Integrated geophysical interpretation and hydrogeochemistry investigation for groundwater aquifer assessment at El – Farafra depression, Western Desert, Egypt

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ABSTRACT
The aeromagnetic data is utilised to determine the depth of the crystalline (basement) rock-sand subsurface structures where the basement depth ranges from 1777 - 3778 m. and the area is dissected by several faults with various trends, especially in the NWW-SSE direction. The well-logging data is used to investigate the subsurface stratigraphy where the interpretation of well-logging data indicates that the area is composed of seven geologic units, with the third, fifth, and seventh units representing the main aquifer. The first zone of the Nubian sandstone aquifer is represented by the sandstone that makes up the third geologic unit with a low gamma ray, which is sandwiched by clay layers. The Nubiansandstone aquifer’s second zone is represented by the fifth geologic unit, which is composed of sandstone with minor clay layers. It exhibits low to modest gamma-ray values and moderate to high resistivity values. The seventh geologic unit is composed of sandstone and represents the third zone of the Nubian sandstone aquifer, which is sandwiched by clay layers. It has high resistivity values and a low gamma-ray. The aquifer in the study area has transmissivity and belongs to a high potential aquifer. The aquifer in the study area has transmissivity and belongs to a high potential aquifer V.

1. Introduction
The study aims to determine the depth of the basement rocks and thus determine the thickness of the sedimentary cover (Nubian Sandstone Aquifer thickness), as well as determine the subsurface structural elements affecting the study area, also to determine the subsurface layers in addition to exploring the identification of groundwater occurrences and knowing the type of water. Farafra Oasis is considered one of the most promising areas for future agricultural development in Egypt. The current research implements integrated hydrogeologic and hydrogeochemical approaches to investigate the origin and recharge conditions of groundwater in Farafra Oasis. The main aquifer in the oasis is the artesian Nubian Sandstone which is overlain by the Khoman fractured limestone in the north and Dakhla shale in the south of the study area (Ameer et al. 2022).

The integration of the methods including magnetic, well-logging, pumping tests, and hydro-chemical analyses can be given reasonable results and a clear picture of the subsurface formations. The magnetic tool provides a vivid image of subsurface formations where a magnetic approach is useful for estimating the upper surface of crystalline rocks, along with additional tools like well-logging, pumping tests, and hydro-chemical analyses (Sultan et al. 2009; Araffa et al., 2021; Araffa et al., 2019). Additionally, the magnetic approach is utilised to determine structural patterns governing the regional geometry of groundwater aquifers and to explore groundwater (Murty and Raghavan 2002). Well-logging is used to identify subsurface layers and assess the potential of groundwater. The hydraulic properties of the El Farafa aquifer were calculated by the data from the pumping experiments (transmissivity and hydraulic conductivity). The hydro-chemical examination of groundwater is performed to determine if it is suitable for a variety of uses. Mohamed et al. 2012; Araffa 2013. The integrated geophysical interpretation was employed by authors Mohamed et al. (2012); Sultan and Santos (2008) for groundwater exploration and subsurface structures. The research area, which covers an area of 6000 km², is situated in the middle of Egypt’s Western Desert in latitudes 26° 44’ 54.69" and 26° 56’ 19.56” N and longitudes 27° 38’ 55.46" and 28° 42’ 49.46” E. (Figure 1).

2. The research area’s hydro-geological and geological settings
Numerous authors have conducted thorough analyses of the surface and underlying geology of El Farafa
Oasis (Zaghloul 1983; Salem 2002). The sedimentary rocks’ lithostratigraphy spans the Upper Cretaceous to the Quaternary (Figure 2). The Wadi Hennis, El Hafhuf, Khoman Chalk, and Dakhla Formations are all part of the Upper Cretaceous sequence. The Nubian aquifer’s hydrology and geology were revealed by the recently drilled boreholes. With a thickness of 200 m, the Dakhla shale, Farafra limestone, and dolomitic limestone cover the Nubian sandstone, while the Nubian sequence is composed of alternating sand and shale layers. Esna Shale, which is 123 metres thick, and Tarawan Chalk Formation are the rocks that make up the Palaeocene era (73 m thick). The Eocene rocks are present in the north, west, and east of Farafra Oasis and are formed of fossiliferous limestone with modest shale intercalations, with a thickness of 65 metres. The Mingar-et-Tahan Formation, which is made up of lacustrine sandstone, siltstone, and limestone, represents the post-Miocene rocks. Playa and aeolian deposits are included in the Quaternary sediments. While the playa deposits are formed in the depression as fine sand, silt, and clay mixed with halite and gypsum, the aeolian sand is dispersed as sand dunes (Salem 2002). The study area’s structural context is represented by four N-E folds: El Ghard, El Quss-Abu Said synclines alternate with the Ain Dalla and Farafra anticlines.

Two faults near the boundary of El Quss and Abu Said, as well as smaller faults in the NE-SW, NW-SE, and N-S directions, cut across the study region and serve as conduits between the upper chalky limestone aquifer and the main aquifer (Nubian) (Zaghloul 1983).

The Nubian sandstone aquifer is said to be made up of thick, coarse clastic deposits of sandstone and sandy clay interbedded with shale and clay layers, where sandstone layers form the aquifer zones, according to Barakat and Abdel Hamid (1974) and Ebraheem et al. (2002).

3. Methodology

In the area being explored, hydro-chemical analysis, pumping tests, well logging, and magnetic are all used. Through the interpretation of magnetic data, basement depth and underground structures are mapped. The research area’s underlying layers are identified and their groundwater potential is detected using the well-logging data. The pumping test is used to calculate the aquifer’s hydraulic properties and features. The hydrochemical analysis of various water samples that were obtained in the research region is used to determine the groundwater quality and validity for various uses.

3.1. Magnetic data

The total intensity magnetic map reduced to the pole (RTP) was represented by the magnetic data in the current investigation, which was digitised from the aeromagnetic map created by the Aeroservice Company in 1984 and rebuilt using the Oasis Montaj software (2015) (Figure 3). Magnetic anomalies in RTP range in value from −128 nT to a maximum of 100 nT. The RTP anomalies may be classified into many categories according to the values of the magnetic anomalies. East, northeastern, and southeastern portions of the research area exhibit strong magnetic anomalies with values between (43 nT-100 nT); these high magnetic anomalies signify shallow basement relief in these regions. In the west, northwestern, and northern hemispheres, low-magnetic anomalies with levels between (−128 nT-58 nT) are common. Low
3.1.2. Magnetic anomalies are prevalent in this part of the research region and suggest deep basement relief. Moderate magnetic anomalies with values between (−58 nT and 43 nT) are present in other areas.

3.1.1. Interpretation of magnetic data
The removal of the magnetic field's inclination in this region is reflected in the reduction magnetic pole map (RTP) (Figure 3a) as a repositioning of the inherited magnetic anomalies to the north.

3.1.2. Magnetic 2-D modelling
Using an average magnetic susceptibility of 0.00075 CGS units, 2-D is utilised to create an image of the basement relief map for the basement rocks in the study area. For 3-D magnetic modelling, the outcomes of 2-D magnetic modelling are used as the initial model. Utilising Oasis Montaj, 2015, five profiles going from west to east with a length of 106,000 m are subjected to the 2-D magnetic modelling approach (Figure 3a).

The results of 2-D modelling indicate that the basement depth ranges from about 1777 m to about 3778 m. The depths of the basement found in the central part of the study area are very deep and have values of more than 3500 m at a distance of 35 km to 45 km from the starting point (west) of the profile, which indicates that a thick sedimentary cover, but they decrease gradually in western and eastern directions to reach depths of less than 2000 m (Figure 4).

3.1.3. Magnetic 3-D Modelling
To create the final basement elevation map of the researched area, 3-D magnetic modelling was applied (Figure 5(a,b)). The depth of crystalline (basement) rocks ranges from approximately 1777 m to approximately 3778 m, according to the basement relief map that was produced. These findings are consistent with those of 2-D modelling. The central part of the area under investigation has deep underground depths that can reach 3500 m. However, they steadily decline in the northern, western, and eastern directions to go to depths of under 2000 metres.

3.1.4. Delineating of structure elements
The regional-residual separation approach separates the residual component from shallow sources from the regional component (Figure 3b), which is associated with deep-seated sources. After eliminating the regional influence, the high pass filter map [residual magnetic anomaly map (Figure 3c)] depicts the distribution of the magnetic field at shallow depths. The research area’s residual magnetic anomaly field has a maximum value of (10 nT) and a minimum value of (−18 nT).

The high pass filter map (residual) and Euler decomposition may be used to identify the structural trends cutting through the analysed area. These structural trends, as shown in (Figure 3d), have many trends that run in the N-S, E-W, NE-SW, and NW-
Figure 3. a) Total Intensity Magnetic Map Reduced to the Pole (RTP Map) with the Location of 2-D Magnetic Modelling. b) Regional Magnetic Anomaly Map (Low Pass). c) Residual Magnetic Anomaly Map (High Pass). d) Fault Elements Dissecting the Study Area. e) Rose Diagram for the Major Trend Faults Detecting from Residual Anomaly Map.
SE directions. NNW-SSE are the main trends that divide the research area. Additionally, as a tool for the prospective field, the authors employed Euler deconvolution to outline the structural components dividing the research area. Using various structural indices (SI) of the magnetic anomalies, this method uses the Euler deconvolution tool to solve each solution, where the depth of magnetic sources can be estimated and structural trends. In the current work, the Euler deconvolution is used to find the optimum solution using different SI, such as 0, 0.5, and 1. Better solutions are provided by the structural index 0 (Figure 6a) compared to SI = 1 (Figure 6b) and SI = 2 (Figure 6c).

### 3.2. Well-log study and pumping test

#### 3.2.1. Borehole data

Sixteen boreholes were drilled in the research area (Figure 1) with varying depths ranging from 700 to 1000 m to outline the El Farafra aquifers to identify the hydraulic parameters and estimate the underlying lithology (Figure 7).

#### 3.2.2. Geologic cross-sections

Using information from well-logging and core samples, four geological cross-sections along four profiles are created, as illustrated in (Figure 1). The 3rd, 5th, and 7th units represent the main aquifer (Nubia) in the investigated area. The subsurface section is made up of seven geologic units, according to the geology cross-sections. The first zone of the Nubian sandstone aquifer is represented by the third geologic unit with low gamma-ray, which consists of sandstone and is surrounded by clay layers. The majority of the drilled boreholes have it documented. The fifth unit, which consists of sandstone with clay and constitutes the second zone of the Nubian sandstone aquifer, displays intermediate to high resistivity values and low to high gamma-ray values. The seventh geologic unit is composed of sandstone and represents the third zone of the Nubian sandstone aquifer, which is sandwiched.
It has high resistivity values and a low gamma ray (Figure 8(a-d)).

### 3.2.3. Hydraulic parameters of El Farafra aquifer

The hydraulic parameters and aquifer properties are calculated using the pumping tests. The pumping test, which is used to ascertain the hydraulic properties of the aquifer, depends on monitoring the well’s discharge and the outcome of the drawdown at a certain period. A step decline, a constant discharge, and a recovery test are examples of the B-35 well’s pumping test results in the researched region shown in (Figure 9).

### 3.3. Step drawdown test

In the step drawdown test, the pumping well’s discharge rate is raised for well B-35 from a starting low constant rate through a series of pumping intervals, as shown in (Figure 9a) and Table 1. Each step, according to Kruseman and de Ridder in 1994, is a kind with an equal duration, lasting somewhere between 30 minutes and 2 hours. The line’s intersection with the S/Q axis (Q = 0) determines the formation loss coefficient (B), which may be estimated by plotting (S/Q) vs. (Q) (Figure 9) and fitting a straight line across the points. The slope of the line determines the well-loss coefficient C. (Tood 1980). The following equation (1) can roughly describe the overall drop (Jacob 1964),

\[ S = CQ^2 + BQ \]

where C and B are constants that stand in for the well-loss and formation loss, respectively, and S is the whole drawdown in m, Q is the discharge rate in m³/
Figure 5. a and b) 3D-Presentation of the Basement Relief Map.

d, and (Figure 9a) provides a definition for these constants.

4.1. Constant test and recovery test

A straight line with a slope of s is produced when the observed drawdown (s) against time (t) is plotted on a semi-logarithmic paper (t in the log scale), and this line may be used to calculate the constant discharge test for well B-35 (Jacob 1964).

\[ T(p, r) = 0.183xQ/ST(p, r) = 0.183xQ/S \]  

where \( T_p = 5110 \text{ m}^2/\text{d} \), which denotes a high potential aquifer, S (metres) (slope of line), Q (m\(^3\)/d) (discharge), and T = transmissivity (m\(^2\)/d) (Figure 9b). \( T_r = 4547 \text{ m}^2/\text{d} \) (Figure 9c). \( T_p \) and \( T_r \) are the transmissivity values for the constant and recovery tests, respectively. The classification of aquifer potentiality based on transmissivity levels is displayed in (Table 2). (subsequent to Gheorhge 1979) According to Table 2, the maximum drawdown (s) ranges between 11.47 m and 18.02 m, the recommended discharge (Q) (m\(^3\)/h) ranges between 200 m\(^3\)/h and 235 m\(^3\)/h, the transmissivity for the constant test (\( T_p \)) (m\(^2\)/d) is between 3570 m\(^2\)/d and 7040 m\(^2\)/d, while the transmissivity for the recovery test (\( T_r \)) ranges between 4162 and 5549. Tables 1 and Table 2 list the results of pumping tests for all boreholes.

3.2. Hydro-chemical data

The hydro-chemical data for 24 groundwater samples were collected from 24 boreholes drilled in the El Farafra aquifer at depths between 700 and 1000 m. The hydro-chemical information was shown by pH, electrical conductivity (EC), and total dissolved solids (TDS) (Figure 10a). Table 4 provides a summary of the hydro-chemical data. The pH limit for drinking and irrigation water is between 6.5 and 8.5 in clean water, according to WHO 1984 and FAO 1985 as shown in Table 5. The pH ranges from 5 to 9 according to the
findings of groundwater samples tested in the research region (Table 3) (Figure 10b).

The electrical conductivity (EC) is related to the (TDS) (ions) in the water. The groundwater samples had EC values ranging from 180 (mhos/cm) for well no. K1 to 375 (μmhos/cm) for well no. K15. EC values are lowest in the northwest and southwest and rise towards the northeastern and southeast, according to the distribution of EC in groundwater samples (Figure 10c). Finally, the measured TDS in groundwater ranges from 118 mg/l at sample number K1 to 242 mg/l at sample number K15. There is a significant correlation between the trends of the measured TDS and EC (Figure 10d). According to the cross plot (Figure 10e), the proportionate association between TDS and EC has a confidence level of 0.9 ($r^2 = 0.938$).
3.2.1. **Groundwater classification**

3.2.1.1. **Classification using the Piper diagram.**

According to Piper (1944), this method is used to categorise groundwater and identify the hydro-chemical facies of water samples specifically water type. In general, all of the examined samples fell into field 4’s mixed Ca-Mg-Cl type, which describes the mixed water type consisting of marine and meteoric water and indicates anthropogenic and dissolution activities (Figure 11a).

3.2.1.2. **Schoeller diagram.** When plotted on semilogarithmic paper, the Schoeller diagram shows the connection between various ions. The following relationship is illustrated by the Schoeller diagram relationship (Figure 11b):

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**Figure 7.** Log Analysis of Well A2, This Figure Indicates a Record of Gamma Log of Green Colour and Resistivity Log of Brown and Blue Colour and refer to Lithology, Zones of the Aquifer and Salinity Decrease with Depth.
Figure 8. a, b, c and d) Geologic Section along profile −1, profile −2, profile −3 and profile −4 Respectively, Showing Different Geological Units, Well-Logging Records and Ground Level.
3.3.2. Evaluation of groundwater for different purposes

3.3.2.1. Evaluation of groundwater for drinking purposes. As shown in Table 5, the World Health Organization (WHO (World Health Organization) 1984; ECAFE and UNESCO.1963; Hem 1970) and other international quality standards are used in the current study to evaluate the quality of water for various uses. The total salinity varies from 118 (mg/l) to 242 (mg/l), which is appropriate for drinking by the WHO limit of 1500 (mg/l), according to (Table 4).

3.3.2.2. Groundwater assessment for livestock and poultry. The National Academy of Science recommended many concepts as a general framework, and

K < Na < Mg < Ca > CO3 < HCO3 < Cl > SO4

(Calcium-Magnesium-Chloride groundwater type)
Figure 9. a) Step Drawdown Pumping Test, for Well B-35. b) Constant Pumping Test. c) Recovery Pumping Test.

Table 1. Data of step drawdown test for the tested wells.

| Well No | Results | B-3 | B-5 | B-35 | B-40 | C5 | C6 | C8 |
|---------|---------|-----|-----|------|------|----|----|----|
| Total Well Depth (m) | | 926 | 926 | 910 | 860 | 940 | 906 | 905 |
| Water Table (m) | | 10.28 | 54.2 | 42 | 11.1 | 0 | 0 | 0 |
| Step time (min) | | 180 | 180 | 180 | 180 | 180 | 180 | 180 |
| Q (m$^3$/h) | | 160 | 177 | 160 | 160 | 160 | 150 | 200 |
| Drawdown (s) (m) | | 7.25 | 10.73 | 8.45 | 7.5 | 9.55 | 3.25 | 3.26 |
| S/Q (day/m$^2$) | | 1.89*10$^{-3}$ | 2.53*10$^{-3}$ | 2.2*10$^{-3}$ | 1.95*10$^{-3}$ | 2.49*10$^{-3}$ | 1.35*10$^{-3}$ | 1.36*10$^{-3}$ |

Table 2. The results of the transmissivity values of constant test and recovery test ($T_p$ and $T_r$).

| Well no. | Discharge (Q) (m$^3$/h) | Max. drawdown (s) (m) | Transmissivity ($T_p$(m$^2$/day) (Constant Test) | Transmissivity ($T_r$(m$^2$/day) (Recovery test) |
|---------|------------------------|-----------------------|-------------------------------------------------|-------------------------------------------------|
| B-3     | 235                    | 13.5                  | 5640                                            | 4162                                            |
| B-5     | 235                    | 18.02                 | 4411                                            | 4845                                            |
| B-35    | 235                    | 16.02                 | 5110                                            | 4547                                            |
| B-40    | 220                    | 11.63                 | 3976                                            | 5549                                            |
| C5      | 200                    | 13.6                  | 5975                                            | -                                               |
| C6      | 200                    | 11.47                 | 3570                                            | -                                               |
| C8      | 210                    | 12.81                 | 7040                                            | -                                               |
Excellent water for all classes of livestock and poultry is present in every sample taken from the investigation area (TDS Less than 1000 mg/l) (Table 5).

3.3.1.3 Groundwater evaluation for irrigation purposes. Groundwater classifications for irrigation reasons depend on EC, TDS, and SAR.
Table 3. Hydro-chemical analyses for 24 water samples.

| Sample ID | Calcium (mg/L) | Magnesium (mg/L) | Sodium (mg/L) | Potassium (mg/L) | Bicarbonate (mg/L) | Sulphate (mg/L) | Chloride (mg/L) | Iron (ppm) | T.D.S (ppm) | EC (µmho/cm) | pH | SAR (mg/L) |
|-----------|----------------|------------------|---------------|------------------|-------------------|----------------|----------------|-----------|-----------|----------|----|-----------|
| K1        | 12.36          | 3.988            | 10.77         | 3.091            | 40.18             | 12.96          | 20.14          | 20.14     | 118       | 75       | 7   | 3.76      |
| K2        | 13.56          | 8.077            | 10.31         | 8.077            | 40.18             | 31.61          | 23.73          | 3.1       | 139       | 220      | 7   | 3.13      |
| K3        | 13.63          | 8.142            | 10.35         | 7.379            | 40.27             | 31.7           | 30.84          | 8         | 155       | 238      | 8   | 3.13      |
| K4        | 12.36          | 7.678            | 10.27         | 7.429            | 80.97             | 8.575          | 16.95          | 16.95     | 160       | 247      | 7   | 3.24      |
| K5        | 15.56          | 6.082            | 10.77         | 4.288            | 80.97             | 8.575          | 30.71          | 30.71     | 146       | 247      | 8   | 3.27      |
| K6        | 11.37          | 9.473            | 10.77         | 12.07            | 80.97             | 12.46          | 23.43          | 23.43     | 146       | 247      | 5   | 3.18      |
| K7        | 14.56          | 5.684            | 10.27         | 10.17            | 80.97             | 6.182          | 16.95          | 16.95     | 146       | 247      | 7   | 3.38      |
| K8        | 14.56          | 3.789            | 10.27         | 10.17            | 80.97             | 5.105          | 20.14          | 20.14     | 146       | 247      | 8   | 3.39      |
| K9        | 11.37          | 8.775            | 10.27         | 14.46            | 8.575             | 51.05          | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K10       | 12.36          | 5.783            | 10.4          | 10.17            | 10.17             | 64.51          | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K11       | 12.36          | 11.27            | 9.852         | 15.95            | 10.17             | 48.66          | 30.71          | 30.71     | 146       | 247      | 8   | 3.39      |
| K12       | 11.37          | 3.889            | 10.31         | 7.777            | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K13       | 14            | 8.81             | 10.31         | 3.8              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K14       | 22            | 8.51             | 10.31         | 7.4              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K15       | 12            | 6.08             | 10.31         | 7.4              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K16       | 12            | 6.08             | 10.31         | 7.4              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K17       | 12            | 5                | 10.31         | 7.4              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K18       | 12            | 5                | 10.31         | 7.4              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K19       | 12            | 5                | 10.31         | 7.4              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K20       | 12            | 5                | 10.31         | 7.4              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K21       | 12            | 5                | 10.31         | 7.4              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K22       | 12            | 5                | 10.31         | 7.4              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K23       | 12            | 5                | 10.31         | 7.4              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
| K24       | 12            | 5                | 10.31         | 7.4              | 10.17             | 48             | 23.73          | 23.73     | 146       | 247      | 8   | 3.39      |
**Table 4.** International Drinking Water Standards (WHO (World Health Organization) 1984).

| Property          | Acceptable Limit | Permissible Limit |
|-------------------|------------------|-------------------|
| TDS (mg/l)        | 500              | 1500              |
| pH                | 7–8.5            | 6.5–9.2           |
| Colour            | 5                | 50                |
| Hardness          | 250              | 500               |
| SO₄²⁻ (mg/l)      | 200              | 400               |
| Turbidity         | 5                | 25                |
| Cl⁻ (mg/l)        | 200              | 600               |
| HCO₃⁻             |                  |                   |
| Mg²⁺ (mg/l)       | 50               | 150               |
| Fe³⁺ (mg/l)       | 0.3              | 1.00              |
| Na⁺ (mg/l)        |                  | 200               |
| Ca²⁺ (mg/l)       | 75               | 200               |
| Mn²⁺ (mg/l)       | 0.1              | 0.5               |
| Cd²⁺ (mg/l)       |                  | 0.01              |
| Pd⁻ (mg/l)        |                  | 0.5               |
| Cu²⁺ (mg/l)       | 1.0              | 1.5               |
| Zn²⁺ (mg/l)       | 5                | 15                |

**Table 5.** Instructions for Using Saline Water on Livestock and Poultry (After National Academy of Science (NAS) and National Academy of Engineering (NAE) 1972).

| TDS (mg/l) | Remarks                                | Sample No. |
|------------|----------------------------------------|-------------|
| < 1000     | Excellent for all classes of livestock and poultry. | All samples |
| 1000–2999  | Very Satisfactory                       | –           |
| 3000–4999  | Satisfactory                           | –           |

**Electrical conductivity (EC),** According to Fipps (2003), groundwater is classified depending on EC values into five classes (Table 6), with 80% of water samples falling into the excellent group and 20% falling into the good group.

**Total dissolved solids (TDS),** Fipps (2003) states that groundwater is divided into five classes based on TDS values (Table 7), with 75% of water samples falling into the excellent groundwater group and 25% falling into the good groundwater group.

**Sodium adsorption ratio (SAR),** The SAR values in the analysed water were categorised using Toss’s system (Tood 1980) (Table 8), and 100% of the total samples belong to the excellent irrigation water.

### 4. Discussion

The depth of the basement rocks was determined and ranged between 1777–3778 from the magnetic tool, thus determining the possibility of the thickness of the sedimentary cover (Nubian Sandstone Aquifer and post Nubian Sandstone Aquifer), and from well-logging, the upper surface of the Nubian Sandstone Aquifer was identified (190 m to 238 m from Ground Level). The Nubian Sandstone aquifer of this region consists of three zones. This study recommended drilling from the second zone for two reasons, the first reason is that it is distinguished from the first zone with less salinity and with its highest productivity, and the second reason is distinguished from the third zone that it has the same characteristics, but it is less expensive in reaching it and therefore more economic feasibility, which maintains the aquifer in the region with a longer age when not using the third zone now. The upper surface of the second zone at depths ranging from 380 m to 488 m from the ground surface, the depth mainly increases toward south eastern direction. The average thickness of this zone is 310 m, and from hydro-chemical analysis, the average salinity of the second zone is 190 mg/l.

While well loss values vary between 4.57 * 10⁻⁷ and 2.01 * 10⁻⁷, formation loss values fall between 6.5 * 10⁻⁴ and 1.19 * 10⁻³. The maximum drawdown (m) of the wells ranges from 11.47 m to 18.02 m, while the recommended Discharge (Q) of the wells (m³/h) ranges from 200 (m³/h) to 250 (m³/h). The transmissivity for the constant test (Tp) (m²/d) ranges from 3570 (m²/d) to 7040 (m²/d), whereas the transmissivity for the recovery test (Tr) (m²/d) ranges from 4162 (m²/d) to 5549 (m²/d). The aquifer is characterised by high potentiality. El Farafa aquifer’s hydraulic conductivity ranges from 24 m/day to 39 m/day, with an average of 32 m/day.
Figure 11. A) Piper Diagram Shows the Samples water type. b) Schoeller Diagram Shows the Groundwater Chemical Type of the Study Area.

Table 6. According to Fipps (2003), Suitability of Groundwater for Irrigation Based on Electrical conductivity.

| EC (µS/cm) | Water class     | Water Samples | Percentage |
|------------|-----------------|---------------|------------|
| Less than 250 | Excellent       | K1,K2,K3,K4,K5,K6, K7,K8,K9,K10,K11, K13,K16,K17,K18,K19 | 80 %       |
| 250 to 750  | Good            | K12,K14,K15,K20, K21, K22, K23, K24 | 20 %       |
| 750 to 2000 | Permissible     | -             | -          |
| 2000 to 3000| Doubtful        | -             | -          |
| 3000        | Unsuitable      | -             | -          |

Table 7. According to Fipps (2003), Suitability of Groundwater for Irrigation Based on Total dissolved solids.

| TDS (mg/l) | Water class | Water Samples | Percentage |
|------------|-------------|---------------|------------|
| Less than 175 | Excellent | K1,K2,K3,K4,K5,K6, K7, K8,K9,K10,K11,K12,K13 | 75 %       |
| 175 to 525  | Good        | K14,K15,K20, K21, K22, K23, K24 | 25 %       |
| 525 to 1400 | Permissible | -             | -          |
| 1400 to 2100| Doubtful    | -             | -          |
| More than 2100 | Unsuitable | -             | -          |
5. Conclusion

From the integrated interpretation of magnetic, well-logging, pumping tests, and hydro-chemical studies, we can conclude that: the depth of basement rocks ranges from 1777 to 3778 m. The main fault trend in the research area is NNW-SSE, with minor trends in the directions of N-S, E-W, NE-SW, and NW-SE. The main aquifer (Nubia) is represented by the third, fifth, and seventh units, according to the geologic cross-sections, which show that the subsurface section is made up of seven geologic units. The first zone of the Nubian sandstone aquifer is represented by the sandstone that makes up the third geological unit with a low gamma-ray, which is sandwiched by clay layers. It is recorded in most of the drilled wells. The fifth geologic unit consists of sandstone and clay and represents the second zone of the Nubian sandstone aquifer, which is sandwiched by clay layers. It displays intermediate to high resistivity values and low to high gamma-ray. It is recorded in most of the drilled wells. The seventh geologic unit is composed of sandstone and represents the third zone of the Nubian sandstone aquifer, which is sandwiched by clay layers. It has high resistivity values and low gamma ray.

The resistivity values increase with depth, indicating that the groundwater salinity in El Farafra area decreases with depth. The chemical analysis also shows that the salinity of the groundwater is 700 mg/l at a depth of 350 m, 250 mg/l at a depth of 800 m, and a minimum salinity of 200 mg/l at a depth of 1000 m.

The TDS value is classified as “Good Potable” and ranges from 118 mg/l to 242 mg/l.

The pH ranges from 5 to 9 according to the findings of groundwater samples tested in the study area. According to these values, the groundwater in the study area is slightly moderately alkaline. The mixed Ca-Mg-Cl water type is reflected in the hydro-chemical composition.

The region under investigation can provide for residential use, cattle, poultry, and irrigation.

6. Recommendation

The authors recommended to drilled boreholes in the western part of the study area according to less values of TDS.

Table 8. According to Tood (1980), Suitability of Groundwater for Irrigation Based on Sodium adsorption ratio.

| SAR | Water class | Water Samples | Percentage |
|-----|-------------|---------------|------------|
| S1 < 10 | Excellent | All samples | 100% |
| S10–18 | Good | - | - |
| S18–26 | Doubtful | - | - |
| S > 26 | Unsuitable | - | - |

Disclosure statement

No potential conflict of interest was reported by the author(s).

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