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ORIGINAL ARTICLE

Planning for groundwater management using visual MODFLOW model and multi-criteria decision analysis, West–West Minya, Egypt

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Abstract

This study presents a planning model to assist decision-makers in implementing proposed sustainable development policies based on the government's development schemes. It focuses on the exploitation of groundwater from the Eocene aquifer in the West–West Minya region in the Western Desert of Egypt as one of the new development areas. The visual MODFLOW model is applied to serve as a base model for the study area's local modeling and assess the impact of operating scenarios on the groundwater aquifer. An optimal scenario for groundwater sustainability is achieved by considering the water meter consumption in the newly reclaimed area with a value of 6 m^3/d for each acre to irrigate 3953.68 acres; the maximum drawdown of about 60 m is formed after 9700 days of simulation. The GIS multi-criteria analysis model is used to assess the impact of groundwater deficiency as a result of reclamation. Results of the groundwater model are merged as input layers in multi-criteria decision analysis, which include groundwater salinity, groundwater levels, aquifer transmissivity, and aquifer storativity. The prospective groundwater zones are categorized into most suitable (1584 km^2, 9.9%), suitable (4592 km^2, 28.7%), good (4784 km^2, 29.9%), moderate (1488 km^2, 9.3%), and unsuitable (3552 km^2, 22.2%). It is recommended to optimize levels of groundwater withdrawal from the current or future drilling wells to achieve a balance between the use and the protection of water potential.

Keywords Groundwater management · Groundwater modeling · Visual MODFLOW model · Multi-criteria decision analysis

Introduction

On a global scale, groundwater is the primary source of freshwater. It accounts for about one-third of freshwater withdrawals (Siebert et al. 2010; Famiglietti 2014). An estimated 2.5 billion people worldwide depend on groundwater for their use (Chakrabarti 2017). This condition is a fact in arid and semi-arid regions because of the scarcity of rainfall and the limitation of surface water masses which are sometimes even absent. Due to high population density, global climatic change, and seawater intrusion in coastal aquifers, the demand for groundwater resources is expected to increase by about 110 billion cubic meters per year (BCM/Y) (Alfy and Abdalla 2021); in addition to the compounded environmental effects of the Grand Ethiopian Renaissance Dam (GERD) as will reduce the flow of water in the Nile River between 11 and 19 billion m3 (BCM) (Yihdego et al. 2017). In Egypt, the surface water from the Nile River is a primary source of daily drinking water production about 22.1 million m^3 with 82.1% (HCWW 2017); and the groundwater is an integral part of its national policy where it is used for drinking, domestic, and industrial purposes. With the continuous deficiency of fresh water and the importance of groundwater, the Egyptian government started a new development project to reclaim 1.5 million acres to increase agricultural areas. Groundwater is the only source of irrigation water in the newly reclaimed areas; it is also a supplementary source of irrigation in the old, cultivated areas. Two main aquifer systems are relevant in Egypt. The first is the sandstones and gravels interbedded with clays aquifer system represented by Nile Valley and Delta, Nubian sandstone, coastal and Moghra systems. The second is the fissured and karstified aquifer system represented by limestone and hard igneous and metamorphic rocks (Hefny and Shata 2004; Alfy and Abdalla 2021).

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These aquifer systems comprise five hydrological zones: the Nile Valley and Delta, Western Desert, Eastern Desert, Coastal region, and the Sinai Peninsula; they are referred by many authors (RIGW 1989, 1992; MPWWR 1988; RIGW/IWACO 1993, 1999; Abdel Moneim 2009). The purpose of the present work is to present a planning model for decision-makers for groundwater management and to predict the environmental impact of long-term extraction schemes on groundwater. And to achieve the optimum groundwater exploitation plans for sustainable development projects (domestic water supply, agriculture, and industry) with further rationing of the existing wells in line with groundwater potential and detect the suitability of groundwater after reclamation proceeded. The Eocene fractured limestone aquifer, occupying the West–West Minya area in the Western Desert of Egypt, has been investigated as a case study of one of the new agricultural development areas. The West–West Minya agricultural development area extends further west from the West Minya agricultural zone.

The study area lies at the eastern border of the Western Desert in the central part of Egypt between latitudes 27°00′–29°00′ and longitudes 29°30′–31°00′ with an area of about 16,000 square kilometers (Fig. 1). Its climate is typically characterized by hot, dry summers and mild winters. According to the NCEI (2021) and EMA (2016), the average climatic records for the period (2000–2019) are of temperatures ranging from 31.9 to 14.1 °C, and the average moisture percentage ranges from 30 to 40%. Annual precipitation intensity is around 0 to 5 mm/year. For the implementation of this work, two effective techniques have been employed. In the first technique, a three-dimensional groundwater flow model based on GIS-Database integration is applied to simulate the hydrological conditions of the Eocene aquifer in the study area and interpolate the aquifer response and groundwater level variation under different pumping stresses. Model development scenarios involving government operating plans have been suggested. In the second technique, the obtained output results of the optimal proposed scenario have been merged under the GIS framework and used as input criteria for GIS-multi-criteria decision analysis (MCDA) model to delineate the groundwater suitability zones after groundwater withdrawal during reclamation processes. Alfy (2014), Abdel Moneim et al. (2016), and Abdelhalim et al. (2019) applied the numerical groundwater model to assess the responses of the aquifer under different pumping scenarios. It proved the efficiency of this technique in managing groundwater resources. Sayed et al. (2019) investigated the feasibility of using solar energy to exploit groundwater supplies from the Moghra Oasis in the Western Desert of Egypt using a

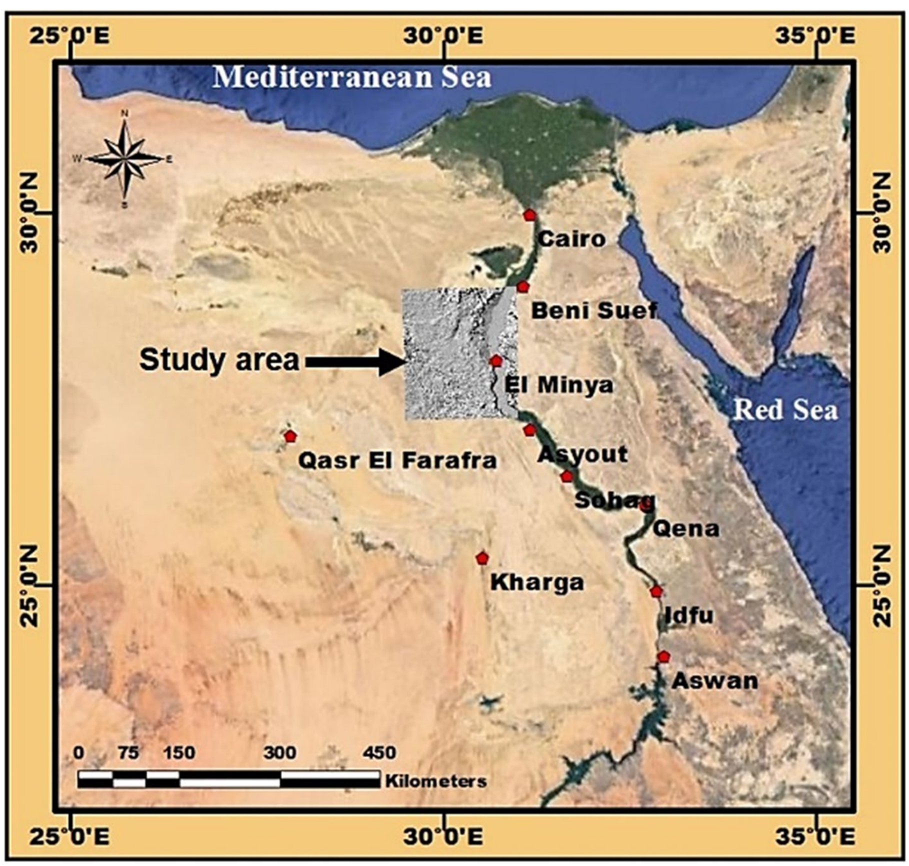

Fig. 1 Map of study site location

multi-criteria analysis model. El-Hadidy and Morsy (2022) integrated the visual MODFLOW model and GIS model and applied the weighted overlay approach to produce the groundwater potentiality map in the Nile Valley region.

Geologic characterization

Studying the surface and subsurface geological characteristics of the area concerned is vital for detecting the hydrogeological configuration in terms of aquifer properties, water potentiality, and water flow. The geomorphology of El Minya province resembles the prevailing conditions in the Nile Valley. The limestone plateau borders the valley from both sides along its length, causing a steep slope of the earth's surface on both sides of the Nile Valley to the east and west. Three geomorphological units are studied (Fig. 2) (Said 1981):

a. Young alluvial plains (Holocene silty clay) form the cultivated lands bordering the course of the Nile River on both east and west sides and dissected irrigation canals and drains.
b. Old alluvial plains (sand and gravel from the Pliocene and the Quaternary) are exposed as terraces at different heights above the young alluvial plains.
c. Limestone Calcareous Structural Plateau (Middle Eocene limestone) is structurally formed and bounds the Nile Valley east and west. The surface lithologic units exposed in the study area range from Middle

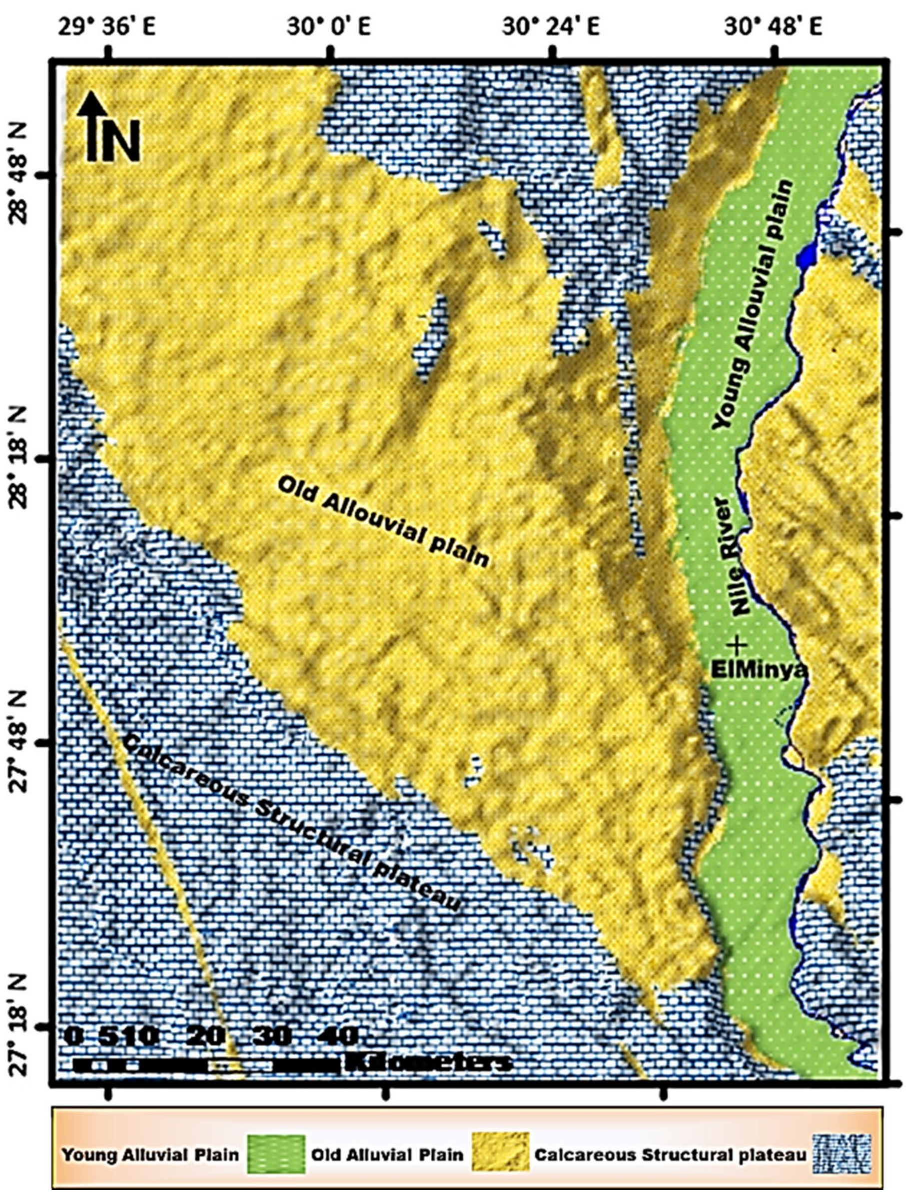

Fig. 2 Geomorphological features of West–West Minya agricultural development area, Egypt. (Modified after said, 1981)

Eocene limestone to Oligocene-Pleistocene gravel and sand and Quaternary deposits (Fig. 3) (Abdel Aziz 1994; Abu Heleika and Niesner 2009). The subsurface stratigraphic sequence in the study area ranges from the Pre-Cambrian to the Quaternary ages; it is built-up up from the base to the top as follows:

a. Pre-Cambrian Basement Complex's surface elevations in the study area range from −1500 to −4000 m (CEDARE 2002).
b. The Nubia Sandstone Sequence rests unconformably on the rugged surface of the basement complex. It comprises all clastic sediments ranging from the Upper Cretaceous to the Pre-Cambrian Basement consisting of alternating sandstone beds, shale, and clay with thickness ranges from 500 to 2500 m in the study area (LaMoreaux et al. 2008).
c. Upper Cretaceous shale mainly consists of shale, clay, and mudstone with thin limestone interbeds with phosphates bands forming the confining formation to the Nubia Sandstone.
d. Northward El-Kharga and El-Dakhla Oases. The thickness of these variegated shales varies between 126 m in El-Dakhla and 265 m in El-Kharga (MPWWR 1998).

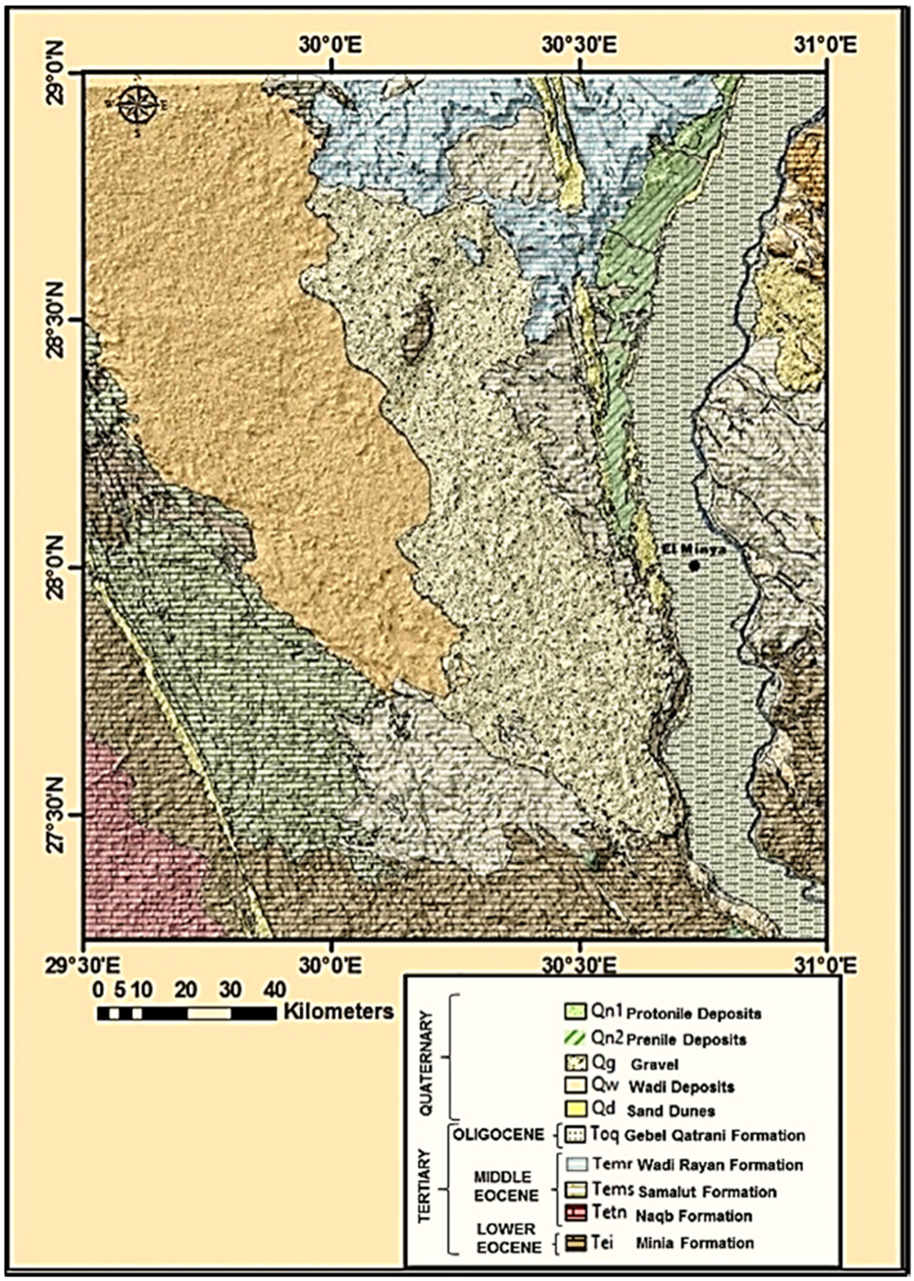

Fig. 3 Geologic units of the study area (CONOCO 1987)

e. Tertiary carbonate rocks of the Eocene age consist of limestone dolomitic limestone and cover the plateau area surrounding the depressions of south-Kharga, El-Kharga, El-Dakhla El-Farafra, El-Bahariya, Siwa, and Qattara. Their thickness ranges from 200 to 1200 m (RIGW 1992, 2015).
f. The Oligocene sequence consists of alternating classics, siltstone, and claystone. It overlays the Eocene limestone and occupies the western part of the Western Plateau (Abdel Moneim et al. 2016).
g. Quaternary deposits are widely distributed on the eastern side, including the Nile silt, dunes, and fanglomerates (Korany et al. 2008).

The structural framework is composed of a system of wrench faults parallel either to the NW–SE trend of the Gulf of Suez or to the NE–SW trend of the Gulf of Aqaba. These faults play a vital role in the groundwater aquifers in the study area (Youssef 1968; Shabana 2010; Kashouty et al. 2010; Embabi 2018).

Four aquifers are present in the study area: Quaternary alluvial deposits, Oligocene sandstone, Eocene limestone, and Nubian sandstone aquifers. The groundwater of the Quaternary and Oligocene sandstone is recorded under unconfined conditions, and Pleistocene sediments overlie the fractured Eocene limestone. In contrast, the Nubian sandstone is registered as a confined aquifer (Yousif et al. 2018). Regionally, groundwater exhibits a northward trending gradient in this area. The recharge of the Upper Eocene water-bearing units may occur by seepage from the Nile and by upward percolation of groundwater in hydraulic charge from the deep NSS through the upper confining Cenomanian shale. No recharge of the upper Pleistocene aquifer is expected to occur from the average 4 mm of the annual rainfall occurring as very limited precipitations and believed to be lost in evaporation (Tantawi et al. 2005). The Middle Eocene aquifer has an isotopic signature of the modern Nile. (Yousif et al. 2018). The investigated groundwater flow pattern in the Eocene aquifer shows the flow direction from the southwest. The total hydraulic head value is 50 m.a.m.s.l. and reaches 30 m.a.m.s.l. northeast (Fig. 4). Figure 5 shows the hydrostratigraphic cross sections in the study area. The present estimation of groundwater quality of the Eocene aquifer in the new development study area is based on the results of the chemical analysis of groundwater samples collected from the boreholes. The total dissolved solids (TDS) content varies

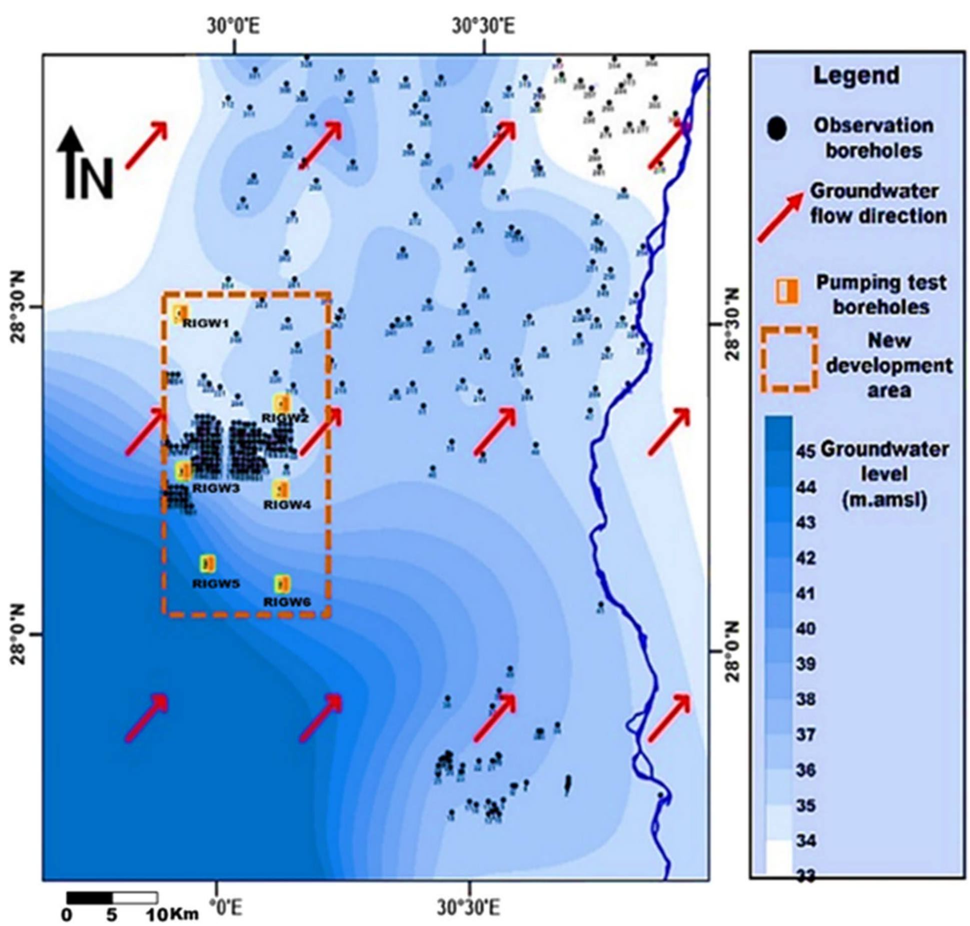

Fig. 4 Potentiometric surface of groundwater levels and the outline of the new development area

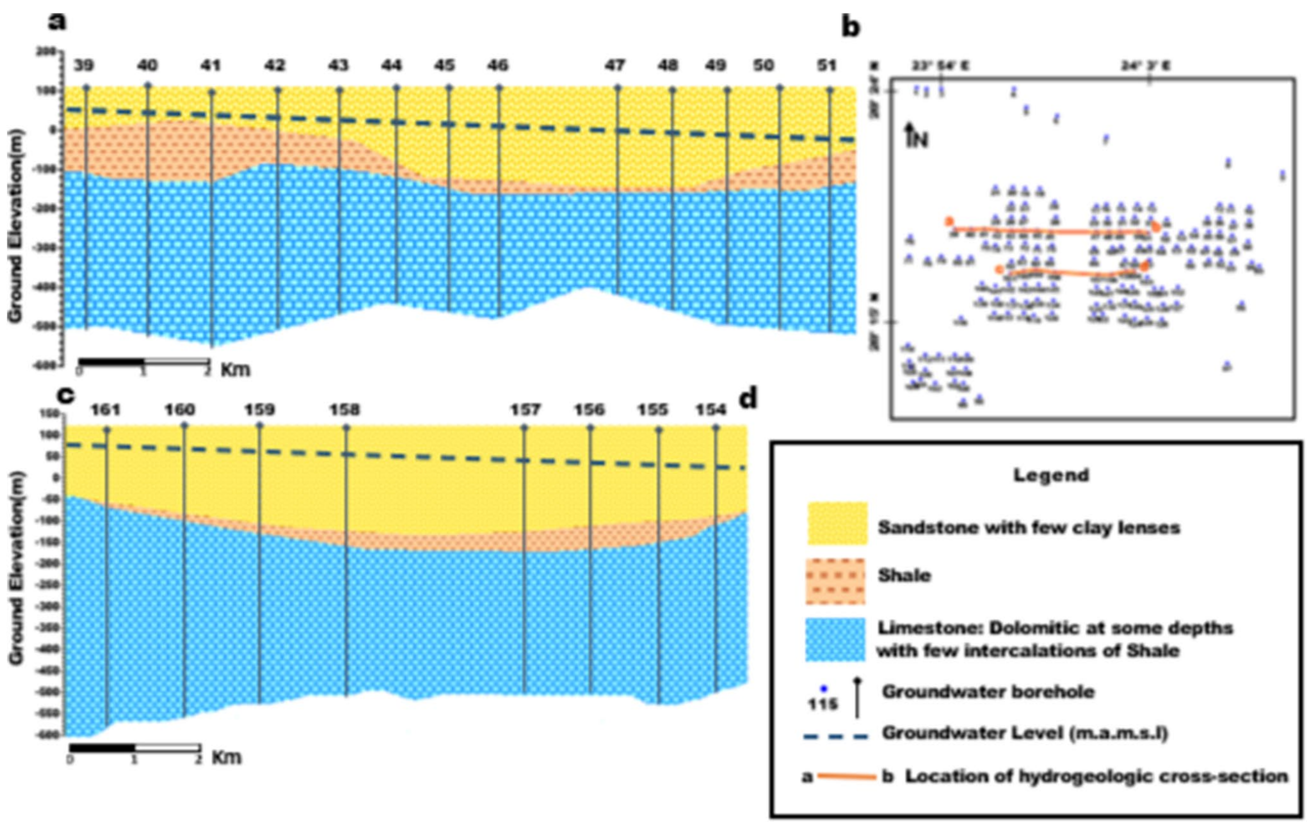

Fig. 5 Hydro-stratigraphic cross sections in the new development area

between 2000 and 3000 mg/l (Fig. 6). The spatial extension of the Eocene aquifer in the study area and its approximated thickness is calculated using spatial interpolation inverse distance weighted (IDW) in GIS Tools (Fig. 7).

Methodology

The procedures of this work are based on applying and integrating two techniques, the visual MODFLOW USGS 2005 software groundwater model and multi-criteria decision analysis (MCDA) model. The operational steps and modeling processes are illustrated in a flowchart (Fig. 8).

Numerical modeling for groundwater system

Designing the conceptual model

Groundwater flow models are used to calculate the rate and direction of groundwater movement through aquifers and confining units in the subsurface; these calculations are referred to as simulations (Mandle 2002). The model is also used to simulate possible future changes in hydraulic head or groundwater flows due to future changes in aquifer system constraints. MODFLOW 2005 is used as a numerical model. It is a standard USGS software developed by McDonald and Harbaugh (1988) and Harbaugh (2005). The integral finite difference method is employed to resolve the transient flux equation. There are virtually no hydrological studies specifically focused on the study area. Currently, the drilling of test wells is being carried out under the Ministry of Water Resources and Irrigation (MRWI) supervision. Available and updated field data from wells in the Eocene aquifer are collected and organized by integrating the attributes and spatial databases with GIS tools. Arc GIS is used to manage the model's spatially distributed input parameters and outputs. The database constructed in the GIS technique is imported into the conceptual model, including the ASTER (Dem) 1-ARC resolution with 30 m, the measured potentiometric water levels, hydraulic properties, and recharge and discharge components.

Grid system and boundary conditions

The model domain's dimensions in the study area are discretized with a uniform, regular 500 × 500 m grid, and the number of rows and columns is 200 and 150, respectively. To obtain results that reflect the hydrological conditions of the aquifer, it is essential to describe its

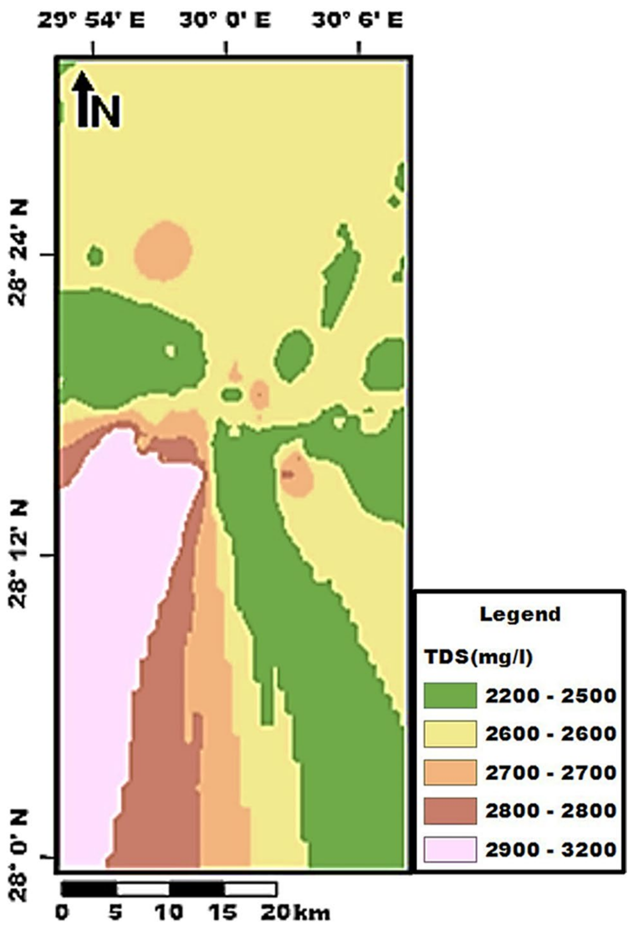

Fig. 6 Spatial distribution of total dissolved solids (TDS mg/l) in the new development area

hydraulic boundaries with known hydraulic heads. Boundary conditions are based on the hydraulic head map and hydrological conditions. Due to the absence of major branches or banks in or near the area at the northern, southern, and western boundaries, the initial hydraulic conditions were used to identify the sources of recharge in the study area. The aquifer is assumed to be extended and represented by constant hydraulic pressure limits. The flow through these boundaries is determined as constant head boundaries (Dirichlet conditions), where the derivatives of the groundwater head are constant and do not change with time. The eastern boundary of the model is a specified head boundary to represent the Nile River. For other areas, the no-flow boundary was specified (Neumann conditions) in which the derivatives of the head (flux) are set to zero. All boundaries were set distance from the area of main interest and simulated pumping wells to avoid the impact of uncertainty in subsurface boundary inflows and outflows and the drawdown effect during transient simulation (Fig. 9).

Initial conditions

When studying the dynamic behavior of the aquifer to determine the amount of change in groundwater levels, it is necessary to decide on the initial conditions of the groundwater levels. Due to the lack of available data for the study area, current static groundwater levels of the investigated wells have been used as the initial distribution head for the model (Fig. 10).

Aquifer hydraulic parameters

The present estimation of aquifer characteristics, including transmissivity, hydraulic conductivity, and storativity, is based on step-drawdown, constant discharge, and recovery tests for the investigated wells in the modeled area. Six wells were selected to represent field measurement data; their locations are shown in Fig. 4. The data of step drawdown tests are plotted on a linear scale (Fig. 11) to estimate the general well equation using Jacob (1947) and Rorabaugh (1953) techniques.

$$S_w = BQ + CQ^2 \tag{1}$$

where S_w is the total drawdown in the pumping well (m). BQ is the formation loss (m) caused by laminar flow through the aquifer. CQ^2 is the well loss (m) caused by turbulent flow inside the well and its filter and damage zones. From this equation, the specific capacity curve is drawn. The initial specific capacity value is used to estimate the transmissivity (T) of the aquifer by using Driscoll (1986) equation:

$$T = 2000 \times \frac{Q}{S} \tag{2}$$

where T = transmissivity (gpd/ft) and $\frac{Q}{S}$ = specific capacity (gpm/ft). By using formula/conversion table for water treatment and water distribution (FDEP 2020), equivalent units for transmissivity (m^2/day) and specific capacity (m^2/hr) values are obtained.

The records of pumping and recovery tests were represented graphically to estimate the transmissivity (T), storativity (S), and hydraulic conductivity (k) values by using Jacob's straight-line method (Cooper and Jacob 1946) and Theis's recovery methods (Theis 1935) (Fig. 12) (Table 1).

Steady-state calibration

The objective of model calibration is to assure that it can produce field-measured heads, which are calibration values. The calibration process has been carried out for the boundary conditions and the hydraulic conductivity

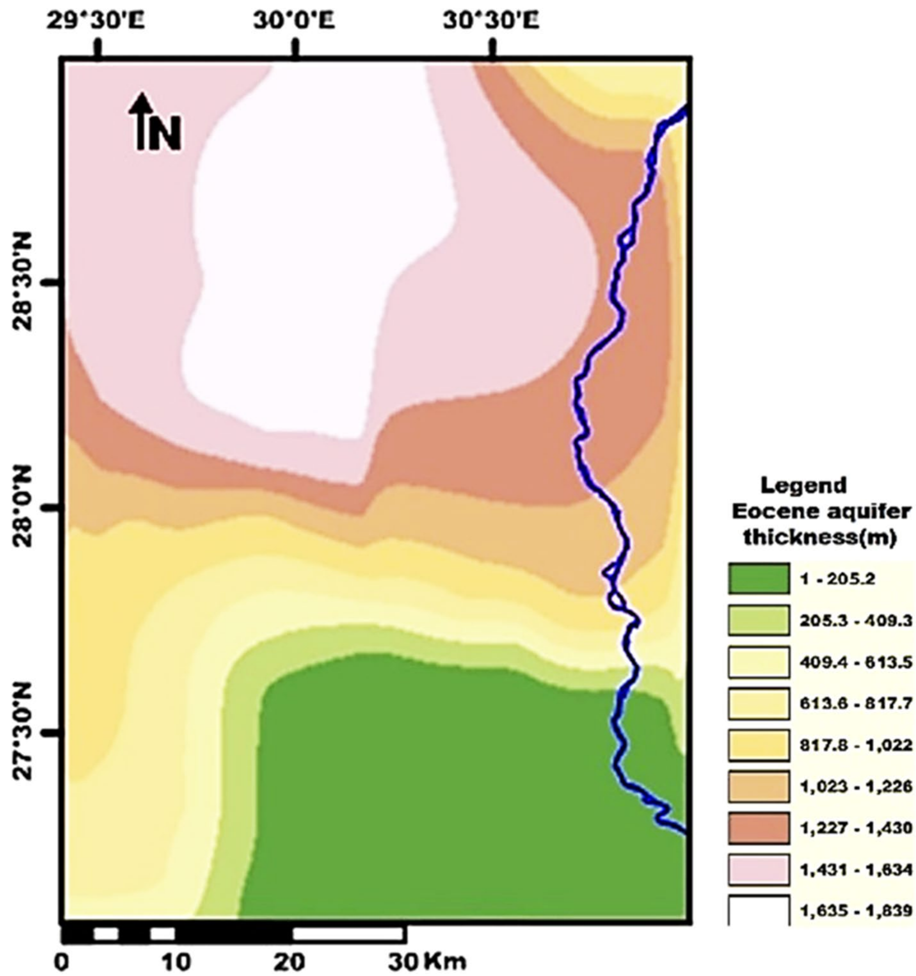

Fig. 7 The spatial extension of the Eocene aquifer and its approximated thickness

spatial distribution modification to match the observed and simulated groundwater heads (Figs. 13, 14). The following basics and assumptions were considered during the model verification:

1. The groundwater flow in the Eocene aquifer occurs under confined hydrologic conditions
2. Currently, the aquifer is in steady-state status as no pumping activities took place in the study area
3. The aquifer constitutes one homogeneous layer
4. The aquifer is mainly recharged through the groundwater influx across the western and south-western boundaries
5. The discharge of the aquifer occurs through the groundwater outflux across the eastern and northeastern boundaries.

Transient simulation

Transient simulation is needed to solve time-dependent groundwater problems. The calibrated steady-state model is run under transient calibration for one year of pumping to adjust the storativity values (Fig. 15). The model is subjected to sensitivity analysis to quantify the uncertainty in the calibrated parameters. It revealed the high sensitivity of the model toward the boundary conditions, hydraulic conductivity, and storativity, respectively. The new agricultural development project in the study area covers 4000 acres. Proposed pumping wells were distributed with a spacing of 1000 m to decrease the pressure on the aquifer and reduce the interference between the wells. Virtual observation wells were distributed among the extraction wells to monitor the groundwater levels under the impact of each development plan.

Model results

Based on the future governmental development plan in the West–West Minya area, model scenarios have been proposed to support the decision-makers with the results and recommendations. The first scenario has been assumed to interpolate the sustainability of the groundwater aquifer in the newly reclaimed area under

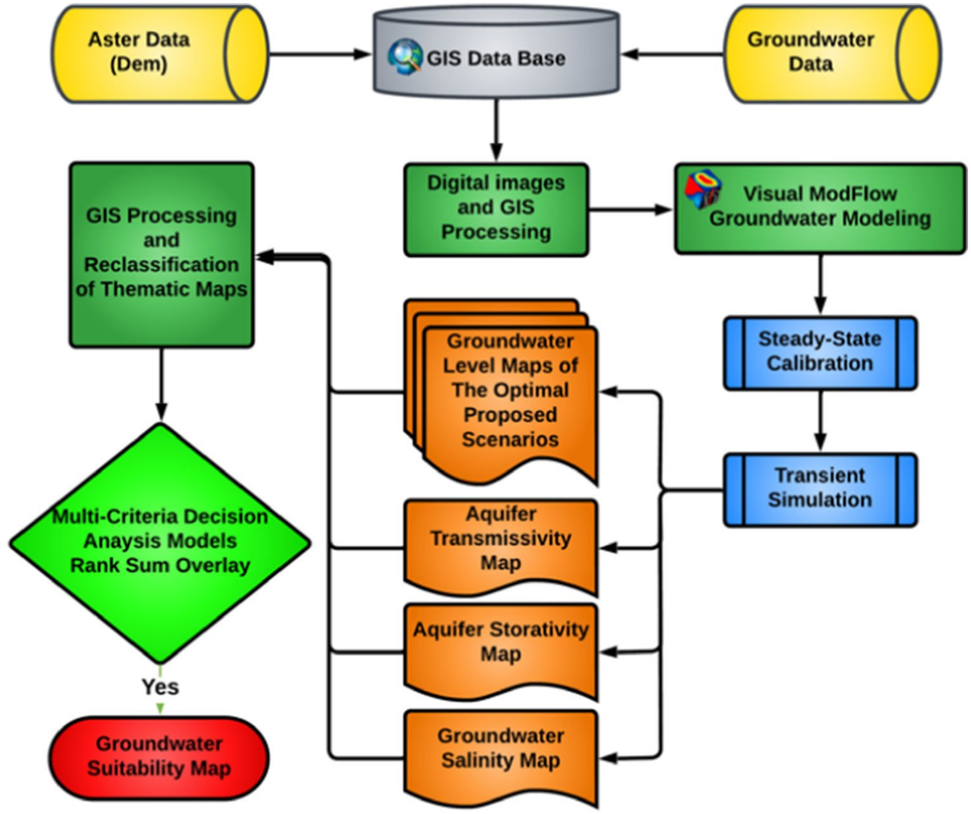

Fig. 8 Flowchart of work procedure

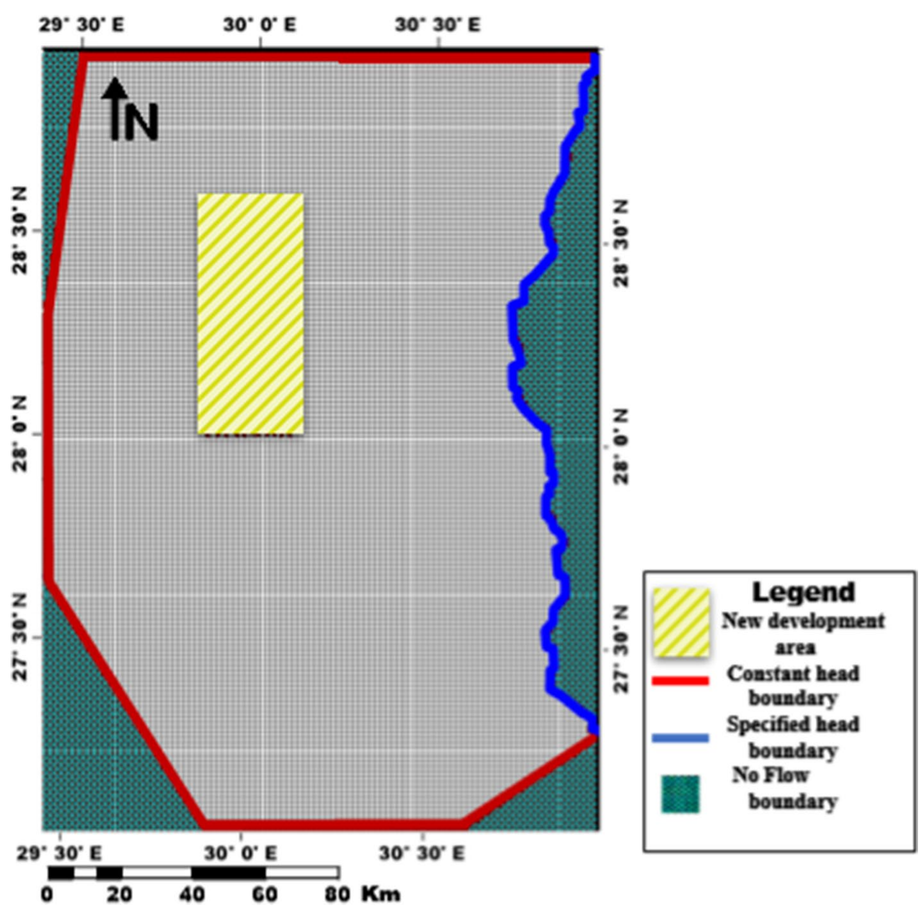

Fig. 9 Numerical grid of the modeled area, hydrologic boundaries, and new development area

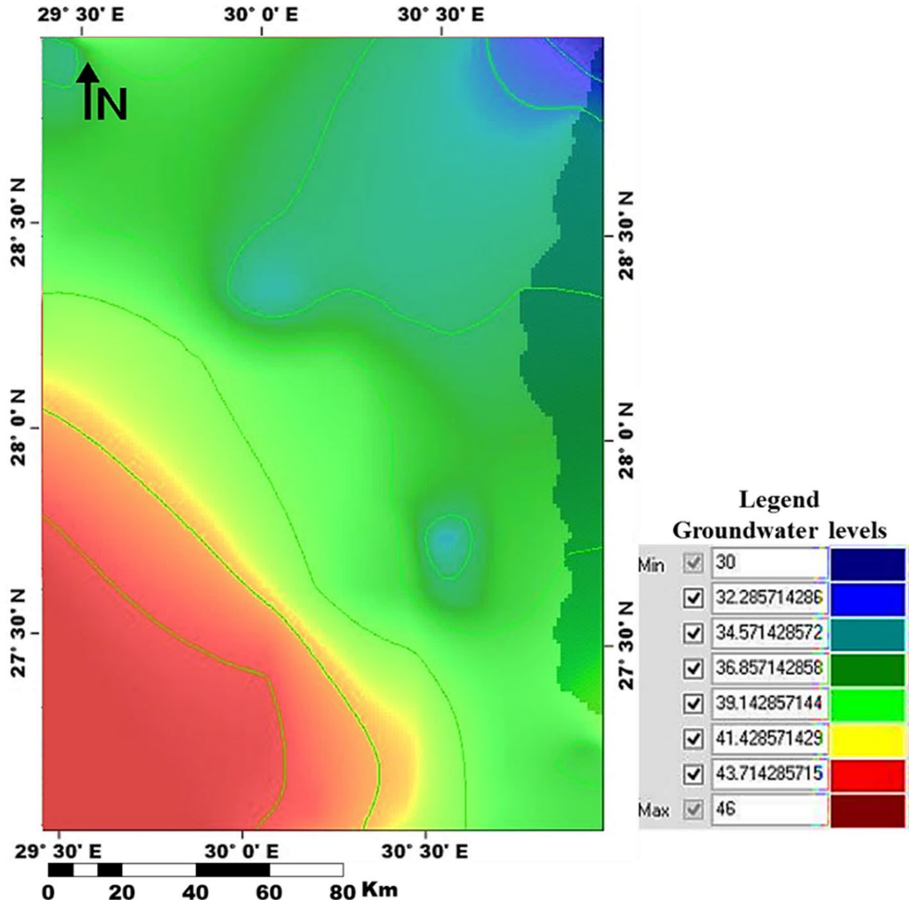

Fig. 10 Initial distribution head in the modeled area

the current operation scheme by applying the proposed pumping wells with pumping rates of 150 m^3/d for irrigation of 3953.68 acres. In the second proposed scenario, the sustainability of the groundwater aquifer in the newly reclaimed area is interpolated by considering the water meter consumption in the newly reclaimed area with a value of 6 m^3/d for each acre (MALR 2007). The transient simulations have been carried out for 100 years divided into 10-time steps. Boundary conditions and wells pumping rates were constant during transient simulation.

Impact of the first proposed scenario

By applying the first proposed scenario, a significant depletion in hydraulic heads results from the end of each time step. The cone of depression is formed gradually at the center of the modeled area, reaching a maximum drawdown of about 100 m. The dynamic groundwater level got steady-state conditions after an estimated period of 5000 days (Fig. 16). Negative values of groundwater levels are recorded; it reached − 80 m.b.s.l

Impact of the second proposed scenario

This scenario results show a smaller decrease in groundwater level than the first proposed scenario. The lowest groundwater level is recorded at − 20 m.b.m.s.l. The maximum drawdown of about 60 m is formed after a simulation period of 9700 days (Fig. 17). The daily withdrawal rate from wells should not exceed 23722.20 m^3/day according.

Multi-criteria decision modeling

Based on the obtained results of the optimal scenario for groundwater sustainability of the applied visual MODFLOW model, multi-criteria decision analysis (MCDA) model technique (Malczewski 1999, 2000) is used to assess the impact of groundwater consumption by detecting the groundwater suitability zones after long run reclamation in the concerned development area. The (MCDA) model is not a substitute for cost-benefit analysis; it is a complement analysis it gives a range of decisions. In this work, the MCDA model integrates geospatial data of the most effective parameters

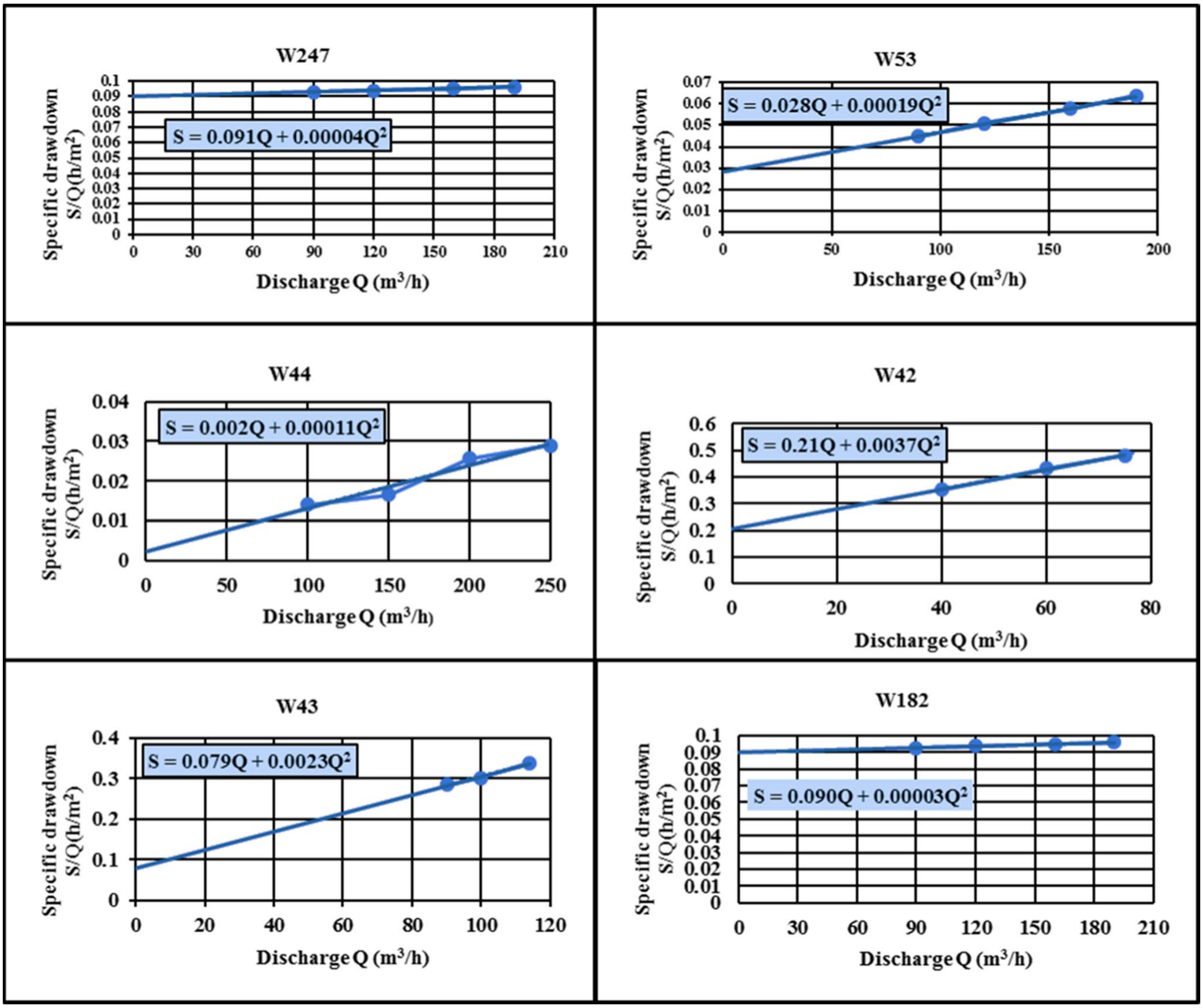

Fig. 11 Step test diagrams from pumping test for the Eocene aquifer, West–West Minya, Egypt

in the groundwater potentials both for aquifer hydraulic characteristics and groundwater quality by merging all multi-criteria layers into one perspective layer for groundwater exploitation. The contributing criteria are groundwater levels (GWL) which are obtained from the outputs of the optimal simulated scenario (second scenario) of the groundwater flow model, groundwater salinity (TDS), aquifer transmissivity (*T*), and aquifer storativity (*S*). ArcGIS is used to generate a thematic map for each criterion. All-controlling criteria thematic maps are reclassified in ARC-GIS to use in the model as a layer (Fig. 18). Each criterion is ranked according to its priority in the groundwater assessment and integrated into a GIS database model using the weighted overlay method. Weighted-sum overlay analysis provides the ability to obtain weight for each ranked criterion. It combines all inputs by overlaying all rasters, multiplying each by its given weight, and summing them together to calculate the overall suitability of each cell and create one output raster layer that defines the appropriate groundwater zones. The ranks, rates, and attributes of input criteria are indicated in Table 2. The equation used in this method is defined as the following:

$$\mathrm{WI} = \frac{\mathrm{Wi}}{\sum_{n}^{i=1} \mathrm{Wi}} \tag{3}$$

where WI is the Relative weight of the *I* criterion. *n* is the number of criteria. Wi is the rank of the criterion.

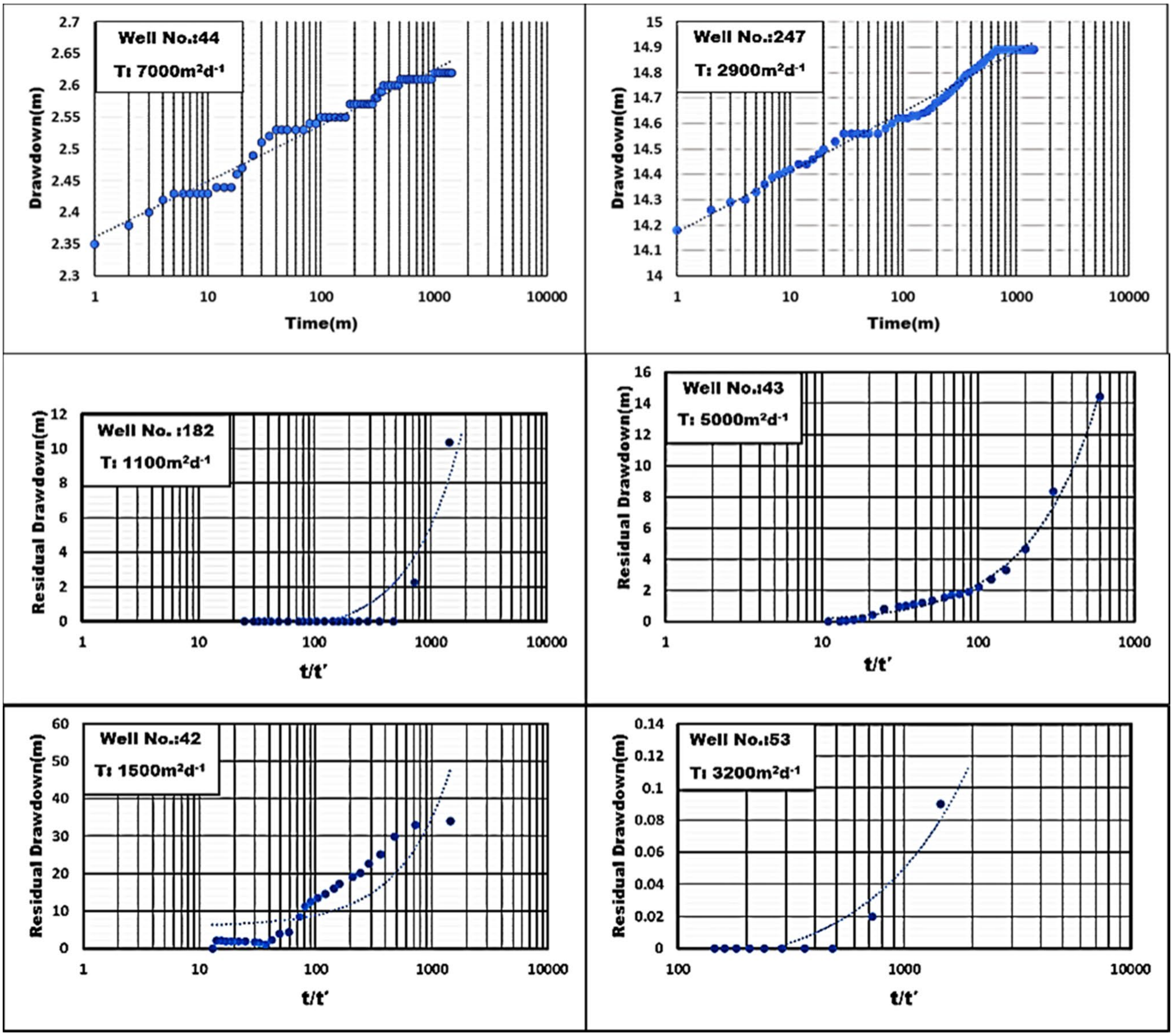

Fig. 12 Constructed curves of constant discharge pumping and recovery tests for the Eocene aquifer, West–West Minya, Egypt

Table 1 Hydraulic parameters of the Eocene aquifer, West–West Minya, Egypt

Well no	Step drawdown test		Jacob straight-line method			Theis recovery method	
	Specific capacity (m^2/hr)	T (m^2/d)	T (m^2/d)	S	K (m/d)	T (m^2/d)	K (m/d)
44	71.43	5952	7000	5.8×10^{-4}	3.88		
247	17.14	1428.60	2900	6.1×10^{-4}	2.41		
182	11.26	938.30				1100	0.916
43	42.20	3516.60				5000	4.166
42	13.20	1100				1500	1.25
53	26.50	2208.33				3200	2.13

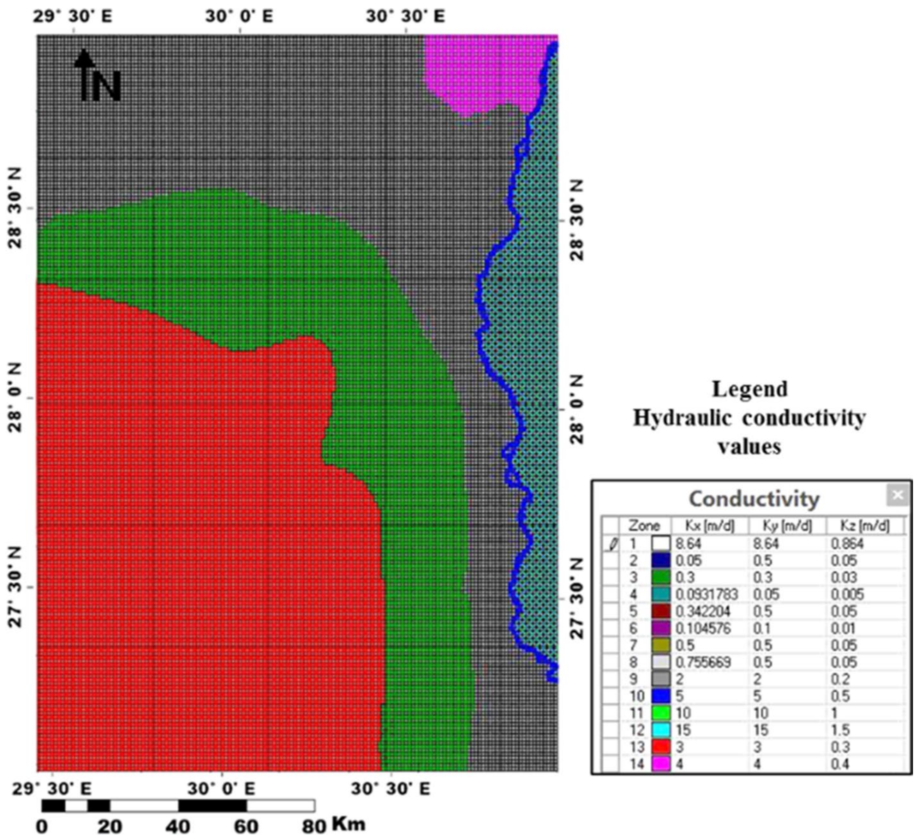

Fig. 13 Spatial distribution of calibrated hydraulic conductivity values in Eocene aquifer, West–West Minya area

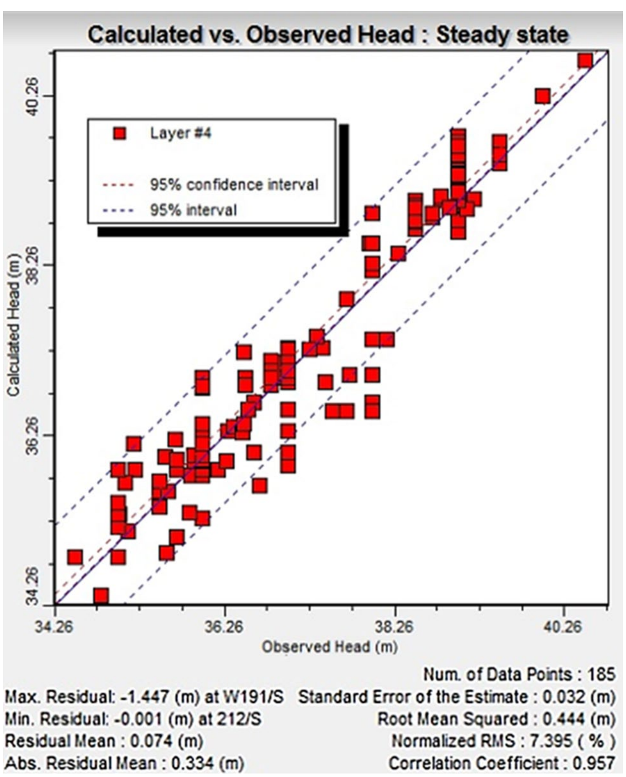

Fig. 14 Scatter plot of observed versus calculated heads in the steady-state calibration

Assessing groundwater prospects in the new development area

The raster layer generated from multi-criteria decision analysis (MCDA) is shown in Fig. 19. It defines the prospective groundwater zones which are categorized into most suitable (1584 km^2, 9.90%), suitable (4592 km^2, 28.70%), good (4784 km^2, 29.90%), moderate (1488 km^2, 9.30%), and unsuitable (3552 km^2, 22.20%). It is observed that nearly 80% of the study area has moderate to good potential for groundwater prospecting. There is a matching between the unsuitable zone of groundwater and the higher-salinity zone of groundwater, which indicates the first rank and the highest weight of the salinity factor in groundwater development. In the rest of the area, where the salinity is almost constant, the most suitable and suitable groundwater zones match with high groundwater level zones, indicating the second rank and the high weight of the groundwater level factor in groundwater development. The outcomes demonstrate the significance of managing groundwater and the sustainability of the Eocene aquifer in the West–West Minya developed area. The results show direct link of the aquifer hydraulic characteristics and the groundwater quality. Due to the complexity of the subsurface environment as the heterogeneous geological media, thus, uncertainty affects the ability to accurately. Data integration provides the quantification and potential reduction of the uncertainties of decision-critical model predictions.

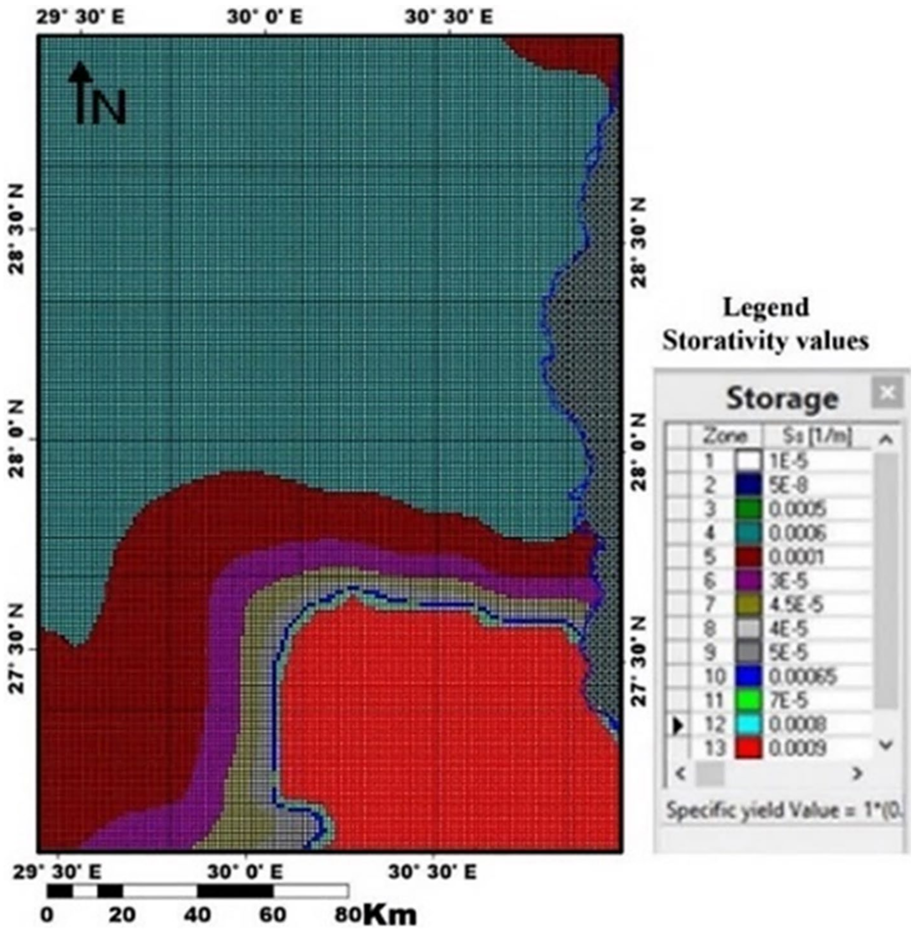

Fig. 15 Spatial distribution of calibrated storativity values in Eocene aquifer, West–West Minya area

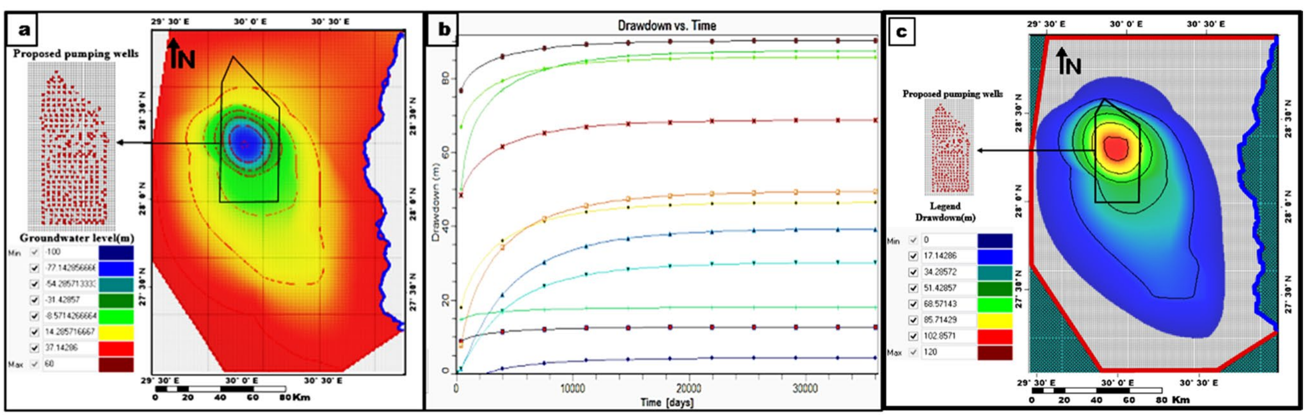

Fig. 16 Model results of the first simulated scenario: **a** hydraulic head distribution, **b** drawdown versus time and **c** drawdown distribution

Conclusion and recommendations

- The Eocene aquifer in the West–West Minya area in the Western Desert of Egypt is one of the new development areas with a total area of 80,000 acres. It has been investigated to assess the aquifer for sustainable development.
- The visual MODFLOW model is a powerful tool to estimate the impact of operating scenarios on the groundwater aquifer and assist decision-makers in implementing proposed policies for sustainable development. The model's output results indicated the high efficiency of the Eocene aquifer as a source of groundwater for irrigation of 4000 acres, and the daily

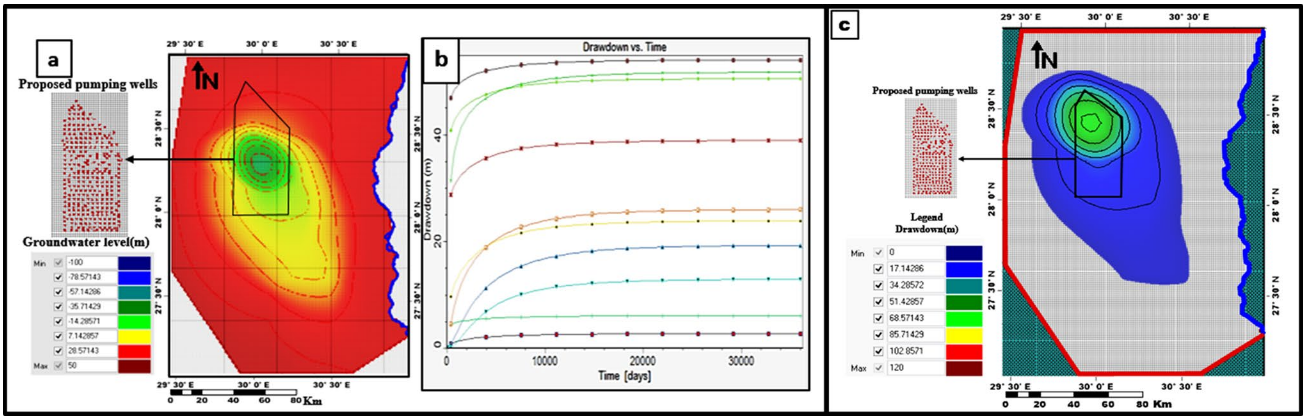

Fig. 17 Model results of the second simulated scenario: **a** hydraulic head distribution, **b** drawdown versus time, and **c** drawdown distribution

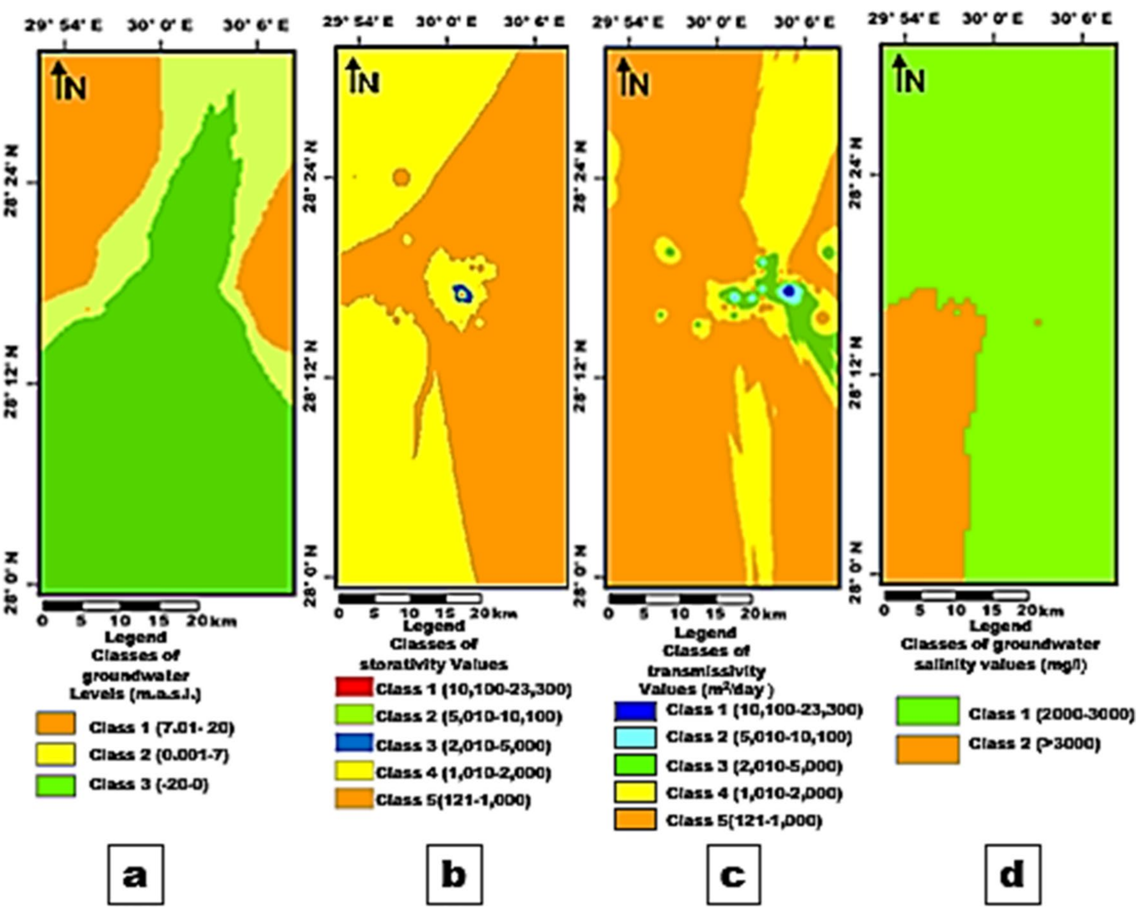

Fig. 18 Reclassified thematic maps: **a** groundwater level, **b** storativity, **c** transmissivity, and **d** groundwater salinity

withdrawal rate from wells should not exceed 23722.20 m^3/day according.

- Applying the multi-criteria decision analysis (MCDA) model revealed the groundwater suitability zones after long-run reclamation. About 80% of the study area has moderate to good potential for groundwater prospecting.
- In sustainable development projects, it is necessary to assess the continuity of groundwater resources under current and future operating conditions considering the expected population increase and increased water needs of industry and agriculture.

Table 2 Categorizing the contributing criteria and their rank, weight, and rate affecting the groundwater assessment

Thematic layer	Rank	Weight	Relative weight	Attribute	Rate
Groundwater salinity	1	4	0.40	2000–3000(mg/l)	1
				< 3000(mg/l)	2
Groundwater levels	2	3	0.30	< 0(m.a.m.s.l.)	3
				7–0(m.a.m.s.l.)	2
				7–15(m.a.m.s.l.)	1
Transmissivity	3	2	0.20	< 1000(m^2/day)	5
				1000–3000(m^2/day)	4
				3000–6000(m^2/day)	3
				6000–10,000(m^2/day)	2
				10,000–23,300(m^2/day)	1
Storativity	4	1	0.10	< 0.00552	5
				0.00552–0.02443	4
				0.02443–0.05911	3
				0.05911–0.11980	2
				0.11980–0.200991	1

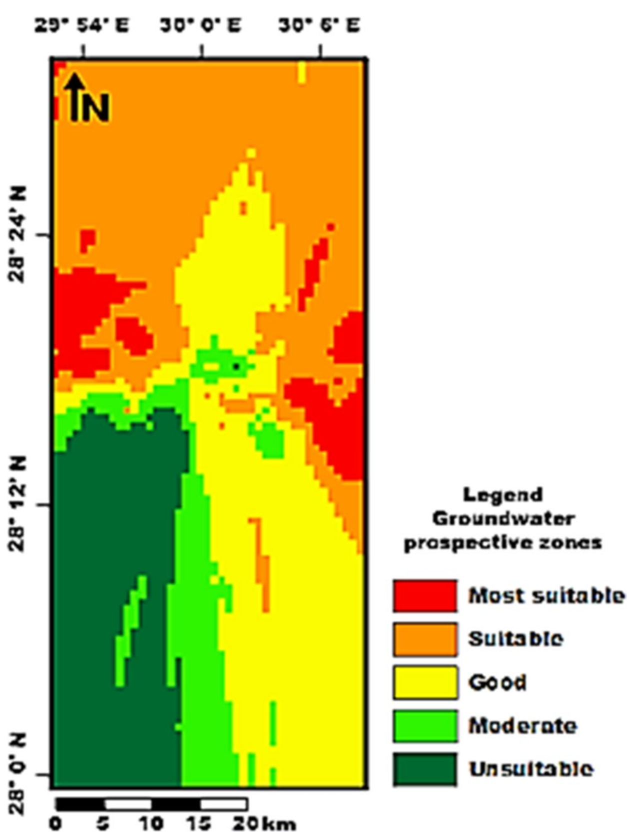

Fig. 19 Prospective groundwater zones

- Optimizing levels of groundwater withdrawal from the current or future drilling wells to achieve a balance between the use and the protection of water potential and address their impacts on aquifer storage and depletion trajectory management is the main target of groundwater assessment policies.

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