Full length article

Utilizing the geological data and remote sensing applications for investigation of groundwater occurrences, West El Minia, Western Desert of Egypt

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ABSTRACT

West EL Minia area is considered one of promising areas for future development plans in Egypt. The current research provides an integrated remote sensing data, microfacies analysis, field studies and geochemical approach to investigate the groundwater resources in West El Minia area. Three aquifers were investigated; Oligocene sandstone, Middle Eocene limestone and Nubian sandstone aquifer. New data about two aquifers (Nubian sandstone and Oligocene) are presented in the current study extracted from well logging interpretation and wells rock samples. The groundwater of the Oligocene sandstone and Middle Eocene limestone aquifers are recorded under unconfined conditions, while the Nubian sandstone is recorded as confined aquifer. The total thicknesses of the three aquifers were identified through interpretation of the well logging data (180 m for Oligocene aquifer, 445 m for the Middle Eocene aquifer, and 145 m for Nubian sandstone aquifer). The present study discusses the groundwater levels, the geological controls and groundwater chemistry of the recorded aquifers. The low salinity values (560–916 mg/l) and water table map as well as the obtained stable isotopes data reveal that the Middle Eocene aquifer is recharged from the Nile River where it has isotopic signature of the modern Nile water with slightly contribution of paleo-water of the Nubian sandstone. The area is affected by sets of faults associated with fractures and joints and facilitates the groundwater recharge. Based on multi GIS data layers, remote sensing data, geologic investigation as well as geophysical data, a future groundwater strategy were presented.

1. Introduction

The continued water deficiency in Egypt and the probabilities for supplemental deficits in Nile River water especially after the Nile Basin countries beginning in constructing new dams; is directing the efforts of the Egyptian government to find solutions to this problem by identifying additional new water resources. The fracture limestone of the Samalut Formation are considered of the most aquifers potentiality in the Western Desert, especially West El-Minia and West Asyut, in addition it has a good water quality (Shabana, 2010; Al Temamy and Abu Risha, 2016). The geoelectrical implementing consummated that the fracture limestone of the Samalut Formation is the leading prospective for bearing groundwater in Western Desert (Abou Heleika and Niesner, 2009). In spite of, the Nubian aquifer system is one of the world's largest aquifers, with areas in Egypt, Sudan, Chad and Libya. This aquifer is tapped in the study area by one water point with total depth of 1500 m. Responding to government endeavors, many huge projects have been launched to fill the gap between the increasing population and the lack of water resources. The most important of these projects at present is a new reclamation project for one and a half million acres, recently launched by the Egyptian government. The area of study can be considered as a part of this huge project. West El Minia is the most desert area which subjected to reclamation during the past ten years depending mainly on the groundwater extracted from fracture limestone aquifer. In this regard, the main objectives of this paper are; (1) Identifying the geomorphological and geological conditions to determine their role in the groundwater occurrences; (2) Assessment of current groundwater situation; (3) Locating the best sites for groundwater exploration based on detailed investigation of surface and subsurface data which obtainable from the existing wells and geophysical data.
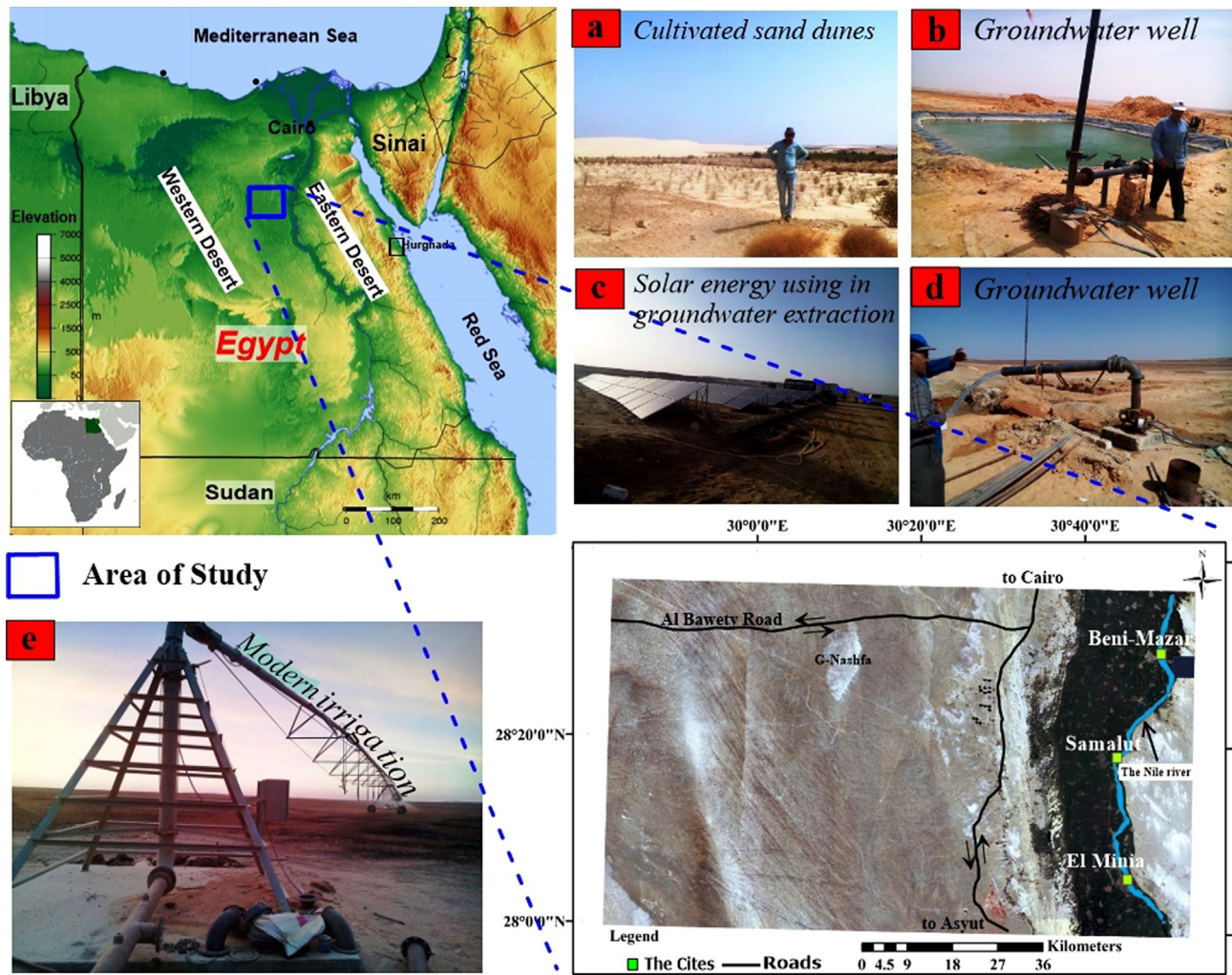
Fig. 1. Location map of the study area, supported by field photographs (a to e) showing some of the current development activities (during years: 2016 and 2017).

1.1. Site description

The concerned area lies to the west of the Nile valley, at the west of the western limestone plateau (Tableland) of El-Minia governorate. It lies between longitudes 29°75′ & 30°64′E and latitudes 28°00′ & 28°58′N. It covers an area of about ~5400 km^2 (Fig. 1). It can be accessed by a good number of asphaltic roads and desert loggers. The study area is described as arid climate with hot summer, warm winter, high evaporation and low rainfall intensity. El Minia meteorological gauging station records for 18 years (1988–2006) were reported as follows; the minimum air temperature varies from 1 °C in the January to 18.1 °C in August. The maximum air temperature ranges from 25.1 °C in January to 44.3 °C in June. Rainfall is rare throughout the region where the rainy months start from October to the end of May; the annual precipitation rate is 19.6 mm/year. The maximum rainfall in one day of rain and heavy storms is 7.6 mm/day in October. Therefore, the contribution of rainfall to groundwater recharge is expected to be scarce. In the present study, four geomorphologic units were identified including; the tableland, isolated hills, three flood plains (silt plain, sandy plain and gravely plain) and sand dunes belt of Western Desert which started from south Qattara Depression and extending to the West of El Minia (Shabana, 2010; Salem, 2015), (Table 1, Fig. 2a and b).

Geology has a main role in the quality and occurrence of the groundwater. Therefore, hydrogeological evaluation needs to recognize the lithostratigraphy of the water-bearing formations and structural elements affecting these formations. Along the area of study, several

Table 1
Parameters of geomorphological units of the study area.

Geomorphological units	Area		Elevation (m.a.s.l)	
	Area (km^2)	Perimeter (km)	from	to
Tableland	661.767	172.709	69	140
Isolated hills	54.671	37.929	130	202
Longitudinal sand dunes	95.244	113.801	70	115
Gravelly plain	1838.099	249.325	110	145
Sandy plain	45.943	65.098	55	74
Silty plain	287.371	139.073	50	70

lithologic units ranging in age from Middle Eocene to Quaternary, were exposed (Abd El-Aziz, 1994; Abou Heleika and Niesner, 2009). These units include (From base to top); Minia Formation, Samalut Formation, Qatrani Formation, Katkut Formation and Quaternary alluvial deposits. The Minia and Samalut Formations, which related to Eocene time, are composed mainly of fractured carbonate rocks. Qatrani and Katkut Formations consist mainly of a sequence of clastic deposit (siltstone and claystone), limestone fragments and gravels, respectively (EGSMA, 2005). The Quaternary alluvial deposits consist of sand dunes, Nile silt, proto-nil and pre-nil deposits (Klitzsch et al., 1987).

The study area is affected by a network of faulting system. These faults play a great role in the occurrences of the groundwater aquifers in this area; (Said, 1981; Fitzner et al., 2002; Abou Heleika and Niesner, 2009; El Kashouty et al., 2010). Abdel Baki (2013) referred to the
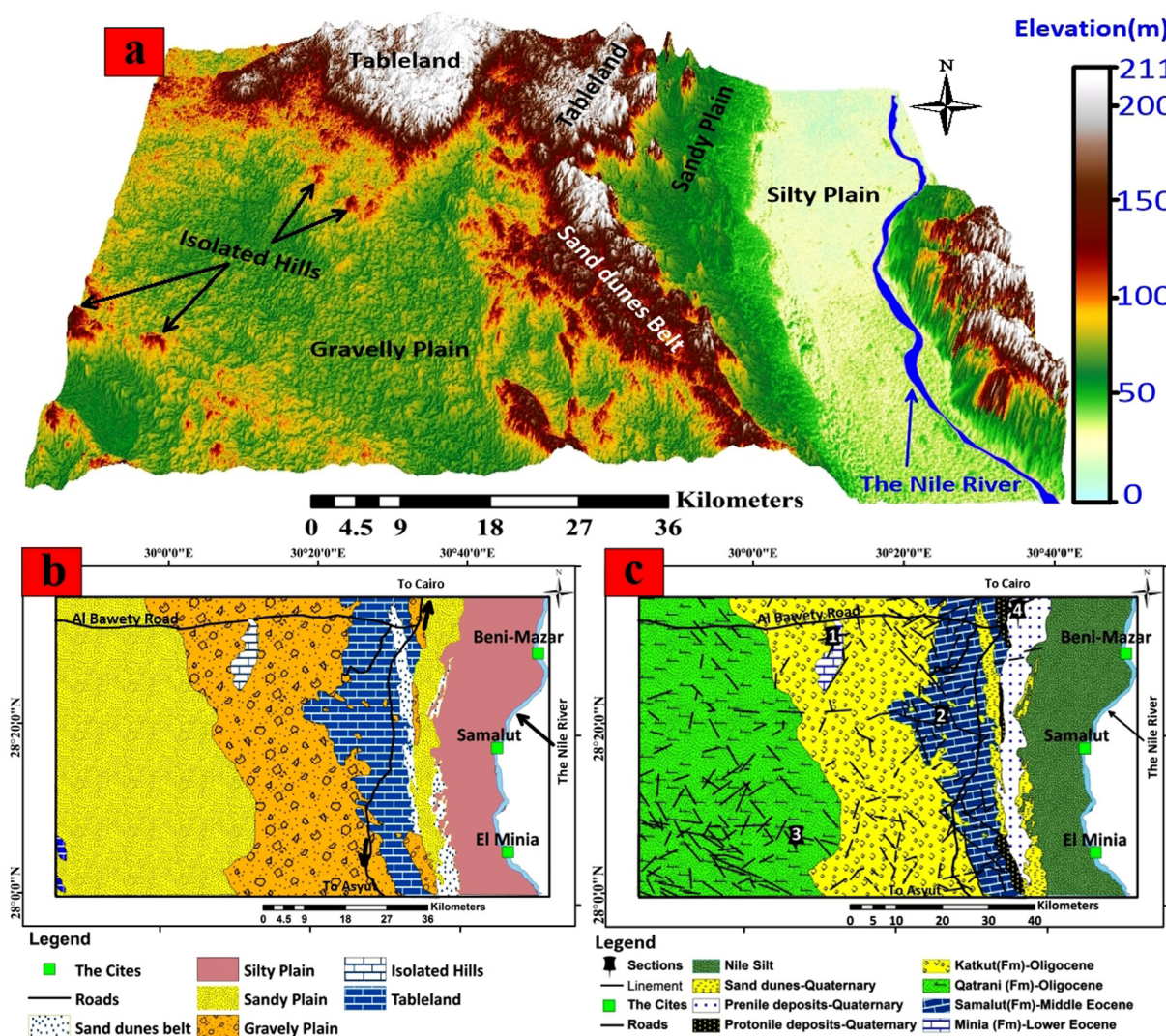
Fig. 2. Geomorphological and geological setting of the study area. (a) Three dimensional view showing the main landform of the study area. (b) Geomorphology map of the study area (c) Geology map of the study area (Combined: Klitzsch et al., 1987; EGSMA, 2005).

existence of buried channels pass through structural grabens along with NW-SE trend in the western borders of study area. These buried channels are located below Abu Mhareq depression. According to the works of Tantawi (1992), El Miligy (2004), Osman (2006), El Sayed (2007), Shabana (2010), one water bearing formation were identified in west El Minia area including; Middle Eocene limestone aquifer. The limestone aquifer is locally composed of the Samalut Formation (chalky limestone with thin clay intercalations). The present study introduce new data about two aquifers; the Nubian sandstone and Oligocene sandstone where they were recorded as water bearing formations taped by three wells in the study area.

2. Methods and materials

2.1. Fieldwork

In April 2016 and April 2017, fieldwork was execution to identify the geomorphologic, geological and hydrogeological settings of the target area. Four surface sections, with fifty rock samples from the exposures were measured and sampled. A survey of the existing wells (25 points) was carried out with collecting 24 water samples represents the different aquifers in the study area. Also, the locations (GPS), pH-value, Electrical conductivity (EC) and Temperature (T) were measured

in site. In additional, the hydrogeological data (i.e. total depth and depth to water for wells).

2.2. Geographical Information System (GIS) and Remote Sensing data sets (RS)

The elevation data (DEM) of the Shuttle Radar Topography Mission (SRTM); 2 Scenes; with resolution, 28.5 m; (USGS website) and the Landsat ETM + with chromatic band; spatial resolution, 14.5 m; (USGS website) are provided the basic data for the current research. The remote sensing data of the satellite images and DEM are projected to the metric system (UTM) in Arc GIS environment for more correlation to the data and features. The SRTM DEM data and Landsat mosaic were first re-projected and clipped to cover the whole area of west El Minia using the ENVI v.5.1 application, after that a 3D view for the study area was created using ESRI Arc Scene v.10.1. The 3D image was used to provide a better visualization of the landscape of the study area. In addition, the slopes and elevations layers were created from DEM using (Arc GIS 9.2) to showing the difference of slopes and elevations in the study area. A combined geologic maps for the Western Desert (Klitzsch et al., 1987; EGSMA, 2005; Scale: 1:500,000; 1: 250,000, respectively) were used in this study. Moreover, the drainage networks and catchment areas were created from SRTM DEM using the well-known
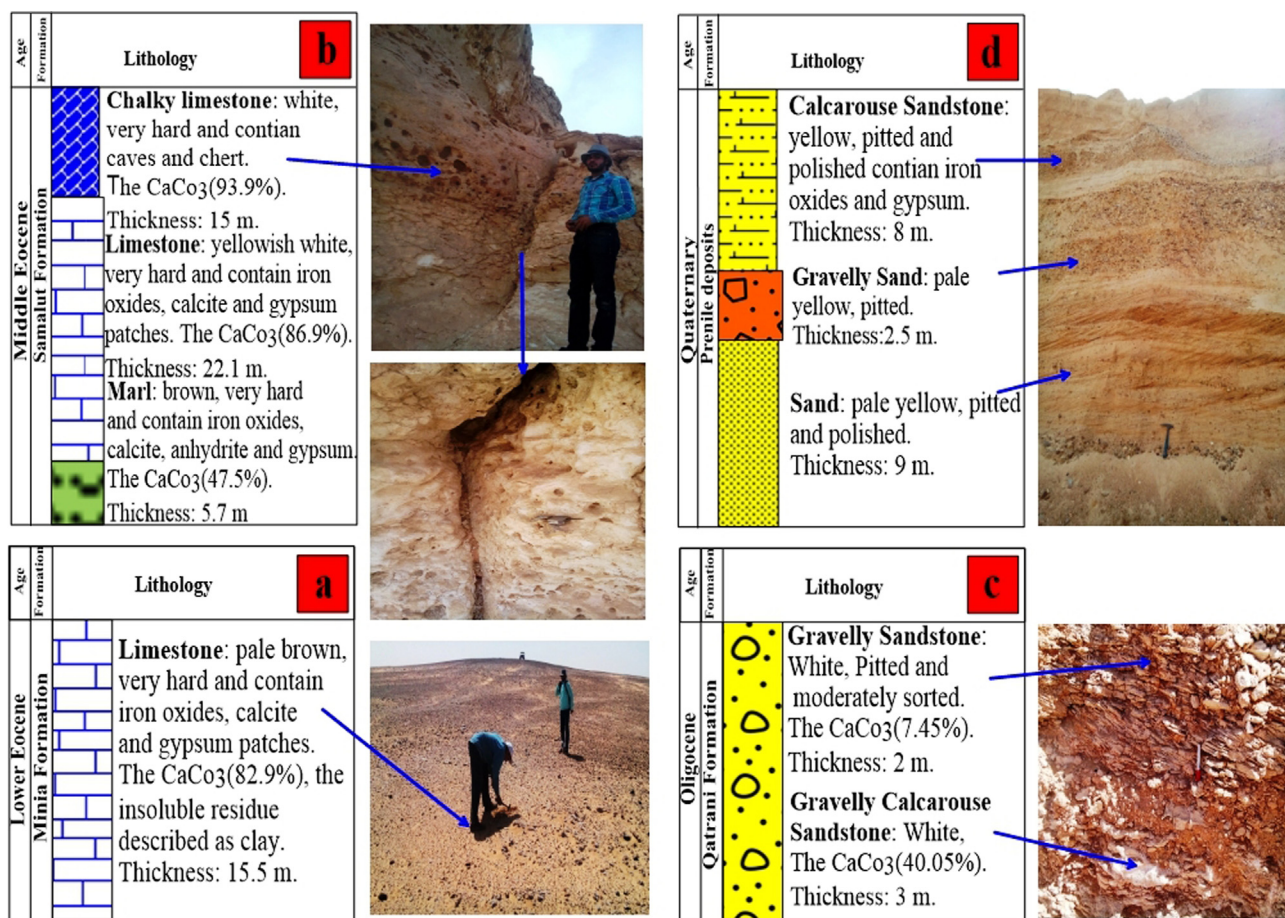
Fig. 3. Measured stratigraphic sections (a) Stratigraphic section of Minia Formation (b) Stratigraphic section of Samalut Formation (c) Stratigraphic section of Qatrani Formation (d) Stratigraphic section of Prenile deposits (with carbonate percentage of each layers), West El Minia area.

method of D8 flow direction algorithms in the Arc Hydro tool (ESRI Arc GIS.9.2). One single mosaic from the geologic maps covering the study area was generated using Arc GIS software. This mosaic was used in digitizing the structural lineament to create the density and frequency contour maps. Based on SRTM DEM, Global Mapper program version 10, surface profiles were created to illustrate the main topographic units of the study area.

2.3. Microfacies analyses

The microscopic investigation for ten thin section samples from Lower and Middle Eocene as well as Oligocene rocks were stained by blue dye to investigate the porosity and permeability. Additionally, the depositional environment, petrographic constituents as well as microfacies associations are identified. The origin of the rock constituents and the digenesis processes were examined. The microfacies recorded were compared with the standard microfacies types of Wilson (1975), Flügel (1982), for the recognition of the studied rocks environment.

2.4. Chemical analyses

Twenty four samples of the groundwater were analyzed in the central laboratory in the Center of the Desert Research according to the American Society of Testing and Materials (ASTM, 2002). The flame photometer was used to measure the values of Potassium ($K+$) and sodium ($Na+$) in the water samples. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) were determined by titration against (Na_2EDTA) by complex metric method. Carbonate ($CO3^{2-}$) and Bicarbonate (HCO_3^-) were determined using titration against sulfuric acid by neutralization

method. Chloride (Cl^-) was determined volumetrically by titration against silver nitrate. Sulfate (SO_4^{2-}) was measured by the turbidity method using a single beam spectrophotometer.

3. Results

3.1. Geological setting

The age of exposed rocks in the study area are ranging from Lower Eocene to Quaternary. Four stratigraphic surface sections were measured including; (section no.1) which has a total thickness of 15.5 m representing the Minia Formation (Fig. 3a), (section no. 2) with thickness of 42.8 m, consists mainly of Samalut Formation (Fig. 3b) and (section no. 3) with thickness of 5 m composed mainly of Qatrani Formation (Fig. 3c). In addition, the Quaternary deposits represented by (section no. 4) which has a thickness of 19.5 m (Fig. 3d).

3.1.1. Eocene and Oligocene rocks

Eocene and Oligocene rocks are covering the most portions of the surface of the study area. Minia and Samalut Formations are representing the Eocene rocks in concerned area. At the northern and eastern portions of the study area, Minia Formation is recorded at Gebel Nashfa (Fig. 2c, section 1), and composed mainly of limestone with clay intercalation. The microfacies analyses of Minia Formation is characterized by Algal biosparit (Fig. 4a and a\), this microfacies is common in all the studied thin sections. The allochems consist of algae, echinoids, foraminifera and brachiopods embedded in calcite spar. The algae are coralline. Sometimes, brachiopods and Mollusca are recrystallized, vugg and channel porosity are recorded. Some fissures and
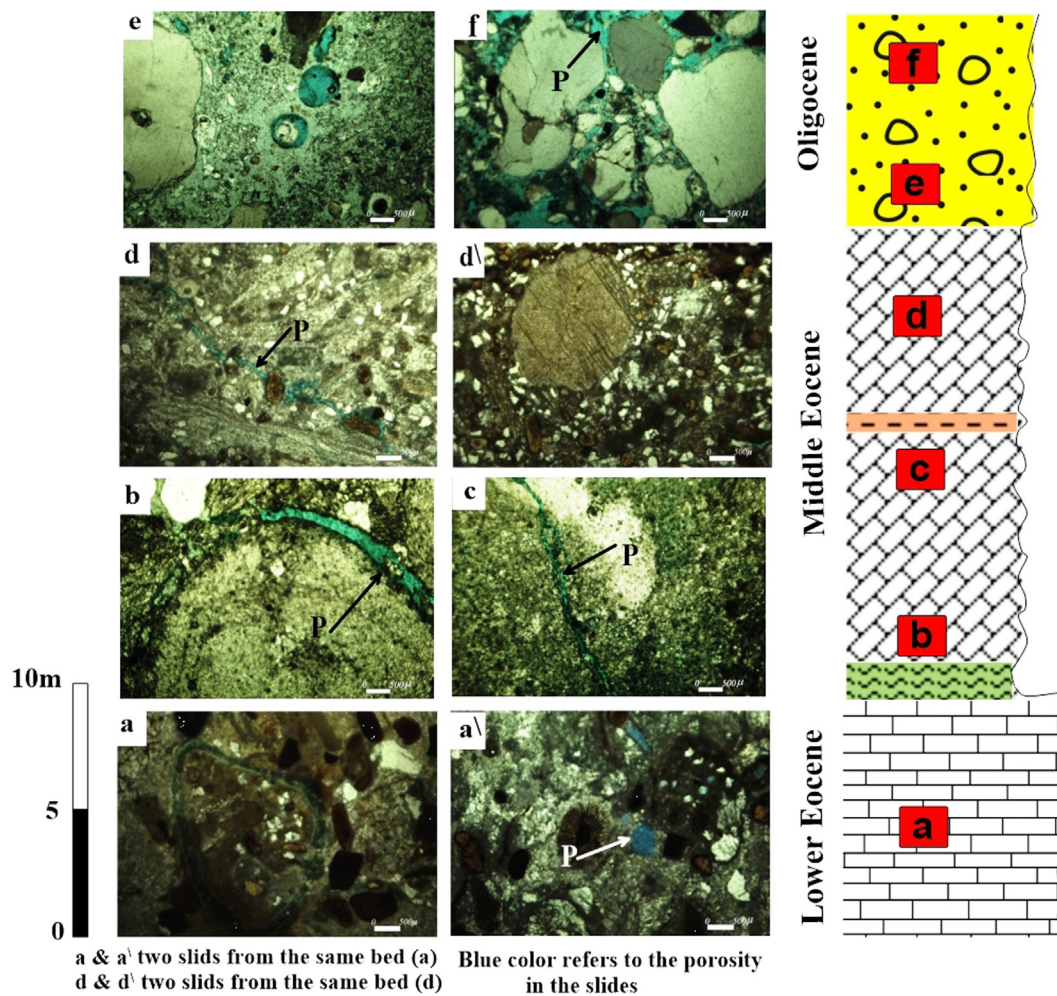
Fig. 4. Composite section with corresponding microfacies association (a to f) of Oligocene, Middle and Lower Eocene rocks.

vuggs are filled with iron oxides. This microfacies type was deposited by gravity flows from the platform margin, so the suggested environmental condition is an open platform (Willson, 1975). The Samalut Formation (Fig. 2c, section 2), occupying the eastern parts of the tableland composed of chalk and chalky limestone with marl and clay intercalation, highly fossiliferous and caverns. The fractured limestone of Samalut Formation considers the main water bearing of the study area. Through microfacies analyses, Samalut Formation characterized by bio-microsparit where microfacies consist of algae, ecinoids, and brachiopods embedded in microcalcite spar. The fissure and vug porosity are seen. Some fissures are filled with iron oxides. Boitite are scattered within the matrix (Fig. 4b). Algal microsparit is recorded where the allochems are made up of algae, channel porosity and drusy cement, are seen (Fig. 4c). Also, fossiliferous biosparit is noted where the allochems are made up of algae, nummulites and other fossils contain spines which have a structure similar to brachiopod valve (Fig. 4d and d\). All these are deposits in an open platform (Willson, 1975).

On the other hand, Oligocene rocks of (Qatrani and Katkut Formations) overlie the fracture limestone of Samalut Formation. The Oligocene deposits are not represented in all measured sections, except Qatrani Formation which recorded at Gebel Qatrani (Fig. 2b, section 3), composed of gravelly calcareous sandstone with clay intercalation. In this study, Qatrani Formation is recorded as water bearing tapped by two water points. The investigation of microfacies analyses of the Oligocene rocks confirms the subdivision of the Qatrani Formation into two units, where each unit has its unique microfacies (Fig. 4e and f).

The first unit is characterized by Calcareous Quartz arenite (Fig. 4e), where it consists of quartz grains and bones fragments. The quartz grains are coarse to very fine in size, ill-sorted, rounded to subrounded, monocrystalline and polycrystalline varieties. The margins of some quartz grains (especially the coarse one) are embayed as a result of corrosion of the quartz during digenesis. This microfacies type was deposited by gravity flows from the fluvio marine. The second unit is Quartz arenite (Fig. 4f), where composed of detrital quartz grains. The quartz grains are coarse to very fine in size, ill-sorted, rounded to subrounded, quartz of monocrystalline and polycrystalline varieties. Intergranular porosity was recorded. The matrix contains clay and iron oxides grains. This microfacies type was deposited by gravity flows from the fluviomarine (Flügel, 1982).

3.1.2. Quaternary

The Quaternary deposits covers the eastern portions of the study area which include; (1) **Nile silt**; which covers the area between the eastern scarp of the western limestone tableland and the Nile River to the east. It is mainly occupied by the cultivated land of the Nile valley. It is mainly consist of fine sand and silt. The thickness different from place to another while the maximum thickness reaches 15 m. (2) **Sand dunes**; they almost run in NW-SE direction and composed of medium to fine sand grains. No doubt that sand dune has a destructive effect on the cultivated lands. (3) **Protonile and Prenile**; which located only around the Nile silt of Nile River. They are consist of pebbles, brown to dark grey and black color gravels, sand and silt, (section no. 4), (FigS. 2c and 3d). Due to the undulated topography of these deposits, they were

Table 2
Hydrogeological data of the recorded groundwater wells in West El-Minia area.

Well	Aquifers	Coordinates		Elevation (m.a.s.l)	Depth to water (m)	Total depth (m)	Screen Interval		Water level (m.a.s.l)	Partially saturated thickness (m)	Salinity (mg/l)
		E°	N°				from	to			
1	Oligocene	29.785	28.525	129	98	–	–	–	31	–	–
2		29.848	28.537	130	99.57	180	120	180	30.43	80.43	2584
3	Middle Eocene limestone	29.911	28.440	138	105.34	500	250	500	32.66	394.66	2103
5		29.963	28.339	124	91.3	300	–	–	32.7	208.7	2095
6		30.112	28.231	120	87.33	–	–	–	32.67	–	2130
7		30.428	28.538	116	82.8	300	215	300	33.2	217.2	2500
8		30.463	28.520	111	77.7	170	–	–	33.3	92.3	2076
9		30.562	28.375	55	21.3	140	26	140	33.7	118.7	830
10		30.538	28.332	74	40.28	120	20	120	33.72	79.72	916
11		30.478	28.346	78	44.32	110	70	110	33.68	65.68	1197
12		30.404	28.358	111	77.33	–	–	–	33.67	–	1370
13		30.359	28.352	138	104.9	170	–	–	33.1	65.1	2272
14		30.317	28.367	144	111	250	–	–	33	139	1884
15		30.404	28.286	122	88.33	233	–	–	33.67	144.67	1780
16		30.441	28.283	111	77.28	233	190	233	33.72	155.72	1033
17		30.534	28.255	69	35.2	100	–	–	33.8	64.8	560
18		30.459	28.168	157	122.8	250	–	–	34.2	127.2	590
19		30.514	28.162	115	80.4				34.6		675
20		30.522	28.072	115	79.5	125	–	–	35.5	45.5	658
21		30.462	28.043	140	104.5	–	–	–	35.5	–	1475
22		30.458	28.033	114	78.3	180	–	–	35.7	101.7	580
23		30.438	28.052	113	78.1	225	–	–	34.9	176.9	2026
24		30.422	28.054	113	77.9	250	–	–	35.1	172.1	2083
25		30.391	28.025	114	78.9	300	–	–	35.1	221.1	862
4	Nubian	29.911	28.430	137	–	1490	–	–	–	–	1664

described as terraces, Said (1962), (Fig. 10c).

3.2. Hydrogeological setting

The groundwater of the concerned area is available from three aquifers include; The Oligocene sandstone aquifer (Taped by 2 wells), Samalut limestone aquifer (Taped by 23 wells) and Nubian sandstone aquifer (Taped by 1 well) (Table 2 and Fig. 5a).

3.2.1. Oligocene sandstone aquifer (Qatrani Formation)
Sandstone of the Qatrani Formation is considered one of the water bearing formations that occupy the western portions of the study area. It is composed mainly of calcareous sandstone with clay intercalation. The depth to water is ranging between 98 m (well no. 1) to 99.57 m (well no. 2) (Table 2). The partially saturated thickness of the Oligocene sandstone aquifer attains 80.43 m (well no. 2). The groundwater level attains + 30.43 m (well no. 2) and + 31 m (well no.1). The TDS value of the Oligocene sandstone aquifer is 2584 mg/l (well no. 2) as shown in (Table 2). The Qatrani Formation is assigned to Oligocene age (Beadnell, 1905).

3.2.2. Middle Eocene limestone aquifer (Samalut Formation)
The fractured limestone of Samalut Formation is one of the mainly targeted aquifers in the study area and surrounding. Lithologically, this formation is made up of hard, white, highly fossiliferous, fractured limestone with shale and marl intercalations. Samalut Formation is assigned to Middle Eocene age. The Eocene limestone is controlled by a network of faulting system and fractures (Said, 1981), (Fig. 8a). Groundwater of Samalut aquifer occurs under unconfined conditions. The depth to water ranges from 21.3 m below ground surface (well no. 9) to 122.8 m (well no. 18). The partially saturated thickness ranging from 45.5 m (well no. 20) to 394.66 m (well no. 3) (Table 2). The groundwater salinity in this aquifer varies greatly from 560 mg/l (well no. 17) to 2500 mg/l (well no. 7) (Table 2). The groundwater flow direction in this aquifer is defined from South-East to North-West (Fig. 5b). Using the recovery method of Theis (1935) the calculated

transmissivity for two wells tapping Middle Eocene limestone aquifer, are 335.5 m²/day (well no. 9) and 600 m²/day (well no. 17) as shown in (Table 3, Fig. 6b and c respectively). In addition to the previous method, the transmissivity of the same aquifer, but for different water point, was calculated using the method described by Cooper and Jacob (1946). The calculated transmissivity in (well no. 5) attains 1650 m²/day (Table 3 and Fig. 6a).

3.2.3. Nubian sandstone aquifer (Baharyia Formation; lower Cenomanian)
The Nubian sandstone aquifer is represented by Baharyia Formation. The Baharyia Formation subdivided into three lithological units (A, B, and C) according to Ghoubachi (2017), depending upon the sand percentages calculated from the records of geophysical well logging. The units A and C represent sandstone (unit C not exposed on the well loges) (Fig. 6d). On the other hand the unit B is claystone. Baharyia sandstone aquifer is encountered in subsurface in one productive well in the study area (well no. 4). This rock unit is recorded from 1080 m to 1490 m under the surface. The great depth is attributed to huge thickness of Eocene sedimentary succession (Fig. 6d). It underlies the Khoman chalk Formation. It belongs to the Lower Cenomanian age (Said, 1962). The groundwater in the studied aquifer characterized by confined condition. This aquifer characterized by flowing condition where the measured groundwater head in the recorded well reaches 0.25 m above the ground surface (April 2016). The exploitation of groundwater in this aquifer depends only on the shallow layer of Baharyia Formation represented by (Zone A) with thickness 160 m. The groundwater salinity reaches to 1664 mg/l in the concerned aquifer (Table 2).

3.3. Estimated porosity from well logging and microfacies analyses

Based on geophysical well logging data, the effective porosity was calculated for sandstone aquifers (Oligocene and Nubian sandstone) using Archie equations, (1942).
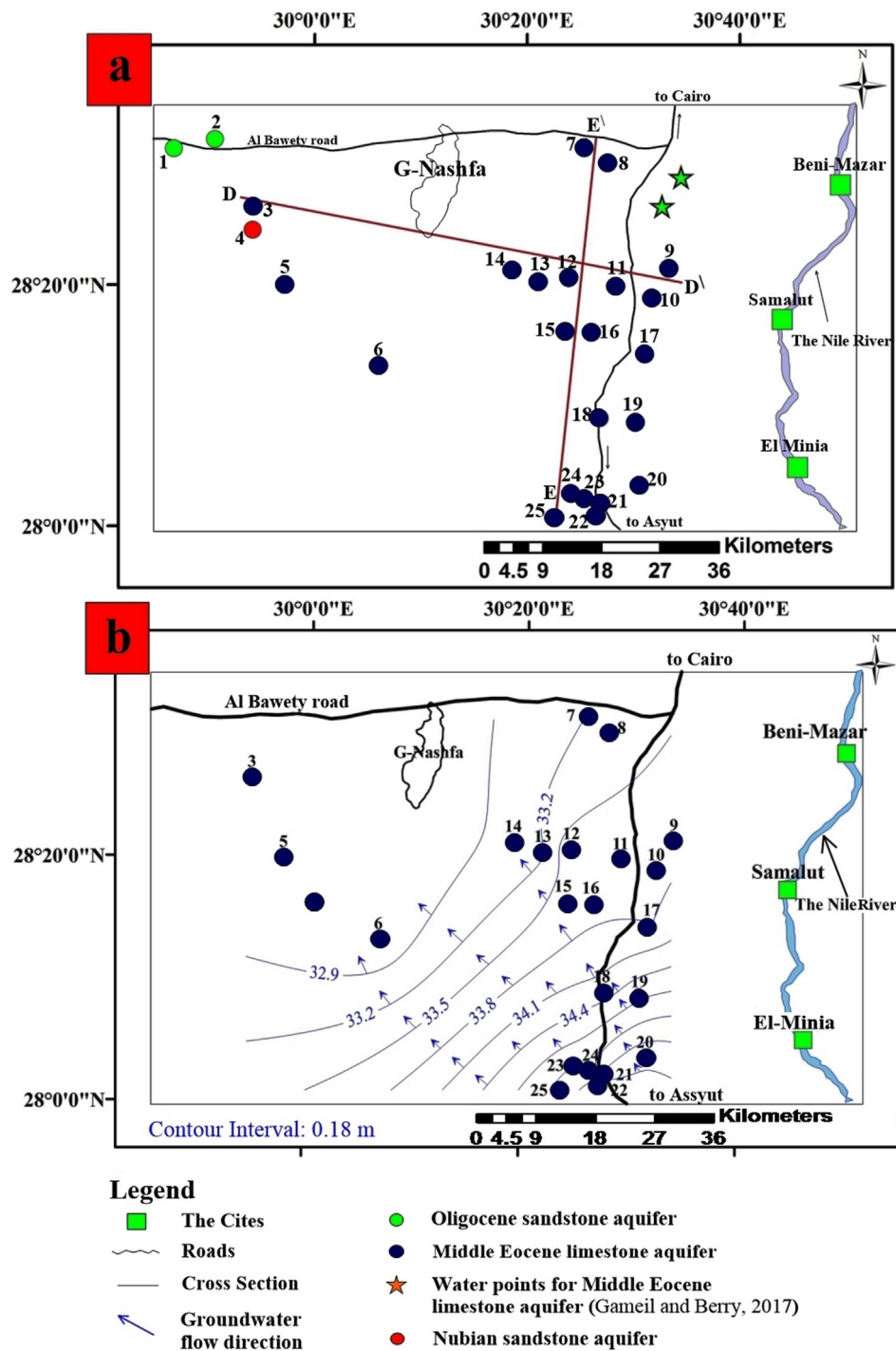
Fig. 5. Wells location map and water table map (Middle Eocene aquifer). (a) Locations of recorded wells showing the hydrogeological cross sections (D-D$^\backslash$ & E-E$^\backslash$). (b) Water table contour map of the Middle Eocene limestone aquifer (April 2016 & 2017) in the study area.

Effective porosity $Q_{eff} = (5400/R_{t*}R_w)^{1/2}$ *(in sodium chloride water type)*

$$(1)$$

where (ϕ_{eff}) is the effective porosity in percentage, (Rt) is the true resistivity in Ω m. and (Rw) is the formation water resistivity in Ω m. 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:

True resistivity $R_t = 1.7R_{LLD} - 0.7R_{LLS}$ *(if $R_{LLD} > R_{LLS}$)*   (2)

The formation water resistivity (Rw) is determined from electrical conductivity (EC) of the groundwater sample, where:

$Rw = 5400/EC$ (3)

Generally, the average of the effective porosity is 14.58% in Oligocene sandstone aquifer and 20.82% in Nubian sandstone aquifer. In addition to the hydraulic conductivity (K) of Oligocene sandstone and Nubian sandstone aquifers is calculated using Martoz equation, 1968. The average of the hydraulic conductivity is 1.34 cm/s in Oligocene sandstone aquifer and 4.5 cm/s in Nubian sandstone aquifer (Table 3).

$\Phi_{eff} = 0.462 + 0.045 \, Ln \, K$ (4)

From thin section investigation, it is clear that the types of porosity

Table 3
Hydrologic data of the studied aquifers in the study area.

Middle Eocene limestone aquifer

Well Number	Coordinates		Transmissivity (m²/day)	
	E°	N°	Theis (1935) (Recovery)	Cooper and Jacob (1946)
5	29.963	28.339	–	1650
9	30.562	28.375	335.5	–
17	30.534	28.255	600	–

Nubian sandstone aquifer						*Oligocene sandstone aquifer*					
Depth (m)	RLLD	RLLS	Qeff (%)	Rt (Ω m)	K (cm/s)	Depth (m)	RLLD	RLLS	Qeff (%)	Rt (Ω m)	K (cm/s)
1240	16	8	21.4	21.6	3.5	130	13	6	19	17.9	2
1220	39	20	13.7	52.3	0.6	110	11	7	21.6	13.8	3.7
1200	10	6	26.8	12.8	11.5	90	33	15	11.9	45.6	0.4
1150	15	9	22.6	19.2	4.6	70	40	16	10.7	56.8	0.3
1100	20	12	19.6	25.6	2.3	50	48	18	9.7	69	0.3
Rw = 1.83 Ω m						Rw = 1.2 Ω m					

Rt: True resistivity	*Qeff: Effective porosity*	*Rw: Water resistivity*	*RLLD: Long resistivity*
K: Hydraulic conductivity		*RLLS: Short resistivity*	
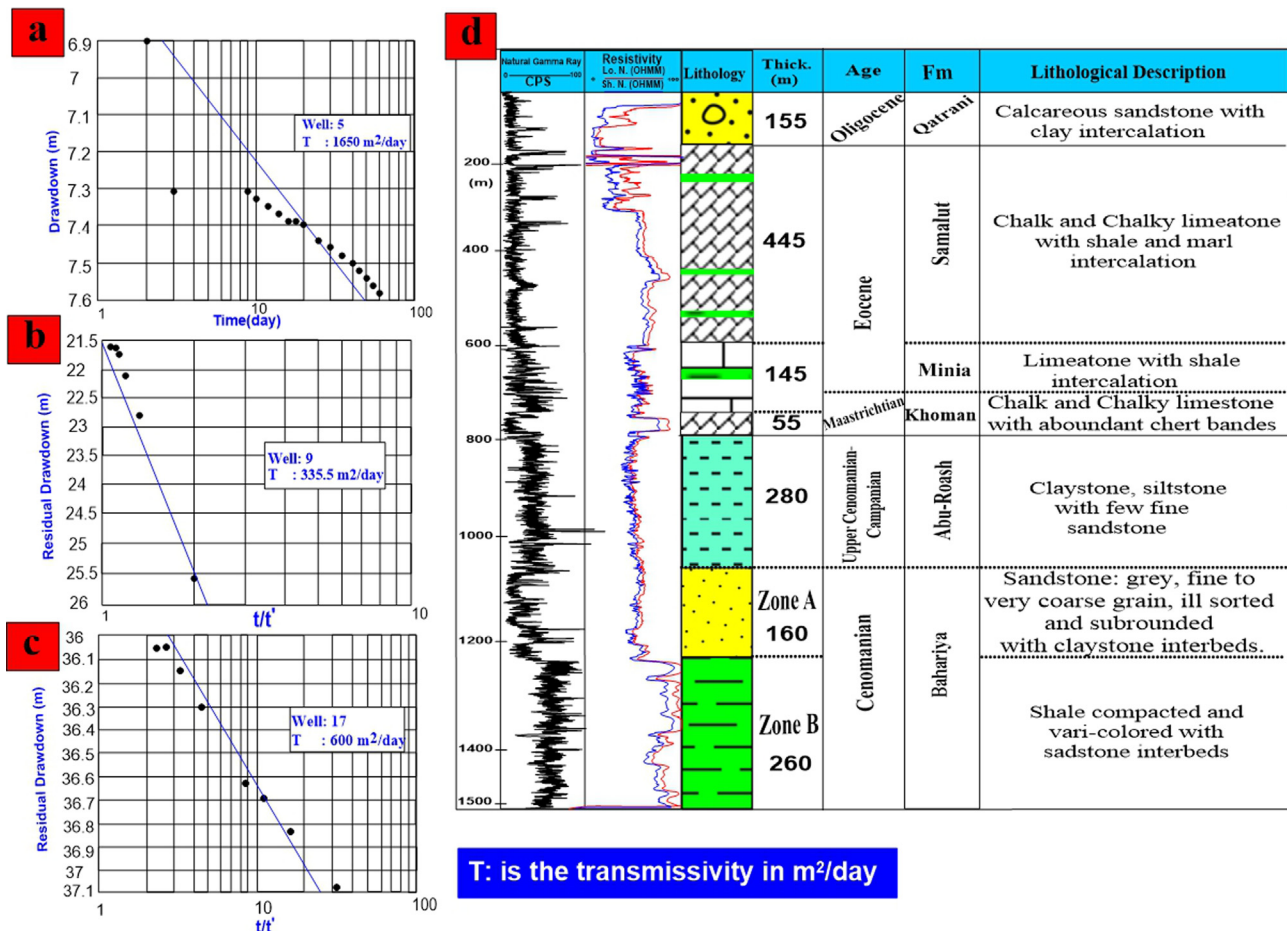
Fig. 6. Hydraulic parameters for some of the studied wells. (a) Time drawdown curves for (well no. 5) (b & c) Time residual drawdown curves for wells (9 & 17) tapping Middle Eocene limestone aquifer of the study area. (d) Composite log of well (no.4) tapping shallow Bahariya sandstone aquifer of the study area.

are vuggs and fracture. The porosity is ranging between 20% and 25% in Qatrani Formation, 6% to 19% in Samalut Formation, and 5% to 10% in Minia Formation (Fig. 4).

3.4. Hydrogeochemistry

The present hydrogeochemical study is essentially based on chemical analyses of water samples collected during two field trips. A twenty four representative groundwater samples were subjected to chemical analysis

Table 4
Chemical analyses of the groundwater samples from the studied aquifers in the study area.

Well	Aquifer	EC (mmhos/cm)	pH	TDS (mg/l)	Cations (mg/l)				Anions (mg/l)			SAR
					Ca^{++}	Mg^{++}	Na^+	K^+	$HCO3^-$	$SO4^-$	Cl^-	
2	Oligocene	4490	7.9	2584	150.3	54.7	745.9	18.4	244.1	163.3	1330	13.4
3	Middle Eocene limestone	3550	7.8	2103	63	30	697	21	195.2	108.9	1086	18.14
5		3580	7.9	2095	67	35	685	21	305	108.7	1026	16.85
6		3290	7.9	2130	130.3	42.5	612.9	29.4	213.5	24	1184	12.2
7		3850	7.8	2500	216.4	21.9	694.6	21.55	305.1	148.9	1250	12.3
8		3490	7.7	2076	94.2	60.8	636.8	2.3	274.6	52.8	1145	12.8
9		1570	7.6	830	98	14	180	14	244	103.6	298.2	4.69
10		1600	8	916	46	22	268	6	280.6	57.21	376.6	9
11		1985	8.5	1197	48	26	382	8	292.8	65	521.3	11.2
12		2300	8.4	1370	40	34	440	11	231.8	66.6	662.4	12.9
13		3830	8.2	2272	40	80	709	19	170.8	139.6	1199	14.9
14		3000	7.86	1884	70.1	69.3	544.8	21.2	305.1	68.7	957.4	11.3
15		2970	7.9	1780	68	34	569	17	305	95.2	844	14
16		1750	8.2	1033	46	20	320	8	366	55	400.7	10
17		1110	8.2	560	38	12	157	5	280.6	37.4	170.2	5.8
18		1160	8.2	590	48	12	157	6	268.4	47.6	184.8	5.3
19		1230	8.2	675	34	20	199	4	231.8	42.9	259.2	6.8
20		1208	8.2	658	36	20	186	4	219.6	44.8	257.8	6.3
21		2580	8.3	1475	62	20	477	8	170.8	71.1	751.8	3.9
22		1150	8.3	580	36	18	164	4	231.8	42.4	199.3	5.5
23		3400	8.4	2026	80	30	654	14	158.6	105.2	1064	16
24		3690	8.3	2183	90	44	683	12	219.6	130.4	1114	15
25		1410	8.4	862	34	22	271	6	244	48.9	358.2	9.1
4	Nubian	2950	7.2	1664	80	12	519	33	280.6	80.81	798.6	14.9
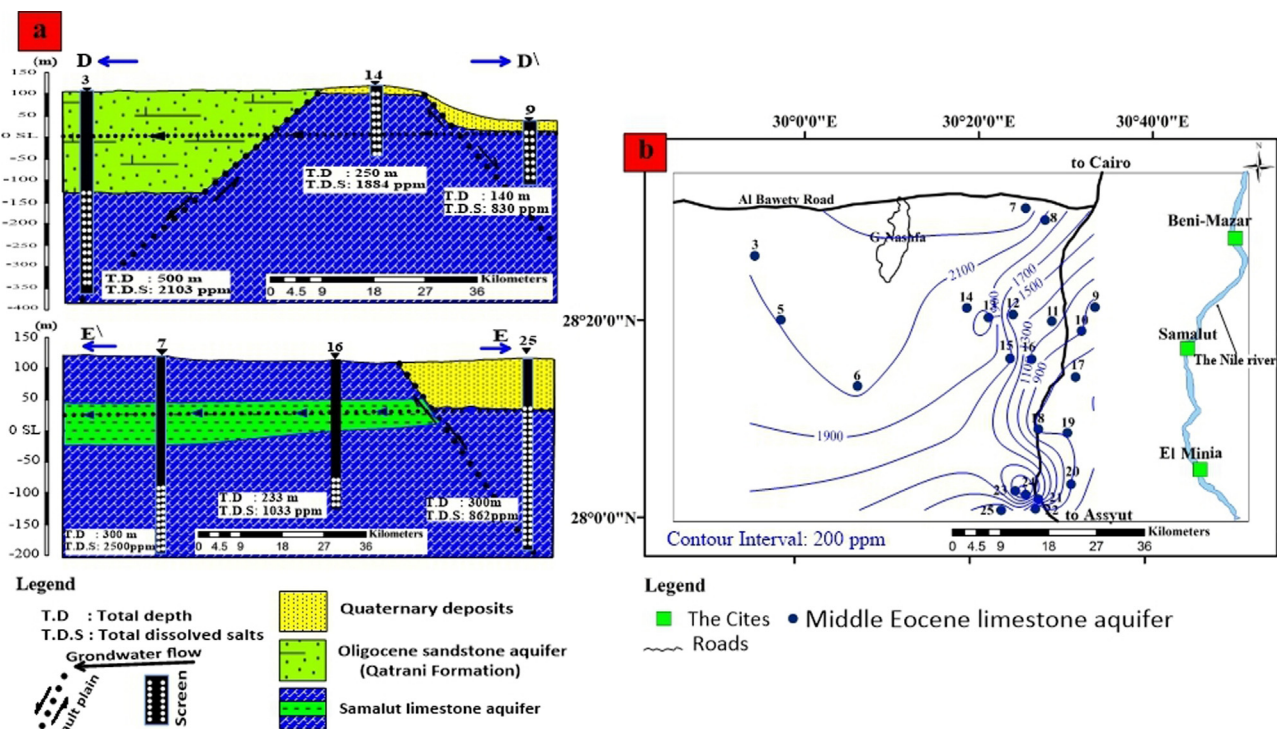
Fig. 7. (a) Hydrogeological cross sections (D-D\ & E-E\) illustrated the connection between the two aquifers (Middle Eocene limestone and Oligocene sandstone aquifers) and the groundwater flow direction of the study area. (Locations of D-D\ & E-E\ are showing a Fig. 5). (b) Iso-salinity contour map of the Middle Eocene limestone aquifer (April 2016 & April 2017) in the study area.

(Table 4). The total salinity reflects the geochemical composition of the groundwater. Based on the classification introduced by Todd (1980), the groundwater of Oligocene sandstone and Nubian sandstone aquifers fall in the brackish range where the TDS is 2584 mg/l in (well no. 2) and 1664 mg/l in (well no. 4), respectively. The groundwater of the Middle Eocene limestone aquifer varies from fresh to brackish; TDS ranges from 560 mg/l in (well no. 17) to 2500 mg/l in (well no. 7). The salinity of the

groundwater in the Middle Eocene limestone aquifer increases from southeast to northwest as shown in (Fig. 7b). It is worth to mention that the flow of groundwater in the Samalut limestone aquifer showing the same direction as the salinity increasing (Figs. 5a and 7b). The sequence of ion dominance in the studied groundwater is $Na^+ > Ca^{++} > Mg^{++} / Cl^- > HCO_3^- > SO_4^-$ in Oligocene sandstone and Nubian sandstone aquifers, while the dominant ions in the
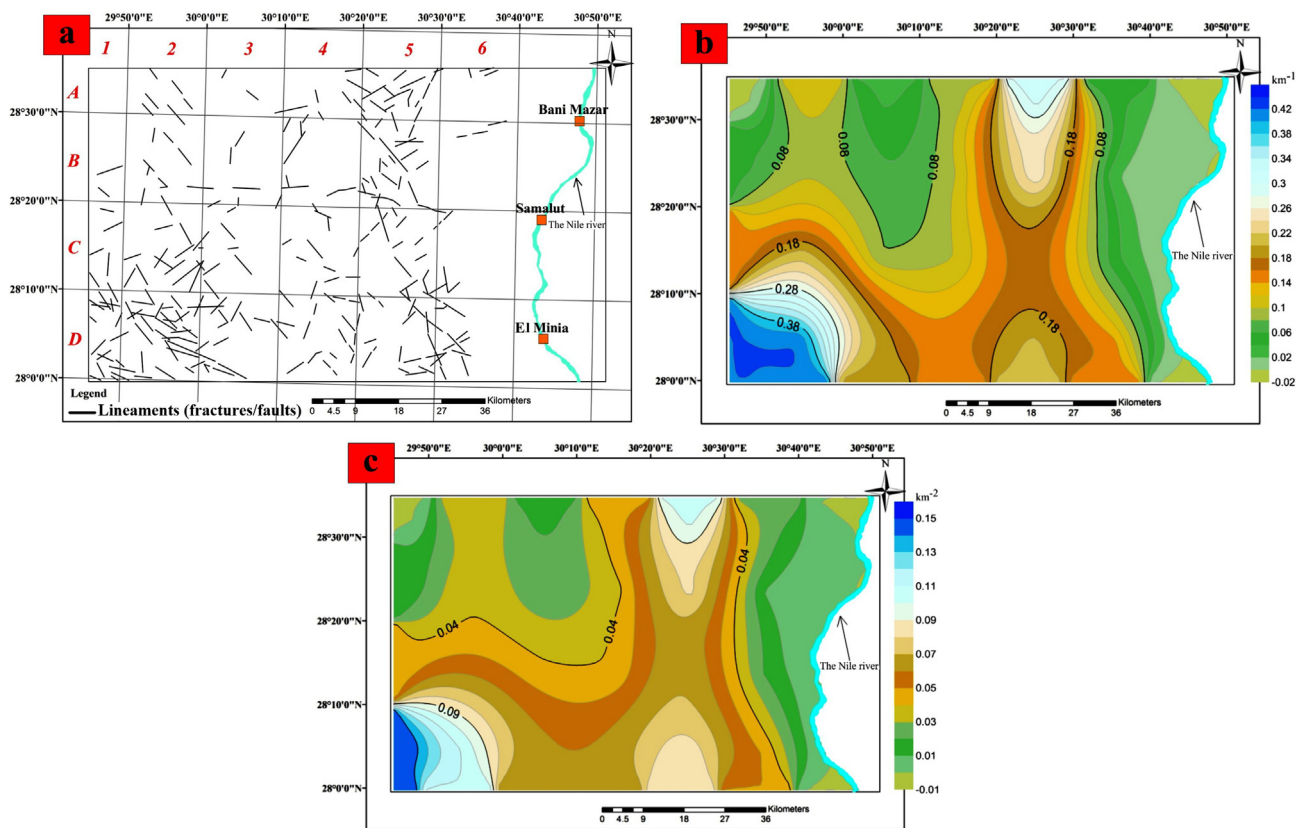
Fig. 8. (a) Structure lineaments (extracted from Klitzsch et al., 1987). (b) Density of structure lineaments contour map. (c) Frequency of structure lineaments contour map.

studied groundwater of Middle Eocene limestone aquifer is $Na^+ > Ca^{++} > Mg^{++}/Cl^- > HCO_3^- > SO_4^-$ and $Na^+ > Mg^{++} > Ca^{++}/Cl^- > Hco_3^- > So_4^-$.

3.5. Structural lineaments

The existence of the structural delineation of the studied area shows that the area is affected by several trends of structural lineaments (faults and fractures). The main trend of lineaments is NE–SW followed by NW–SE directions (Fig. 8a). The density of structural lineament in the study area varies between 0.02 and 0.3 km^{-1} (Fig. 8b), while the frequency of the lineament ranges between 0.009 and 0.1 km^{-2} (Fig. 8c). Structural lineaments are concentrated in the proximities of the southwest, southeast and northeast of the study area. The exposures of Eocene rocks are highly fractured by cracks and joints that are mostly connected.

3.6. Drainage network, slope and elevation

In the current study, the drainage network, slope and elevation data layers are used in the hydrogeological investigation (Fig. 10). They provide information about the nature of the landscape in the study area. The extracted drainage network from DEM illustrated that the area is dissected by drainage pattern of linear shape. This network are oriented to the southeast, coincide with the regional slopes. The slope in the concerned area is less than 14° (gentle slopes). In some parts of the eastern and western borders of the tableland, the slopes values reach to the 55°. The relief difference in the landscape of the study area is due to the tableland and isolated hills which acts locally as watersheds. The elevation values ranges from 9 m at the east of the tableland (cultivated land) to 211 m at the west of the tableland and isolated hills.

4. Discussion

4.1. Impacts of lithology and structural setting on groundwater

A total of 22 wells are extracting groundwater from the Middle Eocene limestone aquifer where the hardness and brittleness of limestone is controlling its susceptibility to fracturing and consequently its ability to be an aquifer. The groundwater salinity is directly affected by the lithologic nature of the water bearing formation. This is not apply for the case of the southeastern portion of the study area; where 8 samples having TDS concentrations ranging from 560 to 916 mg/l that reflect the fresh nature of the groundwater in this area (Table 2). The lower values of the TDS are recording in wells that were drilled in the carbonate rocks adjacent the Nile River. One possible explanation is that these wells receiving a considerable recharge from Nile water. On the other hand 10 samples having TDS concentration ranging from 1780 mg/l to 2500 mg/l, reflecting the brackish nature of the groundwater where it is the normal case for the salinity of the carbonate aquifer. The increasing of salinity values of these water points could be attributed to the process of dissolution of carbonate rocks during the subsurface flow of groundwater through cracks and joints, as well as the presence of clay layers and marl intercalation in the succession of Samalut Formation. Thin section investigation revealed that carbonate rocks of the Samalut Formation was affected by many types of secondary porosity (vuggy porosity and short fractures) (Fig. 4b, c, d, and d\), that resulted from diagensis processes. The karstic transformation or post-depositional alteration of the geological units can playing a role in the hydrogeological condition where the groundwater flow zones occurs through fractures and cracks (Tihansky and Knochenmus, 2001). The fractures and/or joints in carbonate rocks concentrate groundwater flows, thus lead to further leaching and dissolution processes and the creating of sinkholes. This is considered as secondary porosity which
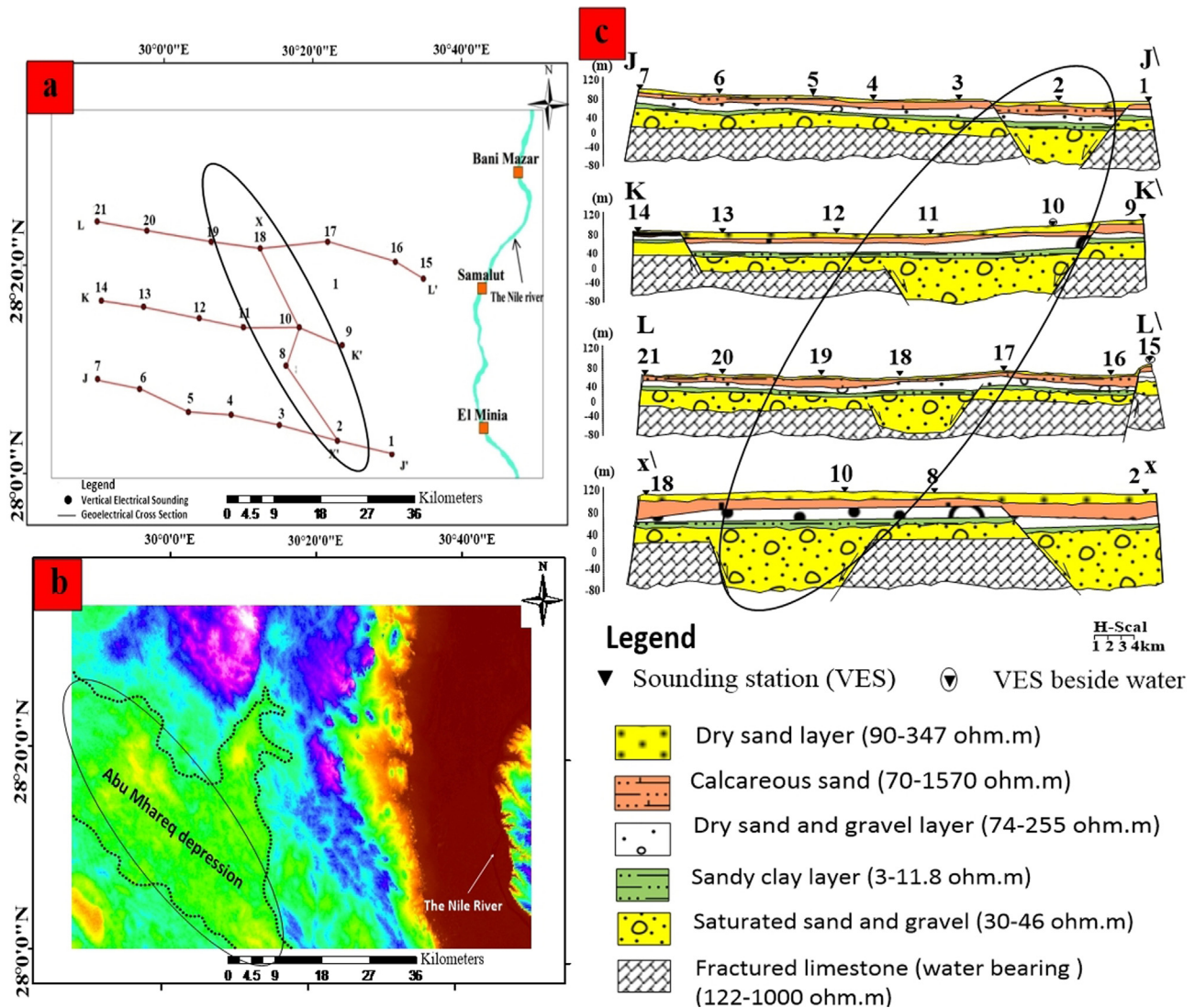
Fig. 9. Geoelectrical profiles, (a, c) in the study area (Abdel Baki, 2013), (b) Two dimensional map illustrated the Abu-Mhareq depression in the study area.

creates a transition zones in the limestone aquifers. Thus, these geological processes allow to increase the recharging opportunities and enhance the aquifer potentialities, which is clear in the areas have high density and frequency values of the structure lineaments in the study area (Fig. 8b and c).

4.2. Indications of groundwater recharge and aquifers relationship

Three evidences are indicating the nature of recharge from the Nile River to the Middle Eocene limestone aquifer of the study area. These evidences showing that the recharge is coming from the southeastern direction and has a local effect on the wells which have fresh groundwater. The evidences can be summarized in the following;

– Groundwater flow

The groundwater table of the Middle Eocene limestone aquifer ranges between 35.1 m. a. s. l (in wells No. 24 & 25) at southeastern portion and 32.7 m. a. s. l (in wells No. 5 & 6) at northwestern portion of the study area (Table 2 and Fig. 5b). Therefore, the general flow is from southeastern (where the Nile River is located) to the northwestern direction.

– Low salinity values

The groundwater salinity is relatively low (fresh water) where it ranges from 560 to 916 mg/l in the eastern and the southeastern parts while it ranges from 2095 to 2500 mg/l (brackish water) in the western and the northwestern parts of the study area. The low salinity values refer to that these wells maybe received an amount of the recharge from the Nile River (Table 2 and Fig. 7b).

– The stable isotope values of the groundwater

The stable isotope values are ranging between (−17.1 and 22.9 of δD, and −3.31 and 2.70 of δ^{18}O, Gameil and Berry Lyons, 2017) in the groundwater of the Middle Eocene aquifer. These values confirm that groundwater receive recharge from the Nile River where it has an isotopic signature of modern Nile water.

On the other hand, the western part of the study area which has brackish groundwater is assumed to be recharged during the past wet periods (pluvial time). This can be indicated through a dense drainage network which covers the study area (Fig. 10b).

The relationship between the aquifers can be shown in the contact between the Middle Eocene limestone aquifer and Oligocene sandstone aquifer as it was indicated in the hydrogeological cross section D-D$^\backslash$ (Fig. 7a). This is resulted from the tectonic movements which led to the existence of these hydrogeologic contacts. Also, the stable isotope values of Middle Eocene limestone aquifer (Samalut Formation) in the
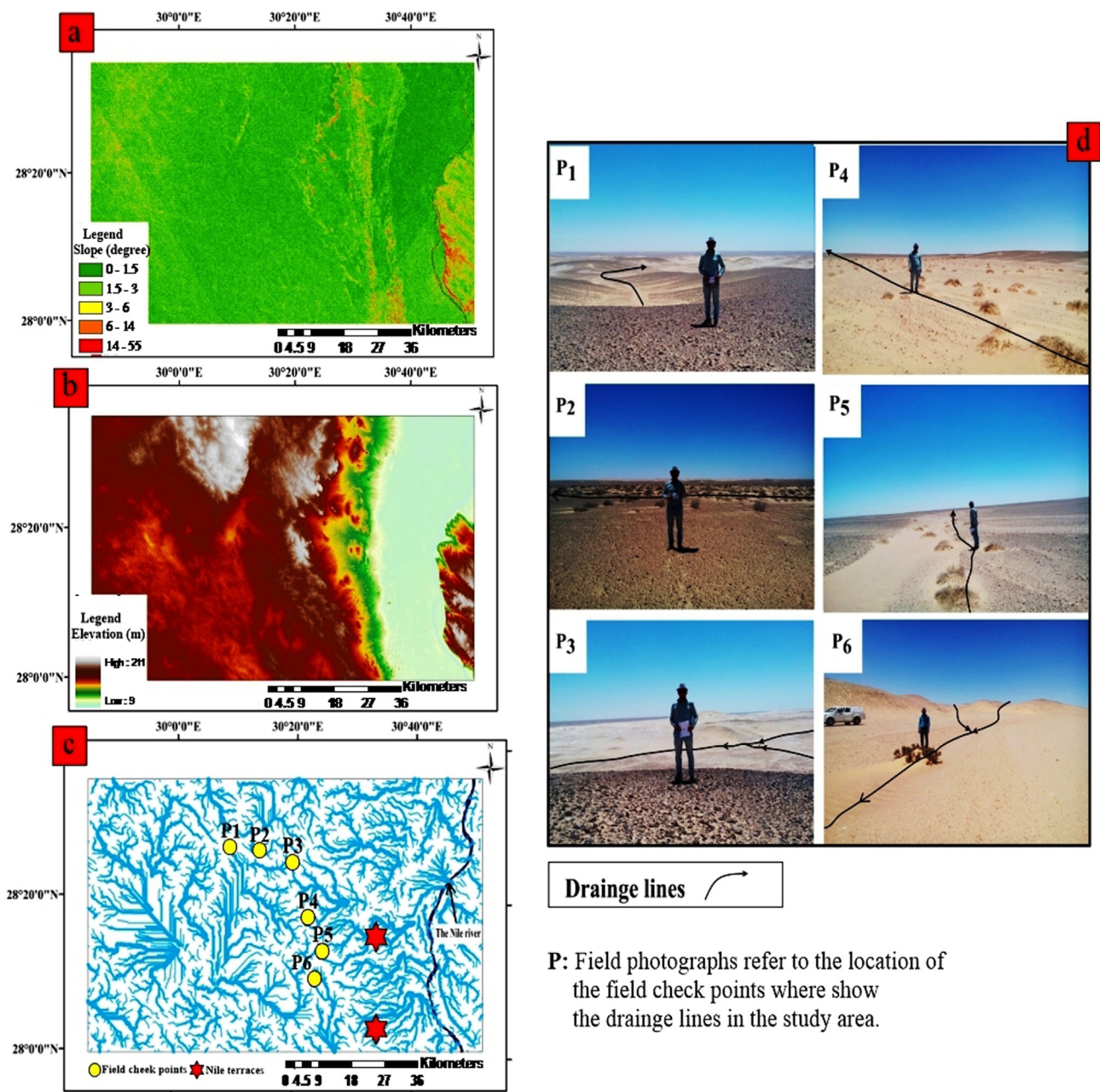
Fig. 10. Different data layers used in the assessment of water resources. (a) Slope, (b) DEM, (c) Drainage lines, (d) Field photographs showing the drainage lines of the study area.

western part reveal a contribution from the paleo-water of the Nubian sandstone aquifer through the upward leakage. This is confirmed by the highly depleted values of stable isotope (-7.7 of δD and -5.46 of $\delta^{18}O$ & -63.6 of δD and -8.32 of $\delta^{18}O$, Gameil and Berry Lyons, 2017) (Fig. 5a).

4.3. Assessment of existing wells

Many of the existing wells tapping the Oligocene and Middle Eocene aquifers are located outside the area affected by the high structural lineaments in the study area. The values of the density and frequency of the structural lineaments indicates (Figs. 8b and c), that the study area has the potential for infiltration and recharge of groundwater during the past wet climatic period in Egypt. The water point of the Oligocene aquifer are located in the western parts of the study area which affected by structural lineaments. In addition, the slope values of this part reach

up to 6° which provides a moderate chance for groundwater recharge. On the other hand, the areas with Middle Eocene limestone wells have lower slope that range between 1.5 and 6° (Fig. 10a), are highly affected by structure lineaments and their location near the Nile River, these factors provide opportunities for recharge process.

4.4. Genesis of the groundwater

The geochemical evolution of groundwater can be investigated through plotting the concentrations of major cations and anions in the diagram of Piper (1944). The diagram is used to deduce the hydrogeochemical facies. In Fig. 11a all samples located within sub-area 7 and are shown to be more influenced by marine conditions (especially these samples collected from the Samalut limestone aquifer). This means that the studied groundwater samples have primary salinity properties. Durov diagram (1948) is used to give more information
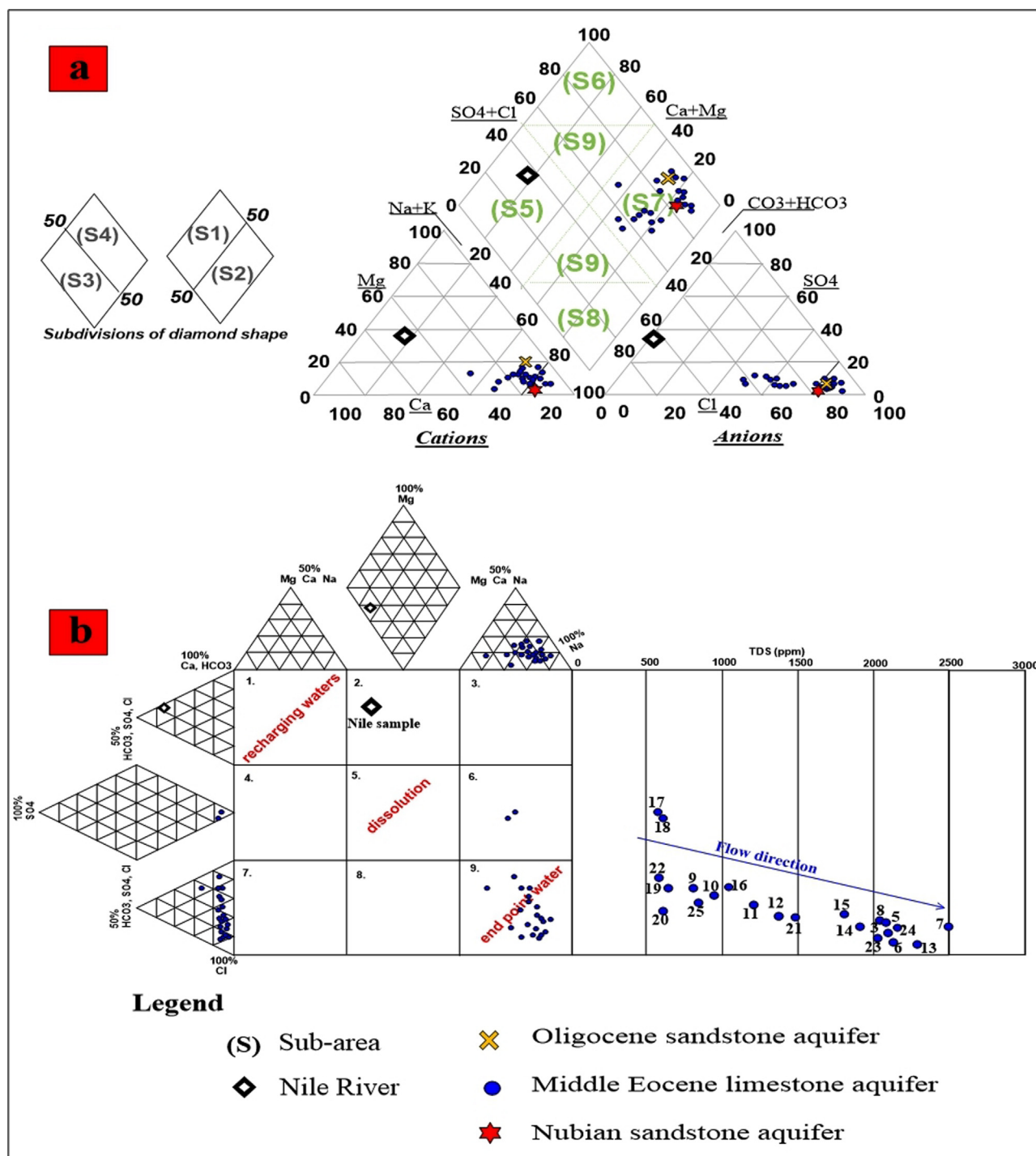
Fig. 11. (a) Geochemical classification of groundwater using Piper diagram. (b) Geochemical classification of the groundwater using Durov diagram.

about the hydrochemical facies and evolution of groundwater quality when compared with other graphical methods (Lloyd and Heathcote, 1985). In Fig. 11b, all wells occupy the Ca(HCO$_3$)$_2$, MgSO$_4$, Na$_2$SO$_4$ and NaCl sub-squares that representing an intermediate stage of groundwater mineralization (fairly fresh water), while the Ca(HCO$_3$)$_2$ sub-square represents an initial stage of mineralization (fresh water, recharge area). The NaCl sup-square represents more advanced stage of mineralization (brackish water, discharge area or end point water). This trend of development indicates that the groundwater is subjected during its movement from the catchment (recharging) area to the discharge area to several changes of salt dissolution accompanied by ion

exchange and metasomatism. The majority of the groundwater samples of the Samalut limestone aquifer lies in type (9), representing the end point (discharge area) except the groundwater samples (nos. 7 & 18) lies on type (6). It has dominance of sulfate and sodium ions indicating the portable mixing infiltration of types (3&5). The figure determine the groundwater flow direction by plotting salinity of wells in expended figure, done determine the groundwater flow direction from the Nile river to the west of the area of study. It is observed that the recharging area has low groundwater salinity, while the end point water has high groundwater salinity. This is attributed to the dissolution and leaching processes during groundwater flow.

Table 5
Proposed areas for groundwater protection and development.

Proposed locations	Area (km²)	Target aquifer for exploration	Landform	Surface lithology	Slope (°)	Structural lineament		Elevation (m.a.s.l)	Number of (VES)	Geophysical data (VES) Saturated Thickness (m)	
						Density (km⁻¹)	Frequency (km⁻²)			Middle Eocene	Oligocene
A	330	Oligocene Middle Eocene	Lowland	Sand	1.5–3	0.1532	0.5298	120 –124	4	~120	~40
B	310	Oligocene Middle Eocene	Tableland	Limestone	3–6	0.3003	0.1007	134–140	2	~80	~30
C	240	Oligocene Middle Eocene	Lowland	Sand	1.5–3	0.8321	0.2564	118–125	2	~80	~40
D	240	Middle Eocene	Lowland	Limestone	3–6	0.2037	0.0867	109–114	2	~100	~20

For the location of areas (A to D), please review (Fig. 12).
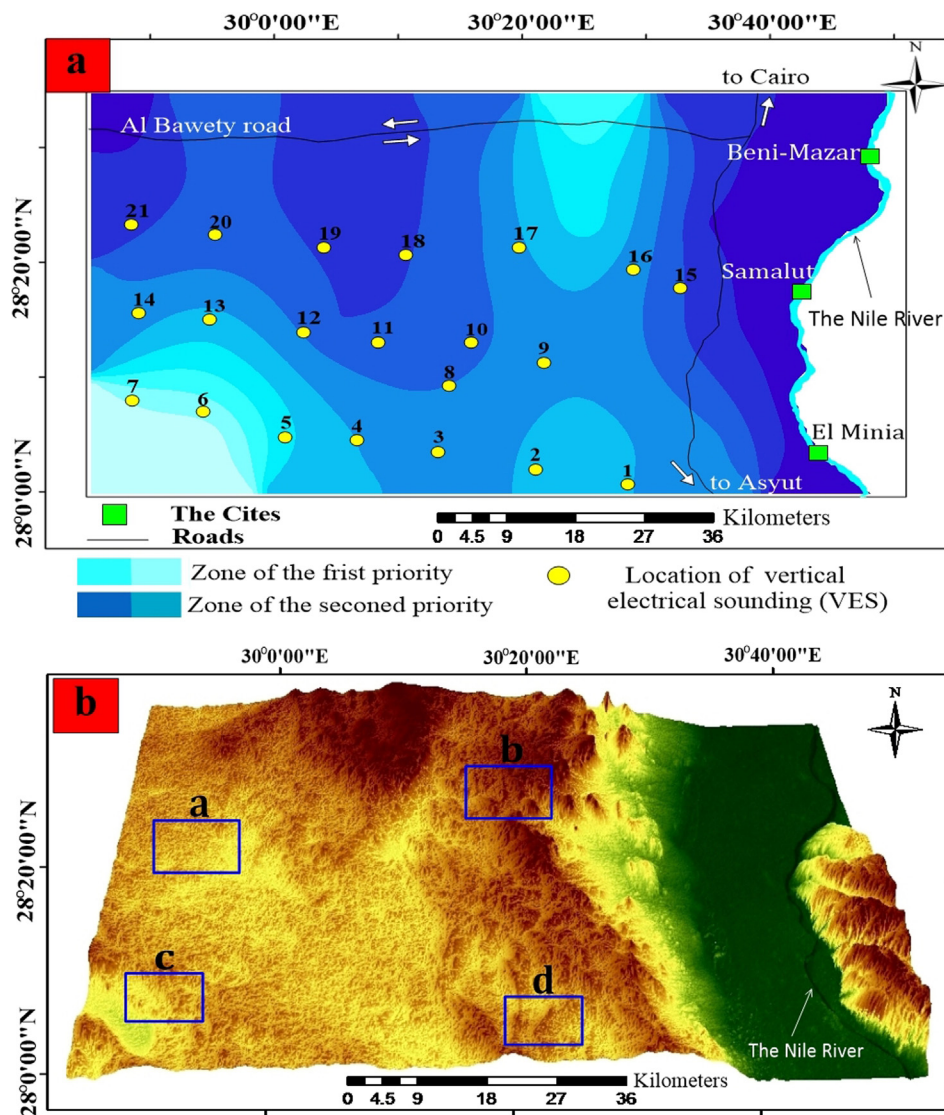
Fig. 12. Recommendation map for future groundwater exploration based on geological and geophysical data as well as remote sensing applications. (a) Priority map depending on multi-data layers (refer to Table 5). (b) 3D map showing the proposed areas for exploration.

4.5. Groundwater evaluation for different purposes

The aptness of the inspected groundwater for different purposes was determined by comparing its chemical composition with World Health Organization standards for drinking water (WHO, 2011), the Egyptian Higher Committee for Water standards (EHCW, 2007; National Academy of Science and National Academy of Engineering, 1972). The aptness of the groundwater for the drinking uses was analyzed by comparing its parameters with the World Health Organization (WHO, 2011) and (EHCW, 2007). It is clear that the groundwater samples of wells (9, 10, 17, 18, 19, 20, 22 and 25) are suitable for human drinking because TDS values range from 560 to 916 mg/l, while groundwater

samples in other wells exceed the permissible limit 1000 mg/l. For livestock and poultry, the National Academy of Science and National Academy of Engineering (1972), which define the principals for evaluation according to the total dissolved solids (TDS). The groundwater of the studied area has been separated into two classes of quality for livestock and poultry consumption as follows:

1. Excellent groundwater (TDS < 1000 mg/l), is found in well nos. 9, 10, 17, 18, 19, 20, 22 and 25 of the Middle Eocene aquifer.
2. Very satisfactory groundwater (TDS 1000–3000 mg/l) is found in well no. 2 and 4 of the Oligocene and the Nubian aquifers, while found in well nos.3, 5, 6, 7, 8, 11, 12, 13, 14, 15, 16, 21, 23 and 24 of the Middle Eocene aquifer.

On the other hand, the evaluation for irrigation purposes of the groundwater depends on the classification of the US Salinity Laboratory Staff's Classification (1954). It uses the relationship between sodium adsorption ratio (SAR) and electrical conductivity (EC). Therefore, all groundwater samples in wells of the three aquifers (Oligocene, Middle Eocene and Nubian aquifers) are falling into the good class and can be used for irrigation.

4.6. Groundwater protection and development (Recommendations)

The current study proposes the following recommendations for the protection and development of the groundwater. In additional to, detect the best areas for the future groundwater exploration.

1. Based on the main parameters which including; geologic and geomorphologic settings, structural lineaments, drainage network, elevation and subsurface saturated zones, four areas are selected for intensive hydrogeophysical investigation and drilling of test wells for the groundwater exploration (Table 5 and Fig. 12). These areas characterized by; high values of lineament density and frequency, drainage lines which clarify the possibility of paleo- surface runoff, low slope as well as elevations. The four areas showing in (Table 5 and Fig. 12), were tested by a group of Vertical Electrical Sounding (VES) (Abdel Baki, 2013, Fig. 9). This group of VES indicates the subsurface saturated thickness in areas A, B, C and D, where it ranges between 80 m and 120 m for Middle Eocene Aquifer (Samalut), and between 20 m and 40 m for the Oligocene aquifer (Qatrani).
2. Drilling a grid of piezometers in order to record continuously the levels and monitoring the fluctuations.
3. Mismanagement and random drilling by the resident population to extract water from the Oligocene and Middle Eocene limestone aquifers should be regulated by local authorities. The current wells working in the study area are close to each other. Although not yet noticed, this could lead to the deterioration of the groundwater resource when groundwater extraction is not sufficiently controlled.

5. Conclusions

The current research introduced an approach for hydrogeological evaluation which includes; the current groundwater situation and explain the factors affecting its occurrence and quality. The approach is based on amalgamation of geomorphology, geology, hydrogeology, geophysical data, chemical analyses, remote sensing, and GIS applications. The aquifers were subdivided according to their age into the Oligocene, Middle Eocene and Nubian aquifers. Limestone of the Middle Eocene we can say that the main aquifer of the study area. The investigation and understanding of the limestone aquifers is one of the most challenges which face the hydrogeologist all over the world due to its heterogeneous properties. Therefore, the study approach serves to deal with aquifer through multi-disciplinary researches to clarify the recharge nature which has direct impact on the sustainable

development. This was an important factor, especially in existence of low salinity values. The water recharge is mainly from the Nile water due to the following; (1) The water table map indicates that the groundwater flow from Southeast (Nile water) to Northwest, (2) The groundwater salinity in the limestone aquifer is relatively low ranges from 560 mg/l to 930 mg/l in the most of wells. (3) The stable isotope values confirming that groundwater has isotopic signature of the modern Nile water with slightly contribution of paleo-water of the Nubian sandstone. Accordingly, the sustainable development activities can be established after determine the safe yield of this aquifer for its protection from deterioration.

Conflict of interest

The authors declare that there is not any conflict of interest for this manuscript.

References

Abdel Aziz, R.S., 1994. Geological and sedimentological studies in west El Minia – Beni Mazar area, Egypt. M.Sc. Thesis.

Abdel Baki, N.F., 2013. Exploring groundwater possibility in the area west of El Fayoum-Asuit road using remote sensing, geophysical and GIS techniques. Ph.D. Thesis. Fac. Sci., Cairo University, pp. 168.

Abou Heleika, M.M., Niesner, E., 2009. Configuration of the limestone aquifers in the central part of Egypt using electrical measurements. Hydrogeol. J. 17, 433–446.

Al Temamy, A.M., Abu Risha, U.A., 2016. Groundwater interaction and potential: inferred from geoelectrical and hydrogeological techniques in The Desert fringe of Abu Qurqas area, El Menia, West Nile, Egypt. Egypt. J. Geol. 60, 75–95.

American Society of Testing and Materials ASTM, 2002. Water environmental technology. Annual book of ASTM standards, sections: 11.01 and 11.02. West Conshohocken, PA: ASTM.

Archie, G.E., 1942. The electric resistivity logs and an aid in determine some reservoir characteristics: Petroleum technology, v.s., pp. 54–62.

Beadnell, A., 1905. The relations of the Eocene and Cretaceous systems in the Esna-Aswan reach of the Nile Vally. J. Geol. Soc. Lond. 61, 667–678.

Cooper, H.H., Jacob, C.E., 1946. A generalized graphical method for evaluating formation constants and summarizing well history. Am. Geophys. Union. Trans. 27, 526–534.

Durov, S.A., 1948. Classification of Natural Waters and Graphic Representation of Their Composition. Doklady Akad. Nurak, USSK, 59(1), pp. 87–90.

Egyptian Geological Survey and Mineral Authority EGSMA, 2005. Geologic Maps of Minia. Scale 1:250,000 Sheet 2. Geol. Surv. Egypt, Cairo, Egypt.

Egyptian Higher Committee for Water EHCW, 2007. Egyptian standards for drinking water and domestic uses (in Arabic).

El Kashouty, M., El Sayed, E., Kamel, A., 2010. The hydrochemical characteristics and evolution of groundwater and surface water in the western part of the River Nile, El Minia district, Upper Egypt. Arab. J. Geosci. http://dx.doi.org/10.1007/s12517-010-0219-x.

El Miligy, E.M.M., 2004. Groundwater Resources Evaluation Studies of ASSUIT Governorate. Ph. D. Thesis, Fac. Sci., Assiut Univ. pp. 307.

El Sayed, M.H., 2007. Hydrogeochemistry of the Tertiary-Quaternary aquifers in the newly reclaimed areas in El-Minia governorate, Egypt. Bul. Ain Shams Univ. 45, 22 p.

Fitzner, B., Heinrichs, K., Labouchardiere, D., 2002. Limestone weathering of historical monuments in Cairo, Egypt. In: Proceedings of the 5th EC Conference, Cultural Heritage Research: a Pan-European Challenge, Cracow, Poland. ICSC Institute of Catalysis and Surface Chemistry/Polish Academy of Sciences, Cracow/Poland, European Communities, p. 367.

Flugel, E., 1982. Microfacies Analysis of Limestone. Springer-Verlag, Berlin-Heidelberg-New York 633p.

Ghoubachi, S.Y., 2017. The hydrogeological characteristics of the Nubian Sandstone System in Sahl Karawein Area and Its Vicinities, El-Farafra Oasis, Western Desert, Egypt. Ann. Geol. Surv. Egypt. 36, 175–187.

Klitzsch, E., List, F.K., Pohlmann, G., 1987. Geological Map of Egypt, Conoco Coral and Egyptian General Petroleum Company, Cairo, Egypt, 2 Sheets, Scale 1:500,000.

Lloyd, J.W., Healhcote, J.A., 1985. Natural Inorganic Hydrochemistry in Relation to Groundwater, an Introduction. Clarandon Press, Oxford.

Martoz, G., 1968. Techische grundlageneiner wasserspeicherung imm naturlichen untergrund habilitationsschrift. Universitat Stuttgart.

National Academy of Science and National Academy of Engineering, 1972. Water quality criteria: Protection Agency: Washington, D.C., 594p.

Osman E.A., 2006. Hydrogeological Study of East Minia Area, El-minia District, Egypt. M. Sc. Thesis. Fac. of Sci., Minia Univ., Egypt, p. 166.

Piper, A.M., 1944. A graphic procedure in the geochemical interpretation of water analyses. Trans. Am. Geophy. Union, 25, Washington, D.C. 6, pp. 914–923.

Gameil, R.M., Berry Lyons, W., 2017. Assessment of the hydrogeochemical processes affecting groundwater quality in the eocene limestone aquifer at the desert Fringes of El Minia Governorate, Egypt. Aquat. Geochem. 2017 (23), 33–52. http://dx.doi.org/10.1007/s10498-016-9298-y.

Said, R., 1962. The Geology of Egypt. El Sevier 377, p.

Said, R., 1981. Geological Evaluation of the Nile. Springer, Berlin, pp. 151.

Salem, A.A., 2015. Hydrogeological studies on the shallow aquifers in the area west Samalot, El-Minia Governorate, Egypt. Egy. J. Pure & Appl. Sci. 53 (4), 49–60.

Shabana, A.R., 2010. Hydrogeological studies on the Area West Deir Mouas-Mallawi, El Minia Governorate, Egypt. Egypt. J. Geol. 54, 61–78.

Tantawi, M.A., 1992. Isotopic and hydrochemical application to the surface and groundwater assessments in El Minia district, Egypt, Ph.D. Thesis, Fac. of Sci., Al Minia Univ., Egypt.

Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. Am. Geophys. Union Trans. 16, 510–524.

Tihansky, B., Knochenmus, L.A., 2001. Karstfeatures and hydrogeology in west-central Florida: a field perspective. US Geol Surv Water Resour Invest Rep 01-4011, pp. 198–211.

Todd, D.K., 1980. Groundwater Hydrology. John Wiley and Sons Inc, New York, U.S.A. 535p.

U.S. Salinity Laboratory Staff, 1954. Diagonsis and improvement saline and alkali soil: Agric, handbook, 60, Washington, D.C., pp. 1–60.

Wilson, J.L., 1975. Carbonate Facies in Geologic History. Springer-Verlag, Berlin, pp. 471.

World Health Organization WHO, 2011. The guidelines for drinking water quality, 4th edn. Available on: http://www.who.int.