



# GIS-based numerical modeling for the groundwater assessment: a case study in the Quaternary aquifer, Assiut Governorate, Egypt

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## Abstract

The Quaternary aquifer in Assiut Governorate is the most important water resource necessary for irrigation and development in Assiut Governorate. The study area is located between latitudes 26° 47'–27° 37' N and longitudes 30° 37'–31° 34' E, covering about 2500 km<sup>2</sup>. This study is an integrated GIS-supported approach proposed to create and develop a transient three-dimensional groundwater flow model for the Quaternary aquifer in Assiut Governorate. Based on the prevailing climatic, environmental, developmental, and water demand conditions, the model was designed to investigate the most feasible groundwater management option. In this context, a great focus was given to the impact of the construction of the Assiut new barrages on the groundwater situation in the study area. According to the actual and supposed extraction rates of the Quaternary aquifer, six scenarios were suggested; however, only four of them are presented here. For the construction of rigid potentiometric isolines, the available records of water levels in more than 540 wells were used. The model was calibrated under the steady state and transient conditions using the trial and error method. The period 2007–2010 was chosen as a calibration period based on the availability and temporal distribution of the data. The simulation of the actual extraction rates (scenario 1, 767 × 10<sup>6</sup> m<sup>3</sup>/y) indicated that by 2050, the biggest drawdown is happening at the northwestern part with an average value of 8 m. In contrast, the groundwater is rising by about 6 m by 2050 in the same scenario. The simulation of the full capacity, proposed extraction rates (scenario 3, 1534 × 10<sup>6</sup> m<sup>3</sup>/y) resulted in severe changes of the hydraulic head patterns within almost all of the study area of the Quaternary aquifer during the simulation period. This scenario showed clearly a 12-m drawdown which occurs at the northeast part of the study area. Scenario 4 supposed a decrease in the water level of the River Nile by 1 m, a general increase in the groundwater level was detected by the end of the simulation. In scenario 5, the new location of the Assiut new barrage was simulated; the upstream water level has been considered the same as the old one and, however, is displaced 500 m downstream. By 2025, the impact of this scenario was observed by the increase in the hydraulic head in Assiut city by about 0.1 to 0.2 m. During the calibration process, it has been learned that there should be a groundwater recharge from the western and eastern plateau; however, this conclusion still needs further studies to confirm it.

**Keywords** GIS · Groundwater flow model · Quaternary aquifer · Assiut Governorate · Egypt

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## Introduction

Nile Valley is the most important agricultural and industrial area in Assiut, in which the government has later established new reclamation projects, as well as irrigation and drainage networks. The increased in the reclaimed land area and anthropogenic activities together with the decreased in surface water discharge especially in the 1980s led to shortage of surface water. As a way to face this, the Ministry of Water Resources and Irrigation (MWRI) began from 2001 the project of drilling groundwater wells at the dead ends of canals at where the surface water does not reach. Knowing that most of that project lies over the Quaternary aquifer, an increase in abstraction took place which might cause the depletion of the groundwater aquifer.

The main objective of this study is to develop a groundwater flow model for the Quaternary aquifer in Assiut Governorate (Fig. 1). The model should simulate the Quaternary aquifer in order to help estimating the groundwater availability and water levels in response to pumping and potential future droughts resulting from many reasons including establishment of dams on the Nile course, as the Renaissance Dam in Ethiopia. As a first stage towards the groundwater flow model, a complete database for the existing discharge and water levels in the

drinking and agriculture water wells was collected (Desert Research Center 1983, RIGW 1990, 1998, NASA 2004, MWRI 2004, 2005, EEAA 2005, REGWA 2009). Then a three-dimensional numerical groundwater flow model for the Quaternary aquifer was developed and calibrated. The calibrated model has then been refined at the stress areas, model boundaries, or where required to facilitate the detailed input and output information. The refinement was designed to be as small as possible to reveal the minor aquifer responses to the adjusted hydraulic stresses (Moore 1979, Verruijt 1982, McDonald & Harbaugh 1988, Fetter 1994, Richard 2002, Rushton 2003).

The groundwater flows generally from the southern part to the northern part of the study area. Locally, in the northern part, the groundwater flows northeast towards the River Nile; accordingly, the River Nile is considered as a discharge zone, while in the southern part of the study area, the groundwater flows from the eastern side towards northwest direction; therefore, the River Nile is also a discharge zone. Generally, the study area can be classified as a high potential aquifer; the main aquifer underlying the Nile flood plain is generally of higher potential than the rest of the study area. The characteristics, the type, and continuity of recharge of this part make it possible to pump large quantities of groundwater from shallow depths

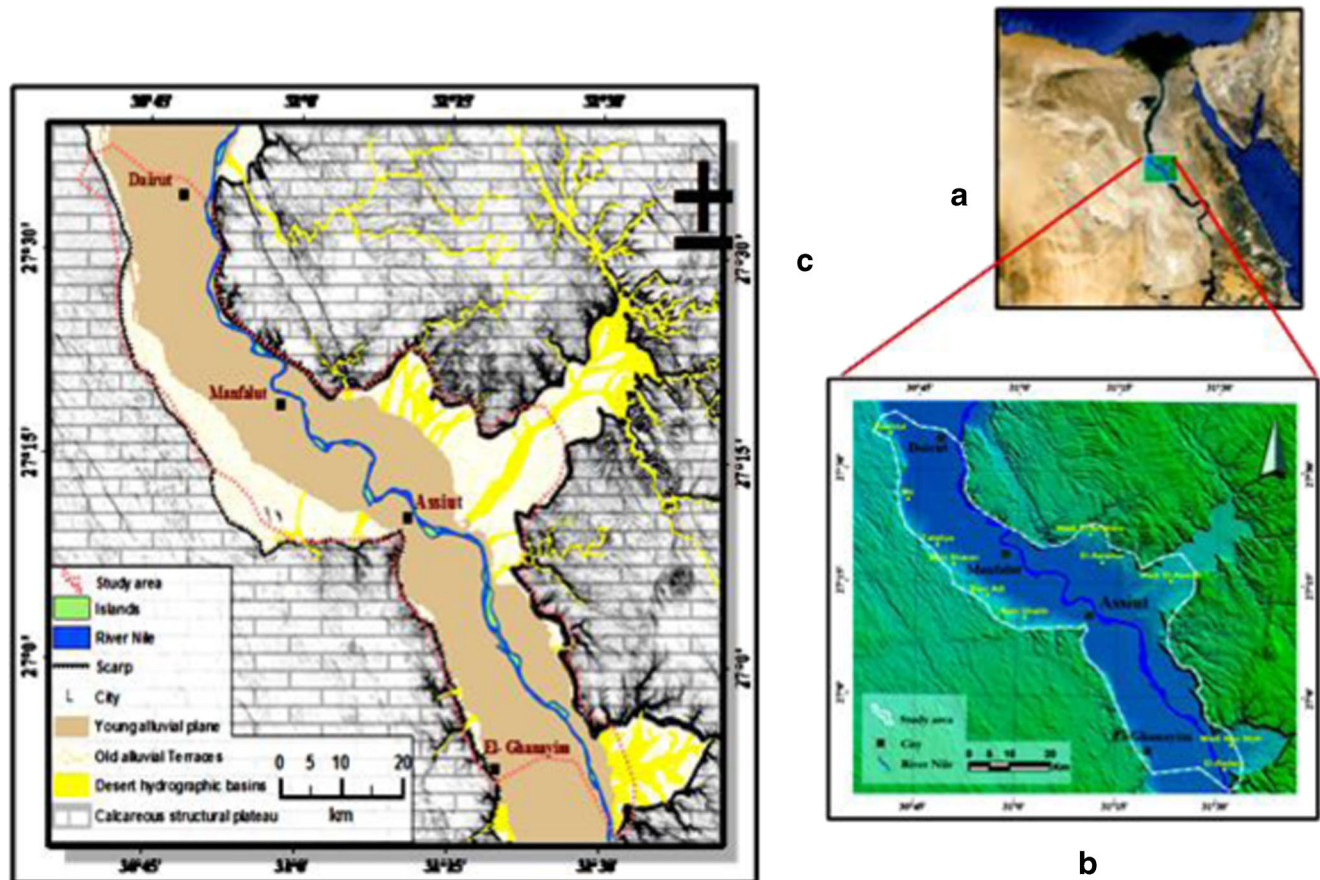


Fig. 1 Location (a), geomorphological (b), and geological (c) maps of the study area

almost everywhere. The groundwater potentiality in the fringes is of magnitude lower than of the Nile flood plain. These areas are characterized by a deep groundwater with low productivity.

## Geomorphology and general geology of the study area

Because of its importance, the Quaternary aquifer has long been subjected to comprehensive geological studies. Examples of these are Said (1962), El Gamili (1964), Mansour (1969), Youssef et al. (1977), Osman (1980), Said (1981), Farrag (1982, 1991), Keheila (1983), CONOCO (1987), Said (1990), Aboul-Fetoh (1994), Abu El Ella (1997), Shaker (1999), Senosy and Ebraheem (2002), El Miligy (2004), El Tahlawi et al. (2007), Saleh (2009), Salem (2009), Abdel Hafeez et al. (2018), and others.

The old and cultivated land covers an area of about 2500 km<sup>2</sup> (Fig. 1). River Nile splits the study area longitudinally into western and eastern parts. The western part is larger than the Eastern one, where its area is about 1500 km<sup>2</sup> (Fig. 1). Land surface in the fringes of each part is generally slopes towards the River Nile. A gradual slope to the north is also a remarkable feature. The study area covers most of the cultivated land either old or recently reclaimed. The sharp declination is the dominant feature of the fringes of the study area because of the limestone plateau which bounds the area from the east and the west, except for the north-western part, which has a gentle slope (Fig. 1).

The Quaternary aquifer occupies the most part of the Nile Valley, which is bounded by the limestone plateau from the east and west, extending along the study area and most of the Nile Valley. A silty clay cap covers the most surface of the Quaternary aquifer and occupies the central part of the aquifer (Elewa 2006; Belal et al. 2015; Attia et al. 2016). The Quaternary aquifer outcrops only at the desert fringes, where those outcrops are wide in the central part of the study area and very narrow at the northern and southern parts of the study area; however, the aquifer does not outcrop at Wadi Abu Shih in the south (Fig. 2). Generally, the rocks cropping out in the studied area are all of sedimentary origin, and belong to the lower Eocene, Plio-Pleistocene, and Holocene (Fig. 2). This aquifer varies in thickness from about 280 m around Manfalut city to about few meters and zero at the fringes (Sefelnasr 2013).

## Material and methods

### Data acquisition

The data that used to build the model were collected and obtained from several sources (Desert Research Center 1983, RIGW 1990, 1998, NASA 2004, MWRI 2004, 2005, EEAA 2005, REGWA 2009) and with different formats. One of the main

problems of these data is the continuity problems. These sources include the Ministry of Water Resources and Irrigation (MWRI) represented in the Groundwater Sector (GWS) in Cairo as a main source, General Administration of Groundwater in Upper Egypt, El-Minia, Groundwater Engineering Office in Assiut, Egyptian Environmental Affairs Agency (EEAA), Research Institute for Groundwater (RIGW) in Cairo, the General Company for Research and Ground Water (REGWA) in Cairo, Wadi El-Nile Company for Drilling, and Alffons Drilling Company as a source of some private well logs in Wadi El-Assiuti. The most part of data that used in the model was obtained as scattered distributions of data sets and in different formats: lithologic logs, well logs, drilling observations, geologic and hydrogeologic cross sections, pumping tests data, geologic maps. A GIS-database structure has been built as a potential professional start with the groundwater flow modeling to form a comparable structure to the hydrogeological information system. That database has been built also to accomplish a trustworthy and logical data set and to facilitate the further work. The following steps have been achieved to construct the GIS-database for which ArcMap/ArcInfo (ESRI® ArcMap™ 9.3, ArcInfo™ 9.3, 1999–2008) was used.

### Model development and design

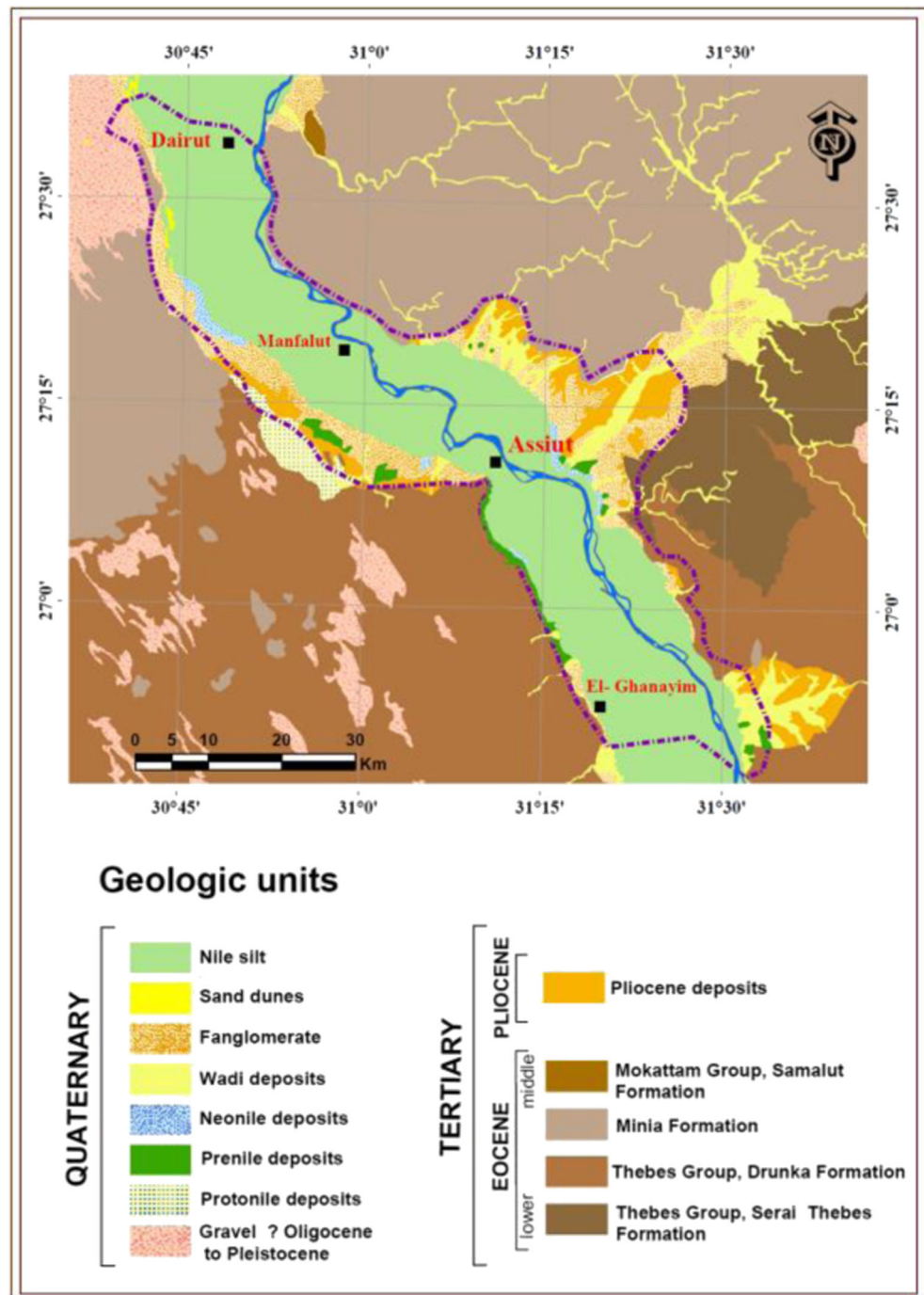
A great effort was given to the development of a coherent, reliable conceptual model for the Quaternary aquifer to simulate the real world as close as possible (Fig. 3). According to the given geologic, hydrogeologic, and hydrostratigraphic information for the area, the model was designed to be two layers with different hydraulic parameters as given in Figs. 3 and 4. All the grids in the model (surfaces and parameters) were generated sophisticatedly using the proper variograms and kriging procedure (Freeze & Witherspoon 1967, Neuman & Witherspoon 1969, Francke et al. 1987, Kruseman & De Ridder 1990, Anderson & Woessner 1992, Kumar 1992, Walton 1996, Hill 1998, Delleur 1999, Mandle 2002, Wels 2012, El Tahawy 2013). The evapotranspiration was applied to the middle and fringes of the study area. The estimation of the evapotranspiration of the Quaternary aquifer corresponds to a mean of 10–15 mm/year (Sonntag 1986; Sonntag and Christmann 1987; Nour 1996, Sefelnasr 2007, Sefelnasr et al. 2015).

### Boundary conditions

The study area of the Quaternary aquifer in Assiut Governorate was considered as a semi-confined system due to the natural boundaries consisting of the Pliocene deposits that consist of clay as an impermeable base. In addition, the aquifer is bounded by limestone plateau at the east and west along the study area which acts as natural no-flow boundaries of the Quaternary aquifer (Fig. 5). The southern and northern borders of the model were designed as general head boundaries. The River Nile and other



**Fig. 2** Geological map of the Quaternary aquifer (modified from CONOCO (1987))



irrigation canals were handled as constant head boundaries (Fig. 5). The groundwater wells were applied as a fourth kind boundary condition (Zimmerman & Zimmerman 1991, Wali 1992, Pannatier 1996, Omran 2008, Surfer@9 User's guide 2009, Omran et al. 2015).

### Suggested scenarios

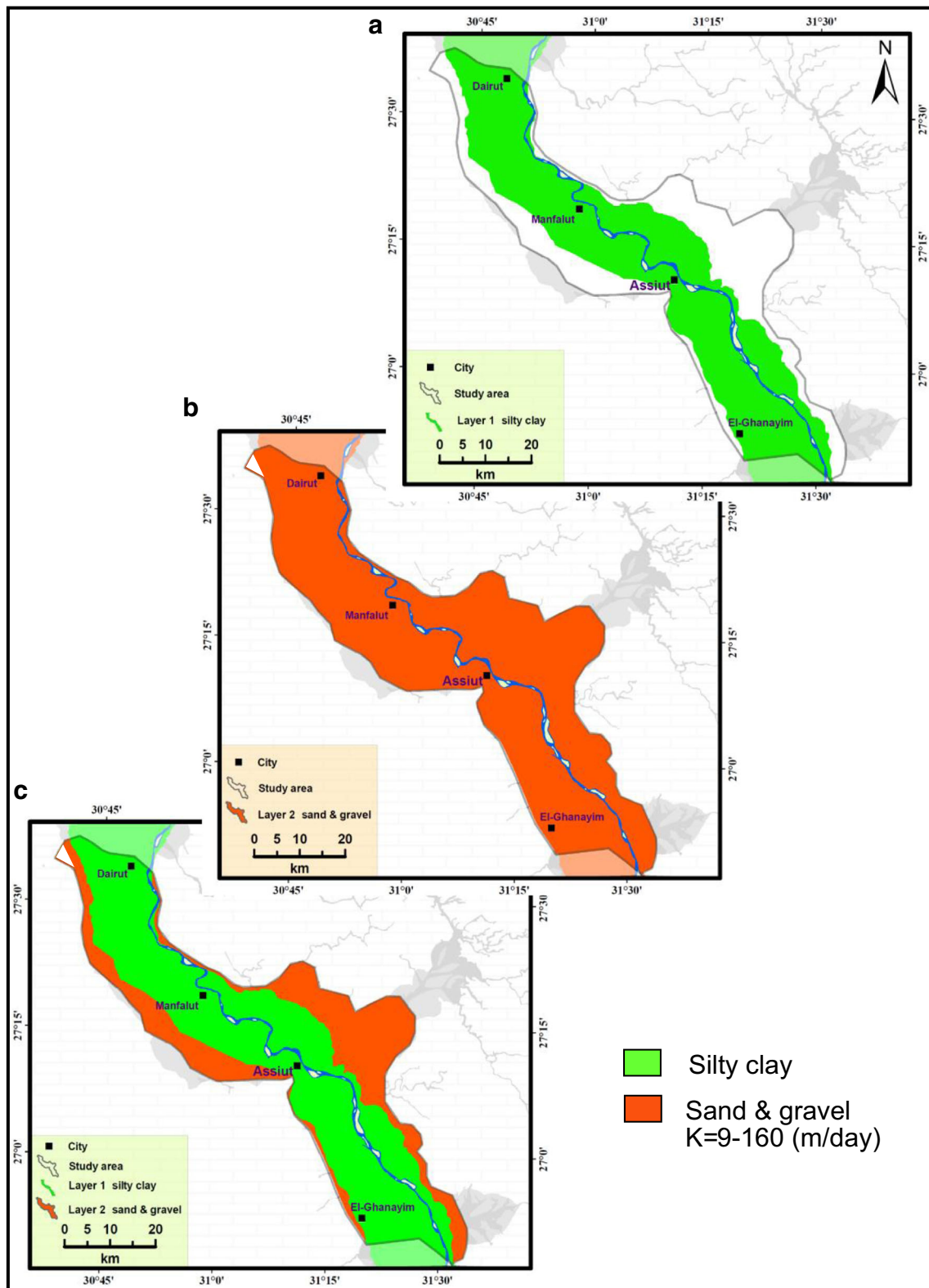
Several scenarios have been proposed according to the growing groundwater demand for domestic, agriculture, and industrial

use; one of these scenarios was proposed according to current change in the environment which is the construction of Assiut new Barrage. Table 1 shows the different proposed scenarios.

### Calibration

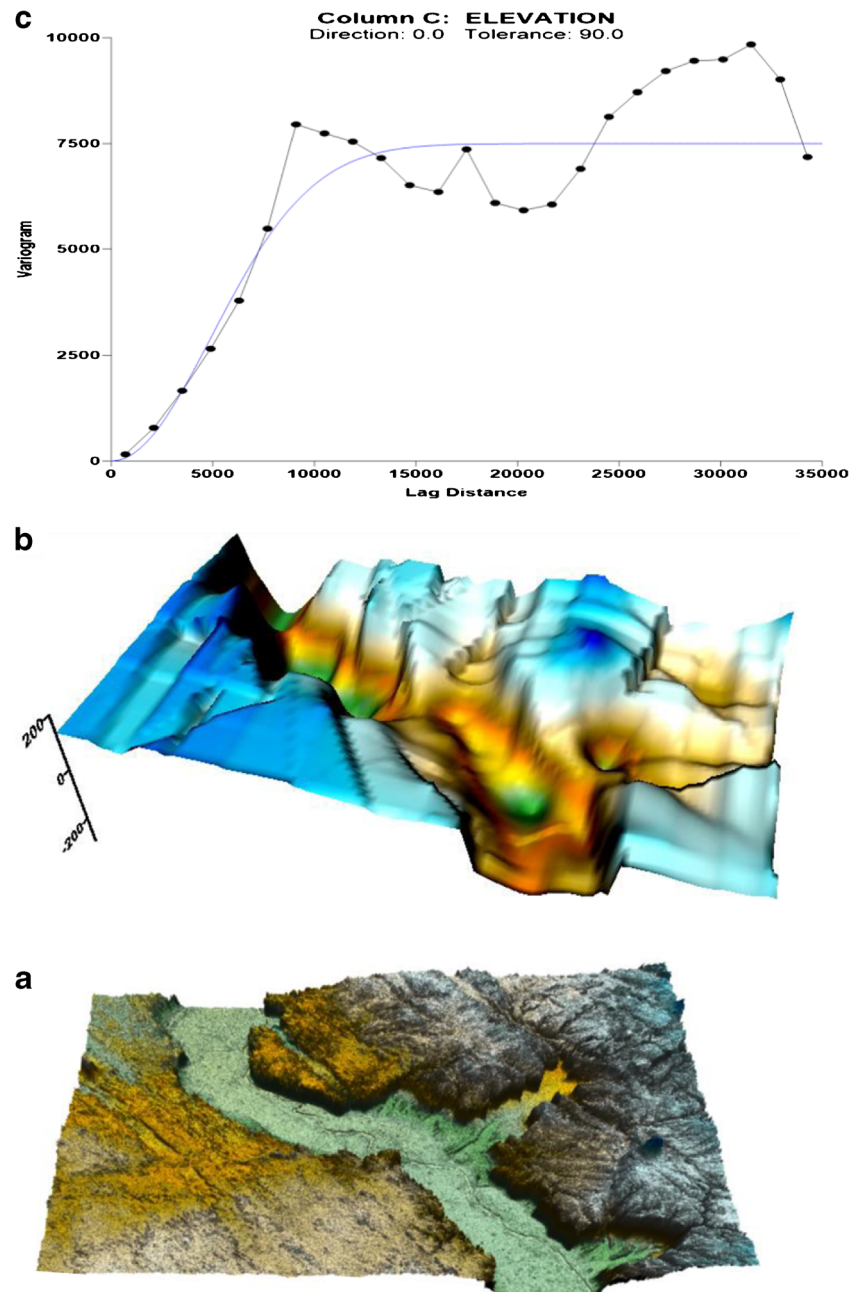
The groundwater flow model of the Quaternary aquifer was calibrated principally under steady state conditions; however, no real steady state condition was obtained. The model was then calibrated under transient conditions by use of the available





**Fig. 3** Conceptualization and spatial distribution of the Quaternary aquifer layers. (a) layer 1 (top layer) silty clay; (b) layer 2 (aquifer) sand and gravel; and (c) the two layers, visible from the surface

**Fig. 4** Digital elevation model (a) and bottom relief of the Quaternary aquifer (b), as well as a corresponding Gaussian variogram for the bottom relief (c)



historical hydraulic head records as calibration targets and was adjusted using a trial and error parameter estimation method through a series of groundwater flow simulations (Zimmerman & Zimmerman 1991, Wali 1992, Pannatier 1996).

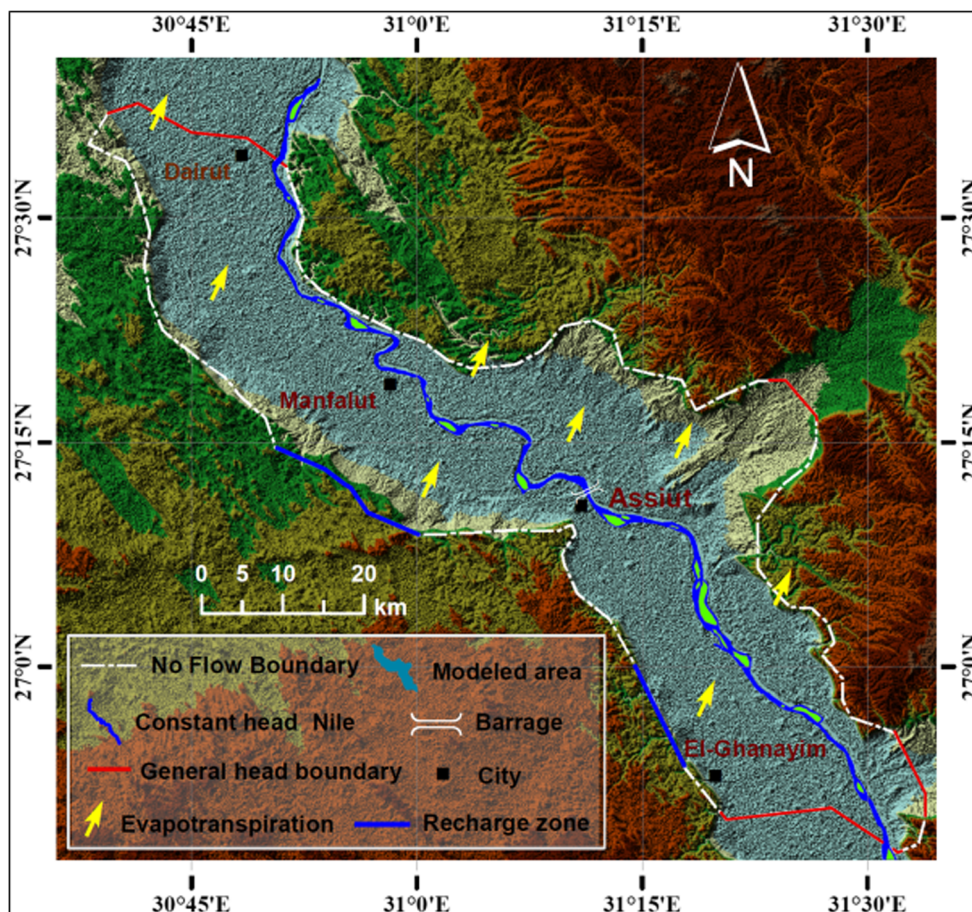
The period 2007–2010 was chosen as a calibration period based on the availability and temporal distribution of the data. The calibration process indicated that the direction of the groundwater flow within the model area is kept by the original trend of the initial head measured at 2007. However, the values and local trends of these contours showed some changes where new contour lines with lower values appeared. To calibrate the model, the boundaries were adjusted one by one (recharge,

evapotranspiration, G.H.B, constant head) using a trial and error to reach the best fit between measured and calculated hydraulic head. The calibration was held by using the historical records of hydraulic head data of about 150 wells in different locations in 2007 (Fig. 6).

## Results and discussion

The calibrated regional model was first used to forecast the changes in the flow regime that result from the natural stresses and the anthropogenic activities on the aquifer

**Fig. 5** Schematic drawing shows the location, extent, and boundary conditions of the Quaternary aquifer



resources during the coming 40 years. In the analysis procedure of the simulation results, emphasis was given to the changes in hydraulic head and drawdown, as well as the groundwater balance to evaluate the potential and response of the aquifer to the abovementioned stresses within the prediction period.

**Current situation**

By 2008, the simulation indicated that the ground water regime has the same general flow directions which was from southwest to north east, especially at the northern half of the study area. The calibrated model was used for further prediction simulations to investigate the response of the

aquifer to the different management options in the next 40 years. The parameters of the calibrated model were kept constant and the boundary conditions were adapted to the scenarios.

**Scenarios**

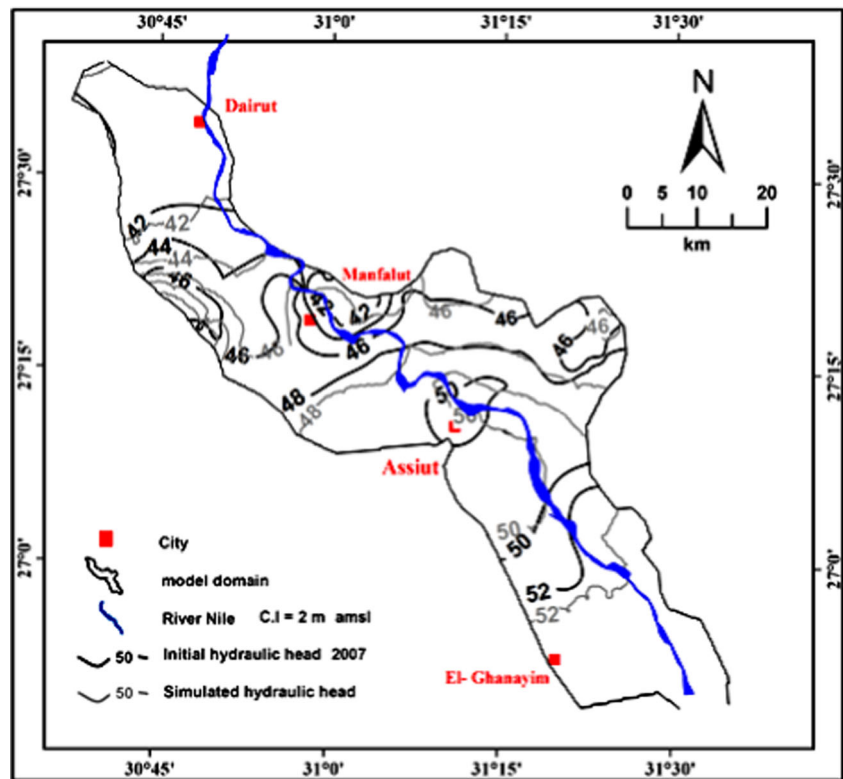
According to the actual and full capacity extraction rates of the Quaternary aquifer, six extraction scenarios were suggested in an attempt to investigate the most feasible groundwater management option in terms of groundwater demand; however, only four of them are presented here.

**Table 1** The different suggested groundwater extraction scenarios for the Quaternary aquifer in Assiut Governorate

Scenarios	$Q$ (Mill $m^3/y$ )	Description
1	767	The current extraction rates ( $Q$ ) are proposed to be constant until 2050.
2	1150	The extraction rates ( $1.5*Q$ ) are proposed to be constant until 2050.
3	1534	The extraction rates ( $2*Q$ ) are proposed to be constant until 2050.
4	767	The static water level of River Nile was proposed to decrease 1 m.
5	767	Constructing a new Barrage at 500 m to the north of the old one.
6	767	Increasing the front static water level of the new Barrage with 0.5 m.



**Fig. 6** The result of model calibration under steady state conditions at year 2007



### Scenario 1

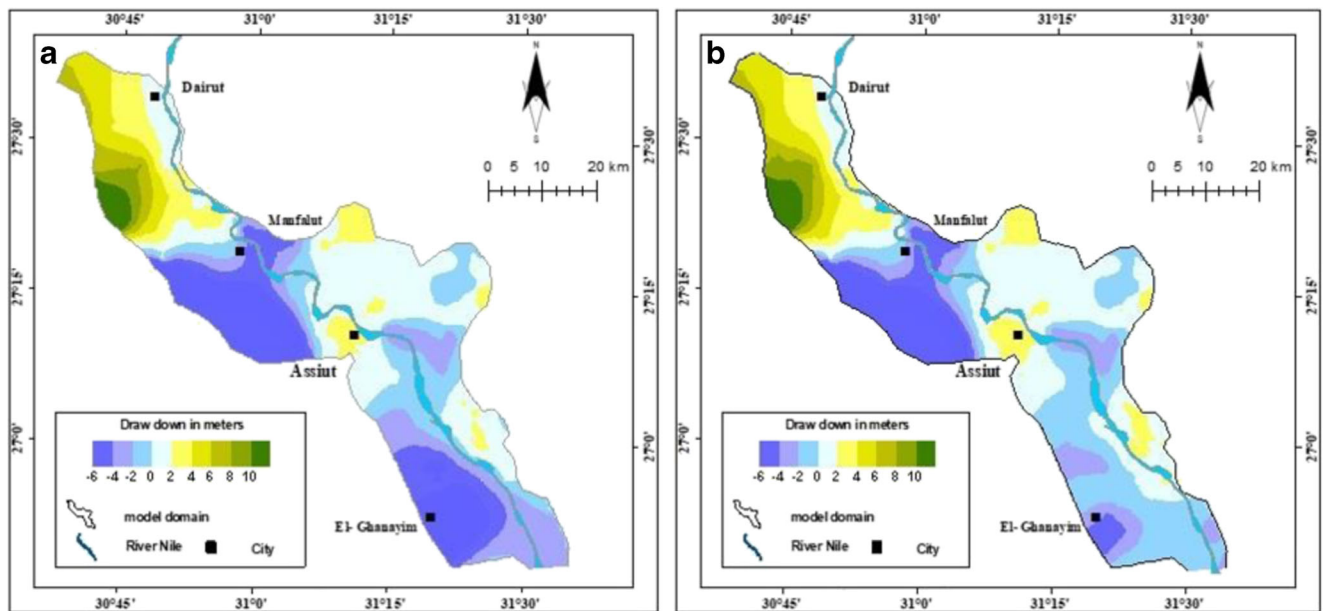
In this scenario, the current pumping rates (767 MCM/y) were used and supposed to be unchanged until 2050. Generally, the direction of groundwater flow within the model area is still following the regional groundwater flow trend (southeast-northwest) like the trend of the initial head (at 2008). However, as expected, the values and local trends of these contours prevailed some changes in some places. At the northern-western part, the contour values decrease gradually with time forming an obvious cone of depression. At the southern part, it was noticed that the groundwater increases towards the north (against the expected natural trend), which means that there is a source of flux from the eastern plateau. This phenomenon has been portrayed on Fig. 7 a and b, where the drawdown is expressed by negative values to express that the head at the desired time is higher than that of the initial one. The results obtained from scenario 1 indicated that the major cones of depression are centered in the northwest part with average drawdown of 8 m by 2025 (Fig. 7a) and slightly increase to roughly reach 10 m by 2050 (Fig. 7b). This is a typical response of the Quaternary aquifer that shows apparent equilibriums after a while of stress implementation (Fig. 7a, b). At the southwest, scenario 1 indicated that this area is gaining an amount of water by which led to a groundwater rise of about 6 m; this confirms that there is a source of flow coming from the western limestone plateau (Fig. 7a, b).

### Scenario 3

In this scenario, the discharge rates were doubled ( $2 \cdot Q$ ) to accommodate the future artificial discharge as a full capacity extraction scheme. This, in turn, resulted in the appearance of new cone of depression as in Wadi El-Assiuti at the East of the modeled area along with the cone of depression in northwest of the area (Fig. 8a, b). This scenario shows clearly the draw-down which occurs at the east part and the appearance of 12-m drawdown. The blue and yellow colors are the most dominant colors in the area which means a loss of hydraulic head in the study area. It is noticed that the yellow color starts to disappear from the southern parts of the study area. The simulation of the full capacity, proposed extraction rates of scenario 3 (1534 MCM/y) resulted in severe changes of the hydraulic head patterns within almost all of the study area of the Quaternary aquifer during the simulation period. It is worthy mentioned here that with the increase of the extraction rates, the groundwater flux from the surface water bodies (River Niles and canals) increases as well, as indicated by the water budget calculations.

### Scenario 4

This scenario is an attempt to simulate the impact of the climate change or the possible changes in the flux from the River Nile. In this scenario, the current discharge rates are assumed

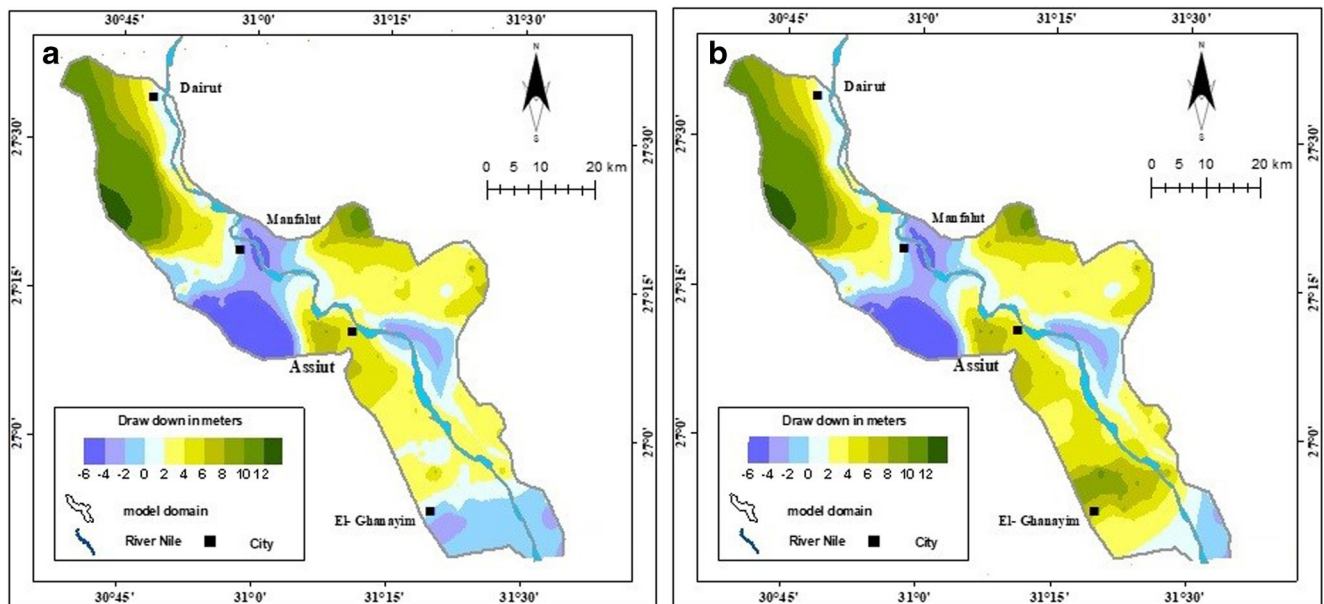


**Fig. 7** The simulated drawdown based on scenario 1 in the Quaternary aquifer (suggesting that the current extraction rates are constant until 2050, by 2025 (a) and by 2050 (b))

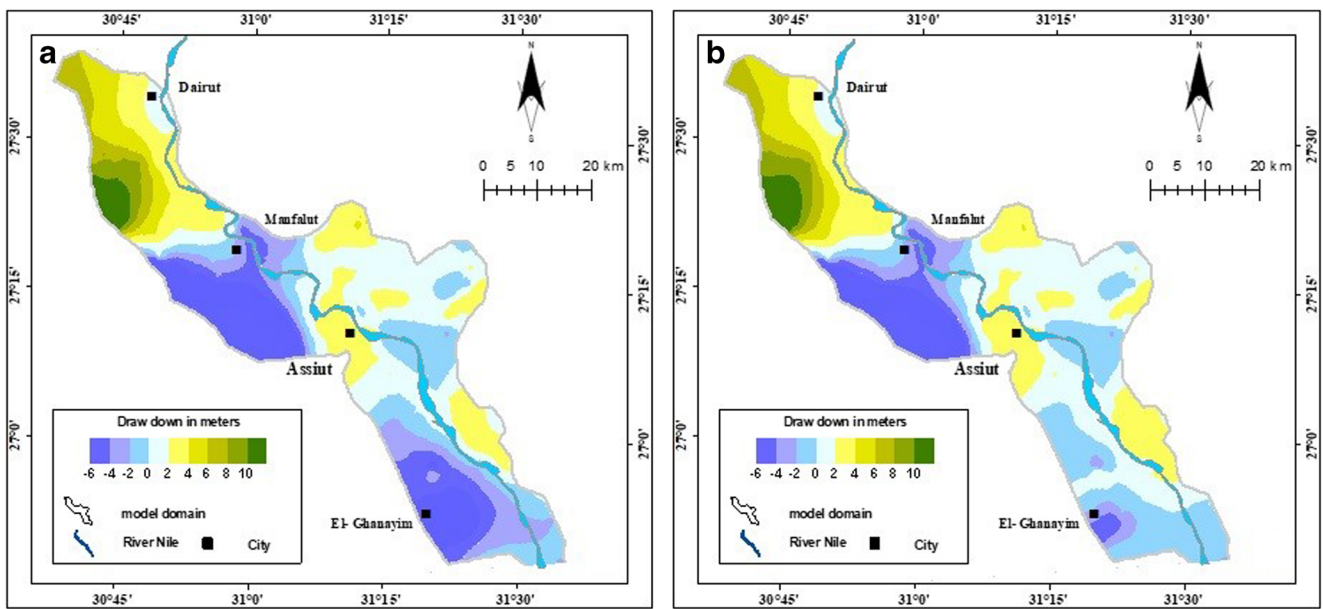
constant until 2050 (as given in scenario 1) with a decrease in the River Nile water level by 1 m. As a simulation result, the hydraulic head is directly affected in the central part (around Assiut Barrage, at which the groundwater level is decreased by 2 m at 2025 (Fig. 9a). By 2050, the aquifer kept its regional regime, but as usual with some changes in water levelling in the western part (Fig. 9b). The fluxes from and to the River Nile have been changed spatially and quantitatively as well, where the influent/effluent conditions have endured some changes.

**Scenario 5**

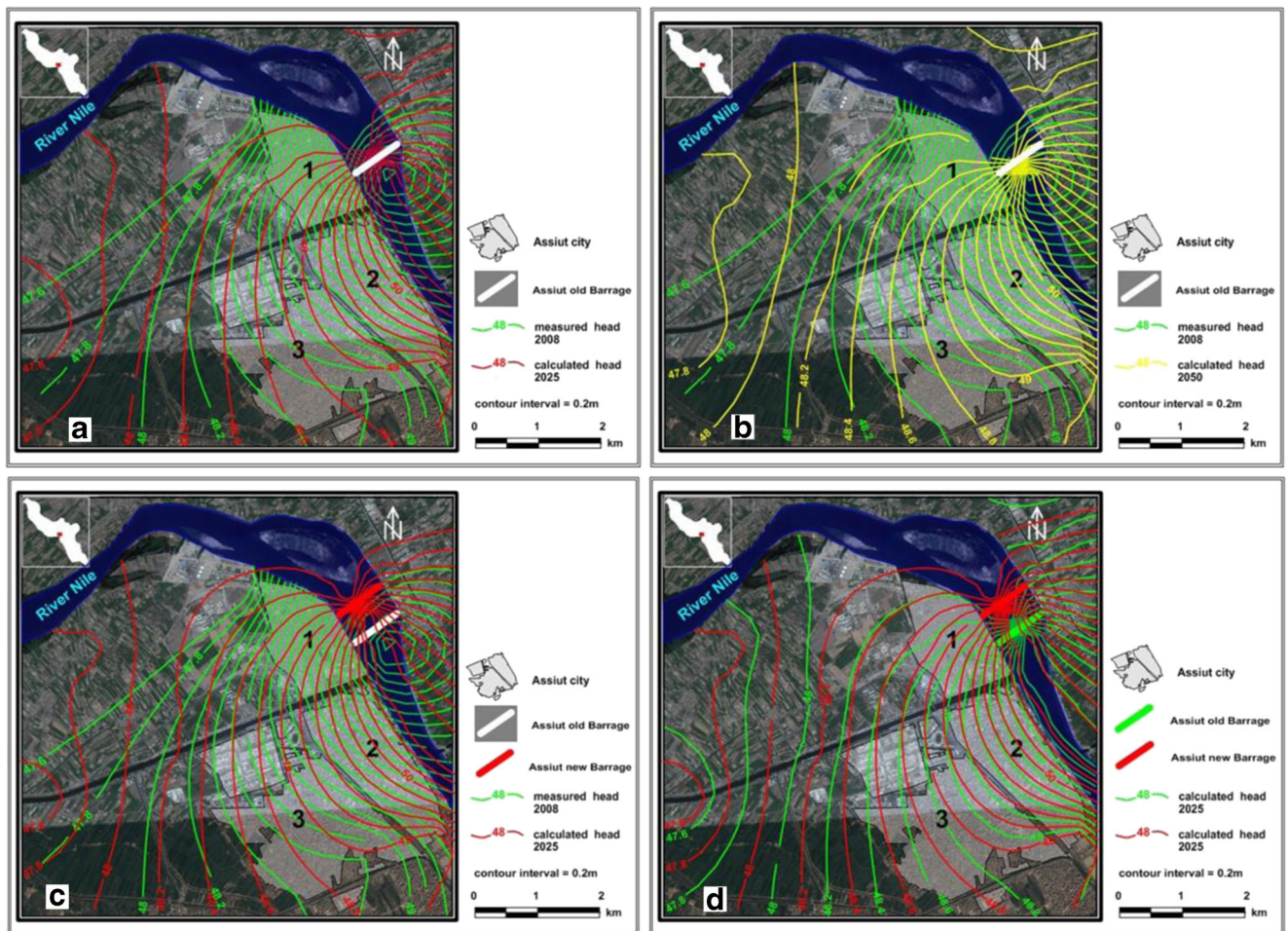
Another scenario was implemented on the Quaternary aquifer in Assiut Governorate, which is investigating the impact of the construction of Assiut new barrage. As a reference, the measured hydraulic head of the aquifer at 2008 was taken and compared with the simulated one by 2025 and 2050 for the old Barrage (Fig. 10a and b, respectively). The two figures show the effect of the old Barrage on Assiut city (areas 1, 2, and 3). By 2050, it is clear to notice the propagation of contour



**Fig. 8** The simulated drawdown based on scenario 3 in the Quaternary aquifer (suggesting that the extraction rates are doubled until 2050, by 2025 (a) and by 2050 (b))



**Fig. 9** The simulated drawdown based on scenario 4 in the Quaternary aquifer (suggesting that the extraction rates are still constant until 2050 and decrease in the Nile water level by 1 m) by 2025 (a) and by 2050 (b)



**Fig. 10 a** Contour map comparing the 2008 measured hydraulic head of the Quaternary aquifer with the simulated by 2025 according to old Barrage. **b** Contour map comparing the 2008 measured hydraulic head of the Quaternary aquifer with the simulated by 2050 according to old

Barrage. **c** Contour map comparing the 2008 measured hydraulic head of the Quaternary aquifer with the simulated by 2025 according to new Barrage. **d** Contour map comparing the hydraulic head of the Quaternary aquifer by 2025 according to the old and new Barrage



lines towards the east crossing Assiut city (Fig. 10b); it is also noticed that the contour lines concentrate on regions 1 and 2 more than region no 3. In this scenario, we supposed that the Assiut new barrage was constructed and its upstream level is the same as the old one, so the new barrage in this scenario has the same conditions of the old one except for the dislocation. The new barrage is already now under construction at a distance of 500 m to the north of the old one. Figure 10c shows the new location of the new barrage and indicates a comparison between the old and new barrage. Figure 10c is comparing the 2008 measured hydraulic head of the Quaternary aquifer with the simulated one by 2025 according to the new barrage. To give an obvious figure on the effect of the barrage displacement, we have to compare between the old and new one at the same time. Figure 10d compares the hydraulic head of the Quaternary aquifer by 2025 according to the old and new Barrage. The comparison indicates that there is an effect according to the new place represented in increasing the hydraulic head with about 0.2 m on regions 1 and 2 and decreasing to about 0.1 m on region 3.

## Conclusions, outlook, and prospects

1. An integrated GIS-supported approach has been applied in creation and developing a transient three-dimensional groundwater flow model for the Quaternary aquifer in Assiut Governorate. The model was calibrated under the steady state and transient conditions using the trial and error method. The period 2007–2010 was chosen as a calibration period based on the availability and temporal distribution of the data.
2. According to the actual and supposed extraction rates of the Quaternary aquifer, six scenarios were suggested. The impact of the construction of the Assiut new barrages on the groundwater situation in the study area has been focused.
3. The simulation of the actual extraction rates (scenario 1, 767 MCM/y) indicated that by 2050, the biggest drawdown is happening at the northeast part with an average value of 8 m. In contrast, the groundwater is rising by about 6 m by 2050 in the same scenario.
4. The simulation of the full capacity, proposed extraction rates (scenario 3, 1534 MCM/y) resulted in severe changes of the hydraulic head patterns within almost all of the study area of the Quaternary aquifer during the simulation period. This scenario showed clearly a 12 m drawdown which occurs at the northeast part of the study area.
5. Scenario 4 supposed a decrease in the water level of the River Nile by 1 m, a general increase in the groundwater level was detected by the end of the simulation.

6. In scenario 5, the new location of the Assiut new barrage was simulated; the upstream water level has been considered the same as the old one and, however, is displaced 500 m downstream. By 2025, the impact of this scenario was observed by the increase in the hydraulic head in Assiut city by about 0.1 to 0.2 m. During the calibration process, it has been learned that there should be a groundwater recharge from the western and eastern plateau; however, this conclusion still needs further studies to confirm it.
7. Since the current groundwater flow model for the Quaternary aquifer is GIS-supported, it can easily be used for any further simulation purposes. It can also be updated to match the newly situations (especially, the urban incursions into agricultural land) or to be improved when new data are obtained.
8. The groundwater resources in the study area have to be utilized wisely and based on clear management schemes and sustainability policies.
9. The drilling activities in the desert fringe have to be ceased or at least minimized, which affect the groundwater regime quantitatively and qualitatively.
10. A groundwater monitoring network has to be implemented and on both sides of the River Nile around the new barrage to detect the groundwater level changes properly.

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