Groundwater and Characteristics of the Tertiary-Quaternary Aquifer System West of Mallawi, Upper Egypt

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Abstract The desert areas in Egypt are suffering from the water shortage, so the groundwater exploration is the main solution for water demands in such areas. The area west of Mallawi, Upper Egypt is considered one of the promising areas for sustainable development. Mallawi area is located to the west of the Nile valley and is bounded by latitudes 27° 23′ 00″ and 28° 00′ 00″ N, and longitudes 30° 25′ 47″ and 31° 00′ 00″ E. The area is arid to semi arid, hot climate, dry, rainless in summer, and mild with rare precipitation in winter. In such area, the groundwater is the only source for sustainable development. So, the evaluation of the groundwater is necessary, where it is characterized by good water potentialities through the existing of three aquifers. These aquifers are; Quaternary sand and gravels, Oligocene-Pleistocene gravels and Middle Eocene fractured limestone. The Quaternary aquifer in the flood plain is considered as highly productive where the aquifer has an average transmissivity value of the order of 8906 m^2/day and average specific capacity of 25 m^3/h/m. The water salinity of this aquifer ranges between 203 and 549 mg/l and increases westward. The second aquifer; Oligocene-Pleistocene aquifer is moderately productive aquifer having an average transmissivity value of the order of 3291 m^2/day and hydraulic conductivity ranges between 13.22 and 59.9 m/day and average specific capacity of 9.6 m^3/h/m. Its saturated thickness ranges between 91.5 and 113.5 m and its salinity ranges between 719 and 801 mg/l. The third aquifer; the Eocene fractured limestone aquifer is considered as highly productive aquifer where it attains an average transmissivity value of the order of 6091 m^2/day and average specific capacity value of 208 m^3/h/m. In this aquifer, the water salinity ranges between 462 and 845 mg/l. The geologic structures play an important role in the direct hydraulic connection between the three aquifers, where; the Eocene fractured limestone aquifer is recharged directly from the Quaternary aquifer and then acts as a rechargeable source for the Oligocene-Pleistocene aquifer. The general flow direction of the groundwater is from east to west with some local change in the Eocene fractured limestone aquifer where there is a flow direction from southwest to the northeast direction which may be attributed to the over-exploitation in this locality or the effect of the fractures orientation in

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this aquifer system. Groundwater salinity in the three dominant aquifers generally increases westwards; i.e. in the same water flow direction.

Introduction

Water is the important component of the development of any area. The human settlement depends on a large extent on the availability of water resources. In the recent years, the consumption of water is greatly increased due to the increase in human population in the study area.

In the last decades, the development of the Upper Egypt governorates desert areas attracted the attention of the decision makers and the investors which is achieved by reclamation of more desert lands and building up new communities. This natural expansion for agricultural, industrial and civil activities in the Western Desert of Egypt necessitates more exploration activities for groundwater resources.

The pilot area is located to the west of the Nile valley occupying the floodplain and the desert fringes between latitudes 27° 23′ 00″ and 28° 00′ 00″ N, and longitudes 30° 25′ 47″ and 31° 00′ 00″ E (Fig. 1). The area is arid to semi arid, hot climate,
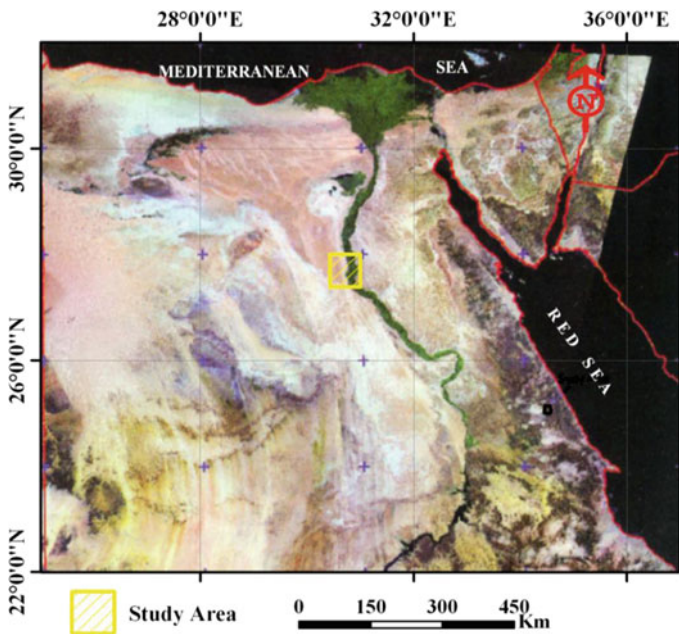

Fig. 1 Satellite image of Egypt showing the location of the study area

dry, rainless in summer, and mild with rare precipitation in winter. The rainfall average value for the last 15 years ranged from 23.05 to 33.15 mm/year, while the evapotranspiration at El Minia is 4897.91 mm/year [1, 2]. The average temperatures during January are 4.5–20.5 and 20.5–37.7 °C during August.

In this area, the water resources are represented by the Nile River as well as the groundwater of the existed three aquifers.

The main objectives of the present study are to evaluate the characteristics of the existed aquifers and assessment of the groundwater potentialities and quality at the west of Mallawi area aiming to realize the sustainable development of such area.

Geomorphological and Geological Setting

The geomorphological and geological setting of the concerned area plays an important role in the groundwater occurrences through the geomorphological features and the geological structures.

Geomorphological Setting

The study area includes three geomorphological units [3]. The first unit is young alluvial plain of the Nile which occupies the area adjacent to the Nile bank from west to the eastern scarp of the limestone plateau The second unit is Nile terraces which lay adjacent to the cliff of the limestone plateau and to the west of the young alluvial plain forming a gently undulated dissected surface made of several broad bench differentiated into old and young terraces. The third one is western limestone plateau which bounds the Nile valley from the east and the west.

Generally, the ground elevation varies widely from less than 38 m in the flood plain area to more than 160 m at the limestone plateau at west as shown in the Digital Elevation Model (Fig. 2).

Geological Setting

The geological map (Fig. 3) [4], shows that the surface of the study area is covered by the Middle Eocene limestone, Oligocene-Pleistocene gravel and sand and Quaternary deposits. The recorded rock units from base to top are [3, 5]:
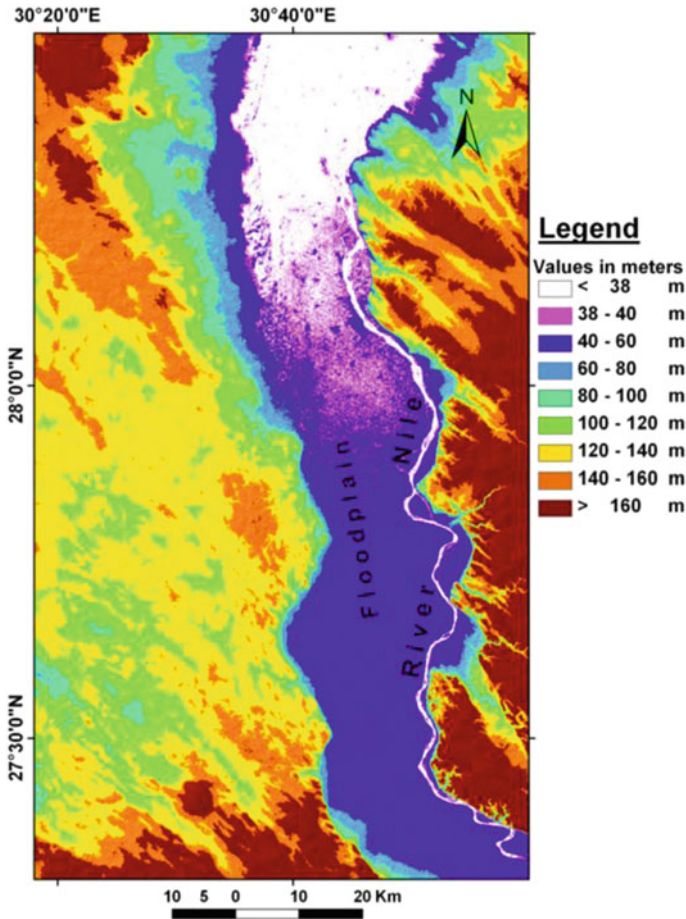
Fig. 2 Digital Elevation Model (DEM) of the study area showing the ranges of ground elevations along the study area

Middle Eocene Limestone (Samalut Formation)

This Formation is the oldest exposed rock unit in the vicinities of the study area overlying El-Minia Formation of Lower Eocene. It consists mainly of massive lime-stone assigned to the Early-Middle Lutetian times. This Formation is exposed at the northern, southern and eastern portions, while in the western portion; it is covered by a great thickness of Oligocene-Pleistocene gravels and sands. Samalut Formation represents one of the main water bearing formations in the study area through its highly fractured systems.
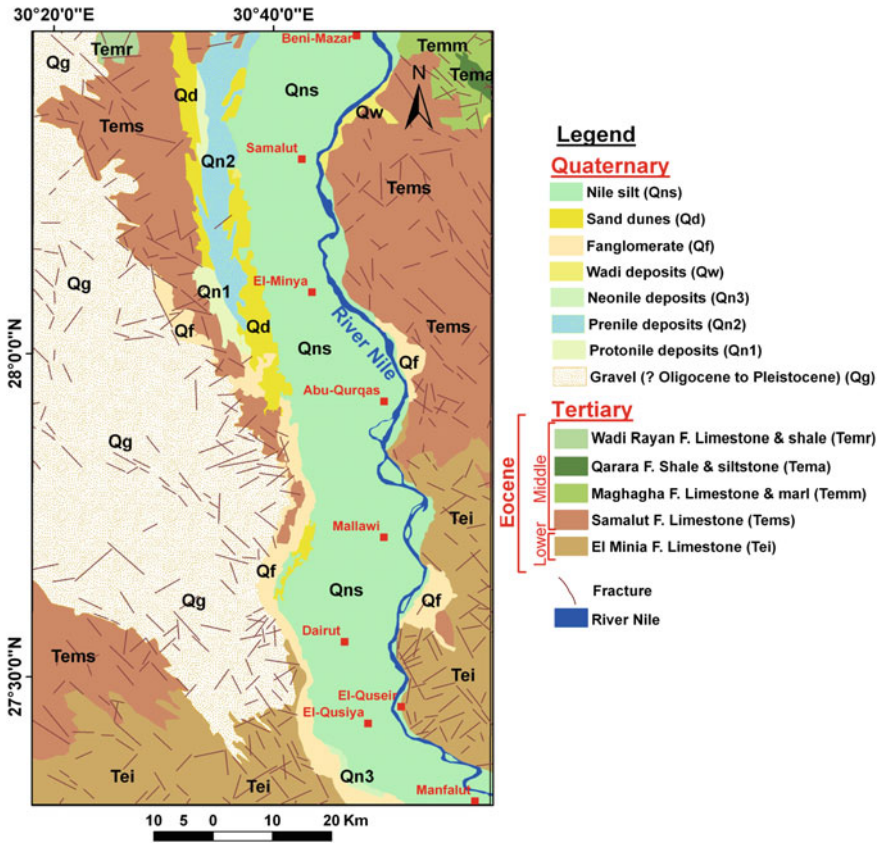
Fig. 3 Geologic map showing the different exposed geologic units in the study area and its vicinities (After CONOCO, 1987)

Oligocene-Pleistocene Gravel and Sand

It covers a wide area and composed mainly of gravel, sand, clay and limestone fragments, varying in thickness from few meters in the northern, southern and eastern portions to more than 200 m in the western portion.

Quaternary Deposits

It has a wide distribution in the study area including the Nile silt, sand dunes, and Fanglomerates.

Geologic Structure

Structures as hydrodynamic contacts impact on the groundwater flow pattern of an aquifer, as well as, the major structural features impacting on groundwater are fractures and folds.

From the structural point of view, the study area affected by a series of fractures and faults which are formed by brittle fracturing of rocks. Fractures are not homogeneously distributed in the rock mass, and because the permeability of the fracture system is mainly depended on the width and degree of fracture connectivity, it is very difficult to predict the yield of a well or borehole in crystalline aquifer [6].

The Nile Valley is essentially bounded by wrench faults that are more or less parallel either to the Gulf of Suez (NW–SE) or Gulf of Aquba (NE-SW) [3, 7].

Aquifer Systems

The investigation of 31 wells (Fig. 4 and Table 1) tapping the three existed aquifers was carried out both in the field and in the lab to assess the groundwater potentialities. Water depths, long term and phase discharge pumping studies, and water sampling for chemical analysis are examples of such investigations.

Quaternary Aquifer (The Nile Alluvium Aquifer)

This aquifer occupies the central strip of the Nile valley system forming the old cultivated lands on both sides of the Nile (floodplain). It is composed of Pleistocene clay, graded sand and gravel and capped by a Holocene silty clay layer which acts as an aquitard. The thickness of this aquifer ranges from 25 m at the desert fringes to 300 m at the central Nile Valley [8] and is recharged mainly from Nile water, irrigation system, drains, and agricultural wastewater [9].

Oligocene-Pleistocene Aquifer

This aquifer is composed of clay, sand and gravel. It occupies the outer fringes of the Nile aquifer system adjacent to the floodplain.
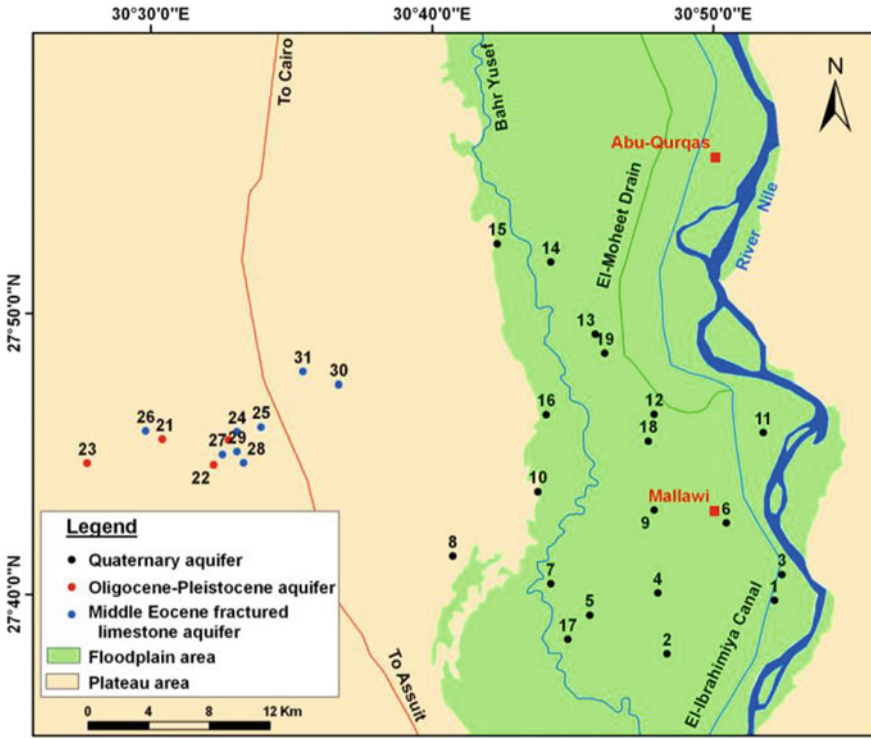
Fig. 4 Well location map showing the distribution of the different existing wells of the three aquifers (Quaternary, Oligocene-Pleistocene and Middle Eocene Limestone Aquifer)

Middle Eocene Limestone Aquifer

This aquifer is not outcropping in the study area but it exists in the subsurface as a fractured system and constitutes the main aquifer through its highly fractured systems which increase its permeability and its productivity. The Middle Eocene limestone aquifer was subjected to different studies including its potentials and its geochemical characteristics. Abdel Moneim et al. [10] studied the groundwater management at west El-Minya desert area, [11] studied the water resources management: of El-Minya Governorate, [12] studied the assessment of the hydrogeochemical processes affecting groundwater quality in the Eocene limestone aquifer at the desert fringes of El-Minya governorate, [13] discussed hydrological evaluation of the tertiary-quaternary aquifer system west Mallawi, [14] studied the hydrogeology of the shallow aquifer in the area west Samalot, [15] utilized the geological data and remote sensing applications for investigation of groundwater occurrences in West El Minia governorate and [16] evaluated the groundwater potentials of Eocene limestone aquifer in West-West El-Minya area.

Table 1 Depth to water and water salinity of the existed wells of the three aquifers (Quaternary, Oligocene-Pleistocene and Middle Eocene)

Well No	Aquifer	Depth to water m	Water salinity mg/l
1	Quaternary aquifer		323.3
2			369.4
3			314.8
4			445.2
5			510.2
6			203.5
7			351.2
8			549.4
9			367.2
10			
11			325.4
12			380.0
13			363.1
14			429.0
15			315.5
16		3.8	
17		3.8	
18		2.67	
19		2.2	
20	Oligocene-Pleistocene aquifer	85.73	785.0
21		92.6	794.4
22		88.49	801.0
23		87	719.0
24	Middle Eocene aquifer		715.0
25		86.2	626.5
26		86.5	844.9
27		83.4	
28		78.1	487.9
29		80.63	490.1
30		113.6	461.8
31			475.8

Hydrogeological Cross Sections

The lateral and vertical distributions of the aquifers mentioned above, as well as their interrelationships, are depicted by constructing two hydrogeological parts A-A′ (Fig. 5) and B-B′ (Fig. 6) that cross the study region in North–South and West–East directions, respectively. The following is a discussion of these hydrogeological cross sections based on these cross sections:

Cross-Section A-A′

With a length of around 20 km, this cross-section runs nearly parallel to the Nile River and runs nearly parallel to the flood plain (Fig. 5). The following conclusions can be drawn from this section:

1. The Quaternary aquifer, which consists of sand, gravel, and clay and has a penetrating saturated thickness of about 97 m, is the water-bearing formation along this line. A capping layer of semi-pervious silty clay with a thickness of 10–15 m sits on top of the aquifer. As a result, the aquifer around the Nile River is in a semi-confined state. This makes the aquifer to exist under a semi-confined condition around the River Nile.
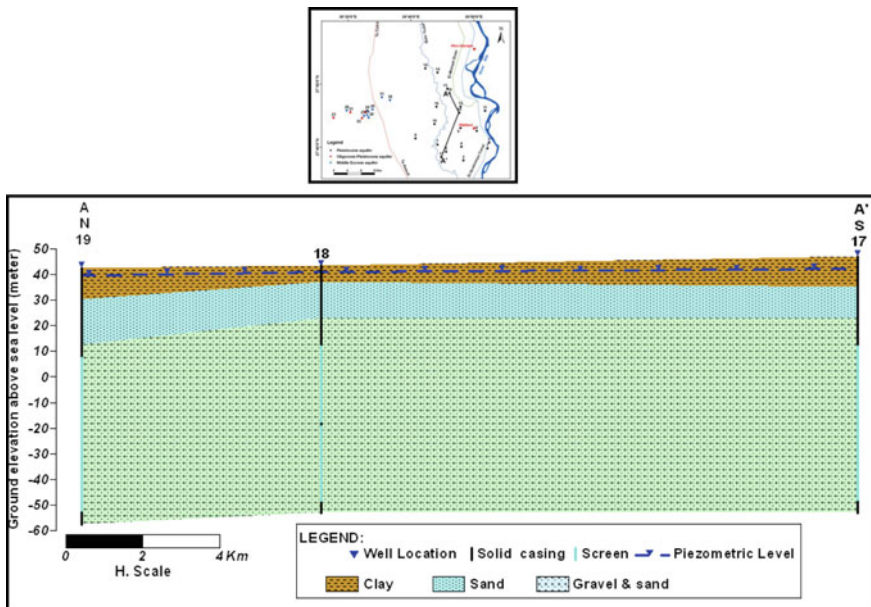

Fig. 5 Hydrogeological cross section A-A′ showing the vertical and horizontal distribution of the lithological succession, the design of the wells and the piezometric level of the surface of the groundwater

Fig. 6 Hydrogeological cross section B-B′ showing the vertical and horizontal distribution of the lithological succession, the design of the wells, the piezometric level of the surface of the groundwater and the different inferred faults
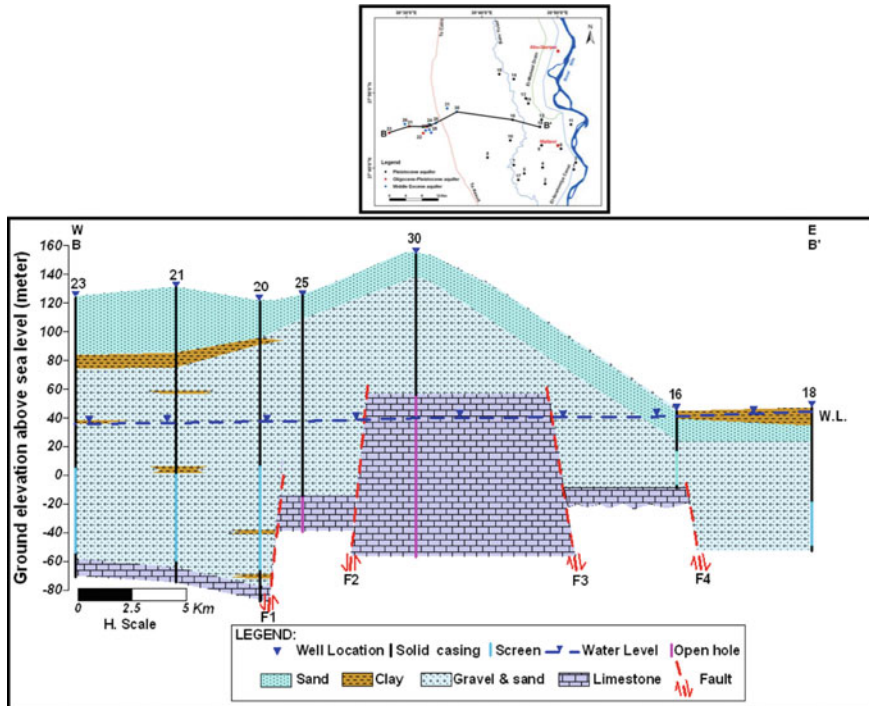
2. The depth to water varies between 2.2 m at well No. 19 and 3.8 m at well No. 17, with a general northward gradient.

Cross-Section B-B′

This section has W–E direction which is nearly perpendicular to the River Nile with a length of about 33 km. It passes from the west to the east through wells Nos. 23, 21, 20 (fully penetrating the Oligocene-Pleistocene aquifer), 25, 30 (penetrating the fractured Eocene limestone aquifer), 16 and 18 (penetrating the Quaternary aquifer) respectively. From this section some important features can be concluded as follows:

1. Faults are common along the whole section causing a pronounced fault rising for the fractured limestone aquifer in the middle part of the section (well 30). This rising brought the fractured aquifer in juxtaposition with the Quaternary aquifer from the eastern side and the Oligocene-Pleistocene aquifer from the other side. This situation favours the hydraulic interconnection between these aquifers forming one hydraulic continuous system. On the other hand, the comparison between the water levels in wells 16 and 18 of the Quaternary aquifer with those

of the Oligocene-Pleistocene aquifer shows slight difference of about 8.33 m higher at the east than at west indicating slow motion of groundwater from east to west.

2. The depth to the Eocene fractured limestone ranges between 98 m at well No. 30 and 199 m at well No. 20. Through the present study, the base of this aquifer was not reached; accordingly, its thickness is not recorded.

3. In the western part of the cross-section, the Oligocene-Pleistocene aquifer is fully penetrated through the wells Nos. 23, 21 and 20, which is mainly composed of sand and gravel with few clay intercalations having a saturated thickness ranges between 95 m at well No. 23 and 113.5 m at well No. 20.

4. In the study area, the groundwater in the Oligocene-Pleistocene and the fractured Eocene limestone aquifers are generally under phreatic conditions.

Groundwater Movement

The groundwater movement in the study area is discussed through the construction of water level contour maps for the studied aquifers (Figs. 7 and 8). The water level ranges between 44.33 m above mean sea level at the eastern part of the study area (Quaternary) and 36 m above mean sea level at the western part (Oligo-Pleistocene) with general trend of movement from east to west.

The intervals and the spacing between the contour values show different gradient values ranging from 0.3 m/km at the east where the groundwater flow is through the granular aquifers to 0.47 m/km in the fractured limestone aquifer. The groundwater flow through that aquifer is faster than the flow in granular media due to the width of existing fractures (Non Darcyan flow). This could be attributed to variation in fractures orientation where they can form a well-connected network for fluid flow [17].

Aquifer Parameters

The determination of the hydraulic parameters of the aquifers is essentially in evaluation of groundwater resource in the study area. Better and more reliable data are obtained if pumping continues until steady or pseudo-steady flow has been attained.

Long Duration Pumping and Recovery Tests

To evaluate the groundwater of the different three aquifers, 15 constant discharge pumping and recovery tests were carried out including; 3 in the Quaternary, 4 in
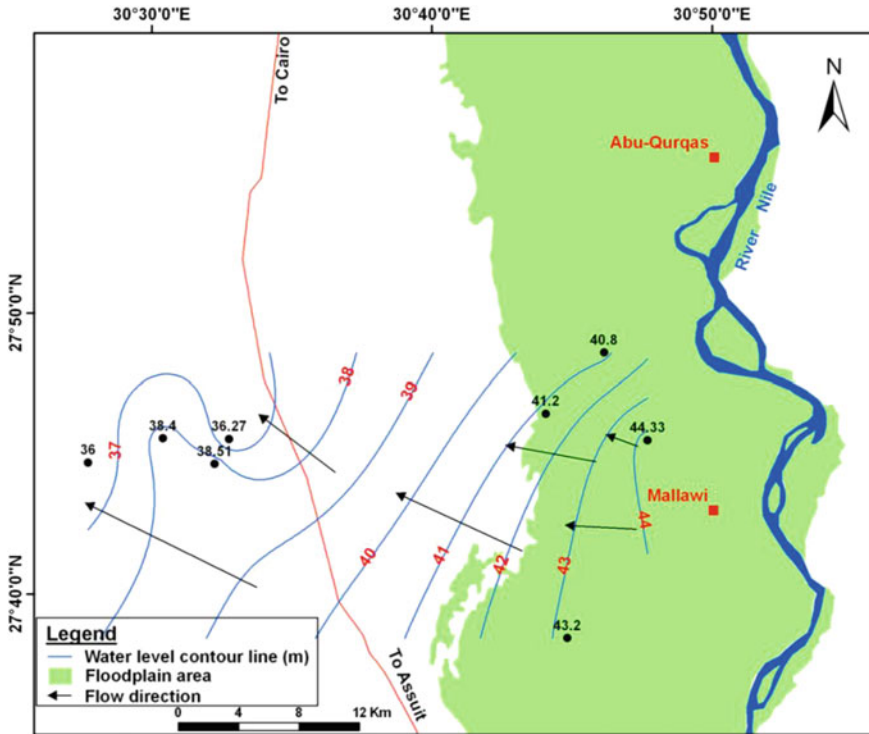
Fig. 7 Hydrogeological cross section B-B′ showing the vertical and horizontal distribution of the lithological succession, the design of the wells, the piezometric level of the surface of the groundwater and the different inferred faultsWater-level contour map of the Quaternary and Oligocene-Pleistocene aquifer showing the water level with respect to mean sea level

the Oligocene-Pleistocene and 8 in the Eocene fractured limestone aquifers. The analyzing of the pumping tests for both the Quaternary and Oligocene-Pleistocene aquifers (porous aquifers) was carried out according to [18]. On the other hand, the transmissivity of the Eocene fractured limestone can be approximated estimated from the specific capacity according to the following equation [19]:

$$T = C\ (Q/s)\ [19]$$

where,

T is the transmissivity m^2/day.

Q/s is the specific capacity m^3/day/m.

C is a constant value and is found to vary from 0.9 to 1.5 with an average of 1.2 [20] or 1.22 [21].

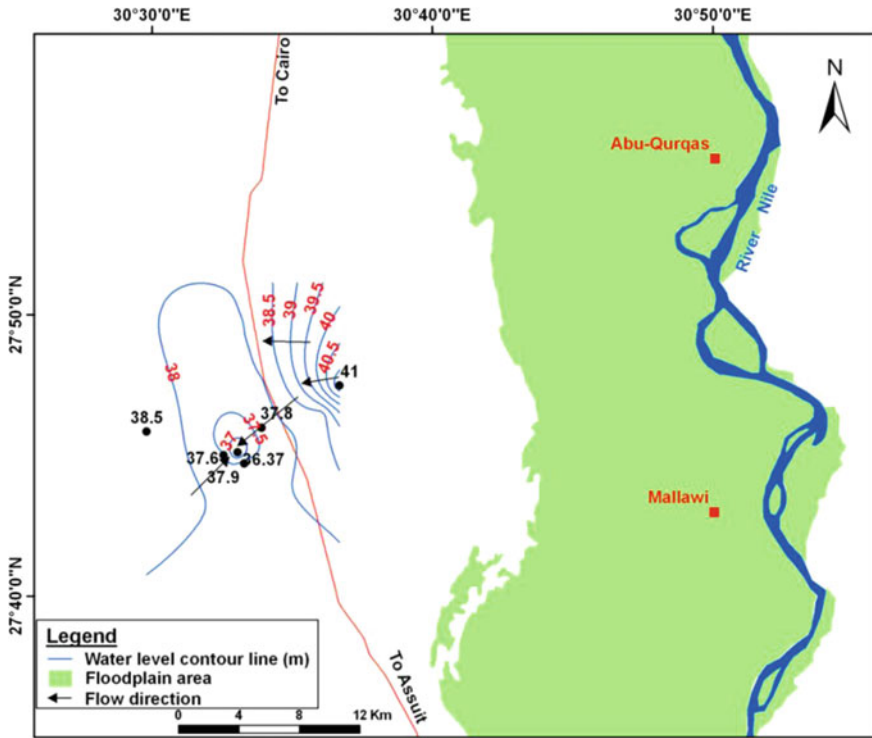The results of these tests (Table 2) reveal the followings:

Fig. 8 Water-level contour map of the Eocene fractured limestone aquifer showing the water level with respect to mean sea level

- The Quaternary aquifer shows high values of transmissivity range between 6592 and 12,700 m^2/day with an average value of 8906 m^2/day, while the Oligocene-Pleistocene aquifer has transmissivity values ranging between 1256 and 6800 m^2/day with an average value of 3291 m^2/day. The approximated transmissivity values for the Eocene fractured aquifer range between 1083 m^2/day and 14,054 m^2/day with an average value of 6091 m^2/day.
- In the Quaternary aquifer, the specific capacity values (Q/s) range between 11.8 and 46 m^3/h/m and according to well productivity classification [22], the Quaternary aquifer can be classified into highly productive (Q/s more than 18 m^3/h/m) and moderate productive (Q/s from 1.8–18 m^3/h/m) while all the Oligocene-Pleistocene aquifer have moderate productivity. In the fractured limestone aquifer, the specific capacity (Q/s) ranges between 37 m^3/h/m (Well No. 31) and 480 m^3/h/m (Well No. 24), reflecting the high productivity of the aquifer [22].
- Drawdowns in the wells tapping the granular aquifers (Quaternary and Oligocene-Pleistocene) are always greater than drawdowns in the wells tapping the fractured rock aquifer (Eocene fractured limestone) where the former type achieving final drawdowns ranges between 14.34 m in well No. 22 and 17.28 m in well No. 21 with

Table 2 Analysis of long duration pumping test data for selected wells tapping different aquifers

Final No	Aquifer	Aquifer type	Q (m³/h)	Drawdown S (m)	Specific capacity (m³/h/m)	b (m)	K (m/day)	T (m²/day)	Well productivity classification [15]
17	Quaternary	Semi-conf	195	16.57	11.8	Partial penetration	Undefined	6592	Moderately productive
18	Quaternary	Semi-conf	338	18.27	18.5	Partial penetration	Undefined	7427	Highly productive
19	Quaternary	Semi-conf	300	6.52	46.0	Partial penetration	Undefined	12,700	Highly productive
20	Oligo-Pleist	Unconfined	93	5.86	15.9	113.5	59.9	6800	Moderately productive
21	Oligo-Pleist	Unconfined	122	17.28	7.0	102.4	30.8	3154	Moderately productive
22	Oligo-Pleist	Unconfined	120	14.34	8.4	91.5	21.3	1953	Moderately productive
23	Oligo-Pleist	Unconfined	120	17.23	6.9	95	13.22	1256	Moderately productive
24	Eocene	Unconfined	120	0.25	480.0	Partial penetration	Undefined	14,054	Highly productive
25	Eocene	Unconfined	125	0.63	198.0	Partial penetration	Undefined	5797	Highly productive
26	Eocene	Unconfined	125	0.5	250.0	Partial penetration	Undefined	7320	Highly productive
27	Eocene	Unconfined	125	0.52	240.4	Partial penetration	Undefined	7039	Highly productive
28	Eocene	Unconfined	125	1.5	83.3	Partial penetration	Undefined	2439	Highly productive
29	Eocene	Unconfined	122	0.9	135.6	Partial penetration	Undefined	3970	Highly productive
30	Eocene	Unconfined	120	0.5	240.0	Partial penetration	Undefined	7027	Highly productive
31	Eocene	Unconfined	110	2.97	37.0	Partial penetration	Undefined	1083	Highly productive

pumping rate approximately of 120 m³/h while in the latter, representing fractured type, the drawdowns values range between 0.25 m in well No. 24 and 2.97 m in well No. 31 with approximately the same rate of pumping (120 m³/h). The low values of drawdowns in the Eocene fractured aquifer is attributed to the large volumes of water that move very rapidly through the karst features that develop in rocks where groundwater has widened fractures and porous zones into solution cavities by dissolving soluble minerals. References [23–26] concluded that, secondary porosity features such as conduits and caves are formed by dissolution and act as highly permeable pathways for water to flow through karst aquifers. The presence of these solution cavities are observed during the well drilling process in the Eocene fractured limestone aquifer where complete loss is occurred at different depths in the wells. Generally, this widening is limited in the carbonate rocks such as limestone and dolomite.

- For the wells tapping the granular aquifers, unsteady-state flow occurs from the moment pumping starts until steady-state flow is reached where the flow is considered to be unsteady as long as the changes in water level in the well is measurable. In these aquifers the time taken to reach the steady-state varies in the tested wells and ranges between 1000 min in well No. 18 and 1260 min in well No. 17 from starting well pumpage in the Quaternary aquifer while in the Oligocene-Pleistocene aquifer, this time ranges between 160 min in well No. 22 and 720 min in well No. 21.

- In the Eocene fractured limestone wells, flow attains its steady-state after few minutes (2–6 min) from starting well pumpage and the aquifer shows a pseudo-steady-state where the changes in the water level in the wells have become so small with time which can be neglected and this indicates that the recharge boundary is able to provide enough water to compensate for discharge.

- The difference between the complete recovery times for the wells tapping the granular aquifers (Quaternary and Oligocene-Pleistocene) and that for the fractured aquifer (Eocene fractured limestone) is attributed to the nature of the karst aquifers which have multiple types of porosity and two flow types of water: laminar and turbulent flow. The laminar flow occurs within the matrix domain of the karst aquifer with slow velocities and the turbulent flow occurs in the large diameter void spaces that are well connected forming conduit domain with high permeability and fast water movement or may be attributed to a direct connection between the Nile and the karst Eocene aquifer through step faulting.

Well Performance Test (Step Drawdown Test)

A number of seven step-tests and one step-test were carried out for the porous sands & gravels and fractured limestone aquifer, respectively. Three rates of well discharge were applied during the conducting of these tests. The parameters of aquifer loss, well loss, and well efficiency (Table 3) were calculated through the application of the **GWW Software** (Ver. 1.10).

Table 3 Calculated parameters of analyzing step-tests data for the porous and fractured limestone aquifers in the study area

Well No	Aquifer type	Maximum rate of pumping (Q_{max}) m^3/h	Total drawdown (S_t) corresponding to Q_{max} M	Aquifer loss S_a %	Well loss S_b %	A * 10^{-2} day/m^2	B * 10^{-6} day^2/m^5
17	Porous	190	15.56	63.8	36.2	0.2176	0.2786
18		300	16.45	75.9	24.1	0.1733	0.0781
19		300	6.49	70.6	29.4	0.0636	0.0366
20		90	5.74	67.9	32.1	0.1805	0.3960
21		121	16.77	85.7	14.3	0.4950	0.2825
22		120	14.11	72.4	27.6	0.3545	0.4711
23		120	17.26	82	18	0.4918	0.3753
31	Fractured limestone	110	2.86	8.4	91.6	0.0093	0.3782

The total drawdown (s_t) in the 8 pumped wells consist of the drawdown (s_a) in the aquifer and the drawdown (s_b) that occurs through the moving of water from the aquifer into the well and up the well bore to the pump intake. The total drawdown (s_t) can be defined in the following equation:

$$s_t = s_a + s_b$$

where s_a is the drawdown in the aquifer at the effective radius of the pumping well, s_b is well loss.

From Table 3, it can be concluded that, the aquifer loss percentage (S_a%) in the total drawdown (S_t) ranges between 63.8% in well No. 17 and 85.7% in well No. 21 which are representing the granular aquifers (Quaternary and Oligocene-Pleistocene). On the other hand, it is 8.4% in the well No. 31 which represents the Eocene fractured limestone aquifer and its well loss percentage (S_b%) is 91.6%. The low percentage of the aquifer loss in the well tapping the fractured aquifer could be attributed to the dominance of large diameter void spaces reflecting high permeability and subsequent fast water flow through aquifer.

Hydrochemical Characteristics of Different Aquifers

To study the variation in groundwater quality of the different dominant aquifers and its relationship with surface water, 25 samples were collected (2010) to represent the different aquifers besides 4 surface water samples from Nile River, canals and drains.

Groundwater Salinity

The water salinity of the three aquifers (three parts of one hydrogeologic system) is less than 1000 ppm (the maximum recorded salinity is 845 ppm of well 26 (Middle Eocene aquifer)). This means that groundwater of the study area (in the three aquifers) is fresh to fairly fresh water (Figs. 9 and 10).

Variation in salinity may be attributed to several factors, among them; local change of lithology, occurrence of clay adjacent to the well site, depth of the well (where salinity increases by depth) and arid conditions.

Sodium/Chloride ratio (rNa^+/rCl^-) indicates that, for surface water samples, the ratios are more than unity and range between 1.37 and 2.31.

The comparison of the rNa^+/rCl^- ratio of groundwater of all the dominant aquifers in the study area with those of River Nile and sea waters (>2 and <1, respectively) shows that, the sources of recharge for the Quaternary aquifer, Oligocene-Pleistocene and Eocene limestone aquifers are directly from the Nile water and the seepage from irrigation canals and drains. Also, the percolation of the excess irrigation water may contribute significantly in recharging the aquifers.
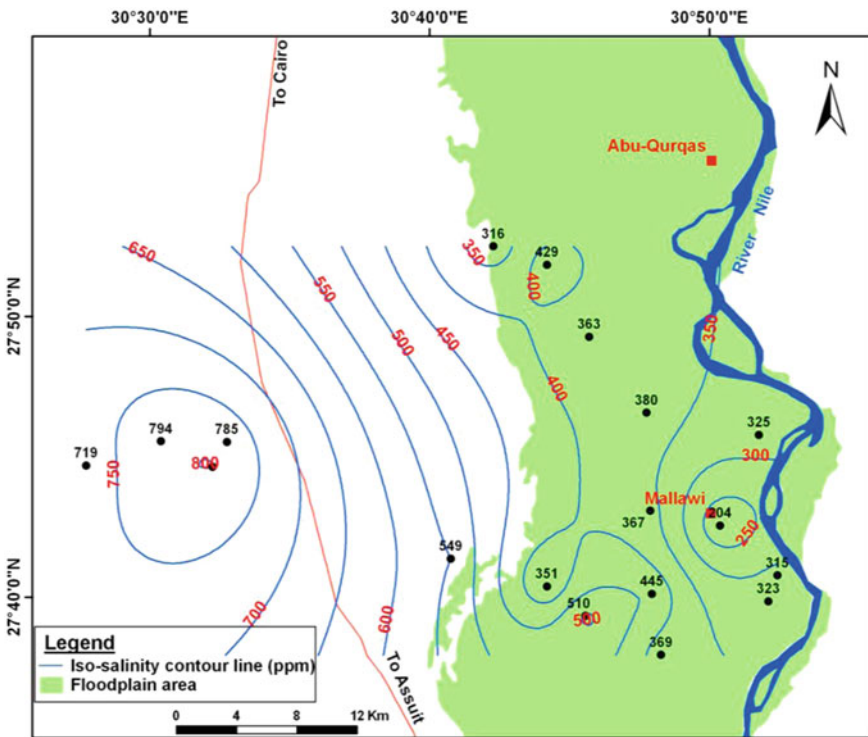

Fig. 9 Iso-salinity contour map for the Nile aquifer system (Quaternary and Oligocene-Pleistocene aquifers) showing the water salinity in ppm at each well and its areal distribution
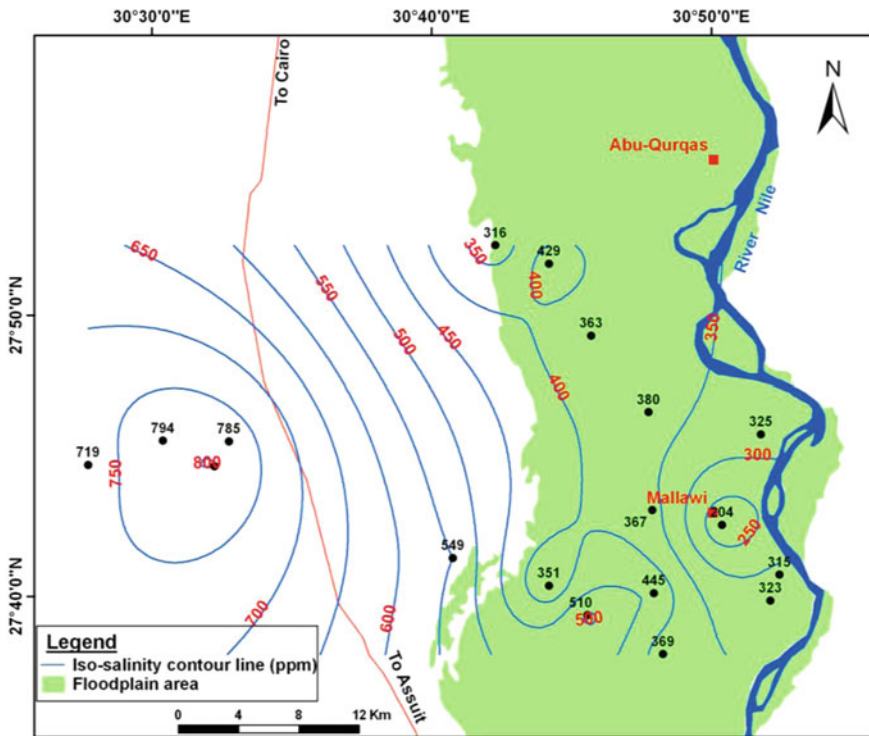
Fig. 10 Iso-salinity contour map for the Eocene fractured limestone aquifer system showing the water salinity in ppm at each well and its areal distribution

The decrease in the rNa^+/rCl^- ratio of the Oligocene-Pleistocene (0.88–1.04) and Eocene limestone (1–1.43) aquifers than the Quaternary aquifer (1.17–2.28) may be attributed to possible contamination, change of facies, depth of wells and hardly to consider it to marine effects.

The Quaternary aquifer shows one assemblage of hypothetical salts for all samples: $NaCl$, Na_2SO_4, $NaHCO_3$, $Mg(HCO_3)_2$ and $Ca(HCO_3)_2$.

For the Oligocene-Pleistocene aquifer, two assemblages of hypothetical salts combinations are recognized:

– $NaCl$, Na_2SO_4, $MgSO_4$, $Mg(HCO_3)_2$ and $Ca(HCO_3)_2$ in wells Nos. 20, 21 and 22.
– $NaCl$, $MgCl_2$, $MgSO_4$, $Mg(HCO_3)_2$ and $Ca(HCO_3)_2$ in well No. 23.

The Eocene fractured limestone aquifer shows two assemblages of hypothetical salts combination as follows:

– $NaCl$, Na_2SO_4, $NaHCO_3$, $Mg(HCO_3)_2$ and $Ca(HCO_3)_2$ in wells Nos. 30 and 31.
– $NaCl$, Na_2SO_4, $MgSO_4$, $Mg(HCO_3)_2$ and $Ca(HCO_3)_2$ in wells Nos. 24, 25, 26, 28 and 29.

From the above mentioned assemblages of the hypothetical salts combinations for the different aquifers, it can be concluded that:

1. The Quaternary aquifer has chemical composition similar to the chemical composition of the Nile River water where the hypothetical salts of the Nile water is $NaCl$, Na_2SO_4, $NaHCO_3$, $Mg(HCO_3)_2$, and $Ca(HCO_3)_2$ which indicate that the Nile water is the main recharging source for this aquifer.
2. It is obvious that the two assemblages of the Eocene fractured limestone aquifer are represented in the Quaternary and Oligocene-Pleistocene aquifers which mean that the Eocene water is a mixed water of these two aquifers i.e. the Eocene fractured limestone aquifer is recharged from the Quaternary aquifer through their direct connection and then recharges the Oligocene-Pleistocene aquifer as illustrated by the hydrogeological section B-B′ (Fig. 6).
3. From the studied 25 groundwater samples of the three aquifers, only sample of well 23 (Oligocene-Pleistocene aquifer) which reflects a marine conditions (due to the occurrence of $MgCl_2$). This may be attributed to a limited local condition around this well.

Groundwater Types

The Piper diagram [27] has been used to illustrate the possible relationship among the investigated aquifers and the surface water. The plotted data on the diamond field shape (Fig. 11) could be differentiated into two groups:

1. The first group occupies the lower part of the diamond shape, where water is characterized by sodium- bicarbonate and calcium/magnesium- bicarbonate water types. It includes the surface water of the Nile River together with almost all samples of the Quaternary aquifer and some samples of the Eocene fractured limestone aquifer (25, 28, 29, 30 and 31).
2. The second group which represents all the Oligocene-Pleistocene aquifer water samples and some samples of the Eocene aquifer (24 and 26) occupies the upper part of the diamond shape. Its chemical properties are dominantly characterized by sodium-chloride water type.

Conclusions

This chapter is mainly focused on the following main approaches related to the potentials and relationships of the dominant aquifers in the study area. From the abovementioned discussion, the followings are the main conclusions:

1. The dominated aquifers in the study area fall into two broad categories: The unconsolidated aquifers (granular) represented by Quaternary and Oligocene-Pleistocene. The consolidated fractured aquifer (fractured rock) represented by Eocene fractured limestone which considered as karst aquifer.
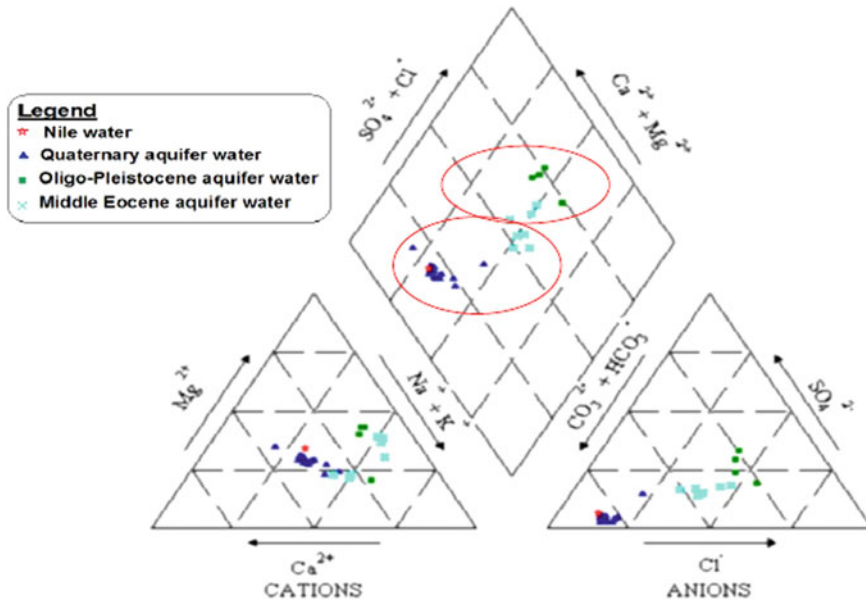
Fig.11 Piper's diagram showing the plotted data on the diamond field shape, where the water of the first group occupies the lower part of the diamond shape characterized by sodium-bicarbonate and calcium/magnesium-bicarbonate water types representing the surface water of the Nile River together with almost all samples of the Quaternary aquifer and some samples of the Eocene fractured limestone aquifer and the water of the second group occupies the upper part of the diamond shape characterized by sodium-chloride water type representing the all samples of the Oligocene-Pleistocene aquifer and some samples of the Eocene fractured limestone aquifer

2. The Quaternary aquifer in the flood plain is considered as highly productive where the aquifer has transmissivity values ranging between 6592 and 12,700 m^2/day and specific capacity ranging between 11.8 and 46.0 m^3/h/m. The water salinity of this aquifer ranges between 203.5 and 549.4 ppm increasing from east to west. The main source of recharge of this aquifer is the Nile water as indicated by the ion relationships.

3. The Oligocene-Pleistocene aquifer is classified as moderately productive having transmissivity values ranging between 1256 and 6800 m^2/day and hydraulic conductivity ranges between 13.22 and 59.9 m/day with saturated thickness ranges between 91.5 and 113.5 m. This aquifer has specific capacity values between 6.9 and 15.9 m^3/h/m. The water salinity of this aquifer ranges between 719 and 801 ppm. rNa^+/rCl^- ratio, hypothetical salts combinations, Piper (1944) and Schoeller (1955) diagrams show that the groundwater of this aquifer is in the progress stage of evolution than the other two aquifers (Quaternary and Eocene fractured) where it has sodium- chloride chemical type.

4. For the Eocene fractured limestone aquifer, the aquifer is considered as highly productive aquifer having transmissivity values range between 1083 m^2/day and 14,054 m^2/day and attaining specific capacity ranges between 37.0 and 480

m^3/h/m. Its water salinity ranges between 462 and 845 ppm. The groundwater of this aquifer is, chemically, in the middle stage of evolution as its groundwater is a mixture from the other two aquifers (Quaternary and the Oligocene-Pleistocene) due to the direct hydraulic connection between the Quaternary aquifer and the Eocene fractured limestone aquifer through faulting. The conclusion of this situation is that, the Eocene fractured limestone aquifer is recharged directly from the Quaternary aquifer and then acts as a rechargeable source for the Oligocene-Pleistocene aquifer.

5. The general flow direction of the granular aquifers (Quaternary and Oligocene-Pleistocene) is from east to the west as the Eocene fractured aquifer with some local change where there is a flow direction from southwest to the north east direction which may be attributed to the over-exploitation in this locality or the effect of the fractures orientation in this aquifer system.

6. The groundwater salinity in the three dominant aquifers increases generally in the west direction since the groundwater movement is towards west.

7. A direct connection between the Nile and the karst Eocene aquifer through step faulting is quite believable as indicated from the pumping test data carried out in the present study. Such important conclusion needs to be verified and emphasized by geological and geophysical surveys to establish a new approach about the hydro-structural aspects affect groundwater occurrence and potentials along the Nile valley.

Recommendations

From the above mentioned discussions, the followings can be recommended:

1. Generally, the whole area should be subjected to a monitoring network of wells representing the three aquifers. The monitoring system includes both water levels and salinity on periodical basis.

2. It is recommended to increase the drilling depth in the Eocene aquifer in order to maximize, as much as possible, the groundwater potentials of this karstic phenomenon.

3. Since the study area is a new development area, it is strongly recommended that a mathematical model be built in order to forecast future conditions based on anticipated heavy pumping programs by investors. The management should take into consideration the safe distance between drilled wells as well as the pumping rates.

4. The safe distance between drilled wells, as well as the pumping speeds, should be considered by the management.

5. Since the fractured limestone (Eocene) has good groundwater quality and availability, water extraction should be based on this aquifer, which would directly improve the reclamation of new areas.

6. It is recommended that a modern irrigation system be used.

7. To make the necessary management on groundwater extraction in the study area, cooperation between the Ministry of Irrigation & Water Resources and the Ministry of Agriculture and Land Reclamation is critical.

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