Isotopic, Geophysical, and Hydrogeochemical Investigations of Groundwater in West Middle Upper Egypt

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ABSTRACT: The groundwater of the west Assiut and El-Minia districts was evaluated in this paper using geoelectrical, hydrogeochemical, and stable isotope (oxygen-18 and deuterium) studies. In the studied localities, 42 vertical electrical soundings (VES) were taken to evaluate groundwater potential, and the analysis, as well as collection, of 74 samples of Eocene groundwater was carried out. In accordance with the vertical electrical soundings’ interpretation, there are four geoelectrical formations and two major water-bearing units that act as aquifers (Pleistocene and Eocene). To determine irrigation suitability, the sodium absorption ratio (SAR), electrical conductivity (EC), residual sodium carbonate (RSC), sodium percentage (Na %), magnesium hazard (MH), Kelley’s ratio (KR), and permeability index (PI) were evaluated as irrigation quality parameters. The EC, Na %, and the diagram of the US salinity laboratory indicated that most of the collected samples of groundwater were suitable for irrigation, whereas the RSC and PI pointed out that all of the collected water samples were safe for irrigation. The oxygen and hydrogen isotope values in groundwater samples showed that the Eocene aquifer was recharged by both surface water and the Nubian aquifer.

1. INTRODUCTION

Egypt faces numerous water resource challenges, as overpopulation and a sharp increase in water demand for urban, agricultural, and industrial developments. The amount and quality of groundwater are frequently affected by increased groundwater abstraction, and the introduction of additional recharge sources as urban and agricultural development expands. Egypt’s rapid population growth has put a strain on the quantity and quality of freshwater, necessitating careful management of water resources for long-term development. Geophysical investigations, particularly geoelectrical methods, are extremely beneficial in groundwater exploration. These methods are frequently used in determining the groundwater level depth, the layer thickness, and the groundwater carrier. Groundwater geochemistry investigations provide an excellent understanding of the main hydrogeochemical processes that control the groundwater environment and their relationship to groundwater migration. The study of environmental isotopes is used to solve many hydrological problems involving surface and groundwater resources, as well as to determine the source of groundwater recharge. New water can differ isotopically from water in the catchment area, and environmental isotopes (d18O and d2H) are useful tools for determining the old and new water contributions to a stream or shallow groundwater.

The rapid expansion of land reclamation projects in desert areas, as well as rising population and urbanization, have resulted in increased consumption and demand for water for the purposes of irrigation, drinking, and domestic usage. Groundwater resource management provides a comprehensive understanding of the aquifer’s hydraulic characteristics and chemical composition changes. Climate, recharge water quality, geology, time of residence, flow of groundwater through rocks from areas of recharge to areas of discharge, and associated processes (i.e., dissolution, precipitation, and cation exchange), as well as anthropogenic activities, have an impact on groundwater chemistry.1–5 In the last few decades, the mineralogical, geological, hydrological, and structural features and their influence on the flow and geochemistry of groundwater systems have been inferred by geochemical methods. Geophysical studies, particularly geoelectrical methods, have emerged as a valuable resource in environmental and engineering applications.6 Over the last 10 years, the progress in the micro-

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processors and the solutions of associated numerical modeling resulted in a significant increase in the use of geophysical surveys for both mapping of groundwater resources and assessment of water quality. They are extremely useful in groundwater studies, such as the determination of the groundwater level depth and layer thickness. Similarly, isotope techniques are useful in hydrogeology for determining the sources of groundwater recharge.

The examined area was extensively studied to investigate hydrogeology and hydrogeochemistry, as well as to evaluate groundwater quality and its appropriateness for different purposes using numerous approaches. Furthermore, many authors used isotope analysis to investigate groundwater sources in the Western Desert. Groundwater is under serious threat of overexploitation in the study area, particularly for irrigation. Industrial and domestic uses have significantly increased groundwater pollution and abstraction, resulting in significant changes in the hydrologic system. Groundwater pollution is also on the rise because of anthropogenic activities, for instance, wastewater leaching and using large amounts of fertilizer in agriculture. Consequently, geochemical, geophysical, and isotopic methods are distinctly important tools in the development of sustainable and integrated water-management policies to protect the study area’s water resources. As a result, the primary goal of this study is the integration of hydrogeochemical, geoelectrical, and isotopic analyses (18O and 2H) to identify the recharge origins and the hydrochemical characteristics of groundwater and its quality.

2. STUDY AREA

2.1. Location. The studied area is located along the west bank of the Nile Valley in El-Minia and Assiut Governorates. It
extends from the northwest of the city of Assiut to Maghagha town, between latitudes 27° 15' 03 and 28° 45' 00 N and longitudes 30° 00’ and 31° 00’ E (Figure 1). It covers an area with topographical heights between 30 and 80 m above sea level.

2.2. General Geology and Hydrogeology. The study area consists of sedimentary deposits with a time span from the Eocene to the Quaternary. Land reclamation extends in the area from the Eocene limestone plateau in the west and the recent Nile deposits in the east. Various lithostratigraphic studies have been conducted by many authors. Quaternary (mainly of Plio-Pleistocene) sediments are found at the foot of the scarps along the Nile’s banks on both sides. The majority of Assiut is covered with recent to subrecent alluvial deposits on both sides of the Nile’s banks. These sediments include Neonile silt; clay; and prenile, paleonile/protonile, and paleonile sediments. Eocene rocks of the Drunka, El-Minia, and Samalut Formations mainly comprise the limestone plateau.

The Eocene aquifer, represented by Samalut and EL-Minia Formations, is the primary aquifer in the study area. The rocks are composed of hard, snow-white, strongly fractured limestone with intercalations of shale and marl, and it is unconformably overlain by Pliocene clay and Pleistocene deposits. The aquifer discharge includes pumping wells used for irrigation and human consumption, and the recharge comes from the underlying Nubian sandstone aquifer via fractures and fault planes, in addition to the surface runoff from occasional flash floods.

3. SAMPLING AND ANALYSES

Along three profiles, measures of 42 vertical electrical soundings (VES) were done (Figure 1). These VES were obtained using a Syscal-Pro instrument and the Schlumberger configuration.

Table 1. Equations Used in the Calculations of the Irrigation Quality Parameters

| Item | Equation | Reference |
|------|----------|-----------|
| TH   | \[TH = 2.497Ca^{2+} + 4.115Mg^{2+} \text{ ions in mequiv/L} \] | 47 |
| SAR  | \[\text{SAR} = \frac{\text{Na}}{(\text{Ca} + \text{Mg})/2} \text{ all ions in mequiv/L} \] | 44 |
| Na (%) | \[\text{Na\%} = \frac{(\text{Na} + \text{K})}{(\text{Ca} + \text{Mg} + \text{Na} + \text{K})} \times 100 \text{ all ions in mequiv/L} \] | 46 |
| RSC  | \[\text{RSC} = (\text{HCO}_3^{-} + \text{CO}_3^{2-}) - (\text{Ca}^{2+} + \text{Mg}^{2+}) \text{ all ions in mequiv/L} \] | 44 |
| MH   | \[\text{MH} = \frac{\text{Mg}}{(\text{Ca} + \text{Mg})} \times 100 \text{ all ions in mequiv/L} \] | 48 |
| SSP  | \[\text{SSP} = \left(\frac{(\text{Na}^{+} + \text{K}^{+})}{(\text{K}^{+} + \text{Na}^{+} + \text{Ca}^{2+} + \text{Mg}^{2+})}\right) \times 100 \text{ all ions in mequiv/L} \] | 49 |
| PS   | \[\text{PS} = \text{Cl} + \sqrt{\text{SO}_4} \text{ all ions in mequiv/L} \] | 50 |
| KR   | \[\text{KR} = \frac{\text{Na}}{(\text{Ca} + \text{Mg})} \text{ all ions in mequiv/L} \] | 51 |

Figure 2. Geoelectric cross section A−A’.
technique with current spacings ranging from 300 to 1000 m during the measuring process. A gradual increase in the distances between the potential electrodes from 0.5 to 50 m for each VES profile was applied. The electrical data were interpreted by the iteration technique using three inversion programs (ATO by ref 33, RESIST by ref 34, and RESIXP by ref 35), in which the lithological data from the drilled wells, including thickness and resistivity of each lithologic layer in the study area, were used as constraints for the starting models.

Seventy-four samples of Eocene groundwater were gathered in new precleaned polyethylene bottles (1 L capacity) from various wells located in the study area after pumping out the water for about 1 h and sent to the laboratory in an icebox for further analysis (Figure 1). After sampling, the Ultrameter SM101 equipment was used to measure pH, total dissolved solids (TDS), electrical conductivity (EC), and temperature. The water level, water depth, and drilling total depth were collected with the help of the owners of the wells. These parameters were utilized to make water table and water level

Figure 3. Geoelectric cross section B–B′.

Figure 4. Geoelectric cross section C–C′.
contour maps to interpret the flow of water. The complete chemical analyses of the obtained groundwater samples were performed at the Ministry of Agriculture Laboratories in El-Minia Governorate, Egypt, in accordance with the American Public Health Association’s standard methods. The measurements of magnesium (Mg$^{2+}$), calcium (Ca$^{2+}$), and bicarbonate (HCO$_3^-$) were obtained by the methods of volumetric titration, and chloride (Cl$^-$), potassium (K$^+$), and sodium (Na$^+$) were measured using a flame photometer, while sulfate (SO$_4^{2-}$) was determined using a UV spectrophotometer.

Zinc reduction and CO$_2$ equilibration methods were used to determine the isotope ratios of hydrogen and oxygen in water, respectively. The isotope ratios of oxygen in the carbonates were identified by CO$_2$ produced by the reaction with phosphoric acid. A VG prism mass spectrometer was used for the measurements of the stable isotope ratio. Stable isotope data for oxygen is calculated as shown in eq 1.

$$\delta^{18}O = \left( \frac{^{18}O_{\text{sample}}}{^{18}O_{\text{standard}}} - 1 \right) \times 1000$$

(1)

The same equation is used to calculate the stable isotope data for hydrogen but with the replacement of oxygen isotopes by hydrogen isotopes in eq 1. The reproducibility of $\delta$ values for $\delta^{18}O$ is <0.1‰ and for deuterium (D) is <1‰. Uranium-series analyses were performed by $\alpha$ spectrometry.

A variety of indices were used to assess the appropriateness of groundwater for human consumption and irrigation. The results are compared to the World Health Organization’s quality standards of drinking water as well. Electrical conductivity (EC), sodium percentage (Na %), sodium absorption ratio (SAR), residual sodium carbonate (RSC), magnesium hazard (MH), Kelley’s ratio (KR), and permeability index (PI) were all calculated using the equations given in Table 1. The classification of the groundwater quality for various purposes was obtained from the correlation of analytical data by plotting various graphical representations.

4. RESULTS AND DISCUSSION

4.1. Geoelectrical Aspects. Three geoelectrical cross sections were constructed using the interpreted resistivity data (Figures 2–4). These sections are useful not only for understanding the nature of the subsurface configuration and its characteristics, including thickness, depth, and kind of each layer, but also for identifying water-bearing formations.

Geoelectric Cross Section A–A’. In this section, three geoelectric layers can be identified (Figure 2). The first has a resistivity range that varies from 39 to 2532 Ω·m and a thickness range that varies from 1 to 16.6 m. The presence of loose sand and gravel can explain the high resistivity. The resistivity of the second geoelectric layer is in the range of 60–440 Ω·m with a thickness range of 12–86.5 m. This thick layer represents the first water-bearing formation (Pleistocene aquifer). The third layer’s resistivity ranges from 134 to 6597 Ω·m, with the high resistivity resulting from fractured limestone. The second water-bearing formation is represented by this layer (Eocene aquifer). Because of the presence of a fault, the thickness of this layer is not detected in VES Nos. 24 and 26.

Geoelectric Cross Section B–B’. The surface layer is formed of loose sand and gravel with a thickness range of 1.5–4 m and a resistivity range of 440–4905 Ω·m (Figure 3). The water-bearing formation (Pleistocene aquifer) is the second geoelectric layer, with a resistivity range of 106–436 Ω·m and a thickness range of 12–46 m. The third layer is the second water-bearing unit and is made of fractured limestone (Eocene aquifer). It has resistivity in the range of 1037–5159 Ω·m with a thickness range of 34–100 m.

Geoelectric Cross Section C–C’. The first layer possesses resistivity in the range of 436–4290 Ω·m. This layer is made up of loose sand and gravel and has a thickness range of 1–3 m. The second geoelectric unit, representing the Pleistocene aquifer, has resistivity ranging from 21 to 349 Ω·m with a thickness range of
20–101 m (Figure 4). The third geoelectric layer has resistivity ranging from 526 to 6597 Ω·m with a thickness range of 39–93 m. It is the second water-bearing unit (Eocene aquifer) formed by fractured limestone. Because of the presence of two faults in this area, this layer is not recorded under VES stations 38 and 39.

4.2. Groundwater Level. The water depth of the Eocene aquifer varies by location and ranges from 65 to 300 m (Figure 5), with water levels ranging from 6 to 124 m. Groundwater flows primarily north and east toward the Nile in the study area (Figure 6).

4.3. Hydrogeochemical Characteristics of Ground-water. The hydrogeochemical aspects of the present study are primarily dependent on the chemical analysis of 74 water samples. The pH values of the samples of water examined range from 7.16 to 8.50, owing to the interaction between carbonate-rich formations and water resources in the catchment area. The electrical conductivities of the groundwater samples range from 497 to 6130 S/cm. Electrical conductivity (EC) measures the total amount of soluble salts in water because of limestone leaching and dissolution. The total dissolved solid (TDS) concentrations in the investigated waters range from 318 and
3923 ppm. The collected water samples fall between freshwater and moderately saline water.52 The TDS values and the high EC values of the examined water samples are due to a longer residence time, which allows for rock−water interactions. The study area’s isosalinity contour map (Figure 7) shows an increase in salinity in a westerly and north-easterly direction due to limestone leaching and dissolution.

The total hardness of the examined water samples ranges from medium to very hard water.52 The dissolution and leaching of calcium- and magnesium-bearing sediments (i.e., limestone) are attributed to the high total hardness values.

Plotting the chemical data of the collected samples of water on a piper’s diagram (Figure 8) reveals that 64% of the investigated samples are in subarea (2), which represents the water type NaCl, and 36% of the samples are located inside subarea (4), which represents the water type mixed CaMgCl.

Plotting samples relative to the variation in the ratios of Na/ (Na + Ca) as well as Cl/(Cl + HCO3) as functions of TDS enables an assessment of the functional sources of dissolved ions.45 To characterize the chemistry of groundwater and the interaction between the chemical components of the water and their corresponding aquifers, the geochemistry of rock types, the chemistry of precipitated water, and the evaporation rate are all used. The chemical data from the obtained samples of groundwater indicates that chemical weathering of rock-forming minerals via host rock dissolution has an impact on groundwater quality (Figure 9a). To further identify the relative contribution of the weathering/dissolution processes to the ion concentration in groundwater of the Eocene aquifer, binary relationships of some ions were plotted (Figure 9b−f). The plot of Ca2+ + Mg2+ versus HCO3− + SO42− showed that most samples fall along the 1:1 line with few above (excess Ca2+ + Mg2+) it, indicating ions from carbonate (calcite and dolomite) and non-carbonate (evaporites) dissolution and reverse ion exchange processes (Figure 9b). The excess Ca2+ + Mg2+ over HCO3− suggests extra sources of Ca2+ and Mg2+, i.e., reverse ion exchange processes, rather than carbonate dissolution (Figure 9c). The relationship between Na+ to Cl− and Ca2+ to SO42− along the halite and gypsum dissolution lines (HDL and GDL), respectively, reveals the dominance of halite and gypsum dissolution to the chemical composition of the groundwater (Figure 9d,e).

4.4. Stable Isotopic Composition. The stable isotopic formation of samples gathered from the Eocene and Nubian aquifers was plotted on the δD−δ18O diagram (Figure 10) along with the global meteoric water line53 and data from previous studies of the irrigation canals and drains of the Nile River,54 the Nubian aquifer system of the Western Desert,24 and the Pleistocene aquifer.54

The isotopic composition of groundwater from the Nubian aquifer was depleted, indicating that it came from the same source as the samples from the Western Desert. During wet Pleistocene pluvial periods, the Nubian aquifer is recharged.55,56 Isotopic results from the Eocene aquifer plot (Figure 10) between the enriched Pleistocene aquifer composition and the depleted Nubian aquifer composition indicate the mixing of modern Nile River water and/or the Pleistocene aquifer with more depleted Nubian waters. It has been proposed that deep
Nubian aquifer waters discharge into overlying shallow aquifers via deep-seated faults in the Western Desert.²³,⁵⁷,⁵⁸

4.5. Assessment of Water Quality for Drinking and Domestic Purposes. Groundwater physicochemical parameters are generally used to determine the water’s appropriateness for drinking, industrial, domestic, and agricultural usage. Most of the groundwater studied was colorless, odorless, and especially tasteless. Most groundwater samples (70%) are suitable for drinking in the context of international standards for human drinking water and the Egyptian Standards for water due to their low salinity (TDS 1200 mg/L) and the fact that the major ions are within the permitted limits. Because of their high salinity (TDS > 1200 mg/L), the remaining samples (30%) are unfit for drinking. Groundwater evaluations for domestic and industrial use are primarily based on total hardness. Almost all groundwater samples (99%) have a total hardness of moderately hard to very hard, indicating that the water is unfit for domestic and industrial use.

4.6. Water Quality Assessment for Irrigation Purposes. The quality of water, types of soil, and practices of cultivation determine the extent of the validity of groundwater for irrigation. Excess dissolved ions in the water used in irrigation have physical and chemical impacts on plants and agricultural soils that result in lowering productivity. The physical impact of such ions reduces the osmotic pressure in the structure cells of plants, preventing water from going to the branches as well as leaves. The hydrochemical parameters EC, Na%, SAR, RSC, KR, MH, and PI are utilized to estimate the appropriateness of groundwater for irrigation purposes.

Based on EC, 11% of the collected samples are classified as “good”, 61% as “permissible”, 9% as “doubtful”, and 19% as “unsuitable” for irrigation.⁵⁹ The existence of Na⁺ in irrigated

Figure 9. (a) Gibbs diagram, (b) Ca²⁺ + Mg²⁺ versus HCO₃⁻ + SO₄²⁻ plot, (c) Ca²⁺ + Mg²⁺ versus HCO₃⁻ plot, (d) Na⁺ versus Cl⁻ plot, and (e) Ca²⁺ versus SO₄²⁻ plot of the collected samples of groundwater.
water has an impact on plant productivity. The total solidity of water (Na percent) calculated for the groundwater samples indicates that 10% of the samples have “excellent to good quality”, 19% are “good to permissible”, 43% are “permissible to doubtful”, 9% are “doubtful to unsuitable”, and 19% are unsuitable for irrigation. Kelley’s ratio was used as a quality parameter for determining the suitability of groundwater for irrigation as well. In this study, 47.3% of the samples of groundwater were deemed suitable for irrigation, while 52.7% were deemed unsafe. High sodium absorption ratio (SAR) values indicate a risk of sodium replacing magnesium and calcium, which is harmful to the soil structure. Richards’ classification scheme rates all of the gathered samples of groundwater as “excellent to good” for irrigation use.

According to the combined assessment of salinity and sodium hazards, most of the groundwater in the studied area has a high (57% of the samples) or very high (30%) salinity hazard and is thus inappropriate for irrigation (Figure 11).
The magnesium ratio (MH) is used to assess the quality of water in terms of Mg$^{2+}$ content. The MH of the investigated groundwater samples ranges from 44 to 70, and 89% of the water samples with MH > 50 are regarded as inappropriate for irrigation.

Excess of sodium bicarbonate and carbonate ions leads to the decay of the organic matter in the soil, leaving a black stain on the soil surface when it dries; therefore, they are regarded as harmful to the physical characteristics of the soil. As sodium carbonate is added to the water, an increase in the sodium relative ratio in the water takes place. This surplus is represented by residual sodium carbonate (RSC). Groundwater samples with RSCs less than 1.25 are safe and suitable for irrigation, but samples with RSCs greater than 2.5 are not. All of the groundwater samples collected have RSCs less than 1.25 and are valid for irrigation.

Long-term irrigation water use affects soil permeability, which is influenced by the soil’s content of Na$^+$, Ca$^{2+}$, Mg$^{2+}$, and HCO$_3^-$, and permeability index (PI) values show the validity of groundwater for irrigation. Based on PI,$^{50,61}$ developed a set of criteria for evaluating the validity of water for irrigation, and groundwater is divided into three categories: 1, 2, and 3. According to Doneen’s chart (Figure 12), the study area’s permeability index values range from 16 to 38. The samples are all categorized as class I or class II, indicating that they are suitable for irrigation.

5. CONCLUSIONS

Three geoelectric layers can be identified in the studied area after interpreting resistivity data. The resistivity of the first layer ranges from less than 39 to more than 4905 $\Omega\cdot$m. The thickness varies from 1 to 16.6 m. The second geoelectric layer, made up of saturated sand and gravel, represented the water-bearing formation. Its resistivity ranges from 21 to 440 $\Omega$, and its thickness is between 12 and 101 m. The resistivity of the third layer ranges from 134 to 97 $\Omega\cdot$m, with a thickness range of 34–100 m. This layer represents the fractured limestone and is the study area’s second aquifer.

The main flow direction of groundwater in the studied area is north and eastward toward the Nile River, as shown by the water level map. The TDS of the groundwater samples collected ranges from freshwater to slightly saline, while the TH ranges from moderately hard to very hard. The groundwater quality is influenced by the chemical weathering of rock-forming minerals through the dissolution of the host rock, according to Piper’s diagram, which shows that 64% of the studied samples are NaCl and 36% are mixed CaMgCl. Most of the groundwater samples, according to the Gibbs diagram, show the influence of the chemical weathering of rock-forming minerals on the quality of groundwater.

The enriched composition of the Pleistocene aquifer is plotted against the depleted composition of the Nubian aquifer, indicating that the recharge source of the Eocene limestone aquifer is the mixing of modern groundwater from the Pleistocene aquifer with more depleted Nubian waters.
Most of the collected samples of groundwater (70%) are appropriate for drinking, whereas, virtually, all of the groundwater samples (99%) are unfit for domestic or industrial usage. The US salinity laboratory diagram, EC, KR, and Na % data show that the majority of the collected samples of groundwater are acceptable for irrigation, RSC and PI data show that all of the studied Eocene water samples are appropriate for irrigation, and MH data disclose that most of the studied water samples are unsuitable.

**ASSOCIATED CONTENT**

**Data Availability Statement**
All data that have been used in this work are represented and included in the manuscript.

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All authors have contributed to the conception and design of this research. Preparation of the material, collection of data, and analyses were done by E.I., M.M.K., R.S., A.A., A.A., and M.S.A. The manuscript’s first draft was written by E.I., and all authors provided their comments on preliminary versions of this manuscript. The final manuscript has been read and approved by all authors.

**Notes**

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