

Assessment of groundwater quality using geographical information system (GIS), at north-east Cairo, Egypt

M. F. El-Shahat, M. A. Sadek, W. M. Mostafa and K. H. Hagagg

ABSTRACT

The present investigation has been conducted to delineate the hydrogeochemical and environmental factors that control the water quality of the groundwater resources in the north-east of Cairo. A complementary approach based on hydrogeochemistry and a geographical information system (GIS) based protectability index has been employed for conducting this work. The results from the chemical analysis revealed that the groundwater of the Quaternary aquifer is less saline than that of the Miocene aquifer and the main factors that control the groundwater salinity in the studied area are primarily related to the genesis of the original recharging water modified after by leaching, dissolution, cation exchange, and fertilizer leachate. The computed groundwater quality index (WQI) falls into two categories: fair for almost all the Miocene groundwater samples, while the Quaternary groundwater samples are all have a good quality. The retarded flow and non-replenishment of the Miocene aquifer compared to the renewable active recharge of the Quaternary aquifer can explain this variation of WQI. The index and overlay approach exemplified by the DUPIT index has been used to investigate the protectability of the study aquifers against diffuse pollutants. Three categories (highly protectable less vulnerable, moderately protectable moderately vulnerable and less protectable highly vulnerable) have been determined and areally mapped.

Key words | Egypt, GIS, groundwater quality index, hydrochemical, north-east Cairo, protectability index

M. F. El-Shahat
Chemistry Department, Faculty of Science,
Ain-Shams University,
Cairo,
Egypt

M. A. Sadek
W. M. Mostafa
K. H. Hagagg (corresponding author)
Nuclear and Radiological Regulatory Authority,
Cairo,
Egypt
E-mail: k.hagagg@gamil.com

INTRODUCTION

Great attention is paid by the Egyptian authorities to development and new settlements establishment. The north-eastern part of greater Cairo, which is located at the southern part of the eastern Nile Delta, represents a scene for establishment of various investment activities in the form of big agricultural, industrial and urbanization projects. Securing water resources of appropriate quantity and quality is of prime importance for development programs in this important sector. This gives importance to the evaluation of the water resources sustainability, and vulnerability to cope with the prospective development.

The sustainability of groundwater is constrained by renewability of recharge and continuity of flow. The quality

of the groundwater is a function of its physical and chemical parameters which depend on the soluble products of weathering, decomposition and the related changes that occur with respect to time and space, as well as anthropogenic impacts (WHO 2011).

The present investigation aims at studying the hydrogeochemical and environmental factors that control the water quality of the groundwater resources to the north-east of Cairo. The study also aims to explore the protectability of the groundwater resources against high pollution threats of the contaminants that diffuse to groundwater through the unsaturated zone. This will help to achieve the sustainable use of groundwater resources and to incorporate

water quality constraints into planning and decision making for integrated management. The methodologies of hydrogeochemistry, and a geographical information system (GIS) based protectability index have been used for conducting this investigation.

Physical setting of the study area

The study area, [Figure 1](#), lies in the south-eastern part of Nile Delta to the north-east of Cairo. It covers a surface area of about 2,550 km², between latitudes 30° 05' and 30° 30' N and longitudes 31° 10' and 31° 52' E. It is bordered from the north by the Ismailia Canal and from the south by the Cairo-Ismailia desert road.

The study area is mainly covered by Tertiary and Quaternary sediments. This sedimentary succession varies in thickness and shows an increase toward the Nile Delta recording more than 1,000 m towards the Mediterranean Sea. The top portion of this section is formed of sand and clay facies, whereas the lower portion is dominated by carbonate facies ([El Shazly *et al.* 1975](#)). The Tertiary carbonates are underlain by Cretaceous limestone and dolomite, which are strongly dissected by a complex system of faults striking mostly E-W ([El-Sayed 2005](#)).

In the studied area, groundwater occurs in two main water-bearing formations, namely Quaternary and Miocene. The Quaternary aquifer is mostly found under semi-confined conditions in the Belbeis area due to the presence of an overlying clay bed and is found under unconfined

conditions in the Inshas area ([Hefny *et al.* 1983](#)). The depth to groundwater ranges from 21 (NE) to 91 m (SW). The groundwater flow direction is north-eastward with a regional hydraulic gradient ranging between 50 and 60 cm/km ([Taha *et al.* 1997](#)). The Quaternary aquifer is mainly recharged from the Ismailia canal as well as from irrigation water return flow. The Miocene aquifer within the studied area is either found under unconfined or semi-confined conditions depending on the presence or absence of clay overlay ([El-Mahmoudi *et al.* 2006](#); [Shehata & El Sabrouly 2014](#)). The depth to water varies from 160 to 240 m along the Cairo-Ismailia desert road and reaches about 170 m near Cairo city, the direction of groundwater flow in the Heliopolis basin is from SW to NE ([Sallouma & Gomaa 1997](#)).

MATERIALS AND METHODS

Groundwater samples were collected during summer 2014 from 34 groundwater points tapping the two aquifers (Quaternary and Miocene). These water samples were subjected to both field and laboratory analyses.

The field analyses include electrical conductivity (EC) ($\mu\text{S}/\text{cm}$) which was measured using an EC meter (model: Cole Parmer date meter CON 410 series) and pH which was measured using a pH meter (Jenway, model 3150). The laboratory analyses include the determination of major ions (Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Cl^- , HCO_3^- , and SO_4^{2-})

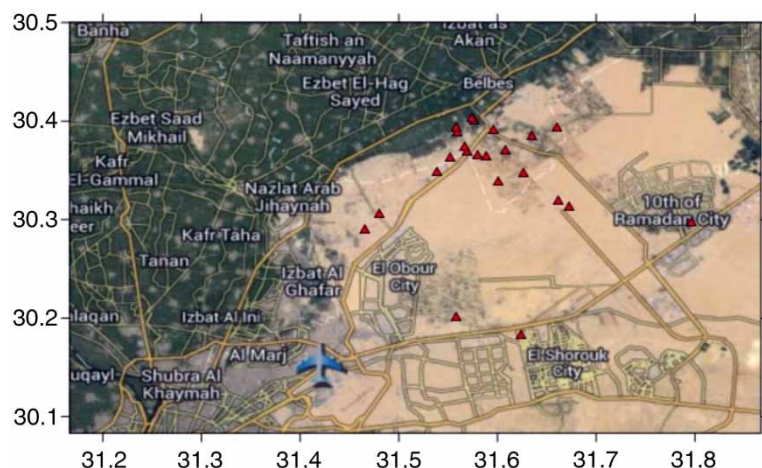


Figure 1 | Location map of the study area showing the collected samples.

and trace elements (Al, B, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Sr, V, and Zn). Measurements were carried out by Inductively Coupled Argon Plasma Poma 6500 Spectrophotometer (Unicom, UK). The analyses were carried out according to the standard methods (Rainwater & Thatcher 1960; Fishman & Friedman 1985; American Public Health Association (APHA) 1998; ASTM 2002). The obtained chemical data are expressed in milligram per liter (mg/l). All of the hydrochemical data have been treated and analyzed for calculating water quality index (WQI) and evaluating its suitability for various purposes.

The index and overlay approach (protectability index) combined with the GIS tool have been used to evaluate the groundwater vulnerability against diffuse pollution through the unsaturated zone. The DUPIT index has been calculated for this. The data required for the index calculation have

been extracted from 42 boreholes distributed in the study area and indicated in the work of El-Sayed (2005).

RESULTS AND DISCUSSION

Hydrochemical characterization

The analyzed groundwater samples that were collected from the main aquifers (Quaternary and Miocene) have been used to identify the chemical characteristics and salinization processes of the groundwater system and to evaluate the factors that constrain its quality. Tables 1–4 show the results of the chemical analysis conducted on the groundwater samples, and the average values and ranges of variation of ionic composition are summarized in Table 5.

Table 1 | Results of major ions of groundwater samples in the Miocene aquifer in the studied area

| No. | pH | $\mu\text{S/cm}$ EC | (mg/l) | | | | | | | | |
|-----|-----|------------------------|---------|------------------|------------------|---------------|--------------|--------------------|------------------|--------------------|---------------|
| | | | TDS | Ca^{2+} | Mg^{2+} | Na^+ | K^+ | CO_3^{2-} | HCO_3^- | SO_4^{2-} | Cl^- |
| 1 | 7.0 | 9,540.0 | 6,157 | 583.3 | 212.8 | 1,200.0 | 12.0 | 6.0 | 97.6 | 1,900.0 | 2,185.3 |
| 7 | 7.9 | 4,410.0 | 3,258 | 79.7 | 31.8 | 1,020.0 | 9.0 | 9.0 | 1,340.2 | 1,085.0 | 938.4 |
| 8 | 7.1 | 13,580.0 | 8,847 | 705.7 | 385.0 | 1,750.0 | 28.0 | 12.0 | 128.1 | 2,616.0 | 3,290.8 |
| 10 | 6.9 | 9,650.0 | 6,037 | 521.8 | 142.2 | 1,400.0 | 11.0 | 0.0 | 42.7 | 1,435.0 | 2,493.8 |
| 12 | 7.4 | 4,680.0 | 2,878 | 200.5 | 47.8 | 760.0 | 7.0 | 3.0 | 109.8 | 519.0 | 1,285.5 |
| 31 | 7.4 | 9,500.0 | 6,074.5 | 637.0 | 297.6 | 1,191.8 | 39.7 | 0.0 | 158.0 | 1,020.0 | 2,730.4 |
| 32 | 7.8 | 8,800.0 | 7,649.5 | 785.5 | 430.2 | 1,309.9 | 22.1 | 0.0 | 346.0 | 1,704.9 | 3,050.9 |
| 33 | 7.2 | 7,500.0 | 4,795 | 471.0 | 290.0 | 900.0 | 23.0 | 0.0 | 30.0 | 181.0 | 2,900.0 |

Table 2 | Results of trace elements of groundwater samples in the Miocene aquifer in the studied area

| No. | (mg/l) | | | | | | | | | | | | | |
|-----|--------|-------|--------|--------|-------|-------|------|-------|-------|-------|-------|-------|------|------|
| | Al | B | Cd | Co | Cr | Cu | Fe | Mn | Mo | Ni | Pb | Sr | V | Zn |
| 1 | 0.04 | 0.460 | 0.0004 | 0.0009 | 0.015 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 2.71 | 0.01 | 0.07 |
| 7 | 0.04 | 0.210 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 2.35 | 0.01 | 0.10 |
| 8 | 0.04 | 0.198 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 1.57 | 0.01 | 0.07 |
| 10 | 0.04 | 0.760 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.004 | 0.001 | 0.006 | 2.44 | 0.01 | 0.07 |
| 12 | 0.04 | 0.602 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.149 | 0.001 | 0.001 | 0.006 | 18.16 | 0.01 | 0.07 |
| 31 | 0.04 | 0.032 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 0.78 | 0.01 | 0.07 |
| 32 | 0.04 | 0.337 | 0.0004 | 0.0009 | 0.007 | 0.012 | 0.01 | 3.741 | 0.001 | 0.035 | 0.006 | 10.67 | 0.01 | 0.15 |
| 33 | 0.04 | 0.410 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 2.21 | 0.01 | 0.01 |

Table 3 | Results of chemical analyses of groundwater samples in the Quaternary aquifer in the studied area

| No. | pH | $\mu\text{S/cm}$ EC | (mg/l) | | | | | | | | |
|-----|-----|------------------------|----------|------------------|------------------|---------------|--------------|--------------------|------------------|--------------------|---------------|
| | | | TDS | Ca^{2+} | Mg^{2+} | Na^+ | K^+ | CO_3^{2-} | HCO_3^- | SO_4^{2-} | Cl^- |
| 2 | 7.6 | 2,470 | 1,779 | 36.85 | 20.26 | 570 | 7 | 6 | 115.9 | 430 | 642.73 |
| 3 | 7.5 | 2,320 | 1,443 | 37.63 | 19.66 | 450 | 6 | 0 | 152.5 | 321 | 527.04 |
| 4 | 7.9 | 4,170 | 2,803 | 121.5 | 40.17 | 780 | 11 | 9 | 140.3 | 930 | 835.55 |
| 5 | 7.4 | 1,461 | 916 | 80.5 | 30.84 | 180 | 8 | 0 | 134.2 | 355 | 179.96 |
| 6 | 7.6 | 1,359 | 893 | 44.31 | 18.93 | 230 | 8 | 0 | 82.35 | 242 | 290.51 |
| 9 | 8 | 486 | 322 | 46.4 | 14.14 | 44 | 7 | 105.5 | 164.7 | 85 | 32.14 |
| 11 | 7.7 | 3,080 | 1,411 | 85.31 | 33.59 | 370 | 13 | 12 | 189.1 | 237 | 565.6 |
| 13 | 7.9 | 4,830 | 3,247 | 116.3 | 36.94 | 960 | 6 | 12 | 131.15 | 970 | 1079.79 |
| 14 | 7.5 | 5,380 | 4,141 | 465.8 | 58.61 | 800 | 7 | 12 | 228.75 | 1964 | 719.86 |
| 15 | 7.6 | 2,465 | 1,495 | 115.6 | 46.99 | 330 | 14 | 15 | 118.95 | 385 | 529.61 |
| 16 | 7.5 | 695 | 465 | 7.437 | 3.27 | 160 | 3 | 4.5 | 155.55 | 102 | 107.98 |
| 17 | 7 | 1,444 | 993 | 89.14 | 33.93 | 185 | 8 | 9 | 94.55 | 425 | 195.39 |
| 18 | 7.2 | 3,780 | 2,657 | 126.7 | 44.21 | 720 | 11 | 9 | 125.05 | 1015 | 668.44 |
| 19 | 7.6 | 2,477 | 1,688 | 94.21 | 37.58 | 420 | 11 | 6 | 176.9 | 640 | 390.78 |
| 20 | 7.2 | 1,115 | 707 | 96.48 | 31.51 | 100 | 7 | 6 | 219.6 | 222 | 133.69 |
| 21 | 7.6 | 1,177 | 765 | 71.55 | 28.37 | 150 | 9 | 15 | 179.95 | 222 | 179.96 |
| 22 | 7.9 | 1,220 | 710 | 61.93 | 31.67 | 147.5 | 7 | 18 | 234.85 | 177 | 149.11 |
| 23 | 7.5 | 1,416 | 884 | 87.29 | 36.84 | 155 | 12 | 18 | 216.55 | 358 | 107.98 |
| 24 | 7.8 | 400 | 304.78 | 40.1 | 7.4 | 31 | 5 | 0 | 172 | 22 | 27.3 |
| 25 | 7.7 | 6,700 | 3,449.59 | 121.9 | 37.7 | 1,046.5 | 9.8 | 0 | 143.5 | 998 | 1,092.2 |
| 26 | 8.1 | 800 | 563.94 | 36.9 | 9.9 | 107.1 | 4 | 0 | 301.4 | 49.8 | 54.6 |
| 27 | 8 | 400 | 333.49 | 35.4 | 10 | 40.6 | 5.3 | 0 | 186.6 | 28.3 | 27.3 |
| 28 | 8.1 | 400 | 294.76 | 32.1 | 14 | 26.8 | 4.6 | 0 | 172 | 18 | 27.3 |
| 29 | 7.4 | 1,600 | 1,149.17 | 246 | 6.1 | 88.7 | 5.1 | | 200.9 | 500 | 102.4 |
| 34 | 8.9 | 1,700 | 1,116.33 | 32.5 | 13.4 | 293.2 | 16.8 | | 250.1 | 280.8 | 229.6 |

Total dissolved salts distribution

The ranges of variation of total dissolved salts (TDS) and major ions in the two aquifers are quite wide reflecting heterogeneity of recharge conditions and salinization processes. Based on the classification of freshness of water (Davis & De Wiest 1967), the Quaternary aquifer is more fresh than the Miocene one and about 90% of its samples have TDS < 3,000 ppm with 60% < 1,000 ppm; the Miocene aquifer has about 90% of its samples > 3,000 ppm up to 9,000 ppm and about 10% < 3,000 ppm. About 10% of the samples of the two aquifers – located at the mixing zone between Quaternary and Miocene – have TDS values >

3,000 ppm in Quaternary aquifer groundwater samples and < 3,000 ppm in Miocene aquifer groundwater samples. The freshness of the Quaternary aquifer is primarily related to the direct recharge source and the high renewability. The GIS based TDS spatial distribution of the Quaternary aquifer, Figure 2, shows a gradual increase along the flow in the north-west direction away from the Ismailia canal which is a major recharge source in the study area. This increase along the flow path is generally controlled by rock/water interaction processes as well as extra use for irrigation and irrigation return, which matches with the results of the stable isotopes in the work of Attia (2009). The TDS of the Miocene aquifer is considerably high as it is

Table 4 | Results of trace elements of groundwater samples in the Quaternary aquifer in the studied area

| (mg/l) | | | | | | | | | | | | | | |
|--------|------|-------|--------|--------|-------|-------|------|-------|-------|-------|-------|-------|------|------|
| No. | Al | B | Cd | Co | Cr | Cu | Fe | Mn | Mo | Ni | Pb | Sr | V | Zn |
| 2 | 0.04 | 0.598 | 0.0004 | 0.0009 | 0.001 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 10.37 | 0.01 | 0.07 |
| 3 | 0.04 | 0.316 | 0.0004 | 0.0009 | 0.001 | 0.006 | 0.01 | 0.009 | 0.001 | 0.001 | 0.006 | 1.15 | 0.01 | 0.07 |
| 4 | 0.04 | 0.290 | 0.0004 | 0.0009 | 0.008 | 0.006 | 0.01 | 0.013 | 0.001 | 0.001 | 0.006 | 1.08 | 0.01 | 0.07 |
| 5 | 0.04 | 0.460 | 0.0004 | 0.0009 | 0.015 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 2.71 | 0.01 | 0.07 |
| 6 | 0.04 | 0.210 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 2.35 | 0.01 | 0.10 |
| 9 | 0.04 | 0.198 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 1.57 | 0.01 | 0.07 |
| 11 | 0.04 | 0.760 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.004 | 0.001 | 0.006 | 2.44 | 0.01 | 0.07 |
| 13 | 0.04 | 0.602 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.149 | 0.001 | 0.001 | 0.006 | 18.16 | 0.01 | 0.07 |
| 14 | 0.04 | 0.032 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 0.78 | 0.01 | 0.07 |
| 15 | 0.04 | 0.337 | 0.0004 | 0.0009 | 0.007 | 0.012 | 0.01 | 3.741 | 0.001 | 0.035 | 0.006 | 10.67 | 0.01 | 0.15 |
| 16 | 0.04 | 0.410 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 2.21 | 0.01 | 0.01 |
| 17 | 0.04 | 0.260 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.12 | 0.024 | 0.006 | 0.001 | 0.006 | 3.47 | 0.01 | 0.01 |
| 18 | 0.04 | 0.830 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.020 | 0.004 | 0.001 | 0.006 | 2.08 | 0.01 | 0.01 |
| 19 | 0.04 | 1.107 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.10 | 0.011 | 0.004 | 0.002 | 0.006 | 6.14 | 0.01 | 0.01 |
| 20 | 0.04 | 0.235 | 0.0004 | 0.0009 | 0.012 | 0.006 | 0.03 | 0.009 | 0.001 | 0.001 | 0.006 | 2.84 | 0.01 | 0.01 |
| 21 | 0.04 | 0.098 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.007 | 0.001 | 0.001 | 0.006 | 0.16 | 0.01 | 0.01 |
| 22 | 0.04 | 0.182 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.005 | 0.001 | 0.001 | 0.006 | 2.20 | 0.01 | 0.20 |
| 23 | 0.04 | 0.546 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.006 | 0.002 | 0.001 | 0.006 | 3.04 | 0.01 | 0.10 |
| 24 | 0.04 | 0.437 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.002 | 0.001 | 0.006 | 2.41 | 0.01 | 0.07 |
| 25 | 0.04 | 0.054 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.004 | 0.001 | 0.006 | 1.20 | 0.01 | 0.07 |
| 26 | 0.04 | 0.182 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.002 | 0.001 | 0.006 | 1.47 | 0.01 | 0.07 |
| 27 | 0.04 | 0.324 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 1.47 | 0.01 | 0.07 |
| 28 | 0.04 | 0.125 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 1.87 | 0.01 | 0.07 |
| 29 | 0.04 | 0.125 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.001 | 0.001 | 0.006 | 1.87 | 0.01 | 0.07 |
| 34 | 0.04 | 0.182 | 0.0004 | 0.0009 | 0.007 | 0.006 | 0.01 | 0.002 | 0.002 | 0.001 | 0.006 | 1.47 | 0.01 | 0.07 |

Table 5 | Statistical analysis of major cations for groundwater samples in both aquifers

| Aquifer type | Item | pH | EC ($\mu\text{S/cm}$) | TDS (mg/l) | Ca ²⁺ (mg/l) | Mg ²⁺ (mg/l) | Na ⁺ (mg/l) | K ⁺ (mg/l) | CO ₃ ²⁻ (mg/l) | HCO ₃ ⁻ (mg/l) | SO ₄ ²⁻ (mg/l) | Cl ⁻ (mg/l) |
|--------------|-------|-----|-------------------------|------------|-------------------------|-------------------------|------------------------|-----------------------|--------------------------------------|--------------------------------------|--------------------------------------|------------------------|
| Miocene | Aver. | 7.3 | 8,457.5 | 5,712 | 498.1 | 229.7 | 1,191.5 | 19 | 3.8 | 281.6 | 1,307.6 | 2,359.4 |
| | Max. | 7.9 | 13,580 | 8,847 | 785.5 | 430.2 | 1,750 | 39.7 | 12 | 1,340.2 | 2,616 | 3,290.78 |
| | Min. | 6.9 | 4,410 | 2,878 | 79.7 | 31.75 | 760 | 7 | 0 | 30 | 181 | 938.39 |
| Quaternary | Aver. | 7.7 | 2,044.9 | 1,381.2 | 93.2 | 26.6 | 335.4 | 8.2 | 11.2 | 171.5 | 439.1 | 355.9 |
| | Max. | 8.9 | 6,700 | 4,141 | 465.8 | 58.6 | 1,046.5 | 16.8 | 105.5 | 301.4 | 1,964 | 1,092.2 |
| | Min. | 7 | 247 | 294.76 | 7.4 | 3.3 | 26.8 | 3 | 0 | 82.4 | 18 | 27.3 |

characterized by high clayey and limy content leading to retarded flow and long water contact. At the zones where contact occurs with the Quaternary aquifer, it decreases

but not to less than 4,410 mg/l. The patterns of the spatial distribution of major ions are highly comparable with TDS, showing a high association and strong correlation

TDS Spatial Distribution

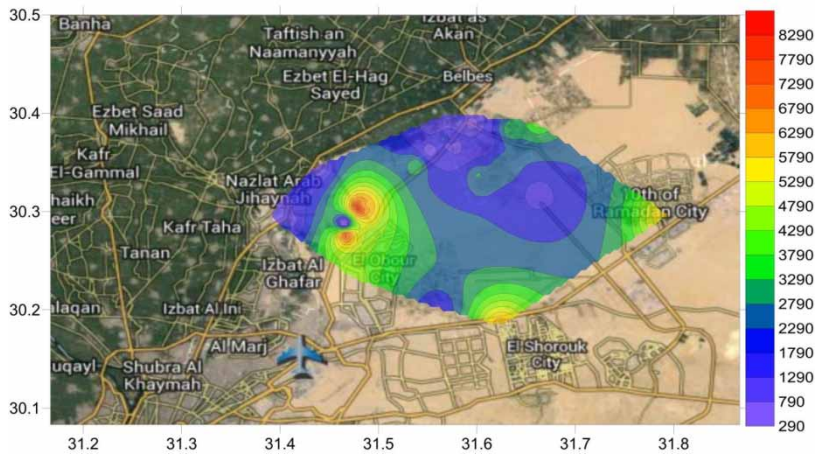


Figure 2 | Spatial distribution of TDS for all groundwater samples in the studied area using Super GIS.

(correlation coefficients of TDS vs Cl^- , Na^+ , Ca^{2+} , Mg^{2+} , and SO_4^{2-} equal 0.92, 0.94, 0.86, 0.8 and 0.8, respectively).

Ion dominance and water chemical type

The ordering of the concentration of cationic and anionic species for the studied groundwater samples highlights the stage of mineralogical evolution and the degree of maturity as follows:

- The ionic order $\text{HCO}_3^- > \text{Cl}^- (\text{SO}_4^{2-}) > \text{SO}_4^{2-} (\text{Cl}^-)/\text{Ca}^{2+} (\text{Na}^+) > \text{Na}^+ (\text{Ca}^{2+}) > \text{Mg}^{2+}$ was recorded for 22% of the Quaternary aquifer samples with bicarbonate-calcium or bicarbonate-sodium water type. This order characterizes the groundwater that has an original fresh water recharge little modified by leaching and cation exchange.
- The ionic order of $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-/\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+}$ with chloride-sodium water type is obtained for about 52% of the Quaternary aquifer samples, and all of the Miocene aquifer samples. This ionic order characterizes the advanced stage of mineralization and the potential salinization processes under long rock/water contact and high attack potential of lithofacies of old marine deposits.
- The ionic order $\text{SO}_4^{2-} > \text{HCO}_3^- > \text{Cl}^-/\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+}$, i.e. sulfate-sodium water type is characterized for 26% of Quaternary aquifer samples, reflecting the increase of SO_4^{2-} and Na^+ content that could be related to excessive use of fertilizers and drainage water effects.

Piper plot

A Piper diagram (Piper 1953) is used to clarify chemical changes of the water quality within the studied aquifers. The groundwater samples of the Miocene aquifer in Figure 3(a) are located within the cationic zone that shows a progressive increase of $\text{Na}^+ + \text{K}^+$ at the expense of $\text{Ca}^{2+} + \text{Mg}^{2+}$ in a narrow range (between 40 and 60%). On the other hand, they are located in the zone of extremely high $\text{Cl}^- + \text{SO}_4^{2-}$ domination over HCO_3^- . This distribution reflects a high stage of mineralization and a salt character developed under the effects of dissolution and ion exchange processes in the aquifer contact.

The distribution on the Piper diagram of the Quaternary groundwater samples, Figure 3(b), is more dispersed compared to that for the Miocene groundwater samples indicating more interactive salinization processes (natural and anthropogenic) versus freshening by active recharge. The hydrochemical facies of $(\text{Na}^+ + \text{K}^+)/(\text{Cl}^- + \text{SO}_4^{2-})$ and $(\text{Ca}^{2+} + \text{Mg}^{2+})/(\text{Cl}^- + \text{SO}_4^{2-})$ appear in about 60% of these samples reflecting the effect of cation exchange processes on the surface of clay deposits. Two other hydrochemical facies of $\text{HCO}_3^-/(\text{Ca}^{2+} + \text{Mg}^{2+})$ and $\text{HCO}_3^-/(\text{Na}^+ + \text{K}^+)$ appear in about 22% of samples reflecting the typical meteoric water with high Na^+ concentration due to leaching or cationic exchange. The rest of the samples fall in $(\text{SO}_4^{2-} + \text{Cl}^-)/(\text{Ca}^{2+} + \text{Mg}^{2+})$ reflecting the effect of fertilizer application.

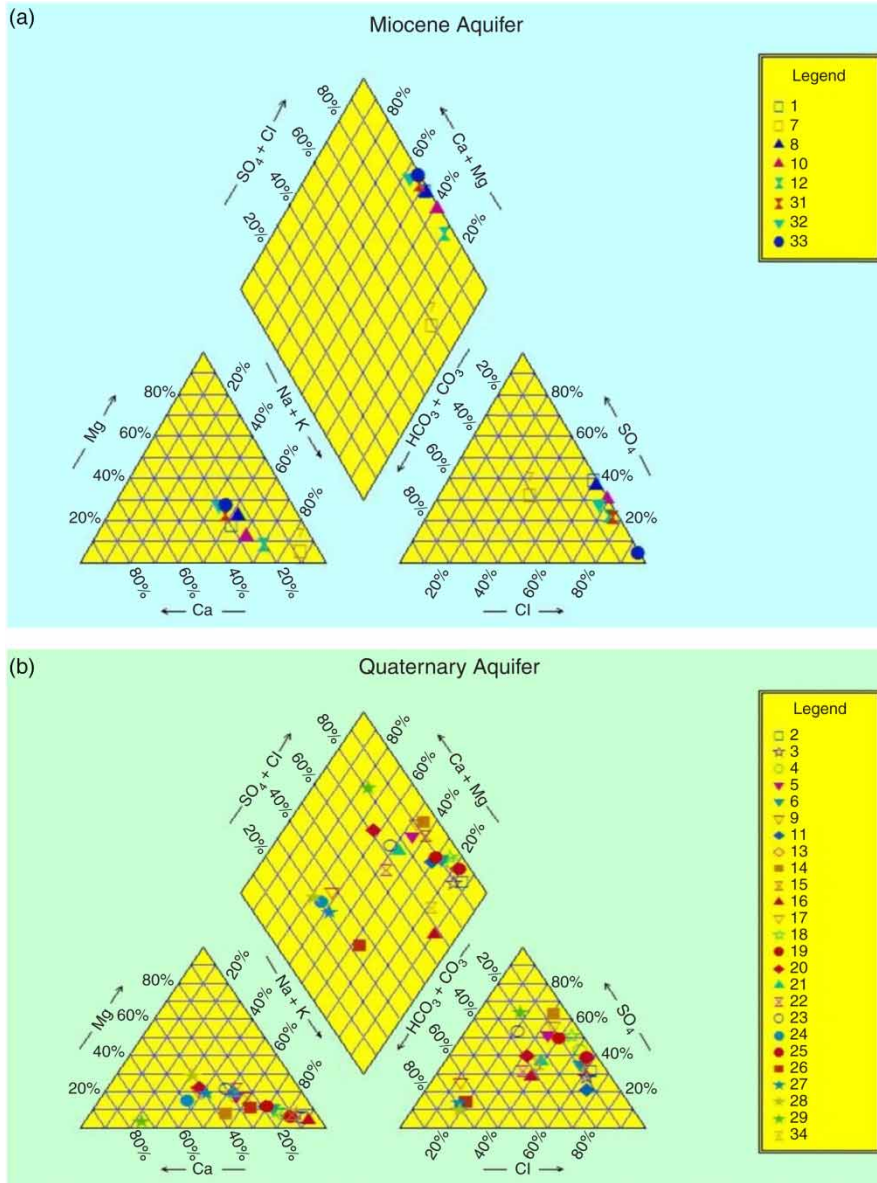


Figure 3 | Piper plot for both Miocene (a) and Quaternary (b) aquifers.

Hydrogeochemical processes of groundwater samples

Ion exchange processes. Ion exchange reactions involve the replacement of one ion for another at the surface of a particle in the hydraulic system, where clay minerals with negatively charged surfaces attract cations to balance the electrical charge and maintain electrical neutrality. The ion exchange process was studied (Jankowski et al. 1998)

by plotting a relation between $(Ca^{2+} + Mg^{2+} - SO_4^{2-} - HCO_3^-)$ and $(Na^+ - Cl^-)$, Figure 4. The water samples were plotted on the slope of -1 in the lower right square indicating that the ion exchange is the dominant processes.

Dissolution and precipitation processes (saturation indices). The 'Solmniq' computer program has been used to calculate the saturation indices (SI) for the studied groundwater samples in relation to the relevant phases in

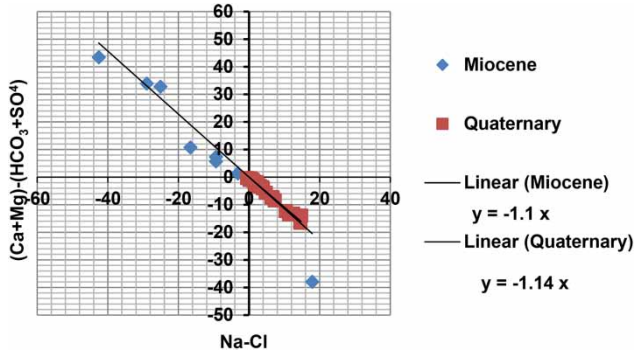


Figure 4 | Relation between $(Ca^{2+} + Mg^{2+} - SO_4^{2-} - HCO_3^-)$ and $(Na^+ - Cl^-)$ for both Quaternary and Miocene aquifer.

the system (calcite, dolomite, gypsum, anhydrite and halite). The SI values determine the extent to which a groundwater has reached chemical equilibrium with the minerals within the aquifer matrix (SOLMINEQ.GW 1999). The results in Tables 6 and 7 show that Quaternary and Miocene groundwater samples have -ve saturation index values with respect to Gypsum, Halite and Anhydrite. This reflects the undersaturation and the continual dissolution of these salts on aquifer contact. On the other hand, about 88% of both the Quaternary and Miocene samples have +ve saturation index values with respect to Dolomite, while 68% of the Quaternary and 63% of the Miocene samples have +ve saturation index values with respect to Calcite. These +ve saturation index values reflect the oversaturation with respect to Calcite and Dolomite and the tendency of the groundwater to precipitate them on rock contact.

Table 6 | Results of calculated SI from 'Solmniq' program for Miocene aquifer samples and their descriptive statistics

| Sample Id | Dolomite | Calcite | Gypsum | Halite | Anhydrite |
|-----------|----------|---------|--------|--------|-----------|
| 1 | 0.66 | -0.12 | -0.19 | -4.35 | -0.47 |
| 7 | 1.26 | 0.18 | -1.02 | -4.73 | -1.31 |
| 8 | 1.36 | 0.15 | -0.10 | -4.00 | -0.34 |
| 10 | -0.52 | -0.64 | -0.32 | -4.20 | -0.61 |
| 12 | 0.75 | 0.03 | -0.89 | -4.71 | -1.18 |
| 31 | 2.02 | 0.51 | -0.43 | -4.30 | -0.72 |
| 32 | 3.60 | 1.30 | -0.21 | -4.20 | -0.50 |
| 33 | 0.20 | -0.50 | -1.22 | -4.30 | -1.50 |
| Av. | 1.17 | 0.11 | -0.55 | -4.35 | -0.83 |
| Min. | -0.52 | -0.64 | -1.22 | -4.73 | -1.50 |
| Max | 3.60 | 1.30 | -0.10 | -4.00 | -0.34 |

Table 7 | Results of calculated SI from 'Solmniq' program for Quaternary aquifer samples and their descriptive statistics

| Sample Id | Dolomite | Calcite | Gypsum | Halite | Anhydrite |
|-----------|----------|---------|--------|--------|-----------|
| 2 | 0.26 | -0.40 | -1.54 | -5.11 | -1.83 |
| 3 | 0.27 | -0.38 | -1.60 | -5.28 | -1.89 |
| 4 | 1.63 | 0.40 | -0.87 | -4.89 | -1.15 |
| 5 | 0.53 | -0.18 | -1.18 | -6.12 | -1.50 |
| 6 | 0.10 | -0.42 | -1.55 | -5.80 | -1.84 |
| 9 | 1.69 | 0.44 | -1.02 | -7.44 | -2.11 |
| 11 | 1.56 | 0.32 | -1.40 | -5.27 | -1.70 |
| 13 | 1.53 | 0.36 | -0.90 | -4.70 | -1.19 |
| 14 | 1.75 | 0.67 | -0.15 | -4.98 | -0.44 |
| 15 | 1.27 | 0.17 | -1.10 | -5.42 | -1.34 |
| 16 | -0.85 | -0.91 | -2.53 | -6.40 | -2.82 |
| 17 | -0.37 | -0.63 | -1.08 | -6.08 | -1.37 |
| 18 | -0.06 | -0.47 | -0.87 | -5.60 | -1.16 |
| 19 | 1.19 | 0.14 | -1.00 | -5.50 | -1.30 |
| 20 | 0.77 | -0.03 | -1.26 | -6.50 | -1.55 |
| 21 | 1.30 | 0.20 | -1.39 | -6.20 | -1.68 |
| 22 | 2.12 | 0.55 | -1.50 | -6.30 | -1.28 |
| 23 | 1.38 | 0.22 | -1.15 | -6.41 | -1.44 |
| 24 | 0.966 | 0.20 | -2.40 | -7.60 | -2.70 |
| 25 | 1.1 | 0.14 | -1.20 | -4.70 | -1.20 |
| 26 | 2.03 | 0.64 | -2.50 | -6.80 | -2.50 |
| 27 | 1.5 | 0.40 | -2.60 | -7.50 | -2.60 |
| 28 | 1.8 | 0.40 | -2.90 | -7.70 | -2.90 |
| 29 | 0.6 | 0.43 | -0.92 | -6.70 | -0.92 |
| 34 | 3.10 | 1.10 | -1.70 | -5.80 | -1.90 |
| Av. | 1.09 | 0.13 | -1.45 | -6.03 | -1.69 |
| Min. | -0.85 | -0.91 | -2.90 | -7.70 | -2.90 |
| Max | 3.10 | 1.10 | -0.15 | -4.70 | -0.44 |

Evaluation of water quality for different uses

WQI for human drinking and domestic uses

The WQI is one of the most effective tools to provide feedback on the quality of water to the policy makers and environmentalists. It provides a single number that expresses the overall water quality at a certain location and time, based on several water quality parameters (Poonam & Ashokkumar 2013). Although there have

been a variety of attempts to create such a WQI, the most successful attempt to date appears to be the index indicated in the Canadian Environmental Quality Guidelines (Canadian Council of Ministers of the Environment (CCME) 2001). The index is based on a combination of three factors; (scope (F1), frequency (F2), and amplitude (F3)) which are determined for a group of water quality variables chosen in relevance to the prospective evaluation. The maximum permissible values of these variables as indicated in a given standard or guidelines represent the objectives on which the corresponding samples are measured.

Choosing variables and objectives. Sixteen parameters have been selected as variables from The Egyptian Higher Committee of Water guidelines for drinking water quality (1995) to generate the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI). Those variables (i.e. physicochemical properties of groundwater samples) and objective (i.e. maximum permissible values) are listed in Table 8.

Calculation of WQI. After the variables and objectives have been defined, the three factors (Scope F1, Frequency

F2 and Amplitude F3) that make up the index are calculated as indicated in the Canadian Environmental Quality Guidelines, 2001 (CCME 2001). The equations used for calculating the overall CCME WQI and the three factors (F1, F2 and F3), for the studied groundwater samples, are indicated as follows:

$$\text{CCME WQI} = 100 - \frac{\left\{ \sqrt{(F_1^2 + F_2^2 + F_3^2)} \right\}}{1.732} \quad (1)$$

F1 (Scope) represents the percentage of variables that do not meet their objectives at least once during the time period under consideration ('failed variables'), relative to the total number of variables measured:

$$F_1 = \left(\frac{\text{Number of failed variable}}{\text{Total number of variables}} \right) \times 100 \quad (2)$$

F2 (Frequency) represents the percentage of individual tests that do not meet objectives ('failed tests'):

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}} \right) \times 100 \quad (3)$$

F3 (Amplitude) represents the amount by which failed test values do not meet their objectives. F3 is calculated in three steps:

- (i) The number of times by which an individual concentration is greater than (or less than, when the objective is a minimum) the objective is termed an 'excursion' and is expressed as follows. When the test value must not exceed the objective:

$$\text{Excursion}_i = \left\{ \frac{\text{Failed Test Value}_i}{\text{Objective}_j} \right\} - 1 \quad (4)$$

- (ii) The collective amount by which individual tests are out of compliance is calculated by summing the excursions of individual tests from their objectives and dividing by the total number of tests (both those meeting objectives and those not meeting objectives). This variable, referred to as the normalized

Table 8 | Selected objective based on the Egyptian High Committee of Water (1995)

| Objective | Value |
|-----------------|---------|
| pH | 6.5–9.2 |
| EC (µS/cm) | 1,200 |
| TDS (mg/l) | 200 |
| Hardness (mg/l) | 500 |
| Ca (mg/l) | 150 |
| Mg (mg/l) | 200 |
| Na (mg/l) | 325 |
| SO4 (mg/l) | 500 |
| Cl (mg/l) | 0.5 |
| B (mg/l) | 0.001 |
| Cd (mg/l) | 0.01 |
| Cu (mg/l) | 0.2 |
| Mn (mg/l) | 0.02 |
| Ni (mg/l) | 0.01 |
| Pb (mg/l) | 0.01 |
| Zn (mg/l) | 500 |
| Fe (mg/l) | 0.5 |

sum of excursions (nse), is calculated as:

$$nse = \sum_{i=1}^n \frac{\text{excursion}_i}{\text{no of tests}} \quad (5)$$

(iii) $F3$ is then calculated by an asymptotic function that scales the normalized sum of the excursions from objectives (nse) to yield a range between 0 and 100.

$$F3 = \left\{ \frac{nse}{(0.01nse + 0.01)} \right\} \quad (6)$$

The CCME WQI has been calculated and compared with the classification of WQIs, Table 9, to evaluate the suitability of the studied groundwater for drinking purposes. A water quality map has been created using GIS, as shown

Table 9 | Categorization of the WQI CCME Method (Canadian Council of Ministers of the Environment 2001)

| Categorization | Index value | Water quality |
|----------------|-------------|---|
| Excellent | 95–100 | Virtual absence of threat or impairment |
| Good | 80–94 | Minor degree of threat or impairment |
| Fair | 65–79 | Occasionally threatened or impaired |
| Marginal | 45–64 | Frequently threatened or impaired |
| Poor | 0–44 | Almost always threatened or impaired |

in Figure 5, showing that the groundwater quality of the study area falls in two categories:

- ‘Fair’ (CCME WQI values range from 65 to 79) for all the Miocene aquifer groundwater samples, which could be attributed to the high salinity values of old marine deposits of this aquifer. Also this category has been noticed in some Quaternary groundwater samples as a result of over-pumping activities.
- ‘Good’ in Quaternary aquifers (CCME WQI values from 80 to 94), this highlighting the presence of an eastern recharge front from the Nile to the Quaternary aquifer direct recharge source and reflecting the high renewability of this aquifer.

Evaluation of groundwater for drinking by livestock and poultry

Comparing the hydrochemical data of the different aquifers in the studied area with the upper limits of concentration for stock and poultry drinking (McKee & Wolf 1963), it appears that nearly all the groundwater samples of the Miocene aquifer are suitable for drinking by livestock, but they are not suitable for poultry. On the other hand, about 12% of the Quaternary groundwater samples are not suitable for poultry and the rest are suitable for livestock and poultry.

Groundwater Quality Map

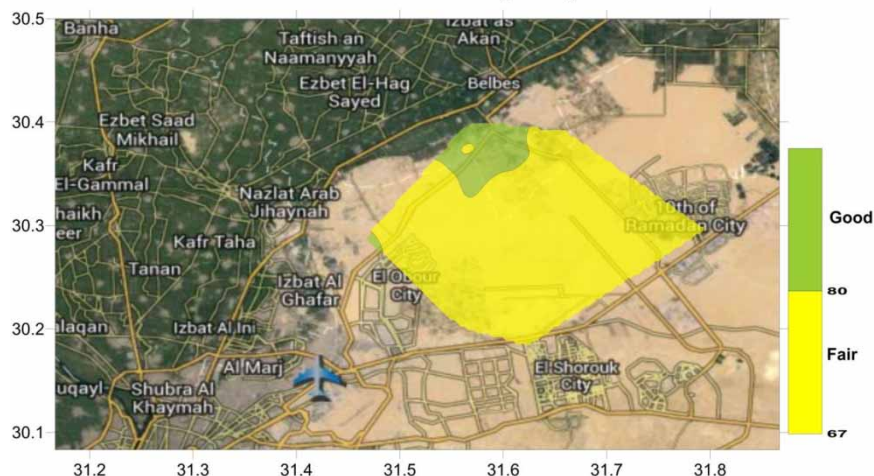


Figure 5 | Groundwater quality map for the study area using Super GIS.

Evaluation of groundwater for irrigation purposes

Evaluation of the water quality for irrigation will be discussed through the following items.

Total dissolved solids. By comparing the results of chemical analyses of the studied samples with the classification of irrigation water according to TDS (Willcox 1955), Table 10 is obtained as an evaluation of the groundwater for irrigation purposes.

Sodium adsorption ratio. The classification of the US Salinity Laboratory Staff (1954) for irrigation water is based on the relation between the sodium adsorption ratio (SAR) and the specific conductance EC (in $\mu\text{S}/\text{cm}$). The SAR estimates the degree to which sodium will be adsorbed by the soil. From Figure 6, it is clear that the Quaternary groundwater samples ranged from good (48%) to moderate (4%) and intermediate water (16%), the rest of the Quaternary

samples and all the Miocene ones were located outside the diagram, reflecting their lack of suitability for irrigation.

Evaluation of groundwater for industrial purposes

The studied area is considered as one of the most promising localities for industrial activities. Industrial water is quite diverse and the required water quality is dependent on the type of industry. Comparing the results of the chemical analyses of the collected groundwater samples with the suggested limits for some selected industries (National Academy of Science 1972), Table 11, we can conclude that about 56% of the Quaternary samples are suitable for most industrial usage but the rest of them have higher salinities and all of the Miocene samples can be used for the petroleum industry only.

Table 10 | Evaluation of the groundwater samples for irrigation in the studied area according to TDS (Willcox 1955)

| Class | Miocene | Quaternary | Comment |
|-------|---------|------------|---|
| 1 | – | 48% | Best water quality |
| 2 | – | 28% | Water involving hazard |
| 3 | 100% | 24% | Water which can be used only with leaching and perfect drainage |

Evaluation of groundwater for building purposes

Water which can be used for building purposes in concrete must be free from some factors that cause concrete degradation. The data of the chemical analyses of the groundwater samples in the studied area were compared with the standard limits (National Academy of Science 1972) presented in Table 12, showing that about 76% of the

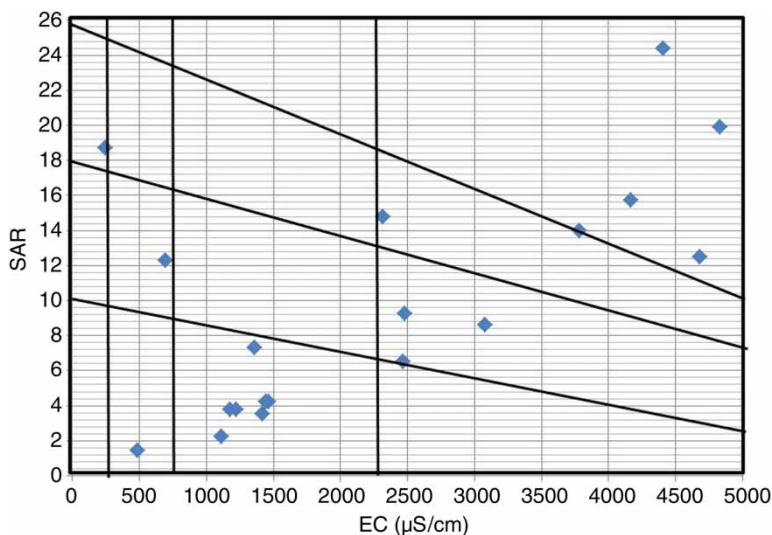


Figure 6 | Relation between the SAR, and the specific conductance, EC (in $\mu\text{S}/\text{cm}$).

Table 11 | Water quality requirements for some selected industries and processes (National Academy of Science 1972)

| Chemical constituent | Industry | | | | Boiler feed water pressure in atm. | | |
|----------------------------------|----------|-----------|----------------------|---------|------------------------------------|--------------|------|
| | Paper | Petroleum | Fruit and vegetables | Textile | Low | Intermediate | High |
| pH | – | | 6.5–8.5 | – | – | – | – |
| TDS | 200–500 | 3,500 | 500 | 100–200 | 700 | 500 | 200 |
| Hardness | 100–200 | 900 | 250 | 0–50 | 350 | 1 | 0.07 |
| HCO ₃ [–] | – | – | 480 | – | 170 | 126 | 48 |
| Na ⁺ + K ⁺ | – | 230 | – | – | – | – | – |
| Ca ²⁺ | – | – | 100 | – | – | – | – |
| Mg ²⁺ | – | 85 | – | – | – | 0.25 | 0.01 |
| SO ₄ ^{2–} | – | 900 | 250 | 100 | 100 | 100 | 100 |
| Cl [–] | 0–200 | 1,600 | 250 | 100 | 100 | 100 | 100 |
| Silica | 20–100 | 85 | 50 | 25 | 25 | 25 | 25 |
| Nitrate | – | 8 | – | – | – | – | – |

Table 12 | Limits for assessing the aggressiveness of water on concrete (National Academy of Science 1972)

| Chemical constituent | Slightly aggressive water | Strongly aggressive water | Very strongly aggressive water |
|-----------------------------------|---------------------------|---------------------------|--------------------------------|
| pH | 5.5–6.5 | 4.5–5.5 | <4.5 |
| CO ₂ | 15–30 | 30–60 | >6.5 mg |
| NH ₄ ⁺ /Kg | 15–30 | 30–60 | >60 |
| Mg ²⁺ /Kg | 100–300 | 300–1,500 | >1,500 |
| SO ₄ ^{2–} /Kg | 200–600 | 600–2,500 | >2,500 |

groundwater of the Quaternary aquifer and about 25% of that of the Miocene one can be used for building purposes.

Groundwater protectability index

Mapping the protectability of the groundwater system against diffusion through the unsaturated zone is a mandatory goal, hence, industrial development as well as new settlements establishment in the study area threaten the groundwater system. On the other hand, those prospective developments are constrained by the availability of water resources which should be secured with active recurrence and suitable quality.

The DUPIT index is one of the weighting/rating driven indicators that are related to the index and overlay

approach (Simsek et al. 2005). It is determined to infer the protectability of the groundwater against diffuse pollution through the unsaturated zone and to delineate the zones of high or low vulnerability to this hazard. The hydrogeochemical, hydrogeological and physical factors inherent in the system (*Depth* to groundwater table, *Upper* layer lithology, *Permeability* of the unsaturated zone, *Impermeable* layer thickness and *Topographic* slope) are explored and assigned weighting and rating scores, Table 13 (Simsek et al. 2005), based on their values in the different water points. An overall DUPIT index is calculated from these scores as follows:

$$\text{DUPIT index} = \text{DrDw} \times \text{UrUw} \times \text{PrPw} \times \text{IrIw} \times \text{TrTw} \quad (7)$$

where Dr and Dw, Ur and Uw, Pr and Pw, Ir and Iw, and Tr and Tw are the rating factors and weighting coefficients for depth to groundwater, upper layer lithology, unsaturated zone permeability, impermeable layer thickness, and topography slope factor, respectively.

The data required for the index calculation have been explored from 42 boreholes dug in the area (El Sayed 2005) as well as the concerned topographic and geologic maps. These data were treated with the GIS tool where their spatial distributions were categorized and mapped separately based on Table 12. They were then overlaid and

Table 13 | DUPIT index parameters and their classification (Simsek et al. 2005)

| Factor | Weight | Range | Rating | Suitability |
|--|--------|---|--------|-------------|
| Depth to groundwater table | 5 | <5 | 1 | Very Low |
| | | 5–15 | 2 | Low |
| | | 15–30 | 3 | Medium |
| | | 30–50 | 4 | High |
| | | >50 | 5 | Very High |
| Upper layer lithology | 4 | Fractured rocks | 1 | Very Low |
| | | Sand and gravel | 2 | Low |
| | | Silty sand, clayey and silty gravel | 3 | Medium |
| | | Silty and clayey sand | 4 | High |
| | | Clay, schists and flysch, massive rocks | 5 | Very High |
| Permeability of unsaturated zone (m/s) | 3 | $>1.0 \times 10^{-2}$ | 1 | Very Low |
| | | $1.0 \times 10^{-2} - 1.0 \times 10^{-3}$ | 2 | Low |
| | | $1.0 \times 10^{-3} - 1.0 \times 10^{-5}$ | 3 | Medium |
| | | $1.0 \times 10^{-5} - 1.0 \times 10^{-7}$ | 4 | High |
| | | $<1.0 \times 10^{-7}$ | 5 | Very High |
| Impermeable thickness (m) | 2 | <3 | 1 | Very Low |
| | | 3–6 | 2 | Low |
| | | 6–12 | 3 | Medium |
| | | 12–24 | 4 | High |
| | | >24 | 5 | Very High |
| Topographic slope (°) | 1 | >60 | 1 | Very Low |
| | | 40–60 | 2 | Low |
| | | 20–40 | 3 | Medium |
| | | 10–20 | 4 | High |
| | | <10 | 5 | Very High |

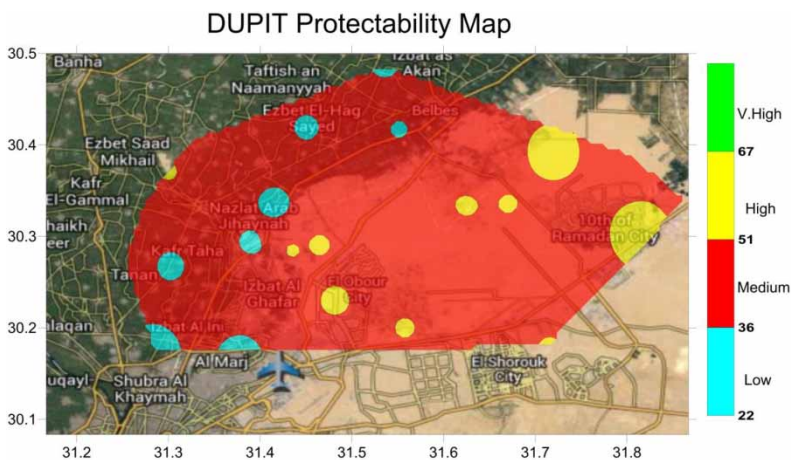


Figure 7 | The protectability map of the study area based on the DUPIT index.

integrated in one map showing the spatial distribution of the overall index, Figure 7.

Based on the thematic map of the DUPIT index for the studied area (having an index values range from 37 to 52) the area can be ranked into three categories specifying

areas of different protectability against diffuse pollutants, based on Table 14 as follows:

- The higher protectability (less vulnerable areas), having an overall index in the range from 52 to 67, are located in the

Table 14 | DUPIT index classification (Simsek et al. 2005)

| DUPIT index | Protectability |
|-------------|----------------|
| <22 | Very Low |
| 22–36 | Low |
| 37–51 | Medium |
| 52–67 | High |
| >67 | Very High |

middle and eastern parts of the domain of interest, especially at Tenth of Ramadan city, El-Obour city, Inshas area and some desert areas near the Cairo-Ismailia desert road.

- The moderately protectable (moderately vulnerable areas) have an overall index in the range from 37 to 51 and are located in the northern sectors of the study area.
- The lower protectability areas are located in some parts of Belbis Al-Asher desert road and have a DUPIT index in the range from 22 to 36.

CONCLUSION

Hydrochemical analyses of the studied groundwater samples (Quaternary and Miocene) have been used to identify the chemical characteristics and salinization processes of the groundwater system. It is revealed that the Ismailia canal is the main recharge source for Quaternary aquifer and that solute content gradually increases along the flow path in the north-west direction under the effects of rock/water interaction processes as well as extra use for irrigation and irrigation return. On the other hand, the Miocene aquifer is less rechargeable and has a retarded flow character. The GIS ground WQI map of the study area delineates the zones of the two determined categories: fair (CCME WQI Value 65–79) for all of the Miocene aquifer groundwater, and also for some Quaternary groundwater samples and good (CCME WQI Value 80–94) for the Quaternary aquifer groundwater samples adjacent to Ismailia Canal.

The GIS based DUPIT index has been used to delineate the zones of different vulnerability against diffuse pollutants in the studied area. It separated the aquifers into two main classes and mapped their vulnerability as follows: more

protectable less vulnerable areas (DUPIT index values 52 to 67) are located to the middle and eastern part of the domain of interest and moderately protectable moderately vulnerable areas (DUPIT index values 37 to 51) are located in the northern sectors of the study area.

ACKNOWLEDGEMENT

This publication was made possible by the support of the Egyptian Nuclear and Radiological Regulatory Authority (ENRRA).

REFERENCES

- American Public Health Association (APHA) 1998 *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, American Water Works Association, and Water Pollution Control Federation. 20th edition, Washington, DC.
- Attia, F. M. 2009 *Environmental Assessment of Groundwater Resources at Northeast Cairo*. MSc, Faculty of Science, Cairo University, Egypt.
- Canadian Council of Ministers of the Environment (CCME) 2001 *Canadian Water Quality Guidelines for the Protection of Aquatic Life: CCME Water Quality Index 1.0*. Technical Report, Canadian Council of Ministers of the Environment Winnipeg, MB, Canada. <http://www.ccme.ca/sourcetop/wqi.html>.
- Davis, S. N. & De Wiest, R. J. M. 1967 *Hydrogeology*. John Wiley and Sons, Inc., New York.
- El-Mahmoudi, A. S., Shendi, E. H. & Mohammed, S. M. 2006 Groundwater Exploration with Schlumberger Soundings at Cairo-Bilbeis District, East Nile Delta, Egypt. The Seventh Annual U.A.E. University Research Conference, UAEU Funded Research Publications, 15, pp. 108–121.
- El Sayed, S. A. W. 2005 Hydrogeological Studies and Application of the Environmental Isotopes Techniques on the Groundwater Resources in the Northeast Greater Cairo, Egypt, PhD, Thesis, Ain Shams University, Egypt, pp. 51–71.
- El Shazly, E. M., Abd El Hady, M. A., El Shazly, M. M., El Kassas, I. A., El Ghawaby, M. A., Salman, A. B. & Morsi, M. A. 1975 Geology and groundwater potential studies of El Ismailia master plan study area. Remote Sensing Research project, Academy of Scientific Res. and Techno., Cairo, Egypt, p. 24.
- Fishman, M. J. & Friedman, L. C. 1985 *Methods for Determination of Inorganic Substances in Water and Fluvial Sediments*. US Geol. Surv. Book 5, Chapter A1. Open File Report 85–495, Denver, Colorado, USA.

- Hefny, K., Morsi, A., Farid, H. S., Khater, A. R., Sharaf, H., Khalil, T. B., El Radi, M. R., Rashed, M. & Attia, D. 1983 *Groundwater Studies for El Obour City Area*. Institute for Groundwater Research, Cairo, Egypt, p. 34.
- Jankowski, J., Acworth, R. I. & Shekarforoush, S. 1998 Reverse ion exchange in a deeply weathered porphyritic dacite fractured aquifer system, Yass, New South Wales, Australia. In: *Proc. 9th Int. Symp. Water-Rock Interaction, Taupo, New Zealand, 30 March-3 April 1998* (G. B. Arehart & J. R. Hulston, eds). Belkema, Rotterdam, pp. 243–246.
- McKee, J. E. & Wolf, H. W. 1963 *Water Quality Criteria*. California State Water Quality Control Board Publication 3-A, 548. Available from: http://www.waterboards.ca.gov/publications_forms/publications/general/docs/waterquality_criteria1963.pdf.
- National Academy of Science 1972 *Water Quality Criteria*. Protection Agency, Washington, DC, pp. 1–594.
- Piper, A. M. 1953 *A graphic procedure in geological interpretation of water analysis*. *American Geophysical Union Transactions* **25**, 914–932.
- Poonam, B. & Ashokkumar, V. 2013 Assessment of physico-chemical parameters and water quality index of reservoir water. *International Journal of Plant, Animal and Environmental Sciences* **3** (5), 89–89.
- Rainwater, F. H. & Thatcher, L. L. 1960 *Methods for Collection and Analysis of Water Samples*. US Geol. Survey water supply, Washington, DC, p. 1454.
- Sallouma, M. K. & Gomaa, M. A. 1997 Groundwater quality in the Miocene aquifers east and west of the Nile Delta and in the North Western Desert, Egypt. *Bulletin Social Geography Egypt*, pp. 47–72.
- Shehata, M. & El Sabrouty, M. N. 2014 Applications of hydrogeochemical modeling to assessment geochemical evolution the Quaternary aquifer system in Belbies area, east Nile Delta, Egypt. *J. Biol. Earth Sci.* **4** (1), E34–E47.
- Simsek, A., Kincal, C. & Gunduz, O. 2005 *A solid waste disposal site selection procedure based on groundwater vulnerability mapping*. *Environmental Geology* **49**, 620–633.
- SOLMINEQ.GW 1999 *Geochemical Application and Modeling Software Ltd*. Edmonton, Alberta, Canada.
- Taha, A. A., Serag El Din, H. M. & El Haddad, I. M. 1997 Water quality assessment in the area between Ismailia canal and Cairo Ismailia desert road for different uses. *Journal of Environmental Sciences* **14**, 45–70.
- The Egyptian Higher Committee of Water Guidelines 1995 *Egyptian Standards for Drinking Water and Domestic Water According to the Act 27/1978 in Regulating of the Public Water Supplies*. Egyptian Governmental Press, Egypt.
- US Salinity Laboratory Staff 1954 *Diagnosis and Improvement of Saline and Alkali Soils*. US Agric. Handbook, No. 60, US Dept. Agric., Washington, DC, p. 160.
- WHO 2011 *Guidelines for Drinking-Water Quality*, 4th edn. World Health Organization, Geneva. Available on the WHO website (<http://www.who.int>).
- Willcox, L. V. 1955 *Classification and use of irrigation waters*, Washington. United States Department of Agric., Circ. No. 969.

First received 8 August 2015; accepted in revised form 27 September 2015. Available online 21 October 2015