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Modelling of Groundwater Resources for Al-Najaf City, Iraq

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***Abstract*—**Groundwater is a vital water resource in many areas in the world, particularly in the Middle-East region where the water resources become scarce and depleting. Sustainable management and planning of the groundwater resources become essential and urgent given the impact of the global climate change. In the recent years, numerical models have been widely used to predict the flow pattern and assess the water resources security, as well as the groundwater quality affected by the contaminants transported. In this study, MODFLOW is used to study the current status of groundwater resources and the risk of water resource security in the region centred at Al-Najaf City, which is located in the mid-west of Iraq and adjacent to the Euphrates River. In this study, a conceptual model is built using the geologic and hydrogeologic collected for the region, together with the Digital Elevation Model (DEM) data obtained from the "Global Land Cover Facility" (GLCF) and "United State Geological Survey" (USGS) for the study area. The computer model is also implemented with the distributions of 69 wells in the area with the steady pro-defined hydraulic head along its boundaries. The model is then applied with the recharge rate (from precipitation) of 7.55 mm/year, given from the analysis of the field data in the study area for the period of 1980-2014. The hydraulic conductivity from the measurements at the locations of wells is interpolated for model use. The model is calibrated with the measured hydraulic heads at the locations of 50 of 69 wells in the domain and results show a good agreement. The standard-error-of-estimate (SEE), root-mean-square errors (RMSE), Normalized RMSE and correlation coefficient are 0.297 m, 2.087 m, 6.899% and 0.971 respectively. Sensitivity analysis is also carried out, and it is found that the model is sensitive to recharge, particularly when the rate is greater than (15mm/year). Hydraulic conductivity is found to be another parameter which can affect the results significantly, therefore it requires high quality field data. The results show that there is a general flow pattern from the west to east of the study area, which agrees well with the observations and the gradient of the ground surface. It is found that with the current operational pumping rates of the wells in the area, a dry area is resulted in Al-Najaf City due to the large quantity of groundwater withdrawn. The computed water balance with the current operational pumping quantity shows that the Euphrates River supplies water into the groundwater of approximately 11759 m^3/day, instead of gaining water of 11178 m^3/day from the groundwater if no pumping from the wells. It is expected that the results obtained from the study can provide important information for the sustainable and effective planning and management of the regional groundwater resources for Al-Najaf City.

***Keywords*—**Al-Najaf city, conceptual modelling, groundwater, unconfined aquifer, visual MODFLOW.

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I. Introduction

WATER resources are commonly referred to the surface water from rivers, lakes and streams, and subsurface water from groundwater, springs and others. The surface water gathered through the constructions of reservoirs, dams and barrages is seen as the main supplier to the needs of the world [1]. However, in fact, only less than 3% of the fresh water that is available on this planet in rivers and lakes, and the rest that constitutes 97% of water resources is available from the underground recourses. It is estimated that approximately 8 million km^3 of 37 million km^3 of water used for drinking is available on the planet. With the rapidly economic development and the population growth at the global scale in recent years, the usage of surface water has seen significantly increased. The change of climate from the greenhouse gas emission, which is the main cause of the global warming, may also lead to the shortage of the surface water resources, especially in the Middle East region [2]. As a result, the use of groundwater is inevitably increased at the present. Water security becomes an extremely urgent problem to tackle and sustainable and effective management of the water resources become desirable globally. In Iraq, the main sources of water are from the Tigris and Euphrates Rivers. The Tigris River originates from the state of Turkey and the Euphrates River originates from Syria. Iraq heavily replies on the water supplied by these rivers. Recently, both Syria and Turkey have been building dams on these two rivers, which leads to the decrease of the running water in these rivers, scarcity of surface water are affecting the needs industrially, agriculturally and domestic use including drinking water. On the other hand, Iraq is characterizing as having a high temperature in summer, reaching sometimes to 60^{o}C and resulting in a considerable increase of the evaporation rates from these rivers [3]-[9]. But, in the winter season, low rainfall in the region also causes the scarcity of surface water from the rivers. For the Al-Najaf City, which is located in the mid-west of Iraq, the water security causes particular concern. In recent years, the residents in Al-Najaf City are suffering from scarcity of water for domestic use especially during the summer seasons. In addition, as Al-Najaf City is one of the largest holy Islamic cities in the world, there are a large number of visitors coming to either visit the holy places in this city or for tourism with approximately 15 million per annum through different occasions. This has a significant impact on the surface water usage from the Euphrates River that passes through the east part of the city. Inevitably, the groundwater sources are used to meet the increasing demand of the water usage. However, efficient management of water resources for the city is yet lacking, which has resulted in the groundwater being unsustainable in some areas.

For the groundwater modelling and management, the MODFLOW software has been widely used. As illustrated in [4] who used the three-dimensional MODFLOW to estimate the groundwater availability and levels of water for the purpose of pumping and future use for the upper and middle trinity aquifer in Hill Country Area in the USA. A mathematical model was built by [5] who used the MODFLOW software to model the movement of groundwater in the lower basin of the Euphrates (Sector Six) in Syria. The results showed that there is a gradual rise in the underground water level due to bad drainage process, as the groundwater levels were sensitive for the recharge and hydraulic conductivity. Based on the GIS database, a model of groundwater flow has been developed in order to simulate the behaviour of the Nubian sandstone aquifer system in Egypt by [6] for climatic changes and modern pumping. According to model results, Nubian aquifer is a fossil aquifer system. Also, a model was developed by [7], focused mainly on the investigation of lineaments by using remote sensing techniques and digital terrain elevations with the MODFLOW software. Lineaments extracted were having a fare jointing with suspected faults and having an elevated permeability zone. Reference [8] used visual MODFLOW to quantify groundwater in Choutuppal Mandal in Nalgonda.

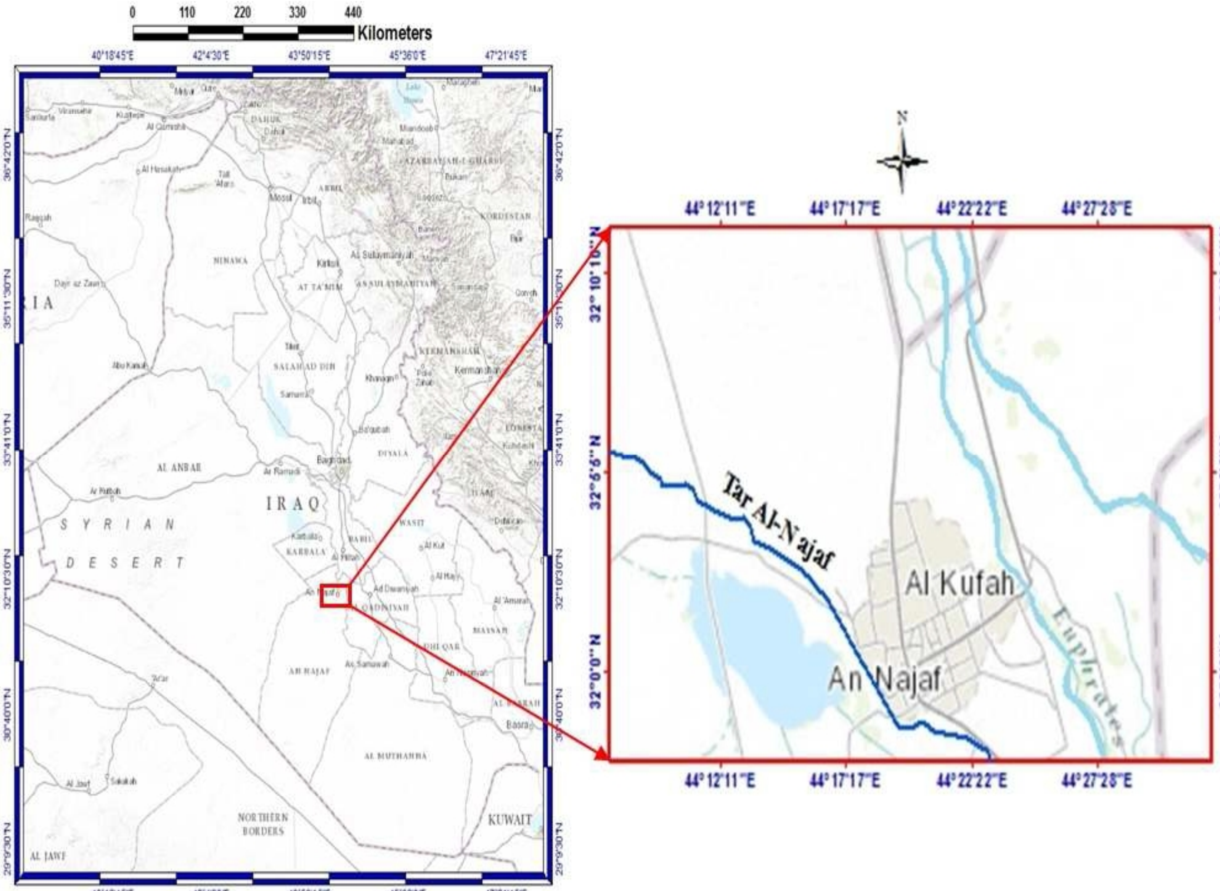

Fig. 1 Location of the study area

The main objective of this study is to use the latest MODFLOW software to explore and ascertain the impact of extraction from the wells in Al-Najaf city and its surrounding field, on the groundwater levels. The water balance between the extraction of the groundwater from wells and the river is also calculated in examining their interaction.

II. Study Site: Al-Najaf City

In this study, Al-Najaf City and its surrounding area are used as the study site, which spans 25.25 km in the longitudinal direction and 38.7 km in the latitudinal direction, covering an area of approximately 978 km^2. It lies between 44^0 07′ 36.082″ E and 44^0 32′ 5.285″ E in the longitude and 31^0 57′ 36.26″ N and 32^0 11′ 22.899″ N in the latitude (the geographical coordinates are between 417474 m and 456150 m easting, and 3536343 m and 3561577 m northing) as shown in Fig. 1. Al-Euphrates River passes through the eastern part of the province of Al-Najaf after bifurcating itself into two branches before entering the study area. On the western part of the study area, there is the Western Desert. In addition, there is a cliff on the south-west side called Tar Al-Najaf and at the foot of that cliff, there is a transversal fault named Abu Jir fault. The geology and hydrogeology information of the study area are illustrated in the following sections.

A. Geology

In Iraq, the aquifers which contain a huge quantity of groundwater are Dibdibba, Fat'ha, Injana, Euphrates, Dammam, Tayarat, and Umm Er Radhumma formations. Indeed, most of these formations are located in the western desert of Iraq (west to the Euphrates River), occupying about 32% of total area of Iraq [9].

Stratigraphic features of the study area are derived from the longest boreholes in the study area. The results suggest that the aquifer to be studied is the formation of Dibdibba. This aquifer is classified as an unconfined aquifer and it consists of two layers. The first (top) layer is made of coarse sand and the second (bottom) layer is made of fine pebbles (bottom layer), with conductivities of 14.43 m/day and 17.1 m/day, respectively. In total, 69 pumping wells are found in the study area, providing important and necessary information for this study. According to the data collected from the field, the transversal fault is located on the south-west of the study area right underneath the cliff (Tar Al-Najaf). The groundwater on the western side of the fault does not have any connection with the groundwater on the eastern side. The groundwater that comes from the western part of the desert will emerge at this fault. Therefore, this area is marked as inactive or removed when building the groundwater model.

To find the elevations of the ground surface of the study area, the "Digital Elevation Model" (DEM) is downloaded from GLCF "Global Land Cover Facility" website. The data are processed using the GIS program to extract the ground surface elevations as shown in Fig. 2. The average gradient slope according to the study of [10] in this study is found to be 0.0018.

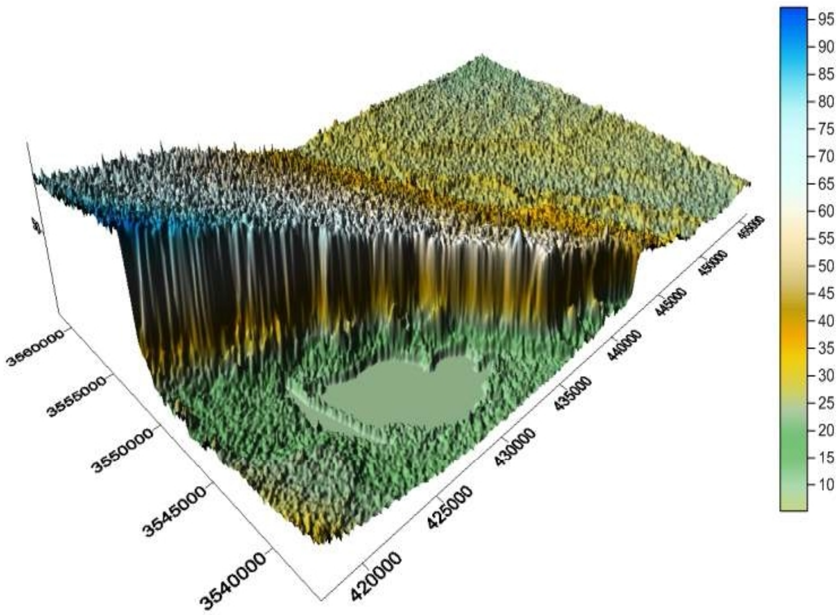

Fig. 2 Topology of the study area extracted from DEM

B. Hydrogeology

In the study area, the movement of the groundwater is observed flowing from west to east. The elevation of the ground surface in the study area in general gradually decreases eastwards, excluding the area at the foot of the cliff (Tar Al-Najaf).

III. Governing Equation and Flow Conditions

Groundwater flow is governed by Darcy law wherein the flow rate represents the proportional of the hydraulic gradient and the hydraulic conductivity which describes the characteristics of the hydraulic media where the groundwater flows [11]. Darcy equation can be expressed as:

$$V = -K \frac{dh}{dL} \tag{1}$$

where, V= velocity of groundwater (L/T); K= hydraulic conductivity of the soil (L/T); h= water table of the groundwater (L); and L= length of flow of the soil particle through the soil media (L).

Flow discharge can be calculated as:

$$Q = -kiA \tag{2}$$

where, Q= discharge (L^3/T); *i*= (dh/dL) (dimensionless); and A= area of flow (L^2). The negative sign in both (1) and (2) is

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used according to the convention for the relation between the flow direction and head gradient.

The general governing equation of groundwater flow is based on Darcy equation and energy conservation equation [12], the integration of both will result in:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \tag{3}$$

where, Kxx, Kyy and Kzz= hydraulic conductivities along x, y, and z coordinates (L/T); h= potentiometric head (L); W= the volumetric flux per unit volume which represents sinks and/or sources of water where, it's value less than (zero) when flow out of the groundwater system, and it will be greater than (zero) when flow is into the system (T^{-1}); SS= specific storage of the porous media (L^{-1}); and T= time (T).

Equation (3) describes the non-equilibrium, heterogeneous and anisotropic groundwater flow conditions that provide the principle axes of the hydraulic conductivity aligned with the direction of coordinates. Moreover, this equation together with the specification of boundary and initial flow and/or head conditions will constitute the groundwater flow mathematical representation of an aquifer system [13].

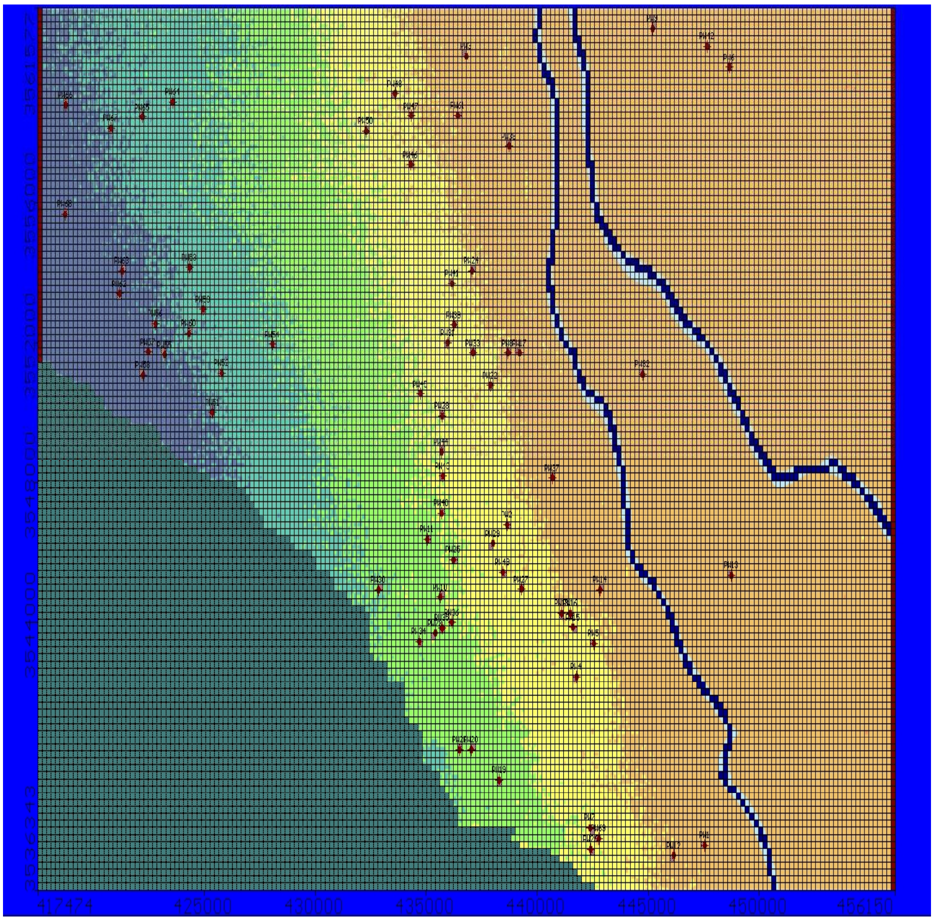


Fig. 3 Computational mesh and location of pumping wells with the specification of boundary conditions

IV. Model Setup

The MODFLOW software is set up for the study area. The computational mesh for the study area consists of 194 columns by 127 rows with two layers as shown in Figs. 3 and 4, with a 3D view. The size of the cells used is approximately 200 m by 200 m, covering an area equals to 38676 m by 25234 m with average 19720 active and 4918 inactive cells respectively. The model is unconfined with two layers to represent the geological features of the study area. The conductivities are set to 14.43 m/day and 17.1 m/day for the top and bottom layers respectively. The recharge rate into the groundwater is 7.55 mm/year and it is simulated in the first layer only through deploying the recharge function of the model. As suggested by the field observations, the movement of groundwater is also eastward in general. Therefore, constant heads along the western and eastern boundaries are set to 50 m and 20 m respectively. Due to the bifurcation of Euphrates River in the study area, it requires the boundary conditions at both sections to be specified separately. The details of those conditions are given in Table I for both branches of Euphrates River.

The study area is classified as an arid area, and it is assumed that there is no active vegetation cover implemented in the model, neither evapotranspiration is considered. 69 observation wells are incorporated in the model to consider the effect of extraction. In addition, pumping rates were inserted into the model and these rates were varying from -435 m^3/day to -3256 m^3/day, where the negative sign indicates the withdrawals of groundwater.

TABLE I
CONDITIONS FOR EUPHRATES RIVER USED IN THE MODEL

Branch	Water Elevation		Bed Elevation (m)	Bed layer Thickness (m)	Width (m)	Hydraulic Conductivity (m/d)
	Northern end (m)	Southern end (m)				
Western	24.65	21.05	19.2	0.6	174	0.364
Eastern	24.55	21.35	19.2	0.6	99	0.300

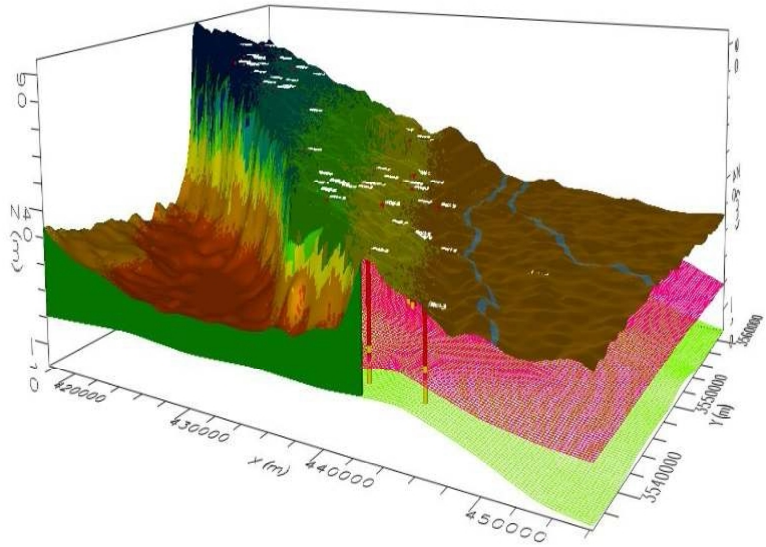


Fig. 4 3D view of the topography of the study area and composition of layers

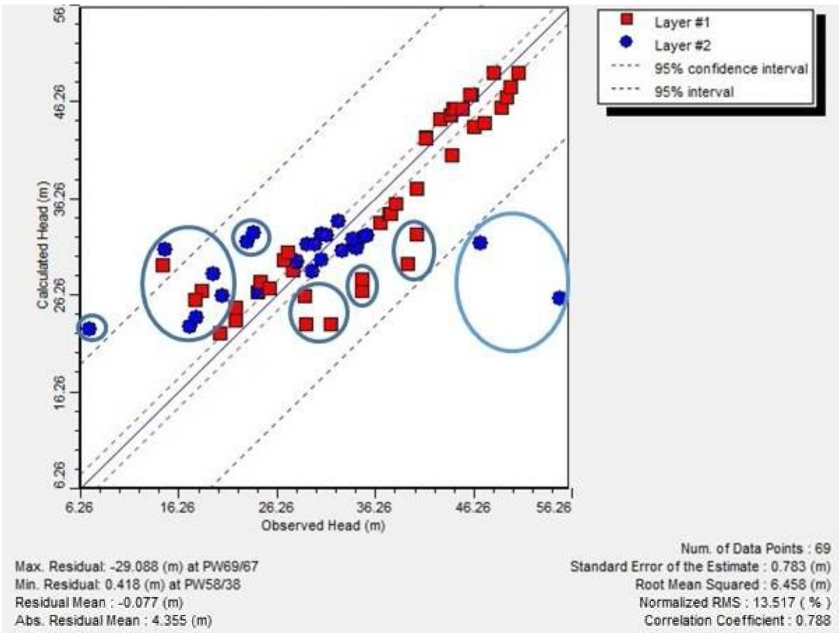


Fig. 5 Comparison of the calculated and observed heads for 69 wells with the recharge rate of 7.55 mm/year

V. Model Calibration

The calibration is carried out with different values of recharge over the model. The computed groundwater levels are compared with observed heads from 69 observation wells. The calibration process is performed for the steady state of non-pumping condition. Fig. 5 shows the comparison of the calculated and observed heads for the best-chosen value of a recharge 7.55 mm/year over the 69 observation wells. To assess the model accuracy, the values of the Standard Error of the Estimate (SEE), Root Mean Square Error (RMSE), Normalized RMSE and Correlation Factor are calculated as 0.783 m, 6.458 m, 13.517%, and 0.788 respectively.

The results indicate a general agreement between the computed and observed heads. However, it can be seen from Fig. 5 that the calculated heads for 19 wells as circled do not agree well with the observed values. By excluding these wells, the recalculated values of SEE, RMSE, Normalized RMSE and Correlation Factor become 0.318 m, 2.253 m, 7.447%, and 0.967 respectively, which can be regarded as acceptable.

VI. Model Sensitivity

Sensitivity criterion is a good measure for the uncertainty of any groundwater model and it is caused by the uncertainty of the aquifer parameters and sometimes the model boundary conditions. The fundamental concept from implementing sensitivity analysis is to understand the influence that caused by the variation of model parameters and the hydrogeological stresses on the groundwater aquifer system through changing the calibrated values systematically to finally identify which parameter needs a special attention in the future studies [14]. In this paper, the approach of sensitivity is performed through using a systemic change in the value of recharge. Model sensitivity to the hydraulic conductivity in the aquifer is also examined.

Fig. 6 shows the relationship between the SEE and recharge rate. The result indicates that the model is less sensitive when the recharge rate is between 10 and 15 mm/year. The model is sensitive for the recharge values less than 10 mm/year and higher than 15 mm/year as an overall trend. Values of SEE are decreased slightly when the values of recharge increase up to 15 mm/year. With higher recharge rates (more than 15 mm/year), the SEE values increase dramatically. This indicates that the model is more sensitive for recharge values greater than (15 mm/year) and less sensitive for recharge values less than that value and also it can be seen that the model is less sensitive when the recharge rate is between 10 and 15 mm/year.

For the model sensitivity to the hydraulic conductivity, a series of tests are carried out with a wide range of variation of the hydraulic conductivity. The logarithmic relationship between the hydraulic conductivity and the Normalized RMSE is shown in Fig. 7. It can be noted from Fig. 7 that all values of the hydraulic conductivity which are greater than approximately 14 m/day have a little effect on the values of the Normalized RMSE and this means that the model is less sensitive for the increasing in the hydraulic conductivities more than this value. However, the sensitivity for decreasing the hydraulic conductivity values to be less than 14 m/day is found very large and resulted in high values of the Normalized RMSE. This suggests that more careful consideration should be given when the hydraulic conductivity is determined, in particular when it is less than 14 m/day because the results can be dramatically changed.

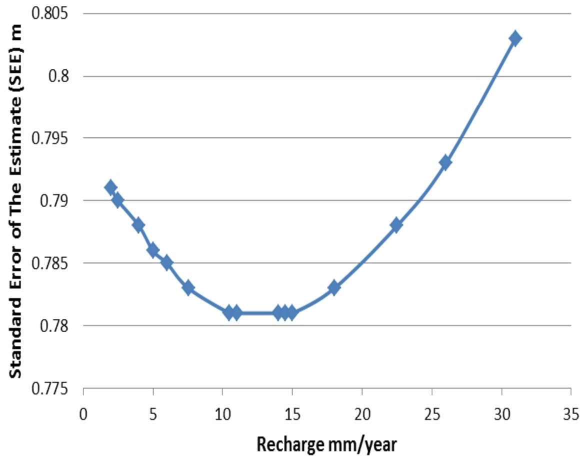


Fig. 6 Relationship between the standard error of the estimate (SEE) and recharge rate

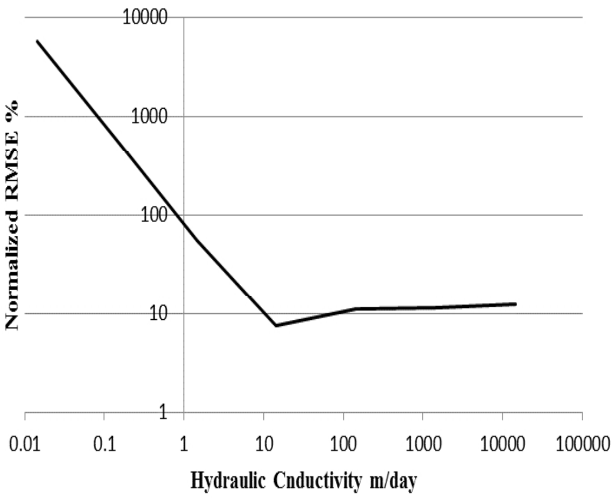


Fig. 7 Logarithmic relationship between the hydraulic conductivity and Normalized RMSE

As demonstrated, the value 7.55 mm/year is considered to be the value of the recharge rate which gives acceptable results between the calculated and observed heads. In addition, the model was sensitive for the changing in the hydraulic conductivity as an overall trend and this situation needs to be considered into account to reach for the accurate model that can be represented the real entire domain of the study area.

VII. Spatially Varying Hydraulic Conductivity

The results presented in the previous section clearly show that the hydraulic conductivity is one of the key parameters to affect the model accuracy. Using a constant hydraulic conductivity for each layer may not be desirable. Therefore, the data collected from the field are further analyzed to generate a map of spatially varying the hydraulic conductivity. In total, hydraulic conductivity values can be extracted from 55 out of 69 wells. These 55 wells are located in the middle, western and northern-east areas as shown Fig. 8. In order to cover all the entire computational area, 5 additional points around the computational domain using the hydraulic conductivity values to their closest points are used in the interpolation. An interpolation process using Kriging method is carried out with the appropriate Variogram in order to reach to the better representation of the soil formation in the study area.

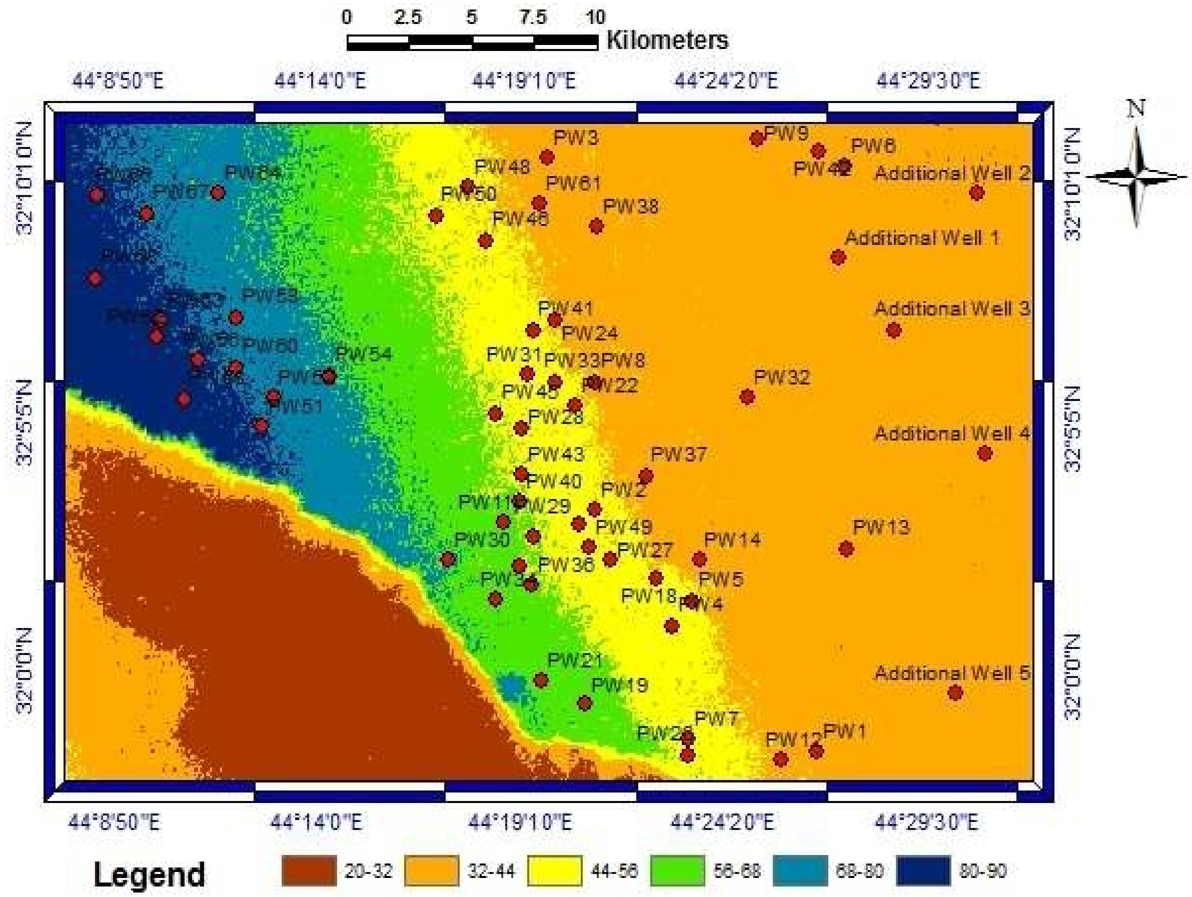


Fig. 8 Names and Locations of the wells having hydraulic conductivities

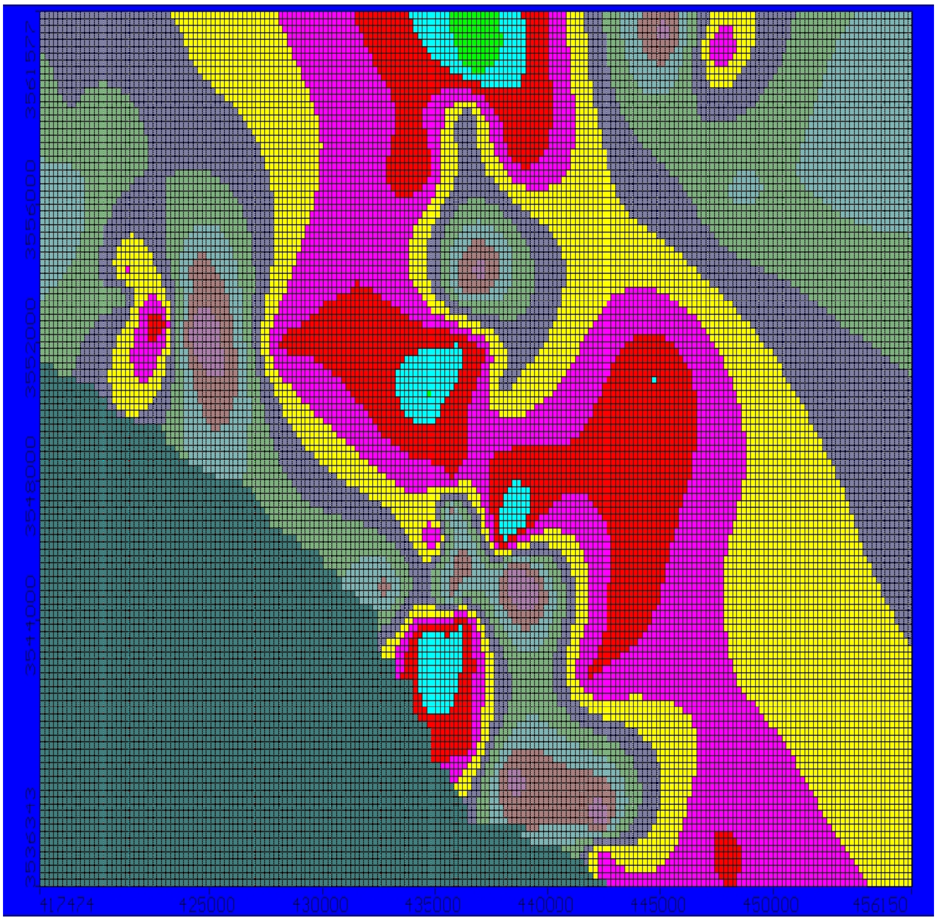


Fig. 9 Map of spatially varying hydraulic conductivity

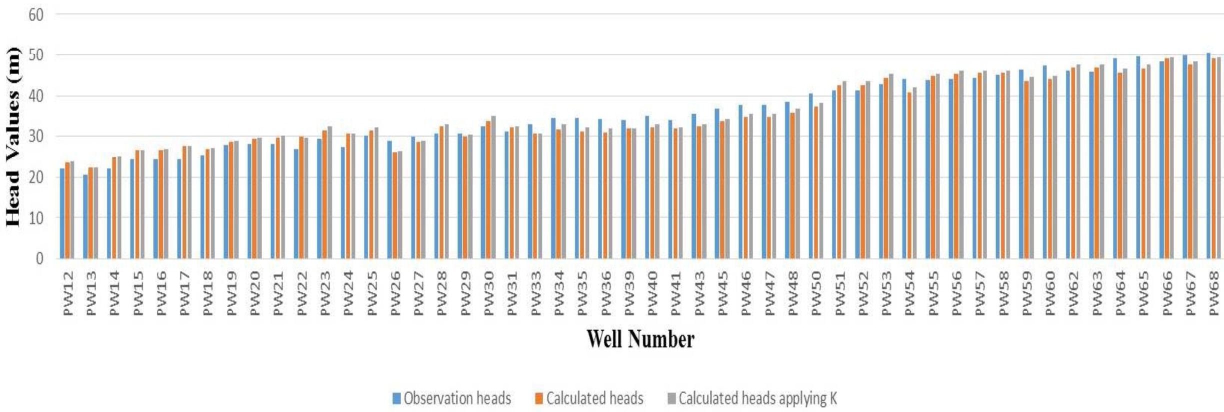


Fig. 10 Comparison of the observed values with the calculated static heads with and without applying Kriging method for 50 wells

Fig. 9 shows the spatially varying hydraulic conductivity in the study area. It can be seen that larger values of the hydraulic conductivity are located in the central part of the computational domain, and the overall range of the hydraulic conductivity is between 11 and 25 m/day.

With the spatially varying hydraulic conductivity map, the head distribution is re-calculated. Fig. 10 shows the values of the observation heads, calculated heads before applying Kriging method, and calculated heads after applying Kriging method as a clustered column chart. It can be seen from Fig. 10 that some values of the calculated heads after applying Kriging method have been either increased or decreased to be closer to the observed heads and this finally leads to appearing the real entire domain of the study area. The RMSE of the values shown in Fig. 10 after applying the Kriging method was 2.087 m and this value is the least as compared with the starting value 6.458 m and the value 2.253 m after excluding 19 wells, when Kriging method is not applied.

Fig. 11 shows the comparison of the calculated heads from the model when the spatially varying of hydraulic conductivity is used with the observations. In comparison with the results shown in Fig. 5, it can be seen that the values of SEE, RMSE, and Normalized RMSE are reduced to be 0.297 m, 2.087 m, and 6.899% respectively, and the Correlation Factor becomes 0.971. It is clear that the spatially hydraulic conductivity over the study area can considerably improve the accuracy of the model results in this study.

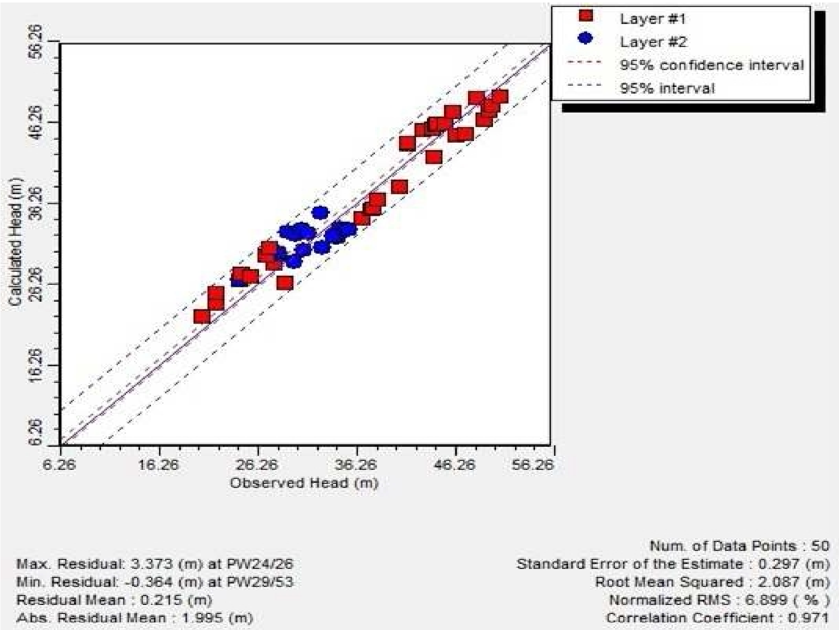
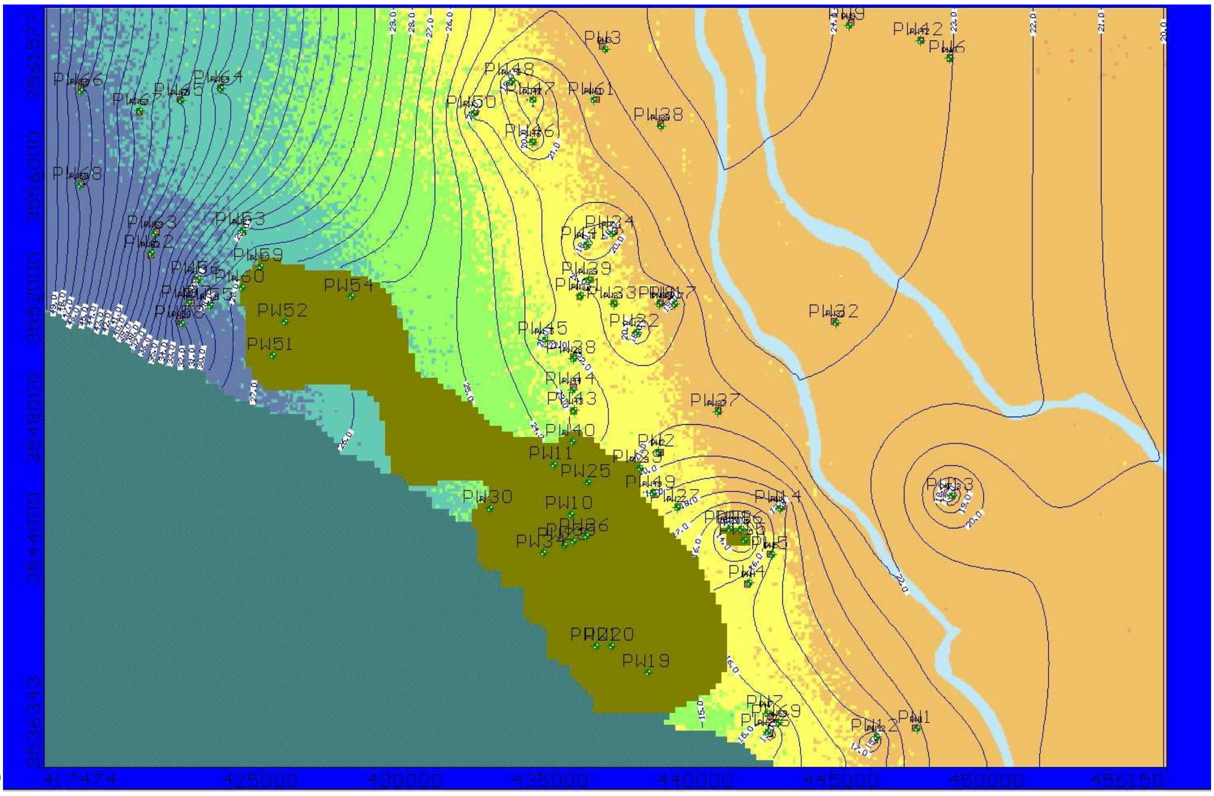


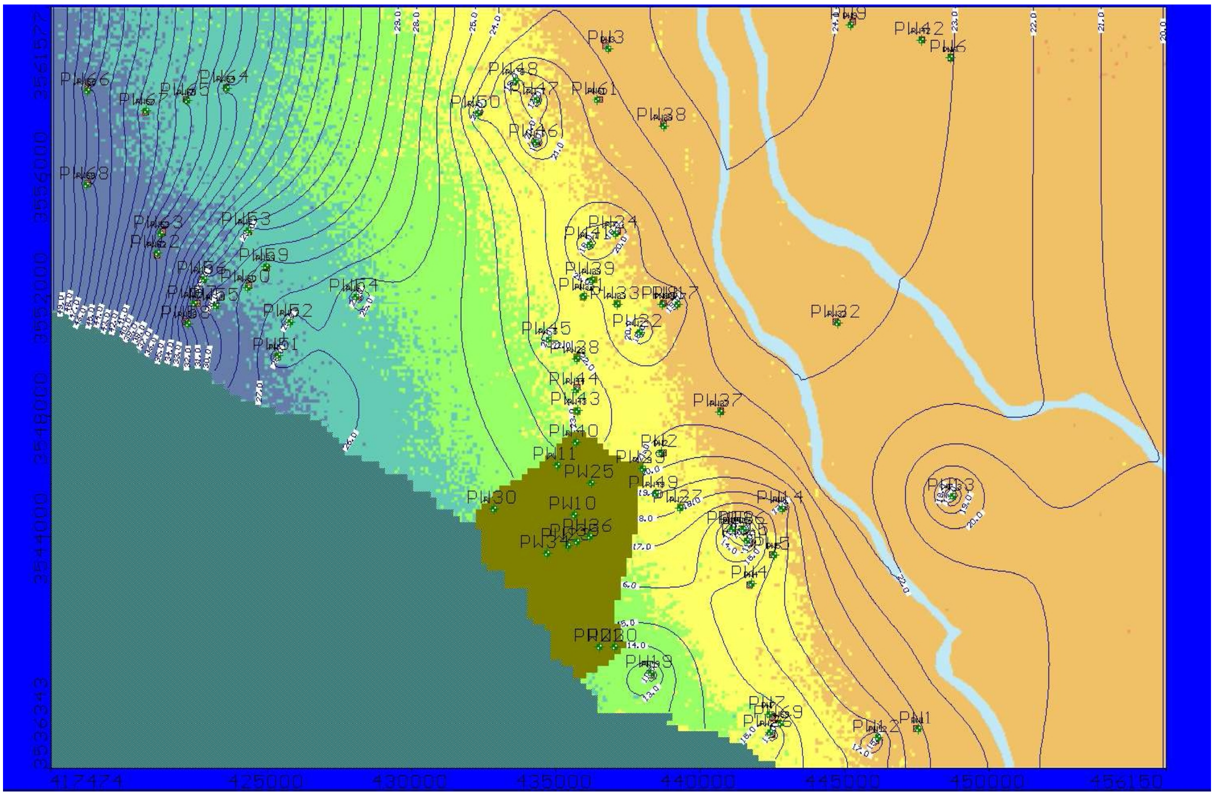
Fig. 11 Comparison of the computed and observed heads with the use of spatially varying hydraulic conductivity

VIII. Results and Discussion

The calibrated model is now applied to the study area to examine the current state of the water resources in the region, with 7.55 mm/year recharge rate and the current pumping rates based on the field data. The model is run for a duration of one year to get a steady state. Fig. 12 shows the computed water table with the conditions described. The results indicate a general eastwards trend of the groundwater flow. The impact of the pumping/extracting the water from the wells, causing significant changes of the water head around the wells, can also be clearly seen. For the top layer of the aquifer, there is a large drying area, due to the water extraction from the wells, as shown Fig. 12 (a), whilst a slightly small drying area can be seen in the bottom layer from Fig. 12 (b). The model results also enable the groundwater balance to be examined. For a steady state without pumping, the Euphrates River gains water from the groundwater flowing from the west to the east by 11178 m^3/day (inflow to the river: 16244 m^3/day and outflow from the river: 5066 m^3/day). However, with the current pumping rates from the wells, the Euphrates River is losing water 11759 m^3/day (inflow to the river: 513 m^3/day and outflow from the river: 12272 m^3/day). Therefore, it is clear that with the current pumping rates in the regions, the Euphrates River is under huge pressure to supply water to the extraction. Even with the current level of supply of the water from the river, there is some degree of insufficiency of water supply as the drying areas indicated in Fig. 12. This highlights the seriousness of groundwater shortage in the region of Al-Najaf City. With the future climate change and potentially reduced water supply for the Euphrates River, which is the further research to the present work, it becomes, even more, important to better assess and manage the water resources in the region to ensure the long-term sustainability and security.



(a)



(b)

Fig. 12 Computed water table with 7.55 mm/year recharge rate and current pumping rates in: (a) top layer and (b) bottom layer

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