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.
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 km² (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 gravelly 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 study area, several 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

| Geomorphological units | Area (km²) | Perimeter (km) | Elevation (m.a.s.l) |
|------------------------|------------|----------------|-------------------|
| Tableland              | 661.767    | 172.709        | 69                |
| Isolated hills         | 54.671     | 37.929         | 130               |
| Longitudinal sand dunes| 95.244     | 113.801        | 70                |
| Gravelly plain         | 1839.099   | 249.325        | 110               |
| Sandy plain            | 45.943     | 65.098         | 55                |
| Silty plain            | 287.371    | 139.073        | 70                |
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
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 (Ca²⁺) and magnesium (Mg²⁺) were determined by titration against (Na₂EDTA) by complex metric method. Carbonate (CO₃²⁻) and Bicarbonate (HCO₃⁻) were determined using titration against sulfuric acid by neutralization method. Chloride (Cl⁻) was determined volumetrically by titration against silver nitrate. Sulfate (SO₄²⁻) 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
vugs 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, echinoids, 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 diagenesis. This microfacies type was deposited by gravity flows from the fluviomarine. 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
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 aquifers include; The Oligocene sandstone aquifer (Taped by 2 wells), described as terraces, Said (1962), (Fig. 10c).

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) as shown in (Table 2). The partially saturated thickness of the Oligocene sandstone aquifer attains 98.43 m (well no. 2). The TDS value of the Oligocene sandstone aquifer reaches to 1664 mg/l in the concerned aquifer (Table 2). The groundwater salinity reaches to 1664 mg/l in the concerned aquifer.

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). 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 Bahariya 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. Bahariya 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 Bahariya sandstone 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).
Effective porosity $Q_{\text{eff}} = (5400/R_t R_w)^{1/2}$ \hspace{1cm} (in sodium chloride water type)  

where ($\phi_{\text{eff}}$) is the effective porosity in percentage, ($R_t$) is the true resistivity in $\Omega \text{m}$, and ($R_w$) is the formation water resistivity in $\Omega \text{m}$. The true resistivity ($R_t$) is determined by correction of the long resistivity log ($R_{\text{LLD}}$) or ($R_{\text{LDS}}$) and short normal resistivity log ($R_{\text{16}}$) or ($R_{\text{LSS}}$). The true resistivity ($R_t$) is obtained by the following equation:

True resistivity $R_t = 1.7R_{\text{LLD}} - 0.7R_{\text{LSS}}$ (if $R_{\text{LLD}} > R_{\text{LSS}}$)  

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

$R_w = 5400/\text{EC}$  

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).

$\phi_{\text{eff}} = 0.462 + 0.045 \ln K$  

From thin section investigation, it is clear that the types of porosity...
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.
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 (TDS 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⁻ > HCO₃⁻ > SO₄²⁻ in Oligocene sandstone and Nubian sandstone aquifers, while the dominant ions in the

| Well | Aquifer            | EC (mmhos/cm) | pH  | TDS (mg/l) | Ca²⁺ | Mg²⁺ | Na⁺  | K⁺   | HCO₃⁻ | SO₄²⁻ | Cl⁻  | SAR |
|------|--------------------|---------------|-----|------------|------|------|------|------|-------|-------|------|-----|
| 2    | Oligocene          | 4490          | 7.9 | 2584       | 150.3| 54.7 | 745.9| 18.4 | 441.1 | 163.3 | 1330 | 13.4 |
| 3    | Middle Eocene      | 3550          | 7.8 | 2103       | 63   | 30   | 697  | 21   | 195.2 | 108.9 | 1086 | 18.14 |
| 5    | limestone          | 3580          | 7.9 | 2095       | 67   | 35   | 685  | 21   | 305   | 108.7 | 1026 | 16.85 |
| 6    | limestone          | 3290          | 7.9 | 2130       | 130.3| 42.5 | 612.9| 29.4 | 213.5 | 24    | 1184 | 12.2 |
| 7    | limestone          | 3850          | 7.8 | 2500       | 216.4| 21.9 | 694.6| 21.55| 305.1 | 148.9 | 1250 | 12.3 |
| 8    | limestone          | 3490          | 7.7 | 2076       | 94.2 | 60.8 | 636.8| 2.3  | 274.6 | 52.8  | 1145 | 12.8 |
| 9    | limestone          | 1570          | 7.6 | 830        | 98   | 14   | 180  | 14   | 244   | 103.6 | 298.2 | 4.69 |
| 10   | limestone          | 1600          | 8   | 916        | 46   | 22   | 268  | 6    | 280.6 | 57.21 | 376.6 | 9    |
| 11   | limestone          | 1985          | 8.5 | 1197       | 48   | 26   | 382  | 8    | 292.8 | 65    | 521.3 | 12.9 |
| 12   | limestone          | 2300          | 8.4 | 1370       | 40   | 34   | 440  | 11   | 231.8 | 66.6  | 662.4 | 12.9 |
| 13   | limestone          | 3830          | 8.2 | 2272       | 40   | 80   | 709  | 19   | 170.8 | 139.6 | 1199 | 14.9 |
| 14   | limestone          | 3000          | 7.86| 1884       | 70.1 | 69.3 | 544.8| 21.2 | 305.1 | 68.7  | 957.4 | 11.3 |
| 15   | limestone          | 2970          | 7.9 | 1780       | 68   | 34   | 569  | 17   | 305   | 95.2  | 844  | 14   |
| 16   | limestone          | 1750          | 8.2 | 1033       | 46   | 20   | 320  | 8    | 366   | 55    | 400.7 | 10   |
| 17   | limestone          | 1110          | 8.2 | 560        | 38   | 12   | 157  | 5    | 280.6 | 37.4  | 170.2 | 5.8  |
| 18   | limestone          | 1160          | 8.2 | 590        | 48   | 12   | 157  | 6    | 268.4 | 47.6  | 184.8 | 5.3  |
| 19   | limestone          | 1230          | 8.2 | 675        | 34   | 20   | 199  | 4    | 231.8 | 42.9  | 259.2 | 6.8  |
| 20   | limestone          | 1208          | 8.2 | 658        | 36   | 20   | 186  | 4    | 219.6 | 44.8  | 257.8 | 6.3  |
| 21   | limestone          | 2580          | 8.3 | 1475       | 62   | 20   | 477  | 8    | 170.8 | 71.1  | 751.8 | 3.9  |
| 22   | limestone          | 1150          | 8.3 | 580        | 36   | 18   | 164  | 14   | 231.8 | 42.4  | 199.3 | 5.5  |
| 23   | limestone          | 3400          | 8.4 | 2026       | 80   | 30   | 654  | 14   | 158.6 | 105.2 | 1064 | 16   |
| 24   | limestone          | 3690          | 8.3 | 2183       | 90   | 44   | 683  | 12   | 219.6 | 130.4 | 1114 | 15   |
| 25   | limestone          | 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.
studied groundwater of Middle Eocene limestone aquifer is \( \text{Na}^+ > \text{Ca}^{++} > \text{Mg}^{++} > \text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{--} \) and \( \text{Na}^+ > \text{Mg}^{++} > \text{Ca}^{++} > \text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{--} \).

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 lineaments 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 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. 8. (a) Structure lineaments (extracted from Klitzsch et al., 1987). (b) Density of structure lineaments contour map. (c) Frequency of structure lineaments contour map.
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. 8b). 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 δ18O, 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\(\text{1}\) (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
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 $\delta^1$D and $-5.46$ of $\delta^{18}$O, Gameil and Berry Lyons, 2017) ($\delta^2$D and $-63.6$ 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 hydro-geochemical 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.
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(HCO₃)₂, MgSO₄, Na₂SO₄ and NaCl sub-squares that representing an intermediate stage of groundwater mineralization (fairly fresh water), while the Ca(HCO₃)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.

Fig. 11. (a) Geochemical classification of groundwater using Piper diagram. (b) Geochemical classification of the groundwater using Durov diagram.
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

### 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) |
|--------------------|-----------|--------------------------------|---------------------------|-----------|----------------------|-------------------|----------------|------------------------|-------------------------|
| A                  | 330       | Oligocene Middle Eocene        | Lowland Sand              | 1.5-3     | 0.1532               | 120 – 124         | 4              | −120                   | −40                     |
| B                  | 310       | Oligocene Middle Eocene        | Tableland Limestone      | 3-6       | 0.3003               | 134 – 140         | 2              | −80                    | −30                     |
| C                  | 240       | Oligocene Middle Eocene        | Lowland Sand              | 1.5-3     | 0.8321               | 118-125           | 2              | −80                    | −40                     |
| D                  | 240       | Middle Eocene Lowland Limestone| Lowland Limestone        | 3-6       | 0.2037               | 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 research introduced an approach for hydrogeological evaluation which includes; 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 (Qatarani), and between 20 m and 40 m for the Oligocene aquifer (Qatrani).

Drilling a grid of piezometers in order to record continuously the levels and monitoring the fluctuations.

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 expected 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 range 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.

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