

Groundwater Assessment for Agricultural Irrigation in Toshka Area, Western Desert, Egypt



Abbas M. Sharaky, El Sayed A. El Abd, and Emad F. Shanab

Abstract Toshka area is located southeastern of the Western Desert. In 1997, Egypt established a development project to irrigate 216,000 ha (540 feddan) by 2017 through pumping surface water from High Dam Lake as a part of the mega project “Developing Southern Egypt.” Currently, the Egyptian government plans to extend the project by about 100,000 feddan depending on surface water irrigation and 25,000 feddan depending on groundwater (through 102 wells) as a part of the recent mega project called “1.5 Million Feddan Project.” Egypt is now fully utilizing its annual share of the Nile waters 55.5 km^3 from the Nile, and it has a shortage of water estimated at 20 km^3 .

The present chapter aims to evaluate the groundwater conditions to determine the sustainability of the groundwater resource, the expected changes in groundwater levels, the amount of recharge and the suitable discharge from the groundwater for irrigation of 25,500 feddan through 100 years, and the changes in water quality. The hydrochemical analysis was carried out using 38 productive wells and 1 surface sample from Aswan High Dam Lake (AHDL) for major ions.

The present study was carried out in Toshka using 102 groundwater wells located west of AHDL using static, dynamic water levels, well depth, discharge, and pumping tests to determine the hydraulic parameters of the aquifer system in the study area and building the groundwater model. Visual MODFLOW 2011.1

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software was used to estimate the expected drawdown in the groundwater levels using four different scenarios. A conceptual model was constructed to simulate water flow system of the Nubian Sandstone Aquifer through 100 years.

The safe water use of groundwater for 100 years is 1,007 m³/day from each well working 8.4 h/day at 120 m³/h, to provide 1,500 m³/feddan/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 1,200 ppm with an average of 648.5 ppm. It increases with increasing distance from AHDL.

Keywords Groundwater, High Dam Lake, MODFLOW, Pumping test, Toshka project

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1 Introduction

Egypt is characterized by an important geographic location that has enabled it to perform its role throughout the historical ages. It is divided into two main parts: the northern part extending from north of Cairo to the Mediterranean Sea, which is known as Lower Egypt for its descent toward the sea, and the southern part that runs south of Cairo on the banks of the Nile to the border of Sudan, which is called Upper Egypt. Egypt has an area of about 1 million square kilometers. It is geologically divided into four natural subregions (see Fig. 1):

1. Nile Valley and Delta (4% of the total area of Egypt)
2. Western Desert (68%)
3. Eastern Desert (22%)
4. Sinai Peninsula (6%)

Egypt is one of the oldest agricultural civilizations in the world. Agriculture is currently a major source in the Egyptian economy, accounting for 11.2% of the GDP in 2015, up to 14.5% in 2014 [1]. The Egyptian agricultural lands are

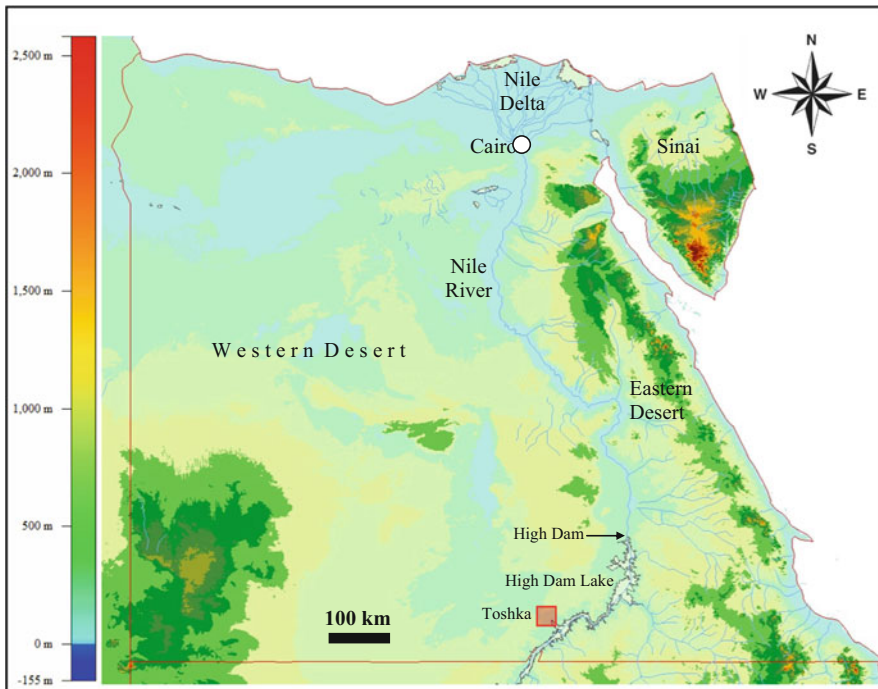


Fig. 1 The four geological regions of Egypt on 3D map using ASTER DEM (USGS)

concentrated in the Nile Valley and the Delta, which consist of sand and gravel overlain by a layer of the Nile silt and clay deposited during floods.

According to the Food and Agriculture Organization (FAO) of the United Nations, the old cultivated area was 6 million feddan (1 feddan = 1.038 acres) that increased from 1964 (the actual start of the High Dam) to 1973 by about 1.1 million feddan. The agricultural sector has also increased by 2 million feddan in 1993 and continued to increase gradually until the total agricultural land reached 9.2 million feddan in 2009. It was decreased after the Egyptian revolution in January 2011 by about 215,000 feddan due to illegal urbanization.

The Egyptian government has planned to reclaim 4 million feddan in few years, starting with 1.5 million feddan in 2016. The first phase of the agricultural reclamation project has been started with 1 million feddan since 2015, which increased 500,000 feddan in 2016. They mostly (90%) depend on nonrenewable groundwater of the Nubian Sandstone Aquifer, Western Desert. About 130,000 feddan from the 1.5 Million Feddan Project is located in Toshka area.

1.1 Aswan High Dam Lake

Construction of the Aswan High Dam in 1964 created the second largest man-made lake (6,000 km²) in the world after Lake Volta, Ghana (8,500 km²). The Aswan High Dam reservoir extends for about 500 km along the Nile River from Aswan, Egypt, to Wadi Halfa, Sudan. At 182 m above sea level (m amsl), its total storage capacity reaches 162 km³. The reservoir in Egypt is known as High Dam Lake, which has a length of 350 km (see Fig. 1). The Sudanese refer to the extended lake in Sudan (150 km) as Nubia [2, 3]. The Aswan High Dam Lake has about 8,000 km shoreline at 180m asl [4]. It is characterized by about 100 dendritic inlets, or side extensions of the reservoir, known as khors or wadies that extend for long distances, 70 km in Wadi Allaqi to the east and 50 km in Toshka Khor to the west.

The depressions west of Toshka Khor are used as a natural flood diversion basin to protect the High Dam from any exceptional flooding that happened only from 1998 to 2001 since the construction of the High Dam. The Aswan High Dam (AHD) was designed to flow water at 178 m level through a free spillway “Toshka Canal” at an elevation of 178 m with a width of 750 m and 40 km length, located at 250 km south of the AHD and west of AHDL.

To reserve the water of the Nile in case of flooding, Egypt built a small earth-fill dam on Toshka spillway at 40 km from the main lake with an elevation of 178 m above mean sea level (amsl).

The water levels in Aswan High Dam Lake (AHDL) vary around 175 m up and down by about 5 m. During the past decade, the minimum water levels have remained above 170 m, fluctuating by 2–4 m/year (see Fig. 2). The lowest level after construction of the High Dam was recorded in 1988, when it reached to 150 m asl, just above the operating level by 3 m.

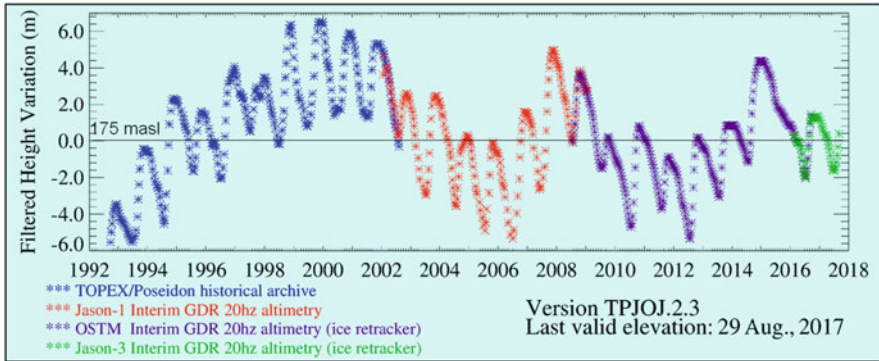


Fig. 2 Aswan High Dam Lake elevation variations computed from TOPEX/POSEIDON (T/P), Jason-1 and Jason-2/OSTM altimetry with respect to a datum that is based on a single flyover date of the Jason-2/OSTM mission (source: [5])

1.2 Toshka Project

Egypt has undertaken agricultural strategies since 1952 with great success at the beginning and limited success later. Land reclamation for agriculture has started in the 1950s during the construction of the Aswan High Dam, followed by two other phases in the late 1990s and in 2014. The Egyptian government reclaimed about 800,000 ha (2.0 million feddan) of desert land from 1952 to 1987 and an additional 250,000 ha (627,000 feddan) from 1987 to 1991 [6].

The second phase of reclamation projects is to cultivate 200,000 ha (500,000 feddan) of desert land through the Toshka project, 88,000 ha (220,000 feddan) in the southeastern part of the Western Desert, Egypt, and 248,000 ha (620,000 feddan) in the eastern part of the Nile Delta and northwestern Sinai (El-Salam Canal Project). In the late 1990s, the Egyptian government has begun a mega project called “Developing Southern Egypt” from Aswan to Assiut. It aimed to have new communities of people from the dense Nile Valley and Delta (about 90 million people in 2017) to a new green landscape. Southern Egypt region comprises an area of 520,000 ha (1.3 million feddan) of arable lands, mainly concentrated in Assiut, Sohag, Qena, and Aswan governorates [6].

Toshka project is a part of the mega project “Developing Southern Egypt.” It is located in the area of Toshka depressions, but independent from them (see Fig. 3). It is a large-scale project of surface irrigation, using pumped water from the High Dam Lake to irrigate 216,000 ha (540 feddan) by 2017. According to the Landsat image of 24 September 2017, the total cultivated area was 24,000 ha (60,000 feddan), representing only 11.1% of the target (see Fig. 4).

As the Egyptian government prepares in its current 4-year master plan to reclaim 1.6 million ha (4 million feddan) from the desert in 4 years through four stages starting from June 2014. The first stage was to reclaim 1 million feddan, raised to be

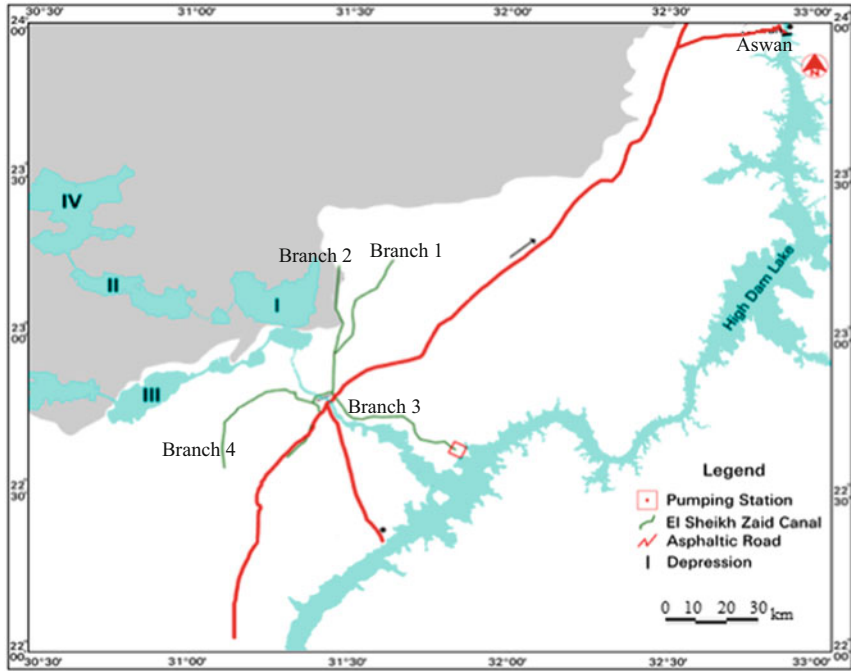


Fig. 3 The Toshka project, Toshka spillway (Khor), and Toshka Lakes (after [7])

1.5 million feddan in August 2015. About 90% of the 1.5 million feddan depend on nonrenewable and deep groundwater through 5,000 water wells. The new reclamation project will be carried out in three subphases in nine areas of the Western Desert, including Toshka, Farafra Oasis, Dakhla Oasis, Bahariya Oasis, Qattara Depression (Moghra), West Minya, and East Owainat.

In addition to the 540,000 feddan in Toshka, about 100,000 feddan depending on surface water and 32,000 feddan depending groundwater (through 102 wells) are included in the “1.5 Million Feddan Project.”

1.3 Toshka Area

Toshka area lies in the southeastern of the Western Desert, Egypt, covering an area of 15,000 km². It is located in the west of the High Dam Lake (HDL), between latitudes 22°30' and 23°30' N and 31°00' and 32°00' E (see Fig. 3). Toshka area is limited from the east by the shoreline of the HDL.

The largest pumping station in the world was constructed in Toshka to pump and transfer water from High Dam Lake at a water head of 52.5 m to cover the difference between the lowest level of the lake (147.5 m) and the water level in

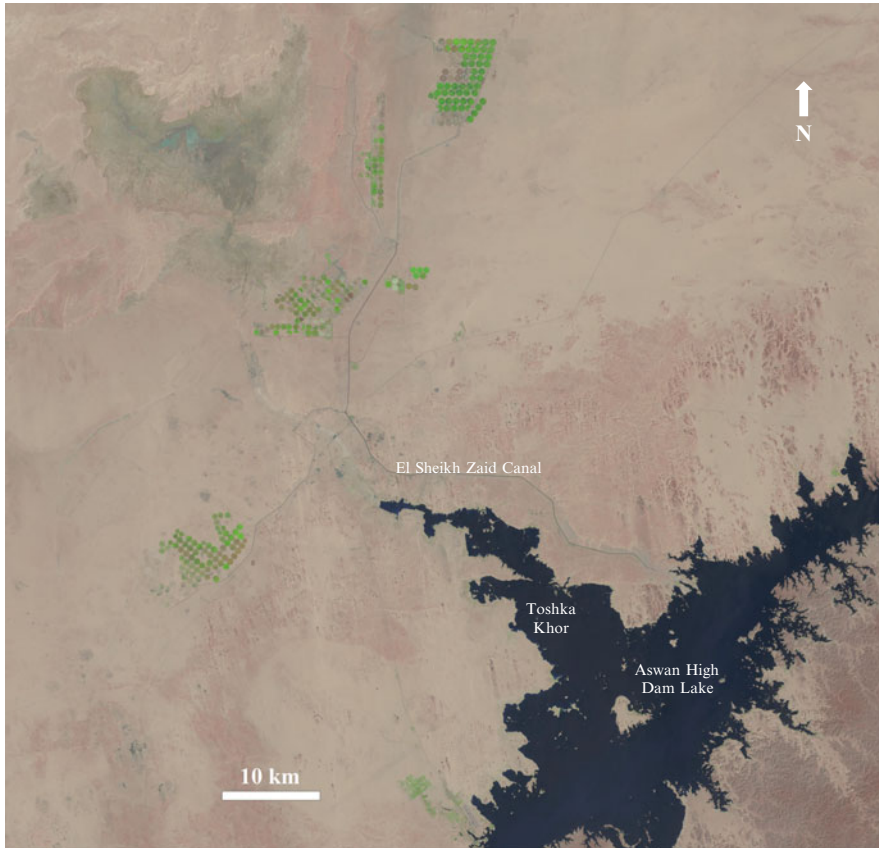


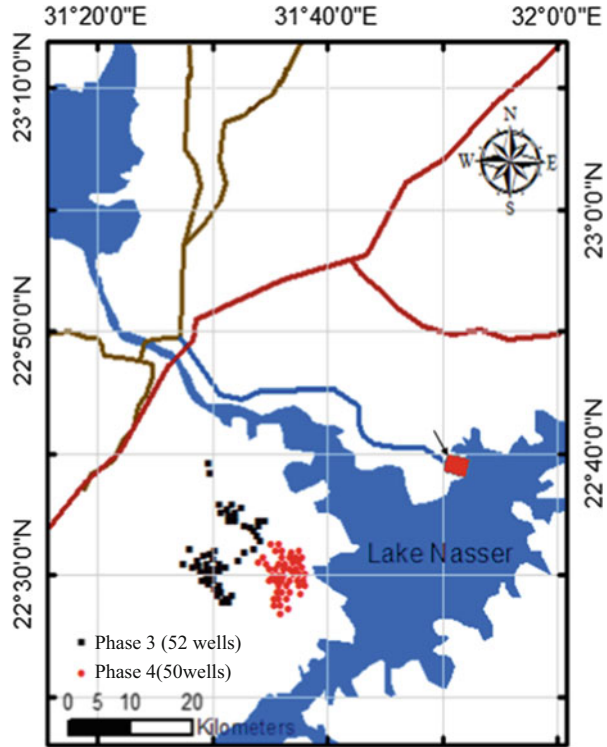
Fig. 4 The Landsat L8 OLI/TIRS image showing the center-pivot irrigation fields (60,000 feddan) as of 24 September 2017

the station canal at 200 m. The main canal called El Sheikh Zayed feeds four distributed canals called branches (1–4) (see Fig. 3).

In 2014, the Egyptian government released the mega project “Reclamation of 1.5 Million Feddan Project,” depending mainly on groundwater. In Toshka region, reclamation of 25,000 feddan on groundwater requires 102 productive wells, 52 wells were implemented in 2002 (from phase 1, 2, and 3), and the 50 wells were implemented in 2015–2016 (see Fig. 5).

The present chapter aims to assess the groundwater conditions from quantity and quality views to determine the sustainability of the groundwater resource and the development life in the study area.

Fig. 5 The water wells (102) in Toshka project area



2 Geologic Setting

The geological and the hydrogeological conditions of the Nubian Sandstone Aquifer System in the Western Desert of Egypt, including Toshka, received the attention of many authors; among them are [3, 7–32]. Toshka area is dominated by a sedimentary succession ranging in age from Cretaceous to Quaternary, with exposures of Late Precambrian basement including granites, granodiorite, and gneiss. The sedimentary rocks are dominated by sandstone overlain by limestone and shale Paleozoic to Cenozoic rocks [7, 33].

2.1 *Geomorphologic and Geologic Aspects*

The Toshka area is a part of the Western Desert of Egypt that has subjected to alternative arid and wet periods that left their effect on the present land features. It shows some geomorphologic units that are distinguished in the study area: High Dam Lake, alluvial plain, Toshka depressions, hilly areas, sandy plains, erosional plains, and pediplain [25].

The Toshka area is mainly covered by sedimentary rocks represented by Upper and Lower Cretaceous and Quaternary as well as by Precambrian basement rocks [34, 35] (see Fig. 6). The basement rocks crop out to the west of the study area within the Nakhelai-Aswan uplift, where they consist of low relief exposures of coarse-grained pink granites, gneisses, and metasediments with an age of about 550–900 Ma [33]. The basement, which represents the basal boundary of the Nubian aquifer system in the area, slopes regionally to the southeast close to the shoreline of the Aswan High Dam Lake [25]. The basement rocks form an impervious lower boundary for the Nubian Sandstone Aquifer acting as a barrier to lateral groundwater flow west of the study area [3]. The sedimentary cover is relatively thin in the northwest of the study area, where the depth to basement varies between 50 and 100 m. Kiseiba Claystone Formation overlies directly the Precambrian basement rocks in this area [36].

In the subsurface, the Paleozoic rocks are mostly represented by the Gifl Formation. It overlies the Precambrian basement rocks and consists mainly of brown shale, sandstone, and shaley sandstone with abundant iron oxides [37]. Cretaceous rocks unconformably overlie the Paleozoic rocks and are differentiated into Lower Cretaceous Formations from base to top as follows: Abu Simbel, High Dam Lake, and Sabaya Formations, Upper Cretaceous Formation, and Kiseiba Formation (see Fig. 7).

Abu Simbel Formation overlies the Gifl Formation and consists mainly of medium- to coarse-grained sandstone of fluvial origin, sometimes intercalated with fine-grained sediment (siltstone or clay lenses). Overlying the Abu Simbel Formation is the fluvio-marine lake (AHD Lake) formation, consisting of siltstone, argillaceous sandstone, and mudstone intercalations. The Sabaya Formation crops out at Gebel El Sad north to Toshka Khor and west of the area of study. It mainly consists of ferruginous sandstone in the lower part overlain by siltstone and fine sandstone [26].

The Kiseiba Formation is composed of fine-grained sandstone with shale and siltstone intercalations cropping out in Toshka depressions. Some Oligocene rocks (basalt extrusions) exposed on the surface of the area of study are widespread, especially near the head of Toshka Khor. The Quaternary deposits are represented by continental sand accumulations (mainly sheets) and alluvial sediments [31].

The study area comprises different structural elements; among them are a basement uplift represented to the west by Nakhelai-Aswan uplift; four major sets of faults generally trending NNW–SSE, E–W, N–S, and NE–SW directions; and three types of folds trending N–S, NE–SW, and E–W directions [29]. The interpreted fault trends are associated with either vertical or horizontal displacements having a significant control effect on the course of River Nile and the western and eastern extensions of High Dam Lake. The depicted folds are influencing either the basement rocks or superimposed on the sedimentary cover [16]. Nubia sandstone sequences in the study area are dissected by E–W and N–S fault systems. The E–W system plays very important role for recharging Nubia Sandstone Aquifer from High Dam Lake [26].

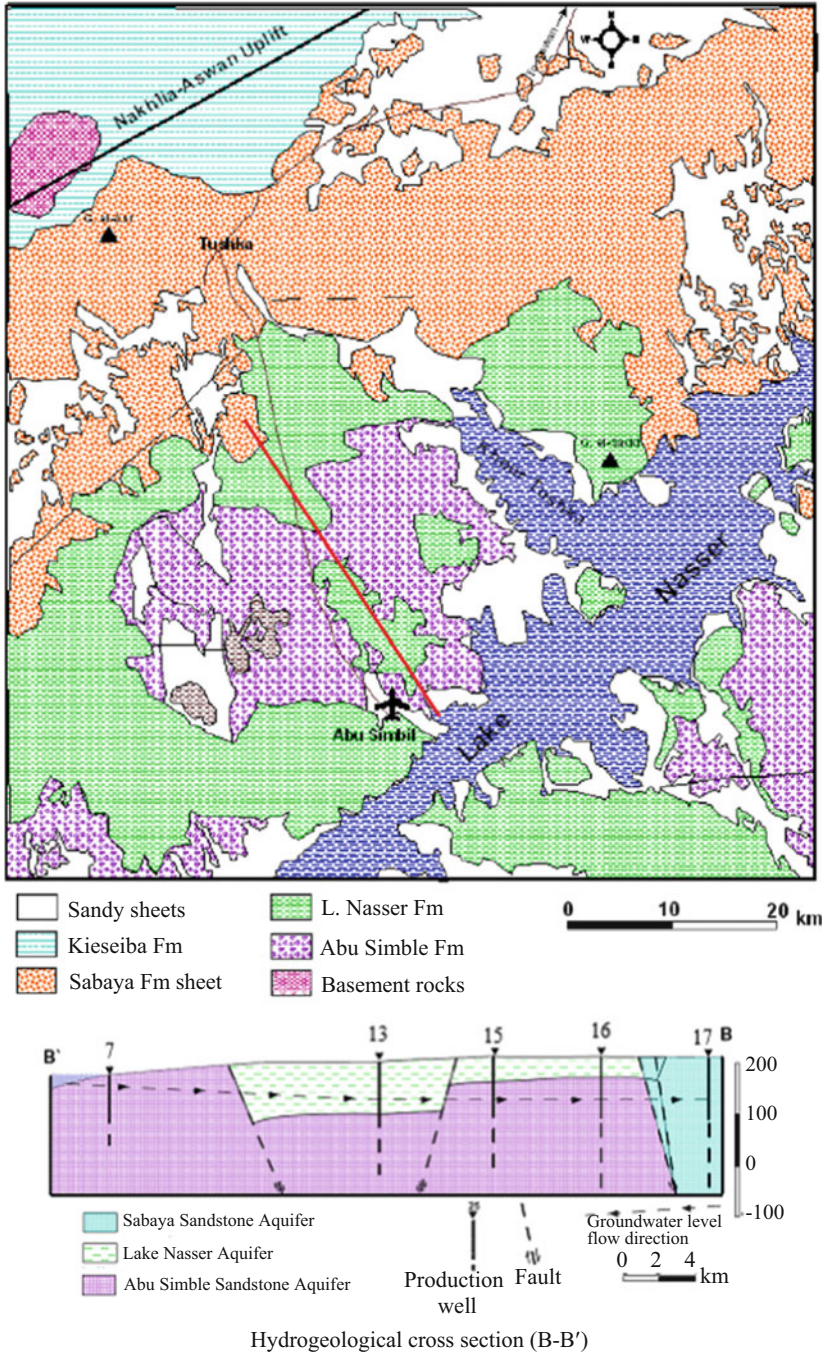


Fig. 6 Geological map of the Toshka area [34, 35] and hydrogeological cross section (B-B') from Ghoubachy [24]

| Age | | | Formation | Lithological Log | Thickness (m) | Lithological Description | Type of bed |
|----------------------------|--------------------------------|-------------------------|-------------|------------------|---------------|--|-------------|
| System | Series | Stage | | | | | |
| Quaternary | | | | | variable | sandy sheet | |
| Cretaceous-Jurassic | Late Cretaceous | Campanian-Maastrichtian | Kiseiba | | 58 | Claystone, siltstone with fine sandstone | Confining |
| | | Turonian | Taref | | 170 | Sandstone: white, medium to coarse grained with claystone interbeds | Aquifer |
| | Early Cretaceous-Late Jurassic | Albian-Cenomanian | Saqaya | | 310 | Sandstone: white, fine to very coarse grained with claystone interbeds | Aquifer |
| | | Aptian | Lake Nasser | | 119 | Claystone, siltstone with fine sandstone | Confining |
| | | | Abu Simbil | | 400 | Sandstone: Grey, pink and greyish brown fine to very coarse grained, ill sorted, subangular to subrounded, with claystone interbeds. | Aquifer |
| Precambrian basement rocks | | | | | | Granitic rocks | |

Fig. 7 Stratigraphic succession (after [26])

2.2 Hydrogeological Conditions

Based upon the lithology of drilled groundwater wells in Toshka area and two hydrogeological cross sections, the groundwater in the Nubian aquifer resides in continental sandstone that unconformably overlies basement rocks and underlies Quaternary deposits. It is the main groundwater aquifer system in the area and composed mainly of sand and sandstone intercalated with clay. The aquifer is of multilayered nature and represents the eastern fringes of the multilayered artesian aquifer of the Western Desert of Egypt. In Toshka, the aquifer system included three formations from top to bottom: Lake Nasser, Abu Simbel, and Gifl (see Fig. 8).

The Lake Nasser Formation varies in thickness from 40 to 80 m as shown in section A-A' (see Fig. 8). The Abu Simbel Formation is mainly composed of

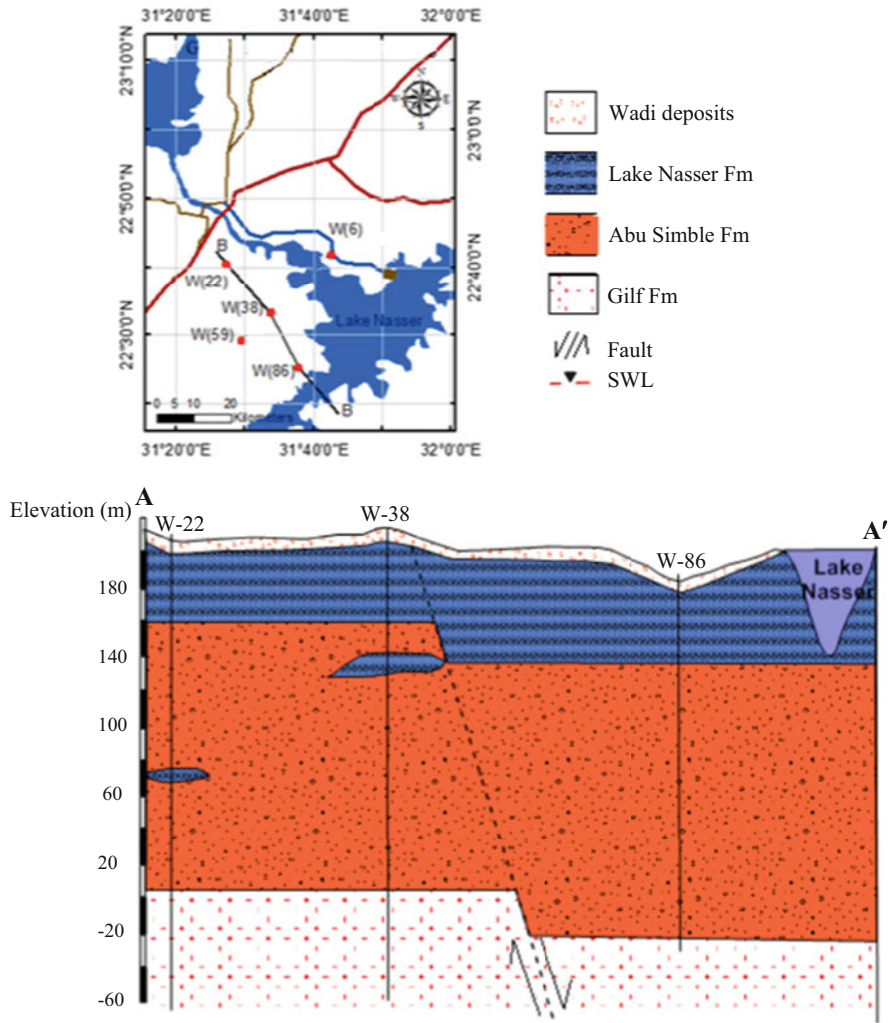


Fig. 8 Hydrogeological cross sections in Toshka area

sandstone with minor varicolored clay intercalations. The thickness of Abu Simbel Sandstone varies from 110 m in the northeast (Well 6) to 140 m to the southwest (Well 59) as shown in cross-section A–A'. It ranges between 80 m in the southeast (Well 86) and 130 m in the northwest (Well 22) as shown in section B–B'. The third formation belongs to Paleozoic undifferentiated sandstones. It directly overlies the basement complex. The thickness of the Gilf Formation ranges from few meters to less than 70 m.

3 Hydraulic Properties of the Nubian Sandstone Aquifer

Pumping tests on 102 productive wells were carried out (step test, long duration test, and recovery test) to determine the hydraulic parameters of the aquifer system in the study area and build the groundwater model.

3.1 Pumping Test

The pumping tests were carried out for 102 productive wells, and the hydraulic parameters were calculated. The influence of each well on the other wells when all of them operated together for 1 day is shown in Fig. 9. Also, the transmissivity distribution in the study area has been mapped as shown in Fig. 10 to describe the groundwater potential briefly in the area. The maximum transmissivity value was $1,558 \text{ m}^2/\text{day}$ (Well 108), and the minimum value was $321 \text{ m}^2/\text{day}$ (Well 123), and the estimated average transmissivity value for the selected 102 wells is $650 \text{ m}^2/\text{day}$. The hydraulic conductivity was calculated, and its maximum value was found as

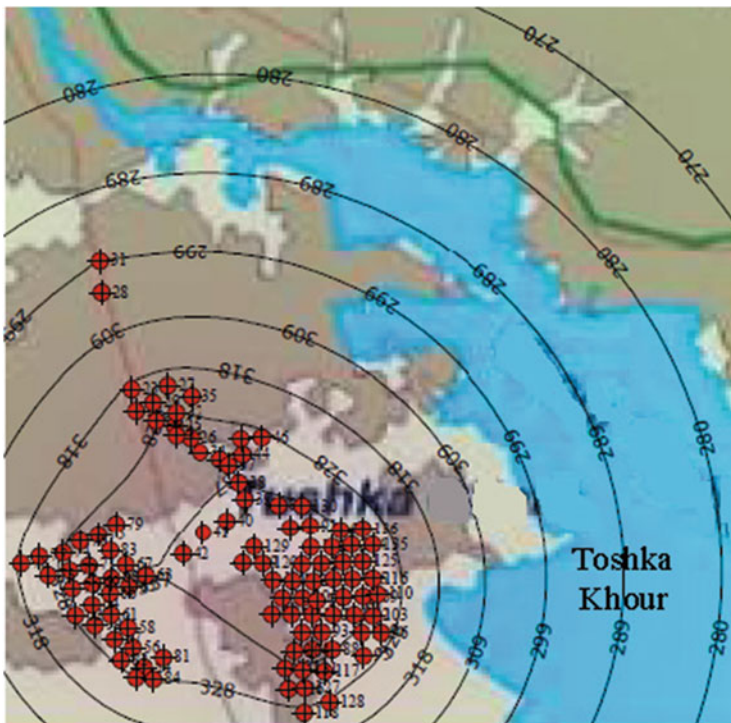
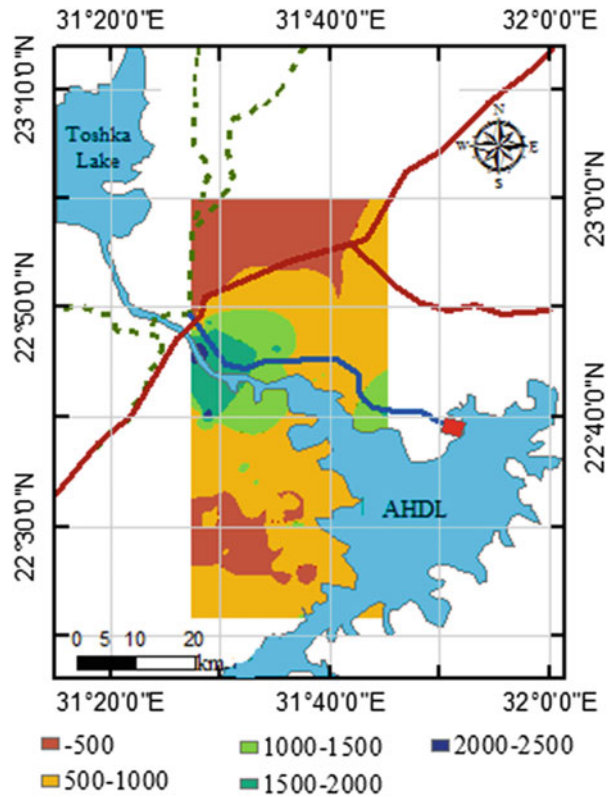


Fig. 9 Drawdown distribution for the 102 wells in Toshka

Fig. 10 Transmissivity (m^2/day) map in Toshka area



21 m/day (Well 3), while the minimum value was found as 3 m/day (Well 15) with an average value of about 6 m/day. The transmissivity distribution map indicates that the aquifer potentiality is increasing toward the northwest of the study area and it is decreasing in other directions. This is probably due to high hydraulic conductivity and aquifer thickness northwest of the area.

The aquifer parameters in Abu Simbel-Toshka area are 2,740 m^2/day for transmissivity and 22.4 m/day for hydraulic conductivity in average [19]. The obtained results recorded high-potential and good-quality aquifer in the eastern and southern parts and low-potential to moderate-quality aquifer in the western and northern parts [15].

The amount of sand of Nubian Sandstone Aquifer in Toshka-Abu Simbel area varies from 6.8% in northwest to about 91% near Toshka Khor, reflecting high potentiality as aquifer at the southeast. The increase of transmissivity toward the shoreline of the lake (close to Toshka Khor) is mainly attributed to the increase of the saturated thickness of the water-bearing units. The expected increase of hydraulic conductivity is associated with the increase of sand percent and the grain size as well as the increase of the fracturing intensities.

The Nubian Sandstone Aquifer System in Toshka receives continuous recharge confirmed by the difference of heads between the aquifer and the HDL. The direct and faster response between the lake and the aquifer is recorded along the shoreline of the HDL. This is mainly attributed to the excited non-equilibrium of the hydraulic conditions between the two water bodies [29]. A regional groundwater movement from south to southwest proved the presence of remote sources of recharge at southwest [8]. The estimated age, using ^{14}C , for the groundwater in the Nubian Sandstone Aquifer East Oweinat and Toshka areas varies between 14,780 and 17,070 years [21]. The aquifer potentiality decreases at the northern and middle areas, where the clay content increases and saturated thickness decreases at such localities [14]. Transmissivity ranges between 336.9 and 2,802 m^2/day with an average value of 1,569 m^2/day [15]. For future impact of the new reclamation activities on groundwater used for irrigation together with surface water, the general pattern of the groundwater level is expected to show considerable changes. The northern and middle areas are subjected to show a decrease in groundwater levels with the exception of an area with shallow impervious basement and in the southern wells. The expected water level decline ranges between 5 and 55 m [19].

3.2 Changes in Groundwater Level

To investigate the changes in groundwater level in the area, data concerning the water elevation in the existing wells were collected and analyzed during the period from 1998 to 2006 (see Fig. 11). Groundwater extracted from these wells is used for land reclamation in the areas. The extracted water is used to supplement the surface water for land reclamation in the area. It is noticed that there is a drop in water level during that period ranging between 0.5 in Well 21 and 13.8 m in Well 4 in 8 years (see Fig. 12). Such drop indicates that the extraction rate of water is much higher than the recharging rate. The drop is expected to continue with the continuous extraction of groundwater leading to aquifer depletion in the area. The average water level drop per year for the observed wells was 0.77 m/year, indicating that the expected drawdown for 100 years' development is 77 m for the old phases of drilled wells. The effect of the new wells drilled in 2015/2016 (50 wells) as a part of the "1.5 Million Feddan Project," will increase the drop in groundwater level in the area. Groundwater model must be used to predict the influence of different development scenarios on the groundwater levels based on the historical data to build, calibrate, and validate the model. The present chapter focuses on estimating the expected change in groundwater levels and water quality for different operation scenarios.

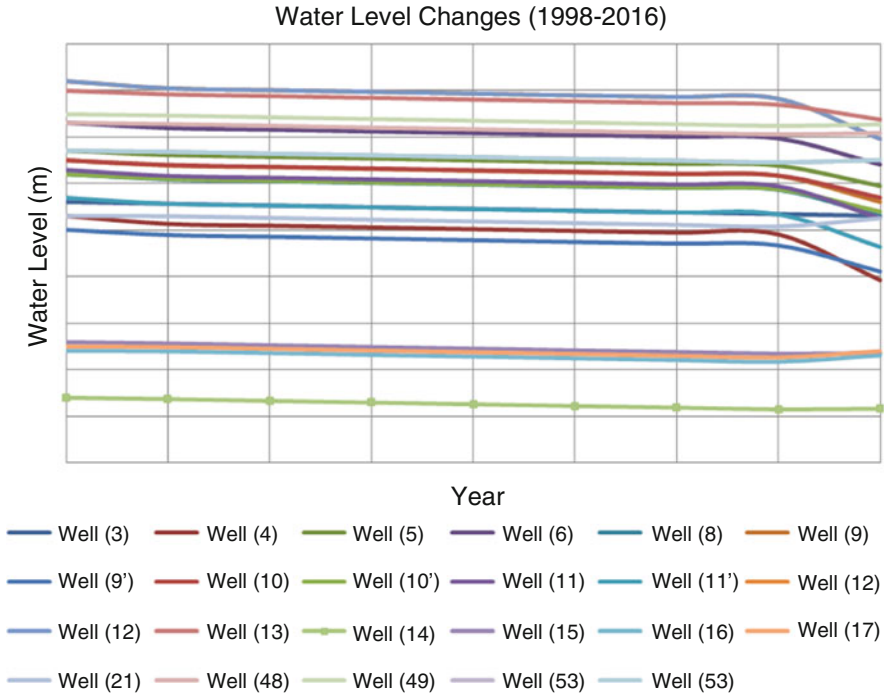


Fig. 11 Change in groundwater levels for some wells in the study area

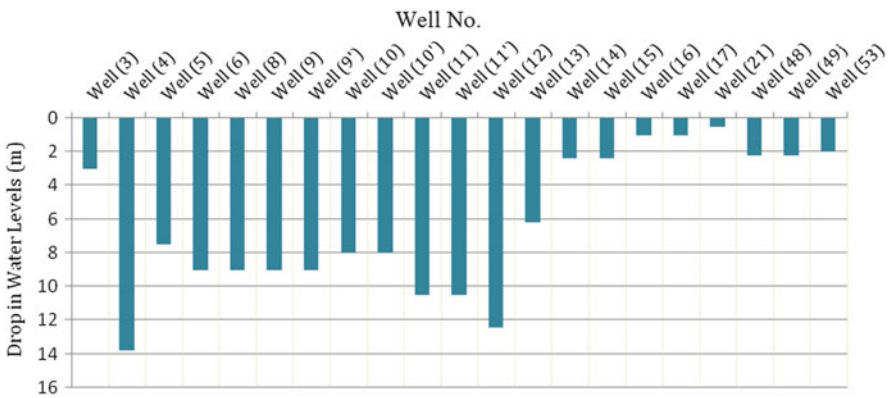


Fig. 12 Drop in groundwater levels for some wells in Toshka area

4 Impact of AHD Lake on the Groundwater

4.1 Changes in Water Level

The study area is surrounded by the High Dam Lake, Toshka Khor, and irrigation system. The relation between the groundwater in the aquifer and AHDL is essential to estimate the annual recharge from the surface water to the vicinity aquifers. After the construction of the AHD and the formation of AHDL with 500 km length (350 km inside Egypt border and 150 km inside Sudan border) and average width of 12 km with a depth of 130 m and a maximum water level of 183 m, the yearly cycle of groundwater fluctuation was changed due to rapid variation in lake water levels. The water level using a piezometer lying west of High Dam Lake ($31^{\circ}51'8''$ E, $22^{\circ}37'10''$ N) was measured four times in 31 December 1965 (during the period of construction of High Dam), 25 December 1969, 2 December 1979, and 22 July 1996. It was compared with the recorded water levels of High Dam Lake (see Fig. 13). There is a direct connection between High Dam Lake and groundwater level with time lag according to the distance of wells from the lake and the nature of the water-bearing formation. Hantush [39] equation was used to calculate the effect of High Dam Lake on groundwater level.

Figure 14 shows the rising in groundwater levels for different transmissivity values, indicating the effects related to the aquifer properties and the distance from the HDL. Therefore, the hydraulic connection is effective for only small distance, not more than 10 km.

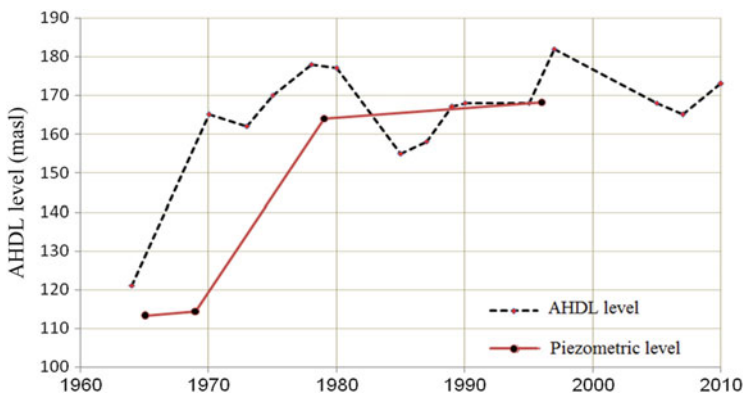


Fig. 13 Changes in AHDL and piezometric levels in Toshka area (AHDL level data from [5, 38])

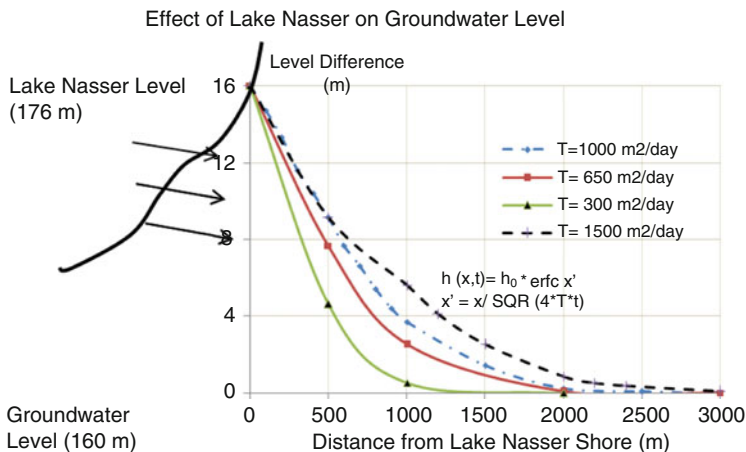


Fig. 14 Effect of Lake Nasser on groundwater levels in Toshka

4.2 Annual Recharge from High Dam Lake

Estimation of the recharge from High Dam Lake into the adjacent aquifers is one of the main factors influencing the water balance of the lake. The discharge or the seepage from High Dam Lake to the adjacent aquifers for 1 km of the shoreline is estimated by Darcy’s law as:

$$Q = K \cdot I \cdot A$$

where Q is the discharge in m^3/day , K is the hydraulic conductivity (m/day), A is the area of discharge ($L \times B$) in m^2 , L is the shoreline length (1,000 m), B is the saturated length of the aquifer (m), and I is the hydraulic gradient $= (\Delta h / \Delta l) = (13 \text{ m} / 1,000 \text{ m}) = 0.0013$.

Applying the Darcy’s law on 1 km sections using the available data on groundwater level distribution and taking into consideration that the transmissivity ($T = K \times B$), the transmissivity map shows that the average transmissivity value is about $650 \text{ m}^2/day$ along the shoreline. The recharge can be calculated as:

$$\begin{aligned} Q &= K \cdot I \cdot A \\ &= K \cdot I \times (L \times B) \\ &= (K \times B) \times L \times I = T \times L \times I \\ &= 650 \times 1,000 \times 0.0013 \\ &= 845 \text{ m}^3/day/km \\ Q &= 308,425 \text{ m}^3/year/km \end{aligned}$$

It is important to mention that the recharge value depends on the changes in the levels of groundwater in the aquifer and surface water of the lake. Therefore, the amount of water recharge changes from one season to another.

5 Assessment of Groundwater Potential

5.1 Radius of Influence

Radius of influence is taken as the designed distance between wells, and it plays an important role to avoid the drawdown interference effect among wells. It must be calculated before designing the well field from the available data. In the current project, the wells were designed at a distance of 1 km from each other. The analysis presented here is a pumping test analysis in which drawdown at a piezometer distance (r) from the abstraction well is monitored over time. This is also based on the Theis method.

For the Theis equation, using $S = 0.0003$ and $t = 0.41$ day (10 h operation per day), the radius of influence (r) for maximum, minimum, and average transmissivity can be calculated. The relation between the drawdown and the radius of influence indicates that the suitable value of r that minimizes or avoids the drawdown interference lies in the range from 1,000 to 2,000 m depending on the value of T and S (see Fig. 15). The radius of influence corresponding to the average value of transmissivity in the study area ($650 \text{ m}^2/\text{day}$) is 1,400 m.

5.2 Groundwater Sustainability

Sustainability of groundwater potential quantity and quality is mainly dependent on the following:

1. The total amount of daily extraction water from the wells

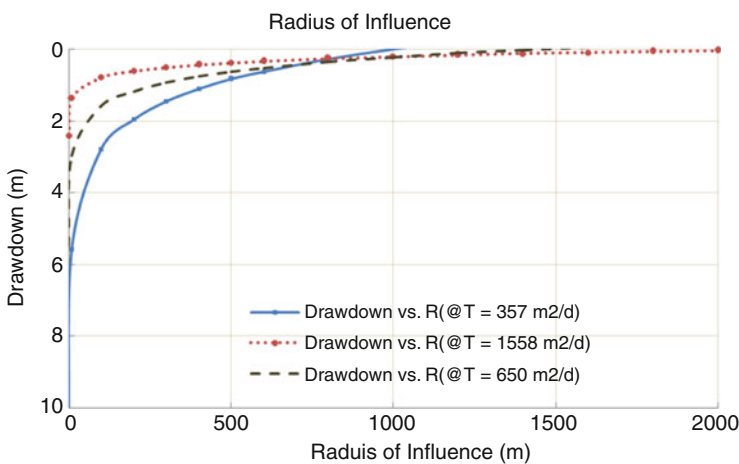


Fig. 15 Radius of influence vs. drawdown in Toshka area

2. The daily operation hours
3. The source of energy used to extract water
4. The agriculture drainage system
5. The crop pattern
6. The climate changes
7. The aquifer geology and properties

To evaluate and predict the future changes in the groundwater potential, Visual MODFLOW 2011.1 software was used to estimate the expected drawdown in the groundwater levels for different scenarios. The model was constructed and built to simulate the study area as follows.

5.2.1 Conceptual Model

A conceptual model to simulate water flow system of Nubian sandstone aquifer is constructed based on the following assumptions:

- Unconfined aquifer.
- One layer based on a basement rock.
- The flow direction moves from south and southeast to north and northwest.
- The hydraulic conductivity has spatial variations according to the variation in the saturated thickness.

5.2.2 Model Design

A grid of 1,600 cells (40×40) is constructed to cover the area including active and inactive cells as shown in Fig. 16. A grid surfer package was used to simulate the aquifer geometry and hydraulic parameters. The basement map (see Fig. 17) and the ground surface levels (see Fig. 18) represent the bottom and the top of the aquifer, and a 3D view of aquifer geometry simulation is shown in Fig. 19.

5.2.3 Boundary Conditions

The southeast boundary is represented by High Dam Lake which is considered as a constant boundary of 176 m above sea level. The north and west boundaries are represented as general boundary heads.

5.2.4 Building the Groundwater Model

The model was built based on the hydraulic parameters which are calculated from the pumping test analysis such as the hydraulic conductivity, transmissivity, initial heads, specific storage, specific yield, etc.

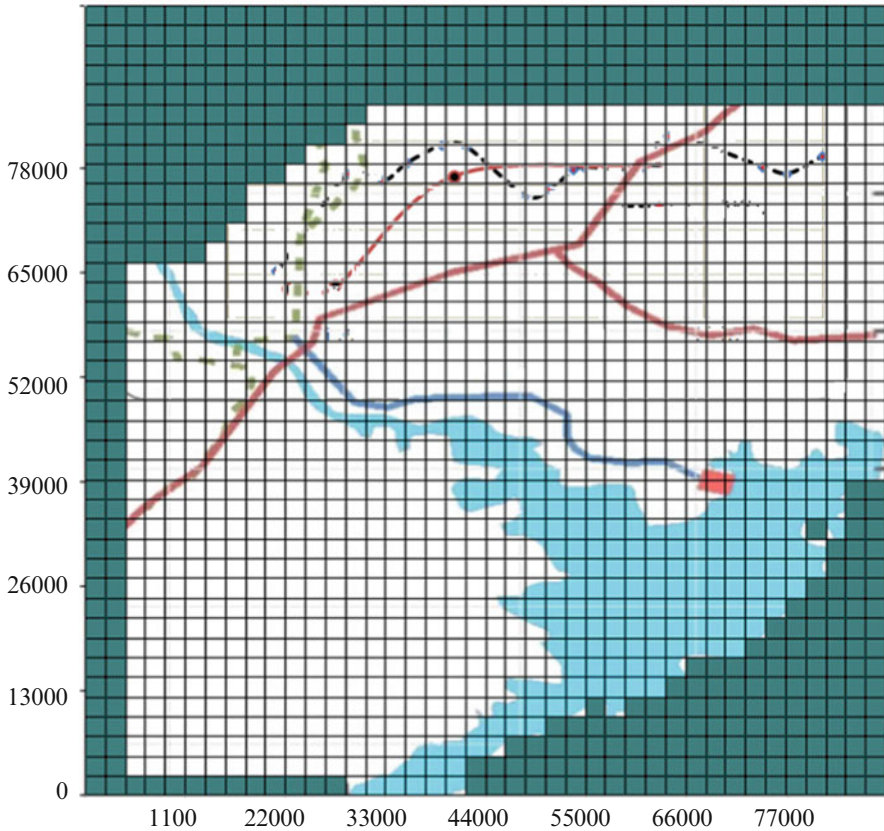


Fig. 16 A grid of 40 row \times 40 column

5.2.5 Model Calibration (Steady State)

Six observation wells were used to check the relation between the calculated and observed heads. After many times of changing the hydraulic conductivity and transmissivity, the produced water head map became close to the measured map. The hydraulic conductivity distribution map and the calibration diagram are shown in Figs. 20 and 21.

5.2.6 Model Calibration (Unsteady State)

Model calibration (unsteady state) is done by changing the time variant into transient by simulation time of 100 years together with the storage coefficient 10 running the model. By changing the storage coefficient several times, the

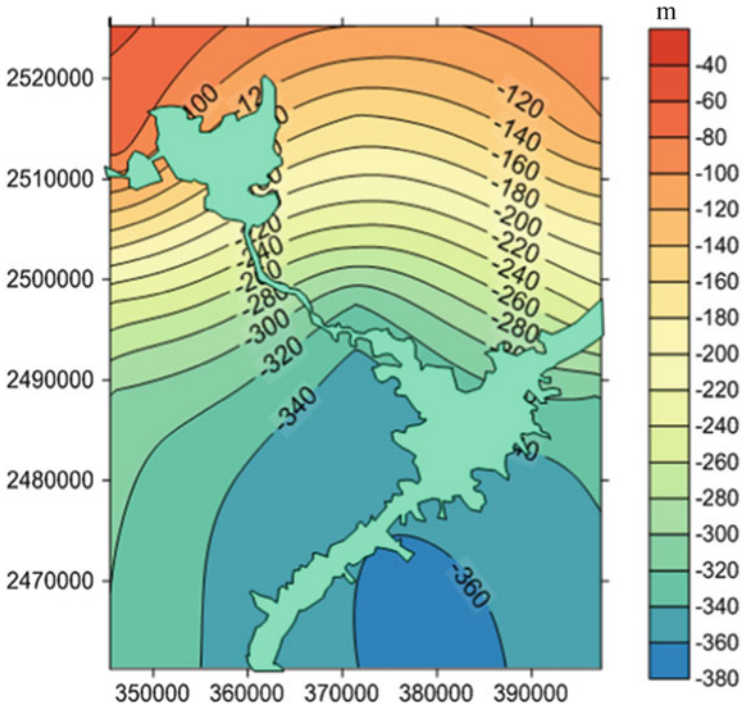


Fig. 17 Depth to basement rock map in Toshka area

calculated heads became close to the observed heads, and the model became suitable for future management of groundwater in the study area.

6 Water Requirement Scenarios for Reclamation of 25,000 Feddan

The government strategy intends to reclaim a total area of 25,000 feddan on groundwater in Toshka. To do this, some development scenarios have been made taking into consideration the groundwater aquifer delimiters, safe yield, and the recovery cost. Four scenarios were made based on the assumed water duty (requirement) per feddan per year and the corresponding drawdown in the groundwater levels (see Table 1).

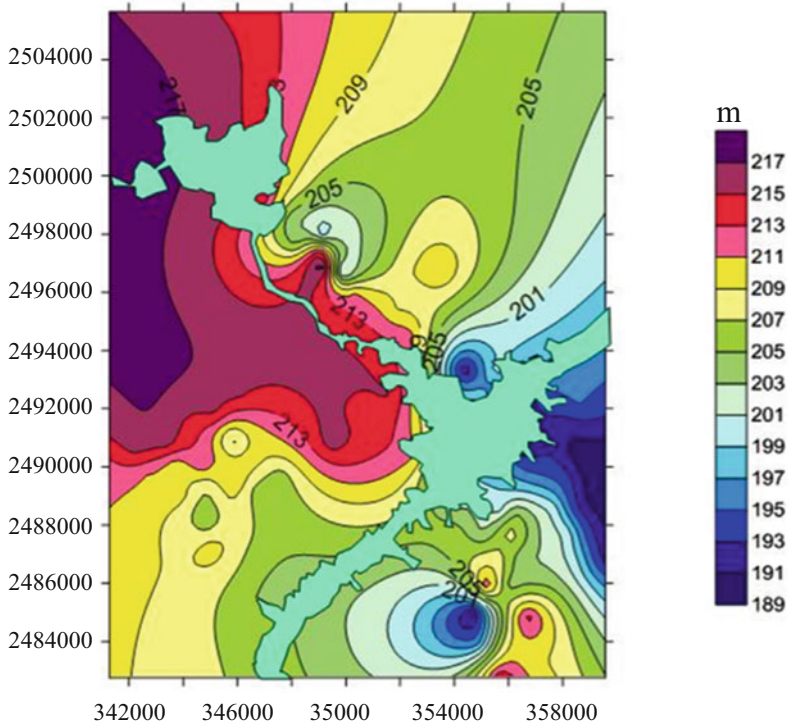


Fig. 18 Ground surface level map in Toshka area

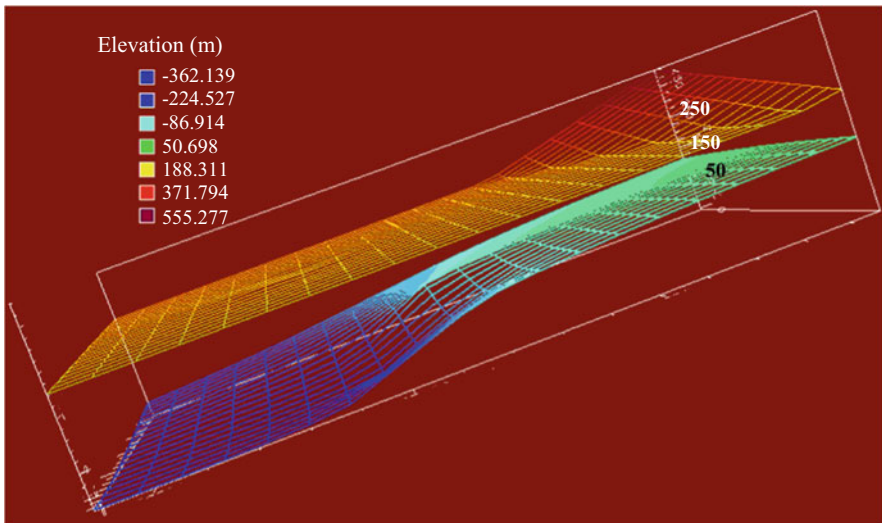


Fig. 19 Geometry simulation of Toshka area

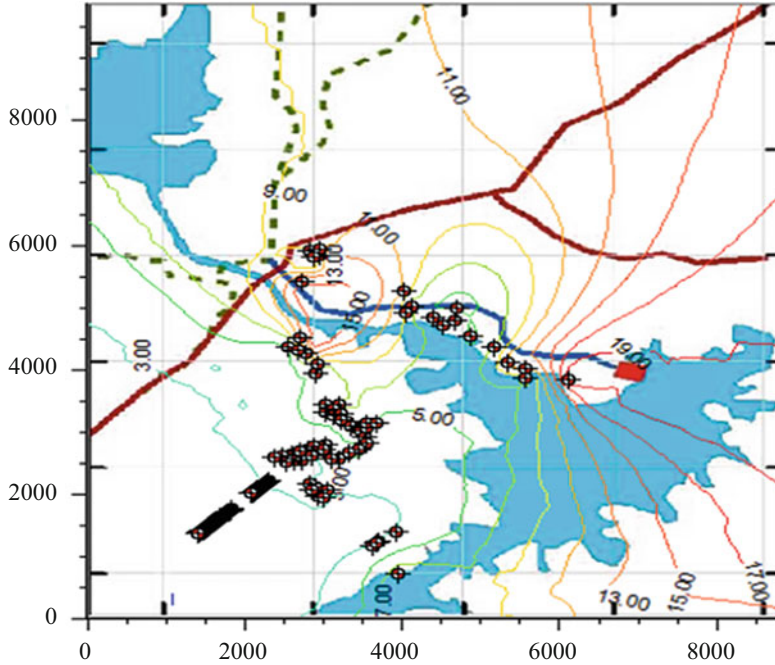


Fig. 20 Hydraulic conductivity distribution map in Toshka area

6.1 Scenario Assessments

1. It is clear that the maximum allowable daily operation time is 16.8 h with the daily discharge of $120 \times 16.8 = 2,014 \text{ m}^3/\text{day}$.
2. The maximum daily sunrise is 12 h with the daily discharge of $120 \times 12 = 1,440 \text{ m}^3/\text{day}$.
3. The preferable total amount of water extracted from 102 wells is $(120 \times 12 \times 365 \times 102 \text{ wells}) = 53,611,200 \text{ m}^3/\text{year}$.
4. For water duty of 5,000, 4,000, 3,000, and 1,500 $\text{m}^3/\text{feddan}/\text{year}$, the maximum cultivated area is 10,700, 13,400, 17,850, and 35,700 feddan, respectively (see Fig. 22).
5. The percentage of the maximum cultivated area with respect to the total required area of 25,000 feddan is 43%, 54%, 71%, and 143% for 5,000, 4,000, 3,000, and 1,500 $\text{m}^3/\text{feddan}/\text{year}$, respectively (see Fig. 23).
6. The expected drawdowns after 100 years for 1,200, 1,400, 1,600, and 1,800 $\text{m}^3/\text{day}/\text{well}$ are 15, 20, 25, and 28 m, respectively.
7. For 1,400 $\text{m}^3/\text{day}/\text{well}$ that assigned as a safe and recommended yield:

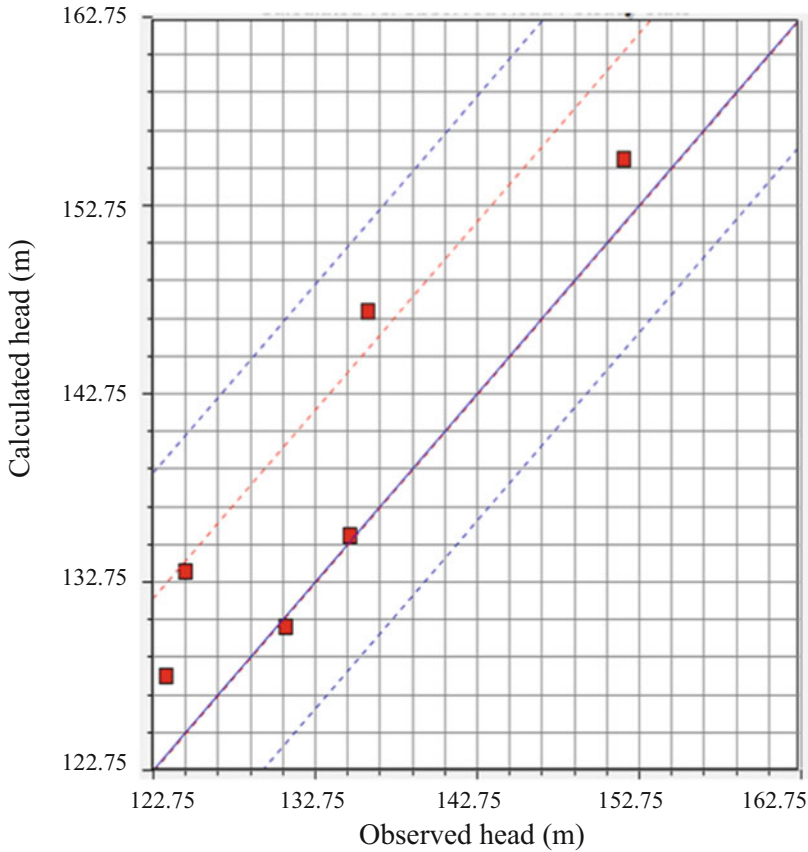


Fig. 21 Model calibration results

- (a) The cultivated area according to the assigned discharge ($1,400 \text{ m}^3/\text{day}$) mainly depends on the crop pattern. It is inversely proportional to the water requirement (see Fig. 23).
- (b) The expected lowering in groundwater levels after 100 years is 15 m (see Fig. 24).
- (c) The mass flow balance indicates that the calculated total recharge from the High Dam Lake in 100 years is 9.41 billion m^3 (94.1 million m^3/year) (see Fig. 25).
- (d) The total extracted water from the wells is 52 million m^3/year , and the calculated recharge from High Dam Lake is 94 million m^3/year . This recharge was only estimated for Abu Simbel area. It means that the inflow is more than the outflow which guarantees the sustainability of development projects.
- (e) Many studies have been done to estimate the recharge from High Dam Lake as the following.

Table 1 Different scenarios of water usage for 100 years

| Scenario no. | Water requirements (m ³ /feddan/year) | Total water requirements for 25,000 feddan (million m ³ /year) | Total water requirements from one well (m ³ /day) | Max drawdown (m) after 100 years | Required operation daily hours (safe discharge of 120 m ³ /h) | Remarks |
|--------------|--|---|--|----------------------------------|--|----------------|
| 1 | 5,000 | 125 | 3,357 | 55 | 28 | Refused 24 h |
| 2 | 4,000 | 100 | 2,686 | 40 | 22.4 | Very dangerous |
| 3 | 3,000 | 75 | 2,014 | 25 | 16.8 | Critical |
| 4 | 1,500 | 37.5 | 1,007 | 15 | 8.4 | Acceptable |

1. The specific yield (S_y) method (see Table 2):

$$Q = A \times \left(\frac{dh}{dt} \right) \times S_y$$

where Q is recharge (million m³/year), A is area estimated from Fig. 26 in km², dh is change in groundwater level (measured), dt is time of groundwater level change, and S_y is specific yield [40].

2. Darcy's law method:

Figure 27 indicates the cross-section method calculation and shows 26 sections and estimated hydraulic conductivity, hydraulic gradient, and saturated thickness for each length. Table 3 indicates the estimated value for each section.

7 Hydrochemistry

Groundwater samples for chemical analysis were obtained from 38 productive wells and 1 surface sample from Lake High Dam in Abu Simbel City. Sampling was carried out in 2000, 2001, and 2002. The major cations of Na⁺, K⁺, Ca²⁺, and Mg²⁺ and anions of Cl⁻, SO₄²⁻, and HCO₃⁻ were measured in the laboratory of the Desert Research Center (see Table 4).

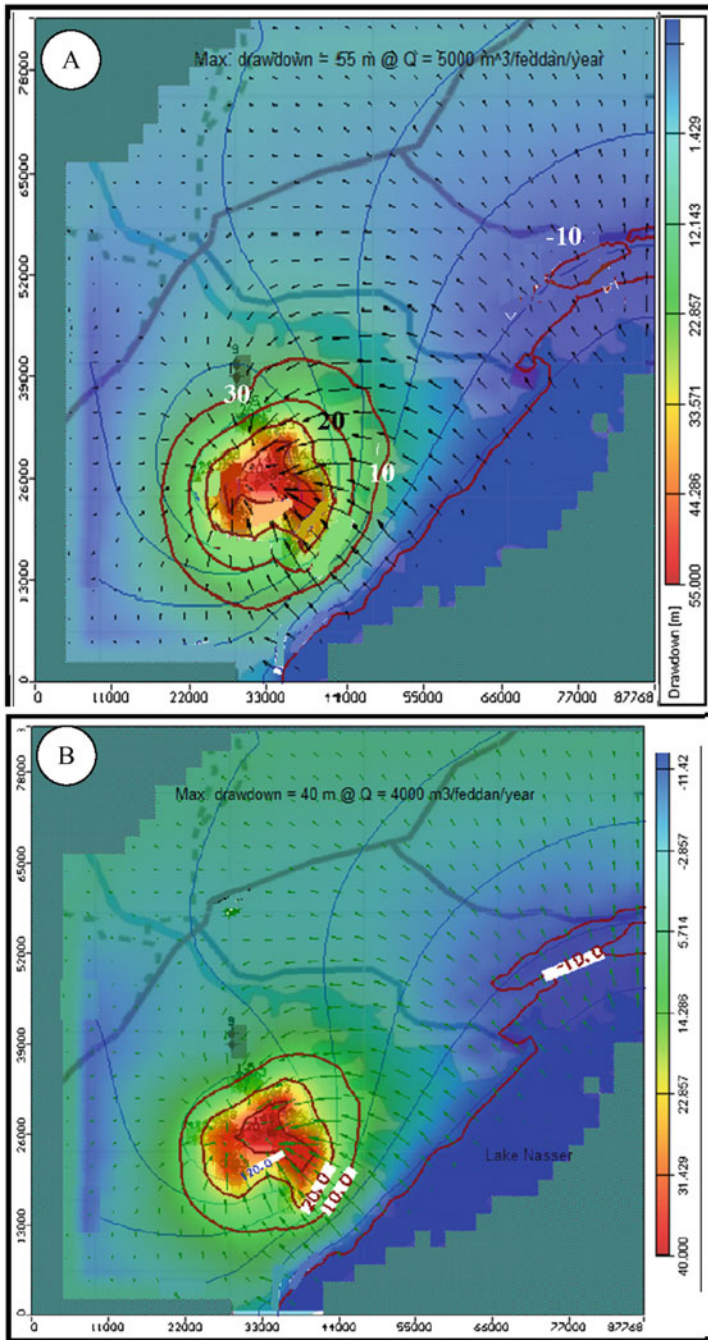


Fig. 22 The predicted drawdown after 100 years for different scenarios: (a) in case of $5,000 \text{ m}^3/\text{feddan}/\text{year}$, (b) in case of $4,000 \text{ m}^3/\text{feddan}/\text{year}$, (c) in case of $3,000 \text{ m}^3/\text{feddan}/\text{year}$, (d) in case of $1,500 \text{ m}^3/\text{feddan}/\text{year}$

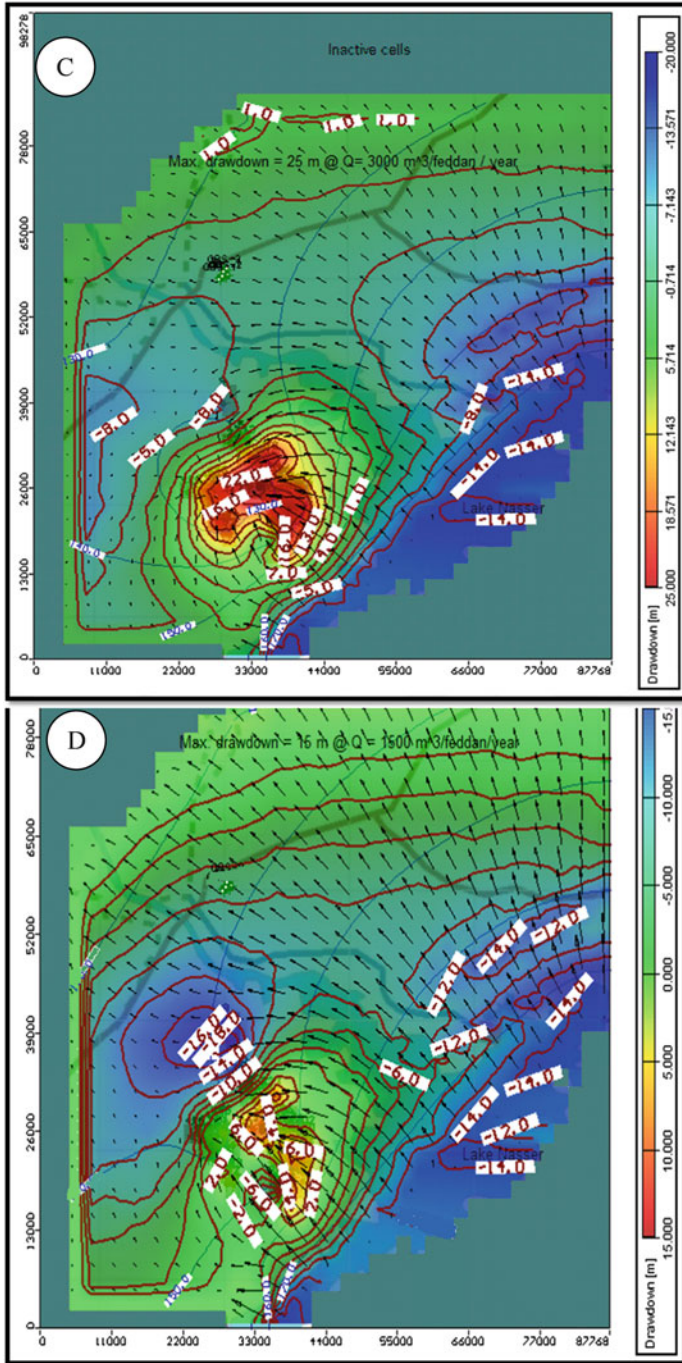


Fig. 22 (continued)

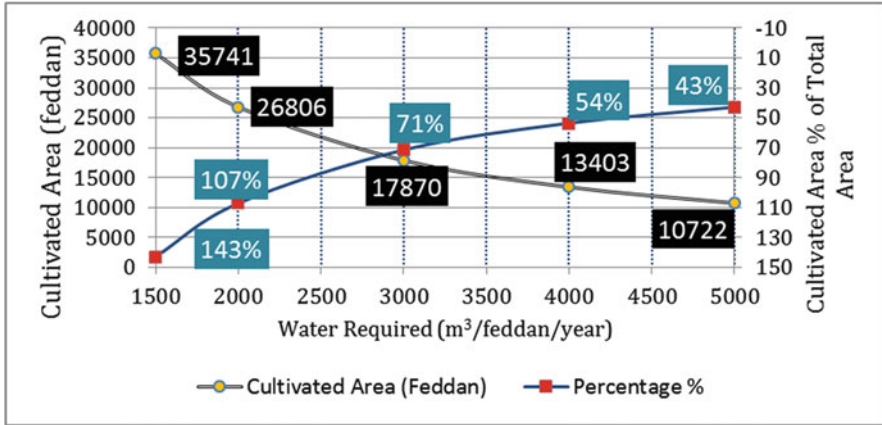


Fig. 23 Drawdown after 100 years for 1,400 m³/day/well (total 102 wells)

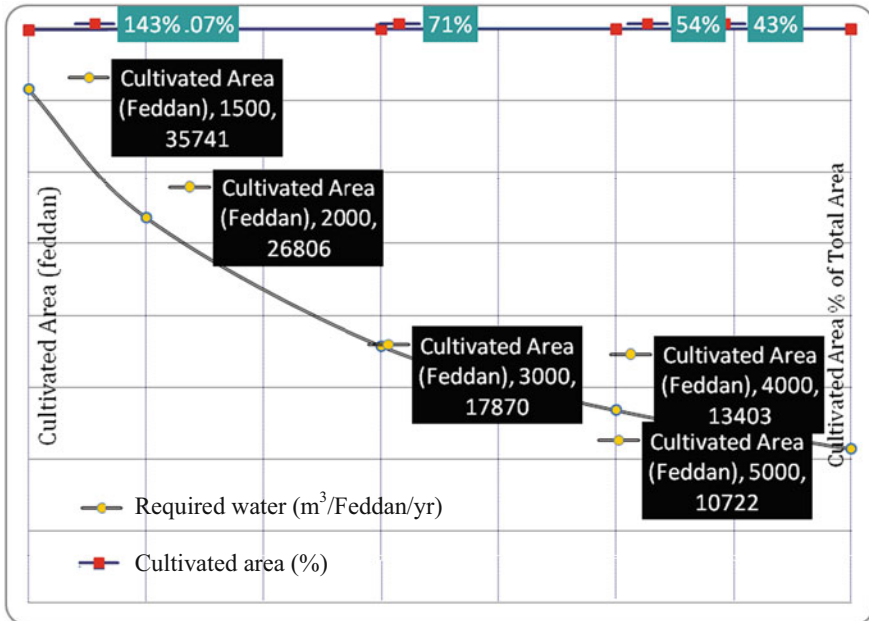


Fig. 24 Cultivated area vs. water requirements in Toshka

7.1 Groundwater Salinity in the Study Area

The majority of groundwater samples (38 samples) of the Nubian sandstone aquifer in the study area belong to freshwater type (<1,000 ppm). The salinity of groundwater increases toward the northwest directions coinciding with groundwater flow.

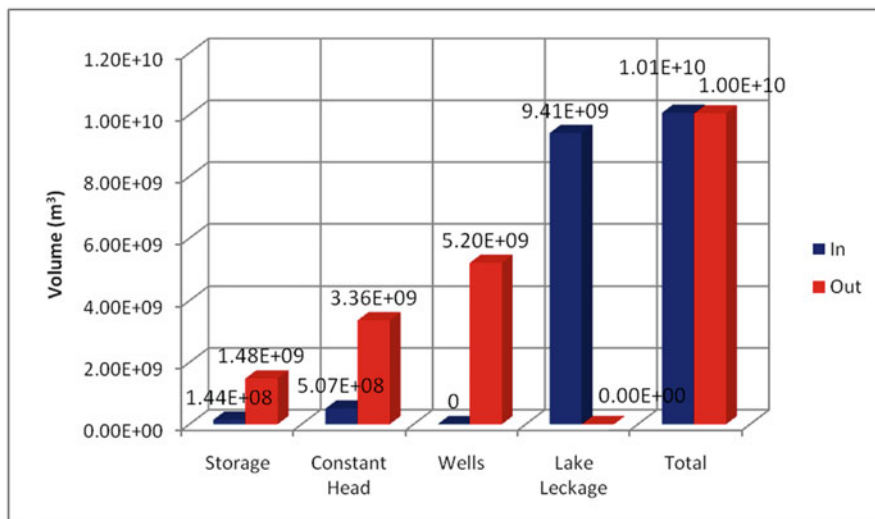


Fig. 25 Mass flow balance after 100 years for 1,400 m³/day/well

Table 2 Total recharge in Toshka (specific yield method)

| Region | A (km ²) | dh/dt | Specific yield | Q (million m ³ /year) |
|-------------------|----------------------|-------|----------------|----------------------------------|
| W. Halfa road | 845 | 0.18 | 0.135 | 20.5 |
| Abu Simbel road | 929 | 0.70 | 0.165 | 107.3 |
| Zayed canal | 507 | 0.83 | 0.145 | 60.6 |
| Amada road | 676 | 0.67 | 0.129 | 58.4 |
| Toshka depression | 338 | 0.11 | 0.030 | 1.1 |
| Total | | | | 259.9 |

Lower groundwater salinity is decreased due to the recharge from the High Dam Lake. The salinity ranges from 480 to 1,200 ppm with an average of 648.5 ppm (see Fig. 28).

7.2 Piper Diagram

Most of water samples belong to (NaCl) water type, and a few samples belong to (NaSO₄) water type for wells 26, 41, 44, 45, 73, 76, and 78 (see Fig. 29).

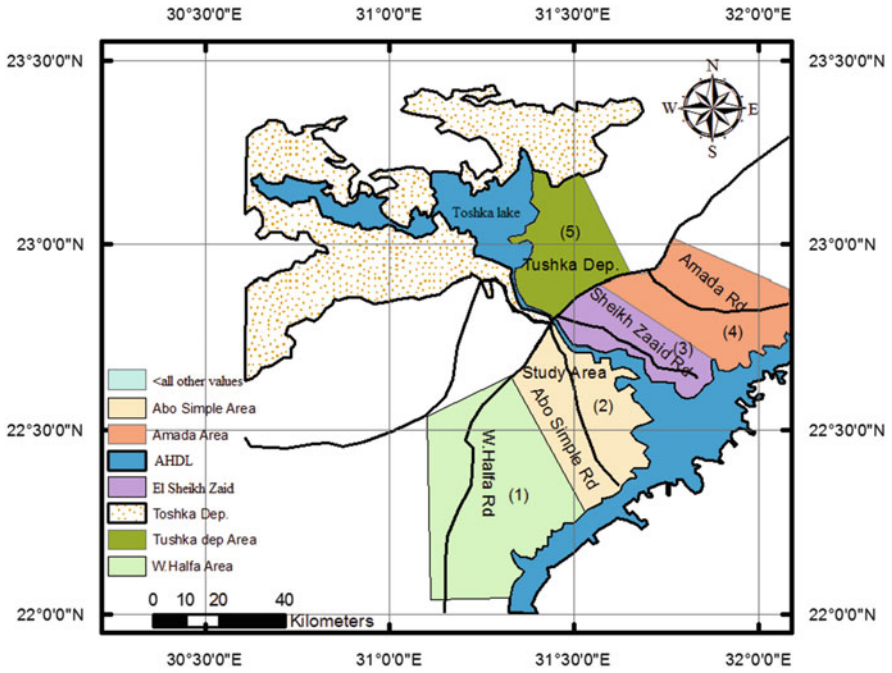


Fig. 26 Specific yield method to estimate the annual recharge

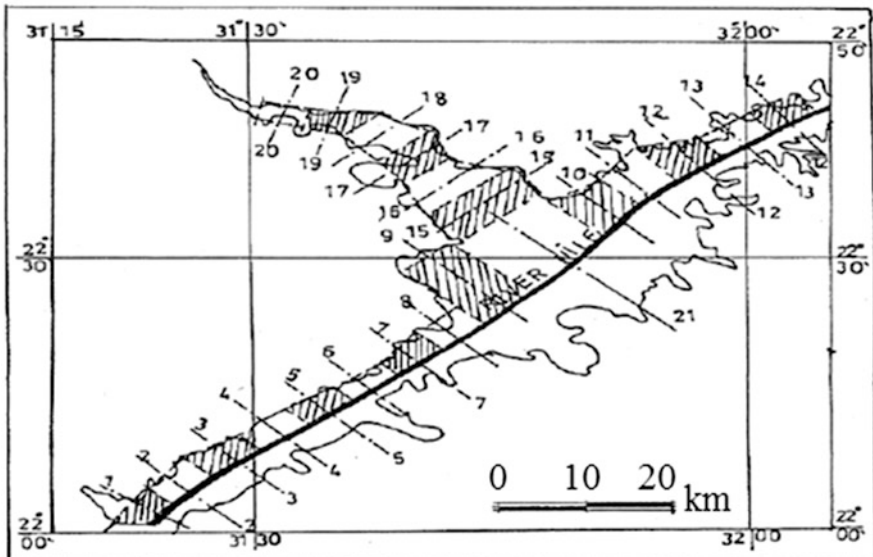


Fig. 27 Darcy's law method to estimate the annual recharge

Table 3 Total recharge in Toshka (Darcy's law method)

| Section no. | Length (m) | Hydraulic gradient (I) | Saturated thick (m) | K (m/day) | Q (1,000 m ³ /day) |
|--|------------|------------------------|---------------------|-------------|---------------------------------|
| 1 | 3,900 | 0.002564 | 250 | 10 | 25 |
| 2 | 5,200 | 0.001923 | 250 | 10 | 25 |
| 3 | 5,200 | 0.001923 | 250 | 10 | 25 |
| 4 | 66,500 | 0.001538 | 250 | 6 | 15 |
| 5 | 6,500 | 0.001538 | 250 | 6 | 15 |
| 6 | 6,500 | 0.001538 | 250 | 6 | 21 |
| 7 | 6,500 | 0.001538 | 250 | 5 | 17.5 |
| 8 | 5,200 | 0.001923 | 250 | 5 | 17.5 |
| 9 | 5,200 | 0.001923 | 250 | 4 | 10 |
| 10 | 3,900 | 0.002564 | 250 | 6 | 15 |
| 11 | 2,600 | 0.003846 | 250 | 6 | 15 |
| 12 | 2,600 | 0.003846 | 250 | 6 | 15 |
| 13 | 2,600 | 0.003846 | 250 | 6 | 15 |
| 14 | 2,600 | 0.007692 | 250 | 8 | 40 |
| 15 | 3,900 | 0.005128 | 250 | 6 | 30 |
| 16 | 5,200 | 0.003846 | 250 | 3 | 15 |
| 17 | 6,500 | 0.003077 | 250 | 3 | 15 |
| 18 | 6,500 | 0.003077 | 250 | 4 | 20 |
| 19 | 7,800 | 0.002564 | 250 | 4 | 20 |
| 20 | 9,100 | 0.002198 | 200 | 4 | 16 |
| 21 | 9,100 | 0.002198 | 120 | 8 | 19.2 |
| 22 | 6,500 | 0.003077 | 120 | 8 | 19.2 |
| 23 | 6,500 | 0.003077 | 150 | 0.1 | 0.300 |
| 24 | 6,500 | 0.003077 | 150 | 0.1 | 0.300 |
| 25 | 6,500 | 0.003077 | 150 | 0.1 | 0.300 |
| 26 | 6,500 | 0.003077 | 150 | 0.1 | 0.300 |
| Total | | | | | 426.6 |
| Total annual recharge = 155 million m ³ | | | | | |

7.3 Wilcox Diagram

Wilcox diagram shows that the majority of samples are located in C3–S1. S1 means low value of sodium hazard, and C3 means high salinity hazard (see Fig. 30).

7.4 Durov Diagram

Durov diagram describes the sample's water type and salinity. Most of the samples belong to NaCl type and salinity from 336 to 1,000 ppm (see Fig. 31).

Table 4 Chemical analysis of Toshka groundwater (mg/l)

| Well no. | Date | N ⁺ | K ⁺ | Ca ²⁺ | Mg ²⁺ | Cl ⁻ | HCO ₃ ⁻ | -CO ₂ | SO ₄ ²⁻ | TDS (ppm) |
|----------|------------|----------------|----------------|------------------|------------------|-----------------|-------------------------------|------------------|-------------------------------|-----------|
| 22 | 9/7/2000 | 188 | 5.8 | 112 | 29.2 | 280 | 108 | 0 | 290 | 1,175 |
| 23 | 24/09/2000 | 114 | 5.2 | 76 | 9.73 | 168 | 104 | 0 | 160 | 662 |
| 24 | 11/10/2000 | 108 | 4.8 | 80 | 17 | 160 | 112 | 0 | 195 | 640 |
| 25 | 12/9/2000 | 132 | 4.5 | 58 | 25.5 | 184 | 114 | 0 | 165 | 722 |
| 26 | 25/12/2000 | 108 | 5.2 | 86 | 18.2 | 136 | 128 | 0 | 210 | 652 |
| 27 | 16/09/2000 | 132 | 4.5 | 58 | 25.5 | 184 | 114 | 0 | 165 | 722 |
| 28 | 25/07/2000 | 136 | 4.8 | 62 | 35.3 | 192 | 140 | 0 | 195 | 744 |
| 29 | 6/12/2000 | 116 | 4.8 | 77 | 14.6 | 160 | 112 | 0 | 180 | 602 |
| 30 | 15/10/2000 | 98 | 4.4 | 76 | 20.7 | 144 | 116 | 0 | 180 | 676 |
| 31 | 1/7/2000 | 144 | 4.3 | 86 | 24.3 | 216 | 108 | 0 | 190 | 766 |
| 32 | 26/10/2000 | 100 | 4.8 | 80 | 15.8 | 142 | 108 | 0 | 160 | 625 |
| 33 | 27/08/2000 | 104 | 4.7 | 78 | 21.9 | 144 | 132 | 0 | 180 | 630 |
| 34 | 28/10/2000 | 88 | 4.6 | 75 | 10.9 | 116 | 124 | 0 | 145 | 545 |
| 35 | 3/6/2000 | 136 | 4.3 | 78 | 13.4 | 168 | 116 | 0 | 205 | 708 |
| 36 | 10/9/2000 | 90 | 4.6 | 64 | 15.8 | 124 | 140 | 0 | 140 | 530 |
| 37 | 18/10/2000 | 86 | 4.4 | 73 | 11.6 | 135 | 138 | 0 | 135 | 532 |
| 38 | 22/11/2000 | 88 | 4.2 | 68 | 13.4 | 112 | 140 | 0 | 130 | 576 |
| 39 | 24/02/2000 | 76 | 4.6 | 66 | 15.2 | 104 | 116 | 0 | 140 | 488 |
| 40 | 20/08/2000 | 100 | 4 | 66 | 21.9 | 136 | 116 | 0 | 140 | 600 |
| 41 | 26/10/2000 | 96 | 4.6 | 72 | 13.4 | 108 | 136 | 0 | 165 | 600 |
| 42 | 3/8/2000 | 108 | 4.4 | 72 | 17 | 128 | 196 | 0 | 150 | 684 |
| 43 | 27/06/2000 | 94 | 4.8 | 50 | 32.8 | 216 | 104 | 0 | 135 | 598 |
| 44 | 2/10/2000 | 98 | 4.4 | 76 | 10.9 | 110 | 132 | 0 | 160 | 575 |
| 45 | 2/10/2000 | 110 | 4.1 | 76 | 14 | 128 | 116 | 0 | 190 | 585 |
| 46 | 25/11/2000 | 104 | 4 | 70 | 12.8 | 136 | 110 | 0 | 165 | 600 |
| 47 | 20/02/2001 | 190 | 5.6 | 104 | 19.5 | 280 | 76 | 0 | 280 | 940 |
| 51 | 21/03/2001 | 210 | 7.1 | 134 | 19.5 | 370 | 84 | 0 | 310 | 1,200 |
| 52 | 20/03/2001 | 280 | 6.8 | 142 | 26.8 | 410 | 84 | 0 | 380 | 530 |
| 60 | 11/5/2002 | 92 | 5 | 68 | 19.5 | 140 | 108 | 0 | 160 | 1,360 |
| 71 | 1/9/2002 | 72 | 5.1 | 56 | 24.3 | 124 | 128 | 0 | 130 | 574 |
| 72 | 12/9/2002 | 76 | 4.4 | 56 | 24.3 | 128 | 124 | 0 | 130 | 480 |
| 73 | 31/01/2002 | 88 | 3.4 | 52 | 21.9 | 112 | 100 | 0 | 165 | 484 |
| 74 | 10/9/2002 | 100 | 5.4 | 64 | 21.9 | 144 | 152 | 0 | 160 | 518 |
| 75 | 11/8/2002 | 88 | 5.3 | 56 | 29.2 | 120 | 136 | 0 | 160 | 604 |
| 76 | 31/01/2002 | 104 | 5.2 | 54 | 28 | 132 | 118 | 0 | 180 | 546 |
| 77 | 20/04/2002 | 100 | 5 | 46 | 25.5 | 130 | 128 | 0 | 134 | 568 |
| 78 | 10/3/2002 | 82 | 5.9 | 32 | 41.3 | 108 | 128 | 0 | 154 | 540 |
| 79 | 12/9/2002 | 112 | 4.8 | 79 | 19.5 | 154 | 120 | 0 | 202 | 540 |
| AHDL | | 12 | 8 | 36 | 4.86 | 24.8 | 100 | 0 | 35 | 170 |

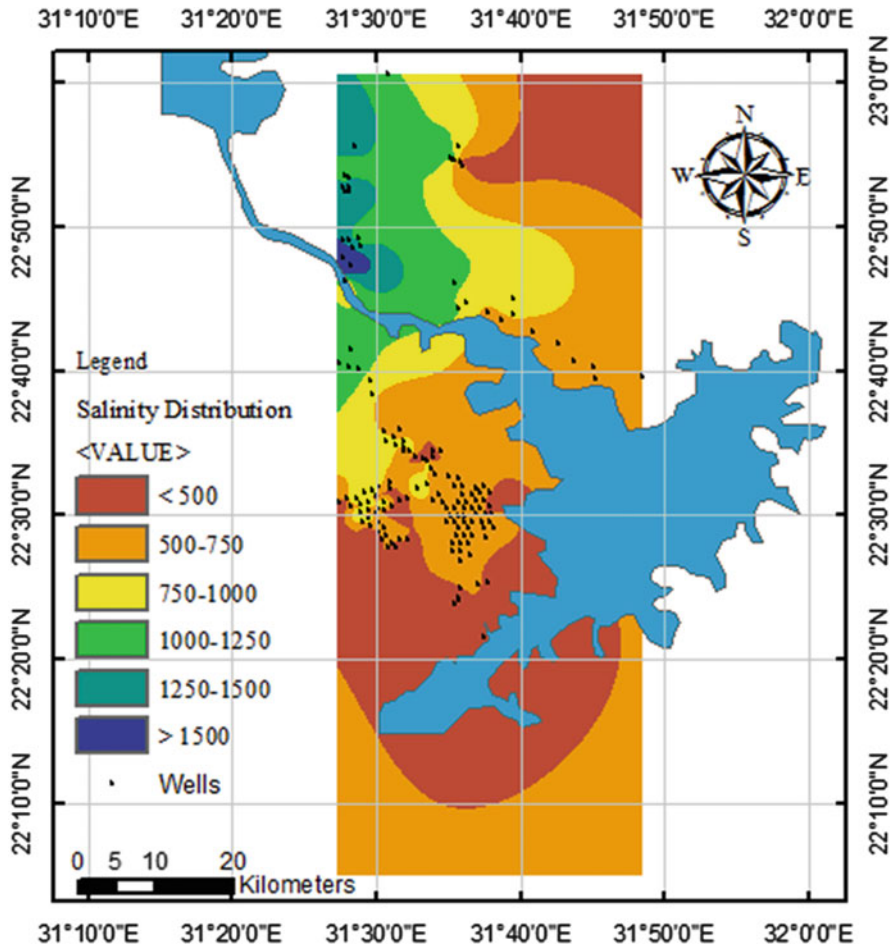


Fig. 28 Distribution of salinity content (ppm) in the study area

7.5 Suitability of Groundwater for Irrigation Purposes

The groundwater quality in the study area was classified according to its chemical properties such as TDS, SAR, RSC, chloride, and trace elements as discussed below.

7.6 Total Dissolved Salts (TDS)

Total dissolved salts (TDS) parameter is one of the most important ones to assess the suitability of water for irrigation. According to the distribution map of salinity

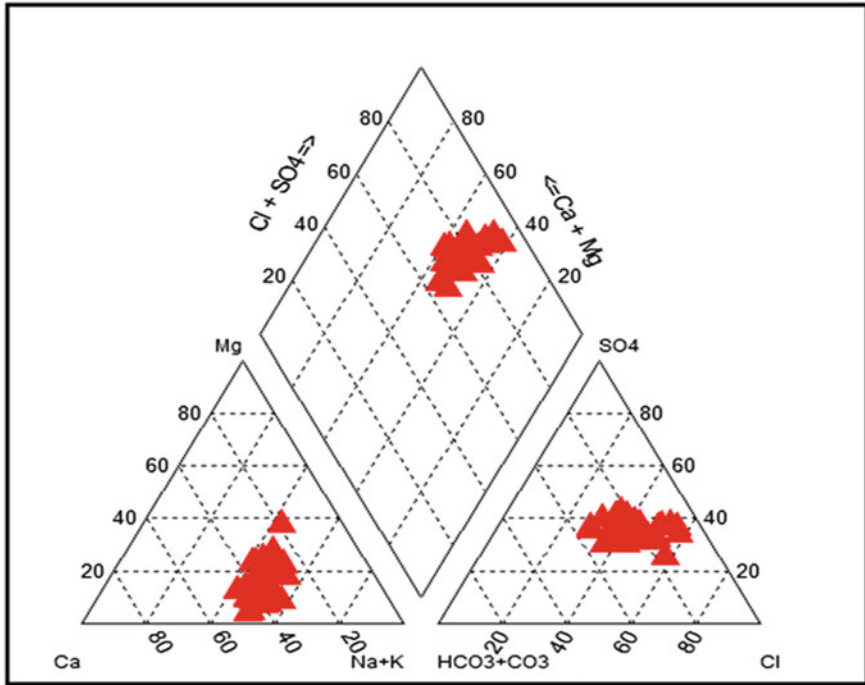


Fig. 29 Piper diagram of hydrochemical classification of groundwater samples in Toshka area

(see Fig. 28), most of the water samples range between 500 and 1,500 mg/l. US Salinity Laboratory (USSL) classification and Wilcox plot show that all of the samples are located in region C3. The salinity of this class ranges between 500 and 1,500 g/l, and electric conductance ranges between 750 and 2,250 $\mu\text{moh/cm}$. It can be used for moderate-good permeable soils, while it cannot be used on soils with restricted drainage. Even in the soils with adequate drainage, special management of salinity control may be required, and plants with good salt tolerance should be selected.

7.7 Sodium Adsorption Ratio (SAR)

Sodium adsorption ratio (SAR) measures the relative concentration of sodium to calcium and magnesium. High sodium ions in water affect the permeability of the soil and cause infiltration problems. Sodium replaces calcium and magnesium adsorbed on the soil clays and causes dispersion of soil particles. Therefore, the soil when dry becomes hard and compact with low permeability [41].

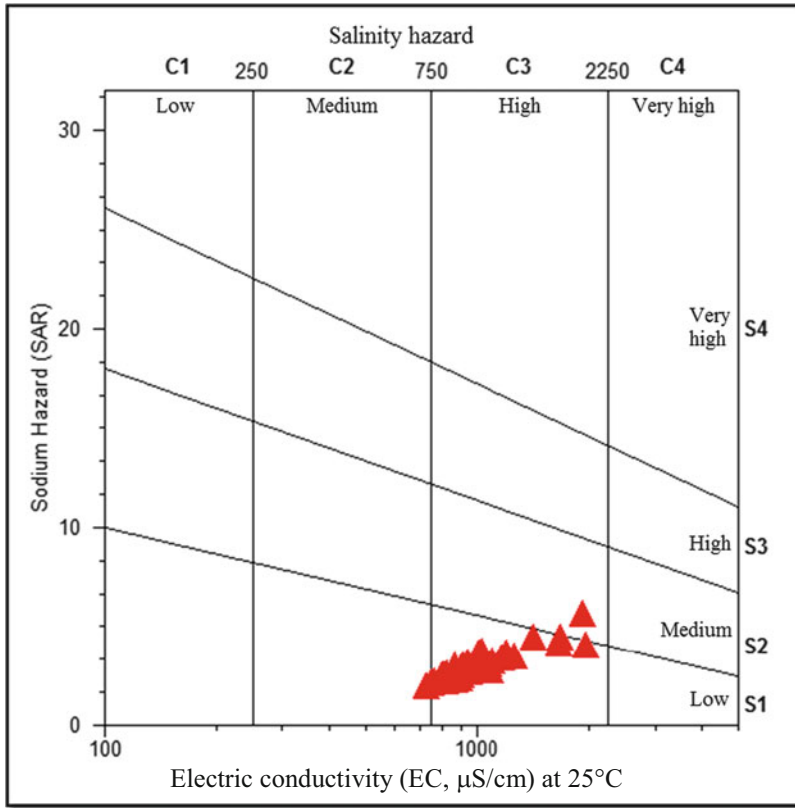


Fig. 30 Wilcox diagram for the groundwater samples in Toshka area

Most of the samples are located in S1 class (see Fig. 32), indicating a low value of sodium. All SAR values are less than 10 emp, which is classified according to US Salinity Laboratory (USSL) as an excellent class for irrigation and good for fruits, nuts, citrus, and avocado.

7.8 Residual Sodium Carbonate (RSC)

In water concentrated with bicarbonate, it has a tendency for calcium and magnesium to precipitate. As a result, the relative proportion of sodium in the water is increased in the form of sodium carbonate. RSC is calculated using the following equation:

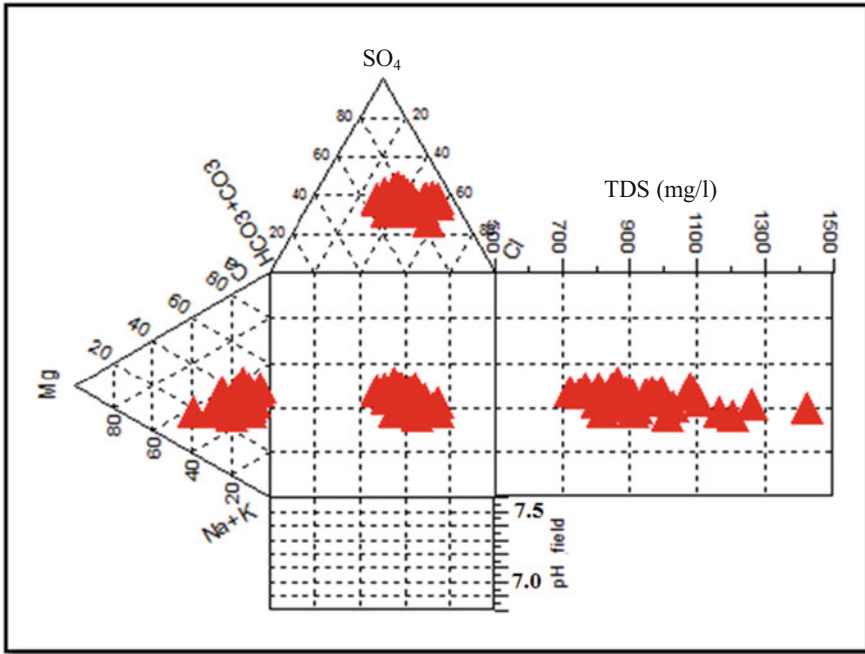


Fig. 31 Durov diagram for groundwater samples in Toshka area

$$RSC = (HCO_3^{3-} + CO_3^{2-}) - (Ca^{2+} + Mg^{2+})$$

According to the US Department of Agriculture, water having more than 2.5 epm of RSC is not suitable for irrigation purposes. RSC is classified into three classes (<1.25, 1.25–2.5, and >2.5) which are good, doubtful, and unsuitable, respectively. By applying RSC equation, the results for all samples showed negative values, indicating good class.

8 Conclusions

The present chapter focuses on estimating the expected change in groundwater levels and water quality for different operation scenarios.

The minimum water level of the AHDL had remained above 170 m, fluctuating by 2–4 m/year. There is a direct relation between the AHDL and the characteristics of the groundwater in Toshka area that is mainly covered by sedimentary sequence up to 300 m. It is represented by brown shale, sandstone, and shaley sandstone, which overlie the Precambrian basement rocks.

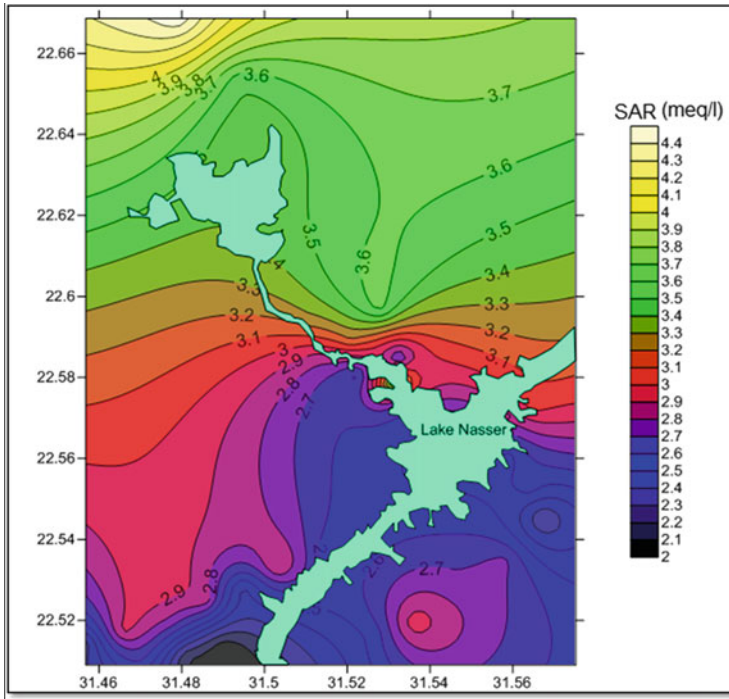


Fig. 32 Spatial distribution map of SAR in Toshka area

The Nubian Sandstone Aquifer System in Toshka receives continuous recharge confirmed by the difference of heads between the aquifer and the AHDL.

The transmissivity varies between 321 and 1,558 m^2/day with an average of 650 m^2/day . The hydraulic conductivity ranges from 3 to 21 m/day with an average of 6 m/day . The aquifer potentiality is increasing toward the northwest of the study area due to high hydraulic conductivity and aquifer thickness in the northwest.

The water drop in water level from 1998 to 2006 ranged between 0.5 and 13.8 m in Toshka. Such drop indicates that the extraction rate of water is much higher than the recharging rate. The drop is expected to continue with the continuous extraction of groundwater.

The effect of the new 50 wells drilled in 2015/2016 to irrigate the 25,500 feddan as a part of the “1.5 Million Feddan Project” will increase the drop in groundwater level in the area.

The preferable total amount of water extracted from the 102 wells is 53,611,200 m^3/year at 120 m^3/h for 12 h/day. For water duty of 5,000, 4,000, 3,000, and 1,500 $\text{m}^3/\text{feddan}/\text{year}$, the maximum cultivated area will be 10,700, 13,400, 17,850, and 35,700 feddan, respectively. The expected drawdowns after 100 years for 1,200, 1,400, 1,600, and 1,800 $\text{m}^3/\text{day}/\text{well}$ are 15, 20, 25, and 28 m, respectively. The cultivated area, according to the assigned discharge for each well

(1,400 m³/day), mainly depends on the crop pattern. It is inversely proportional to the water requirement.

The total extracted water from the 102 wells is 52 million m³/year, and the calculated recharge from AHD Lake is 94 million m³/year. This recharge was only estimated for Abu Simbel area. It means that the inflow is more than the outflow (under the assumptions of the study) which guarantees the sustainability of development projects. The recharge studies showed to be done for the whole area.

The recommended safe water use of groundwater for 100 years is 1,007 m³/day from each well working 8.4 h/day at 120 m³/h, to provide 1,500 m³/feddan/year for a total of 25,000 feddan. The expected lowering in the groundwater level after 100 years is 15 m.

The groundwater in Toshka is classified as a freshwater type (<1,000 ppm). The salinity ranges from 480 to 1,200 ppm with an average of 648.5 ppm. It increases toward the northwest directions coinciding with groundwater flow. Lower groundwater salinity is decreased due to the recharge from the AHD Lake. The groundwater is an excellent class for irrigation.

9 Recommendations

Groundwater model must be used to predict the influence of different development scenarios on the groundwater levels. Building, calibration, and validation of such model could be based on the available historical data. There is a direct recharge from the AHDL to the groundwater in Abu Simbel area. Groundwater recharge is expected to increase from the new surface irrigation. Detailed recharge studies showed to be done for the whole area. The safe abstraction from the water wells in Toshka is 120 m³/day for 8–12 h/day. The 102 wells are good for 25,000 feddan at 1,500 m³/feddan or 12,500 at 3,000 m³/feddan. Water quality monitoring is required for all wells in general and the new ones in particular. Water is very precious in the desert regions; therefore, good feasibility studies are required to be done on Toshka projects. The climatic conditions and consequences of the new irrigation projects in Toshka need detailed studies. New Toshka lakes were formed during the AHDL flood in 1998 to 2001. They disappeared after about 10 years due to mostly high evaporation and water infiltration. Geo-environmental problems especially soil salinization are likely to arise from the concentration of salts after the lakes dry up. Studying the salinity of soil and its effect on the groundwater is strongly recommended to be carried out. The new irrigation projects in Toshka should use the most drought tolerant crops and get benefit from the virgin soils in organic agriculture.

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