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ORIGINAL PAPER

Hydrogeological studies on the Nubian sandstone aquifer in El-Bahariya Oasis, Western Desert, Egypt

Ali M. Hamdan · Rashad F. Sawires

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Abstract The current study aimed to evaluate hydrogeologically the Nubian sandstone aquifer in El-Bahariya Oasis. It represents the main water-bearing horizon in the study area and consists of continental elastic sediments, mainly sandstone alternating with shale and clays. The general flow lines are directed from SW to NE direction, as detected from the constructed potentiometric head contour map. The piezometric surface reaches 149 m in El-Heiz area at the southern part, while it reaches 90 m at the northern, reflecting higher pressure head of the aquifer in the southern part. The map also illustrates that the southern part is considered as the most promising location for development. The structural elements play an important role in the deposition and distribution of the sedimentary succession of the Nubian sandstone sediments. Consequently, this sedimentary pattern affects the occurrences and movements of the groundwater within the aquifer system. Along the structurally high areas, in the study area, the piezometric head increases, while the reverse is recorded along the structurally low areas. The step-drawdown tests data were carried out by calculating the aquifer loss coefficient (*B*) and the well loss constant (*C*). The *B* values are smaller compared with *C* values, indicating that the aquifer under pressure has a behavior of leaky aquifer; therefore, it shows hydraulic connection with surrounding formation. The values of well efficiency range from 78.50% to 87.76%. Analysis of 12 pumping test data (constant discharge tests) was carried out in order to calculate the Nubian aquifer hydraulic parameters (transmissivity, hydraulic conductivity, and storage coefficient). The transmissivity values decrease from 3,045 m^2/day in the southern part (El-Heiz area) to 236 m^2/day in the northeastern part (El-Harra area). Accordingly, the aquifer classified as a high to moderate potentiality. Transmissivity contour map observes gradual increase of transmissivity values from the southern to northeastern direction. This may be due to the increase of shale or clay content in the concerned aquifer in that direction. The storage coefficient values range between 1.04×10^{-4} and 5.22×10^{-3}, as obtained from the results of pumping test analysis, which ensure that the Nubian sandstone aquifer is classified as semi-confined to confined aquifer type. The *S* values show a decrease from southwest to northeast direction as detected from S-map. The hydraulic conductivity values vary from to 0.46 m/day in the northern part to 10.88 m/day in the southern part with an average of 5.67 m/day. According to the classification based on *K* values, the aquifer is mainly composed of coarse sand.

Keywords Hydrogeology · Nubian sandstone aquifer · El-Bahariya Oasis · Western Desert

A. M. Hamdan (✉)
Geology Department, Faculty of Science in Aswan,
South Valley University,
Aswan, Egypt
e-mail: alielaraby1@yahoo.com

R. F. Sawires
Geology Department, Faculty of Science, Assiut University,
Assiut, Egypt

Introduction

With the increasing demands for water due to increasing population, urbanization, and agricultural expansion, groundwater resources are gaining much attention, particularly in arid and semi-arid regions. So, the current study aimed to evaluate the potentiality of groundwater resources on El-Bahariya Oasis.

El-Bahariya Oasis is an interesting area and has attracted the attention due to its valuable economic resources including the iron ore deposits, hydrocarbon-producing fields, archeological sites, and vast reclaimable lands. It was also the subject of intensive studies from hydro-geological point of view, due to its high groundwater potentiality. The Nubian sandstone aquifer is the most important source of groundwater, not only in El-Bahariya Oasis, but also in the Western Desert.

El-Bahariya Oasis is one of the naturally excavated depressions in the Western Desert of Egypt; probably of tectonic origin and differs from the other oases in being entirely surrounded by escarpments and in having a large number of isolated hills within the depression.

The study is mainly based on the data of well logging and pumping test analyses carried out in exploration, domestic and irrigation wells drilled in the studied area, as well as the other published information. Some of these data are given by REGWA Company.

Location of the studied area

El-Bahariya Oasis is a natural topographic depression located in the heart of the Western Desert of Egypt (Fig. 1). It is located between latitudes 27°48′ and 28°30′ N and between longitudes 28°35′ and 29°10′ E, about 370 km southwest of Cairo and about 190 km west of Samalut town at the Nile Valley. It covers an approximate area of 1,800 km^2.

The depression of the oasis is oval in shape. It is entirely surrounded by escarpments, with its major long axis trending NE–SW direction, with a narrow blunt-pointed extension at each end.

Method of study

The acquisition of database and the applied methodology to achieve the present study in El-Bahariya Oasis area required the following field and laboratory works:

- Collecting technical data on wells drilled in the studied area including geographical coordinates, surface elevation, water depth, and discharges of wells.
- The step-drawdown test data were used to give an idea about the design and efficiency of the water wells. Computerized mathematical methods were used for calculating formation loss and well loss.

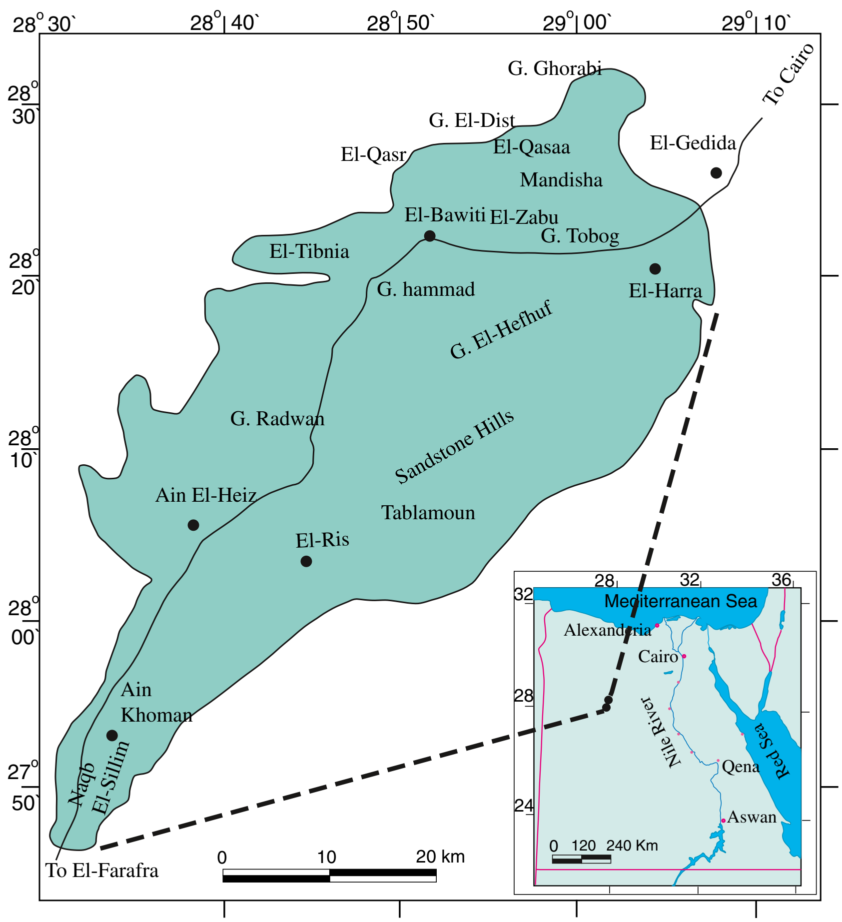


Fig. 1 Location map of El-Bahariya Oasis, Western Desert of Egypt

- Analysis of 12 pumping test data (constant discharge tests) was carried out in order to calculate the Nubian aquifer hydraulic parameters (transmissivity, hydraulic conductivity, and storage coefficient) using GWW software program with Theis's method.

Geological setting

A brief description of the stratigraphic section in El-Bahariya Oasis starting from the base to top according to the subsurface succession (Table 1 and Fig. 2) is as follows:

1. Pre-Cambrian basement rocks. They are composed of dense, grey metamorphosed andesite, matrix made of fine grains of altered feldspar, chlorite, and magnetite.
2. Cambrian rocks. A sedimentary section of 458 m thick (belongs to the Cambrian) rests upon the metamorphosed igneous basement. This section is composed of intercalated siltstone, sandstone, and clay.
3. Cretaceous rocks. A section of 660 m lies on top of the Cambrian deposits of undifferentiated sandstones, sands, and clays intercalated with each other. Cretaceous rocks were divided into four formations starting from base to top as follows:
   (a) *El-Bahariya Formation* (*Lower Cenomanian*). The floor of El-Bahariya Oasis depression is covered by a large expanse of this flat-lying fluviatile sandstone. These 705-m thick deposits are composed of intercalations of sandstone, sands, and clays.
   (b) *El-Heiz Formation* (*Upper Cenomanian*). It conformably overlies El-Bahariya Formation and unconformably covered by the El-Hefhuf Formation (Campanian age). It consists of fossiliferous limestone, shale, and calcareous sandstone and marl with a maximum thickness of 30 m.
   (c) *El-Hefhuf Formation* (*Campanian-Turonian*). It consists essentially of a series of dolostone beds with sandstone and sandy clay interbeds and unconformably overlies the El-Heiz Formation at Gebel El-Hefhuf.
   (d) *Khoman Formation* (*Maastrichtian*). The term Khoman Chalk was introduced by oil geologists in their unpublished reports for the snow-white tortuous escarpment, consisting of chalky limestone bed (40–45 m thick) which conformably overlies El-Hefhuf Formation at the western scarp of El-Bahariya depression.
4. Paleocene rocks: It is represented by the following:
   (a) *Tarawan Chalk* (*Lower Paleocene*). It is exposed to the south of the studied area (20–30 m thick) and consists of chalky limestone and limestone.
   (b) *Esna Shale* (*Upper Paleocene–Lower Eocene).* It is on1y exposed in the southern escarpment of the plateau that separates El-Bahariya and El-Farafra depressions.

Table 1 Composite stratigraphic section of El-Bahariya Oasis

Age	Rock unit	Thickness (m)	Lithology
Early Miocene (16–20 Ma)	Basalt flows and sills	20	Olivine basalt
Oligocene	Radwan Formation	40	Dark brown ferruginous grits and sandstones
Unconformity			
Middle and Late Eocene	El-Hamra Formation	63	Limestone with clastic intercalations forming reef-like structures with inward dips of 10–40°
Middle Eocene	Qazzun Formation	32	White limestone with ball-like concretions of hard dolomitic limestone
Unconformity			
Middle Eocene	Naqb Formation (Ghorabi iron ore member)	68	Pink limestone forming isolated hills
Unconformity			
Early Maastrichtian	Khoman Chalk	25	Chalk and limestone beds with hard dolomitic limestone band at the top
Campanian	El-Hefhuf Formation	120	Dolostone and sandstone with sandy clay intercalations
Unconformity			
Late Cenomanian	El-Heiz Formation	30	Clastics with carbonate interbeds and a dolostone member at the top
Cenomanian	El-Bahariya Formation	170+	Variegated, cross-bedded sandstone

Compiled from Said (1962)

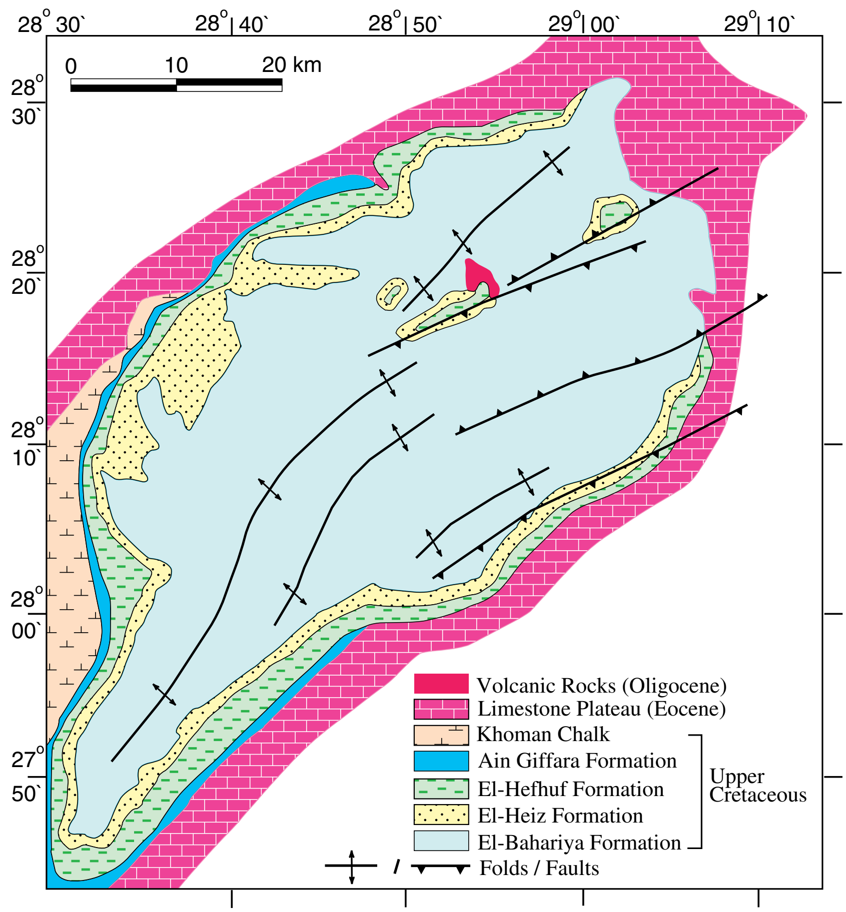


Fig. 2 Geological map of El-Bahariya Oasis (after El-Akkad and Issawi 1963)

5. Eocene rocks. The Eocene limestone rocks form the eroded plateau surface surrounding El-Bahariya depression and some of the isolated hills within it. The Eocene strata rest unconformably on the Upper Cretaceous rocks. It consists of the following formation:

   (a) *Farafra Formation.* It constitutes the upper member of the Eocene succession. It unconformably overlies El-Bahariya Formation at the escarpment east of El-Harra and rests on the eroded section of the El-Hefhuf Formation on the plateau east of the sandstone hills and overlies the Khoman Formation south of Naqb El-Sillim.

   (b) *Naqb Formation* (*Lower Middle Eocene*). It consists of pink to violet Nummulitic dolostone and limestone beds that overlies via angular unconformity the Khoman, El-Hefhuf, El-Heiz, and El-Bahariya formations, from south to north, respectively. Iron-bearing solutions have replaced the carbonate rocks of the Naqb Formation forming deposits of iron ore.

   (c) *Qazzun Formation* (*Upper Middle Eocene*). It consists of white Nummulitic limestones and dolostones. The physiographic characteristics of this formation are snow-white color, low topographic relief, and wind-eroded boulders. It crops out in a 7–10-km wide band to the East, North, and Northwest of the rim of the escarpment.

   (d) *El-Hamra Formation* (*Middle-Upper Eocene*). It conformably overlies the Qazzun Formation with 63 m thick. It consists of fossiliferous limestone beds with a few clastics intercalations, which have been eroded into isolated hills on the eastern plateau of El-Bahariya depression.

6. Tertiary rocks. It represents by the following:

   (a) *Volcanic rocks.* In several localities of El-Bahariya Oasis (Measera Hill, Mandisha Hill, El-Hefhuf Hill, and Basalt Hill), the sedimentary formations are capped with sheets of volcanic rocks (of Oligocene age), mostly extrusive basalt and dolerite.

   (b) *Qatrani Formation* (*Oligocene*). The well-defined Oligocene deposits of El-Bahariya region are those of the Qatrani Formation of the north-eastern plateau. These sediments represent the products of deep weathering processes of the different rock units of Cretaceous and Eocene age. It is unconformably overlying the Upper Eocene sediments.

7. Quaternary rocks (surface deposits): They vary and represented by the following:
   (a) *Aeolian Sands* form the scattered sand dunes within the depression and on the plateau surface. They are composed of yellowish white quartz sand, medium to fine having the seif dune form.
   (b) *Sabkhas and Salt Deposits* are produced due to the seepage of the water from natural flowing springs and wells through the clay horizons on the depression floor giving rise to the formation of gypsum salt crust.
   (c) *Playa Deposits* are developed in the inland depressions. These depressions form the final resting place for the runoff from the adjacent high elevations. These deposits are composed of fine sand, silt and dark brown clay mixed with gypsum, and halite.

Structure and geomorphology of the study area

Structurally, El-Bahariya Oasis situated on the stable–unstable shelf contact, it is highly deformed. It is considered to be a major doubly plunging anticline with a NE–SW trend, a typical structure of the Syrian Arc belt. The axis of this great anticline runs in a southwest trend from Gebel Ghorabi in the north, past the central hills of the depression to the southern part of the oasis, and seems to continue south to include El-Farafra structure. The dips are as high as 60° in the north and become less pronounced in the south, thus showing that the center of the deformation is in the north.

The study area was characterized by three different striking major fault systems. The NE–SW faults are running parallel to El-Bahariya major anticline and representing the most common fault trend with a throw ranges between 40 and 50 m (Fig. 3). The NW–SE faults are the second common trend at the El-Bahariya area. They have relatively low throws compared with NE–SW faults (30–40 m). The E–W trending faults are the least common in El-Bahariya. Their throw reach about 40 m.

Geomorphologically, El-Bahariya Oasis is one of the naturally excavated depressions located in the Western Desert of Egypt; it is believed to be of tectonic origin, started during the Lower Eocene times. It differs from the other oases in being entirely surrounded by escarpments and in having a large number of isolated hills within the

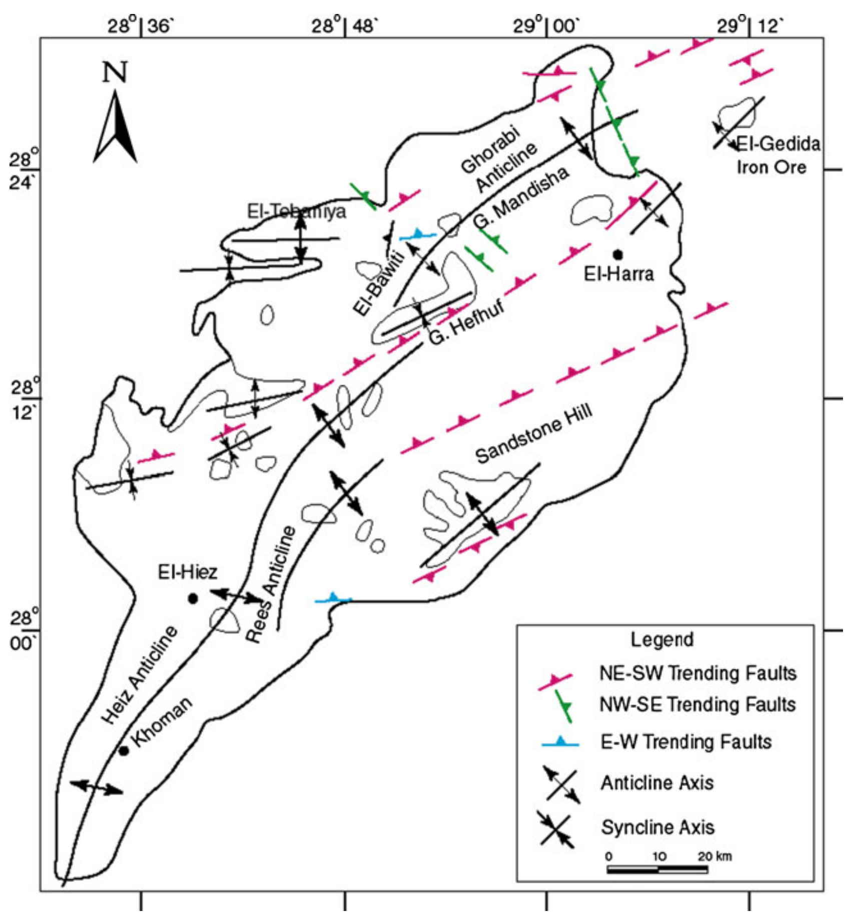


Fig. 3 Structural map of El-Bahariya depression, Western Desert, Egypt (after El-Bassyouny 1978)

depression. The following regional morphological features are distinguished in El-Bahariya depression:

- *The plateau surface:* El-Bahariya depression is excavated in the Eocene limestone plateau. The plateau surface is ragged with a northward slope. The plateau surface is dissected by long and short dry wadies draining into the excavated depression.
- *The bounded escarpments:* The Eocene plateau edges are northerly bounded by conspicuous escarpments having different modes of formation and different degrees of development. The western scarps run in most irregular manner to form well-marked embayment and promontories. In most cases, the escarpments face takes the shape of a questa.
- *The depression:* It represents topographic low occupying structural high. The floor of the depression is excavated in the soft clastics of El-Bahariya Formation. Several landforms are well developed on the depression floor area, where some of them are of structural origin, while the other is of depositional nature. Among them are the isolated hills and sand dunes.

Hydrogeological setting

The Nubian sandstone represents the main water-bearing horizon in the studied area. It consists of continental elastic sediments, mainly sandstone alternating with shale and clays. The groundwater system in the studied area is hydraulically connected with the surrounding and the underlying aquifers through good pathways or channels that permit upward leakage. Accordingly, the Nubian sandstone aquifer in El-Bahariya Oasis is described as a multilayered artesian "leaky" aquifer system that behaves as one hydrogeologic.

The groundwater-bearing horizons in the investigated area follow two aquifer systems. These are, from top to bottom (Khalifa 2006):

1. The Post-Nubian sandstone aquifer system, which occurs to the north of latitude 26° in the Western Desert of Egypt (CEDARE 2001). It is composed of marine sediments mainly consist of clay, marl, and limestone overlain by continental clastic sediments, which exhibit noticeable facies variation in the northern

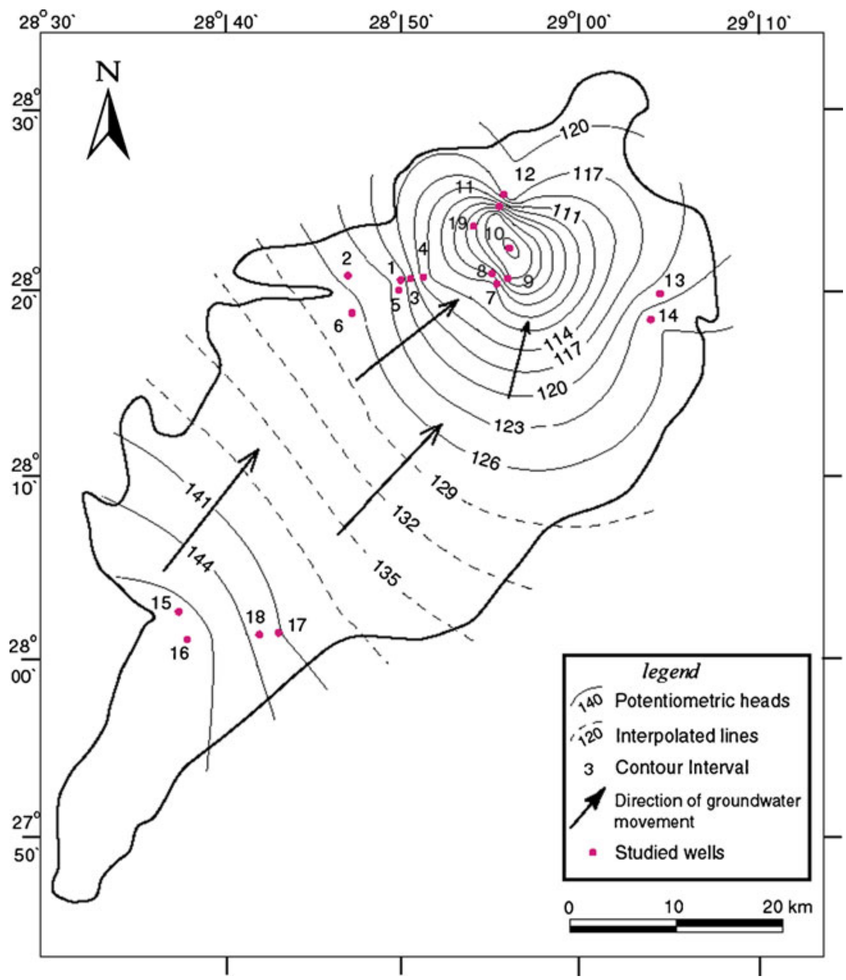


Fig. 4 Potentiometric head contour map of the Nubian sandstone aquifer of El-Bahariya Oasis in 2009

Table 2 Inventoried hydrologic data of water wells penetrating the Nubian sandstone aquifer in El-Bahariya Oasis during the year 2009

No.	Well name	Locality	Total depth (m)	Piezometric surface (msl)
1	Dedela	El-Qasr	806	123
2	Barakat		834	125
3	Al Maftela		1,056	120
4	Ain El-Seir		1,063	112
5	Embash		250	122
6	Madi		345	127
7	Ain Hamra	Mandisha	770	108
8	Alghaba Alqeblia		391	105
9	Al Magaria	El-Zabu	1,054	95
10	Ain El-Qasr		1,065	90
11	Qassa 1	El-Qasaa	780	95
12	Qassa 2		1,102	120
13	Ain Gedid	El-Harra	974	121
14	Ain Abu El-Ez		780	126
15	El-Qarra	El-Heiz	1,147	148
16	El-Sheikh		1,152	149
17	Sayed Ahmed		347	141
18	Ain Gomaa		371	143
19	Abohoil Elghfer	El-Bawiti	145	100

parts of Egypt to pass laterally into carbonate facies. This sequence ranges in age from Late Cenomanian to the recent.

2. The Nubian sandstone aquifer system, which represents the main water-hearing horizon in the studied area. It consists of continental clastic sediments mainly sandstone alternating with shale and clays. These series were classified stratigraphically into three units in El-Bahariya Oasis, namely Cenomanian water-bearing horizon (0–705 m), Pre-Cenomanian water-bearing horizon (705–1,355 m), and Cambrian water-bearing horizon (1,366–1,823 m) (Diab 1972).

Fig. 5 Some pumping tests which had been done in El-Bahariya Oasis

(a) The Cenomanian water-bearing horizons are composed of huge thickness (705 m) of sandstones, sand, and clayey at parts alternating with shale beds. The groundwater in these water-bearing sediments is fresh, with salinity ranges between 165 and 535 ppm.

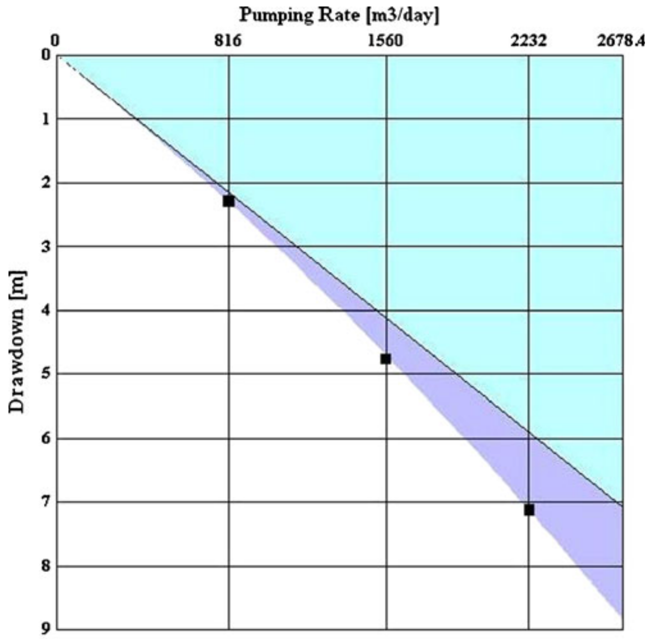
(b) Pre-Cenomanian water-bearing horizons are composed of about 650 m of sand and sandstones alternating with clays. The groundwater of the water-bearing horizons is also fresh with salinity of 276 ppm.

(c) The Cambrian water-bearing horizons are composed mainly of about 460 m of sandstones and sand, occasionally marly and dolomitic. The groundwater of these water-bearing horizons is fresher than the upper horizons with salinity of about 120–200 ppm (Himida 1964; Diab 1972).

Results and discussion

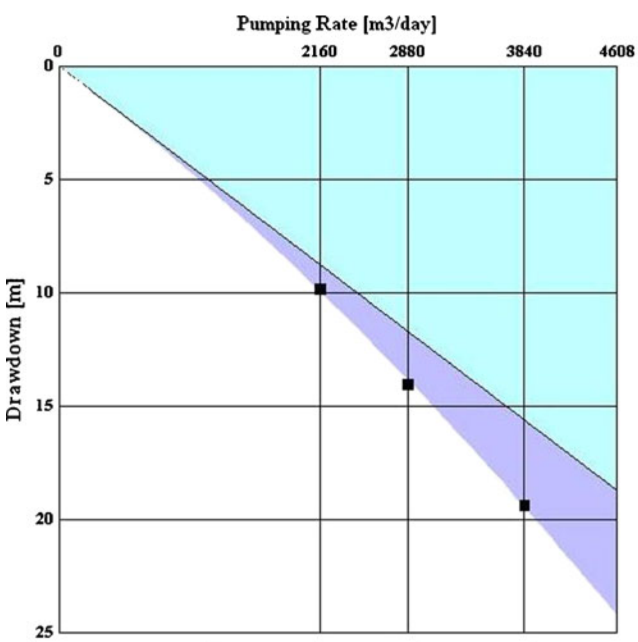
Groundwater flow

In the present work, the potentiometric head contour map (Fig. 4) of the Nubian sandstone aquifer in El-Bahariya Oasis was constructed based on the available water level



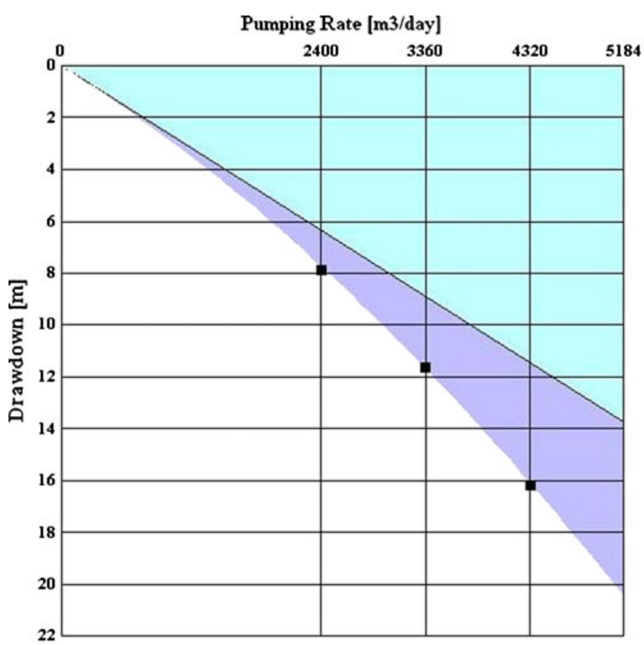
Drawdown	2.29	4.76	7.12	8.86
Pumping Rate	816	1560	2232	2678.4 *
Aquifer Loss	2.16	4.12	5.9	7.08
Well Loss	0.16	0.6	1.23	1.78
Efficiency [%]	94.2	86.6	82.8	79.9

Fig. 7 Step-drawdown pumping test for El-Managem-8 well in the studied area



Drawdown	9.85	14.05	19.39	24.27
Pumping Rate	2160	2880	3840	4608 *
Aquifer Loss	8.77	11.7	15.59	18.71
Well Loss	1.22	2.17	3.86	5.55
Efficiency [%]	89.1	83.2	80.4	77.1

Fig. 6 Step-drawdown pumping test for Ain Haddad well in the studied area



Drawdown	7.87	11.64	16.17	20.49
Pumping Rate	2400	3360	4320	5184 *
Aquifer Loss	6.35	8.89	11.44	13.72
Well Loss	1.45	2.84	4.7	6.76
Efficiency [%]	80.7	76.4	70.7	67

Fig. 8 Step-drawdown pumping test for El-Fasqea well in the studied area

Table 3 Aquifer and well losses and the efficiency of some wells in the studied area

Well name	Aquifer loss (day/m^2)	Well loss (day^2/m^5)	Efficiency (%)
Ain Haddad	0.004061	0.0000002615	85
El-Fasqea	0.002647	0.0000002517	78.5
El-Managem 8	0.002643	0.0000002478	87.76

measurements during the year 2009 (Table 2). The groundwater flow is interpreted from the potentiometric head map as follows:

- The piezometric surface of the groundwater of the Nubian sandstone aquifer reaches 149 m in El-Heiz area at the southern part of El-Bahariya Oasis, while it reaches 90 m at the northern part of the studied area (Table 2). This means that the pressure head of the Nubian sandstone aquifer in the southern part of El-Bahariya Oasis is higher compared to that in the northern part.
- The general flow lines in El-Bahariya aquifer are directed from southwest to northeast direction.
- The groundwater in the studied area has the same general flow pattern (SW–NE) that reported for the groundwater of the great Nubian sandstone aquifer in the Western Desert of Egypt (Ezzat 1959; Ayouty and Ezzat 1961; Shata 1982; Himida 1964, 1966 and 1970; Diab 1972; Korany 1984; Khalifa (2006) and others).
- Also, the pressure head increases due east, west, and south of the oasis. But at the northern sector, the flow becomes from east and west toward El-Bawiti town as a result of intensive groundwater extraction in this town and its surroundings.
- The maps also illustrate that the southern part of El-Bahariya Oasis is considered as the most promising location for development to meet the present and projected socioeconomic development plans of El-Bahariya Oasis.
- Recommend drilling new wells suggested in the central part of El-Bahariya Oasis which give the chance to link and give more detailed and accurate information about the hydrogeological conditions in the studied area.

The aquifer recharge and discharge

The groundwater recharge for the Nubian sandstone aquifer system is possible from the leakage of water from the Nile. It can occur along Lake Nasser in Egypt until Wadi Halfa north of the Sudan, where the Nile River starts to cross the basement outcrops. Another possible seepage zone occurs in the area between Dongola in northern Sudan to Khartoum. In Egypt, north to the 25th meridian, the Nile runs across impermeable sediments of Upper Cretaceous to Tertiary. However, the groundwater–surface water interaction in this zone takes place in both directions (effluent and influent) but on very local scales (Heinl and Thorweihe 1993; Ebraheem et al. 2002; Gossel et al. 2004).

Some parts of the most southern region of the aquifer system are more humid than in the middle or northern parts and get episodic precipitation. Some of this amount in turn infiltrates and adds up to the groundwater recharge. The main discharge from the aquifer occurred by pumping the groundwater from the drilled wells for drinking and irrigation purposes.

The impact of the local structures on the groundwater conditions

Regionally, El-Bahariya is located on the transitional zone between the tectonically stable–unstable shelves of Egypt (Said 1962). It represents a major swell of NE–SW

Table 4 The results of automatic interpretation of the pumping tests data (during 2009) in the studied area (Theis method)

No.	Well Name	Locality	Thickness (m)	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)	Storage coefficient
1	Dedela	El-Qasr	539	246	0.46	7.93×10^{-4}
2	Ain Shawer		503	307	0.61	3.02×10^{-3}
3	El-Fasqea		145	738	5.08	2.06×10^{-4}
4	Ain El-Gherd	El-Zabu	175	459	2.62	1.59×10^{-3}
5	Magareb		180	366	2.03	1.04×10^{-4}
6	Abo Khalawy	El-Bawiti	187	629	3.36	5.22×10^{-3}
7	Ain Haddad	El-Harra	180	506	2.81	8.11×10^{-4}
8	Ain El-Wadi		345	236	0.68	3.47×10^{-4}
9	El-Gazaer	Mandisha	630	886	1.71	3.45×10^{-4}
10	W. El-Aguz	El-Aguz	260	738	2.84	2.17×10^{-3}
11	Tablamoun	El-Heiz	260	2390	9.19	9.88×10^{-4}
12	El-Mehebes		26	3045	10.88	Not defined

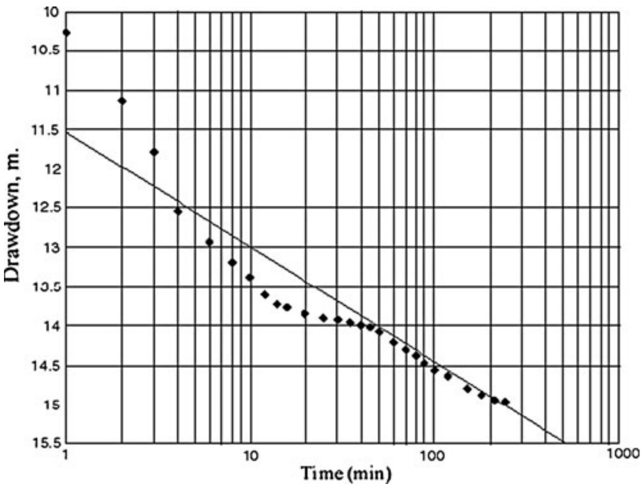


Fig. 9 Pumping test result in Ain-Haddad well in the study area

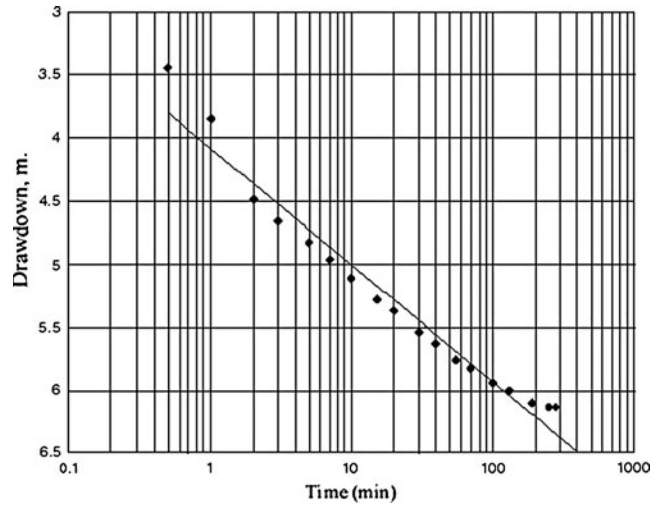


Fig. 11 Pumping test result in El-Bawiti-1 well in the study area

direction. The structural elements play an important role in the deposition and distribution of the sedimentary succession of the Nubian sandstone sediments in the Western Desert (Soliman et al. 1970). Consequently, this sedimentary pattern affects the occurrences and movements of the groundwater within the aquifer system along the Western Desert of Egypt.

The following impacts were recognized in El-Bahariya depression:

1. Along the structurally high areas, the piezometric head increases, while the reverse is recorded along the structurally low areas. The decrease of the head is attributed to the presence of shale and clay intercalations within the water-bearing zones. This is obviously clear in the studied area, where the wells which drilled in El-Harra (El-Harra Anticline) have a maximum head of 126 m. While, the wells which drilled in adjacent structurally low areas have a lower value of head.
2. The wells tapping the fractured rocks in the vicinity of the faulting system have higher piezometric heads.
3. Major faults act as conduit so this may explain the smoothing contours in the potentiometric maps.
4. The old springs in El-Bahariya depression (Hobiga, Meftella, and Geffara) are located along fault zones, where the groundwater flows upward along the fault planes. Thus, faults appear to form networks that facilitate the vertical and horizontal movement of groundwater.

Hydraulic parameters of the Nubian sandstone aquifer system

To estimate the hydraulic properties of an aquifer in the field, the primarily pumping tests (Fig. 5) were used to evaluate well and aquifer characteristics. In addition to the

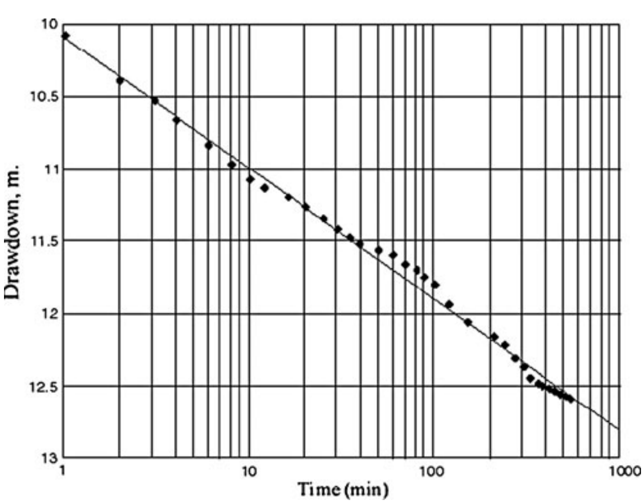


Fig. 10 Pumping test result in El-Fasqea well in the study area

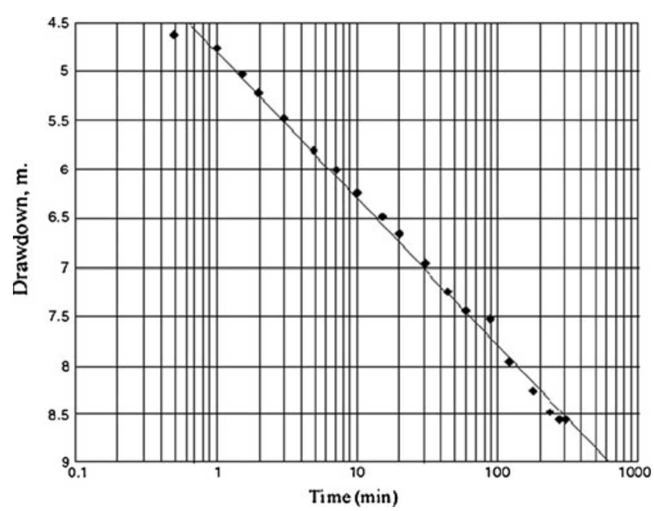


Fig. 12 Pumping test result in El-Bawiti-3 in the study area

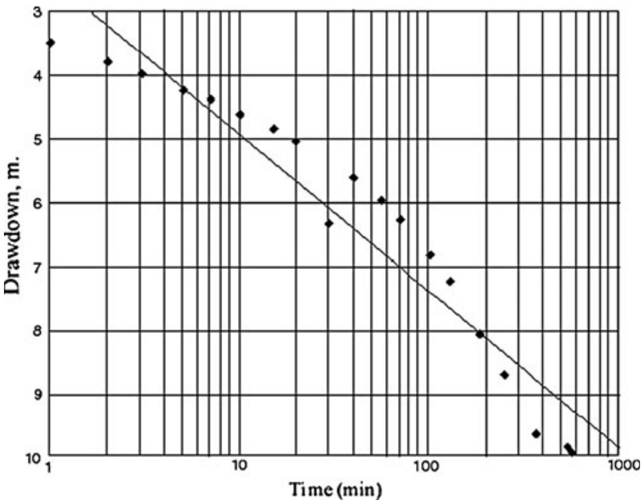


Fig. 13 Pumping test result in El-Habbassy in the study area

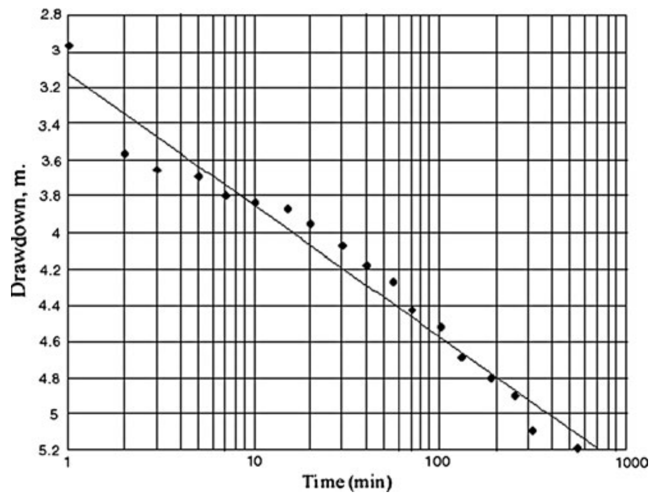


Fig. 15 Pumping test result in Siegam well in the study area

reliable predictions of groundwater variables, among these variables are the groundwater levels, drawdown, and discharge, which may vary with time and space.

The pumping test data for some wells within the study area, comprising discharge, step drawdown test, and constant discharge test, were collected. These data analyzed using a GWW software program (created by Karanjac and Braticevic 1994).

Step drawdown tests

A step-drawdown test (Figs. 6, 7, and 8) is one in which a well is operated during successive periods at constant fractions of its full capacity and is generally recommended prior to running tests specifically designed to determine the formation parameters. Such tests are useful in determining the yield of a well and to establish the depth for the pump setting.

In a production well, it has the following components: the drawdown *BQ* (formation loss) due to water flow through the aquifer towards the well, plus the drawdown CQ^2 (well loss) due to the turbulent flow of water through the screen or well face and inside the casing to the pump intake.

The ratio of the formation loss (*BQ*) to the total drawdown (*S*) is a measure of the efficiency of the well as an engineering structure for abstracting groundwater. The above two main elements (*BQ*) and (CQ^2) of head loss (*S*) controlling the water well design and also the greater head loss (drawdown) the more energy is needed and for good construction of water wells, the well loss (CQ^2) must be kept at a very small value.

To evaluate well loss, a step drawdown pumping test is required. This consists of pumping a well initially at a low rate until the drawdown within the well essentially stabilizes. The discharge is then increased through succes-

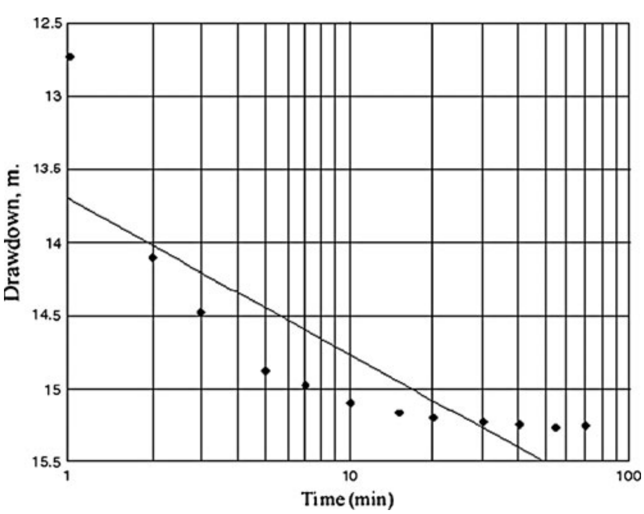


Fig. 14 Pumping test result in Oyoun well in the study area

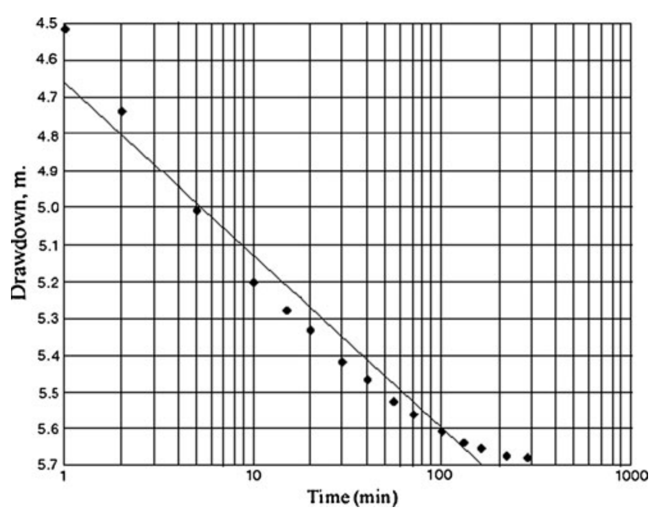


Fig. 16 Pumping test result in El-Agus well in the study area

Table 5 Classification of the aquifer potentiality according to transmissibility values (after Gheorhg 1979)

Potentiality of the aquifer	Transmissivity (m^2/day)
Highly potential	>500
Moderate potential	500–50
Low potential	50–5
Very low potential	5–0.5
Negligible potential	<0.5

sive series of steps. Incremental drawdown ΔS for each step are determined from approximately equal time intervals.

The total drawdown may be represented approximately by the following equation (Jacob 1964):

$$S = BQ + CQ^2$$

where S is the total drawdown in m, Q is the rate of discharge in cubic meter per day, and C is the well loss constant in day^2/m^5, and B is the formation loss constant in day per square meter.

Therefore, by plotting S/Q versus CQ and fitting a straight line through the points, the well loss coefficient (constant) C is given by the slope of the line and the formation loss coefficient B by the intercept Q=0 (Todd 1980).

The hydrogeological data for some wells within the studied area were automatically analyzed using a GWW software program. It used to estimate the aquifer loss coefficient (B) and the well loss constant (C). The obtained values of formation and well losses for the wells in the present study evaluated are given in the Table 3 and Figs. 6, 7, and 8.

From Table 3, the well loss values are smaller compared with formation loss values, indicating that the aquifer under pressure has behavior of leaky aquifer; therefore, it shows hydraulic connection with surrounding formation. The estimated values of well efficiency range from 78.50% to 87.76%.

Constant discharge tests

Hydraulic conductivity K, transmissivity T, and storage coefficient S are the main hydraulic parameters which

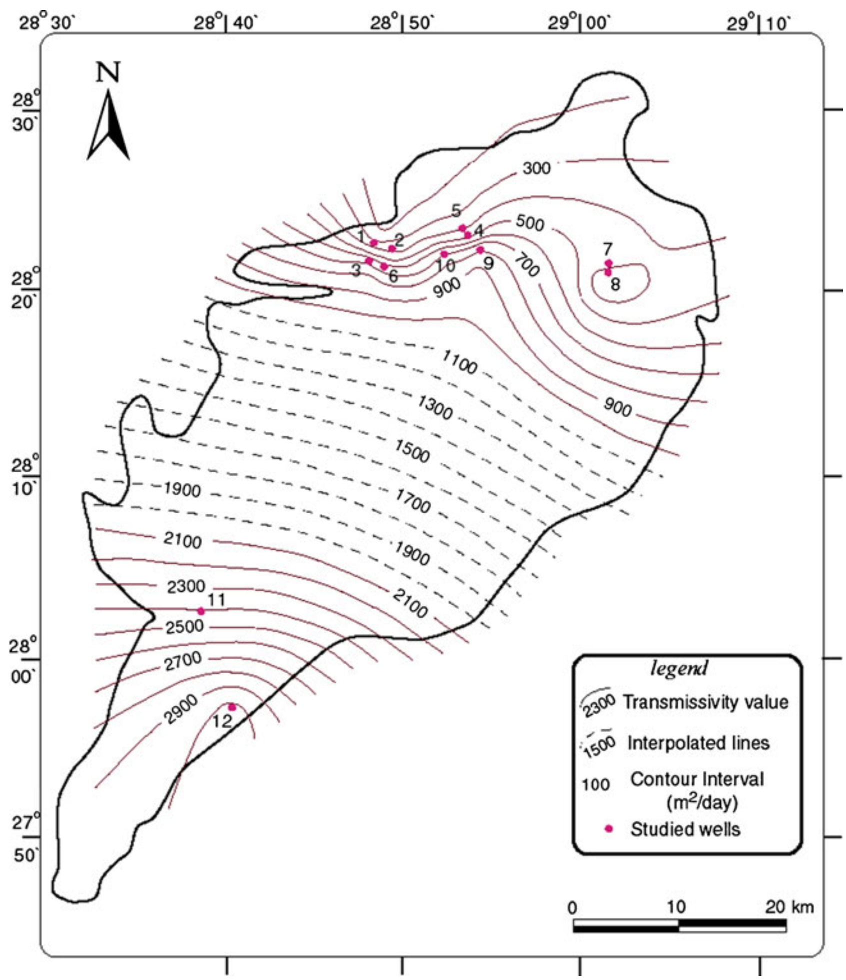


Fig. 17 Transmissivity contour map of the Nubian sandstone aquifer of El-ahariya Oasis

Table 6 Order of magnitude of storativity of different types of aquifers (Kruseman and DeRidder 1970)

Type of aquifer	Storage coefficient
Confined aquifer	From 10^{-4} to 10^{-6}
Semi-confined aquifer	From 10^{-2} to 10^{-4}
Unconfined aquifer	From 0.1 to 0.01

determine the water flow into, through, and out of subsurface formations and the water level response. These properties are important not only in their own right (e.g., wells should be located in high-transmissivity zones), but also are absolutely essential for establishing the state of the groundwater system for estimated future conditions.

In the present study, analysis of 12 pumping test data (constant discharge tests) was carried out in order to calculate the Nubian aquifer hydraulic parameters (transmissivity, hydraulic conductivity, and storage coefficient) using GWW software program with the Theis's method.

The results of pumping test analysis including the values of transmissivity, hydraulic conductivity, and storage coefficient using are summarized in Table 4. Examples of plots which resulted in the present analysis were shown in Figs. 9, 10, 11, 12, 13, 14, 15, and 16.

The transmissivity

The transmissivity is defined as the rate of flow under a hydraulic gradient equal to unity through a cross-section of unit width over the whole thickness of the aquifer. It is also equal to the product of the hydraulic conductivity (or permeability) and the thickness of the aquifer (Todd 1980). It follows that:

$$T = Kb = (\mathrm{m/day})(\mathrm{m}) = \mathrm{m}^2/\mathrm{day}$$

where b is the saturated thickness of the aquifer.

The transmissivity values in the study area decrease from 3,045 m^2/day in the southern part (El-Heiz area) to 236 m^2/day in the northeastern part (El-Harra area). According to Gheorhg (1979) classification in Table 5, the aquifer is characterized by high to moderate potentiality.

Using the obtained results (Table 4), a transmissivity contour map of the Nubian sandstone aquifer for El-

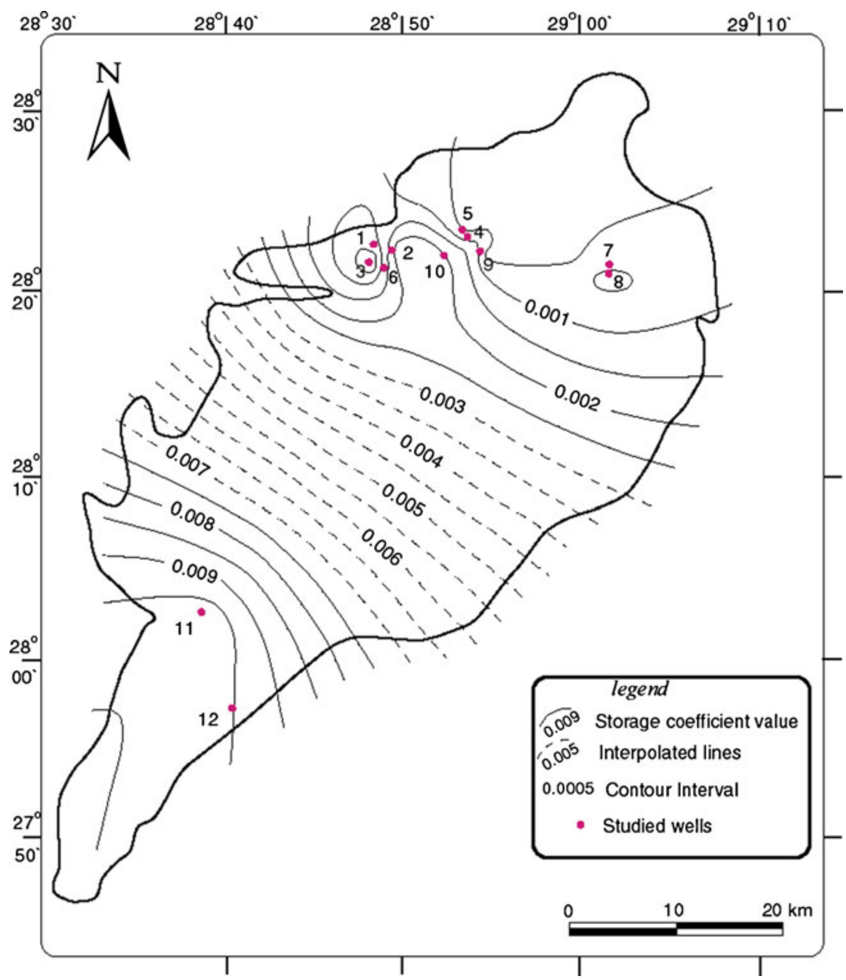


Fig. 18 Storage coefficient contour map of the Nubian sandstone aquifer of El-Bahariya Oasis

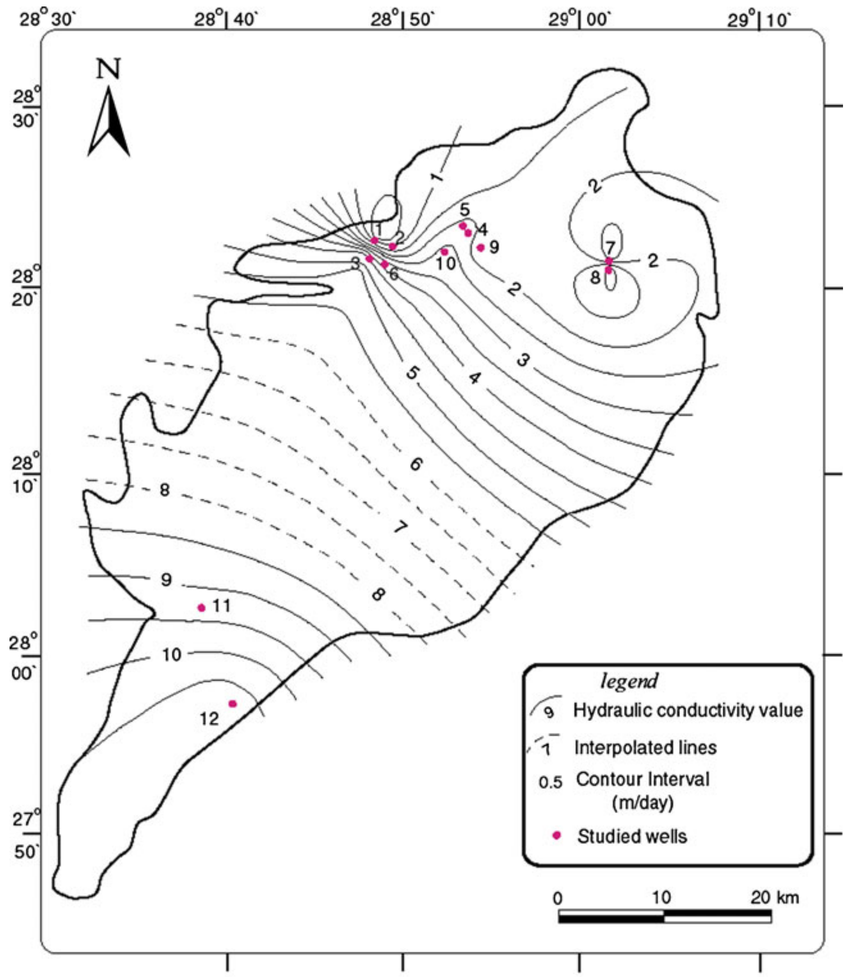


Fig. 19 Hydraulic conductivity contour map of the Nubian sandstone aquifer of El-Bahariya Oasis

Bahariya Oasis was constructed (Fig. 17) to show spatial variation of the transmissivity; an observed gradual increase of transmissivity values from the southern to northeastern direction. This may be due to the increase of shale or clay content in the concerned aquifer in that direction.

The storage coefficient

Storativity is defined as the volume of the water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of head normal to that surface. Storativity is expressed as a dimensionless fraction or percentage. Both hydraulic conductivity and storativity depend on particle size, shape, sorting, and cementation of the aquifer material (Gutentag et al. 1984). Different values of storativity that correspond to different types of aquifers are listed in Table 6 according to Kruseman and DeRidder (1970). The storage coefficient values range between 1.04×10^{-4} and 5.22×10^{-3}, as obtained from the results of pumping test analysis in the study area (Table 4).

A storage coefficient contour map of the Nubian sandstone aquifer was constructed from the results of pumping test analysis (Fig. 18). The S values show a decrease from southwest to northeast direction in the studied area, which ensure that the Nubian sandstone aquifer is under semi-confined to confined conditions according to the classification of Kruseman and DeRidder (1970) (Table 6).

Hydraulic conductivity

Hydraulic conductivity (K) is defined as the ability to transmit in unit time a unit volume of groundwater at the

Table 7 Order of magnitude of the hydraulic conductivity of different types of materials (Schoeller 1962)

Type of material	Hydraulic conductivity
Clay	10^{-5} to 10^{-7}
Silt	0.1
Fine sand	0.1 to 1
Coarse sand	1 to 100
Gravel	100 to 1,000 (or more)

prevailing kinematic viscosity through a cross-section of unit area, measured at right angles to the direction of flow, under a unit hydraulic gradient. Hydraulic conductivity (Fig. 19) is a function not only of the porous medium but also of the fluid and has units of velocity (in meters per day). Schoeller (1962) give an order of magnitude of the hydraulic conductivity of different types of materials (Table 7).

From the results obtained, the hydraulic conductivity values of the Nubian sandstone aquifer in the study area vary from to 0.46 m/day in the northern part to 10.88 m/day in the southern part with an average of 5.67 m/day. A hydraulic conductivity contour map of the Nubian sandstone aquifer was constructed (Fig. 19). The K values show an increase from the northeast direction to the southwest direction in the studied area. According to the classification of Schoeller (1962), the aquifer in the study area is mainly composed of coarse sand.

From the analysis of pumping tests and hydraulic properties of the Nubian sandstone aquifer, it was found that the southern parts of El-Bahariya Oasis (El-Heiz) are distinguished by high potentiality and efficiency of the aquifer, so it is recommended that decision makers should enlarge the agricultural, industrial, and touristic investments in these areas. Alternatively, owing to increasing drawdown at El-Zabu, El-Qasaa, and El-Bawiti localities in the northern part due to excessive groundwater withdrawal, an encouragement of inhabitants to move out from these areas and/or drilling new wells should be reduced.

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