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ORIGINAL RESEARCH PAPER

Steady-state simulation of groundwater flow in Khartoum state, Sudan

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ABSTRACT

The multi-aquifer system of the Nubian aquifer in central Sudan hydrogeological system was simulated using a three-dimensional steady-state model. The goal of the study is to detect the effect of pumping on the groundwater flow and thus, the aquifer productivity. The conceptual model of the study area was built based on the available geological and hydrogeological data guided by geophysical survey. Processing MODFLOW numerical code was used to calculate the hydraulic head and water balance under the existing boundary conditions. The model accurately simulated the hydraulic head with a determination coefficient of 0.88. The calibrated model indicated that the change in storage is 0.56 m^3/day indicating the study area constitutes highly productive zone and is recommended for groundwater developments.

KEYWORDS

Nubian aquifer, Khartoum, groundwater, MODFLOW, Sudan

1. INTRODUCTION

Concerns regarding groundwater availability and quality have been highlighted by the rapidly increasing population, industry, and agriculture in Khartoum state [1]. The spatial distribution of groundwater discharge is highly impacted by urban development [2]. On the other hand, climate change and land use directly affect groundwater recharge, evapotranspiration, and water quality [3]. Sudan relies on groundwater since it cultivates habitation and economic aspirations [4]. Nile River and groundwater are Khartoum's principal water providers. Due to extensive water abstraction for the Khartoum city water supply, the well-field's groundwater table is continuously declining [5]. Groundwater movement simulation ought to be employed regionally to properly comprehend and anticipate the groundwater flow patterns in the area. To determine groundwater potentiality, groundwater flow models predict hydraulic heads and the impact of diverse hydrological stresses on groundwater systems [6, 7].

In order to better understand the critical elements of groundwater systems, groundwater flow models are still employed as a crucial component of decision-making tools for water management [8]. Through the use of boundary conditions and governing equations, the deterministic models analyze groundwater flow indirectly for forecast or system characterization. The type of model, either steady or transient, depends on the input geological and hydrogeological data and boundary conditions. Groundwater flow models help manage groundwater resources by estimating hydrogeological parameters and aquifer flow patterns

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and water table [9]. Mathematical models helped researchers understand aquifers and predict their behavior in different time domains for groundwater management scenarios.

The Khartoum basin supplies drinking and irrigation water for the majority of the population [10]. To fully understand the Nubian aquifer system and predict hydraulic head fluctuations in the Khartoum state, the primary goals of this research are to build a mathematical groundwater flow model assisted with geophysical survey.

2. STUDY AREA

The study region is part of Khartoum state, Sudan, and embraces more than t 2000 km^2 (Fig. 1). Since central Sudan is situated in the Savanna belt, the average annual precipitation is 150 mm/year. Khartoum state features a flat topography [11]. The flat surfaces progressively ascend from 340 m in the west part of the region to 600 m in the east. The study region is situated on the northern edge of the Nile rift basin and is a component of the Khartoum sub-basin. The Pan-African Basement Complex confines this continental sub-basin to the northeast and southwest and defines its bottom limit at a depth of more than 500 m [12]. Geologically, the succession comprises five main units: Precambrian basement rocks, Cretaceous Nubian formation, Omdurman formation, Qoz sand, and Nile silts. The basement rocks consist of gneisses, schist, and granites, and the depth varies between zero when it crops at the surface and reaches up to 500 m in the southern part. The Cretaceous Nubian formation overlies the Precambrian basement rocks. The Nubian aquifer is a transboundary system that covers $2.2 \cdot 10^6$ km^2 distributed in Sudan, Libya, Tchad and Egypt. However, a part of this aquifer covering the northern part of Khartoum state, Sudan is covered in this research. Sandstone, siltstone, and conglomerate constitute this formation. The Nubian formation, with considerable thicknesses, is the primary groundwater aquifer in the Khartoum basin. Omdurman formation is composed of cross-bedded sandstone intercalated by fine sediments. The term Omdurman formation was also used to refer to the silicified sandstone units in the western Nile River, and he divided it into upper and lower Omdurman formations. Conglomerates, quartzite sandstone, and mudstone are the primary units forming the Omdurman formation. The quaternary Nile silts are composed of unconsolidated sand, silt, and clay. Figure 2 shows the geological map of the study area in which the main rock units and geological structure are presented. Groundwater is found in poorly consolidated sandstone strata in confined conditions. This situation is brought on by the presence of silt and clay layers as aquitards and aquicludes [13]. According to their origin and anticipated time of recharging, the two main groups of recharged water in the study area can be distinguished [14]. The primary type is the recharge from the Nile River, which can be infiltrated into the shallow and deep aquifers in the vicinity of the Nile, and the second type is the recharge from ephemeral streams outside the regions of the influence of the Nile River.

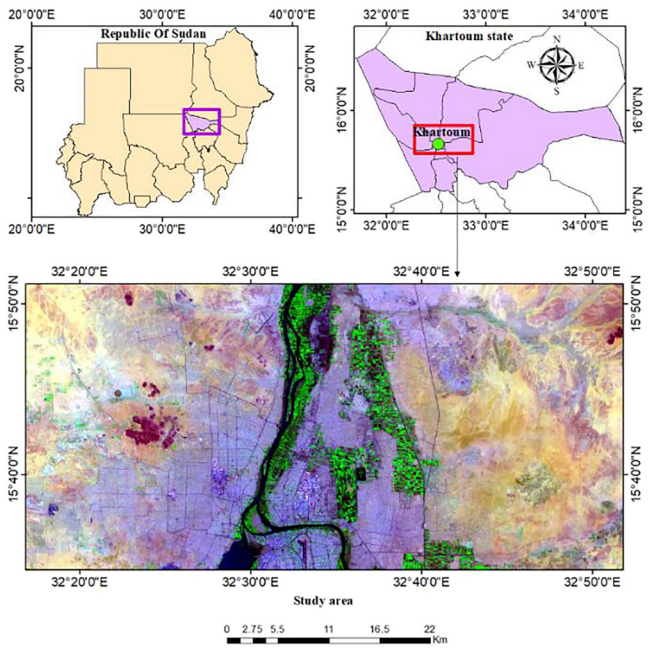


Fig. 1. Location map of the study area

3. METHODOLOGY

3.1. Aquifer conceptualization

The model conceptualization comprises a representation of the aquifer geometry and hydraulic parameters. This research employed the Vertical Electrical Sounding (VES) technique integrated with available geological and hydrogeological data to delineate and characterize groundwater aquifers in northern Khartoum state. Fifteen VES points using Schlumberger configuration were measured along three profiles. The acquired apparent resistivity is processed using IP2Win software to obtain the thicknesses and true

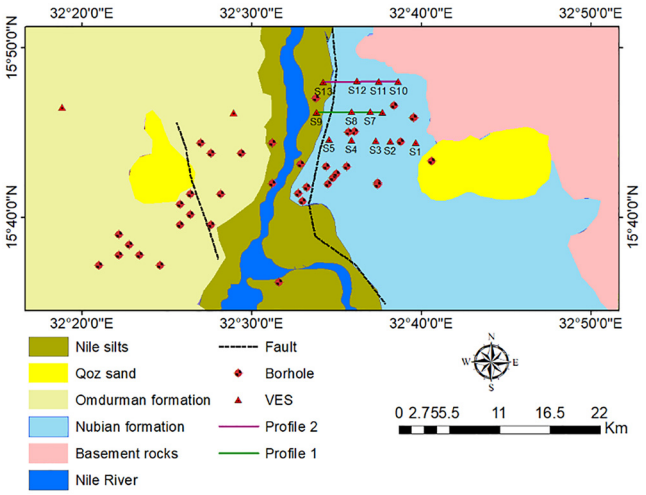


Fig. 2. Geological map of the study area

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resistivity of the subsurface layers. This program applies 1D inversion technique based on the fitness criteria between the observed and calculated data [15] and the resulted fitness indicate the true resistivity and thickness of the geological layers. Example of the modeling is presented in Fig. 3. In this study, the previous geological reports and borehole data is used as constrains to increase the uniqueness of the resulting models. As a result, three geoelectrical cross sections running east-west are obtained and then converted into geological cross sections to reveal the thickness and extension of the aquifers and aquitard and further detect the geological structures that may influence the presence and movement of groundwater.

The parameters affecting current flow, including water saturation and permeability, are the same affecting groundwater flow [16]. This led the researcher to develop empirical and theoretical equations to estimate the hydraulic properties of the aquifers. Detailed information can be found in [5, 17, 18]. In this research, the hydraulic conductivity K (m/day) is measured empirically using a formula suggested by [19] based on the connection between the electrical resistivity of the porous aquifer R_{aq} and hydraulic conductivity and is measured using Eq. (1),

$$K = 386.4\ R_{aq}^{-0.93283}. \quad (1)$$

3.2. Groundwater flow modeling

The groundwater flow was simulated for a saturated, confined Nubian aquifer in a steady-state condition using a 3D, finite difference model. To better understand the complex hydrogeological situation, the flow model was built using Processing MODFLOW (PM) software [20]. The PM computer code is based on solving the partial differential equation for groundwater movement and mass transfer. In this work, the model area was initially covered by mesh nets of 62 rows, 130 columns, and four layers (Fig. 4). The width of the cells is 500 m. The assigned layers from top to bottom are superficial deposits, clay, fine sand, and saturated sandstone, respectively. The research area's Landsat map is overlaid with a grid to help identify the inflow and outflow

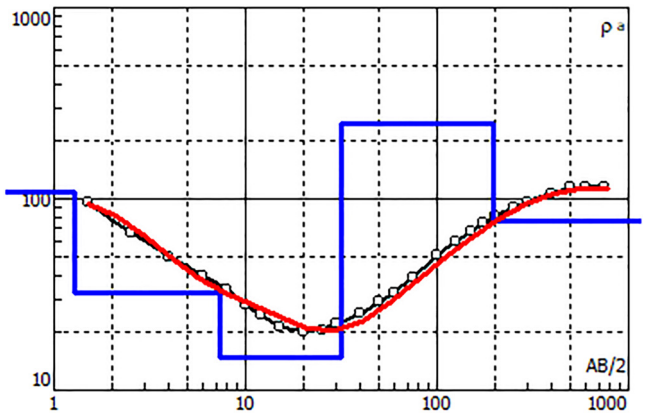


Fig. 3. Fitness of the measured (black line) and calculated (red line) data of VES 8

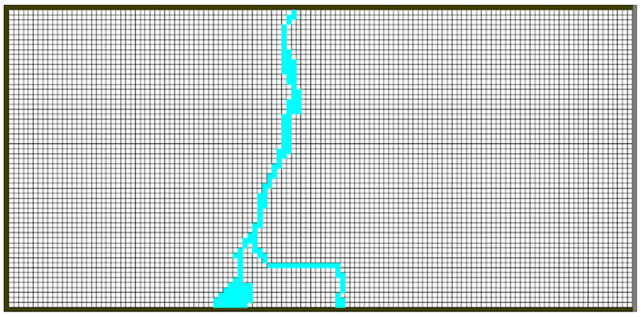


Fig. 4. Spatial discretization of the model domain

zones. The required petrophysical and hydrogeological parameters for building the flow model are aggregated over the cells and supplied to the cell's nodes. The finite-difference method computes the average head value in all model cells. The nodes in which groundwater levels are modeled in the block-centered approach are situated in the middle of the cells. Previous geological and hydrogeological data were used to assign the initial values of hydraulic head and boundary conditions and calibrate the resulting groundwater flow model. Recharge and river packages were applied to simulate the inflow of the rain and Nile River water to the aquifer system.

4. RESULTS AND DISCUSSION

4.1. Model parametrization

The first and most crucial step in groundwater simulation is model conception. Detection of the geological setting and groundwater flow are the key information needed to develop conceptual models. The purpose of building a conceptual model is to simplify the hydrogeological system to the point where a coherent modeling approach can be established. The conceptual model of the Nubian aquifer in the study area is built based on the geoelectrical cross sections obtained from two VES profiles as it is shown in Fig. 5. In general, five geoelectric layers make up these profiles, which is A clay layer with a thickness ranging from 22.7 to 32.1 m and average resistivity of 17 Ωm follows the top layer of superficial deposits, which has an average thickness of 1.8 m and resistivity range from 52 to 243 Ωm. With an average thickness and resistivity of 31 m and 150 Ωm respectively, the third layer is indicated as saturated sand. Underlying this aquiferous layer is an aquitard made of mudstone that has an average thickness of 36 m and the fifth layer represent saturated sandstone of an average resistivity of 170 Ωm (Fig. 6). The high resistivity of the aquifers is likely due to the low sault content of groundwater in Nubian aquifers [11]. It can be said that the groundwater is hosted by two water-bearing formations. The lower aquifer is composed of rather coarse sandstone with thicknesses up to 200 m, while the upper aquifer is made up of sand with thicknesses ranging from 20 to 100 m. These two aquifers are

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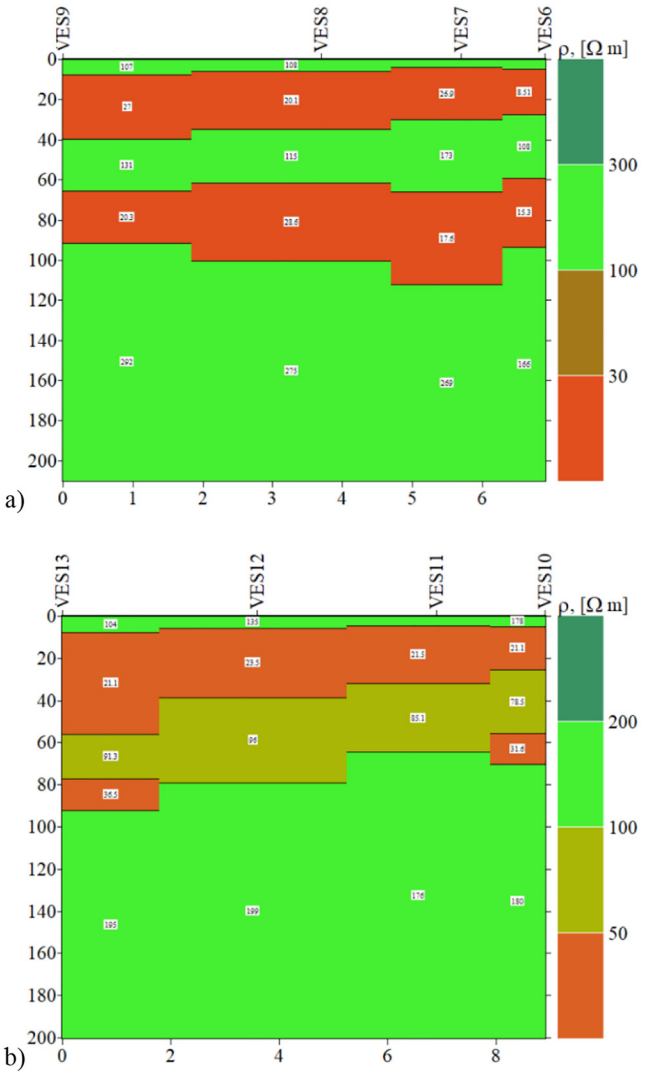


Fig. 5. Geoelectrical cross sections of a) profile 1 and b) profile 2

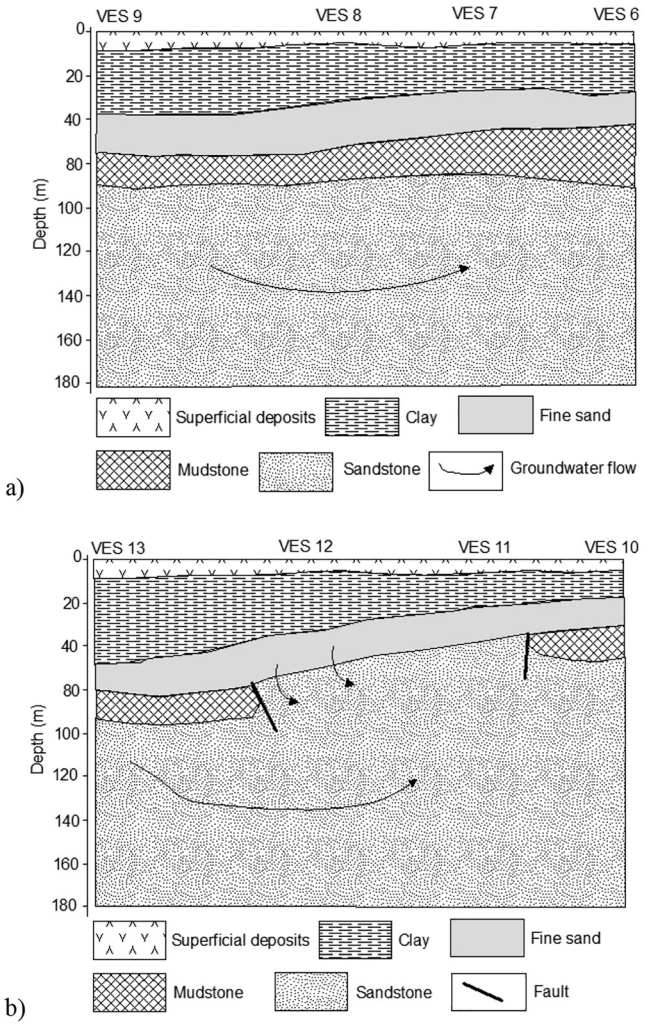


Fig. 6. The simplified conceptual model and geometry of groundwater aquifer

hydraulically linked and are separated by a mudstone aquitard that is fairly thick.

The groundwater flow model used 37 boreholes distributed in the eastern and western Nile River area in Khartoum state. To get an adequate agreement of the actual and calculated hydraulic heads, the boreholes information has also been employed as the model's starting inputs. The observed hydraulic heads from 37 wells were used for the modelling process as the preliminary head variation. Landsat images were used to delineate the recharge and discharge areas and the geographical boundary of the study area; then, the grid was superimposed on the geographical map, and groundwater flow under a steady-state was simulated.

The primary hydraulic parameters represented in hydraulic conductivity are calculated using the available pumping test data. Geophysics-based hydraulic conductivity is used in the absence of pumping data. The superficial deposits, clay, saturated fine sand, and saturated sandstone aquifers area is associated with a horizontal hydraulic conductivity of 5, 0.8, 3.5, and 5 m/day, respectively. Compared to horizontal hydraulic conductivity, vertical hydraulic conductivity is regarded as being ten orders lower. These results are compatible with the previuos studies which indicate the uniqueness of the resulting geophysical models [21]. The effective porosity of modeled aquifer is assumed to be 20%. Based on the geological and hydrogeological data, different types of hydrogeological boundaries are defined to describe the rate of inflow and outflow of groundwater to or from the aquifer system: constant head boundaries (Dirichlet conditions) at the river area to ensure a unique solution. The hydraulic head remains static at these boundaries. On the other hand, no flow boundary is applied to the eastern boundary of the model domain, while the general head boundary is applied to the north, south, and western limits of the area. The hydraulic conductance of the general head boundary and the head in the external sources are assumed to be 0.25 m^2/day and 30 m, respectively. The recharge package was applied to simulate the spatial distribution of the infiltrated water from rainfall and runoff, and 0.00025 mm/year recharge

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was assigned to the top of the active cells. At the same time, river package was employed to simulate the leakage of Nile water to groundwater aquifers. The assigned river parameters are head in the river, hydraulic conductance of the riverbed, and elevation of the riverbed bottom of 8 m, 100 m^2/day, and 1 m, respectively. The main source of groundwater discharge is pumping from the wells, which varies between 200 and 2000 m^3/day.

In general, steady-state modeling is employed for long-term strategy or when the changes in the groundwater system are minimal, but unsteady state modeling is utilized for immediate projections and when the system is experiencing major long-term changes. Further, the steady-state is easier and less computationally intensive compared to unsteady state modeling, which considers the time-dependent changes in recharge and discharge rates. Therefore, and due to the aforementioned reasons, this study assumed system equilibrium.

4.2. Model calibration

The process of calibrating the flow model involves identifying the boundary conditions and hydrogeological characteristics that provide outputs that most closely resemble observations of the actual parameters. The differences between the observed and calculated groundwater heads at ten observations have led to the adoption of a calibration target. The primary objects for calibration are the hydraulic head and water balance. To reduce the difference from the actual and calculated heads, adjustments were made to the general head boundary, riverbed conductance, and recharge at earlier stages of model calibration. The hydraulic conductivity of the aquifer in each simulated zone is assumed to be constant. Using a trial-and-error method, the hydrologic parameters were adjusted to calibrate the model until it roughly matched the estimates of the head that were measured in the field. For model calibration accomplishment, dozens of model runs were conducted to provide a close match of the model parameters. Regression plots of observed and calculated hydraulic heads show the calibration linear fitting (Fig. 7). The coefficient of determination, R^2 was used as a performance metric for the resulting model calibration. Figure 7b shows that considerable agreement between observed and simulated water levels was obtained with R^2 of 0.88, considering the limitation in the available hydrogeological data. The coefficient of determination is calculated (Eq. 2) as

$$R^2 = \left(\frac{\left[\sum_{i=1}^{n} (y(i) - \bar{y})\ (x(i) - \mathbf{x})\right]^2}{\sqrt{\sum_{i=1}^{n} (y(i) - \bar{y})^2 \sum_{i=1}^{n} (x(i) - \mathbf{x})^2}} \right)^2, \quad (2)$$

where n is the number of observations; $x(i)$ and $\bar{y}(i)$ is the actual and predicted value for the i-th number of observations, respectively. $\bar{y}$ and $\boldsymbol{x}$ are the mean for the predicted and actual values, respectively.

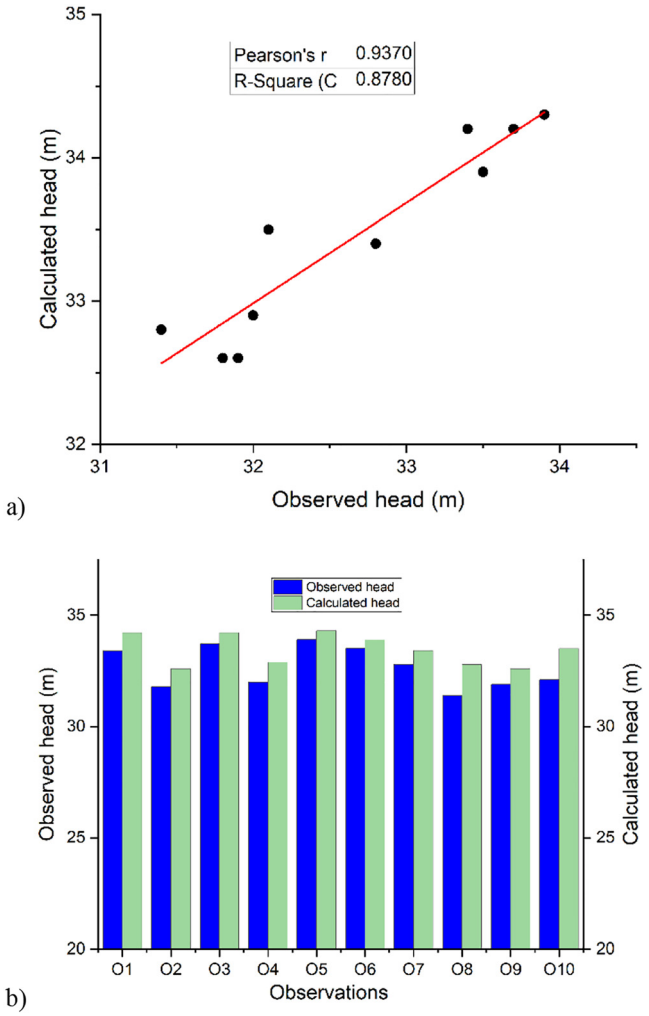


Fig. 7. a) Linear regression between the observed and calculated hydraulic heads and b) the comparison between the measured and simulated heads

4.3. Model findings

The hydraulic head distribution of the Nubian aquifer is calculated using the groundwater flow model. Groundwater levels fluctuate slightly, indicating that hydraulic gradients do not change over time. Thus, groundwater flow was assumed to be steady-state, representing the aquifer conditions in October 2018. Processing MODFLOW was used to create the contour plots of the modeled hydraulic heads. The result is shown in Fig. 8. The water level decreased from the vicinity of the Nile River to the east and west side of the study area, which confirms that the Nile River is the main source of groundwater recharge in the study area. Localized depression in water level in the central part of the model domain is mainly due to heavy pumping. Excessive groundwater abstraction for a long time has a small effect on the groundwater level in the western part of the area, as anticipated by the wide space between contour lines. As a result, it is likely that the modeled area is highly productive and in an optimal situation for groundwater development.

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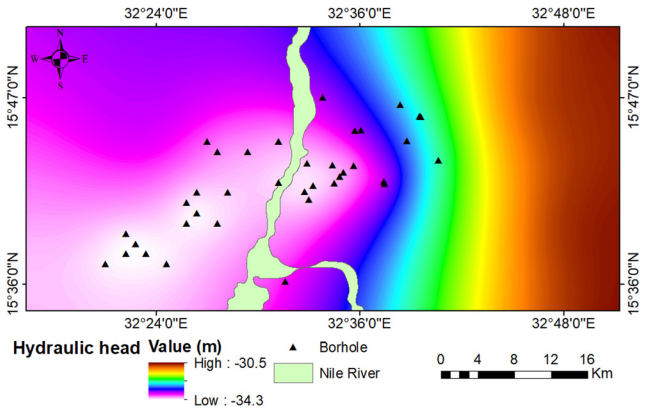


Fig. 8. Spatial distribution of the calculated hydraulic head

Based on the calibrated groundwater flow model under steady-state conditions, the groundwater budget in the model domain is calculated to estimate the rate of inflow, outflow, and change in storage in the model domain. Processing MODFLOW typically computes the cumulative inflow and outflow rates for the whole model domain and for individual zones for long-term water budget estimation. In this study, recharge and general head boundary are the main components of inflow, whereas discharge from wells is the outflow component. The result of the calculated water budget is shown in Table 1. Recharge as a main component of the inflow contributes 26,291 m^3/day for the Nubian aquifer, while the general head boundary contributes 10,844 m^3/day. The groundwater discharge from the wells and the general head boundary is responsible for the outflow of 35,293 and 1844 m^3/day, respectively. The change in groundwater storage is calculated by subtracting the rate of inflow from the outflow. As a result, the deficit in groundwater storage is 0.56 m^3/day. The negative groundwater balances in steady state simulation signifies that there is more water being extracted than is being which is likely due to excessive well pumping or changes in land use that result in decreased recharge. Since this is the first study to deal with the groundwater flow modeling in the northern part of the Nubian basin, these results are compatible with the previous modeling efforts for the Nubian aquifer in the central Sudan hydrogeological system [21, 22] and confirm that the study area is in ideal condition for groundwater exploitation for different purposes. It can be concluded that, the parameterization of groundwater aquifers using geophysical modeling is a powerful tool to be used as an input for groundwater models and thus reduce the expenses of groundwater modeling.

Table 1. Results of the calculated water budget in the study area

Flow term	Inflow (m^3/day)	Outflow (m^3/day)	IN – OUT (m^3/day)
Wells	0	35,293	−35,293
Recharge	26,291	0	26,291
General head boundary	10,844	1,844	9,000
Sum	37,136	37,137	−0.560

5. CONCLUSIONS

The Nubian sandstone aquifer was modeled using 3D finite-difference Processing MODFLOW code in steady-state conditions to calculate the hydraulic head and water balance. The electrical resistivity method employing VES technique is used to delineate and characterize the groundwater aquifer in the study area. Geophysical methods are proved to be powerful tools in aquifer parameterization that can be successfully used in groundwater modeling since it gives a continuous estimate of the hydrogeological parameters. These methods are inexpensive compared to pumping test methods. Based on VES measurements, the hydrogeologic system is vertically discretized into four hydrogeological layers as superficial deposits, clay, fine sand, and saturated sandstone with an average hydraulic conductivity of 5, 0.8, 3.5, and 5 m/day, respectively. The model is calibrated by comparing the observed and calculated hydraulic heads. The compared values showed a reasonable match with a determination coefficient R^2 of 0.88. The hydraulic head decreases from the central part of the area to the eastern and western parts, which confirms that the Nile River is the main source of groundwater recharge in the study area. The deficit in the rate of the inflow to the outflow is 0.56 m^3/day, indicating that the study area is in the ideal situation for groundwater exploitation and development.

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