



Evaluation of the impact of Lake Nasser on the groundwater system in Toshka under future development scenarios, Western Desert, Egypt

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Received: 22 November 2018 / Accepted: 31 July 2019 / Published online: 2 September 2019
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Abstract

A MODFLOW model was applied to predict the current and future groundwater levels under different proposed development scenarios to identify the fluctuation of groundwater levels in the Nubian Sandstone Aquifer in Toshka Area (NSATA), based on changes of Lake Nasser water levels. The model was calibrated and verified then invoked to measure the responses of the Nubian aquifer characterized in water level decline for the next 100 years under six different management scenarios. The results revealed that the maximum predicted groundwater level decline after simulation period of 100 years reaches 25, 45, and 60 m when applying third, fifth, and sixth scenarios respectively, while in the fourth scenario, the groundwater level decline of 25 m has occurred after 7 years, which approves the importance of Lake Nasser in the aquifer recharge and consequently the development of Toshka region. On the other hand, applying the second scenario shows that when the water levels in Lake Nasser are less than 170 m, there will be reverse recharge from the aquifer to Lake Nasser. To conserve groundwater storage in NSATA for longer time, it is recommended to use water-saving agriculture techniques, to minimize the water used by applying new irrigation methods and to select plants and crops of low water consumption that have economic return.

Keywords Sustainable groundwater management · Nubian Sandstone Aquifer · MODFLOW · Toshka · Egypt

Introduction

Due to over-abstraction and mismanagement, groundwater levels have regionally declined in different areas of the world. This phenomenon is an indication of non-sustainable resource utilization. In most cases, falling groundwater levels have

undesired consequences such as resource exploitation that call for careful to ensure sustainable management of groundwater systems.

The groundwater in Egypt, especially in the Western Desert region, is considered a strategic water reserve, because of water scarcity in the region. According to the program of the Egyptian Government, there is a development project named “1.5 million feddan” (1 feddan = 4200 m²); the first stage of this project aims at reclaiming about one million feddan distributed in the West Desert of Egypt; a part of the project is located in Toshka with an area of 25,000 feddan based on the discharge from 102 pumping wells.

Before the construction of the High Dam, there was no groundwater reservoir with reliable potential for development. After the construction of the High Dam and consequently the dam lake, the seepage from the bed of the lake feed the geological layers adjacent to the dam lake. As a result of this feeding over the past 45 years, a shallow Nubian Sandstone Aquifer (NSA) has been formed along the lake. Regarding the impact of Lake Nasser on the groundwater of the NSA in Toshka, the recharge attains 24×10^6 m³/year and groundwater salinity reduces with time (Ghoubachi 2012). The

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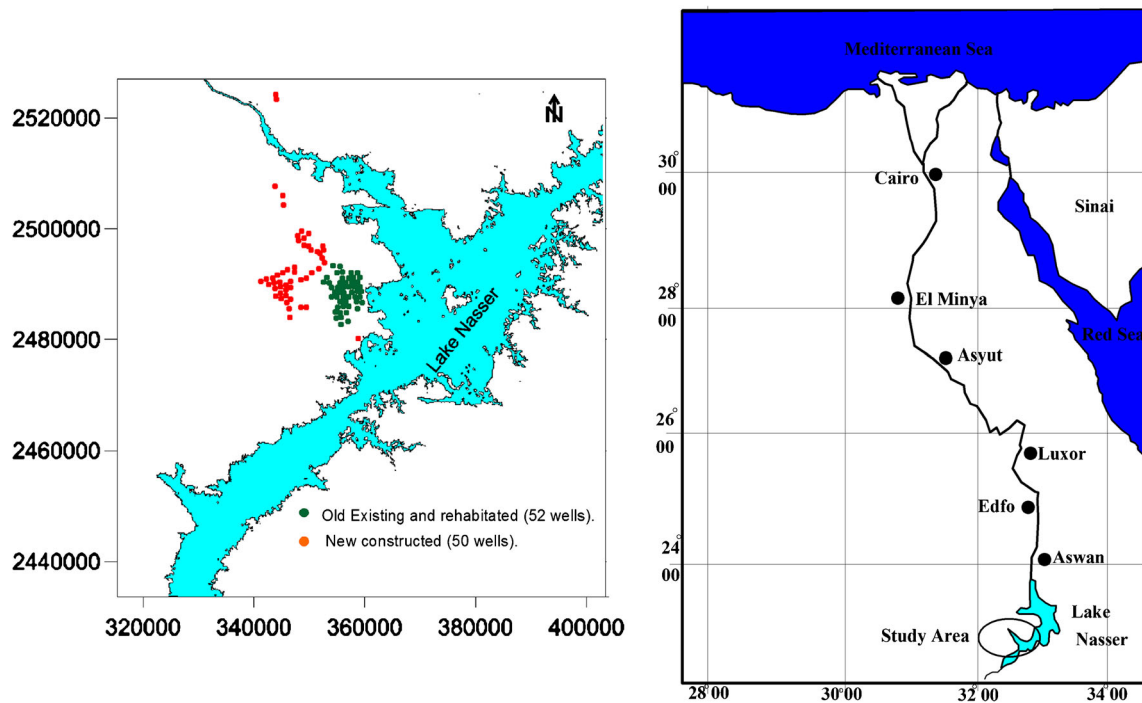


Fig. 1 Location of the study area and well distribution maps

interaction between groundwater–surface water in Lake Nasser was studied by El Sawwaf et al. (2014); a cross-sectional model was utilized to explore the recharge from/or groundwater discharge to Lake Nasser at the seven transects for a 40-year period; it was concluded that for the last 20-year period, the recharge from Lake Nasser was reduced by 37% compared with the estimates for the first 20-year period and the seepage of Lake Nasser to the surrounding was calculated

at $1.15 \times 10^9 \text{ m}^3/\text{year}$ which significantly increases the groundwater table. Recently, Sharaky et al. (2018) assess groundwater in Toshka area for agricultural irrigation; it was found that the safe water use of groundwater for 100 years is $1007 \text{ m}^3/\text{day}$ from each well working 8.4 h/day at $120 \text{ m}^3/\text{h}$, to provide $1500 \text{ m}^3/\text{feddan}/\text{year}$ for a total of 25,000 feddan. The expected lowering in the groundwater level after 100 years is 15 m. The salinity ranges from 480 to 1200 ppm with an

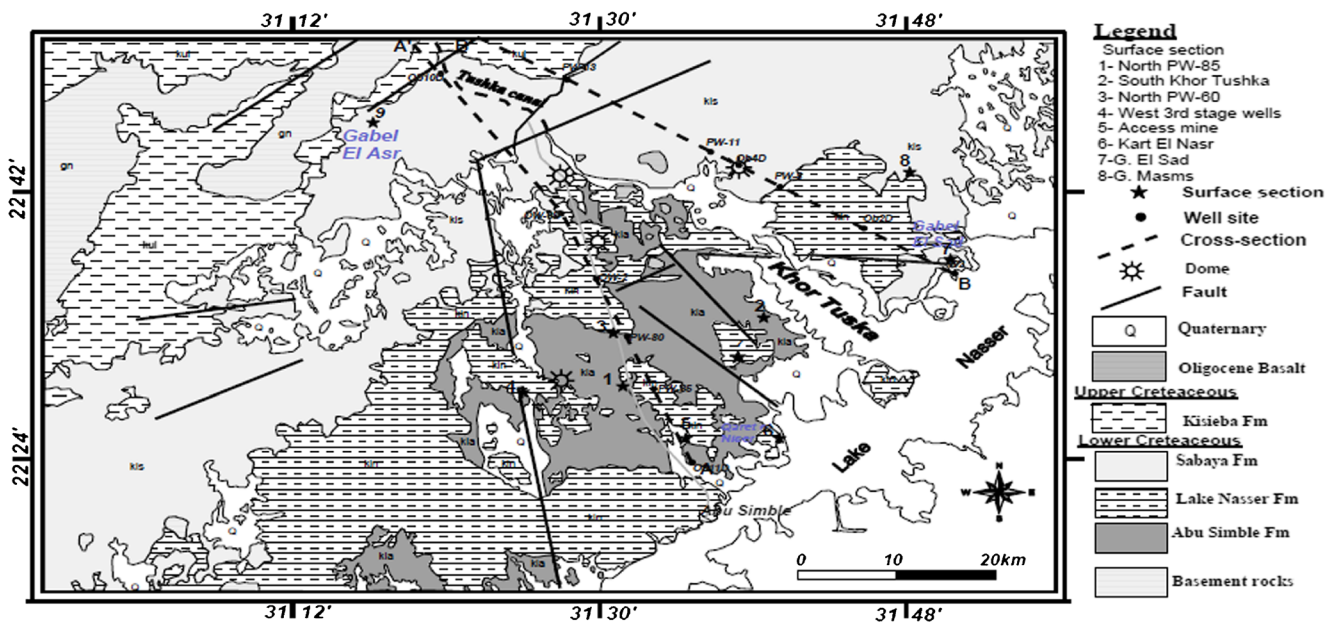


Fig. 2 Geologic map for Toshka (modified after CONOCO (Continental Oil Company) 1987)

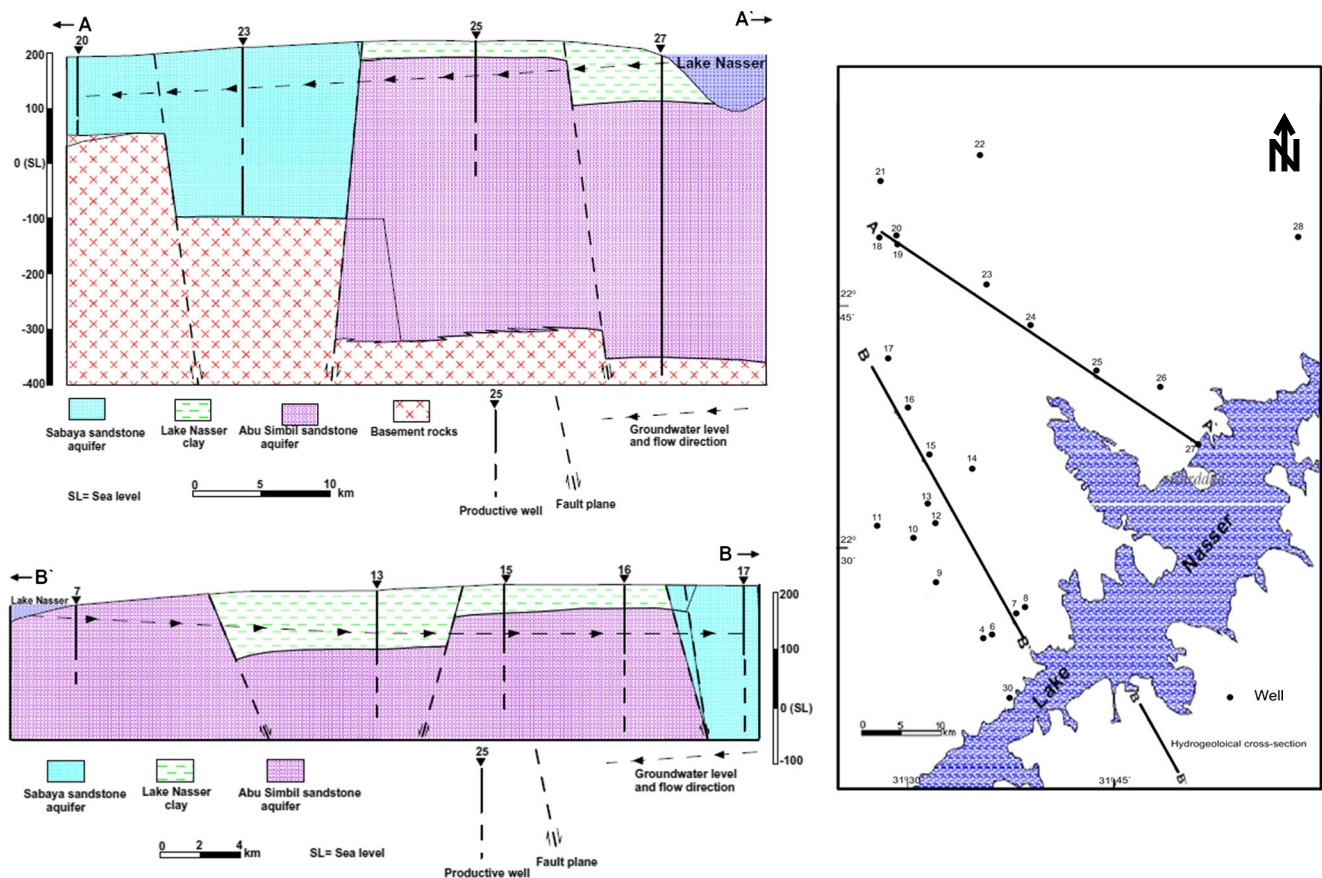


Fig. 3 Hydrological cross-sections in NSATA after Ghoubach (2012)

average of 648.5 ppm. It is directly proportional with the increasing of the distance from Lake Nasser. Also, El-Shirbeny and Abutaleb (2018) use remote-sensing data to assess the change in surface area and water level variation in Lake Nasser using remote-sensing data from Landsat-8 and altimetry data. Results indicated a shrink in the lake surface area in 2016 of approximately 14% compared with the 2015 area. In addition, the evaporation rate in the lake is very high causing a loss of approximately 20% of the total water share from the river Nile.

The objective of this research is to study the aquifer system in Toshka and its dependency on Lake Nasser to identify the impact of six different proposed development scenarios on the aquifer potentiality to maintain sustainable development in the area taking into consideration the effect of the development in the upstream Nile countries such as the Grand Ethiopian Renaissance Dam (GERD) representing in the water levels decreased in Lake Nasser.

Study area

The study area lies between latitudes 22° 30' N and 23° 30' N and longitudes 31° 00' E and 32° 00' E (Fig. 1); it is distinguished by an extremely arid climate in summer and a relatively short-day rainless winter. Altorkomani (1999), Elewa (2006), Ghoubach (2012), Gomaah (2011), Aggour et al. (2011), Abdel Moneim et al. (2014), Khalaf and Gad (2014), and Refaat and Hamdan (2015) studied the geomorphology and geology of the study area. They concluded that the study area comprises five geomorphological units. Lake Nasser is one of the largest artificial fresh water lakes in the world, which was formed as a result of the establishment of the High Dam (completed in 1969). Toshka depression area is an elongated smooth

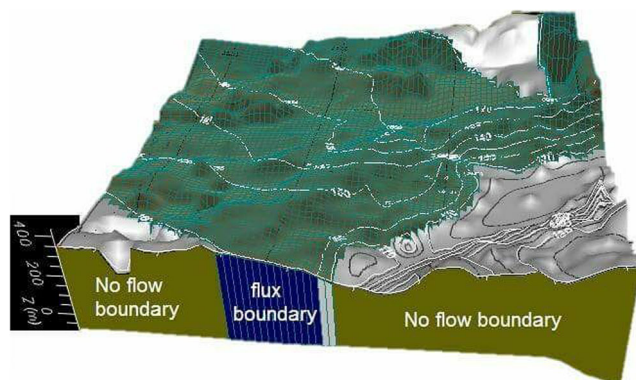
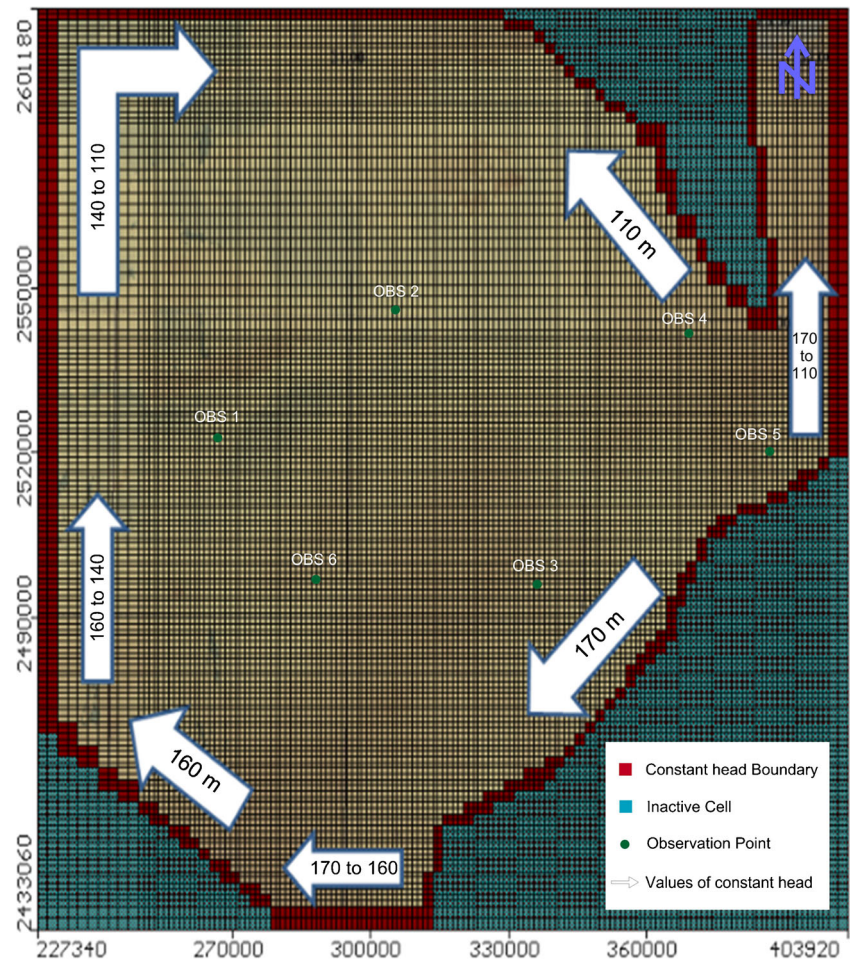


Fig. 4 Conceptual model of the studied aquifer

Fig. 5 Model domain and boundary conditions of NSATA



plain largely covered by sand with some fine clays and chalk. The sedimentary succession in the study area ranges in age from the Paleozoic to the Quaternary, with exposures of igneous and metamorphic rocks belonging to the Late Precambrian basement, Phanerozoic, Late Cretaceous, and Tertiary. The study area also is affected by three major fault systems having NE–SW, E–W, and NW–SE trends (Fig. 2).

Considering the groundwater hydrology, Nubian Sandstone Aquifer in Toshka Area (NSATA) represents the only main source of groundwater in the area. It is divided into two connected water-bearing zones namely Sabaya and Abu Simbel. These

aquifers are hydraulically linked with each other as a result of faulting displacement. Sabaya formation is found on the surface in the study area and overlies directly the Precambrian basement rocks in the northeastern portion of the study area with thickness range of 169 to 235 m, whereas its saturated thickness varies from 113 to 153 m. Abu Simbel formation is considered as the oldest sedimentary rock unit in the investigated area and overlies directly the Precambrian basement rocks and underlies the Lake Nasser formation with thickness of 109 to 500 m, whereas its saturated thickness ranges from 91 to 493.59 m (Ghoubachi 2012), as shown in Fig. 3.

Table 1 Hydraulic parameters from different sources for aquifer in the area of study aquifer

Author	Hydraulic parameters <i>K</i> (m/day)	<i>T</i> (m ² /day)	<i>S</i>
Sallam (2002)	2–13.4	175.8–1970.9	–
Elewa (2006)	0.965	86.4	2.30×10^{-3}
Ghoubachi (2012)	4.5	365–931	–
Aggour et al. (2011)	–	1236–1637	–
Abdel Moneim et al. (2014)	0.9–12.73	122.1–1557.8	–
Khalaf and Gad (2014)	4.33–7.60	400–1900	–

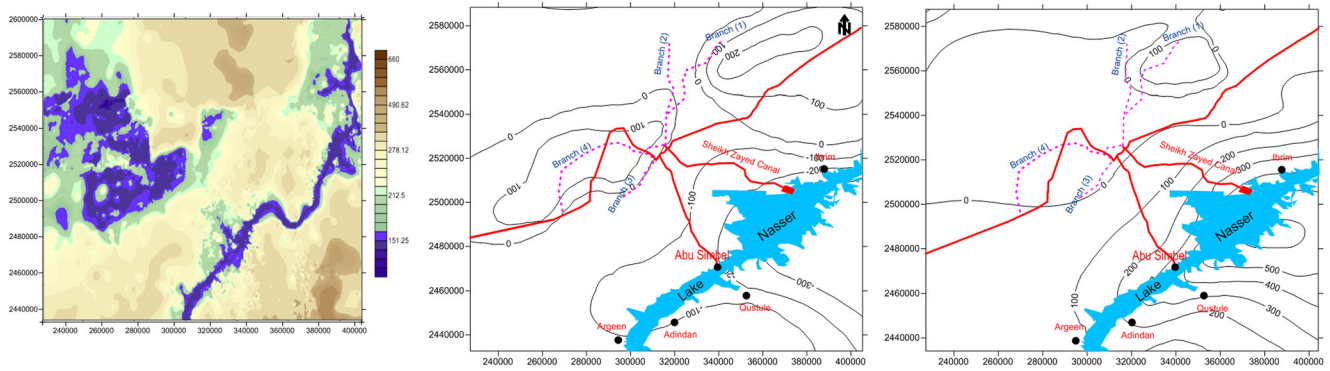


Fig. 6 The topographic contour map of the model domain extracted from (DEM) (left map), the bottom elevation of the aquifer (middle map), and the saturated thickness map of the aquifer (right map) (modified after Sallam 2002)

Methodology

The methodological approach used in this paper is based on the mathematical modeling techniques applying visual MODFLOW computer program. The model describes groundwater flow of constant density under non-equilibrium conditions in three-dimensional heterogeneous and anisotropic medium according the equation of (Bear 1972). The model was utilized the finite difference approach to solve the groundwater flow equation.

Simulation of the groundwater flow in the Nubian Sandstone aquifer requires the definition of the conceptual

model, model domain, and boundary conditions and aquifer properties. The conceptual model of the NSATA is consisting of one layer composing mainly of fine-to-very-coarse grained sandstone with claystone interbeds; the groundwater flow direction is locally from southeast to northwest and the aquifer is under unconfined conditions (Fig. 4).

Model input data

The model domain has a total surface area of 29736 km²; it extends to 168 km in length and 177 km in width; it is divided into 20720 (148 columns and 140 rows) rectangular cells, while the boundary conditions are chosen to be natural boundaries and remote enough from the effect of the proposed well fields. Constant head boundaries were assigned in the north-east direction and in the south-west direction with values of 110 and 160 m respectively. The water body of Lake Nasser is considered a time-constant head (fixed head-boundary condition) at level of 170 m amsl as shown in Fig. 5.

The aquifer characteristics required for the simulation of NSATA are as follows: the aquifer hydraulic parameters, represented in Table 1; the aquifer geometry shown in Fig. 6; and the aquifer stresses. The United States Geological Survey (USGS) has converted the topographic maps of Egypt into digital elevation model (DEM) files. These files represent the land surface as a matrix (grid) of elevation values. The 1:250,000 map series has been converted into 3-arc-second (approximately 90 m)-resolution DEMs. The depth to the impermeable bed (bottom of the aquifer) is used to estimate the aquifer thickness of every cell in the modeled area also the saturated thickness contour map of the aquifer was used. The groundwater contour map used in the model as initial hydraulic head is constructed using data obtained from Ministry of Water Resources and Irrigation (MWRI), Groundwater Sector (Fig. 7). The aquifer stresses represented in the discharge from the 102 pumping wells located in the development area.

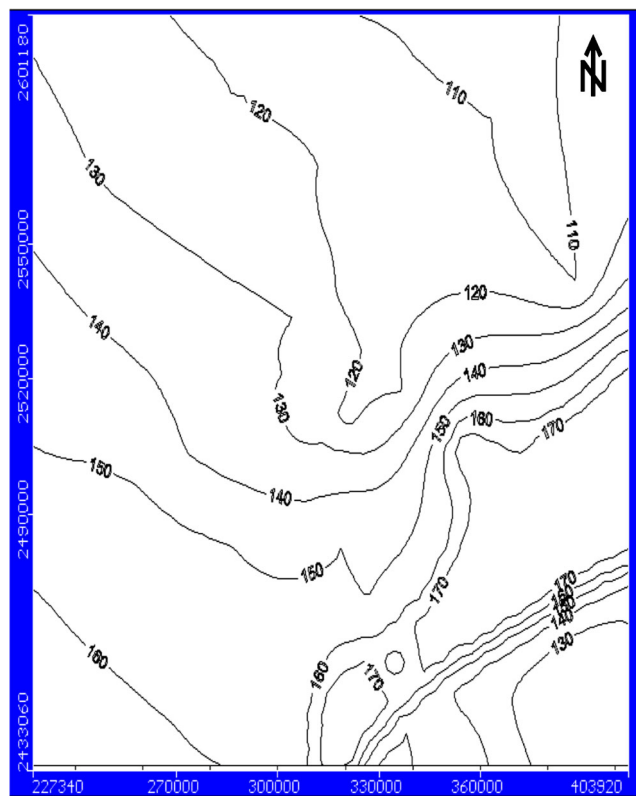
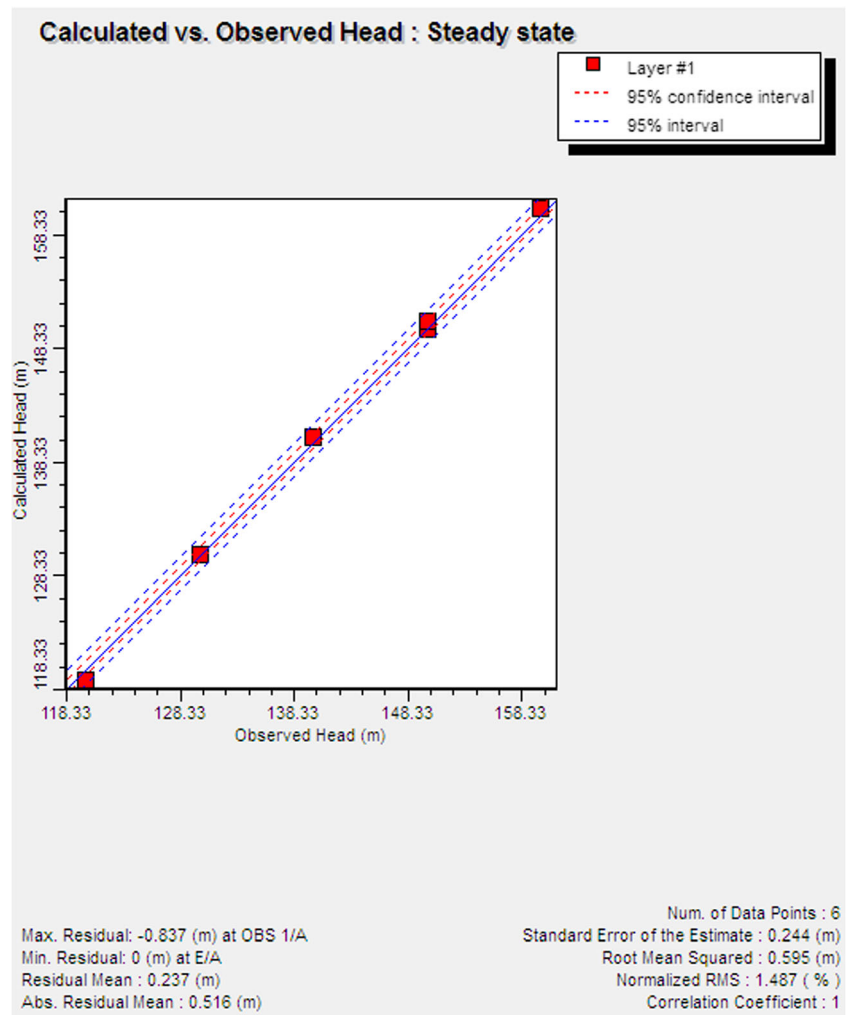


Fig. 7 Observed head map of the study area

Fig. 8 Results of steady-state calibration in NSATA



Model calibration and verification

The initial hydraulic parameters used in the model calibration were collected from the published data in previous studies which has wide different ranges all over the modeled area. The great variance between the collected data leads to many trials of model run to obtain the calculated heads very adjacent to the observed heads as shown in Fig. 8. Model verification was successfully done by comparing drawdown values from the pumping test that carried out on wells number 23, 61, and 82 and the drawdown values of the same wells calculated by MODFLOW. It was found that the values were closely related (Fig. 9).

Model run

Water budget of the model domain is calculated using zone budget tool. The result showed that both inflow and outflow are in balance which is consistent with the steady-state

modeling concept. Table 2 summarizes the water budget calculated for the steady-state conditions.

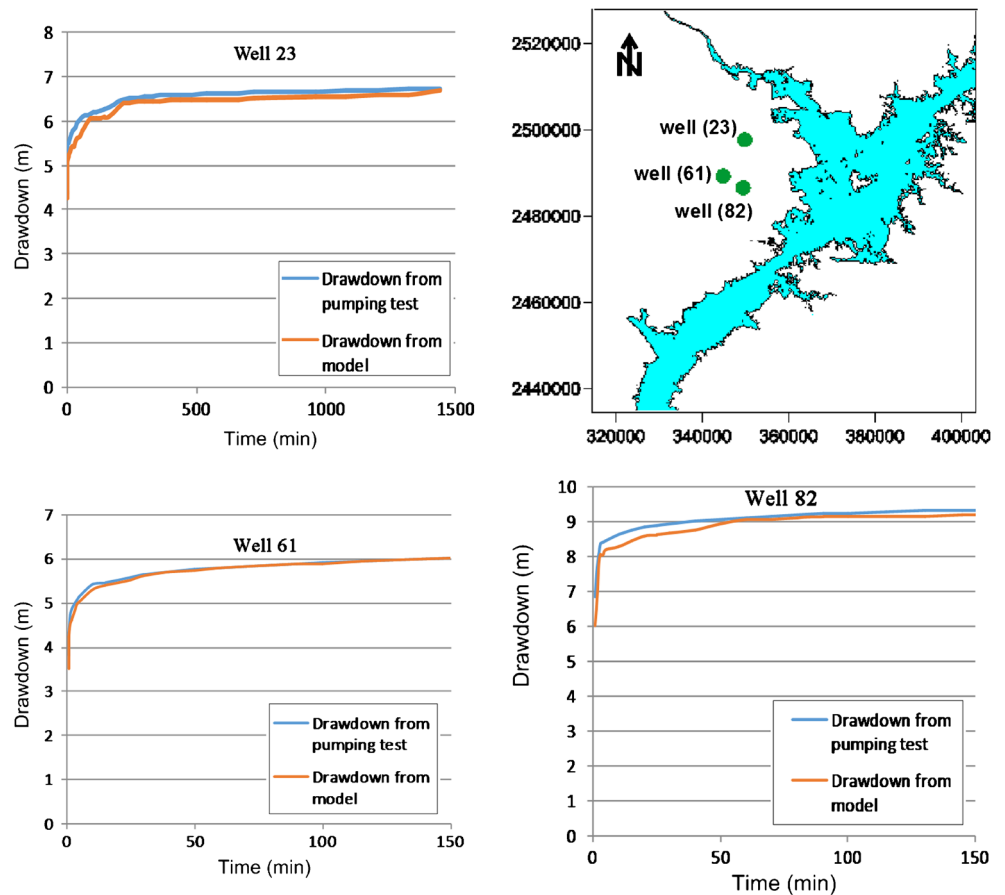
It is worthy to mention that according to the soil condition and water scarcity in the study area, all irrigation practice planned to be dripped or subsurface irrigation to prevent any undesired drainage water problems in addition to conserve water quality of the lake in case of reverse recharge from the aquifer at low water levels in the lake.

Results and analysis

After implementation the calibration process, a planning period of 100 years (2016–2116) was used for the six development scenarios.

The first scenario is the present exploitation strategy represented in total pumping rates of 5000 m³/day from five production wells; the model prediction shows that there is no significant drawdown in the aquifer in the near future

Fig. 9 A comparison between the drawdown from pumping test and the drawdown from the model for wells 23, 61, and 82 and well location map



and the maximum drawdown ranges from 0.5 to 2.5 m after 100 years.

The second scenario simulates the aquifer response with no production wells assuming decrease in Lake Nasser from level 170 to 143 m. The developed model was run for 7 years with regular decrease of 4.2 m each year. The aim of this scenario is to examine the response of the aquifer according to the fluctuations in water levels of Lake Nasser and to calculate the water budget during the simulation period from years 2016 to 2022 as shown in Table 3 and Fig. 10.

It is obvious that when the water levels of Lake Nasser drop from 170 to 166.2 m during the first year

Table 2 Calculated water budget for the steady-state conditions

Flow term (m ³ /day)	In	Out	In–out
Wells	0	5000	– 5000
Lake Nasser	264,204	0	264,204
Other boundaries	10,076	269,280	– 259,204
Sum	274,280	274,280	0

of simulation period at 2016, the amount of recharge from Lake Nasser to the aquifer attains 18,900 m³/day. This value is gradually decreased to reach about zero at the fourth year of the simulation period where water levels in Lake Nasser decline to attain 151 m. The results also show that the outflow from aquifer to Lake Nasser in the first year of the simulation period attains 210,580 m³/day and it increases gradually to reach about 1,073,000 m³/day at the last year of simulation period. It is concluded that when the water levels of Lake Nasser drop down, reverse recharge occurs from the aquifer to Lake Nasser.

The third scenario assumes the beginning of development in the study area with total pumping rate of 102000 m³/day from 102 production wells with pumping rate of 1000 m³/day from each well. The developed model was run for 100 years to obtain the expected drawdown in water heads. The predicted drawdown maps for the aquifer are shown in (Fig. 11a–c).

The fourth scenario presumes pumping rate from 102 production wells with a total discharge of 102,000 m³/day with decrease and increase in the water levels of Lake Nasser alternately every 7 years, then it remains constant for the

Table 3 Water budget for second scenario over the simulation period

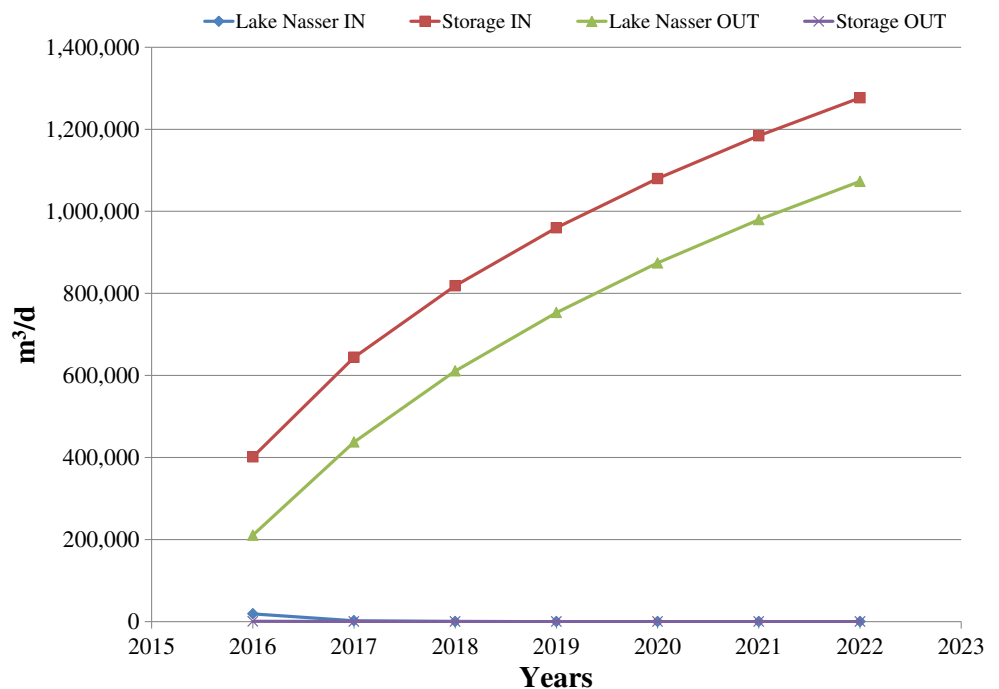
Year	Volume (m ³ /day)	Wells	Lake Nasser (m ³ /day)	Other boundaries (m ³ /day)	Storage (m ³ /day)	Total (m ³ /day)
2016	In	No development	18,900	9930	401,430	430,260
	Out		210,580	219,070	610	430,260
2017	In		2170	10,600	644,140	656,910
	Out		437,670	219,070	170	656,910
2018	In		80	11,430	818,540	830,050
	Out		610,900	219,070	80	830,050
2019	In		10	12,360	960,040	972,410
	Out		753,290	219,070	50	972,410
2020	In		0	13,300	1,079,900	1,093,200
	Out		874,130	219,070	0	1,093,200
2021	In		0	14,400	1,184,200	1,198,600
	Out		979,500	219,100	0	1,198,600
2022	In		0	15,400	1,276,700	1,292,100
	Out		1,073,000	219,100	0	1,292,100

rest of the simulation period. During the first stage (2016–2022), water levels in Lake Nasser gradually decreased from 170 to 143 m; it is obvious that during this period, the maximum drawdown values vary between 5 and 25 m (Fig. 12a). Comparing this result with the results obtained from third scenario, it is clear that the discharge from the aquifer with a lack of recharge from Lake Nasser increases the drawdown values. During the second stage (2023–2029), water levels in Lake Nasser began to increase gradually from 143 to 170 m. It is evident that at 2029, the maximum drawdown values varies decrease to be 2 to 14

m due to the increase in water levels in lake Nasser, which reflects that the NSATA and Lake Nasser are hydraulically connected (Fig. 12b). During the third stage, it is found that after 100 years at 2120, the maximum drawdown values varies between 5 and 25 m (Fig. 12c).

From Figs. 12 and 13, it is noticed that there are wells affected by the increase and decrease of the water levels in Lake Nasser such as wells numbers 96, 100, 110, and 136 due to their close location to the Lake. During the first stage (2016–2022), water

Fig. 10 Water budget for second scenario over the simulation period



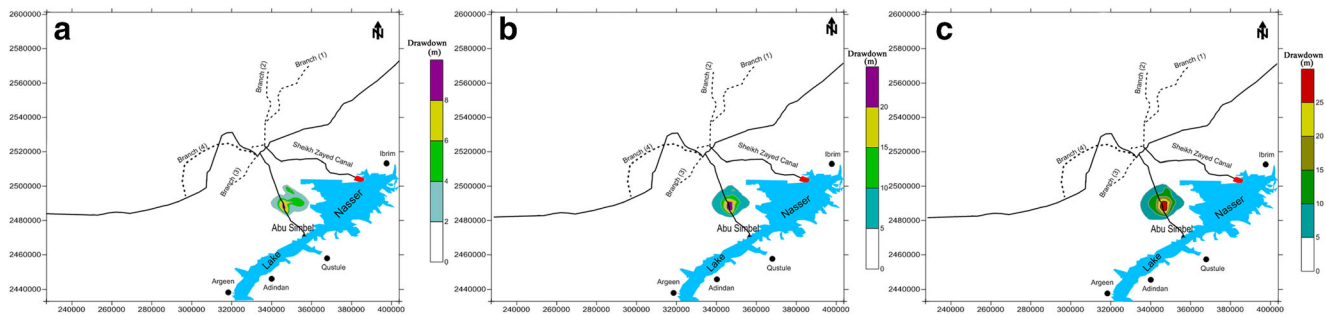


Fig. 11 The predicted drawdown of the aquifer applying the 3rd proposed scenario **a** at 2030, **b** at 2070, and **c** at 2120

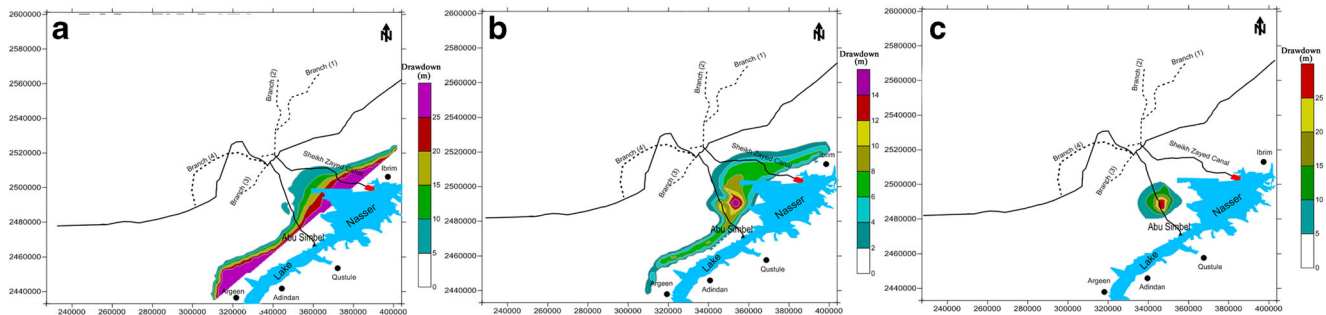


Fig. 12 The predicted drawdown of the aquifer applying the 4th proposed scenario **a** at 2022, **b** at 2029, and **c** at 2120

levels in Lake Nasser gradually decreased from 170 to 143 m. The predicted drawdown of groundwater level in well number 96 reaches 1.9 m at 2016 (Fig. 14). This value is gradually increasing to reach about 23.2 m at 2022. For the second stage (2023–2029), the value of drawdown in the well decreases as a response to increase water level in Lake Nasser until it reaches about 3.4 m at 2029 as shown in Table 4.

On the other side, wells numbers 58, 64, 71, and 75, which are relatively far from Lake Nasser, have not affected by the

increase or the decrease in its water levels, where there were a continuous decline in the water table, which may be attributed to their location from Lake Nasser or due to the geologic formation in this area of the aquifer.

From Table 4, it can be concluded that the influence of Lake Nasser on groundwater level in the area is noticed only in the wells located at distance of less than 10 km from the lake’s shoreline.

The fifth scenario is based on the total discharge of 153000 m³/day from 102 production wells. The developed model was run for 100 years to obtain the expected drawdown in water heads as shown in Fig. 15a–c.

The sixth scenario assumes the increase of pumping rate from 102 production wells to reach 204000 m³/day. The developed model was run for 100 years to obtain the expected drawdown in water heads as shown in Fig. 16a–c.

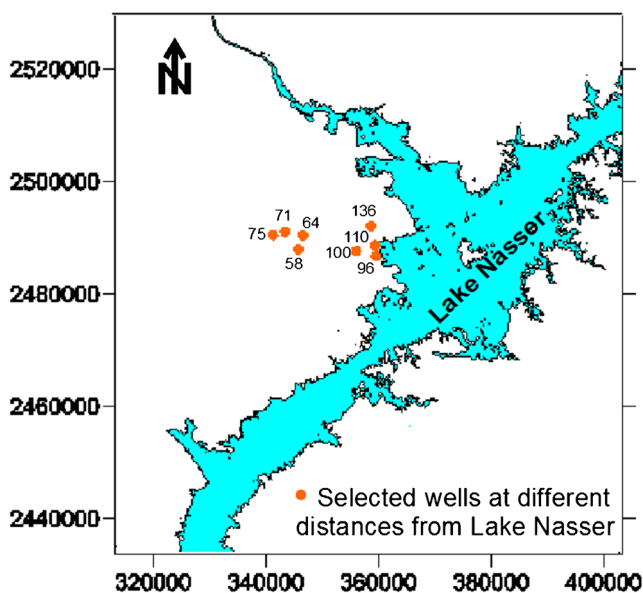


Fig. 13 Well location map

Discussion

From the results shown above, it is clear that only the third, fifth, and sixth scenarios are the scenarios that have a significant impact on the aquifer. The aquifer deterioration according to different pumping rates in these three development scenarios are summarized in Table 5. In order to ensure sustainable

Fig. 14 The expected drawdown in wells versus time for the 4th scenario

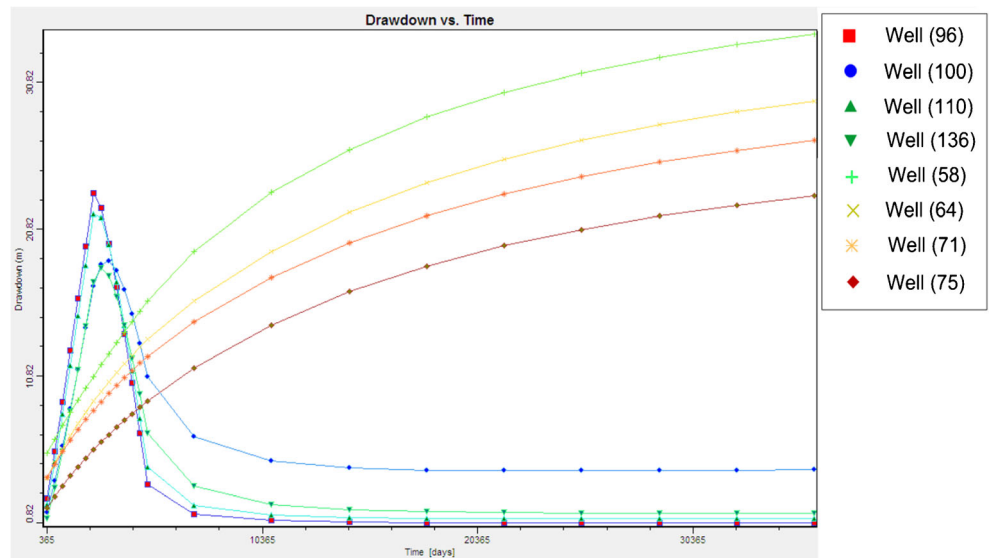


Table 4 Values of drawdown in the selected wells

Well	Distance from Lake Naser (km)	Drawdown of 4th scenario (m)			
		2016	2022	2029	2120
58	16.5	5.9	13	19.5	43
64	20.8	4	10.3	15.5	35.8
71	21	4	9.3	13.5	31.5
75	20.5	1.9	6.4	10.3	27
96	2.6	2.4	23.2	3.4	0.88
100	8.8	1.5	17	10.9	4.8
110	5	2	21.8	4.6	1.2
136	5.9	1.1	17.2	7	17

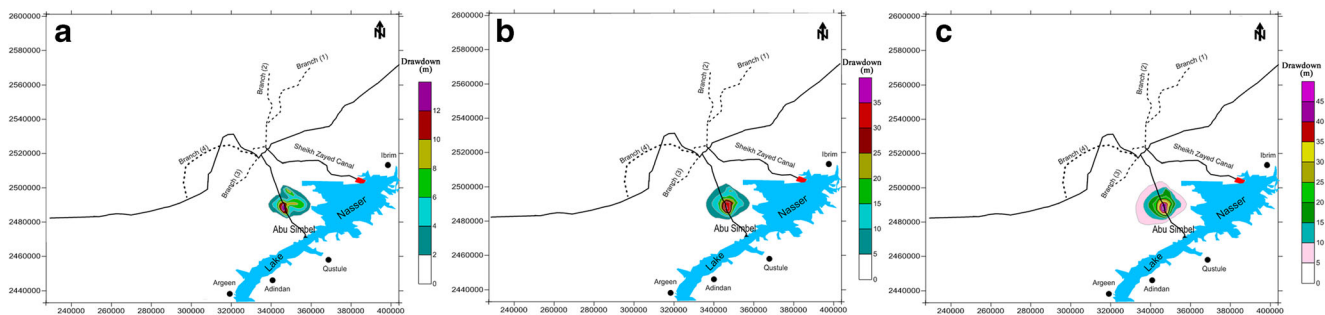


Fig. 15 The predicted drawdown of the aquifer applying the 5th scenario **a** at 2030, **b** at 2070, and **c** at 2120

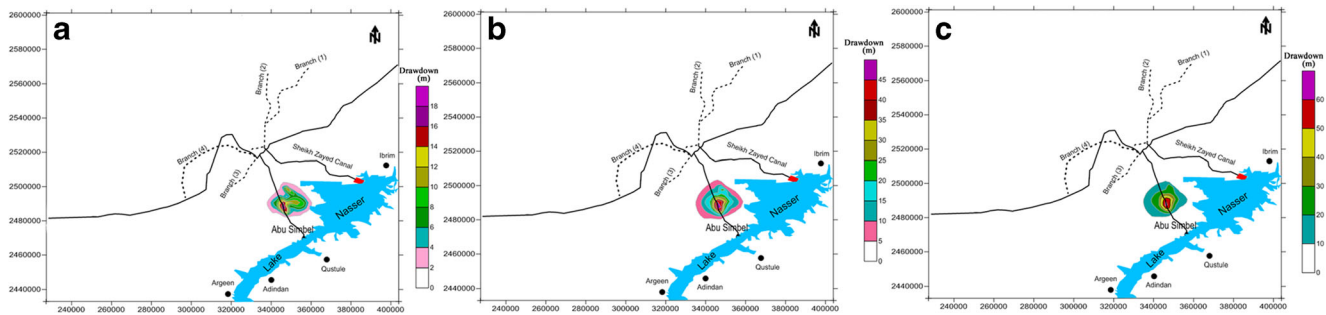


Fig. 16 The predicted drawdown of the aquifer applying the 6th proposed scenario a at 2030, b at 2070, and c at 2120

Table 5 The water extraction values and the maximum drawdown in groundwater level for selected scenarios

Flow term (m ³ /day)	Number of wells	Water extractions	Drawdown after 10 years (m)	Drawdown after 50 years (m)	Drawdown after 100 years (m)
Third scenario	102	102000	8	20	25
Fifth scenario	102	153000	12	35	45
Sixth scenario	102	204000	18	45	60

development strategy, a maximum permissible drawdown value of 40 m was taken according to the average saturated thickness in NSATA. Regarding the fifth scenario, when the extraction rate from each well attains 1500 m³/day, the maximum assumed permissible drawdown will occur after 70 years.

Regarding the sixth scenario, the groundwater depletion will occur after 40 years. Finally, in the third scenario, it needs more than 100 years to reach the maximum permissible drawdown value, as shown in Fig. 17. It is worthy to mention that from the drawdown point of view, the third scenario is most safe extraction policy of groundwater in NSATA.

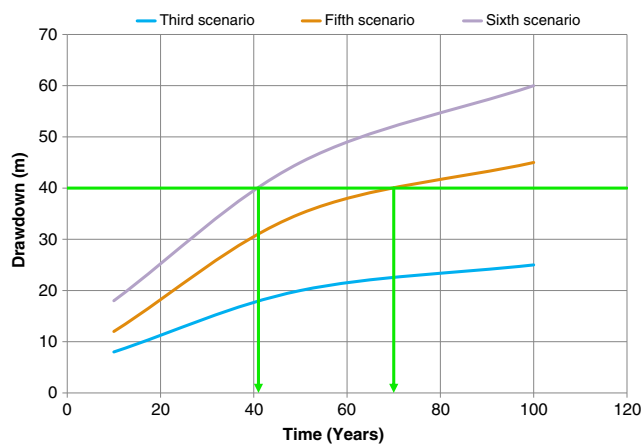


Fig. 17 A comparison between the predicted results of the 3rd, 5th, and 6th scenarios to attain 40 m

Conclusion and recommendations

A MODFLOW model was successfully calibrated and verified. Then, it was applied to simulate the Nubian sandstone aquifer under different operational scenarios.

Six scenarios were tested. The predicted groundwater level decline after simulation period of 100 years, applying the first scenario, will reach 0.5 and 2.5 m. While in the second scenario, the results show that there will be reverse recharge from the aquifer to Lake Nasser. In the third scenario, the predicted decline in the groundwater level after simulation period of 100 years will reach 5 m and 25 m. The fourth scenario is divided into three phases. The first phase was a gradually decline in the water levels in Lake Nasser from 170 to 143 m for seven years. In the second stage, water levels in Lake Nasser began to increase gradually from 143 to 170 m again for 7 years. In the last phase, water levels in Lake Nasser remained constant with value of 170 m until the end of simulation period. The results indicate that during the first phase, the corresponding drawdown varies between 5 and 25 m, while during the second stage, the groundwater declined ranged from 2 to 14 m. Then, the corresponding drawdown ranged from 5 to 25 m during the last stage. The predicted decline in the groundwater levels after simulation period of 100 years in the fifth scenario reaches 5 m and 45 m. Finally, the predicted decline in the groundwater levels after simulation period of 100 years will reach 10 m and 60 m.

To ensure sustainable development in NSATA, it is recommended to:

1. Control and evaluate the aquifer by the Ministry of water resources irrigation by controlling the pumping rates from productive wells and operate them alternately to give the aquifer the opportunity to recover
2. Avoid the continuous operation of wells and prevent the increase of operating hours for more than 12 h in the case of using generators.
3. It is highly recommended to use water-saving agriculture techniques and minimize the water used by applying new irrigation methods and selecting plants and crops of low water consumption that have economic return.

Finally, in order to conserve the water quality in Lake Nasser, constrains should be installed to prevent the use of any fertilizers or pesticides according to the probability of the reverse recharge from the aquifer to Lake Nasser as previously concluded, especially when cultivation process will started (as occurred in the fourth scenario).

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