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Numerical modeling for groundwater resource management in the area southeast of Sohag Governorate, Egypt

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ABSTRACT

The desert area southeast of Sohag is a target area for development and agricultural expansion, where the Quaternary aquifer is the main water resource. In this study, a groundwater flow model was developed for groundwater management and forecasting groundwater levels and flow under different conditions. This model was calibrated under transient conditions for the period 2017-2021. The calibrated model was used to predict the groundwater conditions in this area through three different scenarios. The first scenario assumes that the groundwater extraction rates remain the same for 20 years, while the second scenario suggests that extraction rates were doubled. The third scenario considers the role of surface water in groundwater recharge. It supposes the decrease in the River Nile and the Eastern Nag Hammadi Canal levels by 1 and 0.5 m, respectively. The results of these scenarios indicated that the most drawdown is always in the southeastern part of the study area where the majority of wells were drilled, while the minimum drawdown is in the western side close to the Nile floodplain area where feeding from both surface water and adjacent aquifer unit is predominant. Moreover, the maximum drawdown of 10.5 m was observed in the second scenario in the eastern and southeastern parts. In contrast, the western part is expected to be significantly affected by the third scenario, where the flux from surface water to groundwater decrease. It is necessary to rationalize irrigated water consumption by using the appropriate irrigation method.

1. Introduction

Water is one of the most important renewable resources and vital for the environment, all life existence, and social development. Water is becoming limited in quantity in many areas around the world. Egypt is one of the semi-arid countries where the amount of water available imposes limits on its national economic development. Groundwater is the primary factor in the development of the country, especially in the desert areas where Nile water is challenging to deliver.

Recently, the government began desert reclamation to relieve pressure on the Nile Valley, and the people also began to exploit the vast desert areas for agriculture. The desert areas east of Sohag are the newly reclaimed areas depending mainly on groundwater as tens of wells were randomly drilled.

The continuous increase in groundwater demand in the newly reclaimed desert areas is believed to affect the sustainability of the groundwater supply both quantitatively and qualitatively.

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As a result, the recharge to the groundwater aquifers may not be sufficient to support future large-scale agricultural development, which leads to severe problems concerning the continuous decline in groundwater levels, which could be managed using a proper simulation model. Groundwater flow models were developed to address the groundwater conditions in the Nile valley on both sides of the River Nile, Egypt (Abd El-Moneim et al., 2016; Abdelhalim et al., 2019; El-Rawy et al., 2021; Sefelnasr et al., 2019, 2015)

This research aims to develop a groundwater flow model for the Quaternary aquifer in the desert area southeast of Sohag governorate to characterize the Quaternary aquifer system and investigate changes in groundwater levels in response to groundwater extraction future for better groundwater management in that area. In addition, groundwater flow direction, groundwater budget, and groundwater-surface water balance has been investigated using this model.

2.Study area

The study area is located southeast of Sohag governorate on the eastern side of Nile Valley east of El-Balyana and Dar El-Salam cities. It lies between longitudes 31˚ 57'and 32˚ 15'E and latitudes 26˚ 08'and 26˚ 23'N (Figure 1). This area is important as it is considered one of the most promising areas for reclamation (Elbeih et al., 2021). It is a low land area belonging to the old alluvial plain located between the Nile floodplain and the edge of the eastern plateau. It is mainly underlain by mixed sands and gravels or rock fragments mixed with weathered rock products. The surface is incised by many dry streams, which have their uptake areas located in the adjacent plateau areas outside the Nile valley and are responsible for accumulating the old alluvial deposits (Said, 1962). A high vulnerability for flood characterizes the study area; Qassab and Abu Nafukh watersheds are two major wadis contributing to an increased risk of flash floods (Abu El-Magd et al., 2020). The area has a distance of 4-11 km. from the River Nile with elevation ranges between 61-220 m. The area has a semi-arid climate, with the highest temperature in summer (46.6 °C), and the lowest temperature (8 °C) in winter (EMA, 2012).

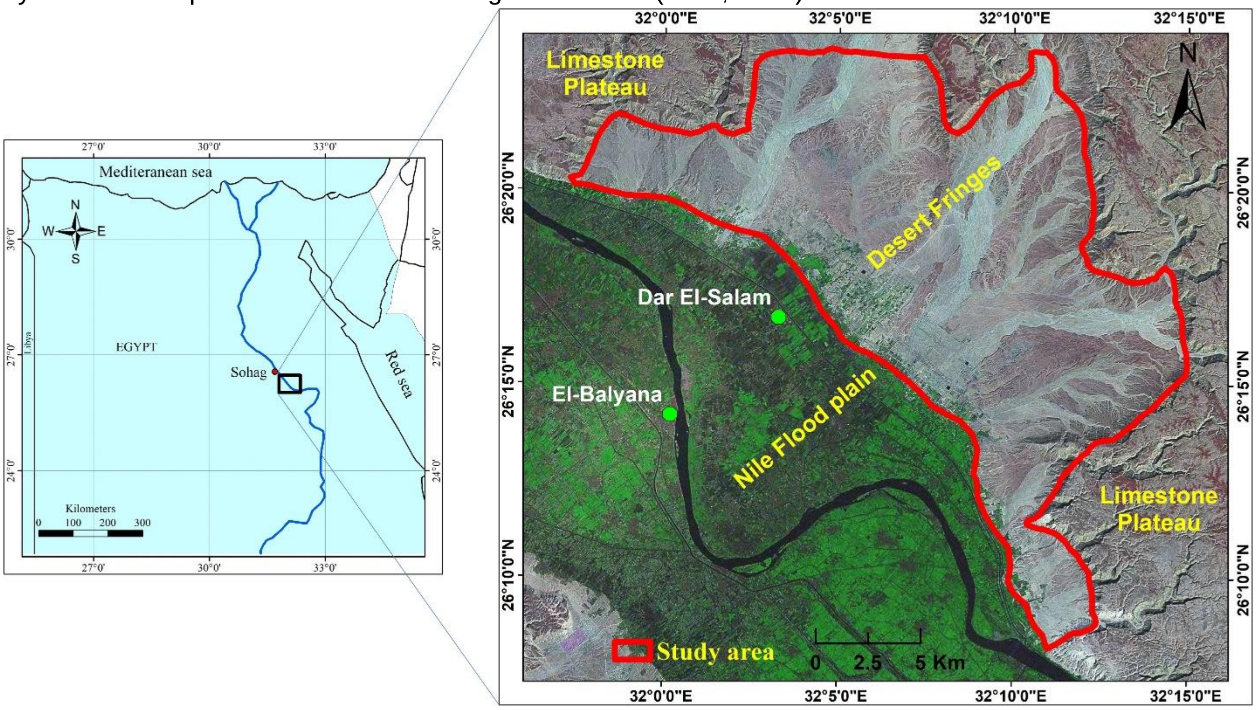

Figure 1. Location map of the study area with the geomorphological units.

3.Geological characteristics

Sohag basin is oriented NW-SE and occupies an area of 40 km in length and 15 km in width. This basin is bounded by linked NW, NNW, NE and N-S striking fault segments (Mahran, 1995; Said, 1990, 1981). The study area is a part of Sohag basin which is located in the Middle Egypt, and probably formed in Early Miocene time during the initial stages of the Nile Valley evolution (Philobbos et al., 2015)

The general sedimentary succession cropping out in the study area ranges in age from Lower Eocene to Quaternary and includes two main lithostratigraphic sequences separated by a major unconformity; the lower Eocene carbonates sequence overlain by Miocene to Plio-Quaternary sequence (Figure 2). The Lower Eocene sequence is subdivided into two rock units; the Thebes Formation overlain by Drunka Formation. The Thebes Formation constitutes the foot of the eastern limestone scarp consisting of thick-bedded limestone with chert bands and nodules (Abotalib and Mohamed, 2012; Said, 1990). Drunka Formation, covering more than 90% of the area around Sohag and is characterized by snow-white limestone with massive bedding (Ahmed, 1980). The unconformably overlying Miocene to Plio-Quaternary sequence belongs to the Pre-Eonile and Eonile stages of the Nile evolution (Mahran et al., 2013), and includes the Katkut, Madmoud, Armant, Issawia, Abbasia and Dandara formations. The Miocene Katkut Formation is dominated by conglomerates and sandstones and occurs as patches overlying directly the western limestone escarpment. The Madmoud Formation represents the Pliocene sediments and consists of chocolate brown claystones and siltstones (Said, 1990). The Armant Formation belongs to Early Pleistocene, and consists of thick bedded tufa and travertine carbonates interbedded with sandstones and conglomerates. The Issawia Formation is Early Pleistocene in age, and composed of mixed red breccias and conglomerates unconformably overlying Armant carbonates. Qena Formation is Middle Pleistocene which composed of dominant sandstones with lenticular bodies of conglomerates (Said, 1981). The Middle Pleistocene Abbasia Formation consists of conglomerates embedded in a reddish brown sandy matrix. The Late Pleistocene Dandara Formation dominated by fine siliciclastic deposits that gathered on the banks of the River Nile. The Holocene and Recent sediments consist of sands intercalated with silts and clays representing the cultivated lands and fertile of the Nile Valley (Ahmed, 1980).

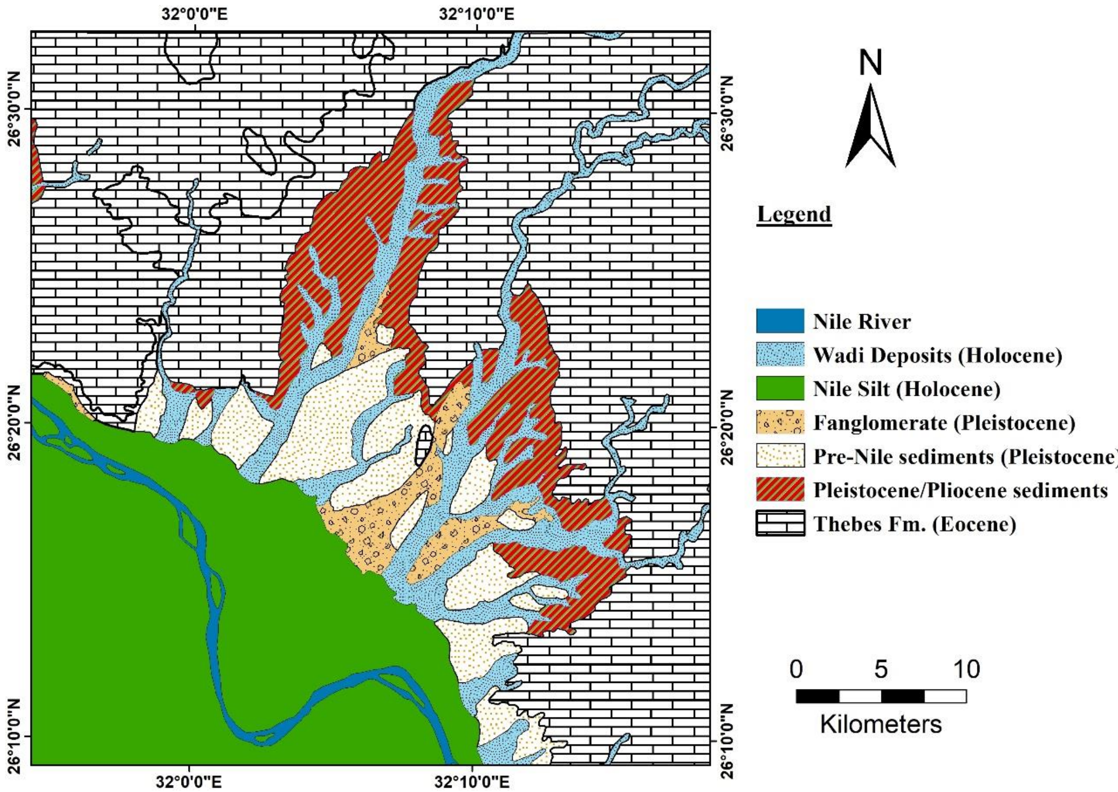

Figure 2. Simplified geological map of the southeast Sohag district (EGSMA, 1983)

4. Hydrogeological Setting

The Quaternary aquifer is formed by alluvial deposits of the River Nile and built mainly of two successive units, from top to bottom; Holocene silty clay unit that capped the water-bearing Pleistocene unit in the young alluvial plain (Nile floodplain) and vanished towards the limestone plateau. It acts as a semi-confining layer to the underlying aquifer. In contrast, in the old alluvial plain (desert fringes), the silty clay layer is absent, and the Quaternary aquifer becomes phreatic (Barber and Carre, 1981) (Figure 3), The Quaternary aquifer system is underlain by the impermeable Pliocene clay. The underlying Pleistocene water-bearing unit is composed mainly of sand and gravel intercalated with clay lenses. It is underlain by Paleonile sediments made of red-brown Pliocene clay overlying the fissured Eocene limestone and forming the Cenozoic clastic aquifer base in most localities of the studied area (RIGW-IWACO, 1989).

The Quaternary aquifer saturated thickness ranges from 200m at the center of the floodplain to 40m at the outer portion at the desert fringes (Warner et al., 1991). The main sources of recharging the aquifer are the subsurface seepage from the surface water systems and the infiltration of irrigation water, while the primary discharge source is through the extraction wells penetrated in the aquifer. The horizontal and vertical hydraulic conductivity of the capping sediments are 0.06 and 0.0086 m/d, the specific storage coefficient is 7.6×10^{-6} (Abdel Moneim, 1999). The Pleistocene aquifer horizontal hydraulic conductivity ranged from 40-100 m/d (Zaki, 2007).

5. Material and Methods

A Numerical groundwater model was applied in this study to represent the groundwater systems and to detect the groundwater balance component in the study area. This study used a large quantity of data from various sources to construct a groundwater flow model. The raw data was evaluated and validated before being used in the modeling process.

In this study, a groundwater flow model was applied in two different time scales of analysis: a steady-state and a transient model. In the steady-state, simulation was first to run for 2017. This year represents the year where little development happened, with much of the data available.

The importance of the steady-state simulation is to investigate the model components, make primary calibration of the model parameters such as hydraulic conductivities, conductance and riverbed thickness of surface water bodies, and recharge values resulting from applied irrigation water, get the initial head for all model layers which are required for the transient model.

Resulted heads from the steady-state model were used as initial heads for the transient model, which simulated for 1825 days between 2017 and 2021 with stress periods every 365 days. MODFLOW, a three-dimensional, block-centered finite difference code, was employed in this model (McDonald and Harbaugh, 1988). MODFLOW was integrated with GIS for data pre- and post-processing.

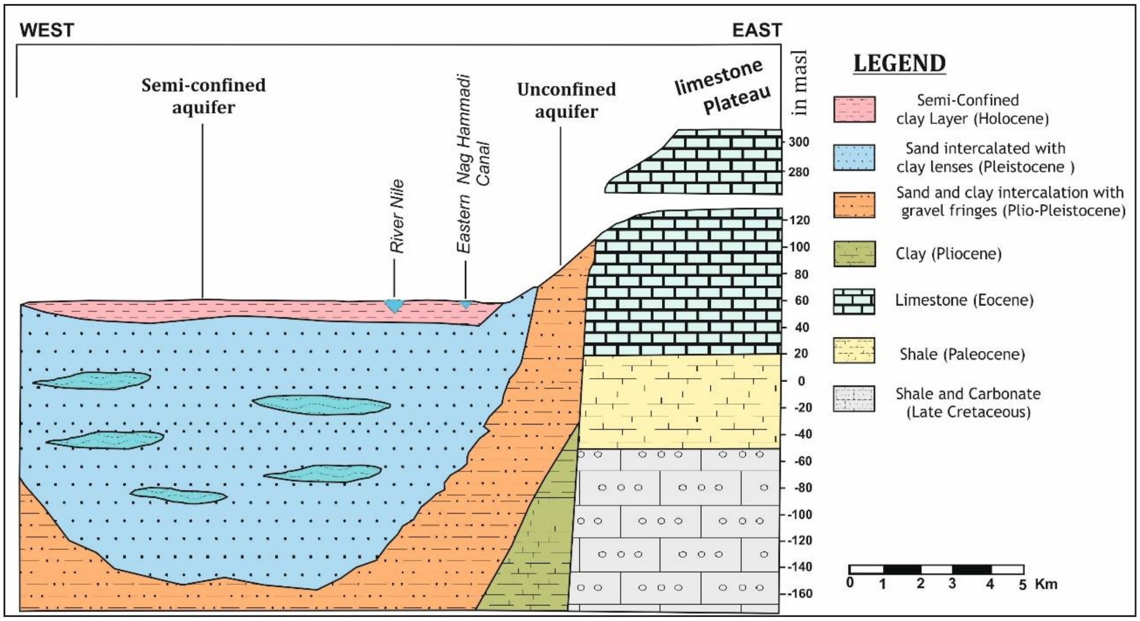

Figure 3. Hydrogeological (East-West) cross-section of Sohag area (RIGW, 1990)

5.1. Data acquisition

The data for the model was gathered and retrieved from a variety of sources, including the Ministry of Water Resources and Irrigation (MWRI) and some private drilling businesses in the study area.

The majority of the data utilized in the model was collected from various sources and formats, including lithologic logs, drilling observations, pumping test data, and geologic maps. A GIS-database structure was designed to produce a reliable and logical data gathering.

5.2. Model conceptualization and design

The purpose of creating a conceptual model is to simplify the real world and arrange the associated field data so that the system may be studied more easily.

The model includes the Nile Valley area south of Sohag governorate. It is 30 km in a north-south direction and 35 km in the east-west direction. The model is developed as 120 rows by 140 columns, as shown in Figure 4a.

The ground surface were generated from SRTM layer (Shuttle Radar Topography Mission-03 Arc Seconds (Farr and Kobrick, 2000; USGS, 2004). All tops and bottoms of the numerical layers were created from boreholes data and hydrogeological cross sections. The upper surface relief of the modeled area is shown in Figure. 4b. The model was divided vertically into three hydrostratigraphic units, in both Nile floodplain and desert fringes districts, with distinct hydraulic properties; silty clay layer, high conductivity water bearing unit, and moderate conductivity water bearing unit, as shown in Figure 4c.

The Quaternary aquifer is mainly recharged from applied irrigation water and seepage from River Nile and canals. The aquifer discharge is mostly through groundwater pumping wells and seepage to River Nile and canals. Evapotranspiration of the Quaternary aquifer was assigned equal to 10–15 mm/year with maximum depth reaches 5 m representing the upper silty clay layer of the aquifer (Abdel Moneim, 1992; Ahmed and Fogg, 2014; Ebraheem et al., 2002). All inputs, grids, and parameter layers were created using complex variograms and interpolation procedures (Anderson and Woessner, 1992; Hill et al., 2000; Wels et al., 2012).

5.3. Boundary conditions

The no-flow condition represents the eastern boundary, where is the east calcareous plateau. This boundary has to be assigned by inactive cells (Figure 4b). The western boundary is defined by the third type boundary condition of Riv. Package as it represents the River Nile and Eastern Nag Hammadi Canal. However, the area is enclosed by the limestone plateau from north and south; the southern and northern boundaries were assigned as general head boundaries. The groundwater wells were applied as a second type of boundary condition.

5.4. Hydraulic Parameters

Hydraulic property values (Kh, Kz, Ss, and Sy) were assigned based on the geologic information and pumping test data applied in the modeled aquifer. The hydraulic conductivity in the unconfined zone of the aquifer within the desert fringes was calculated by performing several in situ pumping tests, and the results ranged between 20 – 80 m/day. Previous studies, and reports collected from (MWRI, Sohag Office) concluded that the hydraulic conductivity of the Quaternary aquifer in the floodplain ranges between 80-150 m/day (Ahmed, 2009; Ahmed Aziz Abdel Moneim, 1999).

5.5. Recharge and discharge rates

The recharge value in the Nile floodplain of the Nile valley in Sohag area has been estimated as 200 mm/year (Abdel Moneim, 1992). In the desert fringes, the surface recharge is mainly from the infiltration of irrigation water. It is assumed to be a percent of the total extraction rate in each cell of the model domain (Jimene-Martinez. et al., 2010). Calibrated mean-annual-recharge values were about 29% of the total daily extraction rate, and this value was divided up between all irrigated areas from this pumped water.

The model implements groundwater extraction by assigning the pumping rate to a grid cell. 268 groundwater wells emplaced penetrating a Quaternary aquifer in the desert fringes southeast of Sohag. Overall pumped groundwater in this area was increased from 73.58 MCM/year in 2017 to 92.98 MCM/year in 2021.

5.6. Calibration

The model was calibrated under steady-state conditions. Several runs were performed to match between calculated and observed water levels. In this model, 10 observation wells were used to calibrate the steady-state model for the year 2017. The resulted hydraulic heads were used as initial heads for the transient model. The transient model was calibrated for 2017–2021 using 15 observation wells with 48 observation measurements. The model was adjusted using a trial-and-error parameter estimation technique through a series of groundwater flow simulations error to reach the best fit between measured and calculated hydraulic heads (Zimmerman and Zimmerman, 1991).

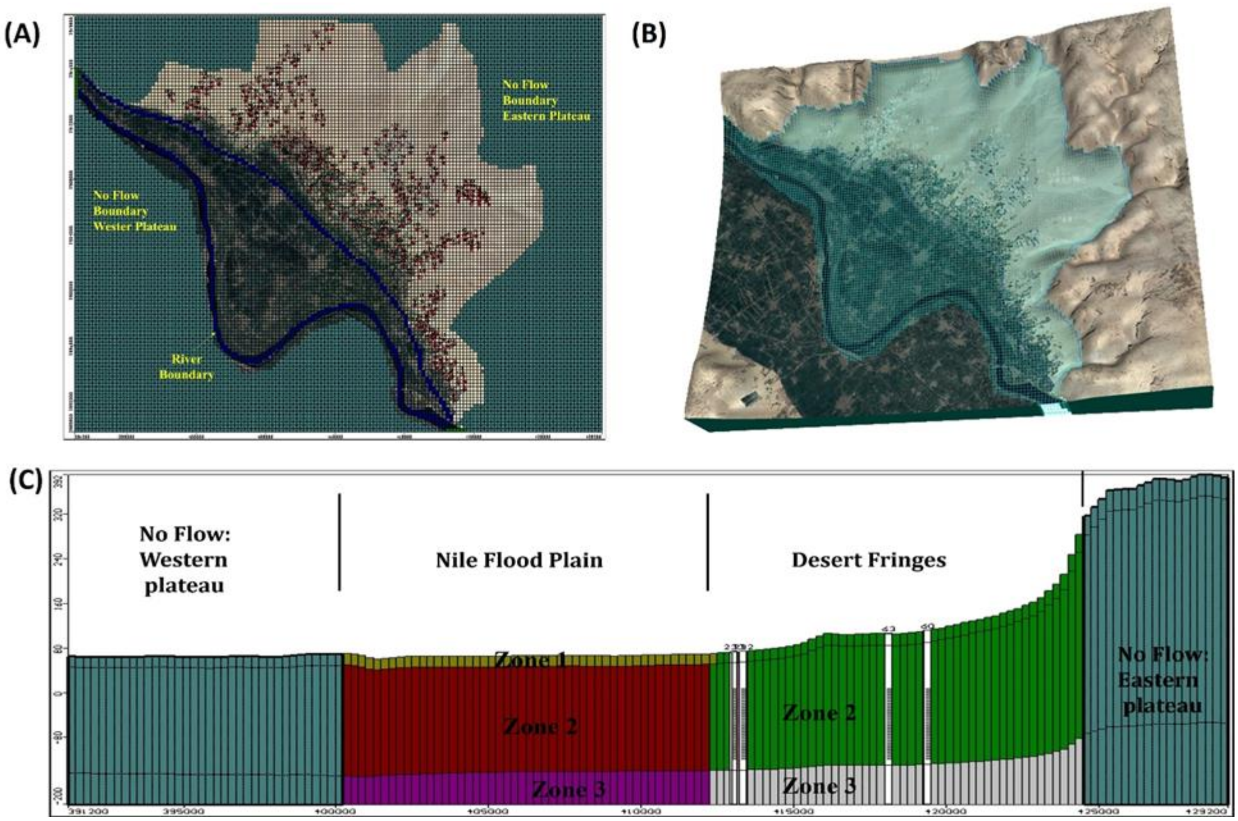

Figure 4. Model input characterization; (A) model domain grids and boundary conditions, (B) Surface relief of the model, (C) layers conceptualizations of the model

6. Results and Discussion

The main aim of the groundwater model is to detect the groundwater flow system in the study area and predict the changes in groundwater levels due to natural stressors and anthropogenic activity on the hydrogeologic system during the next 20 years. More attention was given to the groundwater level changes, the groundwater balance, and the recharge-discharge relationship between groundwater and surface water.

The calibration process of the transient model shows that the maximum residual between the observed and calculated heads is approximately 0.47 m. The minimum residual was -0.55 m with a mean of 0.02 m and a root mean square (RMS) of 0.211 m (Figure 5). Accordingly, the model was well calibrated, and it can be used for future predictions.

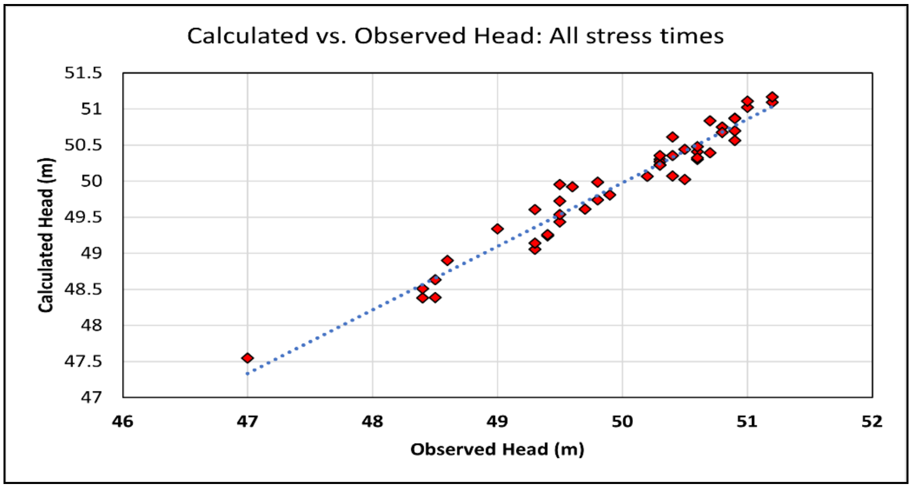

Figure 5. Transient calibration graph of observed vs. calculated heads for all stress times.

6.1. Current State

The regional model results, including the floodplain and desert frings regions, were invistigated. The calibrated model by 2021 has semi-real groundwater characteristics. The resulted groundwater flow has two general trends: the flow to the River Nile, characterizing the Nile floodplain area (cultivated land), where the Nile acts as an effluent stream, and the other flow dominating the desert fringes where groundwater flows toward the plateau. In the Nile floodplain area, the Quaternary aquifer is recharged from surface canals infiltration such as Eastern Nag Hammadi Canal and excess irrigation water. In contrast, in the desert fringes, where no surface canals are available, the recharge would be through the groundwater influx from the Nile floodplain area towards the desert fringes; therefore, the groundwater flows towards the plateau to the east (Figure 6a). These results are in line with the results presented by (Ahmed, 2009).

Groundwater recharge from the River Nile in some localities is because the groundwater level is less than the River Nile water level. The groundwater balance in the current situation by 2021 indicated that the volume of surface water leakage is equal to 148,525 m^3/day, while outflow from the aquifer to surface water is 135,254 m^3/day (Figure 6b). Infiltration from irrigation water is 269,868 m^3/day. On the other hand, extraction water from wells is the main outflux component equal to 338,425 m^3/day. Groundwater influx across the southern boundary is equal to 20,032 m^3/day, which is less than that discharged from the northern boundary, which is 48,122 m^3/day; this is because of the close-up of the plateau from the Nile Valley in the south allows less water to feed the aquifer.

Focusing on the desert fringes where groundwater depletion is studied, the groundwater flows from west to east towards the plateau, and groundwater levels range between 57 m in the west close to the Nile floodplain and 52 m in the east below the cliff of the plateau.

6.2. Predictive Scenarios

Three scenarios were applied to test the aquifer response towards some expected circumstances to study groundwater management due to the expected increased demand for groundwater.

6.2.1. Scenario 1

One of the most important features of the calibrated model is forecasting the aquifer behavior with the same hydrogeological conditions for a long time. In this scenario, the current extraction rates and recharge rates were kept constant and were supposed to be unchanged until 2041.

The results of this scenario indicated that the groundwater flow within the desert fringes is the same as the current groundwater flow (from west to east). However, as expected, the difference between the groundwater inflow and outflow reveals a decrease in groundwater storage, which led to drawdown in the majority of the investigated area with different values depending on the rates of pumping wells and the recharge zones surrounding these pumping wells. The maximum drawdown is in the most southeastern part of the study by 4.9 m (Figure 7a), where there are many pumping wells in this locality. Groundwater levels in the western side of the study area seem to be almost constant due to continuous recharge from surface water and the reliance on irrigation canals instead of pumping wells.

The groundwater influx from the surface water and adjacent Nile floodplain is equal to 98,414 m^3/ day, compensating the groundwater extraction equal to 254,740 m^3/day by 2041 (Figure 7b).

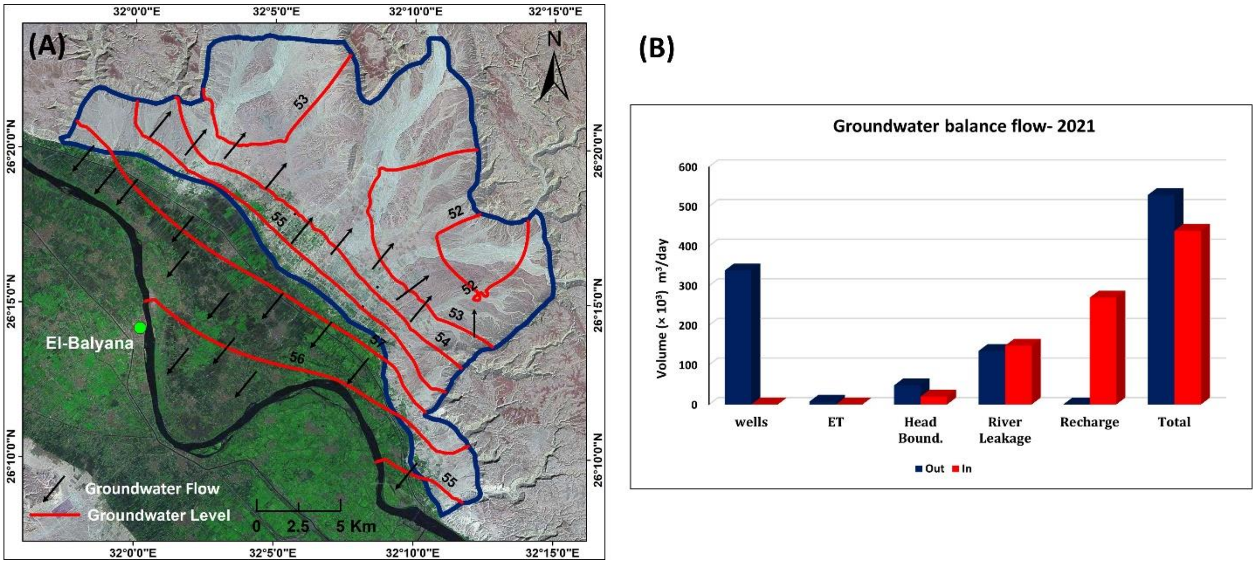

Figure 6. Results of the regional calibrated model by 2021; (A) Groundwater flow map; (B) the Groundwater balance flow

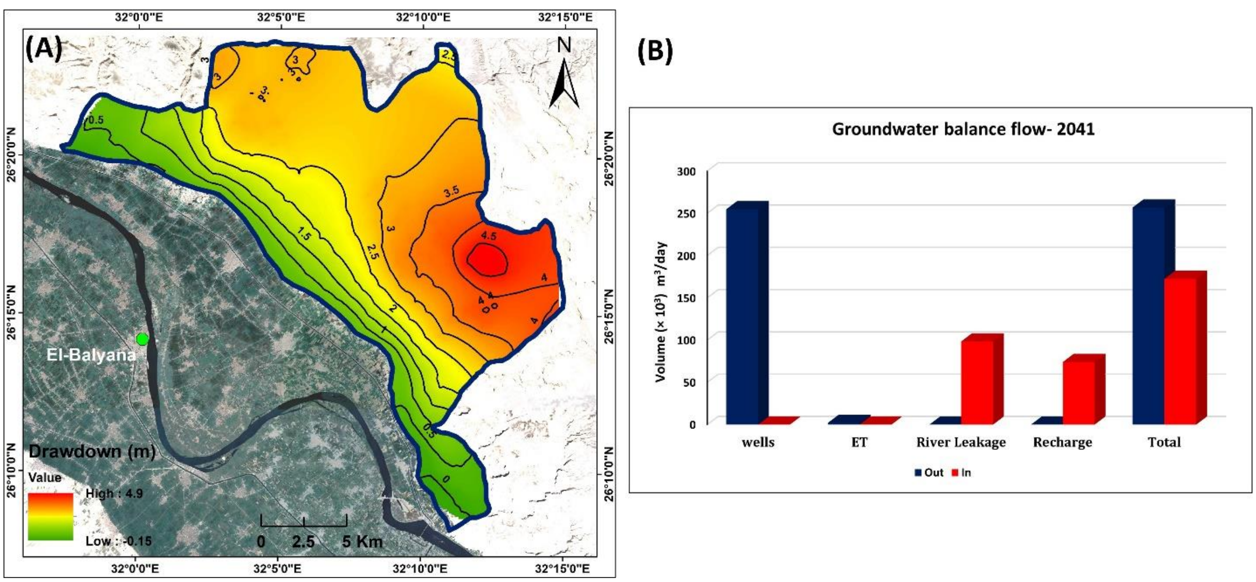

Figure 7. Results of the first scenario by 2041 (suggesting that the current extraction rates are constant; (A) the simulated drawdown; and (B) simulated water budget

6.2.2. Scenario 2

In this scenario, the extraction rates were increased by 100% to accommodate the agricultural expansion in the study area.

The results show that the volume of water discharged through pumping wells equals 509,480 m^3/day, Which is partially compensated by the infiltrated irrigation water by 143,650 m^3/day (Figure 8b). Moreover, with the increase of the extraction rates, the groundwater influx from the River Nile and irrigation canals increase to reach 159,265 m^3/day due to a rise in the hydraulic gradient between the over-pumping areas and the Nile floodplain area. As a result of that, the groundwater drawdown increases to include the entire study area with a maximum value of up to 10.5 m in the southeastern part of the study area, while the lowest drawdown value is about 1.1m in the western side of the study area (Figure 8a).

6.2.3. Scenario 3

This scenario tries to study the impact of the River Nile water fluctuation on the groundwater. However, there is indirect recharge from the Nile water to the groundwater of the desert fringes; the study area is recharged from surface water. In this scenario, the River Nile stage and canals water level were decreased by 1 m and 0.5 meters, respectively. At the same time, the extraction rate is equal to the current extraction rate as in the first scenario. The results of this scenario, after 20 years, the drawdown range between 2 m in the western part of the study area to 7.1 m in the southeastern part of the study area (Figure 9a). The average drawdown in this scenario is greater than the other scenarios, especially in the western part. The influx rate from the Nile water and Nile floodplain aquifer has decreased to 56,652 m (Figure 9b), confirming the significant effect of surface water recharge.

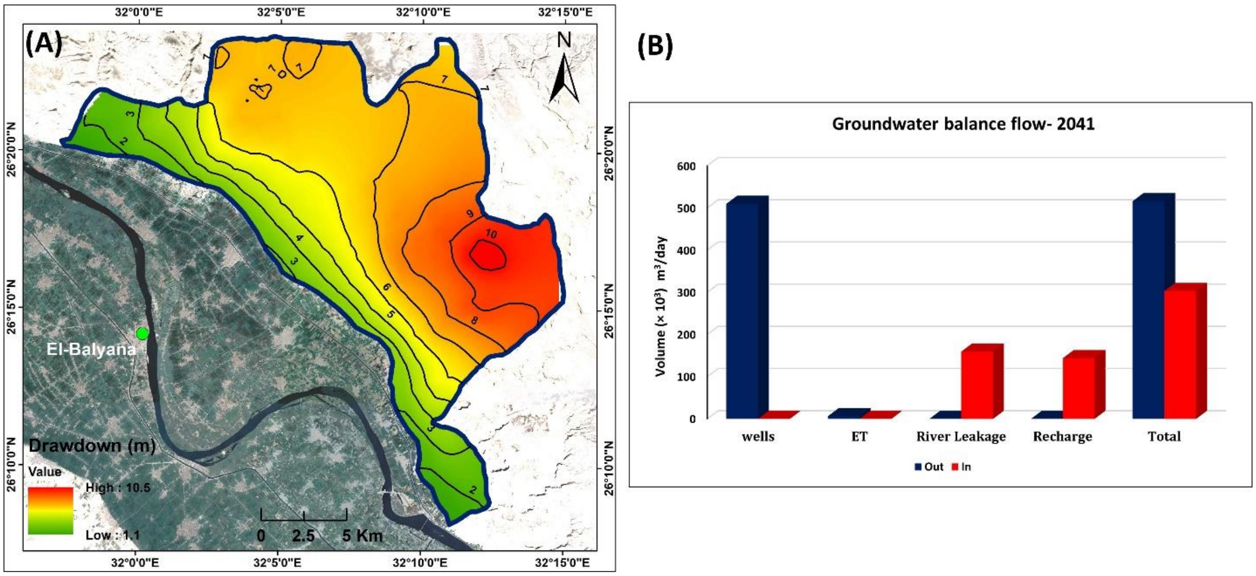

Figure 8. Results of the second scenario by 2041 (suggesting that the current extraction rates are doubled; (A) the simulated drawdown; and (B) simulated water budget

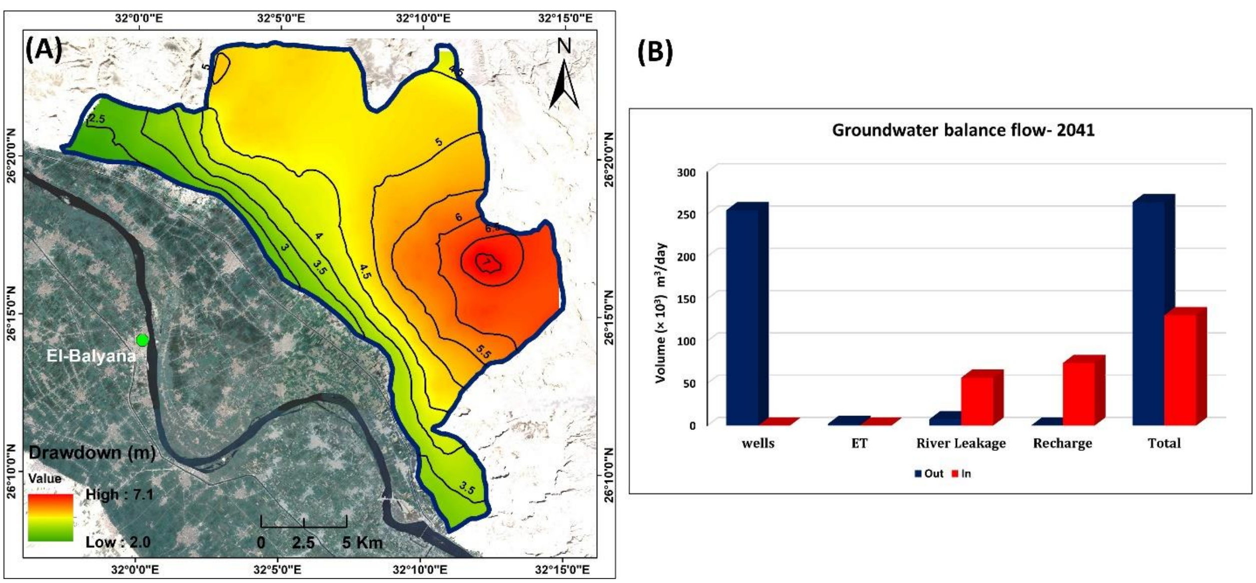

Figure 9. Results of the third scenario by 2041 (suggesting that the current extraction rates are constant and surface water levels are decreased; (A) the simulated drawdown; and (B) simulated water budget

7. Conclusions and recommendations

A groundwater flow model has been applied for the Quaternary aquifer in the area southeast of Sohag, with more focus on the desert fringes district. The model was calibrated under the steady-state condition for the year 2017 year, while it was calibrated under the transient conditions for the period 2017-2021 using 48 observation measurements. This model shows that groundwater flow in the Nile floodplain area is towards the River Nile, where the Nile acts as a drain, while Eastern Nag Hammadi Canal and its tributaries serve as a recharge source to the groundwater aquifer. The groundwater flow takes the east direction in the desert fringes, where the influx is from the western side. The calibrated model was used to predict the aquifer response under future circumstances. Three scenarios were applied where the first scenario is suggested to continue pumping water at the current rate for 20 years. The second scenario assumed that the extraction rate was doubled to accommodate the agricultural expansion. The third scenario suggested the decrease of surface water level due to climate changes. These scenarios showed that the first scenario moderately affects the eastern and southeastern areas. At the same time, the western part of the desert fringes close to the Nile floodplain is not affected by this scenario for the upcoming 20 years. Moreover, the second scenario has the most significant effect on the eastern and southeastern parts, where doubling the pumping rates leads to a groundwater drawdown by 10.5 meters after 20 years, while the western part is expected to be significantly affected by the third scenario in which the surface water level decreases and therefore the flux from surface water to groundwater aquifer will decrease increasing the groundwater drawdown in these locations.

These scenarios confirmed that surface water is the primary source of recharging the Quaternary aquifer in the Nile floodplain and the desert fringes areas. In addition, groundwater extraction in the eastern part of the desert fringes plays a vital role in groundwater depletion in the study area. This study recommends that in case drilling new wells, it should be at a suitable distance from the existing pumping wells, especially in the desert fringes where no surface system flows. In addition, reducing the amount of pumped water is paramount by choosing a modern irrigation method, whether drip or sprinkler.

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