
Water resources and geomorphological characteristics of Tushka and west of Lake Nasser, Egypt

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Abstract The water level fluctuations and geomorphology of Lake Nasser reservoir in Tushka area, Egypt, has its own bearing on the local hydrogeological regime. Comparison of the available data concerning the submerged bottom elevations of Lake Nasser with the static water levels of the groundwater wells reaching the deeper horizons of the Nubia Sandstone aquifer, suggests that Lake Nasser acts mostly as an influent stream. However, in some cases, when the static water levels of some deep water-bearing horizons reach levels above those at the bottom of the lake, water flows from the groundwater reservoirs towards the river which acts as an effluent stream. The constructed equipotentiometric map confirms this conclusion as it indicated that the maximum potentiometric level was attained to the northwestern part of Lake Nasser area, whereas the minimum potentiometric level was encountered to the southeast of this area. Hence, the groundwater flow is generally towards Lake Nasser. However, in some instances, it also flows in an adverse direction. The Piper trilinear diagram revealed the existence of four hydrochemical facies reflecting the quality of the fresh water of Lake Nasser, the slightly saline original water quality of the Nubia aquifer and the mixing facies with no dominant water types.

Résumé Les fluctuations du niveau d'eau ainsi que la géomorphologie du réservoir du lac Nasser dans la région de Tushka, Egypte influencent le régime hydrogéologique local. La comparaison de l'altitude des fonds du lac Nasser avec les niveaux phréatiques des puits qui atteignent les niveaux inférieurs de l'aquifère des grès Nubiens suggère que le lac Nasser agisse le plus souvent comme un cours d'eau infiltrant. Il arrive aussi, lorsque le niveau

hydrostatique d'horizons aquifères profonds dépasse ceux de la base du lac, que l'eau des aquifères soutienne les eaux de la rivière qui agit alors comme un émissaire. Les cartes hydro isostatiques confirment cette conclusion en indiquant que le niveau maximum est atteint au Nord-Ouest de la région du lac Nasser et que le niveau minimum se trouve au Sud-Est de cette zone. Ainsi, les eaux souterraines se dirigent généralement en direction du lac Nasser. Mais, elles se dirigent parfois en direction inverse. Le diagramme de Piper montre l'existence de quatre faciès hydro chimiques, qui correspondent à l'eau douce du lac Nasser, à l'eau légèrement salée de l'aquifère Nubien, et les eaux mélangées sans types d'eaux dominants.

Resumen Las fluctuaciones del nivel de agua y la geomorfología del reservorio del Lago Nasser en el área de Tushka, Egipto, tienen su propia influencia sobre el régimen hidrogeológico local. La comparación de los datos disponibles acerca de las elevaciones del fondo sumergido de Lago Nasser, con los niveles estáticos de los pozos de agua subterránea que alcanzan los horizontes más profundos del acuífero de la Arenisca de Nubia, sugieren que el Lago Nasser actúa principalmente como una corriente influente. Sin embargo, en algunos casos, cuando los niveles estáticos de agua de algunos horizontes acuíferos profundos, alcanzan niveles por encima de aquellos del fondo del lago, el agua fluye desde los depósitos de agua subterránea hacia el río, que actúa entonces como una corriente efluente. El mapa equipotenciométrico construido confirma esta conclusión, pues indica que el nivel potenciométrico máximo estaba localizado en la parte noroccidental del área del Lago Nasser, mientras que el nivel potenciométrico mínimo se encontró al sudeste de esta área. Por lo tanto, el flujo del agua subterránea generalmente va hacia el Lago Nasser. Sin embargo, en algunos casos, también fluye en una dirección contraria. El diagrama trilinear de Piper, reveló la existencia de cuatro facies hidroquímicas que reflejan la calidad de agua dulce del Lago Nasser, la calidad de agua ligeramente salina original del acuífero de Nubia y las facies mezcladas sin tipos de agua dominantes.

Received: 9 November 2005 / Accepted: 5 December 2005
Published online: 17 February 2006

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Keywords Geomorphology · Groundwater resources · Lake Nasser · Tushka area · Hydrochemistry

Introduction

The present work deals with the geomorphological characteristics and water resources of the Tushka area, west of Lake Nasser, Egypt. The study area is located between latitudes 22°30'N and 23°30'N and longitude 31°00'E in the west and Lake Nasser in the east (Longitude 32°00'E).

Recently, the area attracted the attention of many scientists as well as the governmental authorities, who are interested in the development of this remote area for the establishment of new communities, by increasing the cultivated areas in Egypt. This is done in the frame of the National Tushka project (initiated in 1996) (Figs. 1 and 2), which, in its first stage, aims to reclaim about 540,000 Feddans (2,268 km²) of the Western Desert using principally the water from Lake Nasser. The project involves the installation of the world's largest pumps, which will carry water from the lake into a 300 km long canal. It was envisaged that the Tushka canal (Fig. 1) would extend all the way to Kharga Oasis in the heart of the Western Desert, and possibly beyond. Work on the project has already progressed substantially according to its planned phases. Furthermore, the project aims to pump the River Nile water from Lake Nasser to Sheikh Zayed Canal and then to distribute it through four branches, namely Branch 1 (to irrigate 756 km²) and Branch 2 (to irrigate 336 km²) towards the north, and Branch 3 (to irrigate 420 km²)

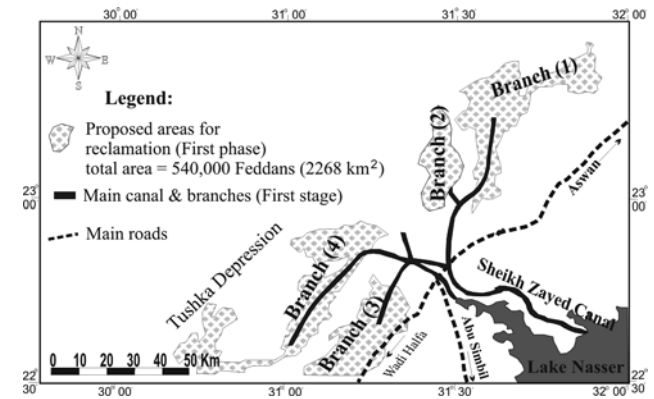
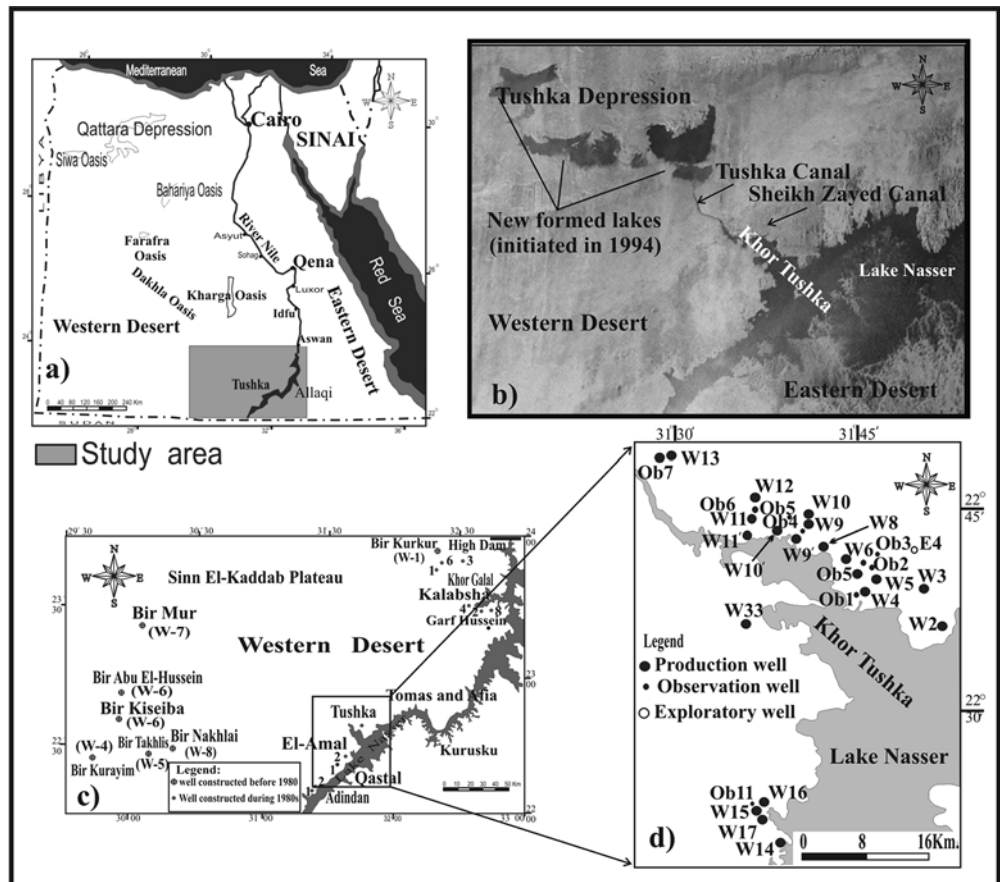


Fig. 2 The planned national development project of the Tushka area, west of Lake Nasser (Sheikh Zayed Canal, its branches and the proposed reclamation areas to be designated for agriculture) (Source: GARPAD 1998)

and Branch 4 (to irrigate 756 km²) towards the west and southwest (Figs. 1 and 2). However, the project also aims to supply 20–44 urban villages as a part of 27 agricultural communities planned to complete the development of south Egypt.

The groundwater wells were drilled in the vicinity of this area to be operated just in case they were needed (observation and production wells). About two hundred wells have been drilled up until now. Most of these wells were drilled around Lake Nasser (around its peripheries). The main source of data used in the present study has been derived

Fig. 1 Location map of study area (in Egypt), its image from space and locations of hydrological features. **a** Study area location. **b** Image taken from the Space Shuttle in September 2000 of the Tushka area, west of Lake Nasser (Provided by NASA 2002). **c** Water wells drilled before/during the 1980s in the Tushka-Kurkur area. **d** Water wells drilled after 2000 around Lake Nasser (upon initiation of the Tushka project)



from the selected production and observation wells drilled by the Aswan High Dam Authority and the production wells drilled by Lake Nasser Development Authority.

Present development status and available water resources

From a historical point of view, Lake Nasser, one of the largest man-made fresh water lakes in the world, was formed as a result of the construction of the High Dam, completed in 1969. It is an elongate body of water some 496 km long, 196 km of which are in Sudan (Lake Nubia), with an average width of 15 km. The water volume in the lake fluctuates greatly, seasonally, and from year to year, depending on the net annual volume of water it receives. The highest recorded water-levels are 178 m above sea level (masl) (in 1996) and 182 masl (in November 1998), while the lowest level recorded so far was 158 masl in July 1988. The vicinity of the lake has vegetation and animal wealth which can be utilized in many pharmaceutical industries. Also, Lake Nasser has a huge resource of fish, with all its relative advantages

Lake Nasser and the regions adjoining it are seen by some of Egypt's planners and scientists as the future food-basket for the country. To date, the region is still largely uninhabited by man. The ongoing activities in the study area are still only dedicated to the investors.

Egypt's Western Desert is known to have the largest groundwater reservoirs underneath, including the whole of northeast Africa, located in the Nubia Sandstone aquifer with a huge vertical and horizontal expansion. Concerning the development of the Tushka area, although it is located within the sandstone regional basin, the groundwater resource potential is limited because that axis lies on the margin of the El-Kharga basin (Tamer et al. 1987). Meanwhile, the on going studies (RIGW 2001) are focussing on the possibilities of setting-up a network of observation/production wells linked to each other and connected to canals and surface reservoirs, to make use of wells in irrigating other areas as an alternative for the surface water. The climate, water and geomorphology of the study area encouraged the agricultural development sectors in Egypt to cultivate crops with relatively high advantages such as early crops or long-range production crops (crops that are adapted not only to the wide-range of environments but also to demographic and socio-political circumstances such as expansion and intensification (Kirch 1991)) in addition to the crops which do not need fertilizers or agricultural chemicals that are potentially hazardous to human health.

Climatic conditions

The Western Desert of Egypt is generally characterized by a wide range of temperature variation between summer and winter and even between day and night in the same season. Generally, the study area is characterized by a high temperature, which is due to the long day hours in summer and

the effect of strong sun rays falling on it with high incident angle. The maximum daily recorded temperature ranges between 41.9 and 42°C, whereas the minimum recorded temperature in winter is 9.5°C at Aswan meteorological station (installed on Aswan High Dam). The southern part of the Western Desert of Egypt occupies the centre of the largest arid area on Earth. The study area is located in this arid zone (arid belt) and rainfall over the area is almost nil. The daily average evapotranspiration is very high and varies from 8 mm/day in December and January to 34 mm/day in June and July (Fig. 3).

Geomorphology

Studying the landforms is very important for planning and management. The investigated area was geomorphologically mapped on a scale of 1:250,000 using Landsat Thematic Mapper (TM) images. The interpretation of the Landsat TM image (taken in 1984) for the investigated area, west of Lake Nasser, has been found to be of valuable application in delineating the main geomorphologic and drainage features (Fig. 4).

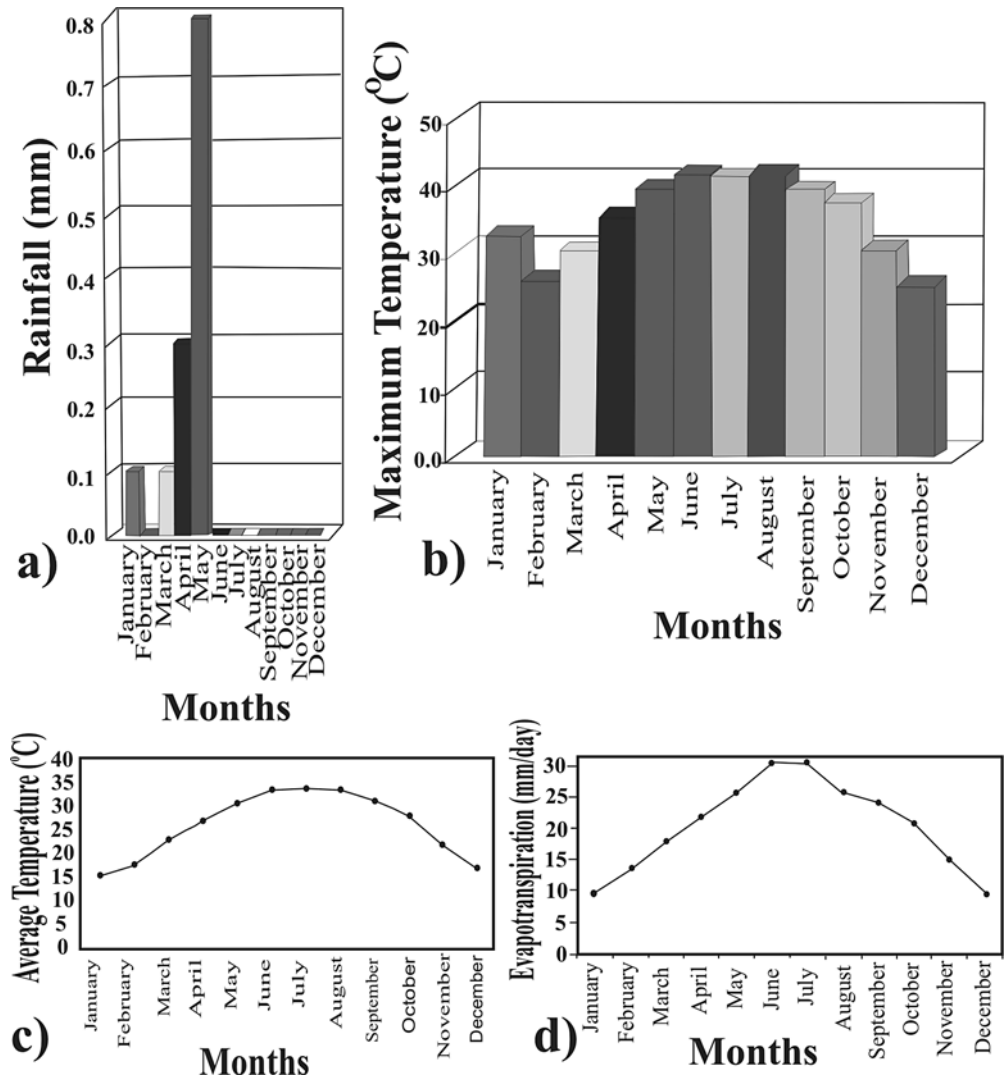
According to Altorkomani (1999), the topographic elevations in the Tushka area are subdivided into three groups; the low lands topography group (less than 150 masl), which constitutes only 1,020 km² (about 2.1% of Tushka total area (48,903 km²)). These low lands occupy the central part of the study area. The moderate relief topography group (150–300 masl), which comprises about 77.63% of the Tushka total area. These topographic elevations are related to the hillslopes, isolated hills and pediplains. The less dissected mountaineous topography group (more than 300 masl), occupies about 20.27% of Tushka total area and embraces mainly the northern and northeastern parts (Sinn El-Kaddab Plateau). However, this group comprises also small areas at the most southern parts of the study area.

The main geomorphologic units recognized in the study area are as follows (Fig. 4):

1. Structural platform, Sinn El-Kaddab Plateau
2. Scarp faces
3. Pediplain of Nubia Sandstones; including:
 - Ferruginous isolated hills
 - Nubia Sandstone hills
4. Inverted wadis
5. Accumulated alluvial fans and playas
6. Lowlands and depressions
7. Sand sheets and sand dunes
8. Tors of igneous and metamorphic rocks of low lands and hills
9. Occasionally tidal zones
10. Wadis and main drainage channels

Some additional geomorphologic features and details were also recognized in the study area, such as: broad wadis (dry valley), V-shaped drainage lines (channels), structural lineaments and water points. Perhaps one of the most outstanding features of Lake Nasser is its very complex nature.

Fig. 3 Graphical representation of some climatologic parameters of the Tushka area as recorded at Aswan Meteorological Station (1985–1995) (Source of data: GALND 1997) showing annual variations in **a** rainfall, **b** maximum temperature, **c** temperature, and **d** evapotranspiration



Its shorelines are composed of numerous *khors*, which are, essentially, inundated desert wadies. Most are narrow and meander into the desert for long distances, although some are very wide. There are 85 major *khors*, 48 on the eastern side of the lake and 37 on the western side. Allaqi, Kalabsha and Tushka are the three longest *khors* in Nasser Lake, which make up a large part of its total area. *Khors* support the richest habitats in the lake. The shallow waters support aquatic flora and provide good breeding grounds for fish; and the often gently sloping shores allow vegetation to grow. Much of the rest of the lake’s shores are steep and rocky with little vegetation. A vast number of islands of various sizes, representing the tops of former hills, are scattered throughout the lake. Lake Nasser is one of the most important sources of fresh water fish in Egypt, contributing 25–40% of the total inland fisheries production.

Geologic setting

The geology of the study area is dominated by a sedimentary succession ranging in age from Cretaceous to Qua-

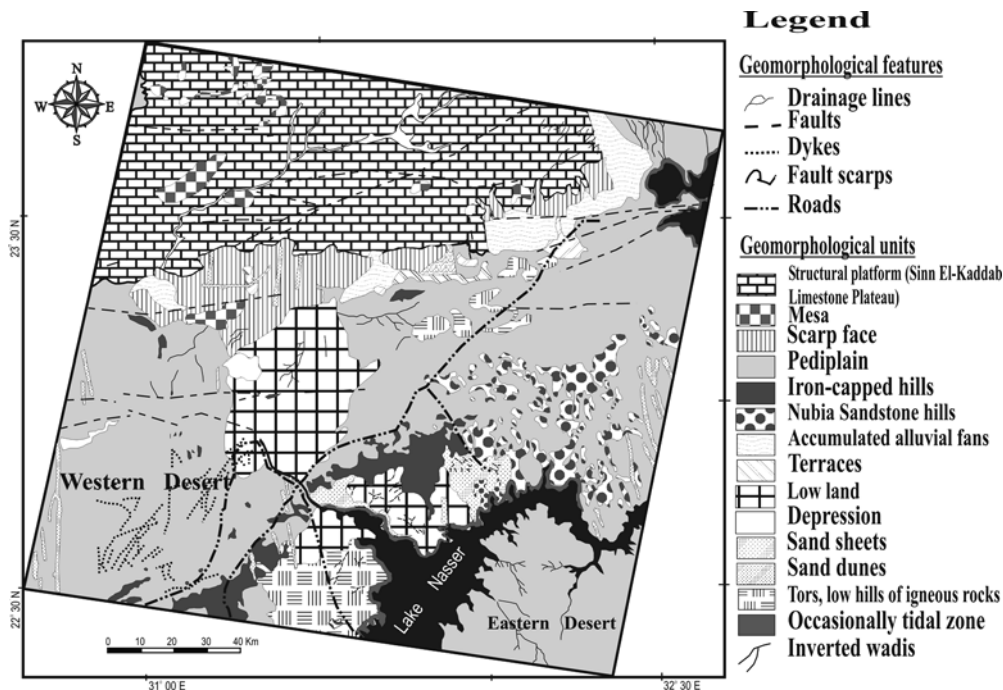
ternary, with exposures of igneous and metamorphic rocks belonging to the Late Precambrian basement, in addition to the Phanerozoic foreland volcanics of the Late Cretaceous and mid-Tertiary age. The sedimentary cover (less than 1,000 m) is dominated by sandstone in its lower part and by limestone and shale in its upper part. The geologic map (Fig. 5) shows the distribution of the main geological units exposed in the studied area. The investigated area is dominated by a large number of fracture lines of various attitudes and ages (Fig. 6).

Groundwater resources

The ‘Nubia Sandstone aquifer’, essentially of Cretaceous age, constitutes the main complex aquifer system, which has a wide extension in the area of study (Fig. 5).

Lithologically, the ‘Nubia Sandstone aquifer’ is dominated by interfingering sandstone, siltstone and claystone, with occasional conglomerate. It rests unconformably on the Precambrian basement rocks at different depths (Fig. 7b). The upper boundary of this aquifer is

Fig. 4 Geomorphological map of Tushka and the area west of Lake Nasser (as interpreted from Landsat TM image, Bands 7 4 2, taken in 1984)



often exposed (Abu Simbil and Lake Nasser Formations), but locally it is capped by Late Cretaceous and younger rocks. In the subsurface, the “Nubia Sandstone aquifer” attains different thicknesses, ranging between zero beside the outcropping basements and some hundreds of meters (e.g. 203 m in a well at Garf Hussein and 260 m in Bir Kurkur (W-1) (Figs. 1c and 7c).

The groundwater in the Quaternary fluvial aquifer system is mainly restricted to the Lake Nasser and is considered a renewable source. However, the groundwater in the other aquifer systems is, to some extent, non-renewable, as it was accumulated during the Pluvial period.

Hydrogeological conditions

The hydrogeology of the study area was studied by several authors, among them; Mitwally 1953, Shatta 1962, Abu Wafa and Labib 1970, El-Shazly et al. 1977, Tamer et al. 1987 and Kim and Sultan 2002.

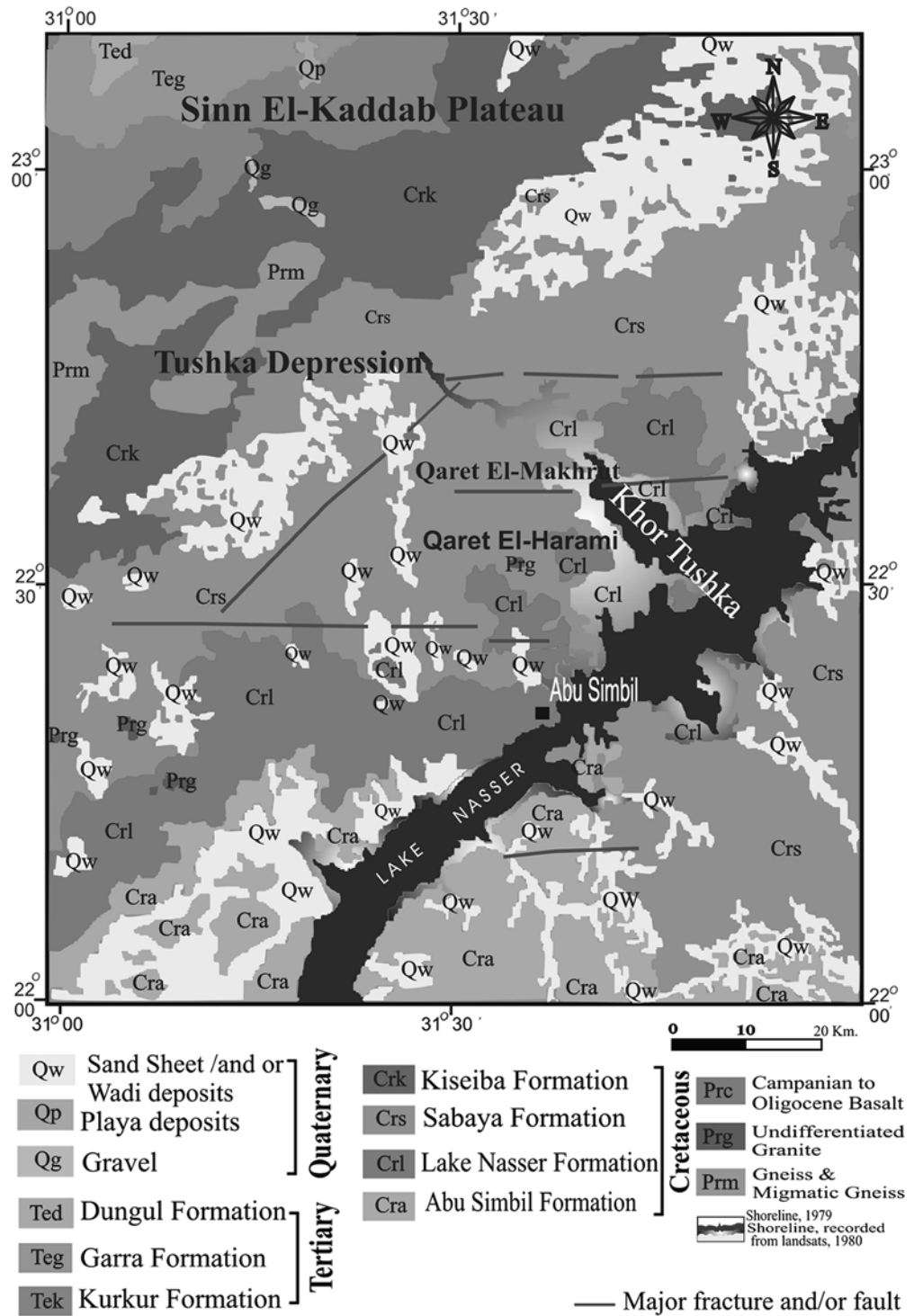
The Nubia Sandstone complex (Paleozoic–Mesozoic) constitutes the main aquifer system in the study area. According to the logs from wells in the Tushka-Kurkur area, and the recently drilled ones around Lake Nasser (Fig. 1c and d), the penetrated Nubian section is composed of fining downward litho-facies. The upper horizons are mostly sandy while shale and claystone dominates the lower ones (Fig. 7a and b). The well screens were put against the most thick sandstone beds at depths ranging between 85 and 173 m below ground level. The sediments that make up the aquifer system may be subdivided regionally into two or three water-bearing layers with intervening shale or sandy shale confining units, some of them are hydraulically connected with the interfingering and local facies change. Locally, it could be possible also to subdivide the two or

three regional water-bearing zones into smaller zones of subregional extent.

According to El-Shazly et al. (1977), it is supposed that the shallow or upper water-bearing horizons exist under the free water table, i.e. under semi-confined conditions, whereas the lower or deeper water-bearing horizons exist under confined conditions. According to the available data, the bottom elevation of Lake Nasser varies from 50 to 90 masl (Fig. 8). The historical data associated with water level fluctuations of Lake Nasser from 1964 to 1997 are given in Fig. 9 and the measured static water levels in the wells tapping the deeper confined horizons of the Nubia aquifer system in Tushka basin area are given in Table 1. Comparing these data, the following could be concluded:

1. The shallow water-bearing horizons (not investigated here) are the most affected and penetrated by the Nile water. In the case of the deeper aquifer, it is clear that the River Nile is mostly influent, but under certain conditions. When the bottom level of the lake is below the static water level of the deeper confined aquifer, the river is supplied from the groundwater and becomes an effluent stream (such as in the case of the static water levels of Kalabsha-2, Kalabsha-4, Kalabsha-5 and Kalabsha-8 (production wells drilled after the year 1980, shown in Fig. 1c), which reach 109.81 masl, 109.75 masl, 110.23 masl and 108.26 masl, respectively). This increases the possibilities of recharging the Nile by groundwater. The other investigated water wells (Table 1) characterize groundwater as having lower static water levels, compared to the level at the bottom of the lake. Thus, the River Nile in this case is an influent stream and logically, is currently recharging the groundwater of the deeper water-bearing horizons

Fig. 5 Geological map of Tushka area (as interpreted from Landsat TM image and CONOCO map, 1987)



of the Nubia aquifer. On the other hand, the measured static water levels in the observation/production wells drilled around Lake Nasser confirms the previous hypothesis. The prepared equipotentiometric contour map (Fig. 10), indicates that the maximum potentiometric level is attained in the northwestern part of Lake Nasser contour value 80 masl, near Well No. 12 (W12 in Fig. 1d) whereas the minimum potentiometric level is encountered in a small area around W6 (contour 50 masl). The

useful picture given by the data from these wells is attributed to the fact that they were drilled very near to the margin of Lake Nasser. Hence, the flow lines show that the groundwater is moving towards Lake Nasser. However, it also sometimes moves in the opposite direction. Thus, the flowlines confirm the previous conclusion that the aquifer system is either recharged by, or recharging, Lake Nasser. In general, the study showed that the upper horizon of the aquifer is semi-confined and shows

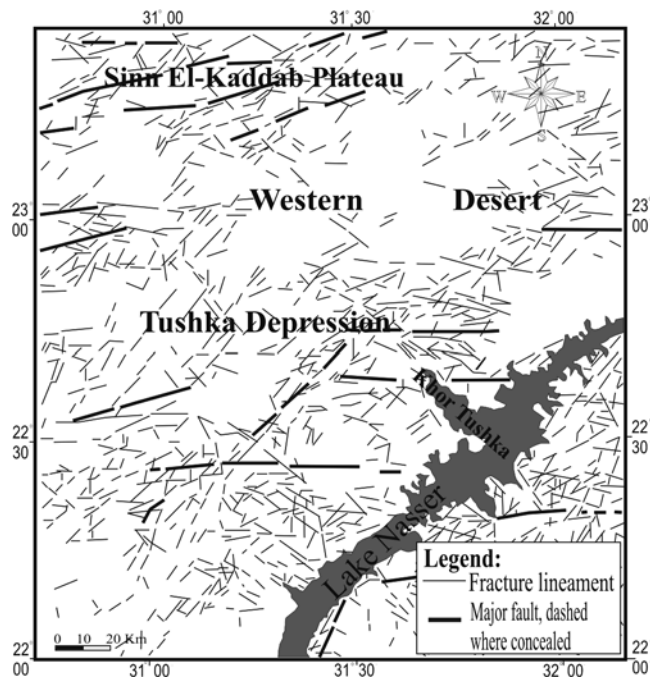


Fig. 6 Structural lineaments map of Tushka area (as interpreted from landsat TM image)

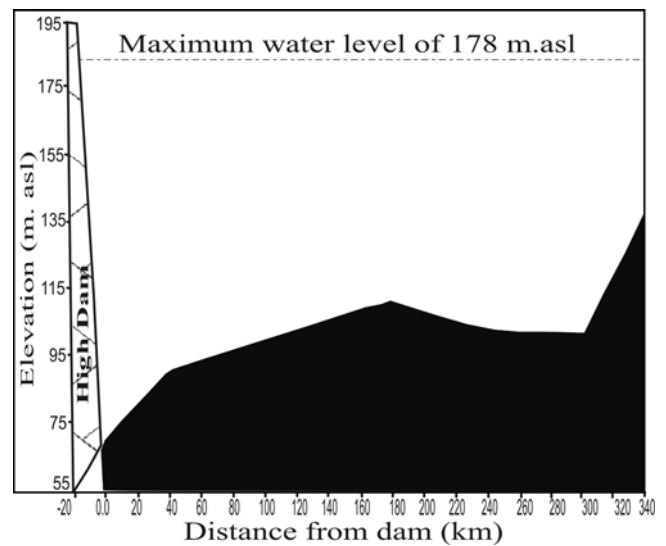


Fig. 8 Bottom levels of Lake Nasser (source: GALND 1997)

a wide lateral and vertical change of facies. This horizon is hydraulically connected with Lake Nasser, and is affected, to a certain extent, by the fluctuation of water level in the lake.

- The intensity and nature of groundwater recharge processes by the Lake Nasser surface water depend on several factors or parameters. Among them are: (i) Seasonal fluctuations in the water level of Lake Nasser, which ranges between 5 and 10 m, the level being highest in autumn then gradually receding to its lowest level

in summer, depending on the amount of water released downstream from the dam, evaporation and the amount received from upstream. Consequently, these fluctuations are accompanied by the corresponding increase or decrease of the surface rock area subjected to direct contact with the lake water (Fig. 11). The rise in Lake Nasser water level led to the formation of new lakes, which were initiated in 1994 through a side canal from Lake Nasser (Fig. 1b). They retain excess water, preventing the water level in Lake Nasser from reaching dangerously high levels, which may affect the Aswan High Dam. The main purposes of the ‘Tushka Lakes’ are to counter balance Lake Nasser and to act as a safety valve for the High Dam. The lakes or reservoirs occupy one of the dry side branches (or khors) of the Nile at

Fig. 7 Subsurface lithological characteristics of the Nubia Sandstone aquifer system. **a** Key map for cross section, **b** Schematic hydrogeological cross section parallel to Sheikh Zayed Canal, near Tushka, and **c** The penetrated lithologic cross-section of the well at Bir Kurkur (W-1) (source of data: RIGW 2001 and GALND 1997)

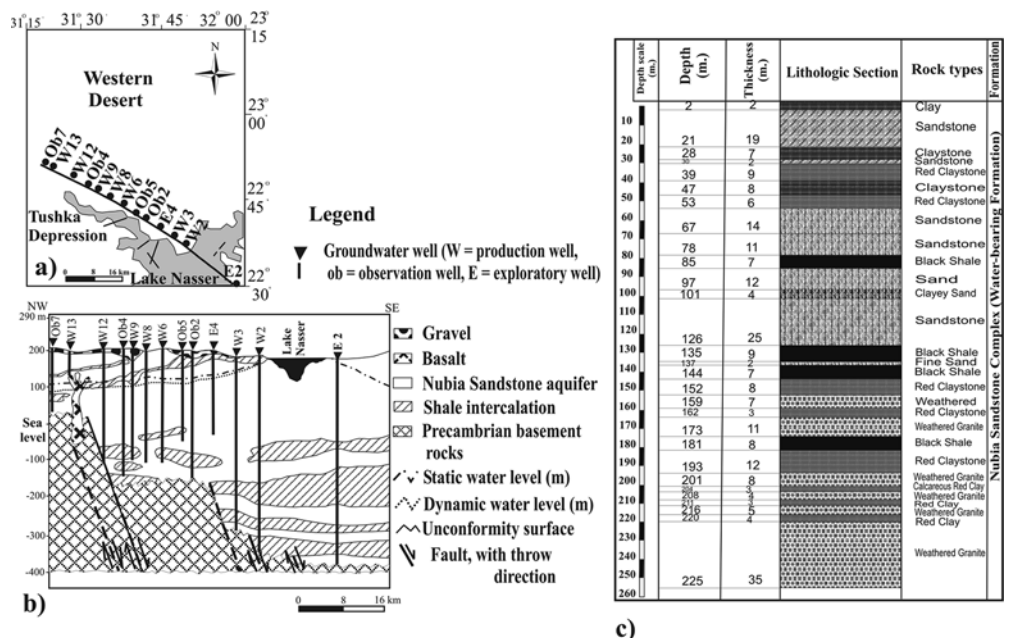


Table 1 The hydrochemical data of groundwater (major elements)

Sample location	TDS (ppm)	pH	RSC	SAR	Static W. L (masl)	Units	Major cations				Major anions			
							K ⁺	Na ⁺	Mg ²⁺	Ca ²⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	CO ₃
Kurkur-1	996	8.00	2.11	21.61	76.66	ppm	7.00	370.00	8.00	9.00	170.00	375.00	196.00	45.00
						e%	0.18	16.09	0.66	0.45	4.79	7.81	3.21	1.50
						e%	1.03	92.59	3.79	2.59	27.66	45.12	18.56	8.66
Kurkur-3	1,342	7.20	0.00	6.10	76.25	ppm	11.00	298.00	52.00	95.00	140.00	602.00	315.00	18.00
						e%	0.28	12.96	4.28	4.75	3.94	12.54	5.16	0.60
						e%	1.27	58.19	19.21	21.33	17.72	56.37	23.21	3.47
Kurkur-6	1,359	6.70	0.00	6.17	77.90	ppm	9.00	298.00	56.00	84.00	138.00	608.00	331.00	0.00
						e%	0.23	12.96	4.61	4.20	3.89	12.67	5.43	0.00
						e%	1.05	58.91	20.94	19.10	17.69	57.63	24.69	0.00
El Amal-1	2,326	8.00	2.31	45.23	91.80	ppm	18.00	879.00	12.50	8.80	545.00	868.00	228.00	88.00
						e%	0.46	38.22	1.03	0.44	15.35	18.08	3.74	2.93
						e%	1.15	95.19	2.56	1.10	38.28	45.09	9.32	16.94
El Amal-2	2,057	8.00	1.25	42.89	89.30	ppm	16.00	747.00	9.20	7.80	356.00	941.00	146.00	60.00
						e%	0.41	32.48	0.76	0.39	10.03	19.60	2.39	2.00
						e%	1.21	95.43	2.22	1.15	29.47	57.62	7.03	5.88
Kalabsha-2	900	7.00	0.00	2.43	109.81	ppm	5.50	110.00	38.00	92.00	120.00	210.00	274.00	10.00
						e%	0.14	4.78	3.13	4.60	3.38	4.38	4.49	0.33
						e%	1.11	37.81	24.71	36.37	26.87	34.78	35.70	1.93
Kalabsha-4	910	7.20	0.00	2.28	109.75	ppm	6.80	108.00	25.00	128.00	120.00	216.00	332.00	0.00
						e%	0.17	4.70	2.06	6.40	3.38	4.50	5.44	0.00
						e%	1.31	35.24	15.43	48.03	25.37	33.78	40.85	0.00
Kalabsha-8	870	7.00	0.00	3.04	108.26	ppm	6.20	297.60	79.63	468.00	61.60	950.40	134.20	12.00
						e%	0.80	12.94	6.55	23.40	1.74	19.80	2.20	0.40
						e%	1.83	29.62	14.99	53.56	7.19	82.04	9.12	3.09
Adindan-1	1,361	8.00	0.00	1.53	26.92	ppm	21.10	103.20	16.85	316.00	104.70	695.60	156.00	54.00
						e%	0.16	4.49	1.39	15.80	2.95	14.49	2.56	1.80
						e%	0.72	20.55	6.35	72.38	6.69	66.48	11.73	13.51
Adindan-2	773	8.00	0.00	0.53	20.64	ppm	5.10	17.80	13.85	174.00	19.40	315.60	154.00	32.00
						e%	0.31	0.77	1.14	8.70	0.55	6.58	2.52	1.07
						e%	1.22	7.20	10.60	80.98	5.10	61.38	23.57	8.01
W33	360	7.00	0.00	2.68	72.83	ppm	4.70	104.00	21.88	78.00	144.0	180.0	132.0	0.00
						e%	0.12	4.52	1.80	3.90	4.06	3.75	2.16	0.00
						e%	1.17	43.72	17.40	37.71	40.68	37.61	21.70	0.00
Lake Nasser	194	7.5	0.69	1.29	20.64	ppm	5.40	23.40	6.60	14.00	8.10	10.30	118.00	0.00
						e%	0.14	1.02	0.54	0.70	0.23	0.21	1.93	0.00
						e%	5.77	42.42	22.63	29.18	9.60	9.03	81.37	0.00

Source of data: GALND 1997. Well locations at Bir Kurkur, El-Amal, Kalabsha and Adindan are shown in Fig. 1c; well W33 is located in Fig. 1d

SAR sodium adsorption ratio $(Na + \sqrt{(Ca^{2+} + Mg^{2+})})/2$ in epm, TDS total dissolved solids (ppm), RSC residual sodium carbonate, $(CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+})$ in epm

Tushka. The Nile and hence Lake Nasser are thus the only influent to the Tushka lakes, and the main 'outflow' is through evaporation and recharge to the Nubia Sandstone aquifer underlying the study area. These lakes provide water for agriculture in nearby land through a net of canals, which provide the third outflow possibility from the Tushka lakes. While the Tushka lakes act at present more or less as reservoirs, their hydrological investigation has yet to be completed, (ii) the thickness of the water column inside Lake Nasser acts as a downward pushing vector inducing the water to penetrate the substratum, (iii) the deep-seated structural elements, affecting the "Nubia aquifer system" and finally, (iv) the

finer deposits of fluvial materials behind the High Dam, which cover the bottom of Lake Nasser, where a prograding delta or thick bottom-seal material constitutes a barrier that prohibits or decreases the vertical recharging possibilities of the groundwater by surface Nile water. On the other hand, lateral recharge is still frequent and intensive.

The pumping tests performed on the recently drilled water wells (GALND 1997), indicate that the productivity of the drilled production wells in the Tushka basin area ranges between 1,228 m³/day (at Qastal) and 1,992 m³/day (at Adindan), with a figure of about 1,400 m³/day for the

Fig. 9 Fluctuations of maximum and minimum water level of Lake Nasser (period: 1964–1996; source of data: GALND 1997)

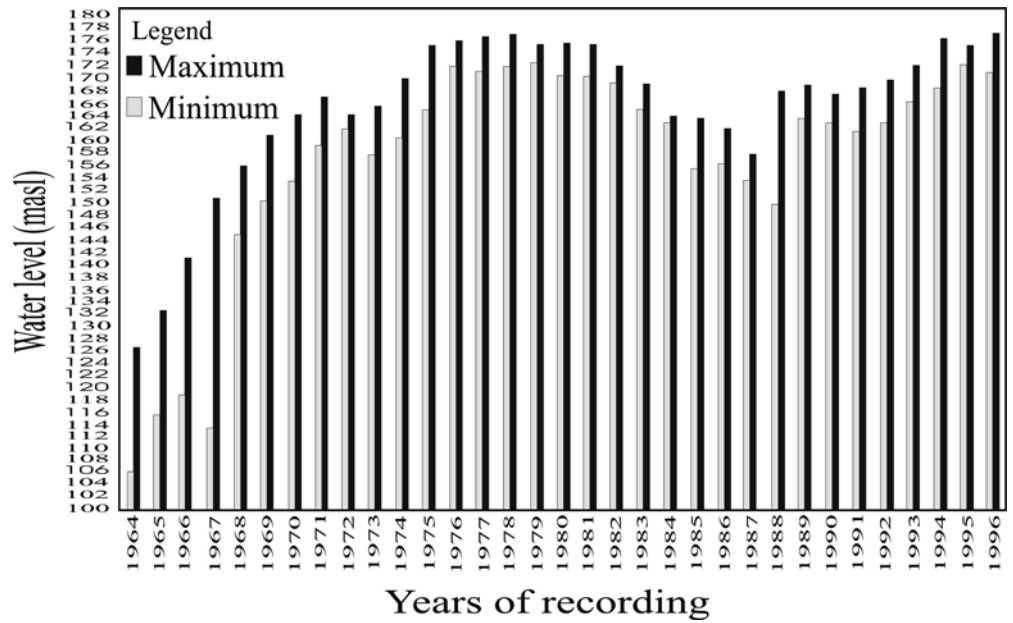
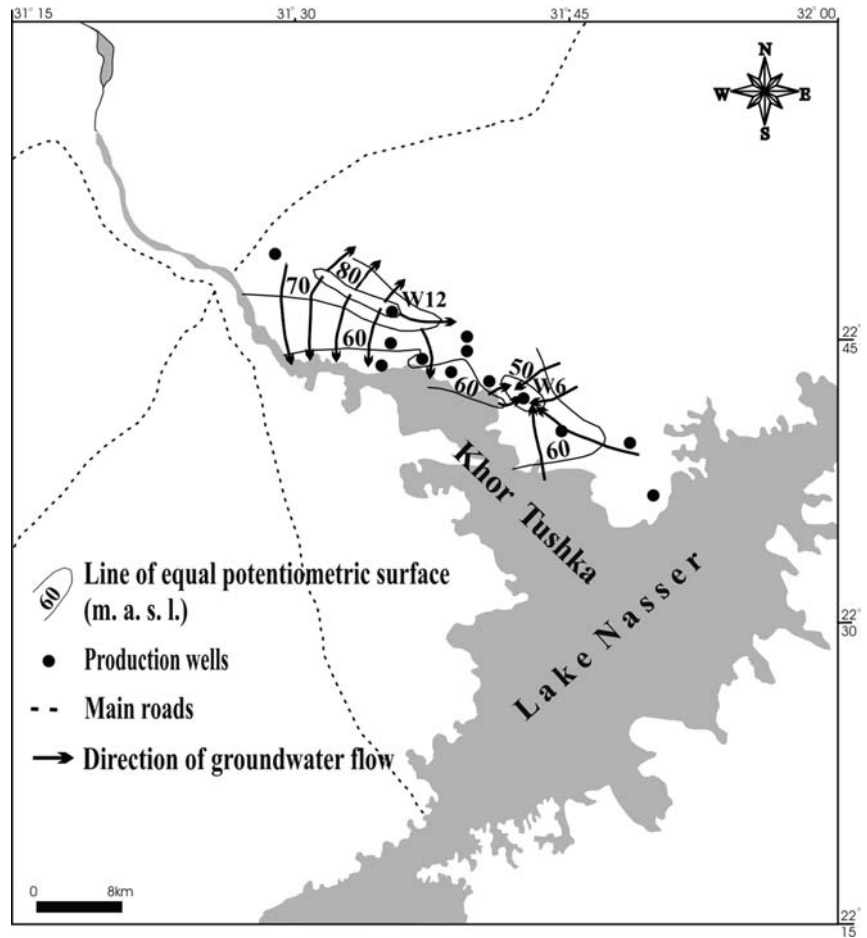


Fig. 10 Equipotentiometric contour map for the northern peripheral area of Lake Nasser (source of data: RIGW 2001)



other wells drilled to the west of the Tushka Depression (El-Shazly et al. 1977). On the other hand, the productivity of water wells drilled near to or around Lake Nasser ranges from 2,268 (W13) to 4056 m³/day (W14) with an average

of about 2,600 m³/day (RIGW 2001). These figures indicate the prolific productivity of the water wells drilled near to, or around, Lake Nasser, compared to those drilled far from the lake. Analysis of single-well pumping

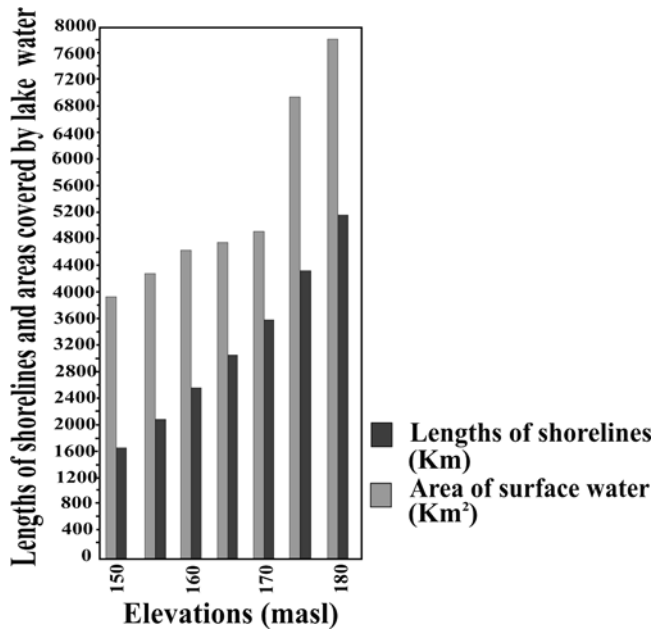


Fig. 11 Areas and lengths of shorelines of Lake Nasser at different water elevations

tests was carried out on some selected wells. An example is that carried out on W33 (see Fig. 1d), for constant discharge and recovery tests using the Papadopoulos and Cooper method (1967), where the storage in the well cannot be neglected (Fig. 12). The constant rate pumping test was performed at a discharge rate (Q) of $106 \text{ m}^3/\text{h}$ for 1,460 minutes (t) and measuring changes in water levels during pumping (drawdown in mbgl) and recovery test (residual drawdown in mbgl) (Fig. 12 a and b). Such tests are used to determine transmissivity and hydraulic conductivity when water level recovery is too rapid and no observation wells or piezometers records are available. After the pump is shut down, water level recovery is monitored with the same time frequency used during pumping (t/t_0) (Fig. 12b). The data obtained from these tests revealed somewhat moderate hydraulic characteristics in terms of transmissivity ($T=8.64 \times 10^1 \text{ m}^2/\text{day}$), hydraulic conductivity ($K=9.65 \times 10^{-1} \text{ m/day}$) and storage coefficient ($S=2.30 \times 10^{-3}$).

The study indicated that all the scattered patches found in the eastern side of the lake and occupied by the recent wadi fillings and the Pleistocene lacustrine deposits could be identified as low productivity area. However, those occurring in most of the southern and southwestern portions and occupied by the upper sandstone horizon are considered as moderate to low productive areas.

Hydrochemical characteristics

The chemistry of the Nubia aquifer system of Tushka area west of Lake Nasser was determined by the interpretation of the data from 11 wells (Table 1) in addition to those recently drilled wells around the margin of Lake Nasser (Table 2). The chemical data used for the present work were obtained from several sources (GALND 1997 and RIGW 2001), and

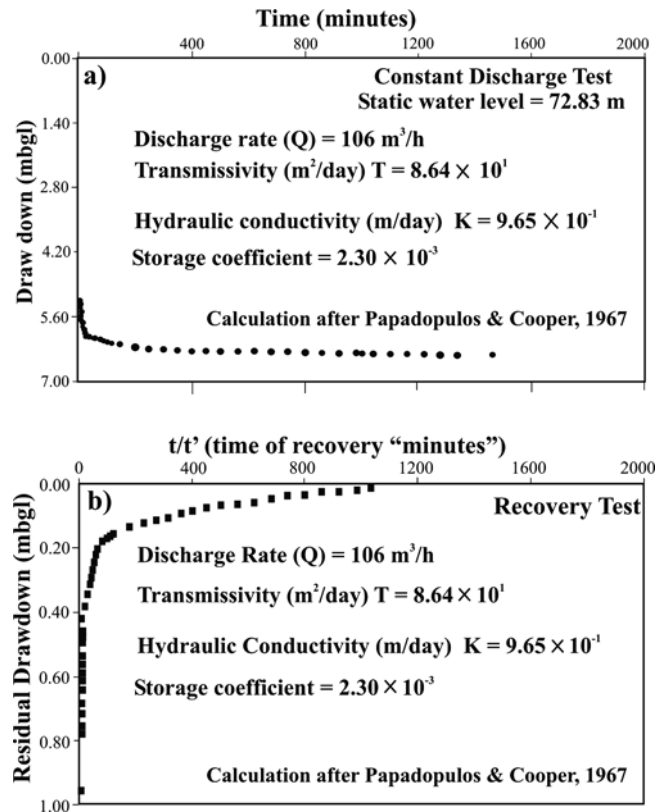


Fig. 12 Pumping test analysis for Well No. (W33). a Constant Discharge Test and b Recovery Test

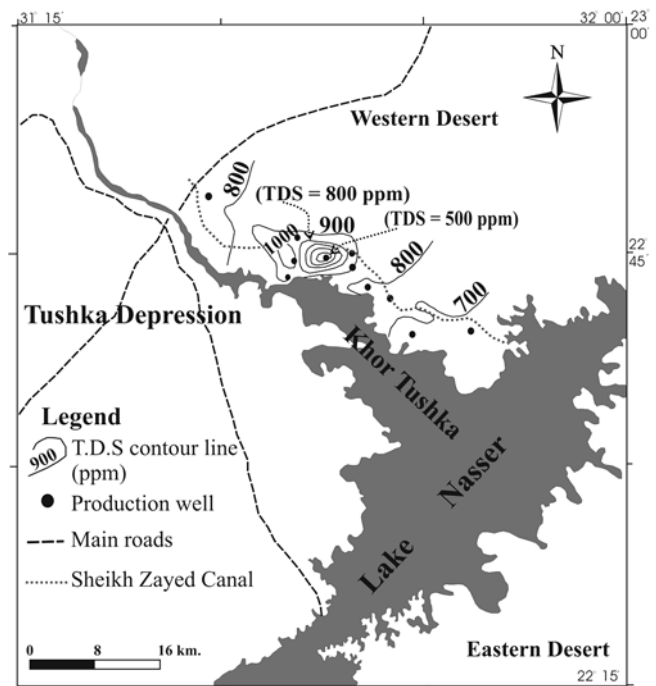


Fig. 13 Isosalinity (total dissolved solids) contours of Lake Nasser wells, (Date of analysis-2000) (source of data: RIGW 2001)

Table 2 Data of the recently drilled production water wells around Lake Nasser (after, RIGW 2001); Well locations are shown in Fig. 1d

Well no.	Total well depth (m bgl)	Discharge (Q ³ /h)	TDS (ppm)	Static water level (masl)
W3	312.4	105	672	56.46
W4	254	100	662	53.2
W5	250	112.5	475	66.8
W6	312	104	736	72.79
W8	312.5	100	732	61.58
W9	250	109	913	65.29
W9'	250	100	660	49.62
W10	312.5	109	870	64.73
W10'	250	100	646	62.27
W11	250	112.5	1053	63.23
W11'	250	150	902	57.16
W12	311	100	966	82.21
W13	207	94.2	737	79.8
W14	250	169.8	532	14.07
W15	260	155.5	475	26.5
W17	250	120	–	24.11

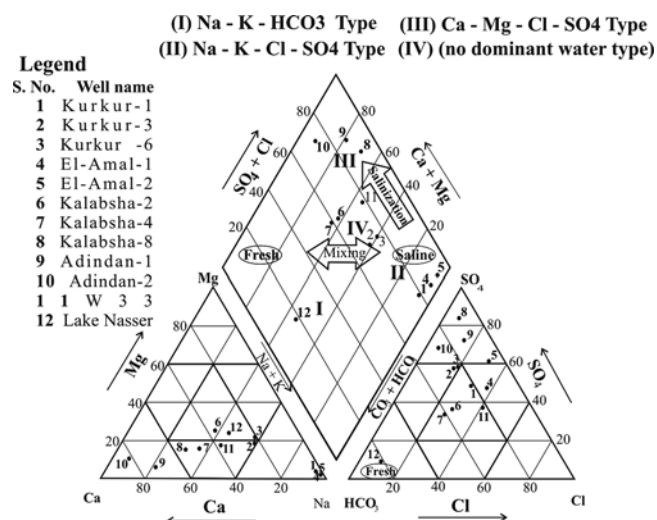


Fig. 14 Piper trilinear diagram of water samples. Production wells at Bir Kurkur, El-Amal, Kalabsha and Adindan are located in Fig. 1c; well W33 is located in Fig. 1d

were interpreted and presented by the present author. The chemical data represents the deeper water-bearing horizons of the Nubia aquifer system.

The total dissolved solids (TDS) of the groundwater of the deeper water-bearing horizons of the Nubia aquifer system (Table 1) range between 360 (Adindan-2, see Fig. 1c) and 2,326 ppm (El-Amal-1), whereas around or near Lake Nasser (Table 2, Fig. 13), the total dissolved solids vary from 457 ppm (in wells W5 and W15, see Fig. 1d) to 1,053 ppm (in W11). It is clear that the TDS is impressively diluted or water is fresher in the wells drilled near Lake Nasser relative to those drilled far from the lake (i.e. in other localities of Tushka area), which is related to the direct recharge of fresh water from Lake Nasser to the adjacent aquifer.

The isosalinity contour map prepared for the marginal area of Lake Nasser (Fig. 13), indicates that the isosalinity

contour line of 800 ppm encloses most of the area mapped, and the salinity decreases to 700 ppm towards the SE direction. The higher salinities were encountered at the centre of the mapped area, with salinities of 900 and 1,000 ppm, then decreases to 700 ppm at the northeastern part of the mapped area.

Water having low dissolved solids concentrations (i.e. wells Kalabsha-2, Kalabsha-4, Kalabsha-8, Adindan-2, Kurkur-1 and all the wells drilled in the marginal area of Lake Nasser), where concentrations less than 1,000 ppm are produced principally as a result of water-rock interactions or by mixing with fresh surface stream waters. Concentrations greater than 1,000 ppm, generally are the result of the combined effects of water-rock interactions and mixing with old saline groundwater. Based on the trilinear diagram (Piper 1944), it is clear that a certain hydrochemical pattern was revealed, which helps in hydrochemical facies classification. Accordingly, the trilinear diagram of the study area is classified into four hydro-geochemical facies based on the dominance of different cations and anions (Fig. 14): facies 1, Na⁺-K⁺-HCO₃⁻ (type I); facies 2, Na⁺-K⁺-Cl⁻-SO₄²⁻ (type II); facies 3, Ca²⁺-Mg²⁺-Cl⁻-SO₄²⁻ (type III); facies 4, no dominant water type (mixed types). However, Fig. 14 shows that nearly half the number of samples occurs in facies 4 (Kurkur-3 (1,342 ppm of total dissolved solids (TDS)), Kurkur-6 (1,359 ppm of TDS), Kalabsha-2 (900 ppm of TDS), Kalabsha-4, (910 ppm of TDS) and Well 33 (360 ppm of TDS) with mixed water types (no dominant water type). This indicates the influence of Lake Nasser on the chemical composition and water quality of these wells, which occur in the vicinity area of the lake. The clogging nature of the shale beds, which intercalate the Nubia Sandstone aquifer (Fig. 7b and c) permits only intermittent flushing of groundwater and hence the relatively fresh water quality characterizing some wells (Kalabsha-2, Kalabsha-4, Kalabsh-8, Adindan-2 and W33) are not sustained in all drilled wells in the vicinity of the lake. Furthermore, the

trilinear diagram (Fig. 14) revealed that the drilled wells (Kurkur-1, El-Amal-1 and El-Amal-2) occur in facies 2, which reflects the original slightly saline groundwater with high percentage of sodium and chloride.

Regarding the suitability of groundwater for human consumption, it is worth mentioning that the desirable TDS is 500 ppm, but it can be permitted up to 1,000 ppm (WHO 1996). Thus, the groundwater drafted from Kurkur-1, Kalabsha-2, Kalabsha-4, Kalabsha-8, Adindan-2 as well as all the marginal wells of Lake Nasser are suitable for human consumption, whereas the other wells are hazardous for human consumption. However, all the water wells are suitable for livestock consumption (Table 1).

For agricultural purposes, the relatively low salinity of water wells (less than 1,000 ppm) could be used for the cultivation of low and medium salt tolerant crops, such as: avocado, lemon, strawberry, peach, apricot, almond, plum, prune, grapefruit, orange, apple, green beans, celery radish, cantaloupe, date and olive. On the other hand, the higher salinity water wells (more than 1,000 ppm) are suitable for the high salt tolerant crops, such as, date palm, spinach, asparagus, kale, hay, sugar beet, cotton, rape and salt grass. The suitability of groundwater for irrigation is judged by sodium adsorption ratio (SAR) (U.S. Salinity Laboratory Staff 1954). This parameter is determined by the measurement of sodium content expressed by the sodium adsorption ratio (SAR), where there is an interrelationship of high sodium percentage with low total salts. Samples having SAR less than 10 are considered excellent water for irrigation (i.e. Kurkur-1, Kurkur-3, Kurkur-6, Kalabsha-2, Kalabsha-4, Kalabsha-8, Adindan-1 and Adindan-2). These water wells are also characterized by relatively low salinity and reduced hazards of sodium adsorption by soils, which is suitable for the cultivation of all sorts of crops.

Conclusions

A Landsat TM image was used to construct essential maps that were used in the geomorphological and hydrogeological investigations of the area. The geomorphologic map gives a clue on the past wet climatic conditions that prevailed over the area of study. The "Nubia Sandstone aquifer system" in the area has a wide areal extension, favourable hydraulic characteristics and its water is of reasonable quality. This water may be used safely for agriculture and human consumption. The Nubia aquifer system could be subdivided into shallow and deep water-bearing horizons. The shallow water-bearing horizons are supposed to be found at unconfined or under semi-confined conditions and is fully penetrated by the surface water of Lake Nasser. On the other hand, the deeper groundwater horizons are found under semi-confined conditions and are only affected by the lake water under certain conditions. These conditions depend on the inter-relationship between the bottom levels of Lake Nasser and the potentiometric levels of the groundwater of the Nubian aquifer in the environs of the lake. Furthermore, the changes in water level of Lake Nasser affect the hydrogeological regime of the Nubia Sandstone

aquifer system in the studied area. The existing water chemistry reflects a recent recharge by surface lake water or it reflects the proximity of the aquifer to the recharge areas. The calculated hydraulic parameters indicated that the Nubia aquifer system in the area has generally moderate to low productivity. The extracted groundwater amounts to 1.0 million m³/year and is used to cover all the current requirements. However, more extraction is needed for the planned future activities. The ongoing Tushka project depends in its first stage upon using Lake Nasser and the new formed Tushka Lakes (initiated since 1994) in irrigating nearby lands. The first stage will depend on lifting water via the huge pumping stations through Sheikh Zayed Canal to cultivate 560,520 acres (2,268 km²). Besides, the new initiated Tushka Lakes, which were formed as a direct impact of the flooding episodes of the River Nile since the early 1990s up-till now, will be used for the installation of different developmental activities. However, the study area is still, to a large extent, not inhabited by man and the major ongoing cultivation activities are dedicated to the investors.

Acknowledgements The Author wishes to express his deep gratitude to the reviewers of this work for their inspirational notes and suggestions. He is also greatly indebted to Sue Duncan, Technical Editorial Advisor of the Hydrogeology Journal for the huge efforts devoted to valuable revision of the present work. Many thanks are also deserved by Prof. Maria-Theresia Schafmeister, Catherine O'Flynn and Christine Watson, the Hydrogeology Journal Managing Editor and Administrators for their helpful support.

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