Feasibility of Lake Bank Filtration on Groundwater Management in Toshka–Egypt

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ABSTRACT

In terms of the importance of implementing integrated water resources managementin Egypt the objective of this study was to assess the feasibility of induced lake bank filtration in Toshka, Egypt. Based on literature research and field investigations a groundwater flow model was set up using Modflow/GMS.Variouswater extraction scenarios were analyzed for its effects on groundwater levels and water balance. The results highlight that extracted discharges are lower than safe yield, which might impose insignificant impact on groundwater level. The results indicate that the safe yield in the Toshkaarea is 115.845 m^3/s.Five scenarios for groundwater extraction from the study areawere evaluated.Results of simulations show the abstraction rates for scenarios 1 – 4 with of about 2.973333, 3.123333, 3.1483333 and 3.273333 m3/s, respectively, the resulting decrease in groundwater levels in the study area was found to be less than 32.6 m during the drought period.

Keywords: ToshkaLake, Lake bank filtration, 3D modelling, MODFLOW

1 INTRODUCTION

Egypt has limited water resources (WR) but its population is growing drastically together with its municipal, industrial, and agricultural activities. Also, Egypt experiences climate change impacts. Many hydraulic works are under construction in Nile Basin countries, which necessitates the adoption of an integrated water resources management (IWRM) approach to develop and manage Egypt's limited WR despite the fact that the riverNile contributes 95%-98% of its WR [7].

Accordingly, in order to cover the water needs, additional water resources should be utilized, where groundwater is a promising conventional WR that could be incorporated in the "$1.5x10^6$ Fadden Land Reclamation National Project" (LRNP). Consequently, this research was initiated to assess the feasibility of usinginduced lake bank filtration in Toshka, Egypt.Lake bank filtration (LBF) and riverbank filtration (RBF) are sub-categories of the bank filtration approach for water supply. Bank filtration is defined as infiltration of surface water into an adjacent aquifer via the bank or bottom of the surface water body (river, lake, canal). It is a low-cost natural water pre-treatment step resulting in improved water quality. Using bank filtration can reduce overextraction of groundwater. Thus, implementing LBF schemes may contribute to the LRNP, where the Toshka area is targeted to be economically reclaimed [1, 3, 6, 10, 15, 16, 17].

However, application of LBF should be based on a profound understanding of groundwater flow conditions and interaction between the lake and the aquifer. For the investigation of various scenarios of water extraction at different distances to the lake a numerical groundwater flow and transport model is helpful. Furthermore, numerical groundwater flow modeling will support managing,optimize and conserve groundwater resources so as surface water and control groundwater extraction in order to visualize groundwater aquifer impact on safe yield [5].For the feasibility assessment of LBF in the Toshka area a groundwater flow model was developed, calibrated and applied to describe groundwater flow conditions and groundwater-surface water exchange, to optimize scenarios for water abstraction and to estimate safe yield of well fields [5].

2 STUDY AREA DESCRIPTION

The study area covers the west of Lake Nasser that includes Toshka area, in the south-western part of Egypt. The study area extends between latitudes 21° 58’ 59.43” and 23° 54’ 23.046” N and stretches between longitudes 29° 40’ 26.15’’ to 32° 41’ 1.12” E. The study area is 220,000 km^2, where the Toshka area is 48,903 km^2. It has an irregular shape where its base is 169 km wide (Fig. 1).

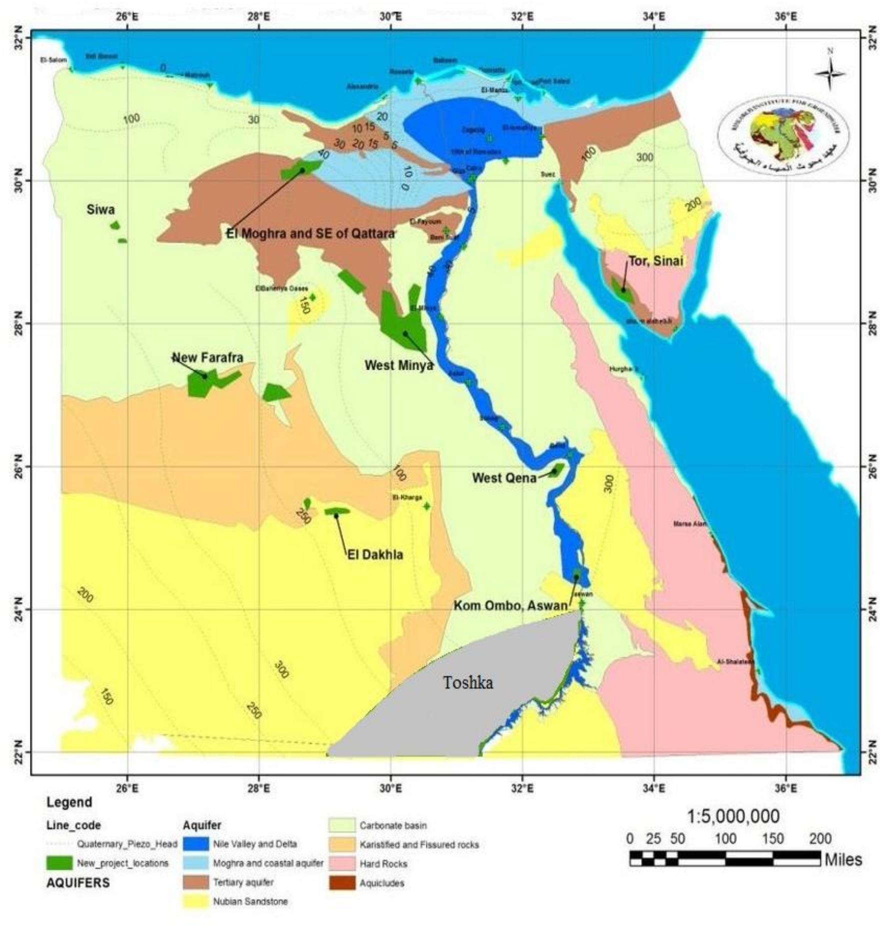

Figure 1: Location map with the Toshkastudy areamarked in grey[10]

The study area ischaracterized by a hot desert climate. It has the hottest, sunniest, and driest cities in the world. The average high temperatures are consistently above 40 °C during summer (June-September) while its average low temperature is 25 °C. It is extremely dry year-round with less than 1 mm of average annual precipitation. Furthermore, it is characterized bythe lowest humidity on the planet, with an average relative humidity of only 26%, a maximum mean of 38% during winter and a minimum mean of 14% during summer [9].

People live in villages that are located south of Aswan around Lake Nasser at Karkare-Thomas and Afia-Abu-Simble and in the west ofLake Nasser in Wadi Elalaaky and Toshkacity. The study area is planned to serve a future population of 5 million. However, the current buildings are designed to accommodate 80,000 peoplewith an expected increase to 238,000 people in the coming few years [4].

Lake Nasser is considered as the main source of water in the Toshka area. Toshka main canal (Sheikh Za-yed Canal) with its four branches is conveying the water of Lake Nasser that is pumped by a giant pumping station to the western desert of Egypt. This canal is designed to carry about 5.5 billion m^3 of water from Lake Nasser to the New Valley. Groundwater is found in the Western Desert within the Nubian sandstone aquifer that extends below the vast area of the New Valley and its sub-region East of Owaynat. This aquifer stores about 200,000 BCM of freshwater [9].

The study area is characterized by base rocky plateaus, sandy plains, and ridges. The topographic elevations in the Toshka area are subdivided into three groups: the lowlands topography group in the central part of the study area (less than 150 masl), the moderate relief topography group withhillslopes, isolated hills, and Pedi plains (150–300 masl), and the less analyzed mountainous topography groupin the northern and northeastern parts (>300 masl). The main geomorphologic units are the Sinn El-Kaddab Plateau, scarp faces and Pedi plain of Nubiansandstones, including ferruginous isolated hills, Nubiansandstone hills, inverted wadis, accumulated alluvial fans and playas, lowlands and depressions, sand sheets and sand dunes, tors of igneous and metamorphic rocks of lowlands and hills, occasionally tidal zones and wadis and main drainage channel. Other geomorphologic features are broad wadis (dry valley), V-shaped drainage lines (channels), structural lineaments and water points. Lake Nasser has been considered as one of the most complex natures[12].

Toshka geologic map represents that main geological units are arranged from Cretaceous to Quaternary as (1) Upper Jurassic-Lower Cretaceous rocks (Abu Simbel Formation), formed from sandstone with intercalations of mudstone and weakly developed paleo soil; (2) Lower Cretaceous rocks, divided into Lake Nasser Formation and Sabaya Formation, both mainly formed from coarse grained sandstone with shale and clayey siltstone intercalations, (3) Upper Cretaceous rocks, Kiseiba Formation, which developed into fine sandstone with shale, silt and sandstone intercalations, bone, and phosphate beds, (4) Paleocene rocks with clastic and reefal limestone intercalations rich in fossils related to Kurkur Formation, (5) Lower Eocene rocks, subdivided into Garra Formation and Dungul Formation and composed mainly of thick limestone beds, partly chalky and occasionally siliceous and dolomitic, (6) Oligocene rocks, developed into dark low hills, and (7) Quaternary rocks, alluvial, lake and playa deposits, as well as aeolian deposits. The Nubian sandstone rocks are ranging from Upper Jurassic-Lower Cretaceous rocks to Upper Cretaceous rocks. Structurally, the study area is a very complicated formation which was formedthrough the action of deep-seated earth forces [8].

3 NUMERICAL GROUNDWATER FLOW MODELING

To simulate the aquifer system, a 3-D finite difference numerical model was set up using the software toolGMS 10.1 based on MODFLOW. The model area was 71,087 km^2 (about 325 km in length and 218.7 km in width). A grid with 2500 cells (50 columns x 50 rows) was designed (Fig. 3). All grid cells had the same area of 16501.6m x 4373.4m. Vertically, the model has five layers summing up to a max. depth of 313 m (lower boundary is at about -50 masl). Simulation was based on Darcy´s law, the continuity equation, a general source/sink term, and a governing equation for 3-D transient flow according to [6].

The aquifer boundaries can be described by two types of hydrological conditions. A specified head boundarywas applied for Lake Nasser that fully penetrates the model aquifers. A specific flow boundary was used at the western boundary as head-dependent flow boundary. The southern boundary is varying gradually. All data were obtained from a hydrogeologic map for theToshka area [9].

Start values for hydrogeological parameters such as horizontal hydraulic conductivity (K_H), vertical hydraulic conductivity (K_V), vertical anisotropy (K_H/K_V), storativity (S_S), and effective porosity (n_e) were estimated based on published studies [13]. The different layers including interfingering sandstone, siltstone, and claystone with occasional conglomerate, sand and shales weretaken from lithology logs from 22 boreholes collected from GWS-MWRI.

The water regime of the river has changed fundamentally in 1970 when theAswan High Damwas completed. Droughts in the Ethiopian Highlands affected Egypt in the period between 1980 to 1990, it led to decreasing water levels in Lake Nasser till a high flood in 1988 and 1989 [2]. During the period from 1911 to 2015, the driest 10 successive years occurred from 1978 to 1987. The driest 6 successive years occurred from 1982 to 1987. The driest year occurred in 1913 as per the data shown in Figure 2. Based on these historic data, a drought frequency of about 65 years was assumed and a 10-years drought modelled.

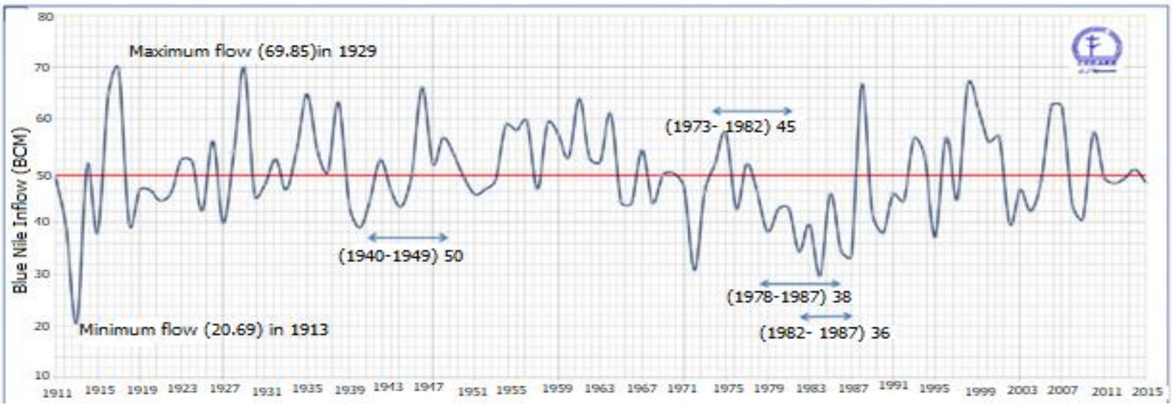

Figure 2:Historical Blue Nile River discharge[2]

The numerical model was calibrated automatically understeady-state and transient conditions through a series of groundwater flow simulations. Calibration also covered automatic parameter sensitivity analysis using PEST (parameter estimation) included in MODFLOW. Calibration results were compared with the corresponding steady state measurement results published by GWS-MWRI. A water balance calculation showed that the available groundwater (safe yield) in the study area is about 115.84m^3/s (Table 2).Transient calibration resultsbased on Lake Nasser varying water levels and water levels from 22 existing wells in the Toshka project showed that the mean square errors varied from 0.249 to -1.755% which can be considered acceptable. Sensitivity analyses calibrationproved that the hydraulic conductivity, horizontal anisotropy, and vertical anisotropy were the most sensitive parameters.

Table 1:Coordinatesof the observation wells(OW, UTM, Zone 36, WGS 84), observed head, calculated head, and head differences after steady state calibration. For the location of OWs see Figure 5.

OW no.	**X**	**Y**	observed head. masl	calculated head masl	Head difference m
1	372072.0	2506151.0	170	170.00	0
2	350661.0	2501297.0	135	135.60	0.60
3	342218.0	2508358.0	108	108.22	0.22
4	326053.0	2538795.0	123	122.48	-0.52
5	288878.0	2484850.0	150	153.59	3.59
6	319576.0	2454160.0	130	127.88	-2.12
7	344728.0	2548176.0	125	124.25	-0.75
8	344736.0	2548185.0	125	124.25	-0.75
9	376132.0	2505825.0	170	170.00	0
10	358683.0	2480516.0	170	170.00	0
11	346951.0	2499292.0	110	108.06	-1.94
12	347767.0	2498644.0	110	108.02	-1.98
13	345851.0	2487519.0	115	114.10	-0.90
14	347596.0	2487696.0	114	113.28	-0.72
15	345729.0	2484183.0	115	114.82	-0.18
16	349043.0	2491898.0	112	111.86	-0.14
17	353546.0	2493368.0	170	170.00	0
18	351002.0	2496401.0	130	127.97	-2.03
19	308047.0	2534584.0	120	121.98	1.98
20	345241.0	2467708.0	130	129.41	-0.59
21	349265.7	2569225.7	215	214.41	-0.59
22	273271.9	2521803.8	122	122.01	0.01

Table 2:Results from steady state calibration: inflow to the aquiferand outflow from the aquifer.

Aquifer	Sources/Sinks	Inflow m^3/s	Outflow m^3/s
NSSA	Constant Head Boundaries	126.9182	-8.099
	Wells	0.0	-2.973
	Evapotranspiration	0.0	0.0
	Total Source/Sink	126.918	-11.073
		Net storage	115.845(m^3/s)

Table 3: Lake Nasser water levels used for transient calibration [11,12].

Year	Water level masl	Year	Water level masl
7/1/1987	149.40	8/1/2005 0:00	172.00
8/1/1988	164.41	8/1/2006 0:00	175.00
8/1/1989	163.77	8/1/2007 0:00	180.00
8/1/1990	162.50	8/1/2008 0:00	174.87
8/1/1991	163.98	8/1/2009 0:00	175.80
8/1/1992	167.45	8/23/2010 0:00	167.45
8/1/1993	169.64	9/14/2011 0:00	171.00
8/1/1994	172.34	10/5/2012 0:00	172.00
8/1/1995	172.76	10/27/2013 0:00	173.34
8/1/1996	175.50	7/8/2014 0:00	174.50
8/1/1997	174.75	3/19/2015 0:00	179.44
8/1/1998	162.50	8/1/2016 0:00	173.00
8/1/1999	181.20	8/1/2017 0:00	175.00
8/1/2000	163.98	8/1/2018 0:00	176.60
8/1/2001	178.25	12/14/2019 0:00	181.75
8/1/2002	180.60	12/15/2020 0:00	163.98
8/1/2003	177.00	8/1/2021 0:00	178.20
8/1/2004	175.00	8/29/2022 0:00	182.00

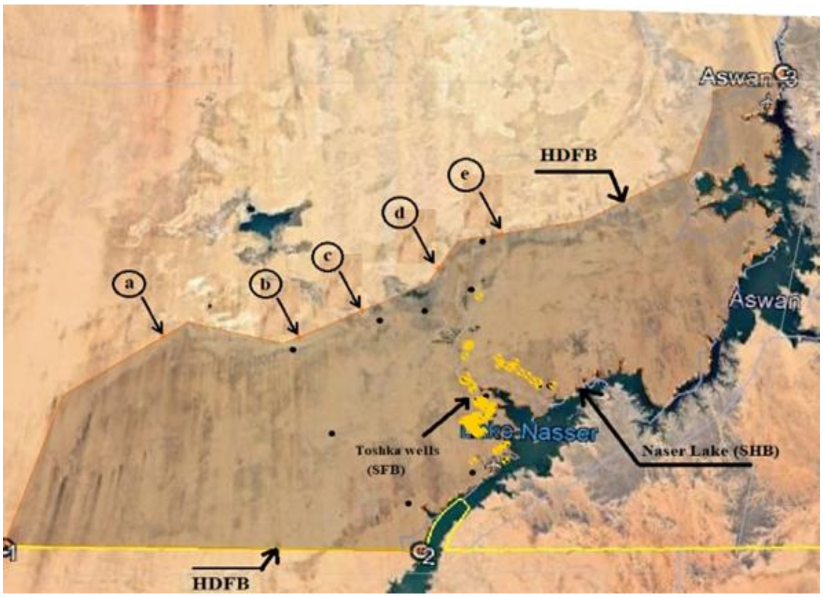

Figure 3:Model grid and boundaries used for Toshka–Lake Nasser area.

HDFB: Head Dependent Flow Boundary.
SHB: Specific Head Boundary (variant head boundary)

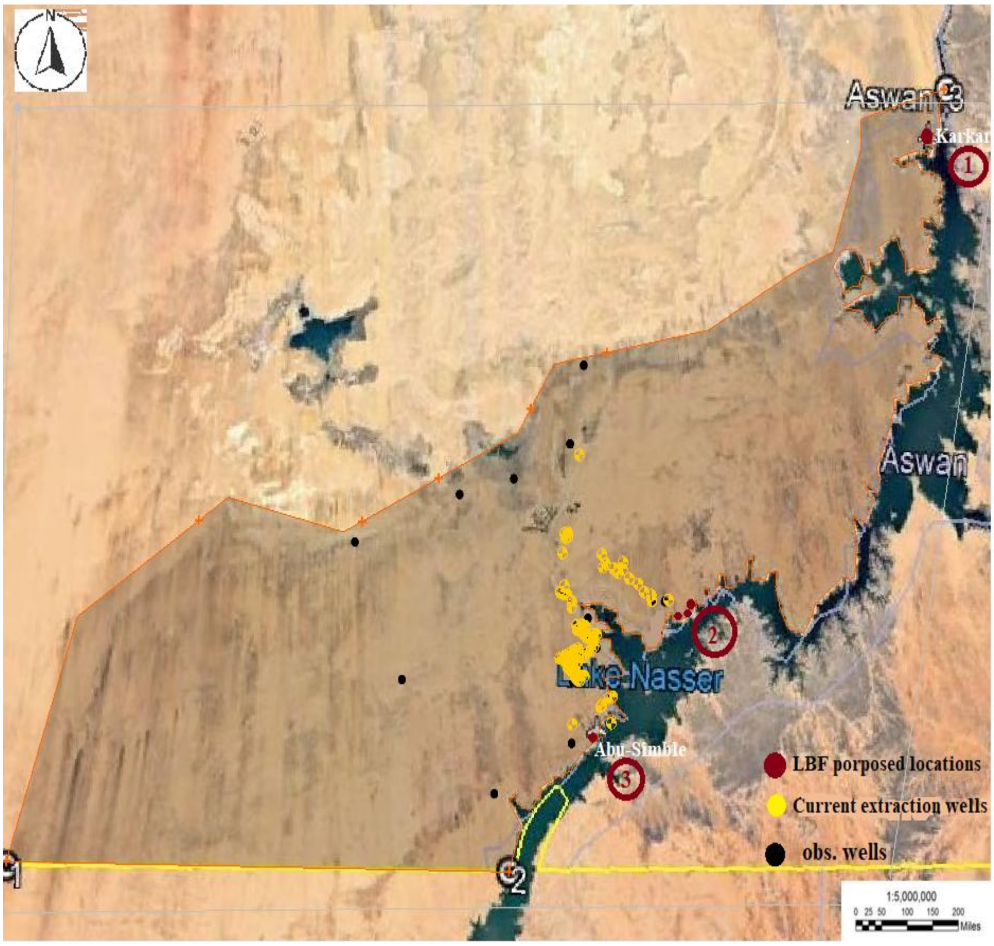

Figure 4:Lake Nasser and location of existing extraction wells and LBF wells for scenarios 2 and 3.

The transient calibration process was carried out with varying water levels of Lake Nasser from 1/1/1987 till 2022 (MWRI). The lowest inflow was observed in 1987, then the water level increased after a seasonal flood in

1988. The simulation results show a cyclic pattern of Lake Nasser water levelsduring 50 years till 2075. At the cyclic pattern the drought occurs in the period 2043 to 2053. Five proposed scenarios for groundwater withdrawal from the study areawere simulated. Data from 22 observation wells (Tab. 1)were used to evaluate the effects of the scenarios on groundwater levels for a period of 50 years. All irrigation wellswere simulated to be operated for 8 working hours daily because most of the wells in Toshkaare supplied with solar energy. All wells for drinking water supply were simulated to be operated for 24 hours daily. The four scenarios are as follows:

S1: Operation of the existing wells in the area,Q_{total}= 85,632 m^3/day (2.973333 m^3/s),

S2: Operation of the existing wells plus LBF wells planned for supplying three resident villages and Toshka city residents (28,000 people),Q_{total} = 92,357 m^3/day (3.123333m^3/s),

S3: Operation of the existing wells plus LBF wells planned for supplying three resident villages and Toshka city residents (80,000 people),Q_{total} = 102,757m^3/day (3.1483333m^3/s),

S4: Operation of the existing wells plus LBF wells planned for supplying three resident villages and Toshka city residents (238,000 people),Q_{total} = 134,357 m^3/day (3.273333m^3/s),see Fig. 6.

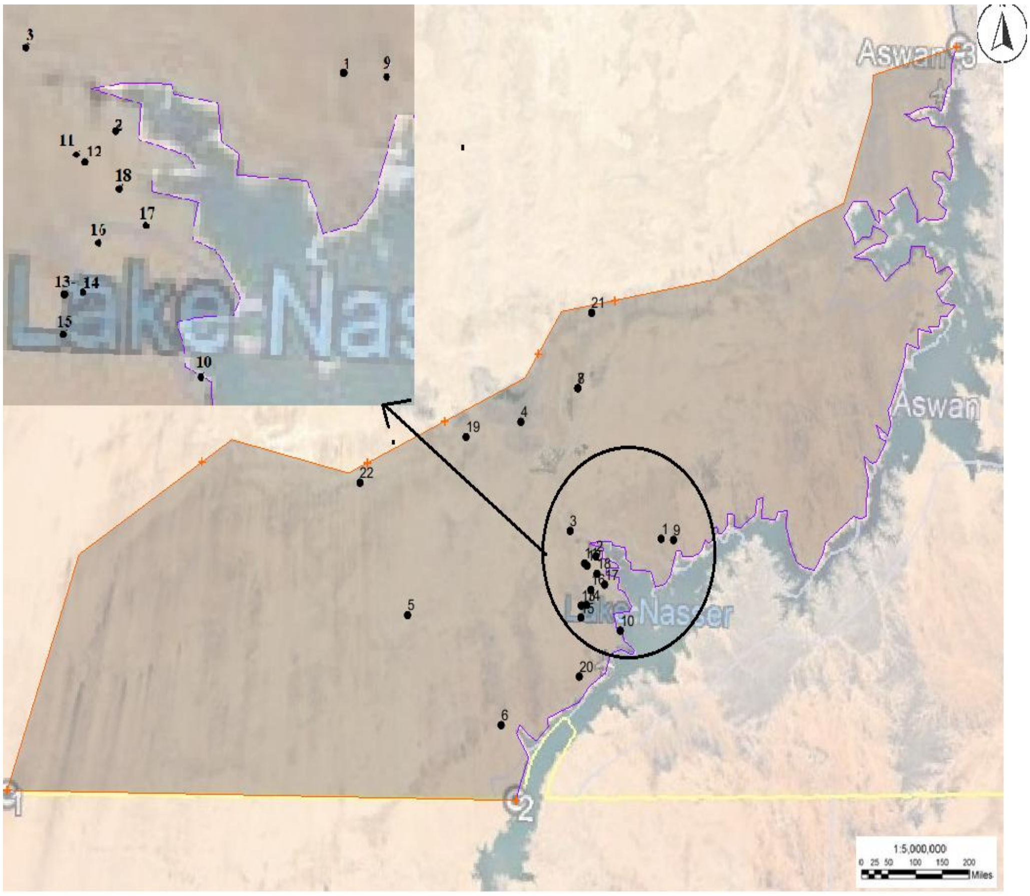

Figure 5:Location and numbers of observation wells used for model calibration.

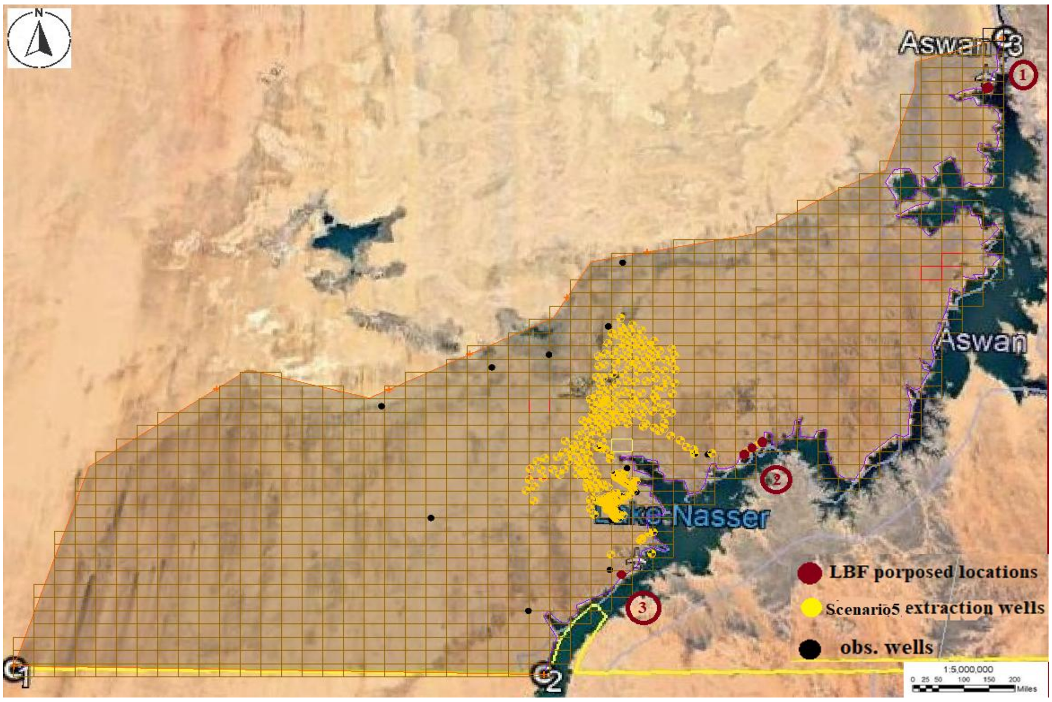

Figure 6:Location of extraction wells implemented in the groundwater flow model for scenario 5.

4 RESULTS AND DISCUSSION

Simulated water levels at the 22 observation wells (OW)for the defined four scenariosrepresenting different water extraction ratesare shown in Figs. 7-12.Within the total simulation time from August 2022 to January 2075, a drought period from January 2043 till January 2053 was simulated by implementing lower lake water levels in the model based on observed fluctuations shown in Tab. 3.

Groundwater levels show a sharp decrease in OW 1 (Fig. 7), 9, 10 and 17 (Fig. 10) during the estimated drought period from 1/1/2043 till 1/1/2053in scenarios 1, 2, 3 and 4. Then they slowly increase over the next years until the end of the total simulation period in 2075. The groundwater level decreases by about 28.8 m inOW1 and 32.6 m in OW9, 10 and 17. This sharp decline in OW 1, 9 and 17 is according to the well's location close to Lake Nasser, so these wells are affected most by the lake water level variations and the operation of waterextraction wells. OW 10 is located at the shortest distance to the lake bank, thus reflecting the lake level variation.

An intermediate decrease in groundwater levels was simulated for OW 2 (Fig. 8), 6 (Fig. 9), 18 and 20. The decline in the groundwater levels was found to be 13.14, 8.11, 10.29, and 14.08 m, respectively. The decline in OW 2,6 and 18 is due to their location close to Lake Nasser and affected by the operation of extraction wells. Well 20 is located closer to Lake Nasser.further its location between abstraction well and LBF well that affected its water level.

No effect was found for the other observation wellsbecause most of these wells are located far away from Lake Nasser and the effect of the extraction wells in addition to their locations near to the other boundaries as shown in Fig. 5.The sharpest decline in groundwater levels has been simulated for eightOWs thatare located close to Lake Nasser, and which are affected by the lake water level fluctuations in addition to their location near to the extraction wells. No effect was found for the other fourteen wells located away from Lake Nasser and from theextraction wells.

The safe yield (storage)in the modeled area based on the water balance results due to the proposed extraction scenarios for the period from 29/8/2022 and to 1/1/2075.The minimum safe yield during the simulated drought period inscenarios1,2,3,4 and 5 is 32.7, 33.8, 46.7, 47.3 and 77.0 m^3/s respectively. While the maximum is 87.8, 88.78, 100.3, 101.3 and 81.2 m^3/s respectively during the period with themaximum water level of the lake.The average safe yield value during the period for the 5 scenarios is 63.8, 64.7, 77.1, 77.7 and 79.0 m^3/s respectivelyover the 50 years.The results in Fig. 12show that more infiltrated water is feeding the aquifer due to higher extraction from the wells and the formed cone of depression due to the positive hydraulic gradient and the high hydraulic conductivity.

Previously published papers state that there are many parameters affecting the groundwater system, such as positive hydraulic gradient, soil characteristics, topography, water quality etc. [e.g.,3, 10]. Figures 13to 14show drawdown maps for 2022, 2050 (during the simulated drought period) and 2074 (end of simulation time period) for scenarios 1, and 3.There is a positive hydraulic gradient from south-west; head reaches 300 m as shown in Fig.1, towards the simulated area, where the head is lower than or equal to Lake Nasser water level. Also, a hydraulic gradient from Lake Nasser towards some areas of the western boundary is observed. The NSS aquifer is characterized by a high hydraulic conductivity which is 0.00025 m/s for sand and 0.00045 m/s for sandstone as per the initial entered data and proven by PEST simulation. The positive drawdown values indicate high recharge from Lake Nasser and the south-west boundary to the modeled area.Results indicate that the infiltration rate from Lake Nasser and the southern boundary of the study area according to the high soil permeability, so that the application of lake bank filtration is promising in the study areaassuming a strong hydraulic connection between Lake Nasser and the aquifer.

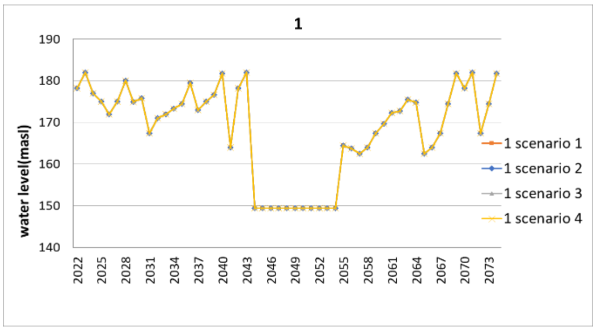

Figure 7: Simulated water levels in OW 1

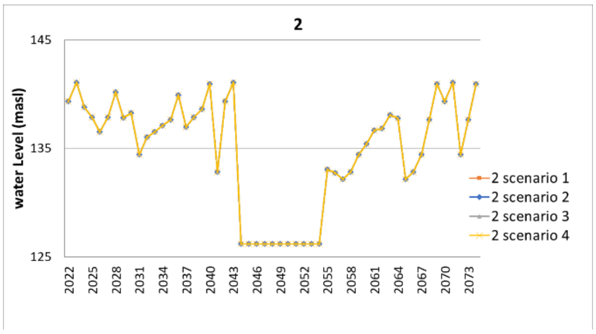

Figure 8: Simulated water levels in OW2

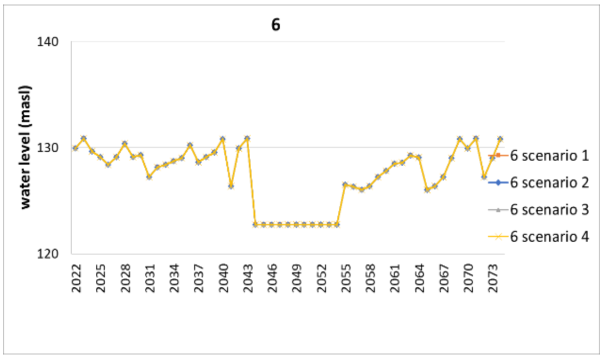

Figure 9: Simulated water levels in OW6

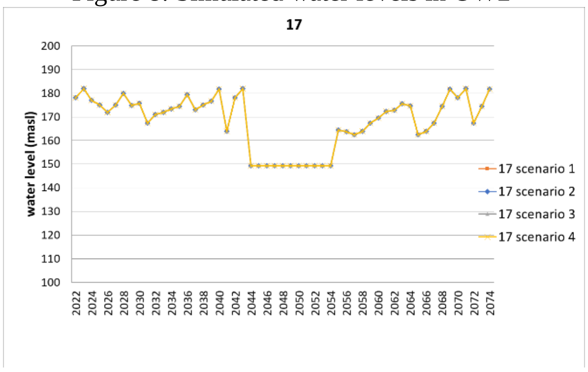

Figure 10: Simulated water levels in OW17

Figure 11: Total inflow for each scenario

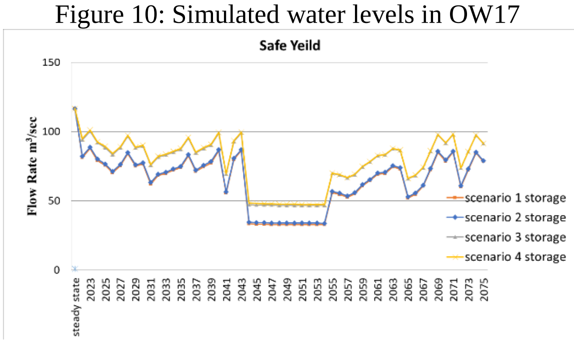

Figure 12: Total storage for each scenario

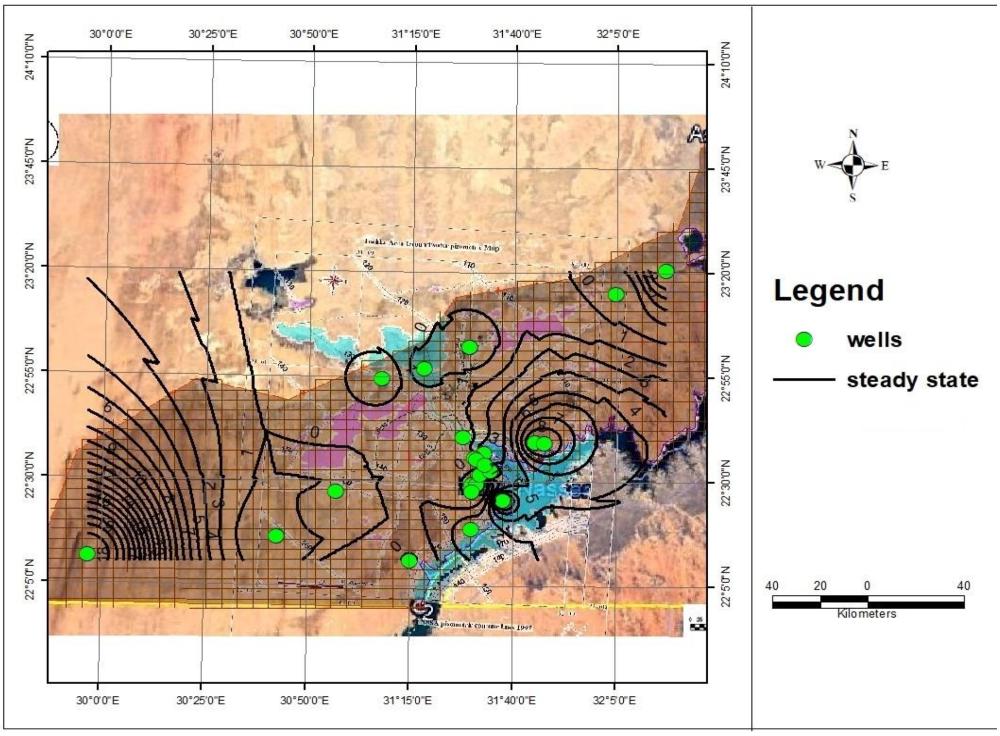

Figure 13: Simulated drawdown for steady state

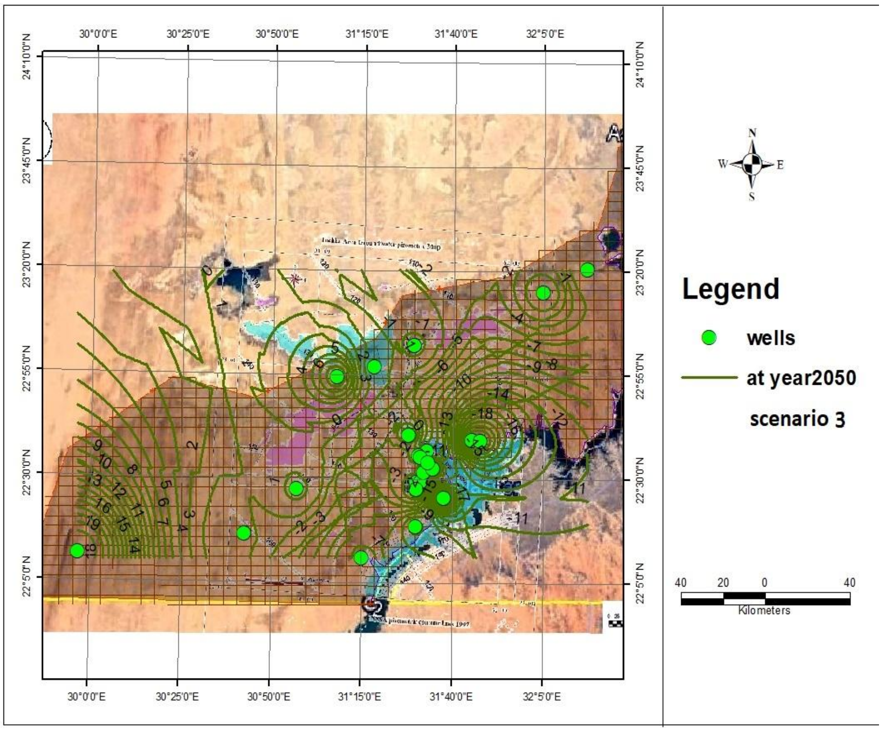

Figure 14: Simulated drawdown for scenario 3 forDrought Period,at2050

5 CONCLUSIONS

A groundwater flow model was designed to simulate realistic scenarios for water abstraction in the near future in the Toshkaarea. Model calibration was done based on water levels and piezometric contour maps published by MWRI [11, 12]. A water balance (groundwater flow budget) showed that the available groundwater resource (safe yield) in the study area is about 115.84m^3/s.

Five scenarios for groundwater extraction from the study areawere evaluated.Results of simulations show that groundwater abstraction rates are below the calculated safe yield. For scenarios 1 – 4with water abstraction rates of about 2.973333, 3.123333, 3.1483333 and3.273333 m^3/s, respectively, the resulting decrease in groundwater levels in the study area was found to be less than 32.6 m during the drought period.

The average safe yield ranging from 63 to 78.7 m^3/s could be used for an extra reclamation area. This area can reach around 162000 feddans.

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