



Numerical modeling constrained by environmental isotopes for sustainable development of partially renewable aquifers in desert area

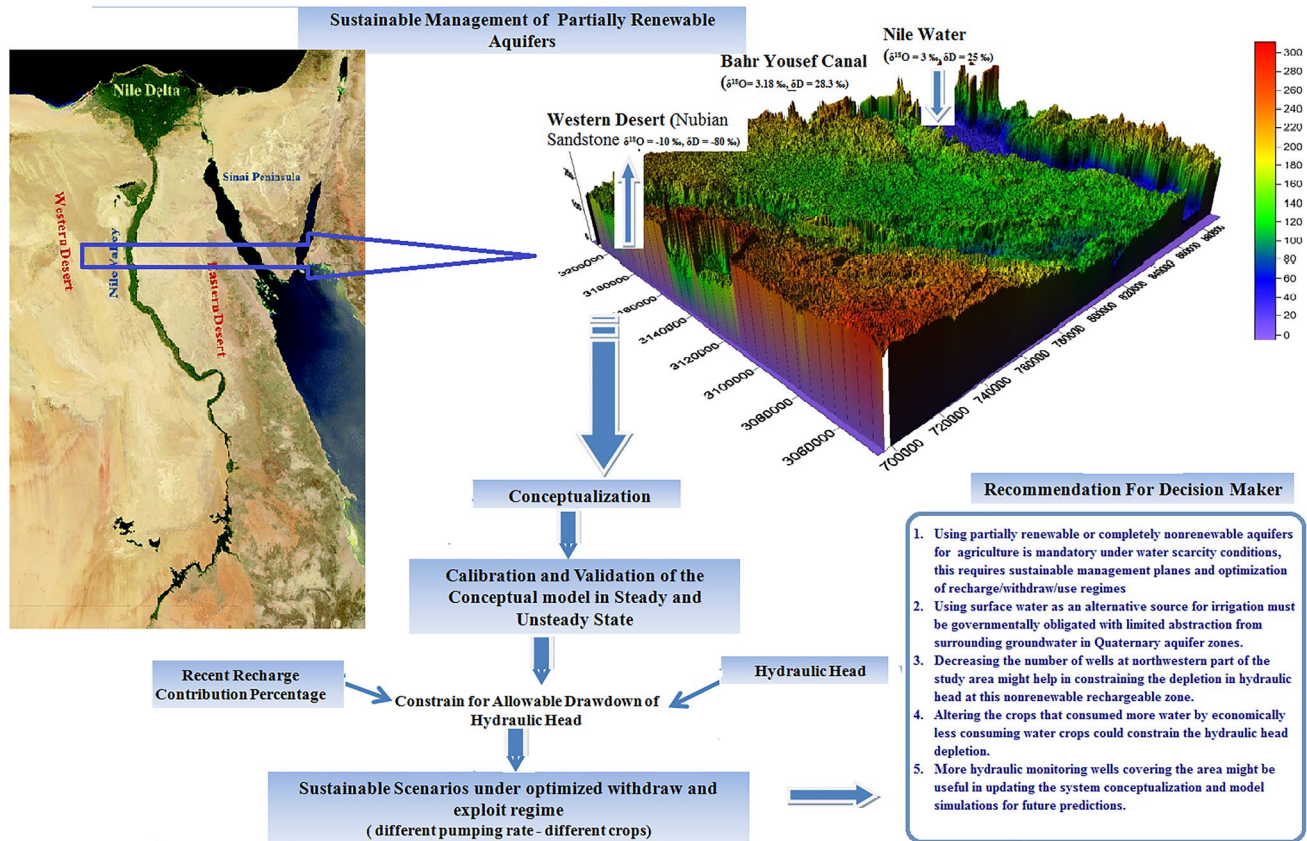
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Abstract

Sustainable groundwater resources are a critical issue for national development in developing countries like Egypt, which is characterized by a semi-arid to arid climate and low per capita share of fresh water as a result of progressive population increase and especially after the construction of the Great Ethiopian Renaissance Dam. It is mandatory to adopt and modify methods suitable for preserving and efficient use of available water resources. The Eocene carbonate aquifer in the desert area under study (West El-Minia, Mid-Upper Egypt) is partially renewable; its sustainable development in irrigation is explored in this work. The (recharge–withdraw–exploit) regimes have been optimized by keeping the well abstraction below the fraction of renewable recharge and maximizing the exploit by selecting low water -consuming crops of high economic value. A novel approach is introduced in this work by integrating isotope hydrology techniques with numerical modeling; environmental isotopes (¹⁸O and D) contents of 62 groundwater samples have been used to determine and map the contribution of recent recharge in the study area (from 10 to 95%) and to constrain the acceptable reduction in hydraulic head allowed under an optimized withdraw and usage regime. Different scenarios were proposed by changing (rate of pumping, number of wells, wells distribution and irrigated crops) and simulating aquifer behavior to achieve the sustainable yield goals and the best plan for groundwater management in the study area.

Graphical abstract



Keywords Groundwater modeling · Environmental stable isotopes · Sustainable management · West El-Minia · Egypt

Introduction

Understanding groundwater resources for sustainable and efficient utilization is vital to ensure the economic development of any African country as it provides quantitative information on water availability and potential. Recently, sustainable groundwater management practices are gaining importance more than ever before, as the pressure on global water resources is increasing as groundwater exploitation without management programs leads to the depletion of present-day storages, which are necessary for relief in emergency situations. Sustainable groundwater resources are a critical issue for national development in developing countries like Egypt, which is characterized by a semi-arid to arid climate and has a per capita share of fresh water generally low and expected to further decline as a result of progressive population increase and development practices as well as the construction of the Great Ethiopian Renaissance Dam (GERD). Therefore, although there are many procedures, formulations, and algorithms for sustainable aquifer management, there is still a great need for effective, practical, and applied methodologies that are believed to

be helpful in preserving available water resources to ensure sustainability. The concept of sustainable groundwater development generally represents an ambitious goal of optimal use of the groundwater resource with limited undesirable impacts both now and in the future. This concept has been adapted and used in the early 1980s (Bredehoeft et al. 1982). It was adopted that extraction of groundwater should be less than groundwater recharge, which might reduce the excessive depletion in the storage of the aquifer. A large number of different approaches, including numerical models and their software, are available for ready uses, but sustainable water management needs special attention for successful local applications (Lohman 1972; Seward et al. 2006; Zhou 2009). The use of numerical models as a tool in the management plans and prediction of groundwater behavior has been gaining considerable importance in recent years, as an aspirational goal for rational and efficient use of water resources, especially in arid areas. In the majority of previous studies that worked with the sustainable yield concept, values of sustainable groundwater extraction were derived by applying optimization concepts within groundwater modeling of aquifers subject to hydraulic flow (Larson et al.

2001; Kalf and Woolley 2005; Don et al. 2006 and Chen et al. 2010). Some decision analysis models were used (Gau et al. 1998; Gau and Liu 2002), in which groundwater was treated as a commodity with special focus on the socioeconomic part of sustainable extraction that is based on the loss function concept. In addition to that, several studies have contributed on an aquifer scale or a basin scale to the definition and factors of sustainable yield (Van Tonder et al. 2001; Alley and Leake 2004; Maimone 2004; Holland and Witthüser 2009; Zhou 2009). Based on those studies, the groundwater sustainable yield is dependent on the amount of water captured (Seward et al. 2006), which is defined by the increase in recharge and the decrease in discharge of an aquifer due to pumping operations (Zhou 2009). Furthermore, methods of water balance have been widely applied in the determination of sustainable yield for groundwater management purposes. According to Kalf and Woolley (2005), methods for determining the sustainable yield must allow various models to optimize the yield output at a new state of equilibrium, which implies that groundwater sustainable yield is not a fixed but a movable quantity along with aquifer pumping stress. It is challenging to provide a general definition and solution that covers different management strategies at global scale, as each aquifer management strategy differs from region to region. As mentioned before; although numerical modeling is significant tool in sustainable management practices, there must be an accepted logistic constraint to control and help in evaluating the significance of predicted impacts (e.g., decrease in hydraulic head) to track the flawed consequences of unmanaged water extraction toward sustainable water management in the aquifer.

An attempt has been made by Smith et al (2016) based on qualitative judgment to propose a scale of sustainable extraction from the aquifer to be between 5 and 70% of the aquifer recharge to limit drawdown of hydraulic head. This scale was derived from hydrological literature from Jordan, Turkey, Iran, Greece, Australia, the United States, Taiwan, South Korea, Israel, India, Namibia, England, Denmark, and China. This approach defines the sustainability of groundwater by the development and use of groundwater in a manner such that the water use can be maintained for an indefinite period of time without causing unacceptable environmental impacts and under the constraint of no degradation of the water quantity and quality (Xu et al. 2003; Alley and Leake 2004). By assuming that the amount of water equivalent supposed to be abstracted under the sustainable development plan is a part of the aquifer's recent recharge (within the range of 5%–70%), inferences should be made for that in aquifer storage and abstraction. Fortunately, stable isotopes contained in groundwater (Oxygen-18 and Deuterium) provide an ideal detrimental tool for aquifer recharge sources and determine any contribution from recent recharge to the aquifer (Hchaichi et al. 2014, Yuan, et al. 2018 and Sadek et al. 2020). Accordingly, and from the context of preferable

groundwater exploitation with a limit of 5–70% of the aquifer's recent recharge, stable isotopic content can be used to constrain the acceptable depletion of groundwater storage (or water level reduction) under continuous development within a sustainable development schemes has been used as a novel approach in this work.

Taking into account the existing situation of fresh water shortage and the expected adverse impacts of Ethiopian dam on the Egyptian water resources, a strategic development project for reclaiming 1.5 million acres has been nationally issued as a primary step toward increasing agricultural production in Egypt; the study area is allocated within it. This work aims to promote a future vision for the management of groundwater used for irrigation in the study area and to aid a sustainable plan for its development. It is based on numerical modeling of the used partially renewable aquifer and optimizing its recharge–withdraw–exploit regimes to preserve and use groundwater resources efficiently. A framework for determining acceptable water level reduction as a portion of harmful recent groundwater recharge using isotopic content as a finger print for recent recharge and as a constrain within numerical groundwater modeling.

Site characteristics

The area under study is located in Mid-Upper Egypt, between longitudes 29° and 31° E, 27° 30' and 28° 50' N. (Fig. 1a) It has a hot, dry summer season with little precipitation in the winter; the average rainfall value over the last 15 years ranged from 23.05 to 33.15 mm/year, while evapotranspiration was 4897.91 mm/year (Korany et al. 2006). It is characterized by hot dry summer season and rarely precipitation in winter, the rainfall average value for the last 15 years recorded to be ranged from 23.05 to 33.15 mm/year, while the evapotranspiration is 4897.91 mm/year (Korany et al. 2006). The average temperatures during January are 4.5 °C–20.5 °C and 20.5 °C–37.7 °C during August with mean relative humidity ranges from 36% in May to 62% in December.

Many authors in the study area have described three geomorphologic units, among them recently (Abdel Moneim, et al. 2016) classified the units from east to west as shown in (Fig. 1):

1. The young alluvial plain that represents the old agricultural areas irrigated with surface water diverted from the Nile and from main canals such as Bahr Youssef and occupies the area adjacent to the Nile bank between the River Nile and the old alluvial plain.
2. The old alluvial plain that includes new desert reclamation lands as well as scattered urbanized areas in the

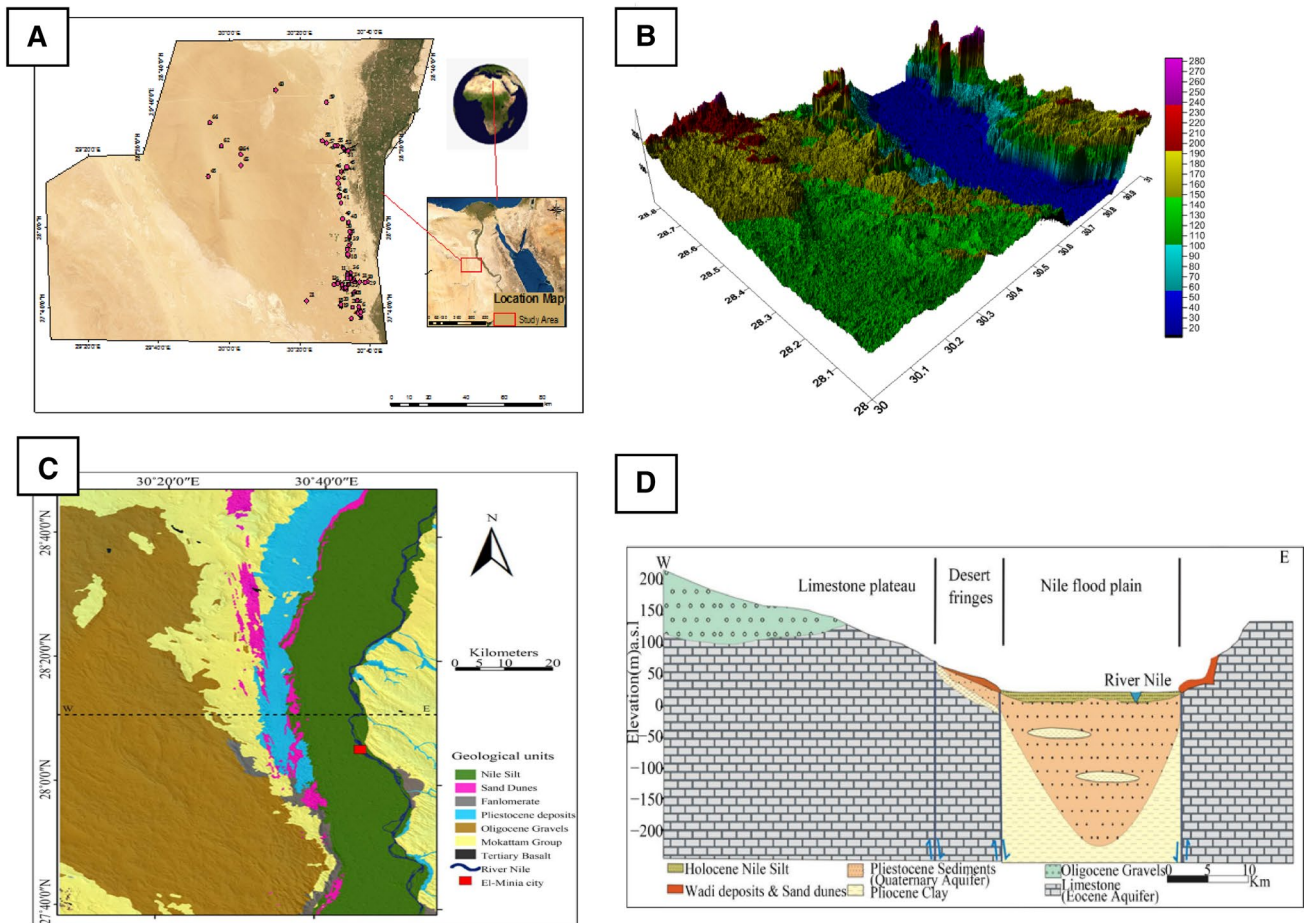


Fig. 1 **A** Study area with samples location. **B** Digital elevation model (DEM). **C** Geological map of the study area (Abdel Moneim, 2016). **D**: General hydrogeological cross section in El-Minia area (RIGW 1992)

western side of the valley is adjacent to the cliff of the plateau and it is irrigated by groundwater.

3. The lower Eocene Plateau is structurally formed, composed mainly of limestone, covered with alluvial deposits of sand and gravel, and bounds the Nile Valley from the east and west.

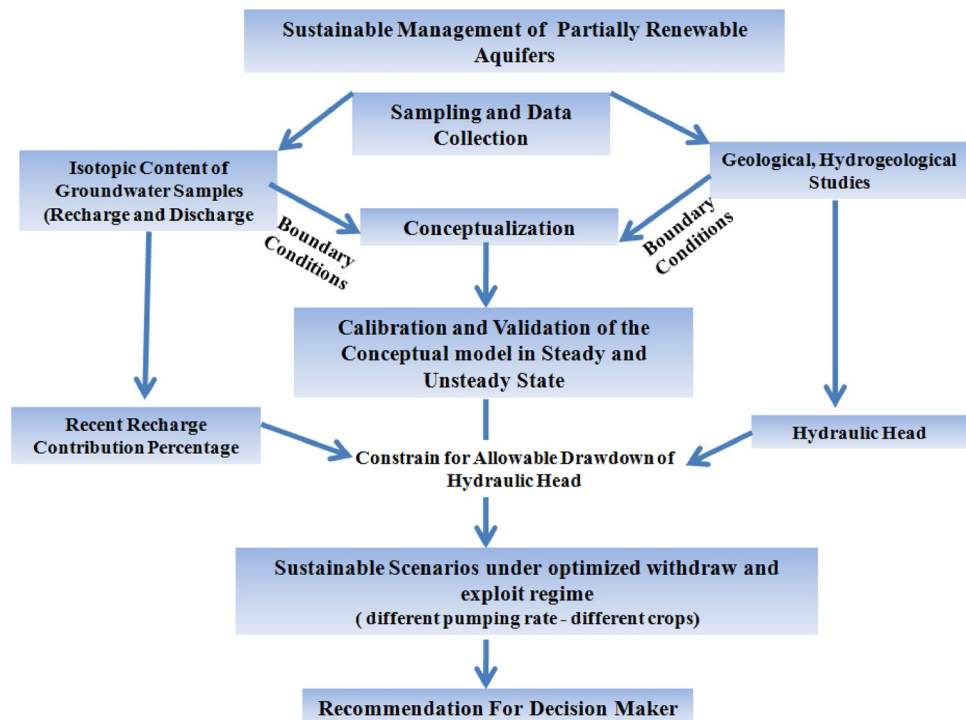
The lithostratigraphic sequence of the study area was described by Abu Heleika and Niesner (2008) and El Kashouty (2013) as follows: (a) The Quaternary deposits, which are formed of Pleistocene sands and gravels intercalated with clay lenses, capped by Holocene Nile Silt and Clay. (b) Pliocene clay beds, which mostly underpin Quaternary deposits and disappear in the north and west. (c) The Eocene limestone that is differentiated into the Samalut, Wadi El-Rayan, El-Minia, and Drunka Formations. The surface geologic map of the area is shown in (Fig. 1).

The Quaternary and Eocene aquifers are the main aquifers in El-Minia area (Said 1997). The Quaternary aquifer

has a large extension in the north–south direction and it is composed mainly of coarse, thick sand and gravel beds intercalated with clay lenses, it is widely distributed in the Nile valley and foot slope of the Eocene plateau; the aquifer is overlain by a semi-permeable to impermeable layer with a thickness varying from zero (at the fringes) to 16 m (near the Nile) and is basically recharged by the seepage of Nile irrigation canals and infiltration of irrigation return.

The Eocene aquifer occupies the extreme western side of the study area. It is formed of jointed, fractured white, highly fossiliferous limestone with shale and marl intercalations. It is unconfined under alluvium aquifer and underlain by Nubian sandstone, and it is probably affected by a network of faults. The Eocene aquifer gets a mixed recharge of two components: (present-day Nile water from interconnected Quaternary aquifers and Paleowater upward leaked from deep aquifers through fractures and structures).

Fig. 2 Flow chart illustrating the applied frame works in this study



Methodology and techniques

A proposed plan has been introduced in this work for sustainable utilization of the groundwater in the study area for agricultural development, starting with characterization of the hydrogeological system and groundwater conditions, then using computer code (USGS-MODFLOW-2000) to model the system, and finally to optimize its regimes and simulate its response under proposed development plans extended for the next 20 years.

The framework applied in this paper is illustrated in (Fig. 2), representing the main sequential steps used to achieve the main goal of this paper as follow.

The first step was to choose a targeted area within the Egyptian government's priorities for the establishment of new agriculture communities to cope with the national demand (Western El-Minia), as described above in the introductory section. Then, a sampling campaign for the collection of 62 groundwater samples covering the main aquifers (quaternary and Eocene) in the study area was conducted. The necessary field measurements (total dissolved salts (TDS), pH, temperature, and bicarbonate concentrations) were conducted for the collected groundwater samples. Oxygen-18 (^{18}O) and Deuterium (D) isotopic content were analyzed using laser spectroscopy PICARRO L-2120i in the Central Laboratory of Environmental Isotope Hydrology, Atomic Energy Authority. Isotope hydrology techniques have been used for identifying sources of groundwater

recharge as well as its continuity and renewability; it is also used to judge the decline of water level under optimal agricultural development, with limited unacceptable impacts both now and in the future. All of the collected data and retrieved review data were used in the conceptualization of the studied area for further modeling, simulation, and prediction of the sustainable development groundwater response in the study area using USGS- MODFLOW-2000 model, (Guiguer and Franz 1996; Chiang and Kinzelbach 1998; Hill 1998).

Model conceptualization

The heterogeneity of the hydrogeological system was simplified into a hydrogeological conceptual model, as it is considered to be the main backbone of the modeling process and the first step in the modeling protocol (Anderson and Woessner 1992). Both Quaternary and Eocene aquifers in the west El-Minia area were portrayed in a three-dimensional space visualized in a conceptual model with the utilization of hydrogeological cross sections and other parameters retrieved from literature. For analysis and visualization, these data were managed as layers in ArcGIS10.3.

The study area is characterized by an arid desert climatic condition where the annual amount of rainfall is not significant. The 3D grid developed for the groundwater flow model, shown in (Fig. 3A) extends over an area covering approximately 166750 acres.

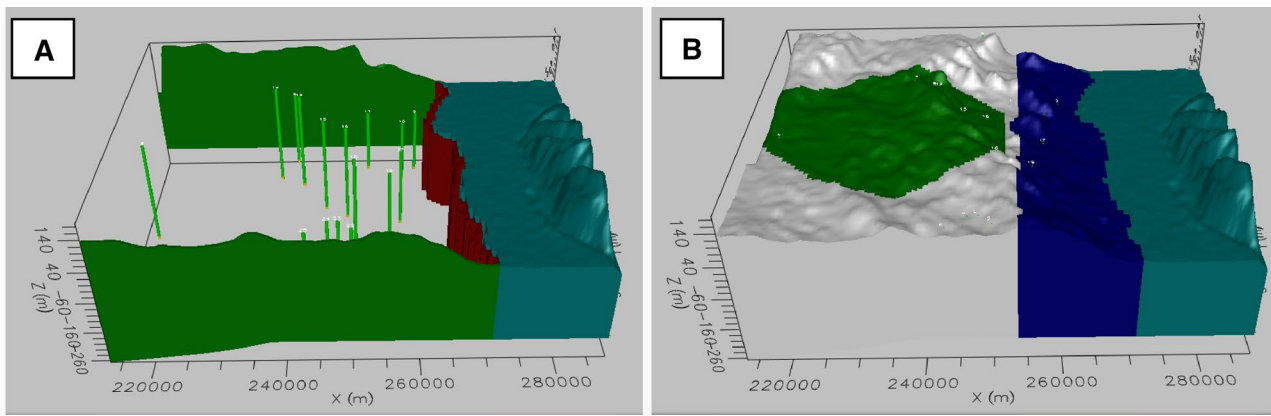


Fig. 3 **A:** Boundary conditions of the conceptual model (Green color representing general head boundary, Red color representing Ismailia canal as constant head boundary, and blue color representing inactive zone). **B:** Zonation of the hydraulic head

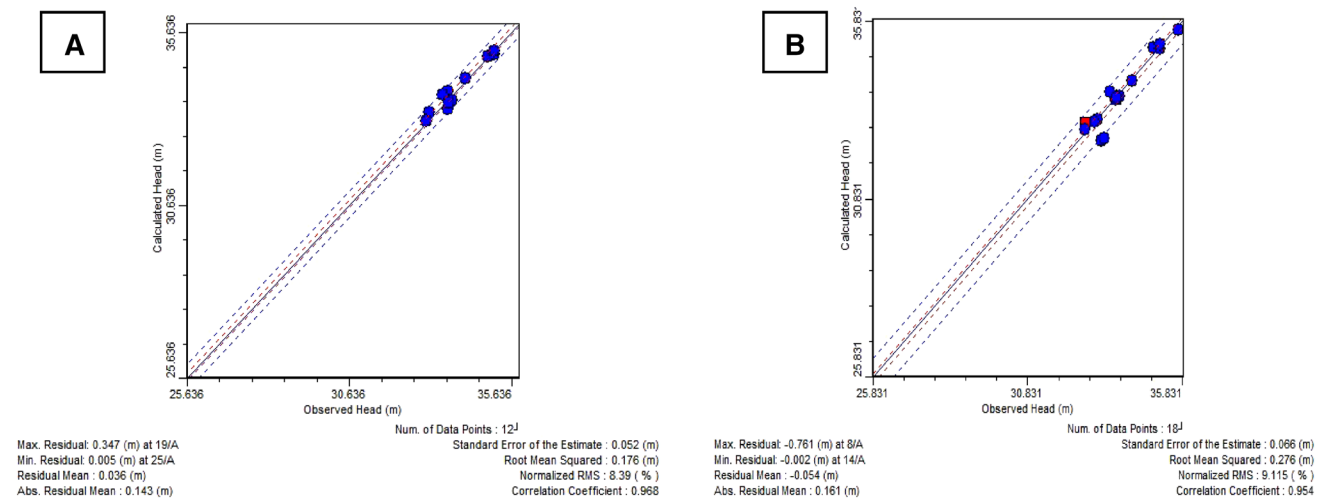


Fig. 4 **A:** Steady state calibration curve, **B:** Unsteady state calibration curve

Natural boundaries were identified and mostly physical boundaries were chosen since they are the most stable features of the groundwater system. The eastern boundary condition was considered as a no flow boundary. While northern and southern boundaries were considered as general head boundaries as they are readily quantified and substantiated. Bahr Youssef was considered to be a specified head boundary. The zoning method has been used to assign hydraulic conductivity, storage coefficient, and recharge since the Eocene aquifer is a heterogeneous one. The model domain was divided into sub-zones depending on the geologic formation. Each sub-zone contains a number of cells that have similar aquifer properties based

Table 1 Average isotopic content of possible groundwater recharge sources in Egypt

Recharge Source	$\delta^{18}\text{O}$ (‰)	δD (‰)	Reference
Old Nile	- 0.6	4.0	Awad et al. (1994)
Paleowater of western desert (Nubian Sandstone)	- 10	- 80	Awad et al. (1994)
Recent Nile (Bahr Youssef)	3.18	28.3	This study

on the areal extent of the hydro-stratigraphic units. The hydraulic conductivity in the study area ranged from 5 to 50 m/day (Korany et al. 2008, Abu Heleika and Niesner 2008) as illustrated in (Fig. 3B).

Model calibration

The available data on depths to groundwater level were used to calibrate and validate the model. The hydraulic conductivity and transmissivity change by the trial and error method, (Doherty and Hunt 2009). The efficiency of the simulation process and the compliance between calculated and observed head values equal 0.96 and 0.95 with a residual mean of 0.036 and -0.054 m for steady and unsteady state, respectively. The normalized error in both steady and unsteady state did not exceed 10%, (Fig. 4A and B) showed an acceptable comparison and satisfactory calibrated results, indicating the readiness of the calibrated model for simulations and predications.

Results and discussion

Environmental stable isotopes constrains

The average conditions under which rain water originates are encoded in its isotopic composition (^{18}O and D) and correlated with that of surface water or groundwater connected to it in the hydrogeological cycle. The different sources of recharge (rain, rivers, seas, lakes, etc.) have specific isotopic compositions that label and facilitate identification and finger printing them in a given aquifer. Fortunately, the stable isotope content (^{18}O and D) of Egypt's major recharge sources is highly differentiated and distinguishable, and accurately encodes the sources of recharge and renewability of groundwater (Table 1).

The present work appraises groundwater recharge sources and renewability based on the results of sixty-two groundwater samples; which helps not only in conceptualization process for the hydrogeological system but also for setting goals and controlling groundwater management scenarios. (Table 2) shows statistical analysis of isotopic data; the δD and $\delta^{18}\text{O}$ contents vary in the ranges from -80.3‰ to 29.85‰ and -10.54‰ to 3.98‰ , respectively. These samples lie within the ranges of the two major sources of groundwater recharge in Egypt (i.e., Nile River water and Nubian Sandstone). Sample distribution in the δD vs. $\delta^{18}\text{O}$ conventional diagram (Fig. 4A), fits a linear pattern ($\delta\text{D}\text{‰} = 8.22 \delta^{18}\text{O}\text{‰} + 2.71$, $R^2 = 0.96$) very tightly complies with that of mixing present-day Nile water with paleowater Nubian

sandstone. This indicates that the major sources of recharge of the sampled groundwater wells are Nile water and paleowater that leaks upward from deep Nubian Sandstone aquifer through faults and fractures. The slope (close to 8) of the linear fitness of the samples indicates that recharge takes place directly in the two interconnected aquifers (Quaternary and Eocene), with nearly no chance for surface evaporation. The point of old Nile water lies very close to the mixing line; this could reflect a contribution of residuals from Nile water floods that occurred prior to High Dam construction, still remaining in the Quaternary aquifer in contact. Areal distribution of $\delta^{18}\text{O}$, (Fig. 5B) shows a general pattern of depletion from East to West in the direction from Nile flood plain–desert fringes to the limestone table land. This direction complies with the decrease of Quaternary aquifer thickness (which gets its major recharge from Nile River and irrigation canal) and increase of the interconnected Eocene limestone aquifer (which gets its major recharge—through fractures—as upward leakage from deep fossil water aquifer). There is a relative consistence between the patterns of isotopic depletion, (Fig. 5B) and that of increasing lineament density in (Fig. 5C); reflecting the role of fractures on fossil water recharge.

The isotopic mixing ratio between different recharge sources (Nile water and paleowater) was determined in the sampled wells using equation no 1, (percentage of Nile water = 1 - percentage of paleowater). The percentage of recent recharge and paleowater recharge in the collected samples is calculated as follows:

$$Q_{Old}/Q_{Total} = (\delta^{18}\text{O}_{Total} - \delta^{18}\text{O}_{New}) / (\delta^{18}\text{O}_{Old} - \delta^{18}\text{O}_{New}), \quad (1)$$

where Q_{Old}/Q_{Total} represents the paleowater contribution in the collected groundwater samples, $\delta^{18}\text{O}_{Total}$ is the content of $\delta^{18}\text{O}$ in the collected sample, $\delta^{18}\text{O}_{Old}$ is the value of the $\delta^{18}\text{O}$ content in the Nubian Sandstone paleowater that has a value of -10‰ and $\delta^{18}\text{O}_{New}$ is the value of the $\delta^{18}\text{O}$ content in the Nile water, which has a value of 3‰ . It was revealed that percentage of Nile water in the samples varies from 10 to 95%. The higher and direct contribution from recent recharge was noticed along the eastern part of the study area, with a decreasing pattern toward the northern and western sectors.

Table 2 Statistical results of physical and isotopic content of collected water samples

Item	Temp (°C)	pH	EC ($\mu\text{S}/\text{cm}$)	TDS (mg/l)	$\delta^{18}\text{O}$ (‰)	δD (‰)
Min	20	6.69	285	185	-2.26	-13.53
Max	21	9.2	6880	5160	-10.18	-78.48
Average	20.5	7.99	1720	1263	2.88	25.29
SD	0.35	0.55	1235	906	1.99	16.21

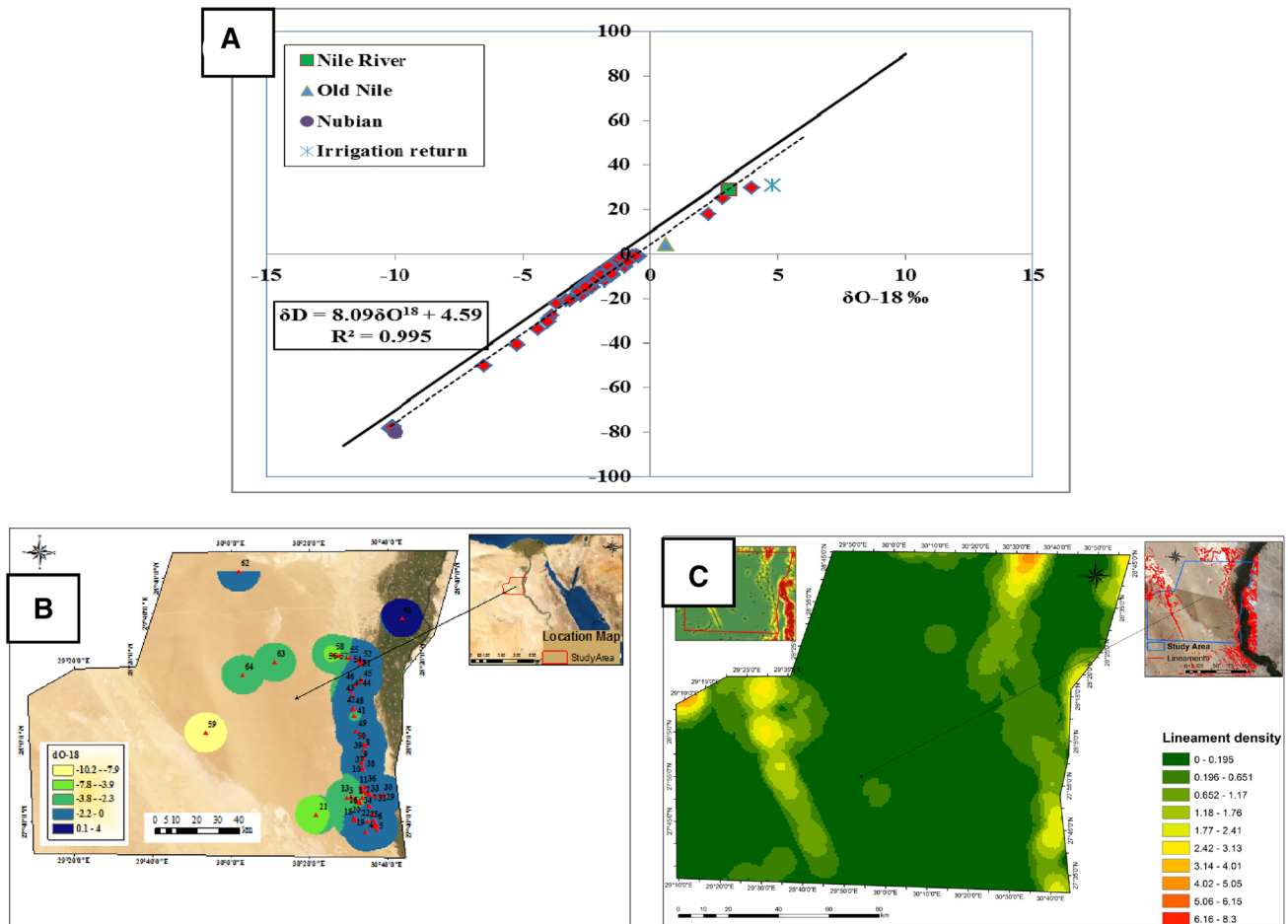


Fig. 5 A: δD vs. $\delta^{18}O$ conventional diagram B: Isotopic pattern of $\delta^{18}O$ for the studied samples. C: Lineament density of the study area

Table 3 The percentage of recent recharge with its equivalent hydraulic head drawdown

Contribution ratio from Nile (%)	Equivalent head to the recharge contribution(m)	Acceptable limit of head constrained for sustainable yield 50%
10	3	1.5
20	8	4
30	10	5
40	14	7
50	16	8
60	18	9
70	20	10
80	25	12.5
90	30	15
100	33	16.5

From this context, the limited recent recharge in the western zone and the expected reduction of Nile water flow to the surrounding Quaternary aquifer due to GERD construction necessitate a prospective strategic plan for this area. With respect to the concept of sustainable yield that equals 50%

of recent recharge; a new maximum allowable drawdown has been established in the study area, (Table 3). This table illustrates the percentage of recent recharge and its equivalent hydraulic head in a trail attempt to control and constrain the limits of maximum allowable reduction for the proposed

sustainable development scenarios. The maximum allowable drawdown in the non-replenished zone at the western border is 1.5 m.

Numerical modeling for sustainable development

The depletion in the hydraulic head represents a less sophisticated indicator that gives an overall picture of the relationship between yield, storage, and replenishment of an aquifer under induced pumping stresses. A trial was conducted to control the hydraulic head depletion under a sustainable development approach. Supposing a scale of sustainable yield in this study that should not be more than 50% of recent recharge to the aquifer (Smith et al. 2016) was used to determine restricted allowable drawdown after 20 years of abstraction under sustainable development. This percentage is conservative within the actual majority of recent recharge percentages in the study area; additionally, this value is conservative for future decrement in Nile system feeding water after GERD construction. If the percentage of recent recharge in different zones is equivalently represented as a fraction of the water level in those zones, the corresponding

reduction of water level would be spatially variable as a result of spatial variations of recent recharge to the aquifer.

Proposed scenarios for sustainable development

The most valuable, essential, food products that are favorable to being cultivated to meet population needs in the study area are mainly wheat, sugar beetroot, olives, and sesame (Moghazy and Kaluarachchi 2020); the yields of these crops are decreasing with time. An attempt has been made to calculate the irrigation water yearly required for these crops (Saleh et al. 2018), it is found 6760 m³/y/acres, 3000 m³/y/acres, 2000 m³/y/acres for semsem, sugar beetroot, and olive/or wheat, respectively. The standard protocol outlined was based on 400 wells covering the study area, in which each well will be sufficient for irrigation of 80 acres, (Saleh et al. 2018). Different scenarios of withdrawal and usage have been proposed in this work to achieve the sustainable yield goal for cultivation in the study area; these will be discussed in the results and discussion section. The environmental isotopes have been used to constrain sustainable development scenarios by judging and controlling the decrement in the hydraulic head.

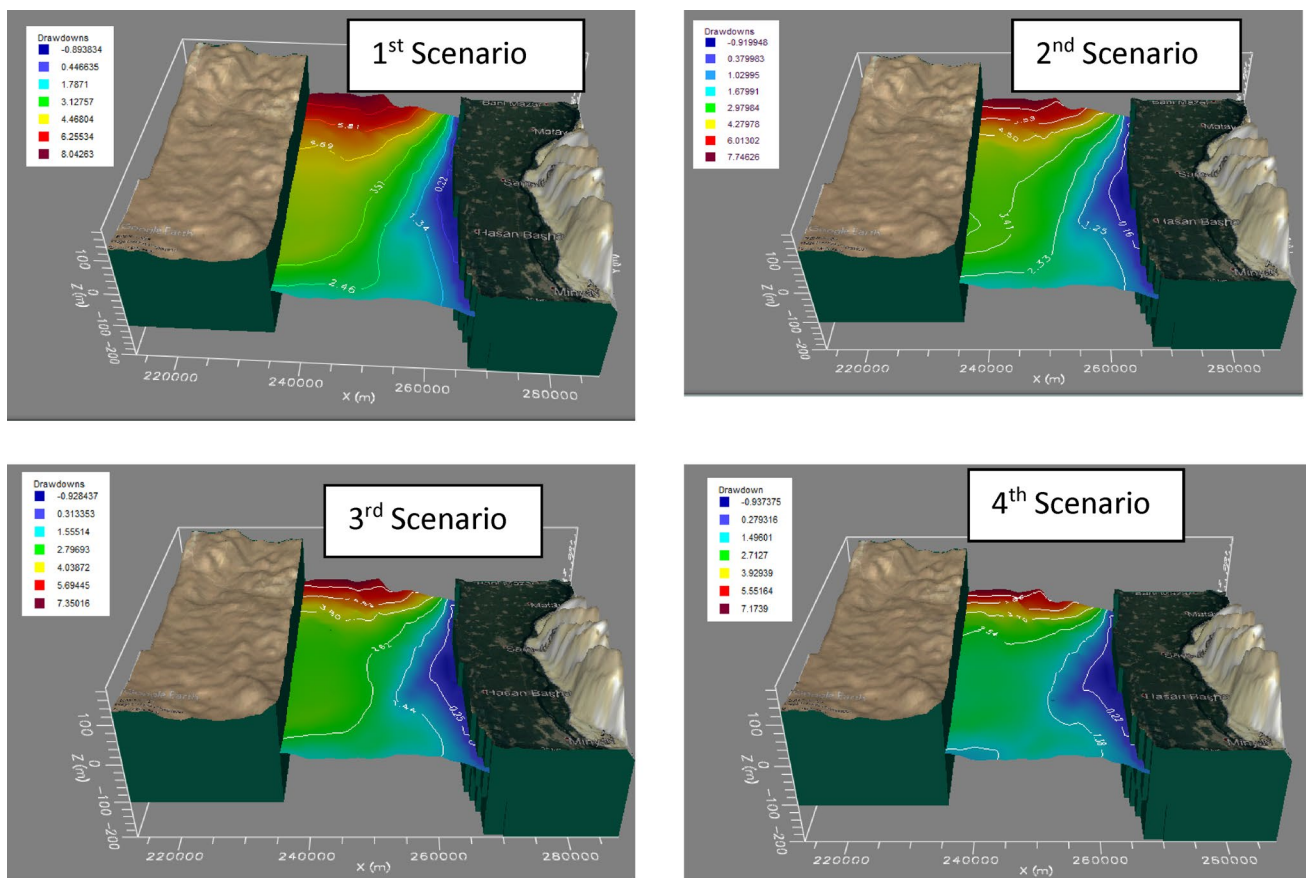


Fig. 6 Drawdown in Head after 20-year simulation time for different scenarios

1st scenario

This scenario adopts a basic consideration; to cultivate the less water-consumable crops in the northwest sector of the study area that receives the least proportion of recent recharge, the higher water-consumable crops (as sesame) in the eastern part close to Nile recharge, while Sugar beetroot be cultivated in the middle sector that receives recent recharge not less than 50%. The pumpage rate of the wells differed based on the actual water requirements of these crops. By applying this case, it was noticed that the calculated drawdown in the hydraulic head ranges from -0.25 m (at eastern parts) to $+8.5$ m (at the northwestern part), although the crop proposed for the sector of highest drawdown is the least water- consumable one. It is clear that the decrement in the northwestern sector and middel one exceeds the max allowable drawdown (equal to 1.5 m and 4 m, respectively), which is equivalent to 50% recent recharge. Based on this scenario, the actual abstraction from the aquifer should be less than $4.11E + 5$ m³/year; as shown in (Fig. 6).

2nd scenario

This scenario proposes switching crop types from sesame to sugar beetroot in eastern zones near the Nile to reduce water extraction by about 33% compared to the first

scenario ($2.73E + 5$ m³/year); this may allow the aquifer to replenish and allow for drawdown compensation in the western sector of the study area, (Fig. 6). It is clear that this scenario reduced the drawdown and allowed the contribution from the Nile to increase relatively in the east, but not to the extent that it compensated for the drawdown in the west. This may indicate that the approach used for sustainability has started to be useful, suggesting only the use of surface water irrigation and restricting the withdrawal from groundwater to give the aquifer a chance to be recharged from the Nile system.

3rd scenario

The western part of the study area and the desert reach do not receive significant continual recharge from the Nile, so decreasing the withdrawn water from this least rechargeable sector might minimize the drawdown. This scenario predicts a decrease of drawdown as a result of decreasing the number of wells in the western locality, where the total abstraction from wells reduced to $2.23E + 5$ m³/year (that representing a decrement of nearly 46% from the base case considered in the 1st scenario). A remarkable decrease in drawdown has been predicted in this scenario, it varies between -0.5 m at eastern zones to 7.2 m at the northwestern part, (Fig. 6). An increase in the recharge of the Nile occurs in the eastern part of the study area, with a decrement in the zones of higher drawdown.

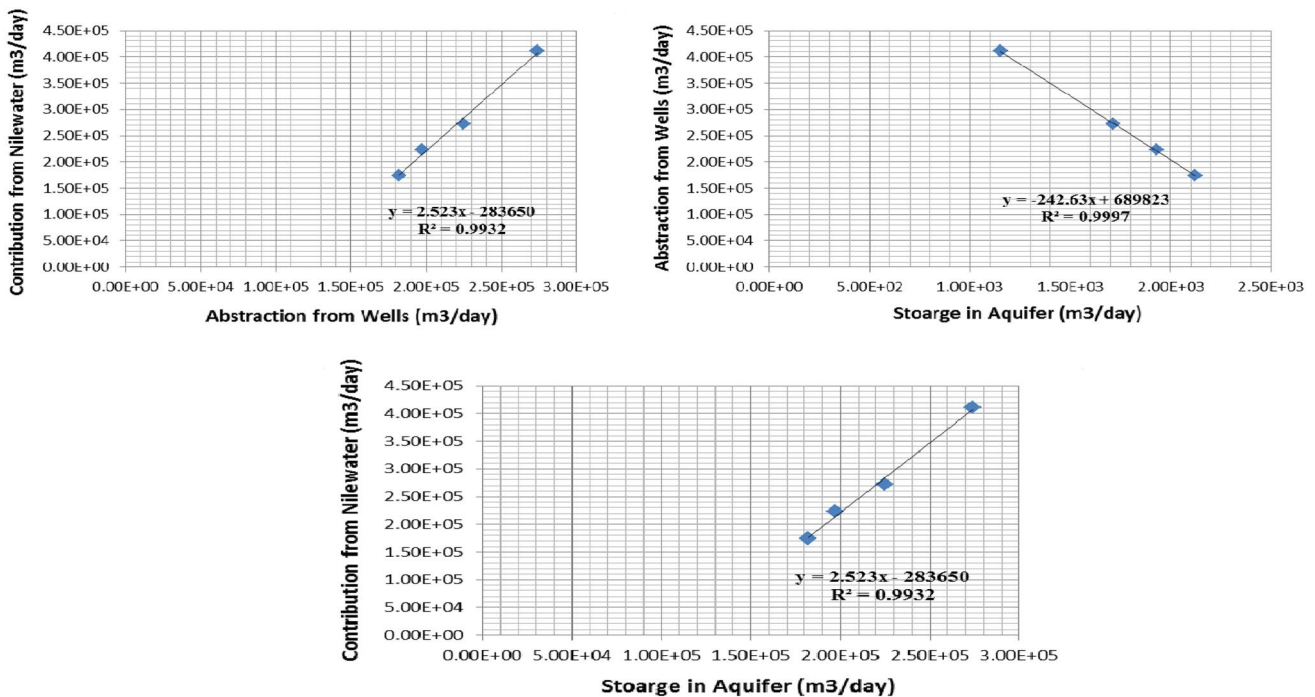


Fig. 7 Relationships based budget analyses of the three scenarios

4th scenario

An attempt has been made by reducing the extraction rate to 58% of that proposed in the 1st scenario ($1.74E+5 \text{ m}^3/\text{year}$), while well intensity is kept. In this scenario, the predicted drawdown is decreased in the northwestern sector and reaches about 6.5 m, (Fig. 6) Within an acceptable drawdown in the rest of the study area. Different alternatives have been tried within this scenario to further lower the depletion of hydraulic head in the western zone, without any further any notice. This scenario could be considered the most favorable one for sustainable management in these desert areas, taking into consideration the non-renewability nature of this zone.

Further description of the drawdown in groundwater heads and its relationship with the major components in the water budget system and the relevance of groundwater flow behavior are presented in the next section.

Water budget analyses of the numerical model for the proposed scenarios

The inflow and outflow parameters of the water budget were calculated from the numerical model used (MODFLOW), where inflow represents all the recharge amount of water contributed to the system, while the discharge components represent the outflow from the model in the budget analysis. Fig. 7 is regarded as a valuable output that may assist the decision maker in better understanding the required amount of water to be recharged versus the available one under stressed conditions. Decreasing the amount of water extraction in the modeled area was accompanied by a decrease in the contribution from the Nile system, proportional linear relationship has been established to express this relation as follows: ($y = 2.523x - 283650$), (Fig. 7); this is coping with the strategy of decreasing the dependence on the Nile river, as a response to the GERD adverse effects. Hence, the proposed 4th scenario seems to be on the track of the Egyptian government's interest. On the other hand; an inverse relationship has been linearly established between the storage in the aquifer after 20 years of development and the extraction from wells in different scenarios ($y = -242.63x + 689823$), Fig. 7. This reveals that decreasing the amount of water extracted from the aquifer gives more time for the storage to be somehow recovered with little contribution from the Nile River, which is also confirmed as seen in Fig. 7.

Conclusions and recommendations

This paper adds valuable insights to the sustainable development of groundwater for irrigation purposes in Egypt. It is consistent with the nationally adopted strategy to achieve

a balance between the environment, society, and economy to achieve high standards of living for current and future generations. The numerical modeling has been integrated with environmental isotopes to introduce an advantageous proposal for preserving and efficient use of groundwater in the west El-Minia area, Mid-Upper Egypt. The numerical modeling framework has been developed by using environmental isotopes to determine recharge sources and renewability of the aquifer being modeled (completely renewable, partially non-renewable, or completely non-renewable), early in the framework to aid not only conceptualization but also setting goals and controlling the selected sustainable yield scenarios for groundwater management. Optimized scenarios of (recharge, withdraw, and usage have been simulated, calibrated, and their impacts predicted. The suggested scenarios are proposed to maximize the value of a 20-year groundwater discharge in terms of optimal head and crop socioeconomics. The following points are recommended based on this paper.

1. Using partially renewable or completely non-renewable aquifers for agriculture is mandatory under water scarcity conditions. This requires sustainable management plans and optimization of recharge/withdraw/use regimes.
2. Using surface water as an alternative source for irrigation must be governmentally obligated with limited abstraction from surrounding groundwater in Quaternary aquifer zones.
3. Reducing the number of wells in the study area's northwestern corner may aid in limiting hydraulic head depletion at this non-renewable rechargeable zone.
4. Altering the crops that consume more water by economically consuming less water could constrain the hydraulic head depletion.
5. More hydraulic monitoring wells covering the area might be useful in updating the system conceptualization and model simulations for future predictions.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by KH, RAH and MAHS. All authors read and approved the manuscript.

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Data availability statement The data used in this study are available on request with the corresponding author and are not available publicly due to ongoing research.

Declarations

Conflict of interest The authors declare that there are no competing interests.

Ethical approval and informed consent Not applicable.

Consent for publication Not applicable.

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