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Groundwater conditions, East Siwa oasis, Western Desert, Egypt

Saad Younes Ghoubachi*

Desert Research Center, Cairo, Egypt

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ABSTRACT

The aquifers in East Siwa Oasis are differentiated using the geophysical well logging into Post Cenomanian limestone, Bahariya sandstone and Alam El-Bueib sandstone aquifers. The present work deals with the hydrogeological conditions of Bahariya sandstone aquifer in East Siwa Oasis. The Bahariya sandstone aquifer represents the fresh water source in the Siwa Oasis. The average thickness of the Bahariya sandstone aquifer is 300 m in east Siwa Oasis and exists under artesian and flowing conditions. The hydraulic parameters of the Bahariya sandstone aquifer are determined in some drilled wells tapping this aquifer using interpretation of geophysical well logging. The calculated groundwater volume of the Bahariya sandstone aquifer in the study area (15,000 km^2) attains 780 billion cubic meters of good quality. Hydrochemical analyses of 9 groundwater samples representing the Bahariya sandstone aquifer indicate that the salinity range from 160 ppm to 197 ppm (part per million), increasing due northeast while the groundwater salinity of the Alam El-Bueib sandstone aquifer is determined using the interpretation of geophysical well logging. The calculated average salinity is 2560 ppm reflecting brackish water type.

Introduction

Siwa Oasis is located 90 km east of the Libyan frontier and 300 km south of the Mediterranean coast and 800 km west Cairo (**Fig. 1**). It lies between Abu Shuruf in west Siwa and Qattara Depression in the east and it represents a depression of about 18 m below sea level. It is located between long. 25^{o} 40`-27$^{o}$ 05`E and lat. 28^{o} 40`-29$^{o}$ 40`E. The East Siwa area represents one of the areas may add about 30,000 Feddans project of the 1.5 million-Feddan reclamation project depending on the groundwater. The Bahariya sandstone aquifer is the source of fresh groundwater in study area.

The present investigation is mainly concerned with the hydrogeologic conditions and hydrochemical characters of Bahariya and Alam El-Beuib sandstone aquifers. The water bearing formations are discriminated into three aquifers (Post Cenomanian limestone, Bahariya sandstone and Alam El-Bueib sandstone) depending on the geophysical well logging. The Alam El-Bueib Formation is differentiated into the lower sandstone unit and upper claystone unit depending on the natural gamma ray of geophysical well logging. The hydrogeological conditions of the studied aquifers are determined based on the interpretation of the geophysical well logging.

* Corresponding author.
E-mail address: Ghoubachi66@yahoo.com

Methodology

The present work intends to study the geology, hydrogeology and hydrochemistry of the studied area. The lithological units were extracted from the available geological map, previous works and geophysical well logging (resistivity and gamma ray) with field verifications. The interpretation of geophysical well logging charts was used to determine the hydraulic parameters of Bahariya sandstone aquifer and groundwater salinity of the lower Alam El-Bueib unit.

Nine water samples were collected from flowing wells (January, 2014). Electric Conductivity (E.C.) was measured in the field after collection directly and these samples were subjected to various chemical analyses in the Desert Research Center to determine the major elements (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} cations and HCO_3^{-}, SO_4^{2-}, and Cl^{-} anions).

Geologic Setting

Based on the geologic map of Siwa Oasis with scale 1:500,000 [1], the geology description of the concerned area is described and the exposed rocks ranging in age from Late Cretaceous to the Quaternary. The lithostratigraphic column in east Siwa is studied through 12-drilled wells (**Fig. 1**). The natural gamma ray occurs naturally in clay content, making it possible to distinguish between sand and limestone (low gamma ray) and clay (high gamma ray). This column is discriminated

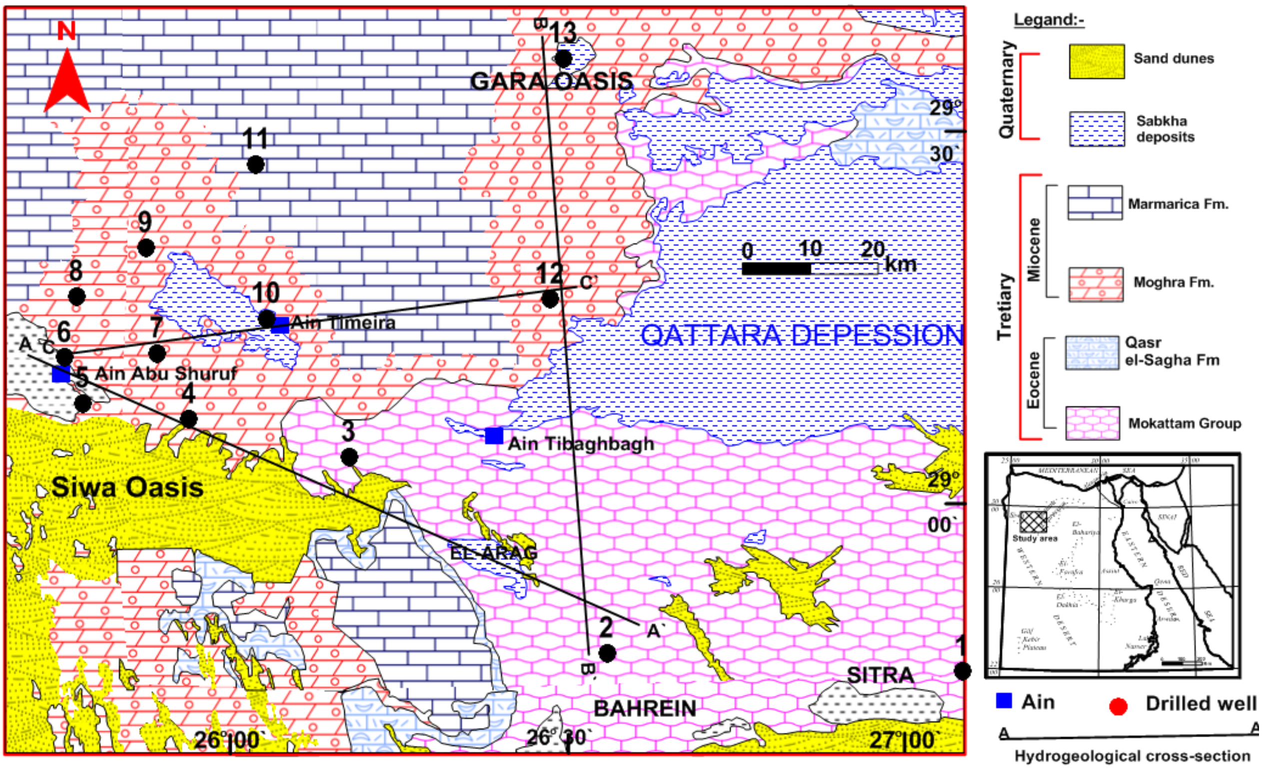

Fig. 1: Well location and geological map, East Siwa Oasis, Western Desert, Egypt [1].

into lithologic units (according to the well logs study; Resistivity and Gamma Ray) and reveals the following units from base to top (**Fig. 2**):

Alam El-Bueib Formation

This formation overlies unconformably the Paleozoic rocks and underlies also unconformably Bahariya Formation. Its type locality is Alam El-Bueib exploratory well no.1. (30° 38` 39``N; 29° 08` 37``E), with total thickness reaches 365 m [2]. Based on the data of the drilled wells [5], the top surface Alam El-Bueib relief map is compiled (**Table 1 and Fig. 3**). It indicates that the altitude of the top surface of this formation varies from 1019 m (below sea level) at southwest (well no. 4) to 1405 m (below sea level) at northeast (well no. 13). Its penetrated thickness ranges from 19 m (well no. 1) to 327 m (well no. 3). This formation is composed of sandstone and shale beds. It is restricted in central and eastern Siwa Oasis while it is eroded in western part of Siwa Oasis [3]. Alam El-Bueib Formation was deposited into shallow marine environment [4].

This formation can be subdivided into lower sandstone unit and upper claystone unit. The sandstone unit is penetrated by three wells having an encountering depths of -1087, -1223 and -1236 m under sea level (wells nos. 6, 4 and 3, respectively). The penetrated thickness of this unit attains 17 m, 80 m and 240 m. The lower unit of Alam El-Bueib Formation represents a water bearing formation.

The claystone unit is penetrated by the majority of wells at depths varying from -1019 (well no. 6) to -1405 m (well no. 13) under sea level (**Table 1**).

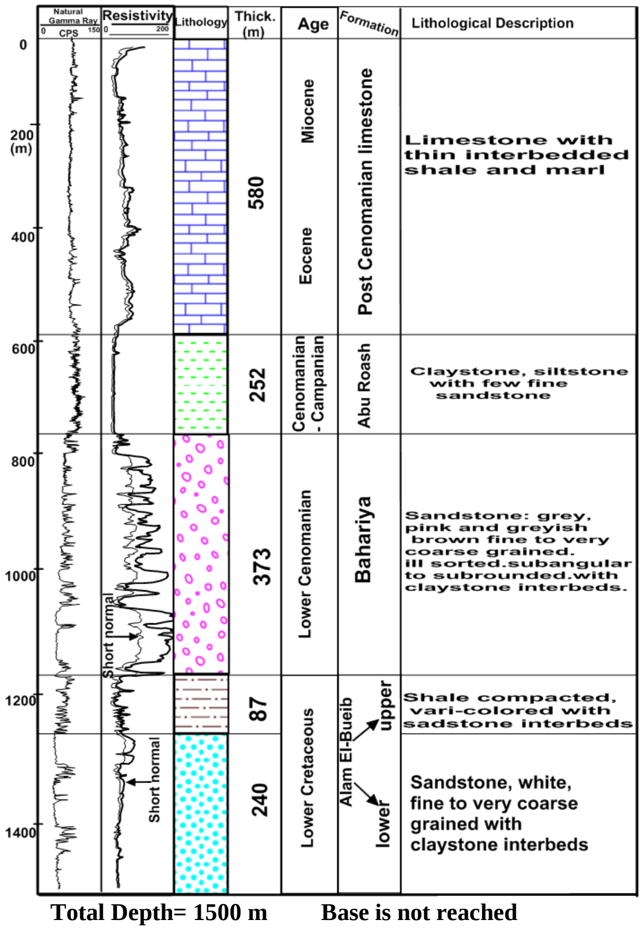

Fig (2): Composite lithostratigraphic section and geophysical logs of well no. 3 (modified after [5]).

Table 1: The inventory geological data of Alam El-Bueib Formation in East Siwa Oasis

Well No.	Depth to top Fm. (m)	Elevation masl	Penetrated thickness (m)	Elevation of top surface (masl)	Claystone unit thickness (m)	Elevation of top surface and stone unit (masl)	Sandston Thickness unit (m)
1	1066	-19	19	-1085	19	-	-
2	1200	74	136	-1126	136	-	-
3	1173	24	327	-1149	87	-1236	240
4	1095	-2	205	-1097	125	-1222	80
6	1005	-14	85	-1019	67	-1087	17
7	1100	-7	100	-1108	100	-	-
13	1376	-29	124	-1405	124	-	-

Note: masl = meter above sea level Fm: Formation

Its maximum thickness attains 136 m (well no. 2), while the minimum thickness reaches 19 m (well no. 1). This rock unit is mainly composed of shale with few sandstone interbeds and it represents a confining unit. It prevents the saline water of the Alam El-Bueib sandstone aquifer unit (lower unit) to flow upward into the overlying Bahariya sandstone aquifer of fresh water.

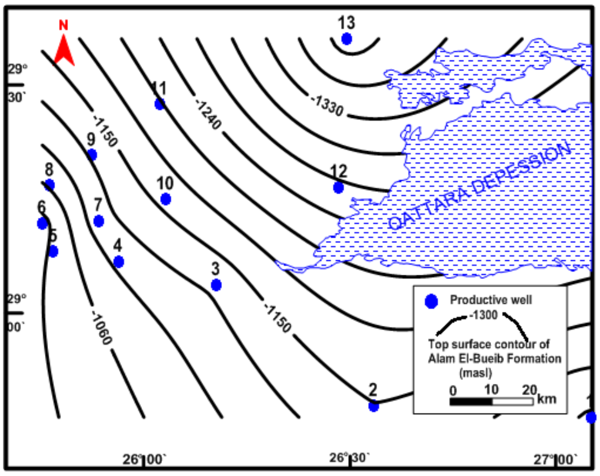

Fig (3): Structure contour map of top surface Alam El-Bueib Formation.

Bahariya sandstone Formation

Bahariya sandstone Formation overlies unconformably the Alam El-Bueib Formation and underlies the Abu Roash claystone Formation [6]. This formation is composed of ferruginous sandstone, medium to coarse grained with clay interbeds. The top of this formation is recorded at depths ranging from -531 m (well no. 2) to -1129 m under sea level (well no. 13), where it gradually dips due northeast (**Figs. 4 and 5**). The thickness of the concerned formation ranges from 253 m (well no. 6) to >400 m (well no. 12), with an average thickness of 300 m. The thickness of Bahariya sandstone Formation increases towards the Qattara Depression (**Fig. 5**). The high thickness of this formation is recorded in downthrown side of faults away from the activity of erosion processes. The Bahariya Formation is encountered in the subsurface in all deep drilled wells at east Siwa Oasis.

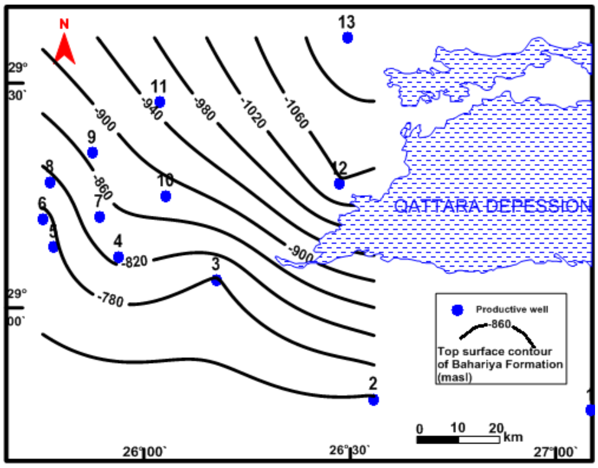

Fig (4): Structure contour map of top surface Bahariya sandstone Formation.

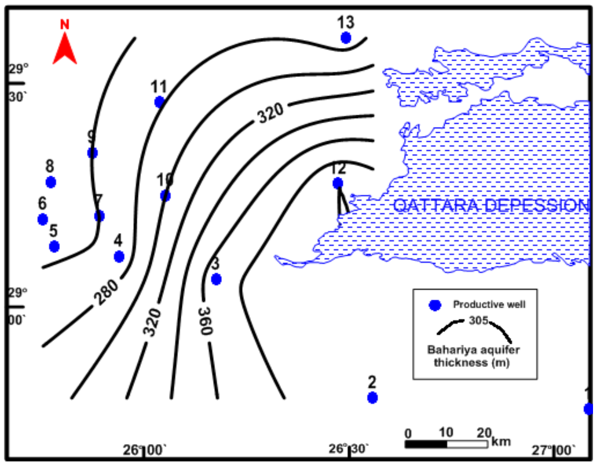

Fig (5): Isopach map of Bahariya sandstone Formation.

Abu Roash Formation

It is encountered in subsurface in the study area. It overlies Bahariya sandstone Formation and underlies Khoman chalk Formation [7]. In the study area, this formation is composed of claystone between sandstone of Bahariya Formation and chalk of Khoman Formation. Accordingly, it represents a marker bed taken as a reference to construct the hydrogeological cross-sections and panel diagram. The top surface of this rock unit is reported at depths of - 524 m (below sea level) at well no. 3 and - 829 m (below sea level) at well no. 13. Its thickness ranges from 18 m (well no. 6) to 300 m (well no. 13) with an increase towards the east direction due Qattara Depression (**Fig. 6**). The differences in thickness are attributed to the structural deformation where the maximum recorded thickness of well no. 13 is located in the downthrown side of the fault (**Fig. 9**).

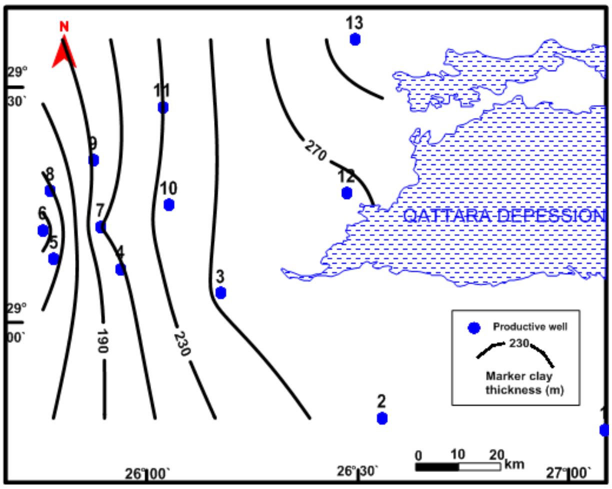

Fig (6): Isopach map of Abu Roash claystone unit.

Post Cenomanian rock units

The Mokattam Group (Middle Eocene), Qasr el-Sagha Formation (Upper Eocene), Moghra Formation (Lower Miocene) and Marmarica Formation (Upper Miocene) represent the post-Cenomanian rocks in the study area. These rock units are composed mainly of limestone, dolomitic limestone, chalky limestone, and shale. Their thicknesses range from 400 m (well no. 2) to 875 m (well no. 12) and increase towards the northeast direction (**Fig. 7**). The maximum recorded thickness of well no. 12 is located in the downthrown side of the fault (**Fig. 9**).

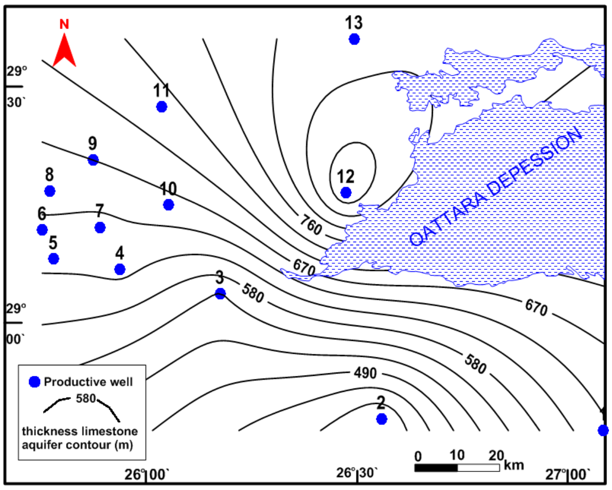

Fig (7): Isopach map of the post Cenomanian rock units.

The limestone of these formations is highly fractured and represents water bearing rocks. The study area is mostly covered by Quaternary deposits in the form of sand dunes and sabkha deposits.

The constructed panel diagram (**Fig. 8**) for the subsurface formations in east Siwa Oasis area shows that the thickness of the Post Cenomanian limestone increases due north. This panel shows also some wells reached to the lower Alam Bueib formation.

Structurally, Siwa Oasis occupies a regional syncline fold trending E-W which encloses a local anticline with NW-SE direction [8]. East Siwa area is affected by number of normal faults and they are created horsts and grabens faults (**Fig. 9**). In this respect, Abu Roash Formation is considered as a marker unit for delineating the fault systems.

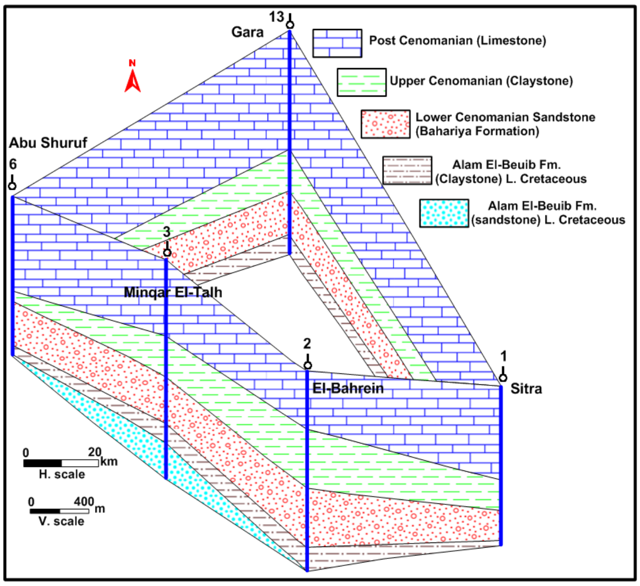

Fig (8): Panel diagram showing the subsurface configuration in East Siwa Oasis, Western Desert, Egypt.

HYDROGEOLOGICAL CONDITIONS

The hydrogeological conditions of east Siwa area are defined from top to base into three aquifers Post Cenomanian fractured limestone, Bahariya sandstone and Alam El-Bueib sandstone aquifers. The present study depends on the available data of twelve deep drilled wells (**Fig. 1 and Table 2**) as following:

1- The Post Cenomanian fractured limestone aquifer

This aquifer directly overlies Abu Roash claystone, all springs and shallow wells tapping this aquifer. The concerned aquifer is composed mainly of fracture limestone and belongs to a long range of geologic time from Eocene to Miocene age. The upper part of the aquifer belongs to Miocene and represented by Marmarica (Middle Miocene) and Moghra (Lower Miocene) Formations.

The average groundwater salinity of this aquifer attains 4000 ppm, while the salinity of groundwater in part of Eocene attains 13,000 ppm. The high difference in the water quality of the carbonate aquifer is due to the change in the aquifer facies [9].

Table 2: Inventory data of some wells tapping Bahariya sandstone aquifer (January 2014).

Well No.	Well name	Total depth (m)	Screen Interval (m)		Thickness (m)	Top surface (masl)	Well Yield (m^3/h) [9]	Salinity (ppm)
			From	to				
1	Sitra	1130	870	1060	197	-889	350	187
2	El-Bahrein	1336	810	1200	390	-531	250	168
3	Minqar El-Talh	1500	800	1170	373	-738	300	191
4	El-Khashabi	1300	830	1090	266	-830	300	187
5	Zihra	1116					250	175
6	Abu Shuruf	1090	820	1000	253	-766	250	192
7	El-Awaf	1208	840	1100	260	-848	300	
8	Umm Hiyus	1308						160
9	Umm Hiymal	1303					200	
10	Timeira	1200	707	1007	300	-700	300	172
12	Tibaghbagh	1502	1110	1500	360	-1057	350	228
13	El-Gara	1500	1100	1370	270	-1129	600	197

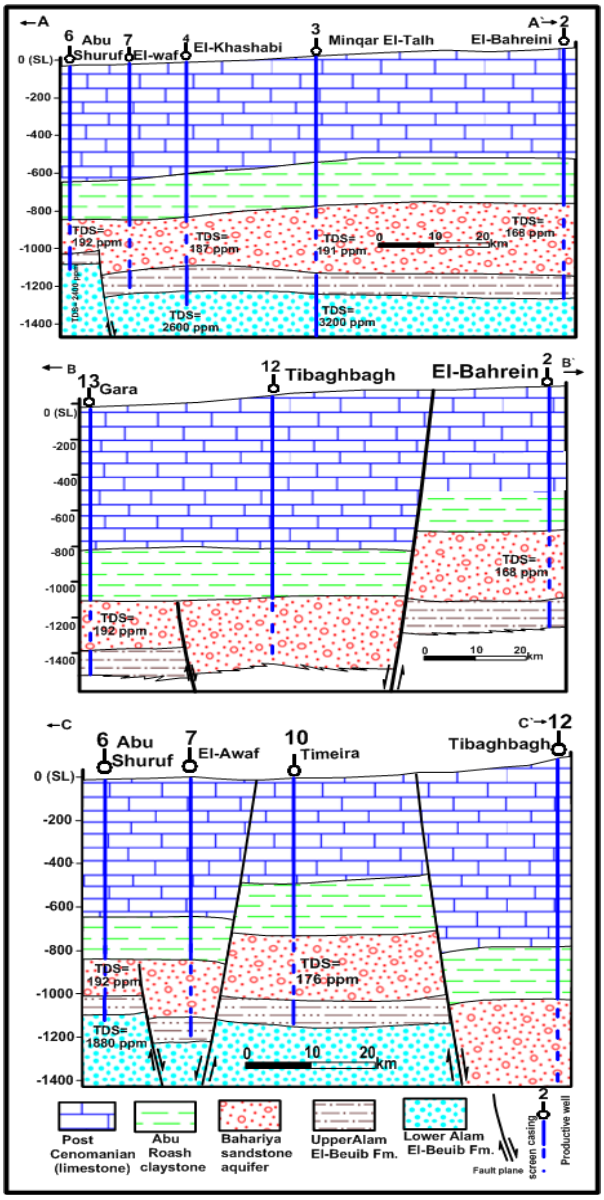

Fig (9): Hydrogeological cross-sections, East Siwa Oasis area.

2- Bahariya sandstone aquifer

Bahariya sandstone aquifer represents the main aquifer and the sole source of fresh water in Siwa Oasis. This aquifer lies between two thick clay beds. It overlies directly the Upper Alam El-Bueib claystone and underlies the Lower Abu Roash claystone unit. It is composed mainly of medium to coarse grained sandstone with shale interbeds.

Twelve deep drilled wells are recorded in east Siwa Oasis tapping Bahariya sandstone aquifer with depths range from 1090 m (well no. 6) to 1502 m (well no. 12) (**Table 2**). The groundwater potential of these wells is estimated to be 85,000 m^3/day.

The groundwater of the concerned aquifer occurs under confined and artesian conditions. It is hydraulically connected with underlying Alam El-Bueib sandstone aquifer and overlying fractured limestone aquifer. These rocks come in contact with each other as a result of faulting displacement or through the connections along fault planes see (**Fig. 9**).

The piezometric head of the investigated aquifer reaches 100 m above ground surface in eastern part, while it attains 80 m at the western part of the Siwa area [9]. The high pressure head of this aquifer in eastern part is attributed to the Bahariya sandstone aquifer being covered by thick Abu Roash claystone confining unit.

2.1. Hydraulic parameters of Bahariya sandstone aquifer

The aquifer parameters are estimated as based on the interpretation of the geophysical well logging. They are estimated as following:

2.1.1. Effective porosity (Φ_{eff})

The effective porosity of the investigated aquifer is determined from the geophysical well logging data applying Archie equation [10]:

$$\Phi_{eff} = (5400xRw/Rt)^{1/2} \text{ (in sodium chloride water type)}$$

Where Φ_{eff} is the effective porosity in percent, *Rt* is the true resistivity in ohm meters; *Rw* is the formation water resistivity in ohm meters.

The true resistivity (*Rt*) is determined by correction of the long resistivity log ($R_{64''}$) or (R_{LLD}) and short normal resistivity log ($R_{16''}$) or (R_{LLS}). The true resistivity (*Rt*) is obtained by the following equation: $Rt = 1.7\ R_{LLD} - 0.7\ R_{LLS}$ (if $R_{LLD} > R_{LLS}$). The effective porosity of the investigated aquifer varies from 15.5% (well no. 1) to 19% (well no. 9) (**Table 3**), with an average effective porosity 17.3% and increases towards the northeast direction with increasing of the sand percentage.

2.1.2. Hydraulic conductivity (K)

The hydraulic conductivity (*k*) of the Bahariya sandstone aquifer is determined by substitution of effective porosity in Martoz equation [11]. The effective porosity is calculated by using Arachi equation. The hydraulic conductivity is obtained by the following equation:

$$\Phi_{eff} = 0.462 + 0.045 \ln K$$

Where Φ_{eff} is the effective porosity in decimal and *K*, the hydraulic conductivity in cm/sec.

The hydraulic conductivity of the investigated aquifer ranges from 5 m/day (well no. 1) to 23.6 m/day (well no. 13) with an average 10.3 m/day and increases due north with increasing the effective porosity and sand percentage.

2.1.3. Transmissivity

The transmissivity is the product of the average hydraulic conductivity (K) calculated from Martoz equation (1968) and the thickness (D) of the aquifer. The transmissivity of the concerned aquifer is obtained by using the Darcy equation [12]: **T = K*D**

Where T is the transmissivity in m^2/day and K, the hydraulic conductivity in m/day, D is the aquifer thickness in m.

The transmissivity of Bahariya sandstone aquifer varies from 985 m^2/day (well no. 1) to 4500 m^2/day (well no. 2). It increases towards the north direction as a function of the increasing of thickness and sand percent. The transmissivity of this aquifer indicates high potential (> 500 m^2/day) according to Gheorhge [13].

The low productivity of well no. 2 is attributed to the location of this well, where it has a high elevation above sea level which decreasing the flowing rate (**Fig. 3**).

2.2. Approximate Groundwater quantity of the Bahariya sandstone aquifer in East Siwa area

The estimated groundwater quantity of the Bahariya sandstone aquifer in East Siwa area depends principally on the thickness and effective porosity of the studied aquifer. It is obtained by approximately the following equation: **Q = D*A*ϕeff**

$$Q = D \cdot A \cdot \phi_{eff}$$

Where Q is the storage capacity of the aquifer in m^3, ϕ_{eff} is the average effective porosity in decimal (0.173), D is the average aquifer thickness in meter (300 m) and A, the aquifer area in m^2 ($15 \cdot 10^9\ m^2$). The aquifer storage capacity of the Bahariya sandstone aquifer attains 780 bcm of fresh water. The groundwater quantity of the Bahariya sandstone aquifer attains 780 bcm of fresh water.

3. Alam El-Bueib sandstone aquifer

The lower unit of Alam El-Bueib sandstone aquifer is detected by the deeper wells in the study area (wells nos. 3, 4 and 6 respectively). Its maximum thickness reaches 240 m (well no. 3) because it is located along the down thrown side of fault away erosion processes (**Fig. 9**). The concerned aquifer is hydraulically connected with the overlying Bahariya sandstone aquifer, where these rocks come in contact with each other through fault planes (**Fig. 9**). The porosity of this aquifer varies from 24 % to 25 % [14].

Hydrochemistry

The hydrochemical characteristics of Bahariya sandstone aquifer are described as based on the analysis of 9 groundwater samples collected from the flowing wells (January 2014) (wells nos. 9, 11 and 12 stopped flowing). The major elements Na^+, K^+, Ca^{++} and Mg^{++} ions as cations, and Cl^-, $SO4^{--}$ and $HCO3^-$ ions as anions, are measured in the Laboratory of the Desert Research Center (**Table 4**). The groundwater salinity and hypothetical salts are discussed.

Groundwater salinity

The groundwater salinity of the Bahariya sandstone aquifer in the study area reflect a fresh water type (<1000 ppm) according to Chebotarev classification [15]. The groundwater salinity ranges from 160 ppm (well no. 8) to 197 ppm (well no. 13). The high salinity is essentially attributed to location in downthrown side of the fault. Where the Bahariya sandstone aquifer comes in contact with lower unit of Alam El-Bueib sandstone aquifer of high salinity as a result of faulting displacement (**Fig. 9**). The constructed iso-salinity contour map of the Bahariya sandstone aquifer reveals an increase of groundwater salinity towards the north direction (**Fig. 10**).

Table 3: Hydraulic parameters of some wells tapping Bahariya sandstone aquifer, East Siwa area.

Well No.	Elevation (masl)	Bahariya Thickness aquifer (m)	Effective porosity (%)	Hydraulic Conductivity (m/day)	Transmissivity m^2/day	Well yield m^3/hour [9]
1	-19	197	23	5	985	350
2	+74	390	26	11.4	4500	250
3	+24	373	25.2	8	2984	300
4	+47	266	26	9.5	2527	300
6	-14	253	24.3	6.7	1695	350
12	-29	360	25	7.77	2800	350

Table 4: Chemical analyses of the studied groundwater samples (January 2014).

Well No.	EC µmhos/sec)	TDS (ppm)	Ca^{++} (ppm)	Mg^{++} (ppm)	Na^{+} (ppm)	K^{+} (ppm)	HCO_3^{-} (ppm)	SO_4^{--} (ppm)	Cl^{-} (ppm)	SAR (epm)
1	310	187	11.6	9.77	30	24	134.81	20	24.58	2.3
2	295	168	19.91	14.39	7.38	28	126.88	12	25.67	1
3	322	191	11.00	7.70	43	16	142.74	10	31.69	3
4	287	187	12.53	8.85	35	25	118.95	10	41.12	2.6
5	305	175	14.38	9.63	25	20	118.95	15	31.25	1.8
6	328	192	10.54	5.62	48	15	142.74	10	31.62	3.5
8	266	160	7.20	9.40	27	21	103.09	15	29.04	2.3
10	298	176	9.12	5.11	45	14	130.84	6	31.69	3.5
13	340	197	6	12.16	40	23	142.74	15	30	2.9

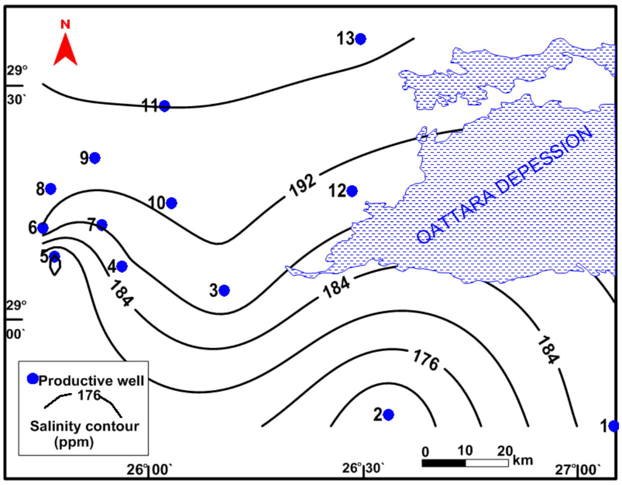

Fig (10): Iso-salinity map (TDS in ppm) of the Bahariya sandstone aquifer, East Siwa area (Jan. 2014).

The combination between ions reveals the presence of different varieties from salt assemblages. The groundwater of the Bahariya sandstone aquifer has one group of hypothetical salts combination: **NaCl, Na_2SO_4, $NaHCO_3$, Mg $(HCO_3)_2$ and Ca $(HCO_3)_2$**.

The groundwater samples of Bahariya sandstone aquifer have **Na_2SO_4** and **$NaHCO_3$** of meteoric origin.

Groundwater quality of Bahariya sandstone aquifer

It is important to know the groundwater quality for drinking, domestic, livestock and irrigation in the study area. Because, in recent times, there has been increased demand for water due to population growth and intense agricultural activities. The evaluation of groundwater of the Bahariya sandstone aquifer in the East Siwa area for drinking, domestic, livestock and agricultural purposes is discussed as follows:

1. Drinking and domestic purposes

Depending on the water quality standards recommended by the (16), the groundwater of the Bahariya sandstone aquifer is excellent for drinking and domestic purposes as the TDS (Total dissolved solids) is less than 500 ppm.

2. Livestock and poultry purposes

According to [17], the groundwater of the Bahariya sandstone aquifer in East Siwa area is excellent (TDS <1,000 ppm) for livestock and poultry uses.

3. Agricultural purposes

The US Salinity Laboratory Staff classification [18] is widely used for the evaluation of water for irrigation purposes. This classification depends on the relationship between the sodium adsorption ratio (SAR) and electric conductivity (EC) of the water samples (**Table 4 and Fig. 11**). It is clear that the groundwater samples are located in class (C2-S1). This type of water is used for irrigation of all plants and suits for medium permeability.

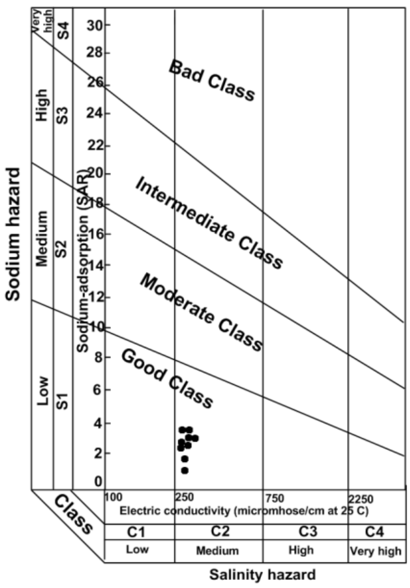

Fig (11): Classification of groundwater for irrigation using U.S. Salinity Lab. Staff [18].

Estimation of groundwater salinity of the Alam El-Bueib sandstone aquifer

Three productive wells nos. 3, 4 and 6 reach to the Alam Bueib sandstone aquifer, but these wells tapping only the Bahariya sandstone aquifer. Accordingly, the calculated total dissolved solids (TDS) of the lower part of Alam El-Bueib sandstone aquifer is based on the geophysical well logging data applying the following equations:

$$F = 0.62 / (\Phi)^{2.15} \text{ for sand} \quad [10]$$

The formation factor (F) of the Alam El-Bueib sandstone aquifer is determined by substitution of the total porosity (Φ) in the previous equation.

The calculated porosity attains 20 % [14]. The calculated formation factor is determined by substitution of the effective porosity in the previous equation. The formation factor attains 20.6.

$$F = Rt / Rw$$ [10]

Equation: Rt= 1.7 R_{LLD} – 0.7 R_{LLS} average formation water resistivity (Rw) of the investigated aquifer is 2.25, 2.26 and 2.82 ohm.m in wells nos. 4, 3 and 6, respectively.

The total dissolved solid (TDS) of the Alam El-Bueib sandstone aquifer is determined from Guyod equation. The TDS is obtained by the following equation:

$$TDS = K / Rw$$ [19]

Where TDS is the total dissolved solids in ppm, Rw is the formation water resistivity in ohm meters; K is the constant equal 5300 in NaCl water.

The total dissolved solids (TDS) of this aquifer are 1880, 2600 and 3200 ppm (wells nos. 6, 4 and 3, respectively) with average salinity of about 2560 ppm. The groundwater of the Alam El-Bueib sandstone aquifer is brackish water. The high groundwater salinity of this aquifer is attributed to this aquifer has high intercalations of claystone [14].

Conclusions

The groundwater of Bahariya sandstone aquifer exists under confined conditions, where being covered by thick claystone of Abu Raosh Formation. Its average thickness attains 300 m. the drilled wells tapping the Bahariya sandstone aquifer are under flowing conditions and its average head is 100 m above ground surface. The average calculated transmissivity, hydraulic conductivity and effective porosity from geophysical well logging are 2582 m^2/day, 10.7 m/day and 17.3% respectively. The calculated groundwater quantity of the Bahariya sandstone aquifer attains 780 billion cubic meters representing a huge fresh groundwater volume. The groundwater salinity of the Bahariya sandstone aquifer ranges from 160 ppm to 197 ppm representing very good fresh water.

The Alam El-Bueib Formation is defined approximately for the first time in the present work into lower sandstone unit representing the water bearing formation and upper claystone unit represents confining unit. The average calculated groundwater salinity of Alam El-Bueib sandstone unit using geophysical well logging is 2560 ppm representing brackish water.

Recommandation

For the manner of proper development of the groundwater resources along East Siwa area, the following activities are recommended. All wells taping the Bahariya sandstone aquifer are under flowing conditions, more attention should be focused on the utilization of flowing wells by constructing surface reservoirs near wells to collect the continuous flow of water and preventing losses and installing regulators on the flowing wells to control the discharge. Groundwater of Bahariya sandstone aquifer has excess iron. Excess iron has a risk on the health of inhabitants, animals, soil and crops. Removing iron is recommended by chemical treatment of groundwater.

Acknowledgements

The author expressed his gratitude to thanks the General Company for Research and Groundwater (Regwa) for obtaining the geophysical well logging charts of the drilled wells in the area of study.

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