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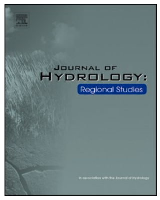

An integrated assessment approach for fossil groundwater quality and crop water requirements in the El-Kharga Oasis, Western Desert, Egypt

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ABSTRACT

Study region: The El-Kharga Oasis in the Western Desert of Egypt is selected as the study area due to its hyberarid climate condition and water scarcity. In this region, the fossil groundwater is the main water source; therefore, preserving groundwater quality and quantity is mandatory.
Study focus: This study evaluated groundwater suitability for irrigation purposes and assessed the water requirements of cultivated crops to optimize the water supply in hyperarid climate regions. In total, 79 deep groundwater samples were hydrochemically tested to determine the suitability for irrigation by assessing the key water quality parameters. Spatial distribution maps of all chemical parameters, such as pH, EC, SAR, RSC, SSP, TDS, total hardness, Na^+, K^+, Ca^{++}, Mg^{++}, Fe, Mn, Cl^-, and $SO4^{--}$, were developed. The FAO CROPWAT 8.0 model, based on the Penman–Monteith equation, was used to forecast agricultural water requirements for three years, 2010, 2011, and 2012.
New hydrological insights for the region: The groundwater had medium salinity and low sodium in 84% of the cases. In comparison, high salinity was found in 16% of the samples, indicating that groundwater can be used for many soil types with a low risk of exchangeable sodium. Except for 15 of the 79 wells, all groundwater samples had chloride concentrations less than 100 mg/l. The sulfate ion distribution map showed a low sulfate ion content in the extreme western south. The total annual irrigation water requirements of all crops for 2010, 2011 and 2012 were 199.4, 215.1, and 231.7 million m^3/year, respectively, reflecting a gradual increase of approximately 16.57 million m^3/total area/year due to the expansion of the cultivated area. The analysis showed that modern irrigation systems reduced the amount of irrigation water by 32% and increased the cultivated area by 45% compared to conventional irrigation methods. Severe groundwater depletion occurred during the dry season from March to July, which exacerbated the water stress

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in the study region. The results confirmed that the region is under water stress. Accordingly, water conservation is urgently recommended.

1. Introduction

Concerns about combining water saving technologies and the hydrochemical features of groundwater quality and quantity have arisen because of growing water demand and global scarcity issues. Owing to the lack of freshwater resources in Egypt's El-Kharga Oasis, there is a significant demand for the use of advanced and innovative water resource management techniques and technologies in the agricultural sector, which is Egypt's largest water user. The agricultural sector accounts for more than 86.8% of the total water use in Egypt (FAO, 2005) and more than 90% of the total water use in the study area. El-Kharga is one of Egypt's most important oases; it is a hyperarid location with hot, dry weather in the western desert, and it is part of the Saharan Nubian aquifer (Jahin and Gaber, 2011). With increasing acreage of crop growth and low water use efficiency, there is a high demand for new and advanced water resource management techniques as the agricultural sector develops (Al-Amoud et al., 2012). This demand may be met by calculating the region's agricultural irrigation water demand and evaluating the temporal features of irrigation water demand and cultivated areas under other irrigation water management scenarios. This research is critical to enhance water management for sustainable and long-term use. There is a crucial need for groundwater quantity, quality and sustainability studies for irrigation and drinking purposes (Gameh et al., 2014), especially in developing countries, which suffer from inconsistent information on irrigation water use. A few analyses have been carried out in El-Kharga to determine water quantity, quality, and sustainability for irrigation, drinking purposes, and water requirements for only a few individual crops, which is a barrier for assessing the whole water management system.

Groundwater assessment for drinking and irrigation has become necessary for present and future groundwater quality management (Gabr et al., 2021; Mehrazar et al., 2020; Sobeih et al., 2017). The quality of groundwater is nearly as important as its quantity. Groundwater quality must be evaluated before it can be exploited appropriately and sustained (Todd and Mays, 2004). Chemical analysis of water samples from different locations in a study area will provide a clear vision of the chemistry of irrigation water (Sadashivaiah et al., 2008). The chemical composition of groundwater is influenced by various factors, including rainfall quality and quantity, rock type, permeability, leakage or recharge, and land use. Groundwater hydrochemistry is influenced by a variety of hydrochemical processes to maintain equilibrium between rock and water interactions as well as the mixing of various fluids. Hydrochemistry research comprises a description of the components of groundwater and their interactions. All types of groundwater include some dissolved ions and are never totally pure. More than 90% of the dissolved solids in groundwater are accounted for by seven ions, mainly cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) and anions (HCO^{3-}, Cl^{-}, and SO_4^{2-}). The lithology, velocity and volume of groundwater flow, type of geochemical processes, salt solubility, and human activities are all variables that impact the concentration of dissolved ions in groundwater (Bhatt and Saklani, 1996; Karanth, 1987). Numerous studies have been conducted in different parts of the world to examine the suitability of groundwater for various uses using a variety of methodologies, e.g., (Berhe, 2020; Gauns et al., 2020; Singh et al., 2020). Many researchers have evaluated groundwater in different regions in Egypt, for example (Ismail et al., 2017; Ismaila et al., 2020; Ismail and El-Rawy, 2018; El-Rawy et al., 2019; Geriesh et al., 2019; Gabr et al., 2021).

The overuse of groundwater for agricultural purposes has resulted in a considerable drop in the water table during the previous two decades, necessitating an immediate and effective management plan (Moghazy and Kaluarachchi, 2020). Due to high consumption rates and overexploitation, the groundwater level in the northern half of the Kharga Oasis declined from 60 to 80 m below the earth and from 40 to 60 m in the southern part between 1967 and 2007 (Mekkawi et al., 2017). Additionally, the number of deep wells increased to 350 during the ten-year period from 2003 to 2013, and the reservoir water level dropped by more than 90 m (Dept. of water resources in Kharga, Personal Communication). It is challenging to meet crops' full water requirements to sustain optimum growth and yield in dry and semiarid locations. Consequently, determining ways to preserve optimal agricultural yields during water shortages is important. This challenge has prompted researchers to seek novel irrigation technologies, methods, and strategies to increase water efficiency (Hamdy et al., 2003). One of the most promising approaches for improving irrigation efficiency is controlled deficit irrigation systems. A second technique involves using modern irrigation systems, which enhance plant water application efficiency. Determining the water consumption of field crops in Egypt's dry environment under various irrigation systems may aid in the irrigation management of vital crops (Phene et al., 1993). Moreover, irrigation systems are a critical component in reducing water losses and increasing agricultural output productivity to satisfy future increases in food demand. However, to realize its full potential, the irrigation sector must be revived by implementing novel management practices and changing its control (Kawy and Abou El-Magd, 2013; Kawy and Darwish, 2014).

The FAO recommends the Penman–Monteith equation for estimating crop water requirements because it is a simple equation with a reliable physical basis. Ground observation data of the cropping pattern area, crop coefficient approach, and irrigation efficiency were integrated using the Penman–Monteith equation to predict irrigation water demand and crop water requirements for three consecutive years, 2010, 2011, and 2012. CROPWAT 8.0 is a decision support tool developed by the FAO's Land and Water Development Division, and all calculation procedures are based on two FAO publications,

(Doorenbos and Kassam, 1979; Allen et al., 1998). It is a software tool that calculates agricultural water needs. This research will establish the validity of available irrigation water and how much irrigation water management may assist in maintaining such a target region's limited water resources, enabling the future expansion of agricultural regions. This research was conducted to determine the suitability of water for irrigation purposes, temporal distributions of agricultural water requirements in the target area, the amount of annual irrigation, and monthly variation in irrigation water requirements based on three years of data. Our investigation also determined the efficiency of other scenarios for water conservation and addressed the future increase in food demand (Kawy and Abou El-Magd, 2013) to fulfill the demand of an increasing population (Allen et al., 2005).

The present study attempted to obtain a comprehensive understanding of groundwater hydrochemical development and assess the water quality conditions for irrigation based on detailed groundwater monitoring wells. In addition, it aimed to evaluate the spatiotemporal variation in reference and crop evapotranspiration of all cropping patterns and the trend of cultivation areas for both the applied and proposed irrigation systems during the study period. Our study marks the first time that an integrated study combining hydrochemical evaluation for water quality and crop water requirements of cultivated crops was conducted in this region to conserve precious water resources and assess the groundwater's quality and/or appropriateness for irrigation. This research is critical in helping to enhance water management for long-term use.

2. The study area

El-Kharga is located in the New Valley governate in the western desert of Egypt between latitudes 24° 00′ and 26° 00′ N and longitudes 30° 15′ and 30° 45′ E (Fig. 1). It consists of a depression approximately 2000 km long that spans 20–885 km wide. Its area is approximately 12,250 km^2. It is one of the significant oases in Egypt. A hyperarid region with hot, dry weather, it is the driest spot in the western desert and is arguably the driest spot on the planet (Salman et al., 2010). The New Valley governate receives less than 2 mm/year of rainfall; therefore, agriculture depends mainly on groundwater (Kuper and Kröpelin, 2006). Locally, the El-Kharga Oasis receives less than 0.1 mm/year of precipitation and lacks naturally occurring surface water, so groundwater is the only water resource (Younis et al., 2016). Despite high temperatures and significant evaporation rates, agriculture is essential for growth and accounts for a portion of the main Saharan Nubian aquifer. It is fully contained inside the Nubian Sandstone Aquifer System and covers the northern part of the Eastern Sahara. This oasis, known to ancient Egyptians as the 'Southern Oasis,' is the current capital of the new valley government and is the largest of Egypt's oases in the western desert, as shown in Fig. 1.

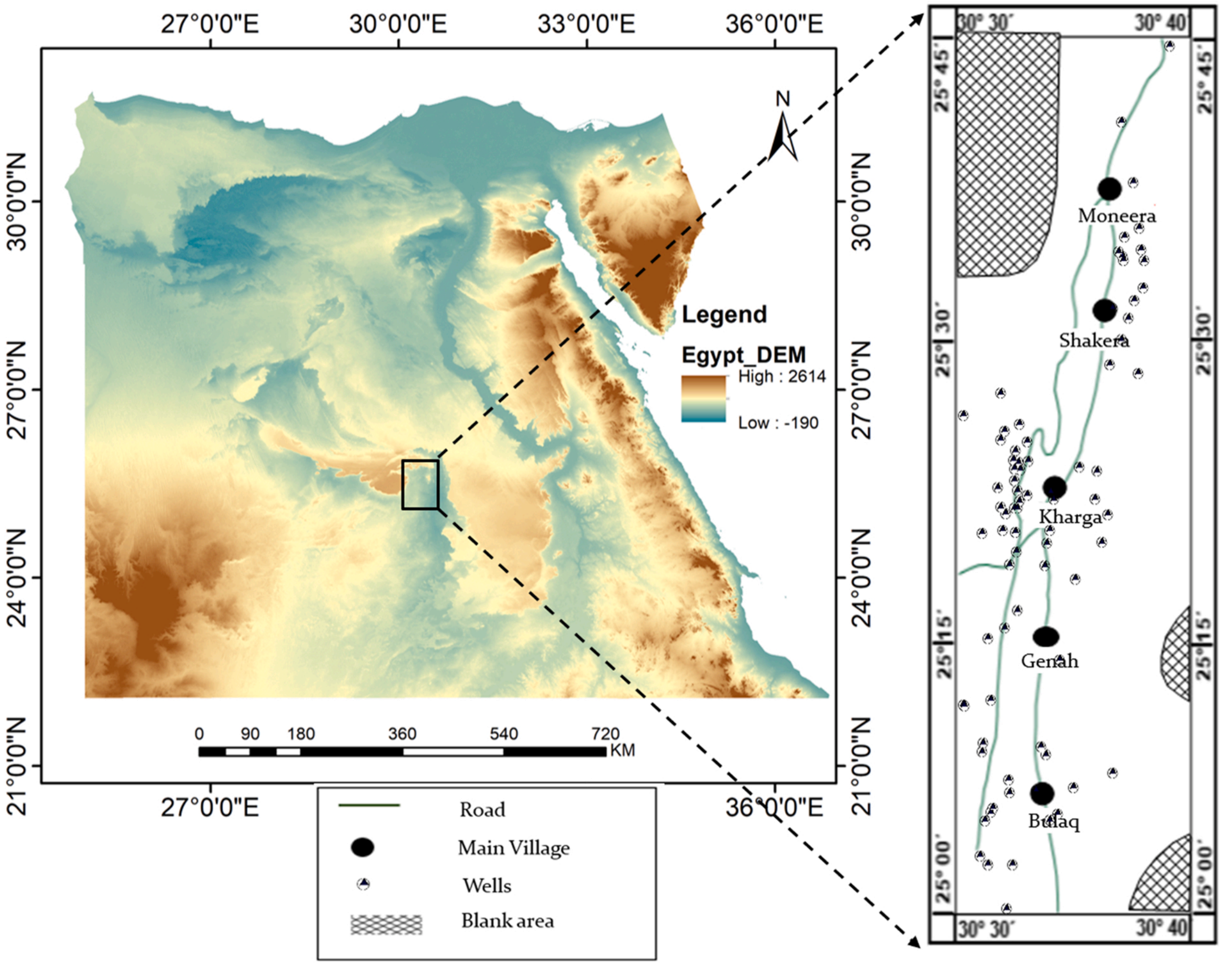

Fig. 1. Location map of the El-Kharga Oasis, showing the localities of groundwater samples (the dashed lines represent roads).

Due to water availability, the Kharga oases have been a magnet for humans since prehistoric times, as evidenced by the presence of hundreds of natural artesian springs, as well as the fertile soil represented by the deposits of the springs and the Playa sediments (dry paleolake deposits) (Bravard et al., 2016). However, since the beginning of the New Valley Project for agricultural reclamation in the 1950s, the Nubian sandstone aquifer has become depleted, as many wells were drilled and water was extracted industrially. Therefore, for the present study, we focused on the area located in the northern part of the Kharga depression between 25°00′ and 25°45′ N, where most agricultural lands are located (Fig. 1).

3. Materials and methods

3.1. Sampling and chemical analysis

Water samples from 79 wells were collected from 2010 to 2012 with 500-mL polyethylene bottles. Before sampling, the bottles were carefully cleaned two to three times with the groundwater obtained after being cleaned with deionized water and distilled water. The samples were collected only from continuously exploited wells. Chemical analyses of groundwater samples were performed to calculate the power of hydrogen (pH), conductivity (EC), total dissolved solids (TDS), and total hardness (TH). A pH meter was used to determine the pH, and the EC was measured in ds m^{-1} using an EC meter at 25 °C. The gravimetric technique was used to determine TDS concentration (Hussein and Magram, 2012). Spectrophotometric methods were used to quantify the content of sulfate (SO_4^{2-}) (American Public Health Association, 1998), whereas volumetric titration methods were used to estimate the concentrations of bicarbonate (HCO^{3-}), calcium ($Ca{++}$) and magnesium ($Mg{++}$) and chloride (Cl^-) concentrations (Maiti, 2004). A flame photometer was used to evaluate the soluble $Na+$ and $K+$ concentrations, and atomic absorption spectroscopy was used to assess the concentrations of trace elements such as Fe and Mn (Hasanien et al., 2010; Sayed, 2013). The locations of the groundwater samples are shown in Fig. 1.

Surfer 12 (Golden Software, LLC. https://www.goldensoftware.com) was used to produce a geographical distribution map of groundwater quality. The spatial interpolation scheme and visualization of the results were performed with Surfer using the kriging interpolation scheme. Piper trilinear diagrams (Piper, 1944) were used to compare the findings of chemical tests of groundwater using AquaChem v.2014.1 software (Waterloo Hydrogeologic https://www.waterloohydrogeologic.com) to understand the hydrochemical facies.

3.2. Groundwater origin and classification

Piper trilinear diagrams (Piper, 1944) are made up of three distinct fields, with two triangles on the lower right and the left sides of a diamond-shaped field in the middle. The major cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) are displayed in the bottom left triangle, while the major anions (SO_4^{2-}, CO_3^{2-}, HCO^{3-}, and Cl^-) are represented in the lower right triangle (Jahin and Gaber, 2011). The final water type is determined by plotting the two points indicating the diamond-shaped portion's principal cation and anion compositions. Based on the ionic composition of distinct water samples, Piper diagrams provide a straightforward way to identify water types obtained from various groundwater resources (Al-Omran et al., 2013; Aly et al., 2015).

3.3. Suitability of groundwater for irrigation purposes

The following are the key characteristics of groundwater that influence its suitability for irrigation.

3.3.1. Salinity hazard

In general, the total soluble salt content of irrigation water is determined by measuring its EC based on the flow of an electrical current through the sample.

3.3.2. Alkali hazard

The sodium adsorption ratio (SAR) indicates the alkali hazard. SAR is a metric used to calculate the sodium toxicity of irrigation water. A high SAR value implies that salt in water can replace calcium and magnesium ions in the soil, causing structural damage (Lloyd and Heathcote, 1985). Eq. (1) defines the SAR metric (Richards, 1969).

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}} \tag{1}$$

where all concentrations of Na, Ca and Mg are in meq/l.

3.3.3. Sodium percentage

The sodium content in irrigation water is also reported as a percentage of sodium or as a percentage of soluble sodium. Apart from directly impacting plant development, salts also affect soil structure, permeability, and aeration, all of which indirectly impact plant growth (Singh et al., 2008). Na % is calculated using equation (Eq. (2)).

$$Na\% = \frac{Na + K}{Ca + Mg + Na + K} \tag{2}$$

where all concentrations of Na, K, Ca, and Mg are in meq/l.

3.3.4. Residual Sodium Carbonate (RSC)

The RSC was computed to assess the effects of carbonate and bicarbonate on water quality for agricultural use (Aghazadeh and Mogaddam, 2010). In irrigated agriculture, RSC is employed as a measure of the anticipated residual carbonate in irrigation water. It is computed by subtracting the soluble calcium and magnesium values from the values of soluble carbonate and bicarbonate in milliliters. It can be computed using equation (Eq. (3)) (Eaton, 1950).

$$RSC\% = HCO_3 + CO_3 - (Ca^{++} + Mg^{++}) \tag{3}$$

where all concentrations of Na, Ca^{++} and Mg^{++} are in meq/l.

3.4. Crop water requirements

Even though there are numerous techniques for calculating crop and irrigation water requirements, the FAO recommends the Penman–Monteith approach. It is a simple equation coupled with ground observation data on the cropping pattern area, crop coefficient approach, and irrigation efficiency to predict irrigation water demand and crop water requirements for three consecutive years, 2010, 2011, and 2012, which offer the most recent available data.

The required data were collected and processed as follows:

a. Climatological and effective rainfall data were obtained from the Egyptian meteorological authority (Egyptian Ministry of Agriculture, 2012) for the El-Kharga Oasis, which include monthly minimum and maximum temperatures, humidity, wind speed, average sunshine duration, and effective rainfall per month.
b. Crop data and cropping patterns were provided by the (Egyptian Ministry of Agriculture, 2012) for three successive years (2010, 2011, and 2012). The tables include detailed data about each crop's cultivated areas (in Fadden). For each year, the data are classified into two seasons (winter and summer), with subtotals of three categories: crops, vegetables, and trees (perennial).
c. The cropping calendar contains the dates of planting (sow/transplanting) and harvesting (end-growth), which differed significantly among areas. The calendar was initially established based on (Egyptian Ministry of Agriculture, 2012) for the district of Upper Egypt to which El-Kharga meteorologically belonged and was based on a field survey conducted by agricultural research center staff members and public farmers in El-Kharga.
d. The length of the growth stages and single crop coefficient were reviewed using many sources to set the actual length of the growth stages of each crop; the primary source was Doorenbos (1977), based on (Allen et al. (1994). However, nonexistent crop coefficients such as that for okra were recorded according to (Doorenbos J, 1977), the crop coefficient for date palm was calculated according to an actual field study by (Kassem, 2007), which provided monthly crop coefficient (Kc) values for 2004 from which the average Kc during the three stages was calculated. Table 1 shows the average Kc of date palm for different growth stages (Kassem, 2007).
e. FAO CROPWAT 8.0 was used to process data on water amounts utilized for agricultural reasons to compute crop evapotranspiration, crop water needs, and irrigation water requirements from existing or new climatic and crop data based on irrigation efficiency. All calculation procedures used in CROPWAT 8.0 are based on the FAO guidelines established in Allen et al. (1998).
f. Reference evapotranspiration (ET_o) was estimated from meteorological data, aerodynamic and surface resistance according to FAO Penman Monteith (Allen et al., 1994) as follows:

$$ET_o = (0{\cdot}408\Delta\ (R_n\text{-}G) + \gamma\ 900/(T+273)\ u_2\ (e_s - e_a))/(\Delta + \gamma(1+0{\cdot}34\ u_2)) \tag{4}$$

where.

ET_o reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T mean daily air temperature at 2 m height [°C],
u_2 wind speed at 2 m height [m. S^{-1}],
e_s saturation vapor pressure [kPa],
e_a actual vapor pressure [kPa],
$e_s - e_a$ saturation vapor pressure deficit [kPa],
D slope of the vapor pressure curve [kPa °C^{-1}], and.

Table 1
Calculation of average Kc of date palm for different growth stages (Kassem, 2007).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
K_c	0.57	0.63	0.66	0.68	0.70	0.70	0.69	0.65	0.61	0.58	0.56	0.56
Growing stage	Initial				Middle						Late	
Growing Length (day)	140				180						45	
Average Kc	0.56				0.46						0.67	

γ psychrometric constant [kPa °C^{-1}].

$$IWR = ET_c / I_e \quad (6)$$

a. Crop evapotranspiration (ET_c)

The crop coefficient is used to link ET_o to the crop evapotranspiration ET_c to account for the influence of crop features on crop requirements. Crop coefficients generated from crop phenomenology phases may be successfully coupled to estimate crop water requirements (CWR). Combining crop coefficients with the crop pattern of the target region provides an individual calculation of each crop's water requirements. The efficiency of numerous irrigation techniques is then calculated to offer a realistic evaluation of overall agricultural water use on an annual time scale. The crop coefficient (K_c value) is related to the evapotranspiration of a disease-free crop produced across vast fields with optimal soil water, fertility, and maximum production potential under the given conditions. Thus, ET_c can be estimated according to the following relationship:

$$ET_c = ET_o \cdot K_c \quad (5)$$

b. The irrigation water requirement (IWR) was calculated from Eq. (6):where.

IWR = Irrigation water requirement,
ET_c = Crop evapotranspiration, and.
I_e = Field irrigation efficiency of the irrigation system.

According to (Jensen, 1980), irrigation efficiencies for sprinkler and drip irrigation systems are 75% and 90%, respectively. However, the irrigation efficiency of submerged crops, such as rice, is approximately 50% (Dastane, 1972; Doorenbos, 1977), and the surface irrigation efficiency is approximately 55%, according to Egyptian Ministry of Irrigation and Water Resources standards (Khedr et al., 2009).

4. Results and discussion

4.1. Hydrogen ion concentration (pH)

The pH values of the analyzed samples in the investigated area varied from 6.05 to 8.84, consistent with the findings of (Gameh et al., 2014; Jahin and Gaber, 2011), revealing that the groundwater samples were slightly acidic to alkaline and that no apparent setup

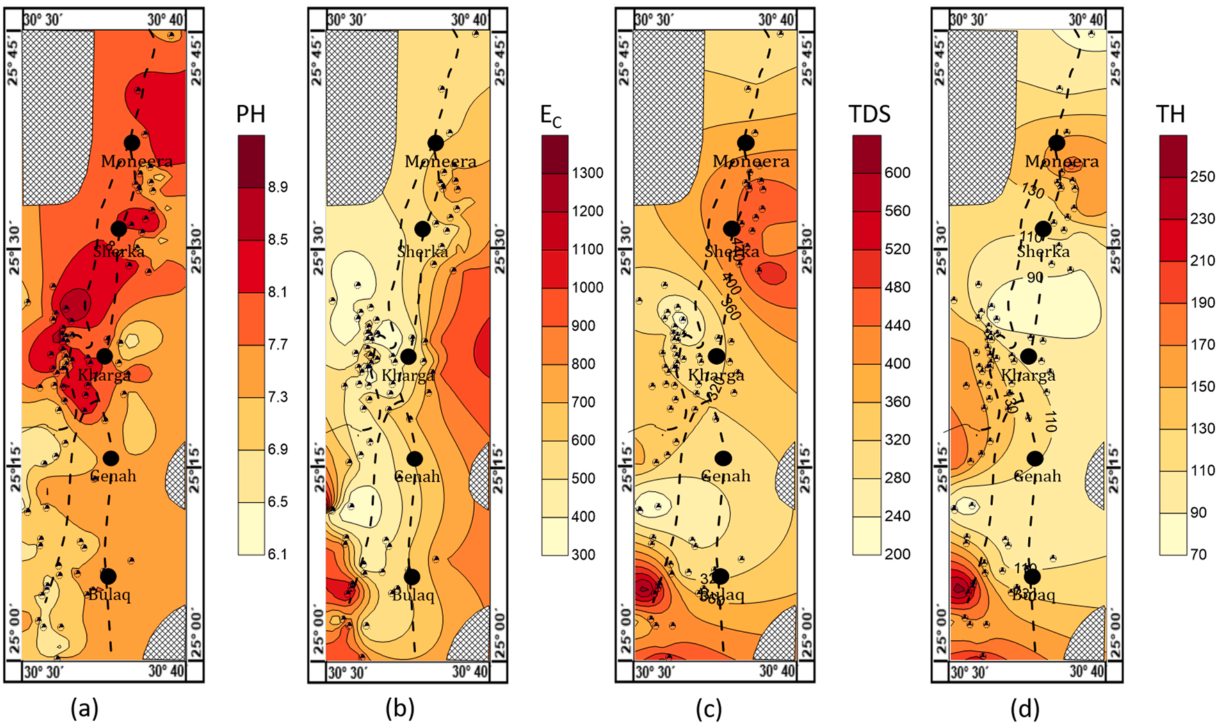

Fig. 2. Spatial distribution maps of a) pH, b) EC (μs/cm), c) TDS (mg/l), and d) TH (mg/l as $CaCO_3$) in groundwater wells across the study area (the dashed lines represent roads).

could control these values (Fig. 2a). In most cases, samples that exceed the maximum permitted level for irrigation purposes have no direct effect (WHO, 2008).

4.2. *Electrical Conductivity (EC) and Total Dissolved Solids (TDS)*

The EC values ranged between 310 μS/cm and 1400 μS/cm in the study region. The EC distribution map of the study area (Fig. 2b) shows that EC increases eastward of Kharga and to the west of both Genah and Bulaq. Relatively low salinity contents ranging from

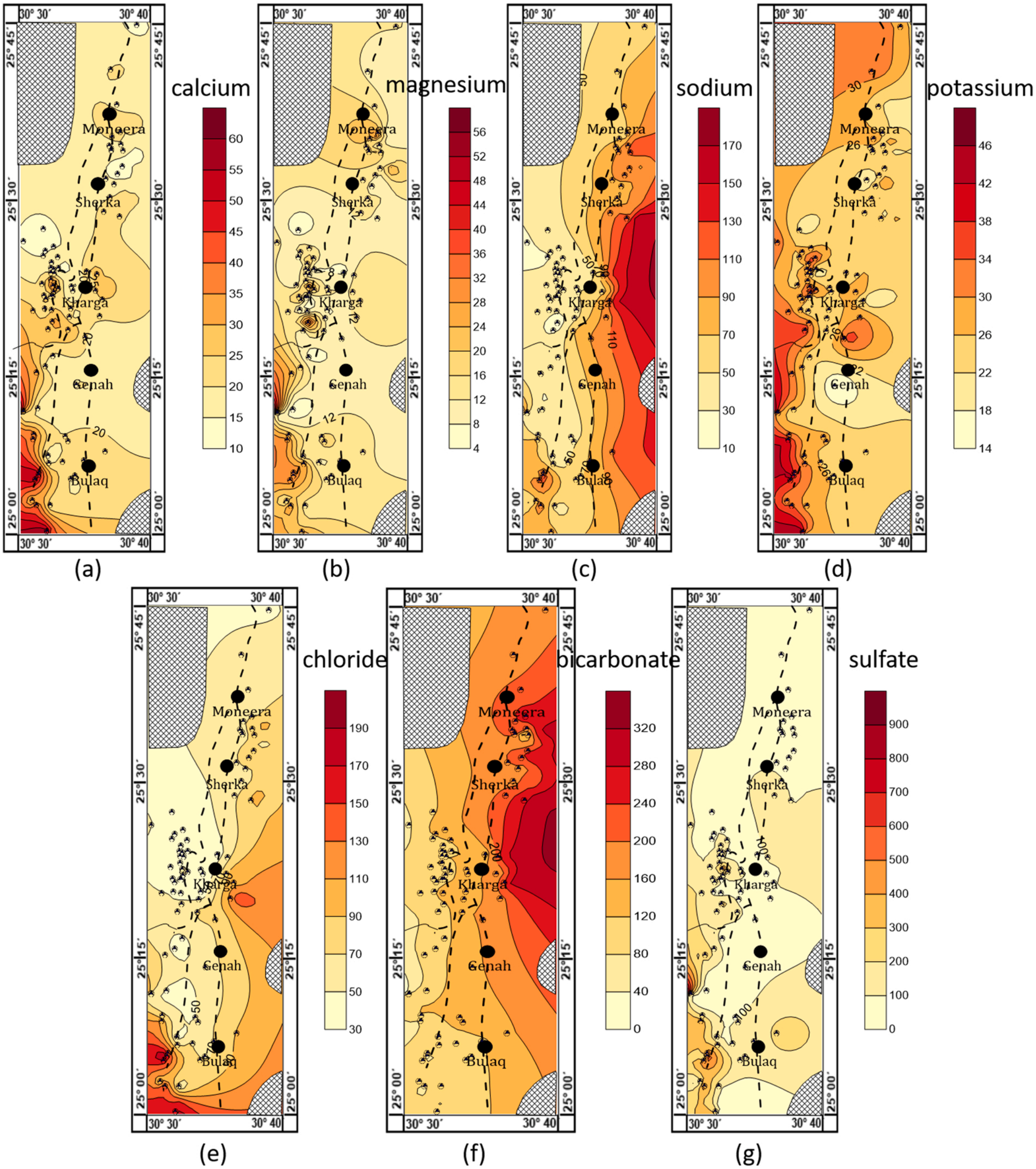

Fig. 3. Spatial distribution maps of a) calcium (mg/l), b) magnesium (mg/l), c) sodium (mg/l), d) potassium, e) chloride (mg/l), f) bicarbonate (mg/l), and g) sulfate (mg/l) in the groundwater wells in the study area (the dashed lines represent roads).

200 mg/l to 500 mg/l were recorded in the majority of production wells. A few samples located in the eastern part of Sherka, and in the western part of Bulaq had evaluated salinity contents ranging from 500 to 896 mg/l. This result agrees with that presented by (Jahin and Gaber, 2011). However, some groundwater samples' high conductivity (from 1060 to 1400 μS/cm) matched the highest concentrations of dominant ions due to the deterioration in water quality. Higher EC fluctuations might be linked to the research region's human activities and geochemical processes. Generally, our data show no problems resulting from salinity.

Total dissolved solids indicate the general state of groundwater quality and pollution levels (Munro and Travis, 1986; Robinove et al., 1958). The TDS value ranged from 198.4 mg/l to 896 mg/l. The TDS levels increased east of Sherka and west of Bulaq, according to the distribution map in Fig. 2c. Increased dissolved solids in irrigation water impact soil efficiency, plant growth, and yield. Salinization occurs when the amount of salts in the soil increases as the salinity of the water rises. The quantity of salts that plants absorb is governed mostly by the soil and plant types and the ease with which water can be drained. The TDS content of the groundwater samples in the study region showed that groundwater may be used for irrigation without problems, as the TDS levels in all samples were less than 1000 mg/l).

4.3. Total Hardness (TH)

Total hardness is an essential characteristic that indicates the quality of groundwater and is defined as the sum of calcium and magnesium cation concentrations reported in mg/l (WHO, 1996). The total hardness of the water samples collected in the research region ranged from 57 mg $CaCO_3$/l to 406 mg $CaCO_3$/l. TH was high only in the western portion of Bulaq, as shown in Fig. 2d. The high value for TH may be due to the presence of alkaline soil, such as calcium and magnesium.

4.4. Spatial distribution of major ions

4.4.1. Analysis of cations

Calcium is found naturally in water and most rocks, and it is easily dissolved in various forms in water. It is the most prevalent alkaline earth metal and may be found in a wide variety of common rock minerals. The calcium concentration ranged between 10.25 mg/l and 61.47 mg/l, as indicated on the distribution map of the calcium ions (Fig. 3a), with the lowest values found in the southwestern part of the study area. This result generally agrees with the finding of Jahin and Gaber (2011). Calcium-rich minerals include calcite, aragonite, dolomite, gypsum, anhydrite, fluorite, plagioclase, pyroxene, and amphibole (Skinner and Porter, 2006). Magnesium is also one of the common elements in rocks. Water becomes harder as a result of magnesium. The magnesium concentration ranged between 4.86 mg/l and 60.76 mg/l. The magnesium ion distribution map (Fig. 3b) shows that the lowest levels were observed in the middle of the study area. This result differed from the finding of (Jahin and Gaber, 2011). The higher levels discovered may be due to the collapse of the limestone plateau, which contains magnesium-bearing rocks such as dolomite ($Ca\,Mg\,(CO_3)_2$).

Sodium is the sixth most abundant element in the Earth's crust. The source of sodium in groundwater depends on the type of rock that the water passes through. The sodium concentrations in the groundwater of the investigated area ranged from 14.25 mg/l to 163.45 mg/l. The majority of the wells surveyed had modest levels of soluble sodium (Fig. 3c), with significant quantities in the east, notably in El-Kharga. High concentrations of sodium ($>$ 170 mg/l) may affect people with heart problems, hypertension, and certain other medical disorders. In addition, sodium may be detrimental to certain irrigated crops, but our findings indicate that sodium is not a concern.

The potassium concentration in the research region was low in all sampled wells except in the extreme southwestern region, where it ranged from 13.29 mg/l to 46.92 mg/l (Fig. 3d). In groundwater, ionic potassium is found in relatively low quantities, as potassium minerals resist weathering and dissolution (Sravanthi and Sudarshan, 1998).

4.4.2. Analysis of anions

Chloride is the most common major anion and is found in all types of water. It is a useful indicator of groundwater quality. Chloride is a key criterion for irrigation water since it is essential for plants and animals. Its concentration in natural groundwater is commonly less than 100 mg/l unless the water is brackish or saline (Fetter et al., 1999). The chloride content of groundwater samples in the study region ranged from 31.91 mg/L to 167.5 mg/l (Fig. 3e). Except for 15 of the 79 samples wells, all groundwater samples had chloride concentrations less than 100 mg/l. A high chloride content has a negative impact on taste and can cause corrosion. A considerable quantity of chloride can accumulate in leaves, causing the leaves to dry up (Jahin and Gaber, 2011). Chloride levels are low in ancient agricultural fields where surface water infiltration and dilution occur, and on the other hand, chloride in soil irrigated for a long time by water with higher chloride contents in areas with extreme evaporation and no precipitation. The majority of chloride in groundwater comes from four different sources: ancient sea water trapped in sediments, solutions of halite and related minerals in evaporated deposits, concentration by the evaporation of chlorides contributed by precipitation, and solutions of dry fallout from the atmosphere, particularly in arid regions (Daviest and Dewiest, 1966).

The decomposition of carbonate minerals such as calcite ($CaCO_3$) and dolomite ($CaMg\,(CO_3)_2$) produces the bulk of bicarbonate ions in groundwater. The bicarbonate content ranged between 12.2 mg/l and 308.15 mg/l in the study area. This composition diverged from the findings presented by Jahin and Gaber (2011), who showed that bicarbonate levels ranged from 78 mg/l in Boulaq to 282.3 mg/l in EI-Mounira. The minimum value was recorded in the western and southern parts of the study area, but the maximum value, especially in the eastern zone, was found to result from the dissolution of carbonate rocks (Fig. 3f). Bicarbonate ions in groundwater are generated by carbon dioxide in the atmosphere, soils, and the breakdown of carbonate rock (Daviest and Dewiest, 1966). The high concentration of HCO_3^- in this aquifer suggests active chemical weathering processes. Natural activities such as the dissolution of carbonate minerals and the release of CO2 gas from the soil might be a source of HCO_3^- in quaternary aquifer groundwater.

The major sources of sulfate in natural groundwater are gypsum and anhydrite. The sulfate content in ordinary groundwater is generally less than 300 mg/l. The sulfate levels in the study area ranged from 19.21 mg/l to 992.3 mg/l, contradicting the conclusions of (Jahin and Gaber, 2011). The sulfate ion distribution map (Fig. 3g) shows that the area's low sulfate ion content was found in the extreme southwest. Higher sulfate levels in wells on newly reclaimed land could be due to gypsum and potassium sulfates being transferred into the soil as fertilizers dissolved.

4.5. Distribution of minor elements

4.5.1. Iron

The amount of iron in the groundwater in the study area ranged between 0.42 and 3.98 mg/l. the results show a steady rise in iron content in the western parts of the research area As shown in Fig. 4a.

A high concentration of iron is produced by the dissolution of iron-bearing deposits rich in minerals. The pH of groundwater is important because it influences the solubility and biological availability of iron once it has dissolved. The pH levels of groundwater samples are plotted in Fig. 2a, which shows that the pH ranged from 6.05 to 8.84. These findings are similar to those of (Sayed, 2013), who utilized 34 groundwater samples in the same research region to create a kriged 3D surface and contour map of iron distribution. The iron and pH value relationship shows that the iron concentration increases as the pH value decreases. A pH below 6.05 encourages

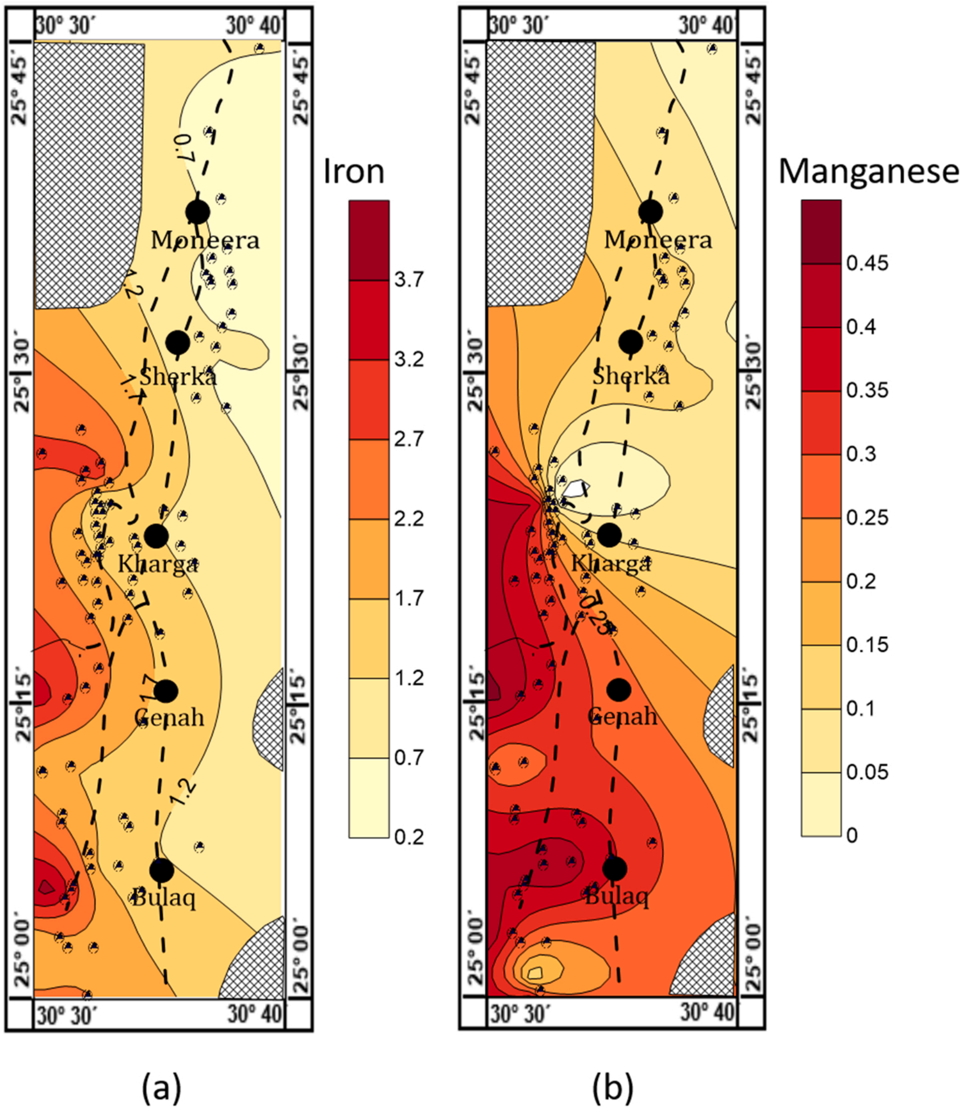

Fig. 4. Spatial distribution maps of a) iron (mg/l) and b) manganese (mg/l) (the dashed lines represent roads).

the formation of iron deposits in solution, which can lead to corrosion. When the pH is higher than 8.5, scaling and encrustation are more likely to develop. If other ions, such as calcium or carbonate, are present, they produce a variety of precipitates that mix with the iron hydroxide precipitates, forming a crusty, gnarled layer that is difficult to remove. The pH values ranged from 6.5 to 8.84, creating a suitable environment for the growth of iron bacteria in a well or water system during drilling, repair, or maintenance (Gad et al., 2016). Once a well is highly infected, the removal of iron bacteria may be exceedingly difficult (Wilson et al., 1999). Bacteria convert soluble ferrous iron into insoluble ferric iron, the formation of ochre, and bacterial slimes, which can clog well intake screens, as well as drip irrigation system filters, laterals, and emitters.

4.5.2. Manganese

Manganese is similar to iron in terms of chemical behavior and natural water occurrence. As shown in Fig. 4b, the manganese concentration of the groundwater in the investigated region ranged from 0 to 0.46 mg/l, with higher concentrations in the south and west. Minor element levels (F, Cu, Mn, Zn, Cd, and Pb) in the groundwater samples were all within permissible limits.

4.6. Ion dominance and water types

Ions in the groundwater samples are ranked in Appendix Table A1 according to Schoeller's (1962) semilogarithmic graphs. The following ranking was found in the majority of the water samples: (Na^{+}>Ca^{++}> Mg^{++})/(HCO3^{-}> SO4^{-}>Cl^{-}), (Na^{+}>Ca^{++}> Mg^{++})/(SO4^{-}>HCO_3^{-}>Cl^{-}), and (Na^{+}>Ca^{++}> Mg^{++})/(HCO_3^{-}>Cl^{-}>SO4^{-}). In the majority of the samples, higher sodium levels relative to calcium and magnesium as cations and higher bicarbonate levels relative to sulfate and chloride as anions reflect the dominance of sodium bicarbonate in sodium sulfate and sodium chloride water types. This outcome is not the same as that reported in (Abdelhafez et al., 2021), whose research areas included El-Kharga, Baris, and El-Dakhla. In their study, sulfate was the primary anion, whereas

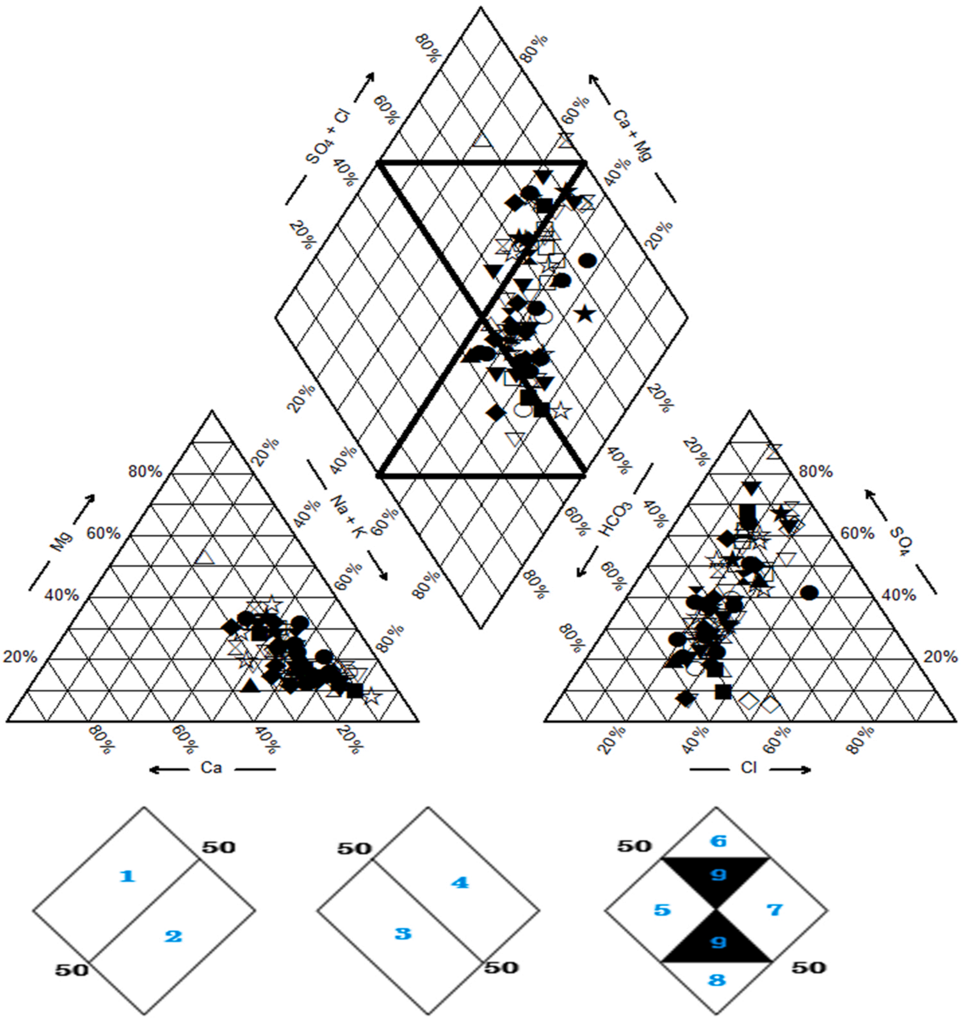

Fig. 5. Piper trilinear diagram assessment of groundwater in the study area.

Ca^{++} was the main cation. The highest concentrations of Ca^{++} were found in El-Dakhla, while the lowest concentrations were found in El-Kharga. This distribution indicates that carbonate, sulfate, and chloride minerals in aquifer media are actively leached and dissolved. However, our results are comparable to the findings presented by (Gad et al., 2016).

4.7. Groundwater origin and classification

Piper diagrams were used to illustrate the findings of the examined samples (Fig. 5). In the majority of samples, alkali ions (Na^+ and K^+) predominated over alkaline earth ions (Ca^{2+} and Mg^{2+}), while strong acids (Cl^- and SO_4^{2-}) predominated over weak acids (CO_3^{2-}, HCO_3^-). As demonstrated in Appendix Table A2, only a few samples exhibited the opposite behavior, with alkaline earth (Ca^{2+} and Mg^{2+}) exceeding alkali (Na+ and K+) ions and weak acids (CO_3^{2-}, HCO_3^-) exceeding strong acids (Cl^- and SO_4^{2-}) according to the chemical data. The water type in the region fluctuated mostly between Na-HC03 and Na-Cl (Piper diagram). According to the cation distribution, the samples ranged in composition from sodium/potassium to mostly mixed cations (Jahin and Gaber, 2011). Magnesium cations were present in a small fraction of the groundwater samples.

4.8. Quality assessment for irrigation purposes

4.8.1. Salinity hazard

The conductivity levels ranged between 310 and 1400 s/cm. Water with an EC of less than 750 s/cm is appropriate for irrigation in terms of the salt content (Staff, 1954). EC is a good predictor of crop salinity hazards. Excessive salinity reduces osmotic activity in plants, preventing them from absorbing water and nutrients from the soil (Saleh et al., 1999). Under normal conditions, 15 of the 79 samples had a high salt content, making them unsuitable for irrigation, as shown in Appendix Table A3. The leaching and dissolution of marine sediments with fresh water, either from irrigation, rain, or vertical upward flows from the underlying aquifers, dictated salinity changes.

4.8.2. Alkali hazard

The frequency of elevated SAR in 79 groundwater samples, as well as the appropriateness of the groundwater for irrigation, was examined as seen in Fig. 6, the lowest SAR value was 0.40, and the highest was 8.50. According to FAO recommendations, the sampled groundwater wells posed no sodium risk to irrigated land and can be used to irrigate any crop, including those that are sodium-sensitive, such as citrus. The distribution map of SAR (meq/l) for groundwater wells in the study area is shown in Fig. 7. Staff (1954) developed a technique for categorizing irrigation water to demonstrate the link between SAR and EC, as indicated in Appendix Table A4.

The El-Kharga Oasis water samples were classified as medium, high, or extremely high salinity hazards. The majority of the

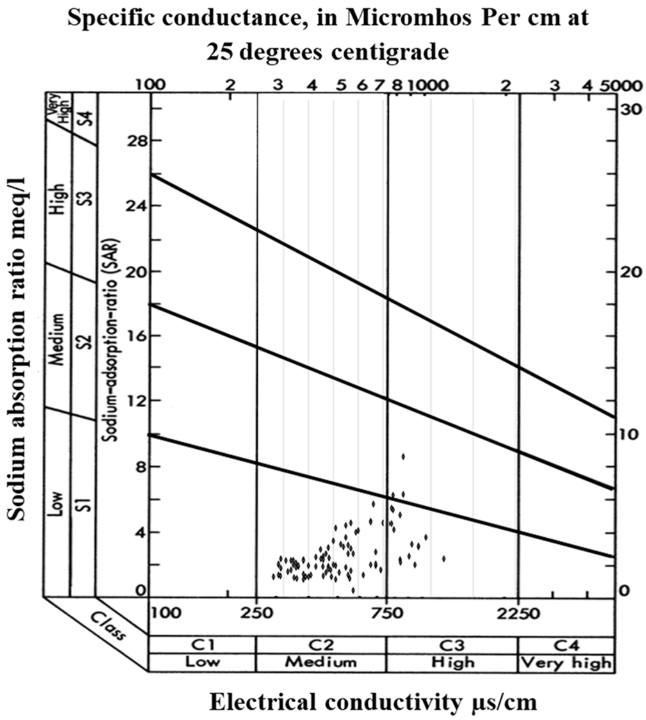

Fig. 6. Quality of groundwater for irrigation in relation to electrical conductivity in μs/cm and the sodium absorption ratio in meq/L (Staff, 1954).

groundwater samples had salinity hazards ranging from medium (C2) to high (C3). SAR was classified into four categories: low (less than 10), medium (10–18 (meq/l)), high (18–26 (meq/l)), and very high (more than 26 (meq/l)). All of the samples were in the 1.1–5.29 range. Therefore, the estimated SAR values in the study region were classified as low. These findings are in line with those

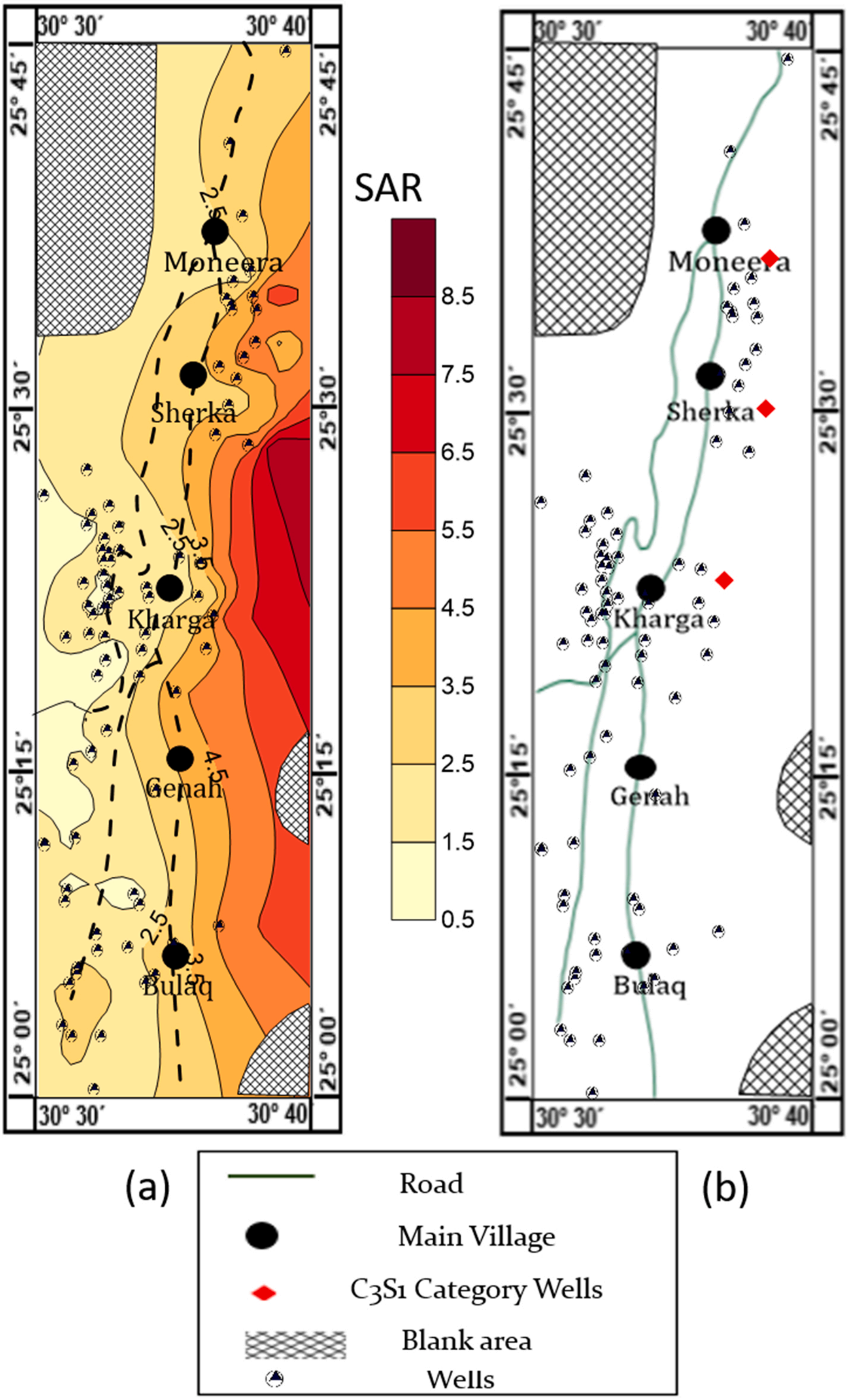

Fig. 7. a) SAR (meq/l) distribution map of groundwater wells in the study area and b) locations of the C3S1 category wells (the dashed lines represent roads).

presented by Yousefi et al. (2018).

Consequently, 64 out of 79 samples (81%) were classified as the C2S1 group, suggesting a medium salinity/low sodium groundwater type. The remaining 15 samples were classified as C3S1 (high salinity/low sodium), accounting for 19% of the total. In most situations, groundwater with a medium salinity hazard rating (C2) may be used without additional salinity management procedures. Water samples that fall into the high salinity hazard class (C3), on the other hand, may have negative impacts on sensitive crops and numerous plants. Such regions require cautious management (shown in Fig. 7a).

Under normal conditions, very high salinity water (C4) is unsuitable for irrigation. If the salts are not leached from the root zone, they will accumulate in quantities that prevent most crops from growing. However, salt accumulation may be utilized occasionally under very specific management methods; for example, soils must be permeable, drainage must be adequate to good, and irrigation water must be provided in excess to allow for significant leaching. It might also be utilized for salt-tolerant plants growing in permeable soils. Salt accumulation on the exchange complex, as in sodic soils, can be reduced by applying appropriate amounts of amendments, such as gypsum. The localities of the C3S1 categories highlight the hazard of groundwater in these areas, as illustrated in Fig. 7b.

4.8.3. Sodium percentage

Appendix Table A5 shows that the sodium percentage in the study region ranged from 39% to 76%. Twenty percent of the groundwater was determined to be unsuitable for irrigation or required special management practices such as salt-resistant plantations. As sodium increases the hardness of the soil while decreasing its permeability, the sodium content is an important factor determining the quality of irrigation groundwater (Tijani, 1994).

4.8.4. Residual Sodium Carbonate (RSC)

According to (Staff, 1954), water with an RSC value less than 1.25 meq/l is appropriate for irrigation and is considered safe. A value of 1.25–2.5 meq/l is considered marginal, while a value higher than 2.5 meq/l is considered unsuitable for irrigation. The RSC values for the groundwater samples in this research are shown in Appendix Table A6. Based on these RSC values, 82% of the sampled groundwater wells were categorized as class one (RSC< 1.25 meq/l), which is regarded as safe and acceptable for all forms of soil irrigation. Approximately 11.4% of the groundwater wells were classified as class two (1.25–2.5 meq/l), which is considered marginal and can be used in well-drained soils. Approximately 6.3% of the sampled wells were classified as class three (>2.5 meq/l), which is considered unsuitable, especially in soil with low calcium and poor drainage, according to the FAO limits (shown in Appendix Table A6).

When the soil solution concentrates under drying circumstances, bicarbonate and carbonate ions coupled with calcium or magnesium precipitate as calcium carbonate ($CaCO_3$) or magnesium carbonate ($MgCO_3$). When Ca^{2+} and Mg^{2+} concentrations fall below those of Na+ , the SAR index rises, resulting in an alkalizing action and a rise in pH, which reduce water permeability and have a detrimental impact on the soil structure (Zaman et al., 2018). Low-quality water was present in the eastern parts of the El Moneera, Shareka, and Kharga villages. Consequently, as part of the water management system, only crops that can withstand high salt should be assigned to these areas (Staff, 1954), which are influenced by geochemical processes, salt solubility, and human activities (Narsimha and Sudarshan, 2013).

4.9. Reference evapotranspiration (ETo)

ETo was calculated using CROPWAT, as shown in Fig. 8. There was a large gap between the high reference values of evapotranspiration during summer months, i.e., Jun. (12.04 mm/day), Jul. (10.61 mm/day), May (10.60 mm/day), Aug. (9.93 mm/day) and Sep. (9.36 mm/day), which were more than three times higher than the low values during winter months, i.e., Jan. 3.74 mm/day, Dec. (3.92 mm/day), Feb. (4.85 mm/day) and Nov. (5.47 mm/day), causing an extreme variation in reference evapotranspiration during the year.

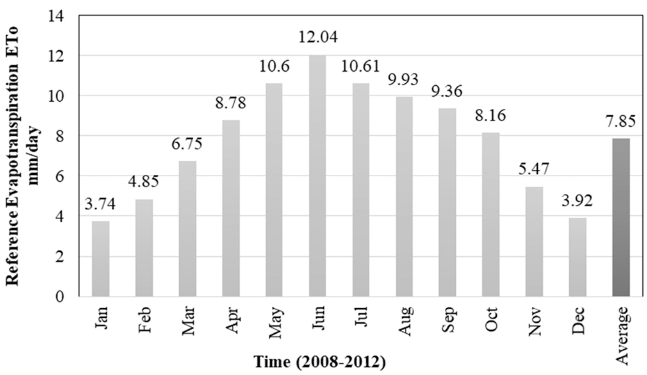

Fig. 8. Average reference evapotranspiration (ETo) of the El-Kharga oasis from 2008 to 2012.

4.10. Crop evapotranspiration and crop water requirements (CWR)

Crop evapotranspiration was estimated for all crops in the El-Kharga cropping pattern by providing CROPWAT with the three data modules: climate, rain, and crop data. The effective rainfall was approximately zero during the previous five years; therefore, the CWR was equal to the crop evapotranspiration. Some crops, particularly forages with several cutting cycles, were split into two or more modules for each growing stage. Fig. 9 demonstrates an accurate assessment of the CWR of all crops included in the El-Kharga cropping pattern with a limited time resolution (10 days). This figure shows that crops with the highest water consumption were alfalfa (perennial), Napier grass, and rice, with annual CWRs of 1926, 1836, and 1720 mm, respectively, while the crop with the lowest water consumption was peas, with an annual CWR of 384 mm. However, this analysis may be misleading because growing duration and growing season play an important role in the total annual CWR.

Another scale, based on the average daily CWR, was created (Fig. 10). This scale appears to be the most dependable and equitable. Rice, sweet maize, and ground nut had the greatest water consumption, i.e., 60.207, 37.811, and 34.614 m3/fed/day, respectively. These findings pose an important consideration for administrative authorities when implementing a water conservation policy.

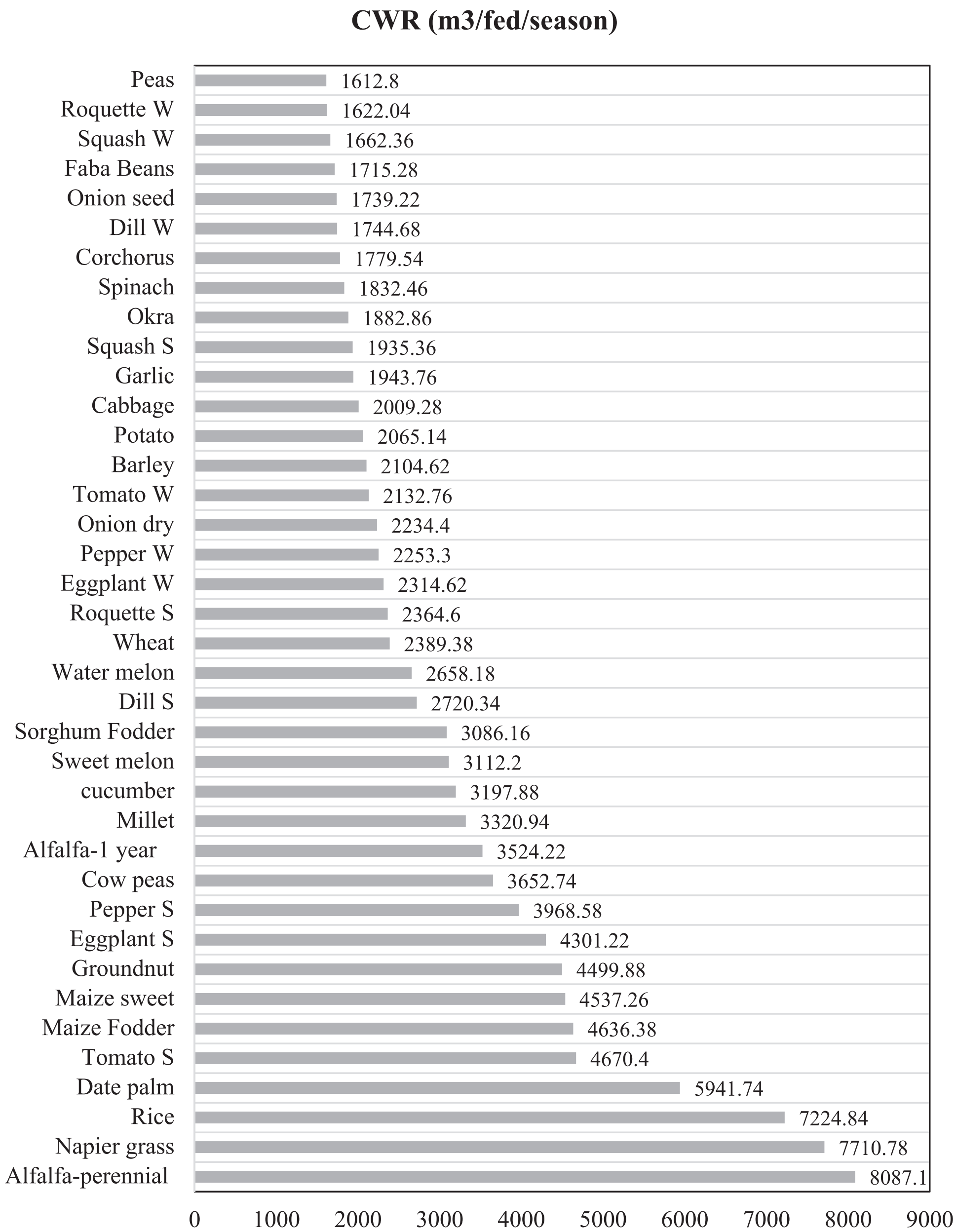

Fig. 9. Annual CWR of El-Kharga crops in m3/fed/season.

4.11. Calculation and temporal variation of IWR under the applied irrigation methods

The irrigation water requirement (IWR) was calculated for all crops from 2010 to 2012 under the applied irrigation method (surface irrigation) per period to generate an accurate configuration of the total IWR of El-Kharga, as shown in Appendix A7, Fig. 11.

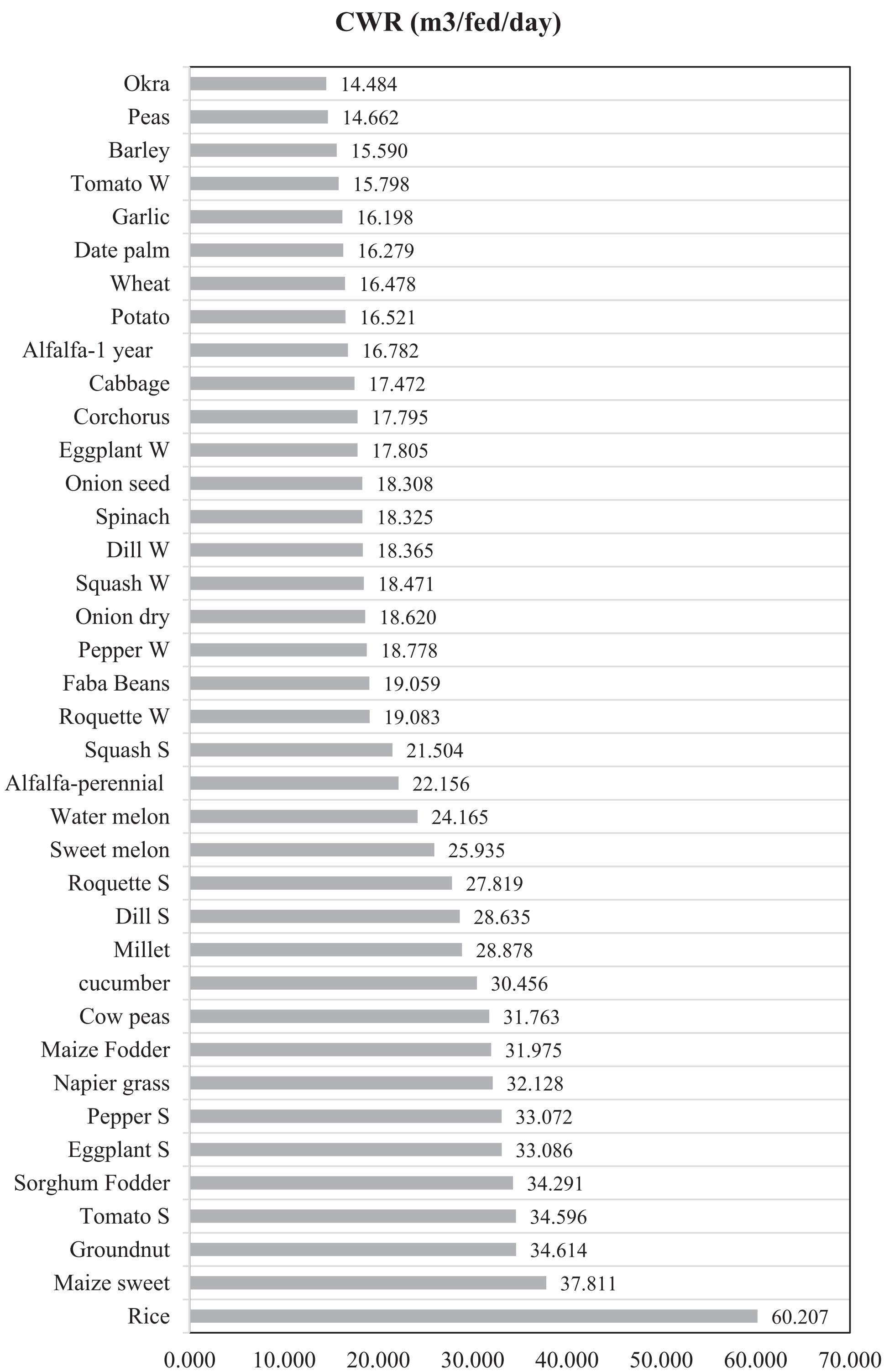

Fig. 10. CWR of El-Kharga crops in m3/fed/day.

The calculations of the yearly crop water requirements for the three years showed a generally comparable configuration and a gradual difference in terms of the water consumption trend. During crucial water-demanding months such as February, March, May, June, and July, the average monthly IWR was 16.735, 17.716, and 19.154 million m^3/total area/month in 2010, 2011 and 2012, respectively. This seasonal water scarcity exacerbated the water stress in the research area.

The IWR results over the three years, 2010, 2011, and 2012, showed that the highest demand was in March, June, and July, and the lowest demand was in September, November, and December. For instance, the IWR in March was 25.854, 26.154, and 28.037 million m3/total area/month in 2010, 2011, and 2012, respectively. This finding could be explained by the fact that March is one of the four highest months in terms of cultivated area, with 20123, 20502, and 21886 fed/month in 2010, 2011, and 2012. The ETo reported in March increased by 1.77 points from the previous month, i.e., 4.32–6.09. This increase was the greatest increase of the year. March is a transitional month between the winter and summer seasons; thus, certain summer crops may be planted sooner to escape the hot weather of the following months. It is also the planting date for a large number of summer crops, such as Napier grass, tomato, pepper, eggplant and cucumber.

The IWR in June was approximately 19.902, 23.837 and 25.460 million m3/total area/month in 2010, 2011 and 2012, respectively. Consequently, the highest ETo during the year was approximately 10.3 mm, even though the cultivated area in this month was slightly greater (by approximately 87 fed on average) than that in the previous month (May).

The IWR in July was approximately 19.700, 23.294 and 25.617 million m3/total area/month in 2010, 2011 and 2012, respectively, showing results similar to that in June, with a slight decrease in the average cultivated area of approximately 88 fed and of ETo, from 10.3 mm to 9.38 mm.

In September 2010, 2011, and 2012, the IWR was estimated to be 10.948, 11.566, and 12.740 million m3/total area/month, respectively. The reason for these estimates could be that September marks the end of the summer season, when, rather than perennial crops, only Napier grass and maize fodder are grown, which resulted in the lowest cultivated areas per month of 9697, 10211, and 10947 fed/month in 2010, 2011, and 2012, respectively, despite the highest rainfall during this month.

The IWR in December was approximately 11.754, 11.734 and 12.789 million m3/total area/month in 2010, 2011 and 2012, respectively. This result may have occurred because December represents a middle stage in the winter season, but all winter crops are cultivated in this month. For example, wheat, which occupied the highest amount of the cultivated area (an average of 26% of the total cultivated area in El-Kharga), and barley, which was cultivated in the second half of November, were cropped throughout the entire month of December, during which ETo was 3.51 mm.

The IWR in November was approximately 12.249, 12.386 and 13.365 million m3/total area/month in 2010, 2011 and 2012, respectively. The cropping of wheat and barley in the second half of this month caused a large difference in the cultivated areas between the first and third periods of approximately 963, 593 and 805 fed this month in 2010, 2011 and 2012, respectively, which decreased the average IWR in this month, and the ETo value was low, i.e., 4.85 mm.

4.12. Calculation and temporal variation of IWR under the suggested irrigation methods

The most appropriate irrigation systems for conserving irrigation water for all farming patterns in El-Kharga were identified for all crops in the target region, as shown in Table 2, in an earlier stage, and according to (Brouwer et al., 2014, 1996, 1988).

It is feasible to recalculate IWR by substituting the increased irrigation efficiency for the entire cropping pattern for the irrigation efficiency of the employed irrigation technology. This approach might offer an estimate of the IWR and the changes that would occur if these proposed irrigation strategies were used. The obtained findings for the years 2010, 2011, and 2012 showed that the IWR for the entire area (Fig. 12) with improved irrigation was approximately 135.5, 146.6, and 158.5 million m3/total area/year, respectively, whereas it was approximately 199.4, 215.1, and 231.7 using real irrigation techniques. An improvement in the irrigation system over the three years would save 63.9 (32.04%), 68.5 (31.85%), and 73.2 (31.59%) million m3/year, or an average of 32%.

4.13. Cultivated areas and their trends

The cultivated areas were computed for a short time series (10 days) using El-Kharga's calendar and cropping pattern, as shown in

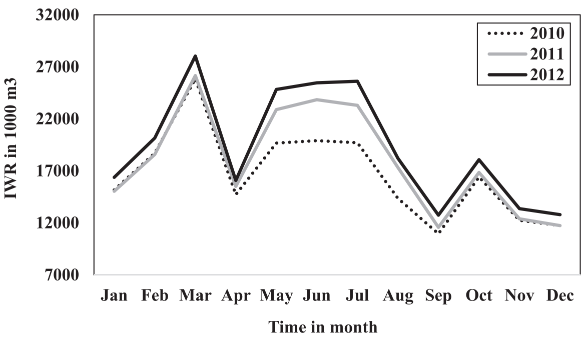

Fig. 11. The IWR of El-Kharga crops at 1000 m3/total area/month in 2010, 2011 and 2012.

Table 2
Suggested irrigation systems for the El-Kharga cropping pattern based on Brouwer et al. (1996, 2014).

Crop	Enhanced irrigation system	Crop	Enhanced irrigation system
Date palm	Drip	Cabbage	Drip
Alfalfa-perennial	sprinkler	Potato	Drip
Alfalfa-1 year	sprinkler	Garlic	Drip
Millet	sprinkler	Corchorus	sprinkler
Maize fodder	sprinkler	Okra	Drip
Sorghum fodder	sprinkler	Onion seed	Drip
Sweet maize	sprinkler	Onion dry	Drip
Cow peas	sprinkler	Pepper	Drip
Napier grass	sprinkler	Eggplant	Drip
Wheat	sprinkler	Spinach	Drip
Barley	sprinkler	Water melon	Drip
Faba beans	Drip	Sweet melon	Drip
Rice	gated pipe	Roquette	Drip
Tomato	Drip	Cucumber	Drip
Groundnut	Drip	Squash	Drip
Peas	Drip	Dill	Drip

Appendix Table A8. In general, according to average monthly estimates, the winter months (January, December, and February) had the greatest cultivated areas because the lowest ETo during these months allowed the available water resources to cover such large regions. The 2nd and 3rd periods of November, i.e., 22023, 22018, and 23916 feds in 2010, 2011, and 2012, respectively, covered most of the area ever recorded. This increase marked the highest increase in cultivated land, with the wheat cropping area accounting for approximately 26% of the total cultivated fields. According to this scale, the increase in the rate of cultivated areas during the 2010/2011 season was approximately zero, while it was approximately 1890 fed during the 2011/2012 season, a difference that could be attributed to a change in the cropping structure. Furthermore, the IWR was approximately the same during the 2010/2011 season but exhibited an increase of approximately 0.5 million m3 of water in 2011/2012. On the other hand, calculations according to the average monthly cultivated areas indicated an average annual increase of 766 fed in the 2010/2011 season and 1246 fed in the 2011/2012 season. Furthermore, the lowest cultivated area was recorded during the three periods of September, which represented the end of the summer season.

Based on the previously indicated calculation, the amount of irrigation water that might be saved by using the recommended irrigation methods is 32%. This savings might result in 45% cultivated area. The cultivated areas under the suggested irrigation techniques are illustrated in Fig. 13. Under the enhanced irrigation methods, the configuration of the new IWR was estimated to be 196.5, 212.6 and 229.8 million m3/year in 2010, 2011 and 2012, respectively, as shown in Appendix Table A9.

5. Discussion

The El-Kharga Oasis has a serious water imbalance problem due to unmanaged groundwater exploitation, little annual rainfall, quick evaporation and transpiration, and severe insolation. The current study focused on evaluating groundwater quality and quantity in the New Valley governorate, which is willing to reclaim the western desert and develop new urban areas, including reservoir water and its environment, which has recently been explored as a potential groundwater resource in the desert.

To classify the fitness of groundwater for irrigation, the values of TDS, SAR, RSC, EC, and sodium percentage were used, and it was discovered that groundwater was suitable for irrigation in the majority of the study area. The EC and SAR values of groundwater samples indicate that the majority of samples (84%) had medium salinity and low sodium, which could be used in most scenarios without special salinity management techniques. Furthermore, approximately 16% of the water samples had high salinity and low sodium, which can be used for almost any type of soil with little risk of sodium exchange. Groundwater salinization increased in 16% of samples from the eastern part of Sherka and the western part of Bulaq due to a decrease in sand content, an increase in shale with

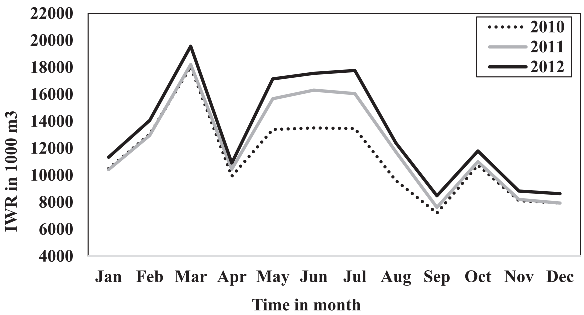

Fig. 12. The IWR of El-Kharga crops at 103 m3/total area/month under the enhanced irrigation system in 2010, 2011 and 2012.

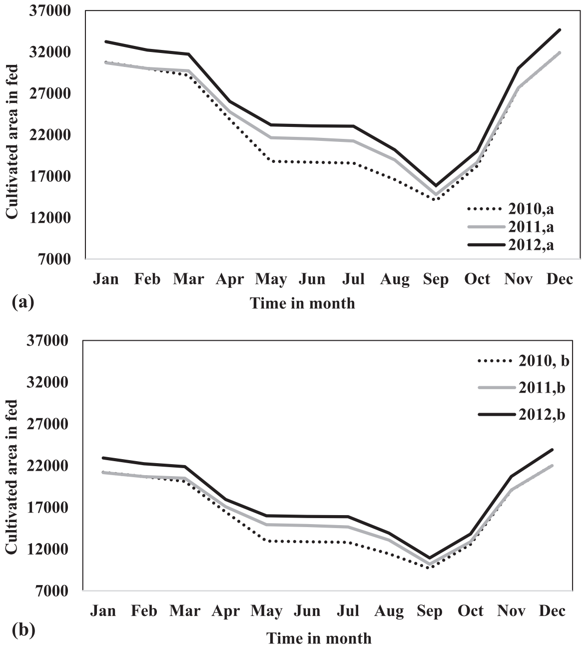

Fig. 13. Average monthly cultivated areas in El-Kharga in fed/month a) before and b) after the application of the suggested irrigation methods.

gypsum and evaporate bands in the aquifer, and a decrease in aquifer transmissivity, all of which increase salt leaching by slowing groundwater flow.

The lithology, velocity and volume of groundwater flow, type of geochemical processes, salt solubility, and human activities are all factors that influence dissolved ion concentrations in groundwater (Bhatt and Saklani, 1996; Karanth, 1987; Rao et al., 2017; Narsimha and Sudarshan, 2013) The majority of samples had more sodium than calcium and magnesium as cations and more bicarbonate than sulphate and chloride as anions, suggesting that sodium bicarbonate flows by means of sodium sulphate and sodium chloride water types. The lowest calcium values were found in the western and southwestern parts of the study area, the potassium concentration in the research region was low, and the majority of the studied wells contained low amounts of soluble sodium. The magnesium ion distribution map (Fig. 3b) showed that the lowest levels occurred in the center of the study area. The spatial distribution changes of magnesium ions in the groundwater wells showed an increase east of Kharga and west of both Genah and Bulaq. Relatively low salinity contents ranging from 200 mg/l to 500 mg/l were recorded in the majority of production wells, with only a few samples having relatively high salinity content. In general, this groundwater is a suitable source of irrigation water.

The general growing trend in irrigation demand in the studied region is attributable partly to changes in the cropping structure and partly to the growth of the farmed area. During 2010–2012, the annual water resource didn't meet the irrigation demand, and there was a significant shortage during some critical water-demanding months, such as March, June, July, and May, when the average monthly IWR in 2010, 2011, and 2012 was 16.618, 17.929, and 19.310 million m3/month, respectively. The average monthly water consumption rate was exceeded during these months. These analyses are necessary for groundwater conservation using optimized irrigation systems. This type of seasonal water scarcity exacerbated the water stress in the research area.

This study can serve as an authoritative reference that provides an accurate evaluation of the groundwater in the El-Kharga Oasis from a hydrochemical perspective to determine its suitability for irrigation, (2) estimate water consumption, and (3) assess the efficiency of water conservation under two main water management system scenarios. In addition, the findings can help decision makers evaluate the current water management system, using their authority to preserve water based on the present study. These strategies can be applied to better manage water resources at a regional scale and in areas with similar conditions. The continuous monitoring of groundwater quality/quantity aids in detecting any degradation in water quality and will allow decision makers to take the required steps to safeguard groundwater quality and regulate crop patterns and irrigation methods in accordance with the available water supply. It is strongly advised that a geographical survey be conducted to integrate these findings with remote sensing data to highlight problems and identify solutions, as well as to determine the optimum water management and irrigation strategies. The results of this study can contribute to the management of groundwater well extraction in response to spatiotemporal changes in quantity and quality under high demand for irrigation activities. In hyperarid environments, sensible water management measures such as water price control, crop planting pattern adjustment, legal and financial implementation incentives, and water conservation technology are urgently needed. Additionally, the study recommends the time series analysis of groundwater quality for future research with a longer time plan to assess groundwater temporal variations.

6. Conclusions

The El-Kharga Oasis is largely an agricultural area with limited groundwater resources, with agricultural water use accounting for more than 90% of total water use. The most significant element impacting water resources in the region is the distribution of water resources into socioeconomic sectors and ecosystems. Seventy-nine deep groundwater samples were chemically analyzed to evaluate their chemical composition and compatibility as an irrigation water source. According to our findings, 82% of the sampled groundwater wells were regarded as safe and acceptable for all forms of soil irrigation (e.g., RSC $<$1.25 meq/l). Special management measures, such as salt-resistant planting, were necessary for high salt samples. According to an old study (Chebotarev, 1955), all water samples in the study area were freshwater (i.e., 20 samples).

The results revealed that the total annual irrigation water needs of all crops increased in 2010, 2011, and 2012, reaching 199.4, 215.1, and 231.7 million m^3/year, respectively, indicating a steady increase in the irrigation water requirements of approximately 16.57 million m^3/total area/year. On the other hand, the largest cultivated areas ever recorded were 22023, 22018, and 23916 fed in 2010, 2011, and 2012, respectively, indicating an average annual expansion of 946 fed/year. This finding indicates decent growth in the crop growing area, leading to a rapid increase in the demand for irrigation water. Improving irrigation methods as part of effective water management, such as through the development of new irrigation technology, e.g., sprinkler and drip irrigation systems, would reduce costs and effort, increase benefits, and save irrigation water by approximately 32% compared to current irrigation methods. If irrigation efficiency improved in 2010, 2011, and 2012, the estimated irrigation water requirement for the entire target area could have been reduced to 135.5, 146.6, and 158.5 million m^3/total area/year, from 199.4, 215.1, and 231.7 million m^3/total area/year under actual irrigation methods, allowing for an expansion of the cultivated area. In other words, an improved irrigation water management system could have used available irrigation water to increase the maximum cultivation areas from 22020, 22013, and 23916 fed to 31929, 31919, and 34677 fed in December 2010, 2011, and 2012. Alternatively, optimized irrigation systems could have conserved groundwater, using the excess water made available by conservation irrigation practices and thus possibly eliminating the significant shortage during the high demand months and expanding agricultural land.

CRediT authorship contribution statement

Conceptualization: M.S., M.M., A.B.; **Methodology**: M.S, M.M; **Software and Validation**: M.S, M.M, **Formal analysis, Investigation, Data curation**: M.M, M.S, A.M.E: **Writing – original draft**: M.M, M.S; **Writing – review & editing**: M.S., M.M., A.B., A.M.E, A.M., A.S., S.A.K., T.S., T.H., A.H., **Visualization**: M.M, M.S, A.M.E, **Supervision**: M.S., A.B., A.M, **Project administration**: M.S., **Funding acquisition**: M.S., S.A.K., T.S.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101016.

References

Abdelhafez, A.A., Abbas, M.H.H., Kenawy, M.H.M., Noureldeen, A., Darwish, H., Ewis, A.M.G., Hamed, M.H., 2021. Evaluation of underground water quality for drinking and irrigation purposes in New Valley Governorate. Egypt. Environ. Technol. Innov. 22, 101486.
Aghazadeh, N., Mogaddam, A.A., 2010. Assessment of groundwater quality and its suitability for drinking and agricultural uses in the Oshnavieh Area, Northwest of Iran. J. Environ. Prot. 1, 30.
Al-Amoud, A.I., Mohammad, F.S., Al-Hamed, S.A., Alabdulkader, A.M., 2012. Reference evapotranspiration and date palm water use in the Kingdom of Saudi Arabia. Int. Res. J. Agric. Sci. Soil Sci. 2, 155–169.
Al-Omran, A.M., El-Maghraby, S.E., Aly, A.A., Al-Wabel, M.I., Al-Asmari, Z.A., Nadeem, M.E., 2013. Quality assessment of various bottled waters marketed in Saudi Arabia. Environ. Monit. Assess. 185, 6397–6406.
Allen, R.G., Smith, M., Perrier, A., Pereira, L.S., 1994. An update for the definition of reference evapotranspiration. ICID Bull. 43, 1–34.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome.
Allen, R.G., Tasumi, M., Morse, A., Trezza, R., 2005. A Landsat-based energy balance and evapotranspiration model in Western US water rights regulation and planning. Irrig. Drain. Syst. 19, 251–268.
Aly, A.A., Al-Omran, A.M., Alharby, M.M., 2015. The water quality index and hydrochemical characterization of groundwater resources in Hafar Albatin, Saudi Arabia. Arab. J. Geosci. 8, 4177–4190.
American Public Health Association, A., 1998. Standard methods for the examination of water and wastewater.
Munro, N.B., Travis, C.C., 1986. Drinking-water standards. Environ. Sci. & Technol. 20 (8), 768–769.
Berhe, B.A., 2020. Evaluation of groundwater and surface water quality suitability for drinking and agricultural purposes in Kombolcha town area, eastern Amhara region, Ethiopia. Appl. Water Sci. 10, 1–17.
Bhatt, K.P., Saklani, S., 1996. Hydrogeochemistry of the upper Ganges river, India. J. Geol. Soc. India 48, 171–182 (Online Arch. from Vol 1 to Vol 78).
Bravard, J., Mostafa, A., Garcier, R., Tallet, G., Ballet, P., Chevalier, Y., Tronchère, H., 2016. Rise and fall of an Egyptian oasis: Artesian flow, irrigation soils, and historical agricultural development in El-deir, Kharga Depression, western desert of Egypt. Geoarchaeology 31, 467–486.
Brouwer, C., Prins, K., Kay, M., Heibloem, M., 1988. Irrigation water management: irrigation methods. Train. Man 9, 5–7.
Brouwer, C., Prins, K., Kay, M., Heibloem, M., 1996. Irrigation Water Management: Irrigation Methods. Training Manual No 5. FAO Land and Water Development Division.
Brouwer, C., Prins, K., Kay, M., Heibloem, M., 2014. Irrigation Water Management: Irrigation Methods Training Manual No. 5. Food and Agriculture Organization of the United Nations.
Dastane, N.G., 1972. Effective Rainfall. FAO Irrig. Drain. Pap., Rome, p. 22.
Daviest, S.N., Dewiest, R.J.M., 1966. Hydrogeology. John Wiley and Sons Inc., NY.
Doorenbos, J., 1977. Guidelines for predicting crop water requirements. FAO Irrig. Drain. Pap. 24. FAO, Rome.
Doorenbos, J., Kassam, A., 1979. Yield response to water. FAO Irrigation and Drainage Paper 33. FAO, Rome.
Eaton, F.M., 1950. Significance of carbonates in irrigation waters. Soil Sci. 69, 123–134.
Egyptian Ministry of Agriculture, A. department (EMAAD), 2012. report of El-Kharga cropping pattern years of 2010, 2011 and 2012 El-Kharga.
El-Rawy, M., Ismail, E., Abdalla, O., 2019. Assessment of groundwater quality using GIS, hydrogeochemistry, and factor statistical analysis in Qena Governorate, Egypt. Desalin. Water Treat. 162, 14–29.
FAO , 2005. water report 29, P3; table2, [WWW Document]. URL 〈http://ftp.fao.org/agl/aglw/docs/wr29_eng.pdf〉.
Fetter, C.W., Boving, T.B., Kreamer, D.K., 1999. Contaminant Hydrogeology. Prentice hall, Upper Saddle River, NJ.
Gabr, M.E., Soussa, H., Fattouh, E., 2021. Groundwater quality evaluation for drinking and irrigation uses in Dayrout city Upper Egypt. Ain Shams Eng. J. 12, 327–340.
Gad, M., Dahab, K., Ibrahim, H., 2016. Impact of iron concentration as a result of groundwater exploitation on the Nubian sandstone aquifer in El Kharga Oasis, western desert, Egypt. NRIAG J. Astron. Geophys. 5, 216–237.
Gameh, M.A., Ebtehag, A.S., El-Habaak, G.H., Abdel-Moneim, M.M., 2014. Groundwater Potentiality and Suitability for Drinking and Irrigation in the New Valley, Western Desert, Egypt. In: Assiut J. Agric. Sci.,(45) No.(2)(113-124)(7th Conf of Young Scientists), Fac. of Agric. Assiut University, p. 2014 (April).
Gauns, A., Nagarajan, M., Lalitha, R., Baskar, M., 2020. GIS-based assessment of groundwater quality for drinking and irrigation by water quality index. Int. J. Curr. Microbiol. Appl. Sci. 9, 2361–2370.
Geriesh, M.H., Mansour, B.M.H., Farouk, H., 2019. Assessment of drinking water quality along Port Said Canal treatment plants, Suez Canal corridor. Egypt. Arab. J. Geosci. 12, 1–13.
Hamdy, A., Ragab, R., Scarascia-Mugnozza, E., 2003. Coping with water scarcity: water saving and increasing water productivity. Irrig. Drain. 52, 3–20.
Hasanien, G.H., Gameh, M.A., Talaat, A., 2010. Suitability of utilizing shallow groundwater in irrigating different soils in el Kharga oasis. Assiut Univ. Bull. Environ. Res 13, 27–46.
Hussein, M.H., Magram, S.F., 2012. Domestic water quality in Jeddah, Saudi Arabia. JKAU Eng. Sci. 23, 207–223 https://doi.org/10.4197.
Ismail, E., El-Rawy, M., 2018. Assessment of groundwater quality in West Sohag, Egypt. Desalin. Water Treat. 123, 101–108.
Ismail, E., El-Sayed, E., Sakr, S., Youssef, E., 2017. Characteristic of groundwater potentialities in west Nile Valley south, Minia governorate. Egypt. Arab. J. Geosci. 10, 1–12.
Ismaila, E., Zakia, R., Rapantovab, N., Licbinskab, M., Sharawia, H., 2020. Hydrogeochemical characteristics of the groundwater in the quaternary aquifer of western fringes of El-Minia Governorate, Egypt using an integration of geochemical modeling and geo-statistical techniques. Desalin. Water Treat. 189, 134–151.
Jahin, H.S., Gaber, S.E., 2011. Study of groundwater quality in El-Kharga Oasis, Western Desert, Egypt. Asian J. Water, Environ. Pollut. 8, 1–7.
Jensen, M.E., 1980. Design and Operation of Farm Irrigation Systems. American Society of Agricultural Engineers.
Karanth, K.R., 1987. Ground Water Assessment: Development and Management. Tata McGraw-Hill Education.
Kassem, M.A., 2007. Water requirements and crop coefficient of date palm trees Sukariah CV. Misr J. Agric. Eng. 24, 339–359.
Kawy, W.A.A., Abou El-Magd, I.H., 2013. Assessing crop water requirements on the bases of land suitability of the soils South El Farafra Oasis, Western Desert, Egypt. Arab. J. Geosci. 6, 2313–2328.
Kawy, W.A.A., Darwish, K.M., 2014. Assessment of optimum land use and water requirements for agricultural purpose in some soils South Paris Oasis, Western Desert, Egypt. Arab. J. Geosci. 7, 4043–4058.
Khedr, H.S.A., Meleha, M.I., Ghaly, F.A., Mosa, A.A., 2009. Using GIS for Mapping Water Requirements for Some Crops (Master Thesis). Kafr Elsheikh Univ.
Kuper, R., Kröpelin, S., 2006. Climate-controlled Holocene occupation in the Sahara: motor of Africa's evolution. Science 313, 803–807 (80-.).
Lloyd, J.W., Heathcote, J.A.A., 1985. Natural inorganic hydrochemistry in relation to ground water.
Maiti, S.K., 2004. Handbook of Methods in Environmental Studies: Water and Wastewater Analysis. ABD publishers.
Mehrazar, A., Bavani, A.R.M., Gohari, A., Mashal, M., Rahimikhoob, H., 2020. Adaptation of water resources system to water scarcity and climate change in the suburb area of megacities. Water Resour. Manag. 34, 3855–3877.
Mekkawi, M., Arafa-Hamed, T., Amatykul, P., Atya, M., Ogawa, Y., 2017. Three dimensional modelling of Kharga Reservoir Water, New Valley-Egypt, using magnetotelluric data. J. Geol. Geophys 7, 2.
Moghazy, N.H., Kaluarachchi, J.J., 2020. Assessment of groundwater resources in Siwa Oasis, Western Desert, Egypt. Alex. Eng. J. 59, 149–163.
Narsimha, A., Sudarshan, V., 2013. Hydrogeochemistry of groundwater in Basara area, adilabad district, Andhra Pradesh, India. J. Appl. Geochem. 15, 224–237.
Phene, C.J., Hutmacher, R.B., Ayers, J.E., Ben-Asher, J., 1993. Subsurface drip irrigation, A BMP for controlling drainage outflow and reducing groundwater contamination. In: Proceedings of Industrial and Agricultural Impacts on the Hydrologic Environment: The Second USA/CIS Joint Conference on Environmental Hydrology and Hydrogeology. Water Environment Federation, Alexandria, VA, p. c1993.
Piper, A.M., 1944. A graphic procedure in the geochemical interpretation of water-analyses. Eos Trans. Am. Geophys. Union 25, 914–928.
Rao, N.S., Marghade, D., Dinakar, A., Chandana, I., Sunitha, B., Ravindra, B., Balaji, T., 2017. Geochemical characteristics and controlling factors of chemical composition of groundwater in a part of Guntur district, Andhra Pradesh, India. Environ. Earth Sci. 76, 1–22.
Richards, L.A., 1969. Diagnosis and Improvement of Saline and Alkali Soils. United States Department Of Agriculture, Washington.
Robinove, C.J., Langford, R.H., Brookhart, J.W., 1958. Saline-Water Resources of North Dakota. US Government Printing Office.
Sadashivaiah, C., Ramakrishnaiah, C.R., Ranganna, G., 2008. Hydrochemical analysis and evaluation of groundwater quality in Tumkur Taluk, Karnataka State, India. Int. J. Environ. Res. Public Health 5, 158–164.
Saleh, A., Al-Ruwaih, F., Shehata, M., 1999. Hydrogeochemical processes operating within the main aquifers of Kuwait. J. Arid Environ. 42, 195–209.
Salman, A.B., Howari, F.M., El-Sankary, M.M., Wali, A.M., Saleh, M.M., 2010. Environmental impact and natural hazards on Kharga Oasis monumental sites, Western Desert of Egypt. J. Afr. Earth Sci. 58, 341–353.
Sayed E.A.A., 2013. the impact assessment of Iron in the drinking water of the New Valley, Egypt MA Thesis, 34–35p.

Singh, A.K., Mondal, G.C., Kumar, S., Singh, T.B., Tewary, B.K., Sinha, A., 2008. Major ion chemistry, weathering processes and water quality assessment in upper catchment of Damodar River basin, India. Environ. Geol. 54, 745–758.

Singh, K.K., Tewari, G., Kumar, S., 2020. Evaluation of groundwater quality for suitability of irrigation purposes: a case study in the Udham Singh Nagar, Uttarakhand. J. Chem. 2020.

Skinner, B.J., Porter, S.C., 2006. Physical Geology, Fourth ed. Wiley.

Sobeih, M.M., El-Arabi, N.E., Esam El Deen, Y.H., Awad, B.S., 2017. Management of water resources to control groundwater levels in the southern area of the western Nile delta. Egypt. Water Sci. 31, 137–150.

Sravanthi, K., Sudarshan, V., 1998. Geochemistry of groundwater, Nacharam industrial area, Ranga Reddy district, AP, India. Environ. Geochem. 1, 81–88.

Staff, U., 1954. United States Salinity Laboratory. Diagnosis Improv. saline alkali soils. US Dep. Agric, Washingt.

Tijani, M., 1994. Hydrogeochemical assessment of groundwater in Moro area, Kwara State, Nigeria. Environ. Geol. 24, 194–202.

Todd, D.K., Mays, L.W., 2004. Groundwater Hydrology. John Wiley & Sons.

WHO, 2008. World Health Organization Guidelines for Drinking Water Quality, (third ed.) (2008), Avenue Appia, 1211 Geneva 27, Switzerland.

WHO, 1996. Guidelines for Drinking Water Quality In: Heal. Criteria Other Support. Information, 2nd ed., vol. 2. World Heal. Organ, Geneva, Switz.

Wilson, A., Parrott, K., Ross, B., 1999. Iron and manganese in household water. Virginia Cooperative Extension. Publication, 356, p. 478 (4p).

Younis, A., Soliman, M., Moussa, S., Massoud, U., ElNabi, S.A., Attia, M., 2016. Integrated geophysical application to investigate groundwater potentiality of the shallow Nubian aquifer at northern Kharga, Western Desert, Egypt. NRIAG J. Astron. Geophys. 5, 186–198.

Yousefi, M., Saleh, H.N., Mahvi, A.H., Alimohammadi, M., Nabizadeh, R., Mohammadi, A.A., 2018. Data on corrosion and scaling potential of drinking water resources using stability indices in Jolfa, East Azerbaijan, Iran. Data Br. 16, 724–731.

Zaman, M., Shahid, S.A., Heng, L., 2018. Irrigation water quality. In: Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques. Springer, pp. 113–131.