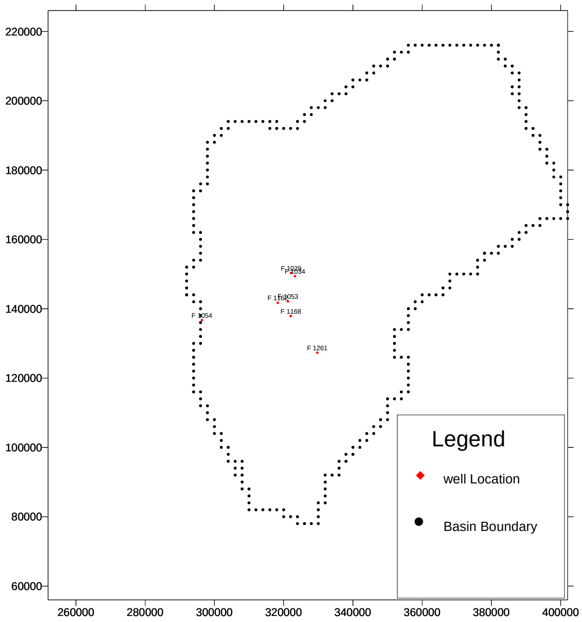


**Figure (7): Location of wells used for transport model calibration**

### Model Prediction

Model prediction of future response was made by running the calibrated model for 10, 20 and 30 years beyond the simulated period. Future predictions of Slim-Fast for TDS concentration for 2000s, 2010s and 2020s are presented in Table 6.

### Sensitivity Analysis

Sensitivity of the model was checked by changing one of the main parameters that control constituents' movement, while other parameters are kept constant, and its effect on the model solution is recorded. In this study, calibrated values for hydraulic conductivity, potential head and dispersivity are changed systematically within a specified range.

Calibration of the transport model indicated values for longitudinal and transversal dispersivity equal to 0.001 and 0.0001, respectively. For studying uncertainty of these values, longitudinal and transversal dispersivity values were changed between –3 and 3 orders of magnitude of the calibrated values. Variation of dispersivity values and its corresponding percent change in predicted TDS values are presented in Table 7.

It is noted that the developed model is sensitive to values of dispersivity at the locations of some wells and insensitive at the locations of other wells. It is also noted that the model diverges from actual data at high dispersivity values.

The calibrated potential head was changed between 70% and 130% of the original value. Table 8 shows variation of TDS prediction with changing values of potential head. It is noted that the model is very sensitive to the potential head at locations of high concentration and less sensitive at locations of low concentration.

The calibrated hydraulic conductivity values were changed between 70% and 130% of the original value, while the other parameters were held constant. Table 9 shows the variation in predicted TDS values with changing values of potential head. Sensitivity analysis shows great variation in predicted values of TDS transport in high TDS concentration areas with lower values of hydraulic conductivity. In addition, predicted TDS values in low TDS concentration areas become more sensitive with higher hydraulic conductivity value.

### Water Age

Determining how old the groundwater is and what route it followed during its movement are two main features that remark using Slim-Fast. As it applies the principle of random walk, it keeps records of particle location and time spent during particle journey. Using these records, flow path can be easily defined and stages of water travel can be clearly understood. Figure 9 shows the flow path that groundwater followed and the location of water since the time of entering the system. It can be seen that some particles have shorter paths than others, thus less time to exit the system. Moreover, for the same particle, it was found that time spent in some areas is longer than in others, which is justified by the variance of hydraulic conductivity and the potential head gradient in these areas.

**Table 5. Comparison between TDS actual data and TDS simulated data (Concentration in mg/L)**

| **Well ID** | **Actual data** | | | **Simulated data** | | | **Absolute change in predicted values %** | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **1970s** | **1980s** | **1990s** | **1970s** | **1980s** | **1990s** | **1970s** | **1980s** | **1990s** | **Ave.** |
| F 1029 | 300 | 313 | 392 | 303.33 | 365.49 | 398.44 | 1.11 | 16.77 | 1.64 | 6.51 |
| F 1034 | 320 | 355.2 | 383.9 | 302.61 | 342.39 | 377.23 | 5.43 | 3.61 | 1.74 | 3.59 |
| F 1053 | 700 | 721.9 | 752 | 709.22 | 775.61 | 797.14 | 1.32 | 7.44 | 6.00 | 4.92 |
| F 1054 | 300 | 331.2 | 425.6 | 314.70 | 379.77 | 418.43 | 4.90 | 14.67 | 1.68 | 7.08 |
| F 1162 | 700 | 768 | 780.8 | 698.35 | 761.35 | 776.78 | 0.24 | 0.87 | 0.52 | 0.54 |
| F 1168 | 1452.8 | 1451.9 | 1574.4 | 1452.73 | 1539.60 | 1569.81 | 0.00 | 6.04 | 0.29 | 2.11 |
| F 1261 | 997.1 | 1024 | 1050 | 986.39 | 1071.37 | 1084.35 | 1.07 | 4.63 | 3.27 | 2.99 |

**Table 6. Future prediction of Slim-Fast for TDS concentration for the periods 2000s, 2010s and 2020s (Concentration in mg/L)**

| Well ID | 2000s | 2010s | 2020s |
|---|---|---|---|
| F 1029 | 349.35 | 394.38 | 452.48 |
| F 1034 | 574.09 | 796.67 | 1024.59 |
| F 1053 | 826.70 | 836.30 | 857.92 |
| F 1054 | 464.88 | 545.13 | 645.28 |
| F 1162 | 797.78 | 798.72 | 815.87 |
| F 1168 | 1631.43 | 1719.48 | 1823.90 |
| F 1261 | 1112.74 | 1139.60 | 1172.74 |

**Table 7. Percent absolute change in TDS predicted values *vs.* change in dispersivity values**

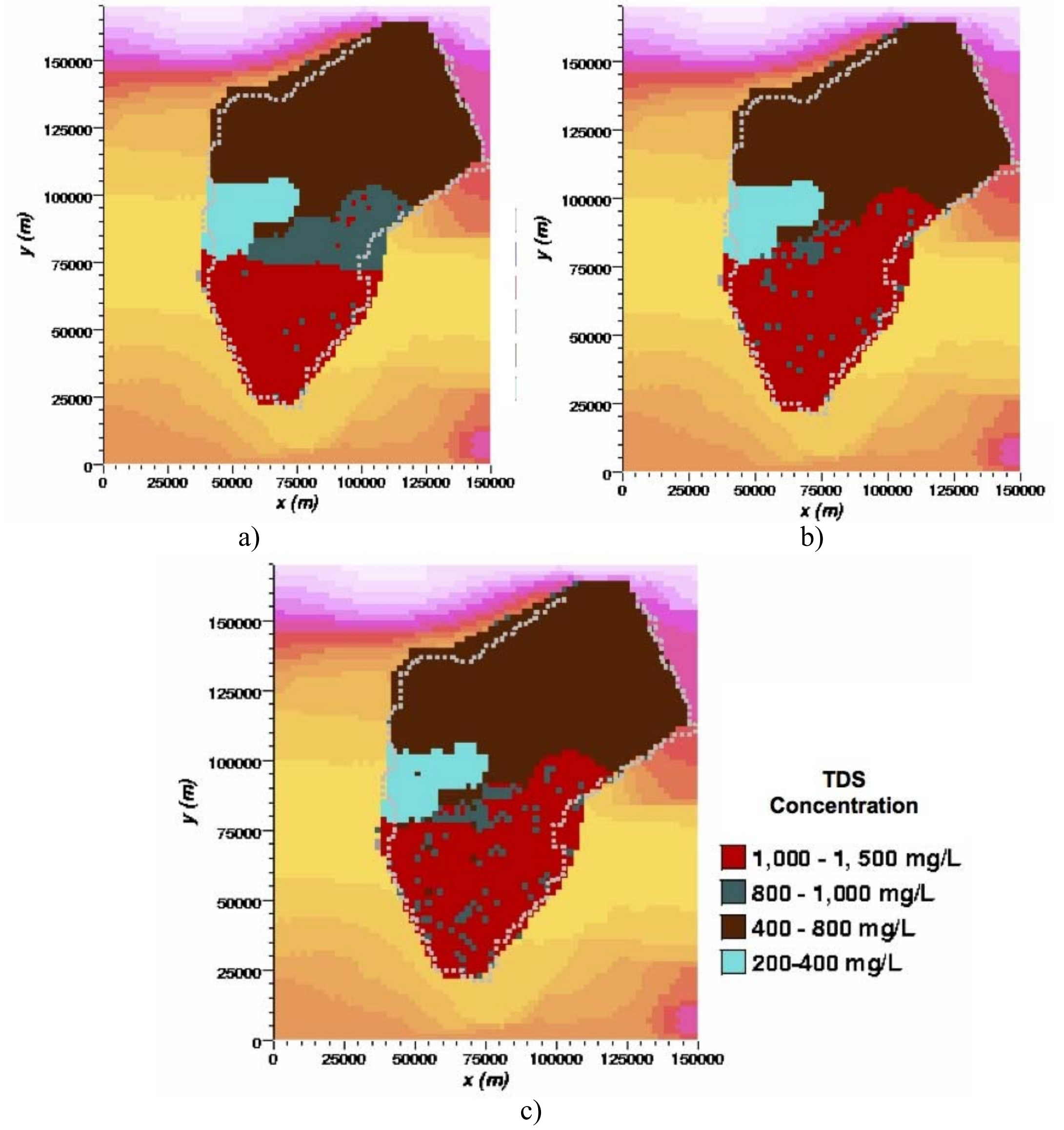
| **Well ID** | **Change of dispersivity in terms of order of magnitude** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **-3** | **-2** | **-1** | **0** | **1** | **2** | **3** |
| F 1029 | 6.43 | 6.35 | 6.43 | 6.51 | 6.21 | 12.98 | 21.92 |
| F 1034 | 3.59 | 3.52 | 3.67 | 3.59 | 3.94 | 3.65 | 21.01 |
| F 1053 | 5.05 | 5.05 | 9.95 | 4.92 | 10.11 | 9.70 | 11.28 |
| F 1054 | 7.08 | 7.08 | 7.08 | 7.08 | 7.08 | 6.90 | 15.41 |
| F 1162 | 0.25 | 0.48 | 0.31 | 0.54 | 0.47 | 0.96 | 6.07 |
| F 1168 | 2.21 | 2.21 | 2.16 | 2.11 | 18.25 | 18.28 | 18.80 |
| F 1261 | 2.94 | 2.94 | 2.94 | 2.99 | 2.99 | 2.89 | 2.09 |

**Table 8. Percent absolute change in TDS predicted values *vs.* change in potential head value**

| **Well ID** | **Change of potential head (%)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **-30%** | **-20%** | **-10%** | **0** | **10%** | **20%** | **30%** |
| F 1029 | 6.89 | 6.51 | 6.47 | 6.51 | 6.50 | 6.34 | 6.70 |
| F 1034 | 3.36 | 3.17 | 3.32 | 3.59 | 3.27 | 3.09 | 3.16 |
| F 1053 | 3.76 | 6.29 | 5.54 | 4.92 | 5.97 | 9.01 | 6.18 |
| F 1054 | 7.47 | 7.71 | 6.89 | 7.08 | 6.52 | 6.61 | 6.55 |
| F 1162 | 0.99 | 0.71 | 0.84 | 0.54 | 0.41 | 0.53 | 0.12 |
| F 1168 | 9.21 | 16.70 | 10.95 | 2.11 | 12.91 | 9.66 | 20.63 |
| F 1261 | 2.61 | 2.80 | 3.13 | 2.99 | 2.84 | 2.85 | 2.94 |

**Table 9. Percent absolute change in TDS predicted values *vs.* change in hydraulic conductivity**

| Well ID | Change in hydraulic conductivity (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | -30% | -20% | -10% | 0 | 10% | 20% | 30% |
| F 1029 | 7.26 | 6.85 | 7.07 | 6.51 | 6.53 | 6.06 | 14.52 |
| F 1034 | 3.15 | 3.37 | 3.04 | 3.59 | 2.96 | 2.94 | 2.96 |
| F 1053 | 4.27 | 5.65 | 6.29 | 4.92 | 5.37 | 9.25 | 9.18 |
| F 1054 | 6.63 | 7.21 | 7.71 | 7.08 | 6.71 | 8.49 | 9.57 |
| F 1162 | 1.06 | 0.77 | 0.84 | 0.54 | 0.24 | 0.46 | 0.19 |
| F 1168 | 5.43 | 3.89 | 17.56 | 2.11 | 18.78 | 2.87 | 20.03 |
| F 1261 | 2.42 | 2.61 | 2.99 | 2.99 | 2.94 | 3.09 | 3.13 |



a)

b)

c)

**Figure (8): Simulated TDS distribution in the upper aquifer at Azraq basin during the a) 1970s, b) 1980s and c) 1990s**

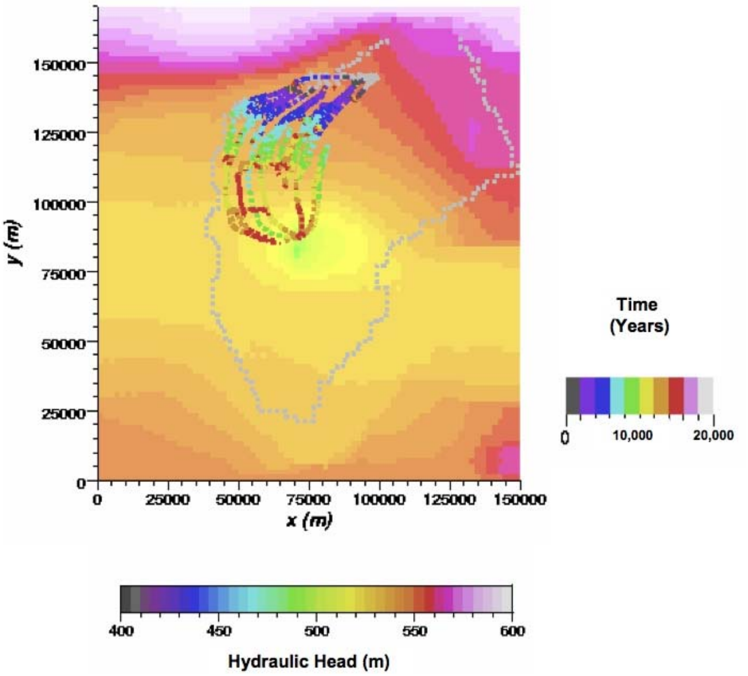


**Figure (9): Time elapsed for groundwater to flow from north towards the springs**

To determine the time it took groundwater to flow from boundaries to exit the system at the springs, a box pulse containing 50 particles was inserted at the location of phase sources with the same volume. Then, these particles were tracked in time until they reached the location of springs. Tracking particles' movement from each source showed that water age varies between 3,000 and 50,000 years as presented in Table 10. Besides, Figures 10 and 11 show the times elapsed during groundwater movement from western, eastern and southern phase sources. Results from the water age study were comparable to the findings of Rimawi (1985) and Al-Momani (1993), which estimated water age from 20,000 to 30,000 years.

**Table 10. Periods of time that groundwater took before leaving the system since its departure from the source**

| Water source | Time to reach springs (year) |
|---|---|
| North | 15,000 |
| East | More than 50,000 |
| South | 30,000 |
| West | 3,000 |

## CONCLUSIONS

Studying groundwater flow and total dissolved solids' transport using ParFlow and Slim-Fast has revealed a new set of speculations, explanations and may be facts based on the principles upon which these computer codes were built. However, it raised new questions regarding the accuracy of input data used and potential use of the results. Nevertheless, the following main conclusions can be made:

Results of the flow model presented in this study using ParFlow simulator indicate that steady state drawdown at the observation wells may reach a value of 28 m. This is much higher than the drawdown value of 15.3 m for 27 years of pumping predicted by the model based on Modflow PM5 used by MWI under similar conditions. Findings of the transport model Slim-Fast provided the means to divide the upper aquifer into five areas (A, B, C, D and E) according to contents of total dissolved solids. These values are: 1300, 1050, 750, 330 and 3000 mg/L, respectively.

Groundwater flowing in the hydrogeological system of Azraq basin is believed to be very old with an age ranging between 3,000 and 50,000 years depending on the origin of this water and the path line it followed during its movement. Groundwater flowing from north boundaries is estimated to be around 15,000 years old, while the age of groundwater from northeastern boundary is estimated at more than 50,000 years. Groundwater that flows from western boundaries is the youngest with an age of 3,000 years and groundwater age in the southern part takes an intermediate duration of about 30,000 years.

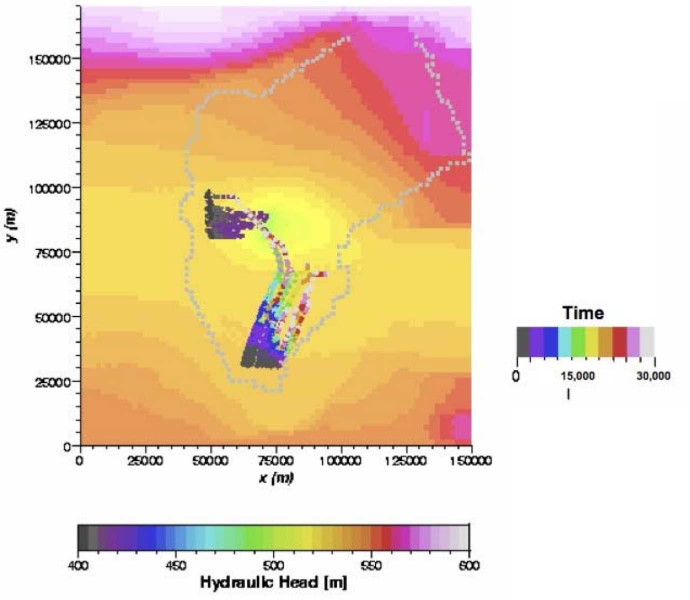


**Figure (10): Time elapsed for groundwater to flow from west and south to the location of the springs**

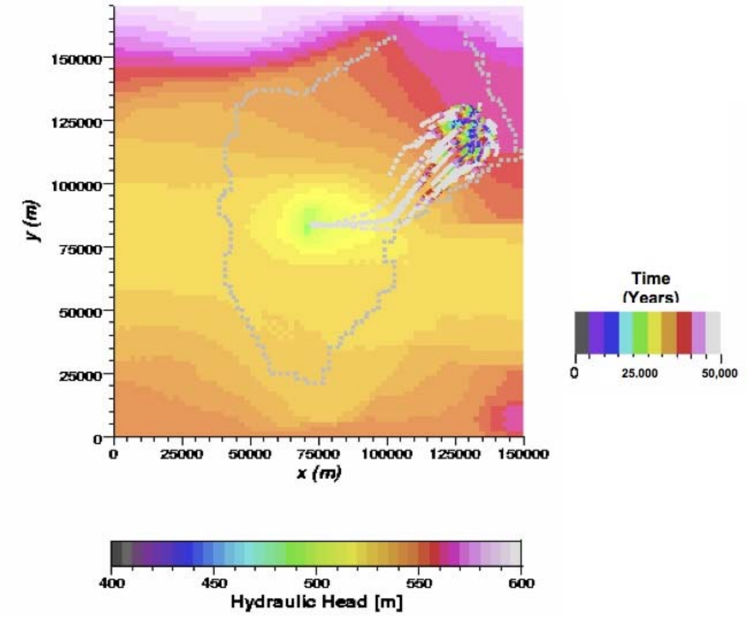


**Figure (11): Time elapsed for groundwater to flow from east to reach the location of the springs**

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