Arabian Journal of Geosciences (2019) 12: 124
https://doi.org/10.1007/s12517-019-4230-6

S. I. GEOLOGY OF AFRICA

Numerical modeling technique for groundwater management in Samalut city, Minia Governorate, Egypt

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Received: 25 September 2018 / Accepted: 11 January 2019 / Published online: 11 February 2019

Abstract

The demand for freshwater supplies is progressively ascending owing to the increase of the population expansion and economic growth. Available water resources have been reduced by pollution and over-pumping. Groundwater modeling is a powerful tool for water resources management, groundwater protection, and remediation. The aim of this study is to develop a numerical groundwater flow model for the Quaternary aquifer in Samalut city, Minia Governorate, Egypt. The model is used to determine the hydrogeological conditions of the aquifer, the flow directions as well as calculating the rates of recharge and discharge between surface water and groundwater in the study area. Furthermore, scenarios were designed in the model to assess the response of the aquifer to increase the groundwater extraction in the future. The model was calibrated by trial and error; simulated results were compared to the observed head and contour maps, which were generally in good agreement. No typical steady-state condition is prevailed in the aquifer and groundwater flow directions are toward northeast direction. The River Nile acts as a drain in the study area, while El-Ibrahimiya Canal and Bahr Yusef act as a source of aquifer recharge. The proposed scenarios showed that surface water plays an important role in recharging the aquifer during increasing groundwater extraction. The results showed that the change in the aquifer storage will be decreased from + 48,125 m^3/day in the current state (2013) to + 27,134 m^3/day and − 869 m^3/day when the groundwater extraction is increased by 25% and 50%, respectively.

Keywords Groundwater modeling · Groundwater management · Groundwater budget · MODFLOW

Introduction

Water is vital to the existence of all living organisms, but this valued resource is increasingly being threatened. Egypt lies mainly within the hyper-arid desert environment, where water resources are critically important. Understanding of water resources is fundamental to future developments and planning. Currently, the availability of water of acceptable quality in Egypt is limited and getting even more restricted. The distribution of fresh water resources and its availability is becoming scarce day by day, owing to population growth and diverse human activities. Egypt depends on about more than 90% of its water supply on the River Nile. Groundwater in Egypt is a vital water resource as it is used for many purposes including drinking, domestic, industrial, and irrigation. Groundwater modeling is a way to represent a system in another form to investigate the response of the system under certain conditions, or to predict the behavior of the system in the future (Thangarajan 2007). Groundwater modeling is a powerful tool for water resources management, groundwater protection, and remediation (Baalousha et al. 2013). Decision makers use models to predict the behavior of a groundwater system prior to implementation of a project or to implement a remediation (Kresic 2006). Much hydrological researches have been carried on the study area and its vicinities to evaluate the suitability of surface water and groundwater for use in different purposes on hydrochemical basis such as El Sayed (1987), Tantawy (1992), Gomma (1999), Wahaab and Badawy (2004), El Kashouty et al. (2012), Salem (2015), and Esam et al. (2017). The numerical modeling tasks proposed for this study are the first attempt of groundwater modeling effort in

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This article is part of the Topical Collection on *New Advances and Research results on the Geology of Africa*

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Samalut city, Minia Governorate, Egypt. In this work, a groundwater flow model was established for the Quaternary aquifer in Samalut city. The model is used to determine the hydrogeologic conditions of the aquifer, the flow directions, and to calculate the rates of recharge and discharge between surface water and groundwater in the study area. To evaluate the response of the aquifer in the future, groundwater extraction scenarios are proposed. The methodology, model construction and groundwater budgets, and level results in the current state of the model and in the proposed scenarios are discussed in this paper.

Geographic location and climate

The study area lies between 28° 9′ 4″ and 28° 21′ 55″ latitudes and 30° 33′ 41″` and 30° 64′ 35″ longitudes, at the western bank of the River Nile (Fig. 1). Samalut district is one of Minia Governorate's cities, which covers an area of about 3375 km^2. It is bounded by Matai city and Minia city in the north and the south, respectively, and by the River Nile and limestone boundary in the east and the west, respectively.

In general, the climate in the district is semi-arid, hot, and rainless in the summer, and mild with rare rainfall in the winter. The climatic features represent one of the active parameters which affect the hydrological and hydrogeological evaluation of the water resources in the study area. According to the Egyptian Meteorological Authority (2016), the average long-term climatic records for the period (2000-2015) of Samalut city are shown in Fig. 2. The maximum temperature varies from 20.5 °C in January to 39 °C in June. The minimum temperature varies from 4.6 °C in January to 20.4 °C in July. The mean monthly temperature varies from 11.8 °C in January and 28.7 °C in July (Fig. 2a). The annual amount of rainfall is not significant in the study area through the year. It is zero in July and gradually increases to a maximum value of 1.74 mm/month in March, while the average annual amount of rainfall is 4 mm/year (Fig. 2b). Evaporation in the study area ranges from 14.85 mm/month in June to 3.54 mm/month in December. The mean monthly value is 8.92 mm/month, while the mean annual value is 107.04 mm/year (Fig. 2c). The mean monthly

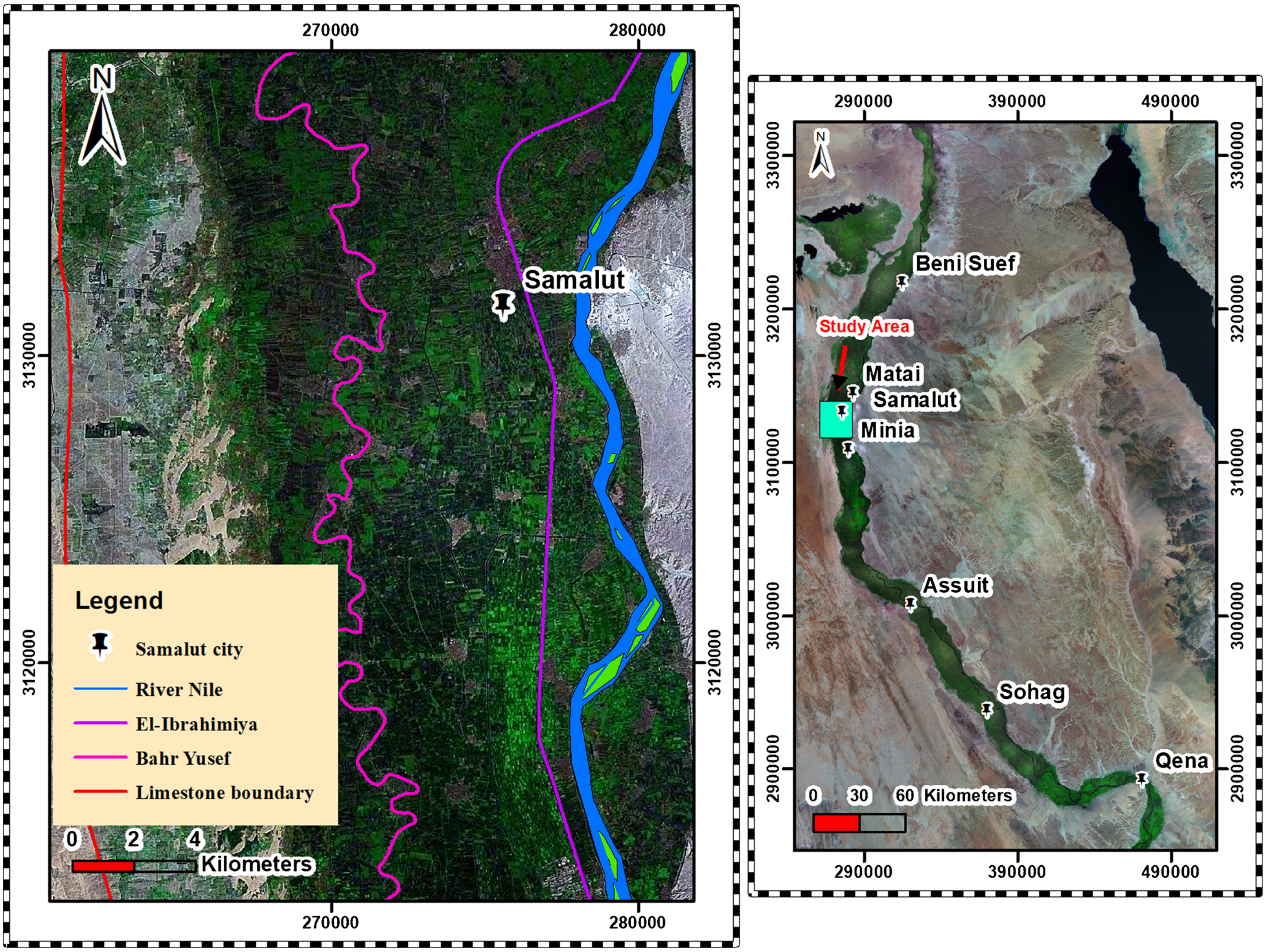


Fig. 1 Satellite geographic location of the study area. Used coordinates: UTM 36 N, WGS 1984

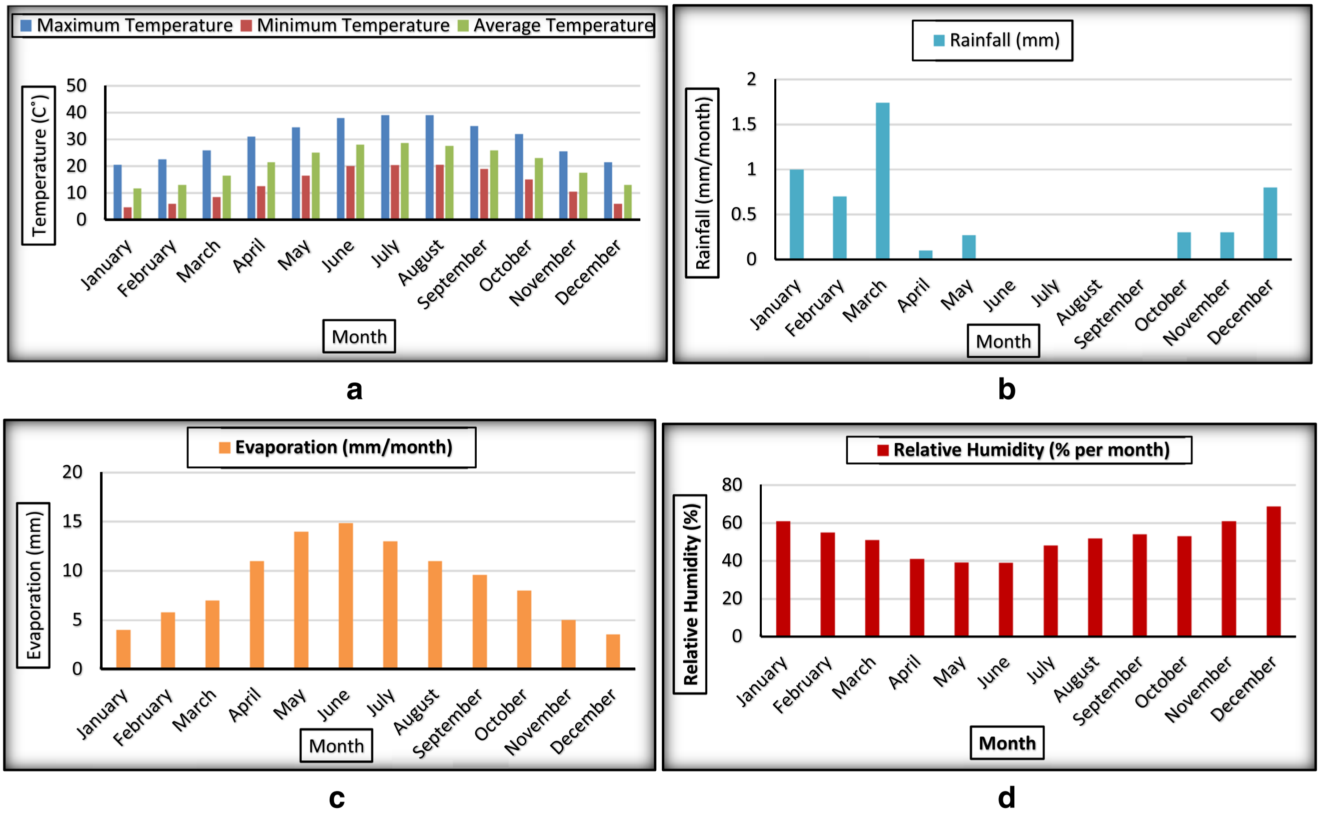


Fig. 2 **a**–**d** Climatic records of the average long-term period (2000–2015) of Minia Governorate (Egyptian Meteorological Authority 2016)

relative humidity ranges from 39.2% in May to 68.8% in December, while the mean annual relative humidity is about 54.76% (Fig. 2d).

Geomorphological and geological setting

Geomorphologically, the study area lies between the Eocene limestone plateau from the west and the River Nile from the east. It is essentially a plain topography devoid of outcrops in most cases (Fig. 3). Different quaternary deposits (e.g., gravels, sands, silts, and clay) cover the plain. It is classified into the following geomorphic units (Said 1981): The young alluvial plains of the Nile, the old alluvial plains of the Nile, fanglomerates, River Nile coarse, the calcareous structural plateau and its bounding slopes, Khefoug landscape, and the hydrographic patterns.

Geologically, the study area is covered by the sedimentary rocks and deposits, which are ranging from the middle Eocene to the recent (Fig. 3). Many authors such as Omara et al. (1972, 1977), Said (1981, 1990), and Conoco (1987) studied the stratigraphic succession of the Minia district. According to Said (1981), the geological succession is mainly consisted of the following rock units from the top to base: Holocene deposits (Nile silts and sand dunes), Pleistocene deposits (sands and gravels with clay intercalations), Plio-Pleistocene deposits (undifferentiated sands and gravels), Pliocene deposits (clays), and Eocene rocks (limestone) which are classified into different formations. Structurally, the area is affected by NW-SE faults and gentle folds (Fig. 4).

Hydrogeological setting

In the study area, surface water system is mainly represented by the River Nile, El-Ibrahimiya canal, and Bahr Yusef canal (Fig. 1). The Quaternary aquifer represents the main aquifer in the study area which is recharging from surface water and excess of irrigation water while it is discharged by groundwater pumping and evapotranspiration. It has the following characteristics:

- Lithology and thickness: Holocene sediments (silts and clays) which represents a semi-permeable bed that cap the aquifer (1 m to 15 m thickness) and Pleistocene sediments (sands and gravels with clay intercalations) which represents the main aquifer in the study area (25 m to 300 m) (El Kashouty et al. 2012; Sadek 2001) (Fig. 5).
- Groundwater occurrence: confined conditions—unconfined conditions in some localities west of Bahr Yusef.
- Groundwater flow: northeast direction (Fig. 6).
- According to RIGW (2015), in the Holocene clay and silt, the horizontal hydraulic conductivity ranges between 1.5 and 2 m/day, and the vertical hydraulic

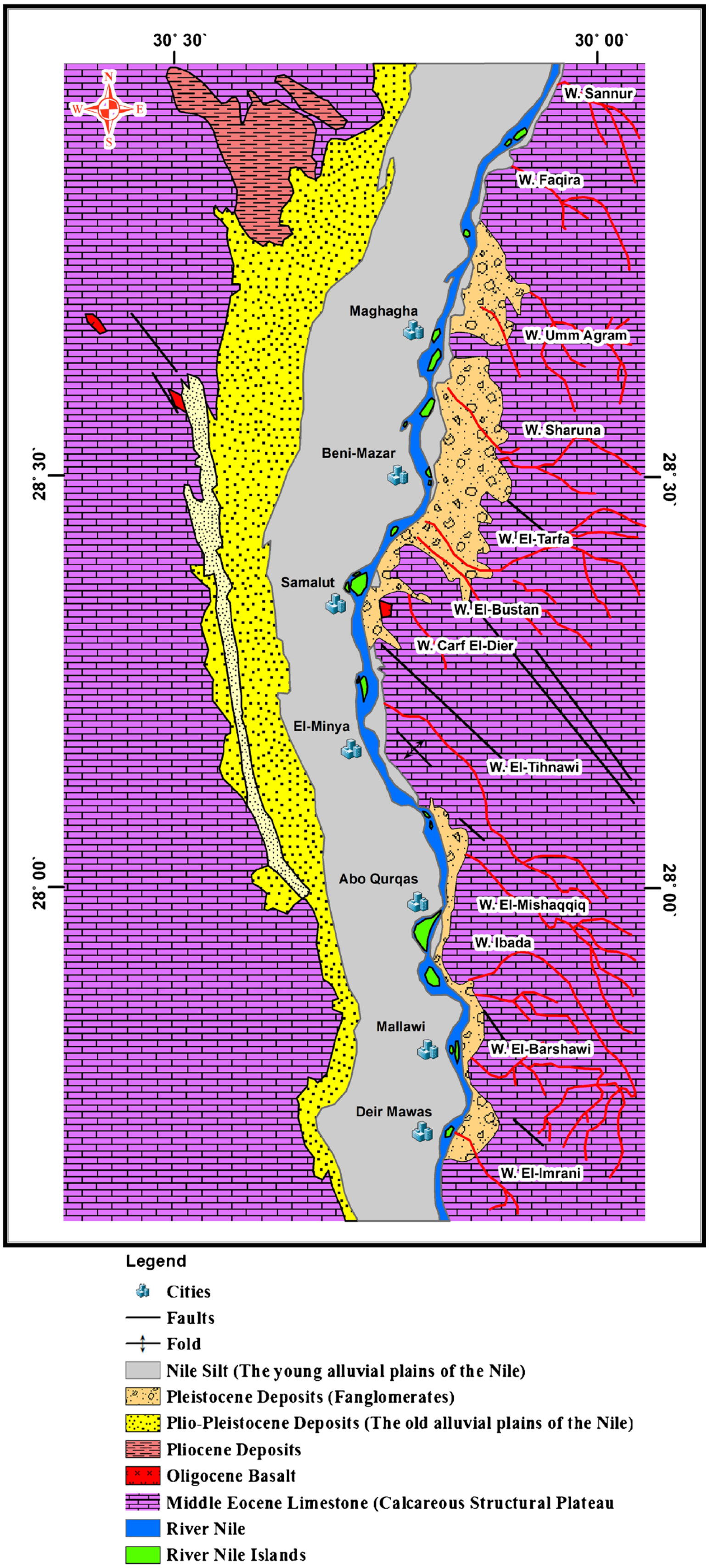


Fig. 3 Schematic geomorphological and geological map of the study area (Said 1981)

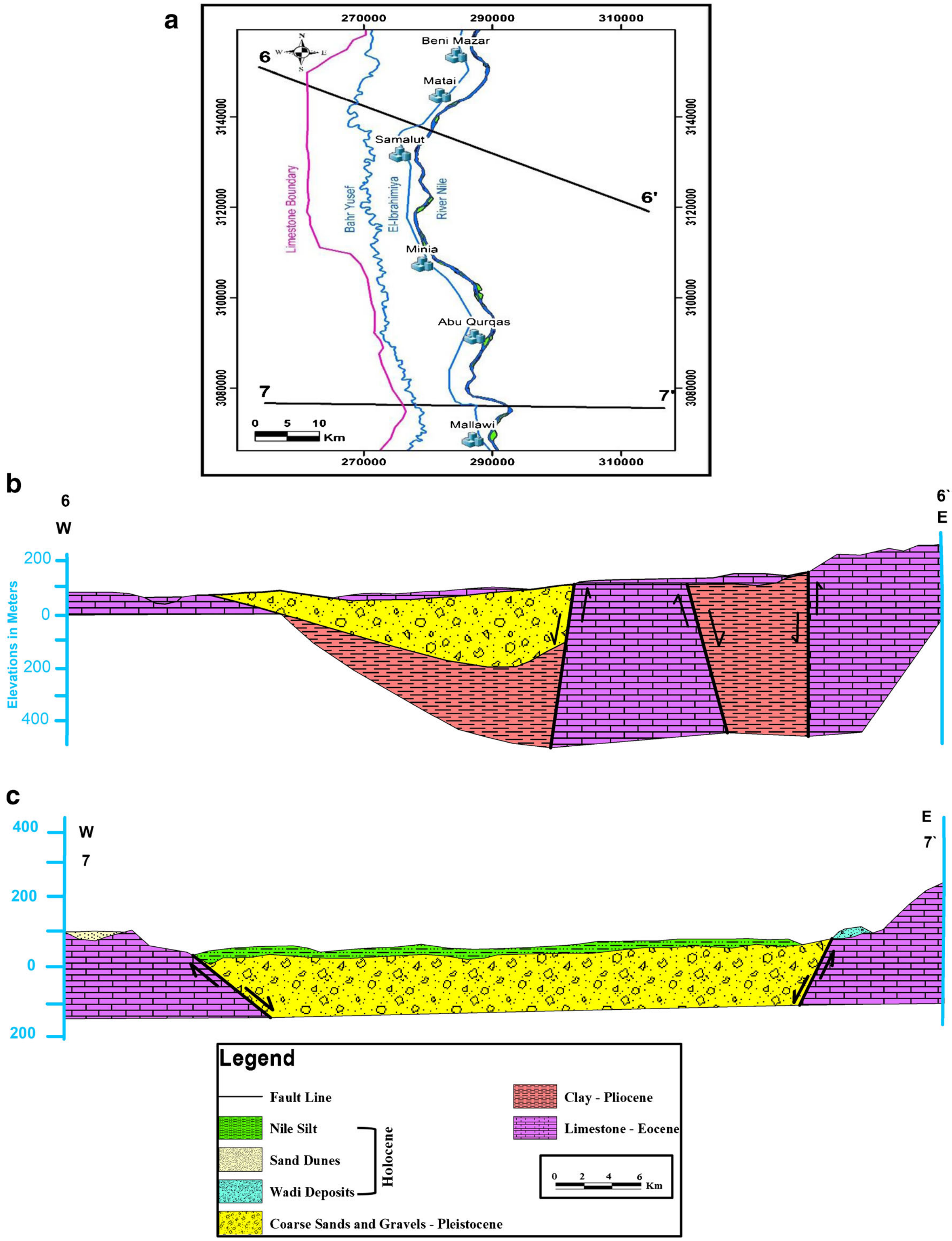


Fig. 4 **a** Geologic cross section locations in the study area. **b** Minia sheet geologic cross section. **c** Mallawi sheet geologic cross section (Said 1981)

conductivity ranges between 0.05 and 0.2 m/day. In addition, the storativity ranges from 0.00001 to 0.0005, the specific yield is about 0.05, the effective porosity ranges from 0.15 to 0.25, and the total porosity ranges from 0.3 to 0.35. In the Pleistocene sand and gravel, the horizontal hydraulic conductivity ranges between 70 and 80 m/day, the vertical hydraulic conductivity is 70 m/day, the storativity is 0.002, the specific yield is 0.2, the effective porosity is 0.2, and the total porosity is 0.3.

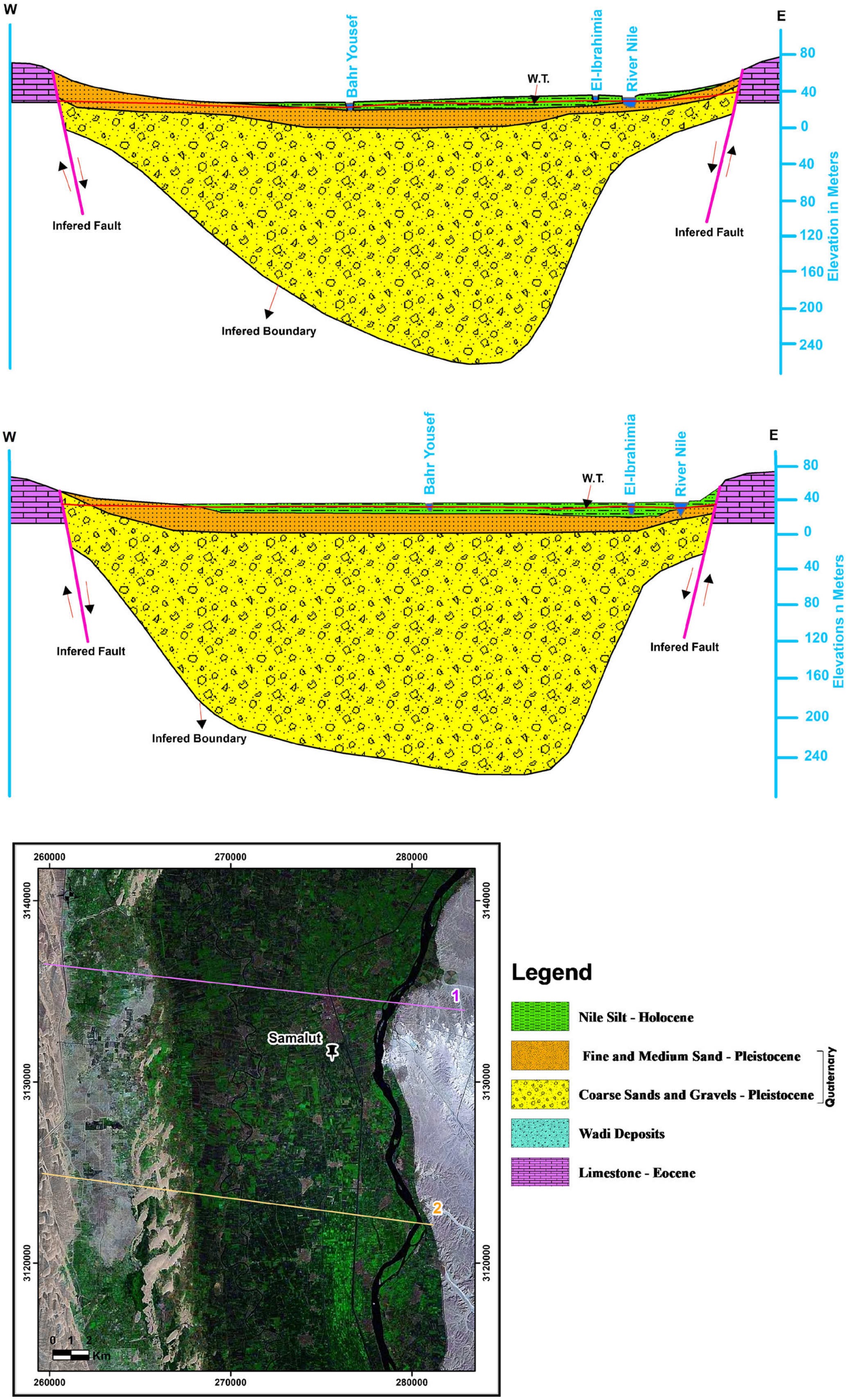


Fig. 5 Hydrogeological cross sections in Samalut city and their locations

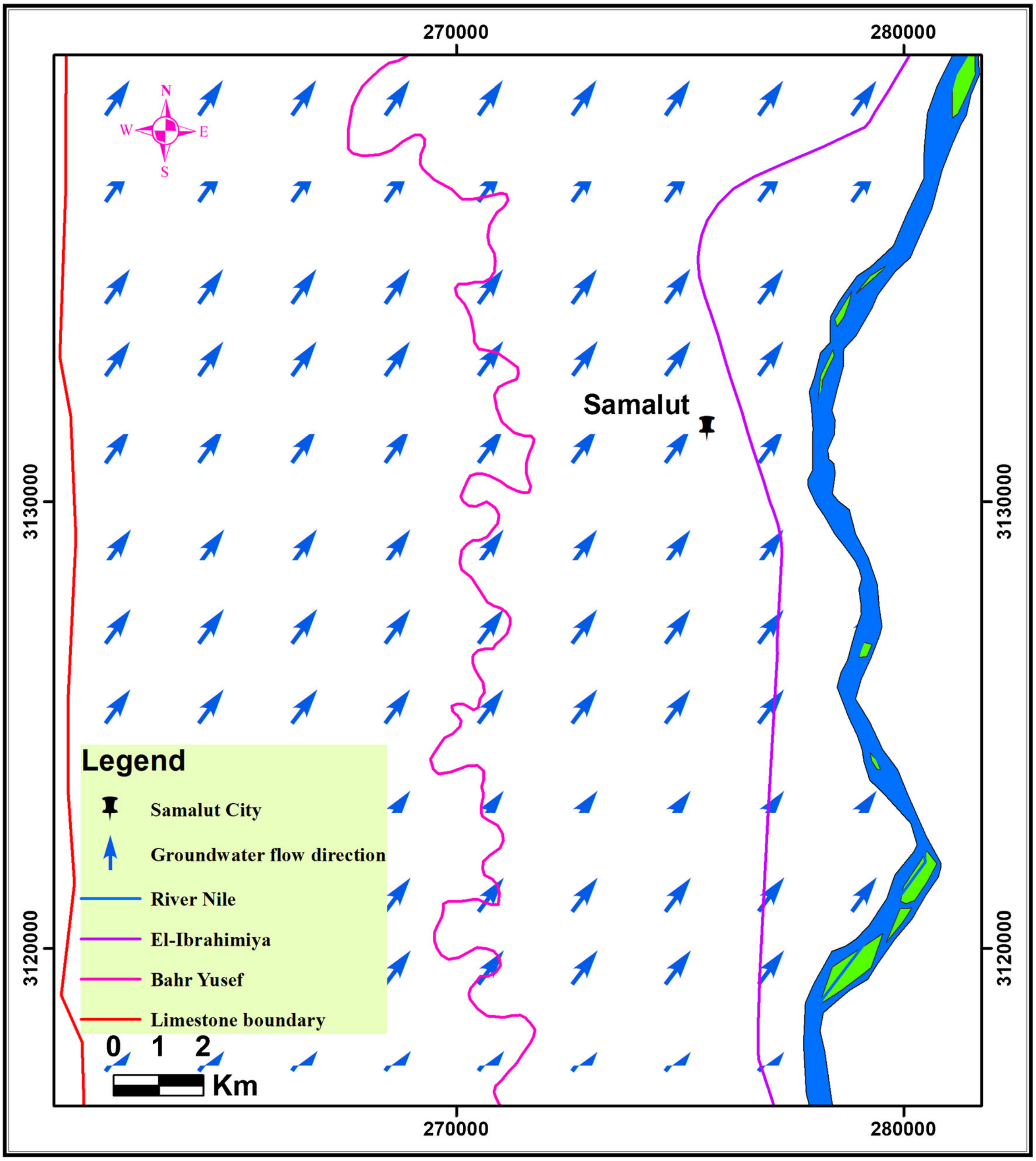


Fig. 6 Groundwater flow directions in the study area

Methodology

Numerical groundwater modeling approach was applied to represent the hydrogeological system, to understand the flow system, to study the recharge possibilities of the aquifer, and to assess the potentiality of the groundwater resources in the study area. Vast amounts of data from numerous sources were used in this work to develop the groundwater flow model. The raw data were analyzed and validated to become reliable enough for the modeling approach. The modeling task goes through the conceptualization, formulation, and construction of a groundwater-flow model. Model construction involved a number of well-defined steps. In summary, these steps are as follows:

1. Establish the minimum area to be represented by the model;
2. Determine the hydrological features that can serve as boundaries to the model.
3. Compile the geological information.
4. Compile the hydrological information.
5. Determine the number of physical dimensions needed for the model.

6. Define the size of the model.
7. Define the model discretization.
8. Input the model boundary conditions.
9. Input the model parameters.
10. Input the model stresses.
11. Run the model.
12. Output the calculated hydraulic heads.
13. Calibrate the model.
14. Apply the prediction runs.

To simulate groundwater flow in the Quaternary aquifer, the three-dimensional, block-centered, finite-difference code MODFLOW (McDonald and Harbaugh 1988) was employed. Data pre- and post-processing was carried out in Geographic Information System (GIS) environment. MODFLOW was integrated with GIS for water resources management in the study area.

Groundwater numerical model

Conceptualization and layers generation

The construction of the conceptual model represents the most critical stage in the model development. Accurate representation of the conceptual model will lead to generate a numerical model with low uncertainties reflecting the actual characterization of the actual system. Therefore, great effort was given to approximate the field situation; accordingly, the conceptual model could be better structured and trustworthy. Setting the conceptualization of the study area was developed by different forms of data such as geologic maps, borings, well logs, cross sections, satellite images, DEM (digital elevation model), and literature data. From the conceptual model, model extent, the types of the boundary conditions and the hydrostratigraphic units were chosen (Fig. 7).

Numerical modeling technique requires continuous spatial attributes of different data at every desired point in the model domain. Consequently, construction of the geologic framework in the study area needs for a continuous distribution to the elevations of the aquifer surfaces. Therefore, all of the available cross sections were designed as a polyline shapefile in ArcGIS (Fig. 8a). The polyline shapefile has been converted into a point shapefile in which the distance between the points along the line is 1 km (Fig. 8b). The known elevations were assigned to these points in the shapefile after dividing of the observed cross sections into points with a distance of 1 km between them and measuring the elevation of each aquifer surface at these points. A polygon shapefile has been constructed in which each polygon includes a group of points that has closed elevations (Fig. 8c). Finally, each point had an observed value of elevation for the three aquifer surfaces. The resulted data were interpolated and the model surfaces were generated (Fig. 9).

Discretization and boundary conditions

The study area is discretized horizontally to 93 rows and 145 columns with cell dimension of 250 × 250 m and vertically into three surfaces (Fig. 10). The model domain is bounded by the River Nile and limestone from the east and the west, respectively, and by Matai city and Minia city from the north and the south, respectively.

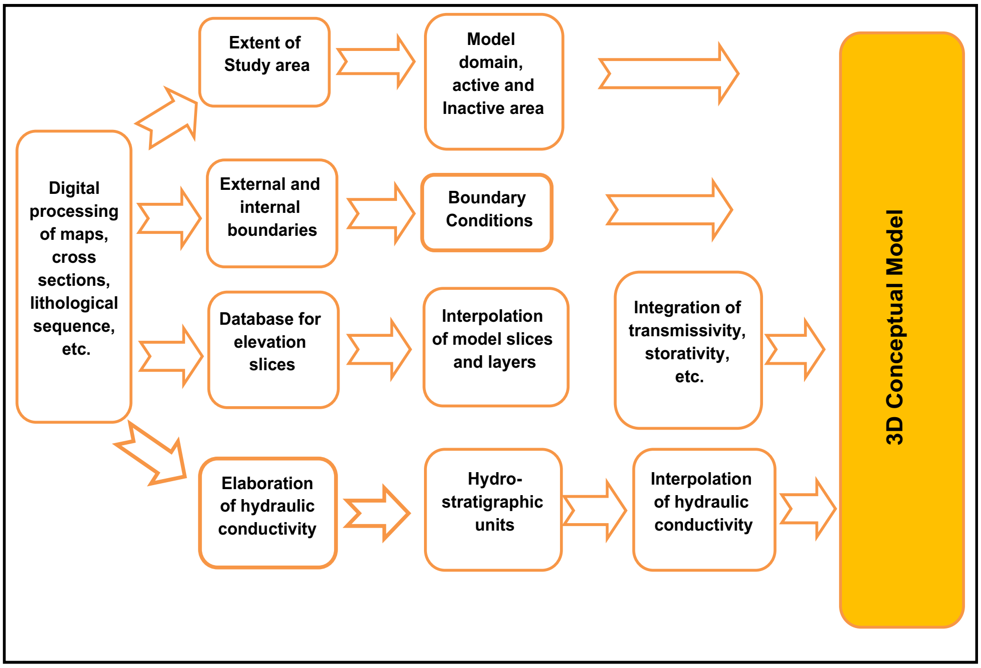


Fig. 7 A flowchart showing block representation of the typical steps for the typical steps for the development of the 3D conceptual model

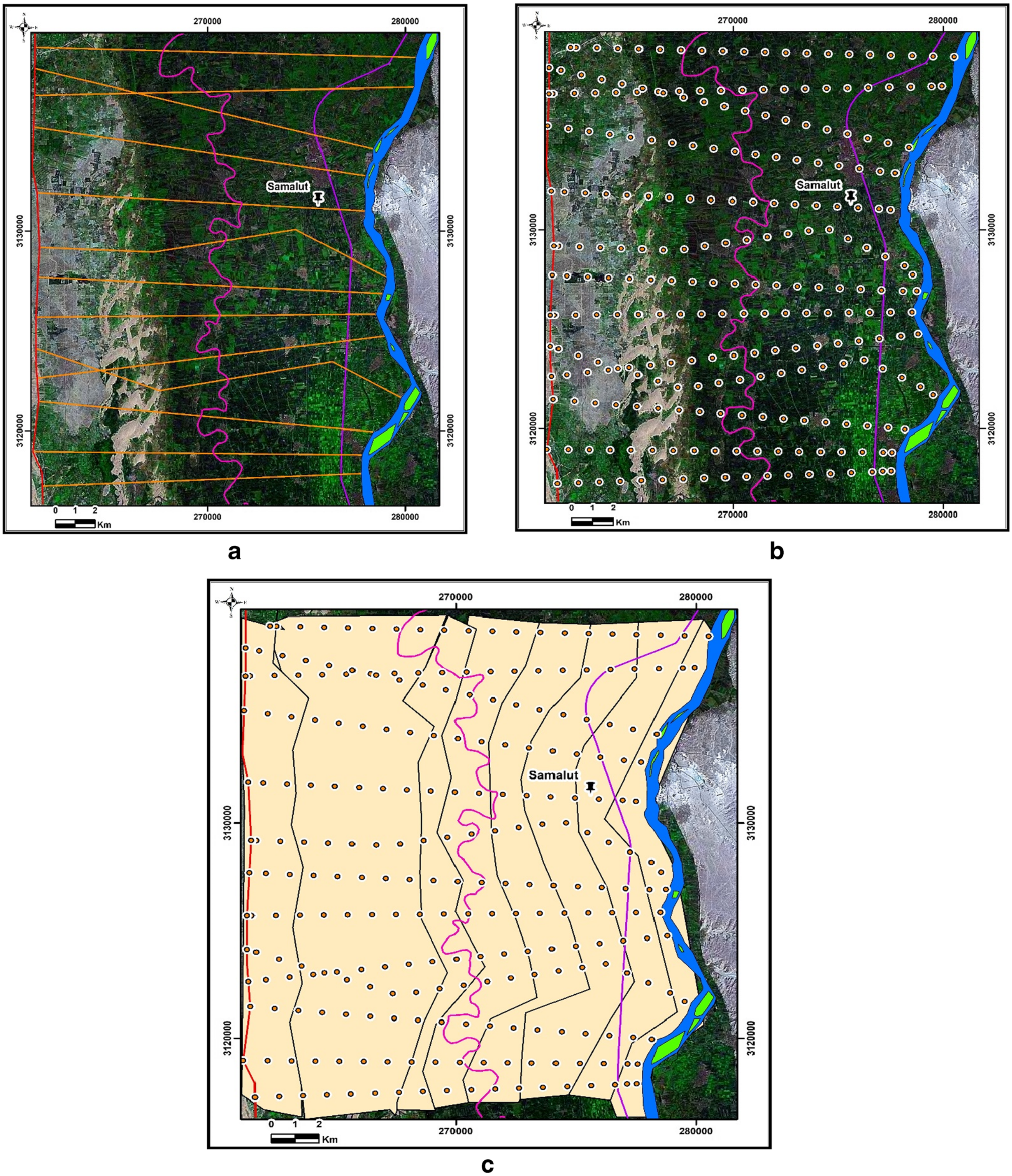


Fig. 8 Stages of constructing database for model layers. Used coordinates: UTM 36 N, WGS 1984

Three boundary conditions were selected in the model:

1. No-flow boundary: Limestone boundary in the western side of the model.
2. River boundary: The Nile and main canals (El-Ibrahimiya and Bahr Yusef) were designed as a river boundary by using the river package in MODFLOW.

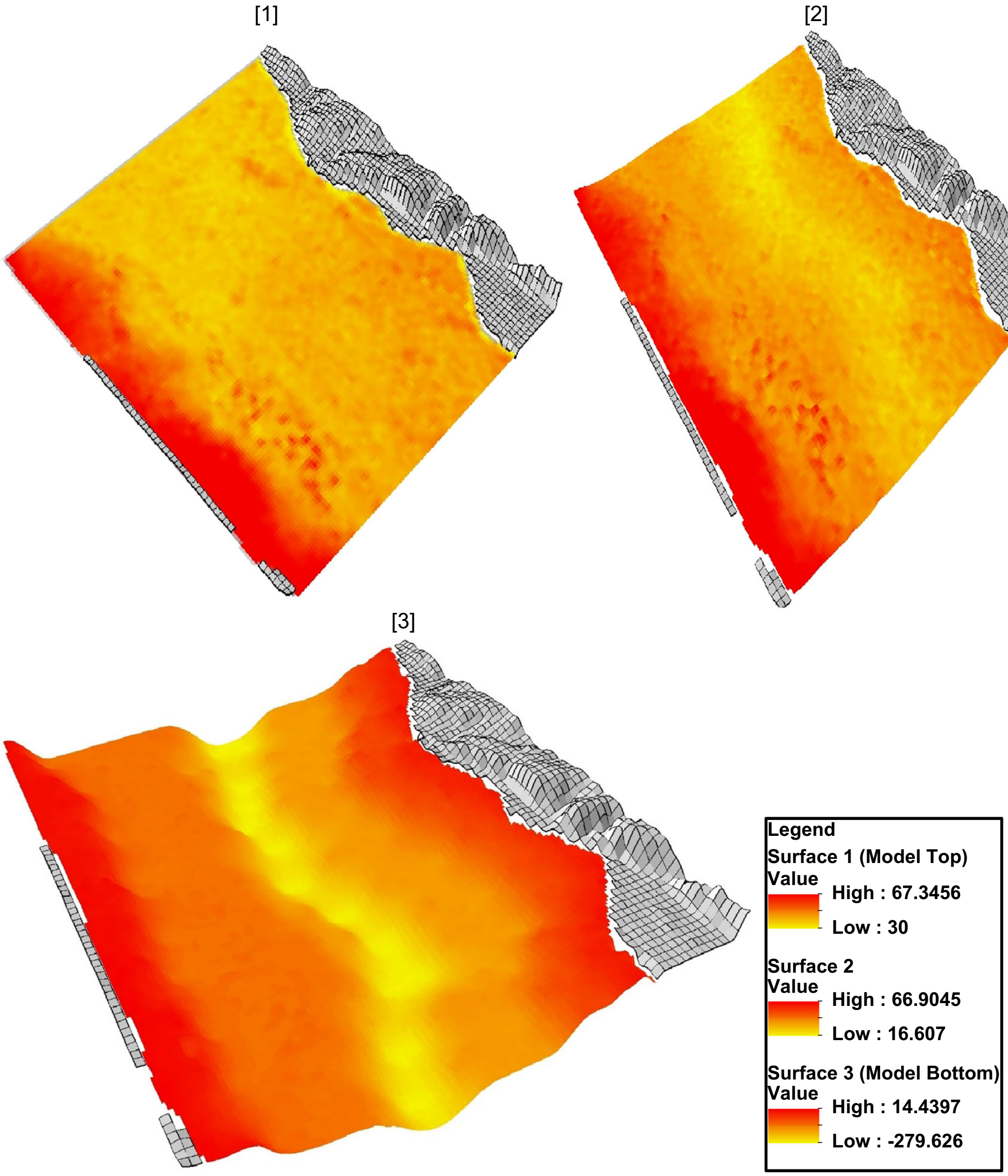


Fig. 9 Interpolated surfaces of Samalut numerical model

3. General head boundary: The northern and the southern boundaries of the model were set as a general head boundary.

Parameters

The field geological observations show that the porous aquifer consists of two layers of quaternary deposits, silts, and clays in the upper layer and sands and gravels in the lower layer. Aquifer parameters control the distribution of groundwater in the aquifer. The initial values of the parameters were obtained from the available pumping tests in the study area as well as the previous hydrogeological studies. On the other hand, the vertical hydraulic conductivity of the riverbed that controls the conductance between surface water and groundwater was calibrated. It has a big influence on groundwater head and the flow interaction between surface water and groundwater in the study area. The parameters were calibrated in the transient simulation. The initial and calibrated parameters in the study area are presented in Table 1.

Recharge and discharge

The aquifer is mainly recharged from the surface water and that will be calculated by the model. Furthermore, it is recharged

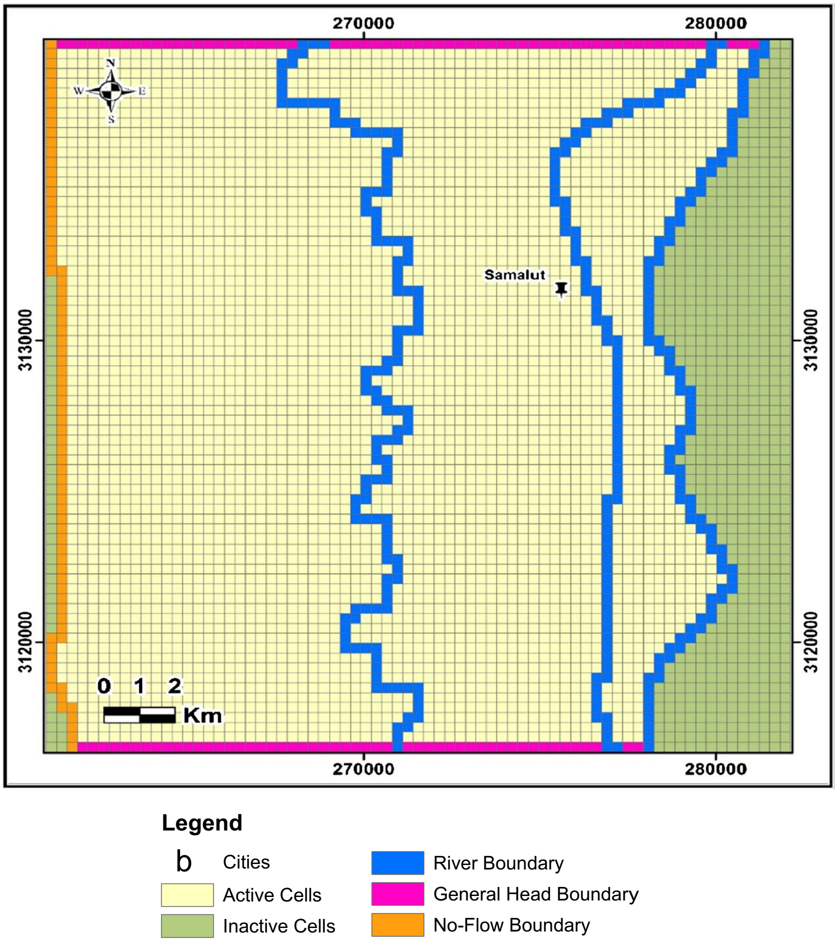


Fig. 10 Model design: active cells, inactive cells, and boundary conditions. Used Coordinates: UTM 36 N, WGS 1984

from the excess of irrigation which ranges from 0.5 to 0.8 mm/day in the old agricultural lands and ranges from 1.0 to 1.5 mm/day in the desert fringes of the new reclaimed lands (Dawoud and Ewea 2011). The discharge includes discharge from pumping wells which equal to 0.246 MCM/day (RIGW 2015) and from evapotranspiration which equals to 4.66 mm/day (Ouda et al. 2016).

Calibration

Steady-state calibration

Steady-state conditions represent a natural balance regime inputs and outputs from the system. Sequential runs were done to match between the observed and simulated water level contours. Figure 11 shows matching between simulated contour lines against observed contour lines. There was no real steady-state condition found from the simulation results.

Transient-state calibration

The model was calibrated in transient-state conditions by the variable heads of 15 observation wells distributed in the study area from 2005 to 2013 that were used as calibration targets. Trial and error was used to calibrate the model in which the hydraulic conductivity and the specific yield were adjusted to minimize the difference between the observed and calculated heads. This

Table 1 Initial and calibrated model parameters

Aquifer parameter	Initial value	Calibrated value
Hydraulic conductivity of the upper layer (m/day)	0.4–1	0.75
Hydraulic conductivity of the lower layer (m/day)	20–80	40–50
Specific storage of the lower layer (main aquifer) (m^{-1})	0.001–0.003	0.0025
Specific yield of the lower layer (main aquifer)	0.2–0.25	0.21
Vertical hydraulic conductivity of the riverbed (m/day)	0.002–0.1	0.0039

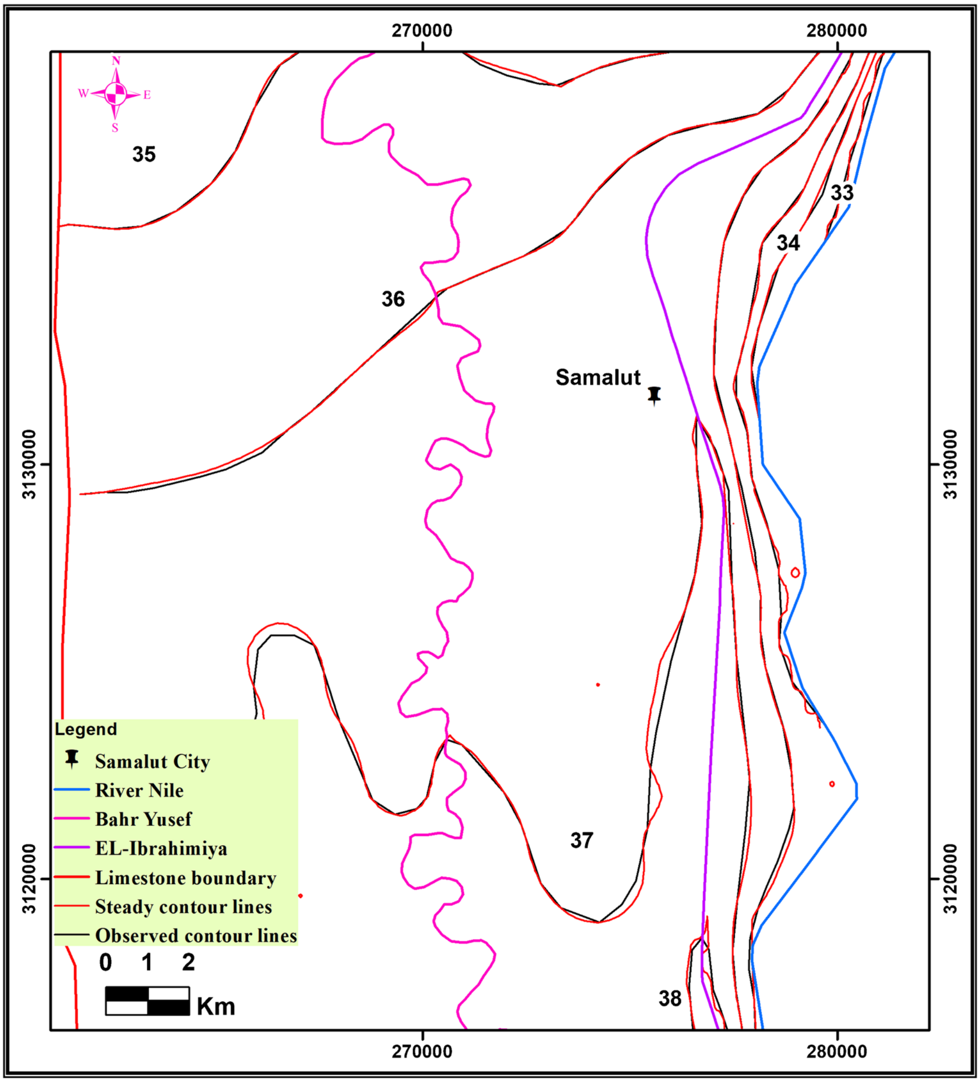


Fig. 11 Matching between simulated and observed contour lines of in model calibration. Used coordinates: UTM 36 N, WGS 1984

procedure was repeated until the variance was in a reasonable range. The goodness-of-fit was measured by hydrographs comparing simulated versus measured hydraulic heads (Fig. 12).

The variables, observed hydraulic head and the calculated head, were compared with the scatter shown in Fig. 13. It can be seen that there was a good match between the observed and calculated head values. The residuals, or difference between simulated and observed heads, ranged from − 0.16 to 0.26 m with a mean of 0.42 m, a root mean square of 0.14 m. So, the model is calibrated and ready for prediction.

Model results and discussion

Water management plans require an accurate water budget and studying the effect of natural or artificial impacts on groundwater levels in the future. The proposed scenarios were designed in the model to assess the response of the aquifer to the proposed stresses. The results of the calibrated numerical model of Samalut city include groundwater budgets and groundwater levels in the current state (2013) and the proposed scenarios (2030).

Current state

In the current state of the model, groundwater budget and level are calculated in 2013 as follows:

Groundwater budget

The main source of recharge to the aquifer system comes from the surface water leakage or recharge from the surface water which is equal to 301,235 m^3/day. Groundwater flux across the southern boundary of the model is 67,182 m^3/day. Infiltration from irrigation water

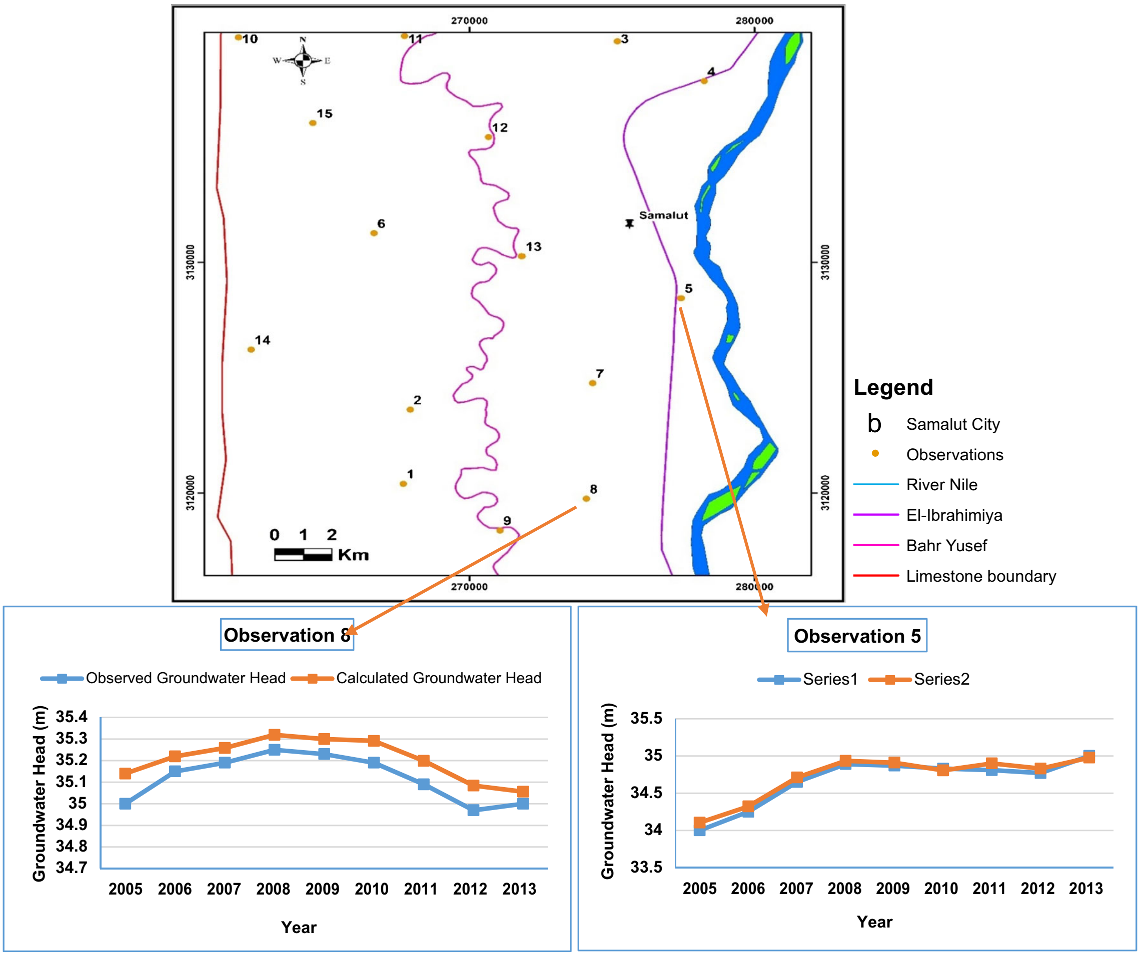
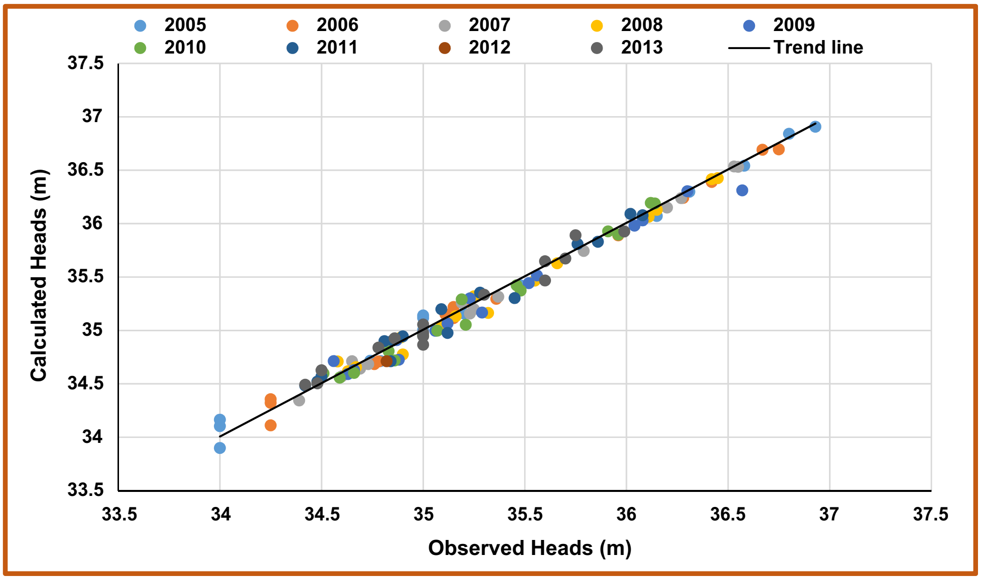


Fig. 12 Matching between simulated and observed contour lines in model calibration. Used coordinates: UTM 36 N, WGS 1984

which is supposed to be constant in the current state and in all scenarios is 62,500 m^3/day. Accordingly, the total inflow to the aquifer is about 430,917 m^3/day. On the other hand, groundwater pumping represents the main water budget component discharging from the aquifer which is equal to 246,000 m^3/day. Another main outflow

Fig. 13 Scatter plot of observed versus calculated values of head for model calibration



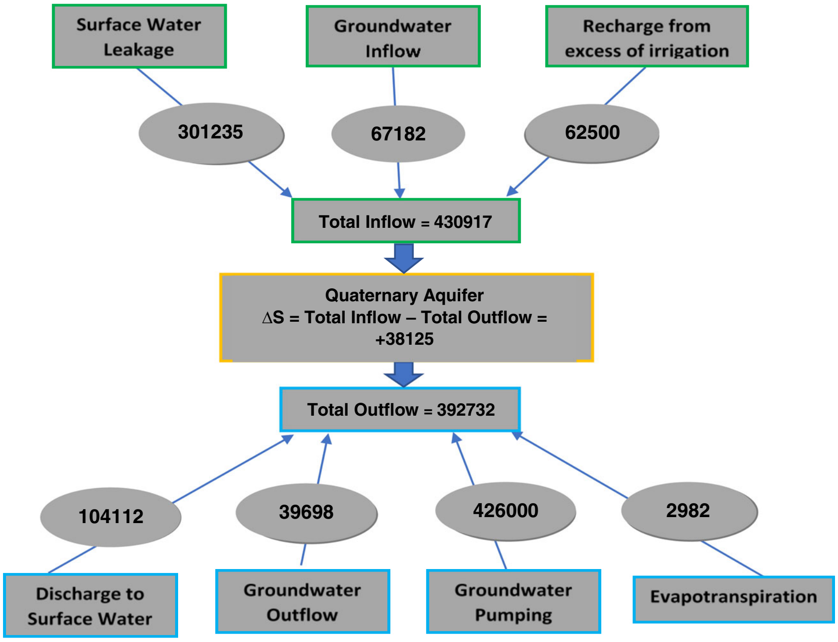


Fig. 14 Simulated water budget for the Quaternary aquifer in the current state (2013). Units are given in m^3/day

component is the outflow from the aquifer to surface water (baseflow) which is 104,112 m^3/day. Groundwater outflow from the northern boundary equals to 39,698 m^3/day. Groundwater evapotranspiration is 2982 m^3/day. Accordingly, the total outflow from the aquifer is about 392,792 m^3/day. Consequently, the change in the aquifer

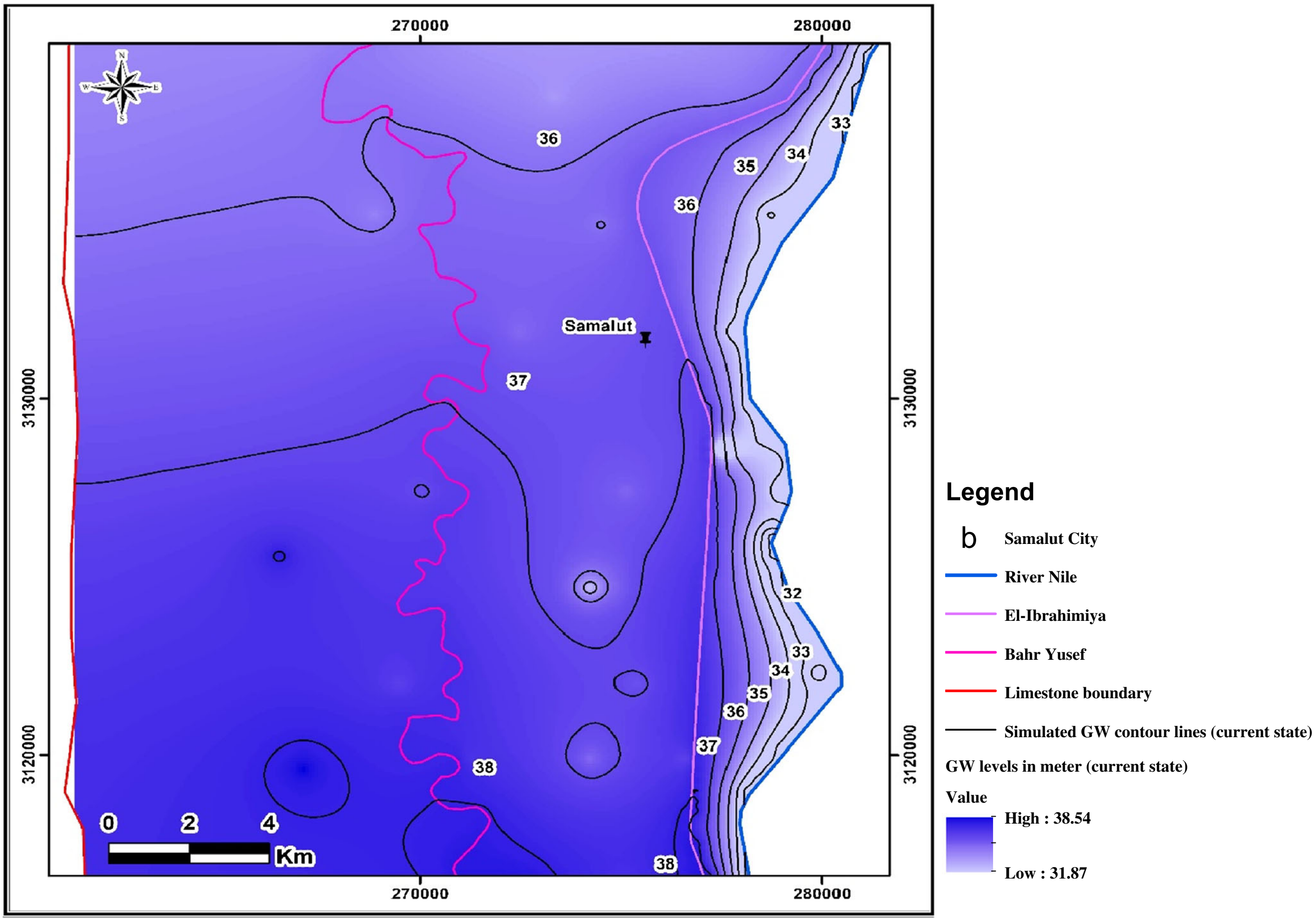
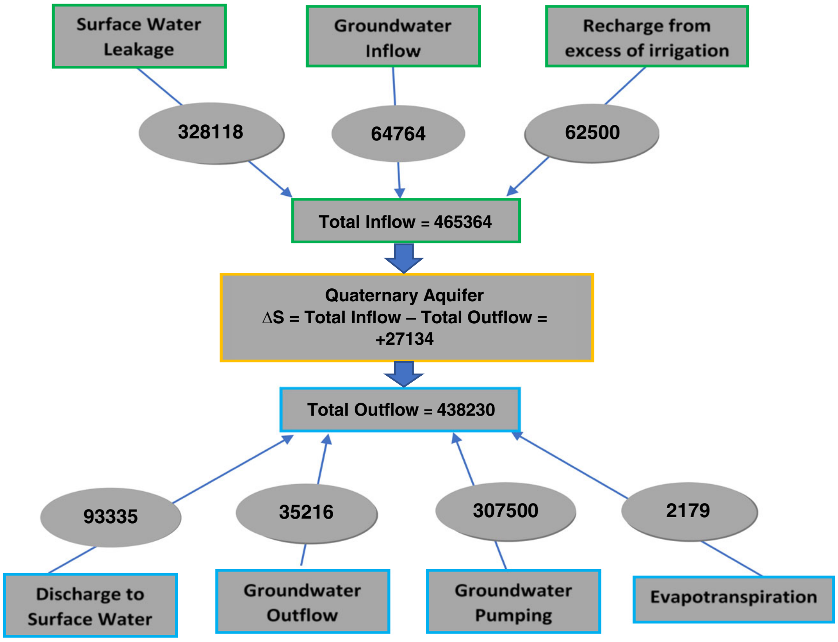


Fig. 15 Simulated groundwater levels of the Quaternary aquifer in the current state

Fig. 16 Simulated water budget for the Quaternary aquifer in scenario 1 (2030). Units are given in m^3/day



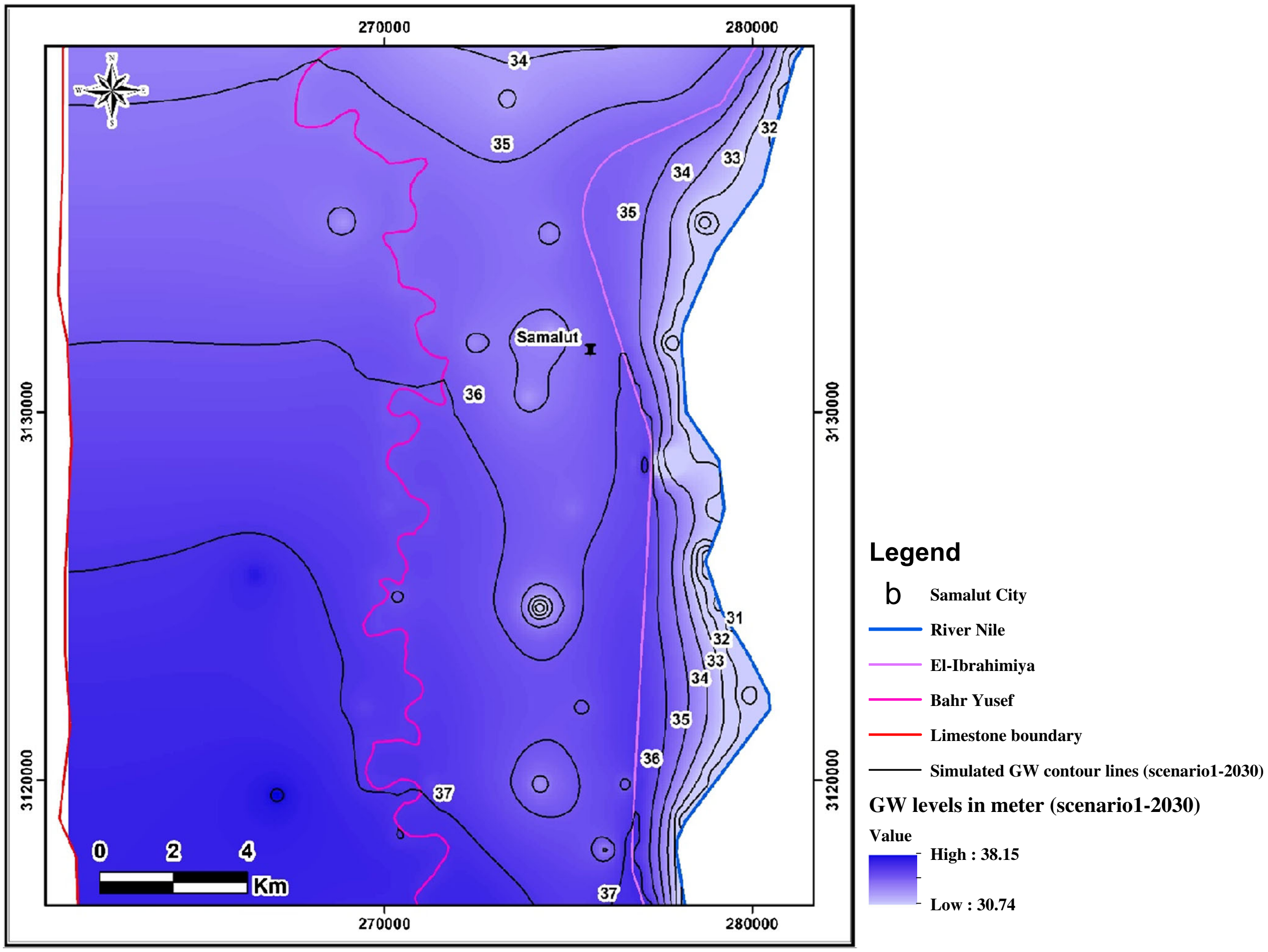


Fig. 17 Simulated groundwater levels of the Quaternary aquifer in scenario 1 (2030)

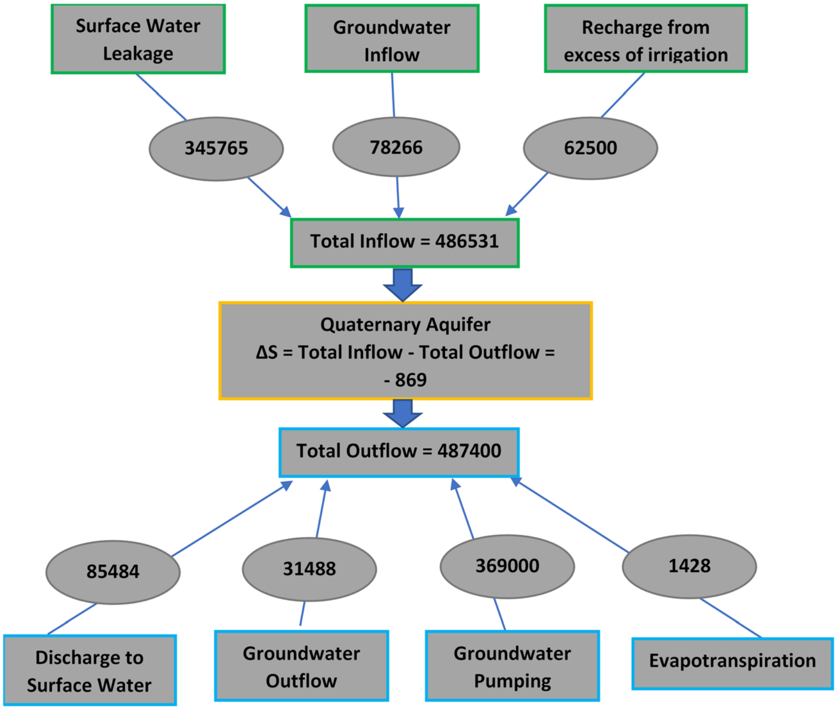


Fig. 18 Simulated water budget for the Quaternary aquifer in scenario 2 (2030). Units are given in m^3/day

storage is positive and equals to + 38,125 m^3/day (Fig. 14). It can be noticed that the positive ΔS of the groundwater is mainly due to the amount of surface water recharged to the groundwater.

Groundwater levels

In the current state, groundwater levels are ranging from 38.54 to 31.87 m. Figure 15 shows the distribution and the patterns of the groundwater level contour lines in the case of current state. It can be seen that hydraulic gradient is high in the area between the River Nile and El-Ibrahimiya while it becomes gentle in the area between El-Ibrahimiya and Bahr Yusef.

Model scenarios

In addition to surface water, groundwater represents an important source for water for different purposes in the area under investigation such as irrigation, industry, drinking, and domestic uses. Therefore, the demand on groundwater extraction is expected to increase continuously. Consequently, two pumping scenarios are proposed to assess the response of the aquifer during increasing groundwater pumping in the future. In the first scenario, groundwater extraction is increased by 25% or to be 307,500 m^3/day while it is increased by 50% or to be 369,000 m^3/day in the second scenario. Groundwater budget and groundwater levels are calculated in 2030.

Scenario 1: increase groundwater extraction by 25% (307,000 m^3/day)

Water budget In this scenario, the recharge from surface water is equal to 328,118 m^3/day. Groundwater which inflows across the southern boundary of the model is 74,746 m^3/day. Infiltration from irrigation water is 62,500 m^3/day. According to that, the total inflow to the aquifer is 465,364 m^3/day. On the other hand, groundwater pumping is equal to 307,500 m^3/day. Discharge from the aquifer to the surface water is equal to 93,335 m^3/day. Groundwater outflow from the northern boundary equals to 35,216 m^3/day. Evapotranspiration is 2179 m^3/day. According to that, the total outflow from the aquifer is 438,230 m^3/day. Consequently, the change in aquifer storage is positive and is equal to + 27,132 m^3/day (Fig. 16).

Groundwater levels

In scenario 1, the groundwater levels are ranging from 38.15 to 30.74 m. Figure 17 shows the distribution and the patterns of the groundwater level contour lines in the case of scenario 1. It can be noticed that the contour line of 38 m disappeared in the south, and the contour line of 34 m appeared clearly in the north. Contour lines are shifted southward from its locations in the current state. In addition, the cone of depressions started to appear around the pumping field in some locations due to increasing of groundwater pumping by 25%.

Scenario 2: increase groundwater extraction by 50% (369,000 m^3/day)

Groundwater budget In this scenario, the recharge from surface water is 345,765 m^3/day. Groundwater which inflows across the southern boundary of the model is 78,266 m^3/day. Infiltration from irrigation water is 62,500 m^3/day. According to that, the total inflow to the aquifer is 486,531 m^3/day. On the other hand, discharge from groundwater pumping is 369,000 m^3/day. Discharge from the aquifer to surface water is 85,484 m^3/day. Groundwater outflow from the northern boundary is 31,488 m^3/day. Evapotranspiration is 1428 m^3/day. According to that, the total outflow from the aquifer is 487,400 m^3/day. Consequently, the change in aquifer storage is negative and is equal to − 869 m^3/day (Fig. 18).

Water levels In scenario 2, the groundwater levels are ranging from 37.57 to 26.95 m. Figure 19 shows the distribution and the patterns of the groundwater level contour lines in the case of scenario 2. It can be seen that contour lines are continuously shifted southward from its locations in the current state and scenario 1 and the appearance of many cone of depression around the pumping fields.

Conclusion

The results of this work showed that the River Nile is in direct contact with the Quaternary aquifer system and acts as a drain in the study area while the main surface water canals, El-Ibrahimiya and Bahr Yusef, represent a source of recharge to the aquifer. Groundwater flow regime takes the northeast direction. The simulation revealed that there is no typical steady-state condition for the Quaternary aquifer in the study area, as the aquifer has been undergoing stresses. The simulation showed that there have to be a groundwater recharge to the Quaternary aquifer from the limestone boundary in the west. Groundwater pumping scenarios confirmed that surface water represents a main source of recharge to the aquifer especially when increasing groundwater extraction. Recharge from surface water to groundwater is increased to compensate the decrease of the aquifer storage during increasing of

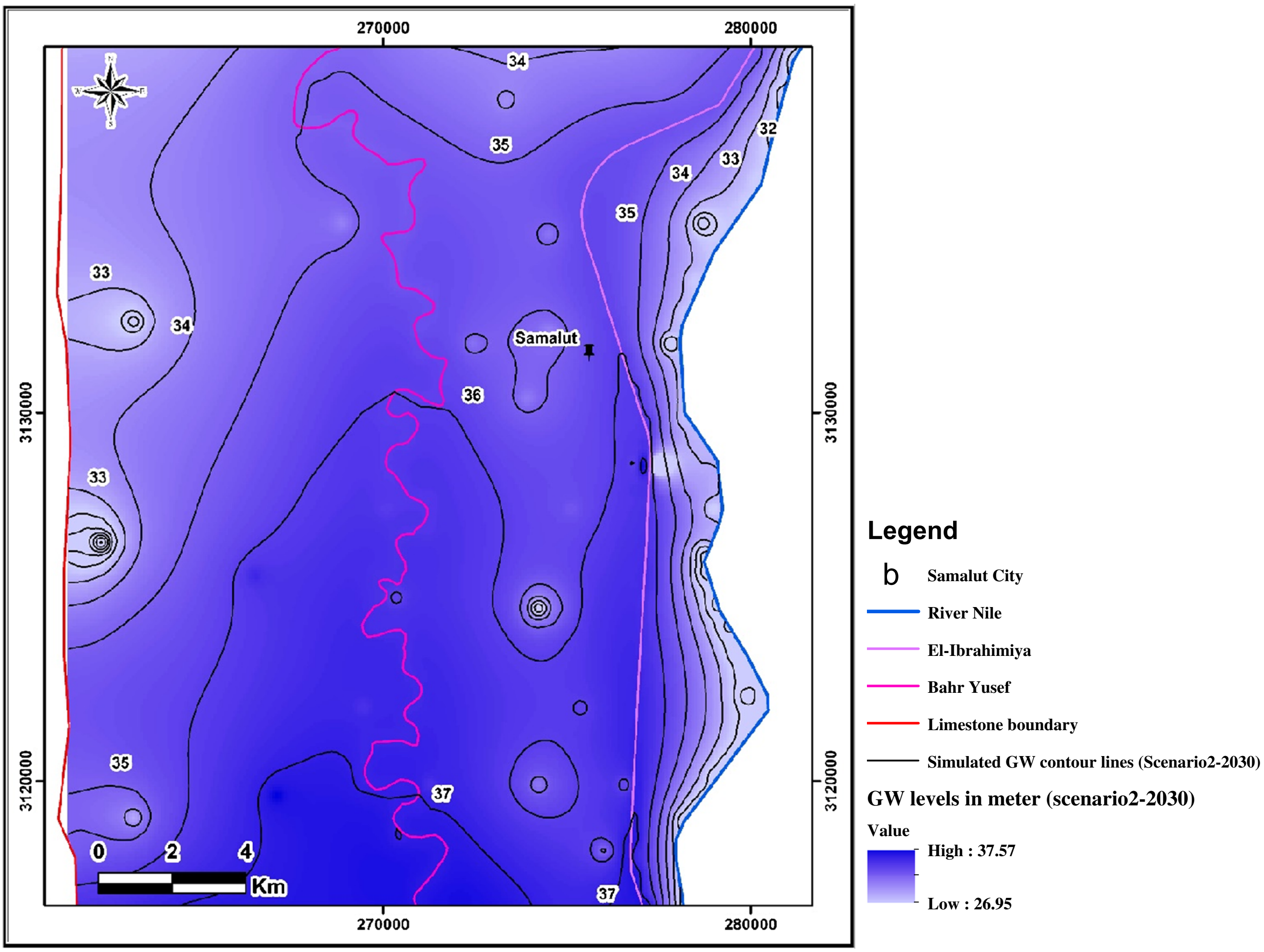


Fig. 19 Simulated groundwater levels of the Quaternary aquifer in scenario 2 (2030)

groundwater extraction. The results showed that increasing of groundwater extraction more than 50% of the current state extraction will decrease the storage of the aquifer to a negative value and that represents a challenge for water management in the study area. Furthermore, groundwater levels are clearly decreased with the increase of the extraction from the aquifer. Due to the hydraulic contact between surface water bodies and the Quaternary aquifer, surface water-groundwater interaction plays an important role in the study area in which any change in the flow and in water levels will affect the regional groundwater budget and the groundwater level in the aquifer. So, understanding this interaction and the nature of this complex flow system represents a great challenge for water resources management in the study area.

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