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Hydrochemical Assessment of Groundwater Quality for Irrigation Using Hydrochemical Indicators and GIS in an Arid Coastal Aquifer: Sudr Area, South Sinai, Egypt

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ABSTRACT* : *Seawater intrusion (SWI) poses a significant threat to groundwater quality in coastal aquifers worldwide, impacting numerous regions across the globe. The objective of this study is to comprehensively evaluate the controlling factors of the Quaternary aquifer in the Sudr area of South Sinai, Egypt. The primary focus is to evaluate the suitability of groundwater quality for irrigation purposes by employing hydrochemical indicators and leveraging GIS technology. Accordingly, sixty groundwater samples were collected from the area to determine the physical and chemical parameters. The findings indicate that the high salinity values are reported in the west and north-west, while the values decrease towards the east near the main stream of Wadi Sudr. The Piper plot suggests that the main water types are Na-Cl, Ca-Cl, and Ca-Mg-Cl. Based on the evaluation using Salinity Diagram (USSL) and Doneen's diagram, a majority of the collected samples exhibit suitability for supporting plant species characterized by high salt tolerance. This conclusion is further supported by the results obtained from SAR, Na%, PI, PS, KI, and MH analysis. Moreover, the findings regarding Residual Sodium Carbonate (RSC) indicate that all groundwater samples are considered safe for irrigation purposes. This study serves as a valuable contribution to the monitoring of coastal aquifer groundwater quality, offering a valuable resource for policymakers and stakeholders.

KEYWORDS: Coastal aquifer; Hydrogeochemistry; Seawater intrusion; SAR; Irrigation; Sudr area

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I. INTRODUCTION

Groundwater is a primary source for irrigation in coastal aquifers. The excessive withdrawal of groundwater from these aquifers frequently surpasses the natural replenishment rate, resulting in a hydrodynamic and hydrochemical imbalance that subsequently initiates the intrusion of seawater laterally in the coastal area and the upward movement of saltwater inland (Tulipano et al., 2005; Custodio, 2010; Werner et al., 2013; Gleick et al., 2013; Mastrocicco and Colombani, 2021).

Salinization resulting from seawater encroachment in aquifers, exacerbated by over-extraction of groundwater (Walraevens et al., 1997; Custodio, 2002; Faye et al., 2005; Khayat et al., 2006; Steyl and Dennis, 2010). Approximately 40% of the global population resides within 100 kilometers of the coastlines, with this proportion expected to rise as a result of growing tourism, internal migration, and rapid population expansion (Agardy et al., 2005; Ferrario et al., 2014). The Quaternary aquifer consists of alluvial sediments and is expected to facilitate agricultural expansion in the Suez Gulf region (Abo Shaala, 2016). This aquifer is known for its high groundwater potential, making it the most productive aquifer in the Gulf of Suez Rift (Mills and Shata, 1989).

Seawater intrusion commonly leads to natural contamination of freshwater zones near the coast, thereby impacting water quality (Askri et al., 2016; Bouzourra et al., 2015). Moreover, Groundwater over-extraction in South Sinai Peninsula, especially in Ras Sudr coastal aquifer, has led to significant salinization of groundwater (Awwad et al., 2008; El-Fiky, 2010; Isawi et al., 2016; Eissa et al., 2016). The hydrochemical analysis provides valuable insights into the groundwater's quality (Selvam et al., 2013).

To maintain current agricultural production and protect sensitive crops, it is essential to ensure that the water quality for irrigation purposes is of high standard (Barua et al., 2021). So, regular monitoring of groundwater quality is essential and should be conducted consistently (Khan et al., 2020). In numerous foreign countries, various researchers have undertaken studies focusing on evaluating groundwater quality through the use of different irrigational indices (Srivastava, 2019; Aziane et al., 2020; Ben Moussa et al., 2021; Eldaw et al., 2021; Gabr et al., 2021; Hekmatnia et al., 2021; Kadam et al., 2021; Zafar et al., 2022).

Several studies have been conducted to assess the status of the Sudr aquifer (Garamoon, 1987; Morad, 2000; Said, 2004; Abdel-Latief and Al-Temamy, 2008; El-Bihery, 2009; El-Fiky, 2010; Hussien, 2015; Zarif et al., 2021; Ibrahim et al., 2021).

The prime objectives of this work are to i) understand spatial distribution variations of major ions and salinity by GIS ii) hydrochemical processes prevailing in the region iii) assess groundwater quality in Sudr area and suitability for irrigation. This work will help decision-makers and stakeholders to monitor the aquifer for good groundwater quality.

Study area

The Sudr area is located in the southwest region of Sinai Peninsula on the eastern side of the Suez Gulf, between latitudes 29°42'57.99" to 29°36'11.99"N and longitudes 32°41'53.99" to 32°43'21.39"E (Fig. 1). This area is a delta of two watersheds: Wadi Sudr (743 km^2) and Wadi Lahata (260 km^2). This location can be easily reached from the city of Suez to the north via the El Tor coastal highway to the south or through the Sudr El Hitan Mountain paved road. Freshwater is not found in the delta of Wadi Lahatah as a result of its proximity to seawater. This can be attributed to the presence of Sabkha and playa deposits (salt evaporites) beneath the wadi deposits (alluvium aquifer) (Said, 2004). Additionally, the delta of Wadi Sudr contains brackish, saline to extremely saline water, with a notable absence of freshwater. This phenomenon is a result of leaching and dissolution processes from coastal saliferous deposits and agricultural activities, leading to saltwater encroachment in the groundwater. The primary water source for irrigation and domestic use is the groundwater extracted from a shallow aquifer, specifically the alluvium aquifer (Said, 2004).

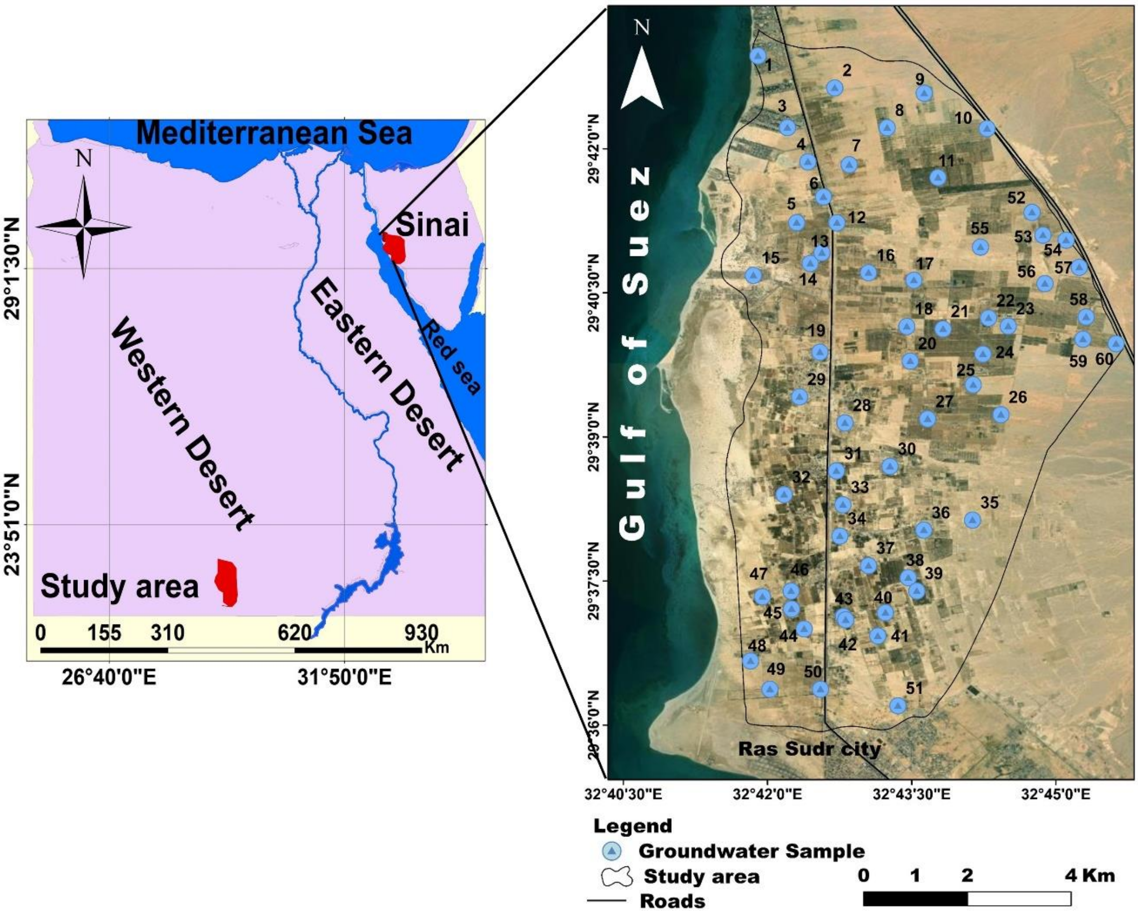

Fig. 1: The study area with locations of the groundwater samples.

The climatic conditions in South Sinai are classified as arid, with high daytime temperatures and cooler nights. Summer months typically receive no precipitation, while winter may bring significant rainfall that can lead to destructive flash floods, impacting infrastructure and human safety. In the Sudr area's alluvial aquifer, water salinity exhibits seasonal variations due to dilution effects during rainy seasons (winter months). Evaporation plays a significant role in the rise of water salinity levels.

The Sinai Peninsula has been categorized into seven structural subdivisions, including the marshy Mediterranean foreshore, the strongly folded area of North Sinai, the hinge belt, the gently folded area of North

Central Sinai, the stable unfolded foreland of Central Sinai, the southern shield area, and finally, the rift area of west Sinai that represents the investigated region (Shata, 1959). Wadi Sudr and Lahata expose rock units ranging from the Upper Cretaceous to Quaternary (Said, 1962; Abo Shaala, 2016), while the subsurface lithology of the penetrated wells in the study area is limited to Quaternary alluvium deposits (Abdel-Latief and Al-Temamy, 2008) (Fig. 2).

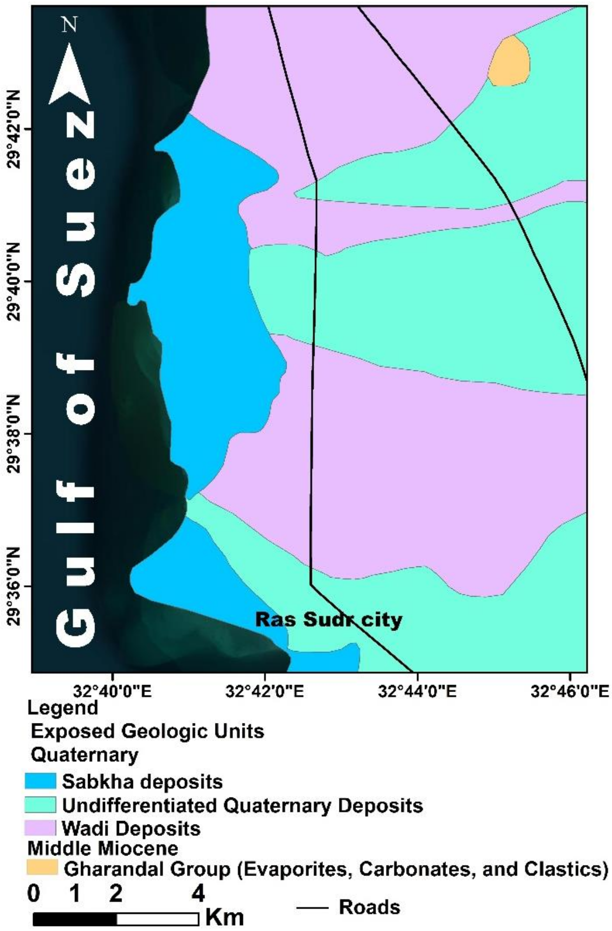

Fig. 2: Geological map of the study area (Conoco, 1987).

The Pleistocene and Holocene sediments overlay the primary channels of the catchment and the delta of Wadi Sudr, predominantly comprising of alluvial deposits with varying sizes of dolomitic limestone boulders scattered along the Wadi's main course, where the distance from the water divide is inversely related to the size of the Wadi fills deposits (Morad, 2000). The Quaternary aquifer is widely recognized as the primary aquifer of the investigated region (El-Sayed and Gomaa, 1999; Abdel-Hafez, 2001). Quaternary deposits thickness shows significant variation from the upper reaches to the lower reaches, particularly at the outlets of the wadis cutting through Gebel Sin Bishr and Gebel El Raha, where it measures less than 5 meters (Morad, 2000). The aquifer is composed of two layers, with the upper layer consisting of 14 meters of gravel and medium sand, and the lower layer containing more than 17 meters of infrequent gravel, sand, clay, and sandstone, separated by occasional shales with a lenticular shape exhibit a varied thickness and a clearly defined extension. This is leading to the classification of the aquifer as an unconfined single layer (Garamoon, 1987). The hydraulic gradient ranges from 0.0009 to 0.01 and the storativity ranges from $3.6*10^{-2}$ to $4.2*10^{-2}$ (Abo Shaala, 2016), with an average hydraulic conductivity reaching 96.28 m/day, transmissivity varying from 1054 to 10328 m^2/day, and a specific capacity ranging from 3.5 to 78 m^3/h/m (Ibrahim, 2012). During the autumn and winter seasons, the substantial direct rainfall of 13.36 mm/year (El-Bihery, 2009), contributes to significant flash floods (Said, 2004; El-Fiky, 2010), while the eastward subsurface flow of the Miocene aquifer at a rate of $2.7*10^6$ m^3/year, also, serves as a major source of recharge (El-Bihery, 2009).

II. Materials and Methods

Analytical procedure

A total of 60 groundwater samples were gathered during a field trip in February 2022 from the Sudr area of the available production wells tapping the Quaternary aquifer at different depths ranging from about 10 m to about 65 m, with each well represented by one sample (Fig. 1). The samples were taken in polyethylene bottles after being cleaned with 5% nitric acid (HNO_3) and rinsed with distilled water after pumping from the wells for 25

minutes to make sure that the samples represented the actual groundwater chemistry. The collected samples' locations were identified in the field using a geographic positional system (GPS) and placed on a map (Fig. 1). All samples were kept in an ice box at temperatures below 5 °C and then sent to the laboratory for analysis. Field measurements, including electrical conductivity (EC), TDS, pH, and temperature, were performed using a portable field kit as these parameters change with storage time.
Chemical analyses of major ions (Ca^{+2}, Mg^{+2}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-}, and Cl^{-}) were carried out at Zagazig University Environmental Geophysical Lab (ZEGL), Zagazig, Egypt. Ca^{2+}, Mg^{2+}, HCO_3^{-} and Cl^{-} were analyzed by volumetric titrations which concentrations of Ca^{2+} and Ca^{2+}+ Mg^{2+} were estimated titrimetrically using 0.01 N EDTA and 0.01 N EDTA, respectively, the versenate method with ammonium purpurate as an indicator for calcium and Eriochrome black T for calcium and magnesium and those of HCO_3^{-} and Cl^{-} by 0.01 N HCl using methyl orange as an indicator and 0.01 N $AgNO_3$ titration by using Mohr's method, respectively. Na^{+} and K^{+} concentrations were determined using a Flame Photometer (Model: PFP7) (Rainwater and Thatcher, 1960; Rhoades, 1972; Fishman and Friedman, 1985). Standard and blank solutions are prepared and run in a repeated manner following every ten samples. All chemical analyses were achieved using the standard procedures of (Hem, 1991, APHA, 1998, and ASTM, 2002). The analytical accuracy was achieved in terms of ions stated in meq/l by calculating the ionic balance error (IBE) that its rate was at a limit of ±5% (Domenico and Schwartz, 1990):

$$IBE = \frac{\sum \text{Cations} - \sum \text{Anions}}{\sum \text{Cations} + \sum \text{Anions}} * 100$$

To be considered valid by IBE, the water excellence assessment allows for a permissible range of 5% (Hem, 1991). All chemical variables are measured in milligrams per liter (mg/L), except for pH and EC. The EC value is expressed in micro-mhos per centimeter (µS/cm) at a temperature of 25 °C.

Total hardness (TH)

Total hardness is expressed as the total Ca^{2+} and Mg^{2+} concentrations, both stated in ppm of $CaCO_3$. These divalent metallic cations cause hardness being the most effective in groundwater (Todd and Mays, 2004). The total hardness of water is divided into two components: carbonate hardness (temporary) including Ca^{2+} and Mg^{2+} that combine with bicarbonate and non-carbonate hardness (permanent) with Ca^{2+} and Mg^{2+} that combine with sulfate and chloride. The total hardness (TH) expressed in mg l^{-1} is determined by (Todd and Mays, 2004) as:

$$TH = 2.497 * Ca^{2+} + 4.115 * Mg^{2+}$$

Sodium adsorption ratio (SAR)

The SAR, denoted by comparing the ratio of sodium to calcium and magnesium ions in water, is widely accepted as an index for evaluating groundwater quality for irrigation (Ayers and Westcot, 1985). The Sodium adsorption ratio (SAR) is frequently employed as a measure of the risk posed by sodium/alkali, as indicated by (Richards, 1954) as shown in the equation:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

The concentrations of sodium (Na^{+}), calcium (Ca^{2+}), and magnesium (Mg^{2+}) ions in irrigation water are expressed in milli equivalents per liter (meq/l), while SAR is expressed as (milli moles per liter)$^{0.5}$ or (mmoles/l)$^{0.5}$.

Sodium Percentage (Na %)

The percentage of sodium content in natural waters is a crucial parameter for assessing its appropriateness for agricultural use, as the combination of sodium with carbonate can result in the creation of alkaline soils, while its combination with chloride can lead to the formation of saline soils (Wilcox, 1955). The significance of sodium concentration lies in its role in the classification of irrigation water, as it interacts with soil to diminish its permeability. The presence of too much sodium in water can lead to negative impacts such as altering soil characteristics and decreasing soil permeability (Kelley, 1951). The calculation of the sodium percentage (Na %) involves the use of the formula provided below.

$$Na^{+}\% = \frac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} * 100$$

The high concentration of sodium in irrigation water leads to the absorption of sodium ions by clay particles, which displaces Mg^{2+} and Ca^{2+} ions, thus reducing soil permeability and resulting in poor internal drainage (Selvam et al., 2013).

The Permeability Index (PI)

The Permeability Index (PI) indicates the extent of influence on the permeability of the soil. Over time, the permeability of the soil decreases with the continuous use of irrigation water containing ions such as Na^{+}, Ca^{2+},

Mg^{2+}, and HCO_3^- (Rawat et al., 2018). Doneen (1964) developed the permeability index (PI) to assess the appropriateness of groundwater for irrigation, with the index being defined as follows:

$$PI = \frac{Na^+ + \sqrt{HCO_{3^-}}}{Ca^{2+} + Mg^{2+} + Na^+} * 100$$

The concentrations are expressed in milliequivalents per liter.

Potential salinity (PS)

PS, developed by (Doneen, 1964), is an index that classifies water for agricultural purposes based on water quality parameters. The salts with low solubility form precipitates and gradually build up in the soil through repeated irrigation, while the presence of highly soluble salts leads to an increase in soil salinity (Gholami and Srikantaswamy, 2009). PS is produced using the equation (Doneen, 1964):

$$PS = Cl^- + (0.5 * SO_4)$$

Residual Sodium Carbonate (RSC) /Residual Alkalinity (RA)

According to (Raghunath, 1987), the RSC (Residual Sodium Carbonate) represents the quantity of sodium carbonate (Na_2CO_3) and sodium bicarbonate ($NaHCO_3$) present in the irrigation water. This indicates the alkalinity level in soil and is applicable when the concentration of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ions exceeds the concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. Conversely, if the carbonates are less than the alkaline earths ($Ca^{2+} + Mg^{2+}$), the absence of residual Na_2CO_3 is observed. The ion concentrations are expressed in meq/l. The levels of carbonate, bicarbonate, calcium, and magnesium concentrations are assessed utilizing the formula introduced by (Eaton et al., 1995).

$$RSC = (CO_3 + HCO_3) - (Ca^{2+} + Mg^{2+})$$

The concentrations are reported in milliequivalents per liter.

Kelly's Ratio (KR) Kelly's Index (KI)

According to the Kelly's ratio (KR) (Kelley, 1963), the expression of sodium levels is based on the ratio of calcium and magnesium levels. The ion concentrations are expressed in milliequivalents per liter (meq/l).

$$KR = \frac{Na^+}{(Ca^{2+} + Mg^{2+})}$$

Magnesium Hazard (MH) or Magnesium Adsorption Ratio (MAR)

The magnesium hazard (MH) is also used to refer to magnesium adsorption ratio (MAR). A state of equilibrium is observed between the calcium and magnesium ions in natural water (Giri et al., 2022). However, calcium ions have a greater efficiency in altering soil clay compared to magnesium ions, while an elevated magnesium content can potentially harm the structure of the soil and ultimately affect the crop yield (Ayers and Westcot, 1985; Strawn et al., 2015; Qadir et al., 2018). According to (Karunanidhi et al., 2021), the accumulation and rise of alkali ions in soil can adversely affect plant growth, agricultural yield, and the quality of irrigation water. Additionally, the presence of Ca^{2+} and Mg^{2+} ions further exacerbate these impacts. The following equation calculates the MH ratio (Raghunath, 1987):

$$MH = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} * 100$$

All ion concentrations are indicated in meq/l.

Geographic information system (GIS) analysis

The GIS tool in ArcGIS 10.8 was utilized to generate spatial distribution images, showing its efficacy in organizing and analyzing digital cartographic data (Shirabe, 2012). The IDW algorithm is utilized for the estimation of measurement values or the spatial interpolation of data (Hossain et al., 2024). According to (Kura et al., 2014), the GIS spatial analyst tool's Inverse Distance Weighted (IDW) method is known for its effectiveness and ability to generate accurate outcomes.

III. RESULTS AND DISCUSSION

Hydrochemistry

Assessing the quality of groundwater is crucial, as it plays a key role in determining its appropriateness for use in drinking, agriculture, and industrial activities (Subramani et al., 2005). Table 1 summarizes the findings of the descriptive statistics of the physical and chemical parameters for the collected samples.

Table 1: Descriptive statistics of the groundwater samples in Sudr area

	Mean	Median	SD	Min	Max
EC (µS/cm)	10600	10120	4268.15	3213	23500
pH	7.46	7.47	0.27	6.8	8.2
TDS (mg/l)	6617.43	6873.5	2666.68	1321	15050
Ca^{2+} (mg/l)	442.73	411	204.66	105.2	915

Mg^{2+} (mg/l)	249.22	254.25	112.63	23	572
Na^{+} (mg/l)	1641.8	1701.5	711.47	304	3860
K^{+} (mg/l)	25.48	22	13.17	10	80
Cl^{-} (mg/l)	2884.63	2965	1355.87	416	7098.9
SO_4^{2-} (mg/l)	1271.2	1204	563.91	288.5	2639
HCO_3^{-} (mg/l)	149.97	138.5	36.7	97.6	241

pH

The pH of a solution shows its acidity or alkalinity and is described as the negative logarithm (base 10) of the concentration of hydrogen ions in moles per liter. The pH scale is 0 to 14, with 7 representing neutral, less than 7 indicating acidity, while a pH greater than 7 indicates basic or alkaline conditions. pH values range between 6.8 and 8.2, with an average of 7.46, which meets the World Health Organization (WHO) standard (6.5 - 8.5) (WHO, 2017), where the higher values are recorded in the East and some parts of the study area (wells No. 2, 27, 35, 52, and 55) which may be attributed to the leaching processes of soil sediments, while the lowest one is detected in the west which is attributed to the seawater intrusion. The distribution of pH values of deltaic deposits in the study area is described by (Fig. 3a).

Total dissolved solids

Total dissolved solids (TDS) are a water quality measurement method. It describes the overall concentration of dissolved substances in water, which includes heavy metals, minerals, salts, and other organic and inorganic substances. TDS levels are crucial in determining the type of water and its suitability for various purposes. It is crucial to identify groundwater based on its hydrochemical characteristics based on its TDS values to determine whether it is suitable for any given use Table 2 (Davis and De Wiest, 1966; Freeze and Cherry, 1979). The total dissolved solids values of the Quaternary aquifer vary from 1321 ppm in Well 60 to 15050 ppm in Well 1 with a mean value of 6617.43 ppm. The present study classified groundwater salinity levels into four categories, as reported by (Phocaides, 2000) (Table 2).

Table 2: The classification of groundwater in Wadi Sudr based on total dissolved solids in (ppm) according to (Phocaides, 2000):

Class	Salinity value (ppm)	Number of samples	Percentage of samples
Slightly saline	<2000	5	8
Medium saline	2000-4000	4	7
Highly saline	4000-9000	45	75
Very saline	>9000	6	10

Spatial distribution of TDS in the Quaternary Deltaic deposits aquifer is shown in (Fig. 3b). The water chemistry in the investigated aquifer is heavily influenced by various parameters including the distance from the coastline and from the main wadi channel, the drilled depth below sea level, and the discharge rate. The East has low TDS values, which are mostly ascribed to recharge sources from direct percolation of surface runoff water through flash floods, which generally occur in autumn and winter (Fig. 3b). This is consistent with the main recharge sources since groundwater flows towards the Suez gulf from east to west. The west and north-west have high TDS values which are mostly rendered to the influence of seawater encroachment, the leaching and dissolution processes of Sabkha and playa, Miocene deposits i.e., shale, anhydrite, and salts evaporites which lie under the wadi deposits (alluvium aquifer), extensive drilling of wells, the successive evaporation from the shallow water table and excessive withdrawal relative to the current recharge (Fig. 3b). According to (Morad, 2000), the evaporation from water surfaces and dissolution of rocks are other factors affecting groundwater salinity. The rates of excessive pumping affect the coastal area too. The number of working hours for well 41, for example, reaches 12 h a day.

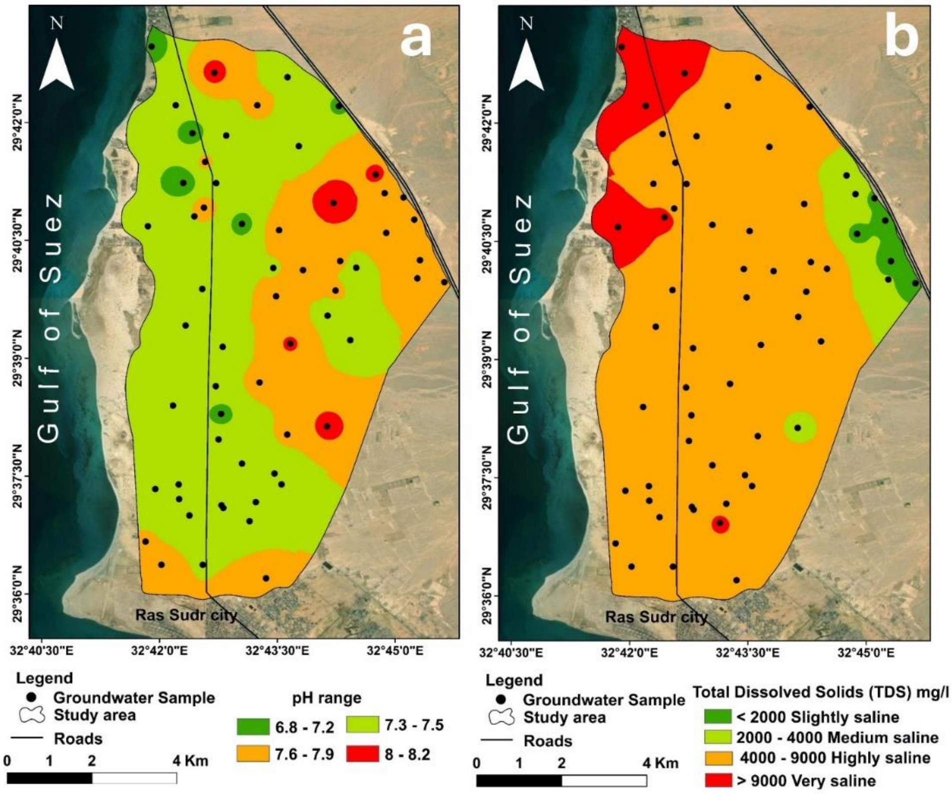

Fig. 3: Spatial GIS distribution in the Quaternary Deltaic deposits aquifer: **a**) pH.; **b**) TDS.

Electrical conductivity

Electrical conductivity is a measurement of a material's ability to transport a current or the amount of electrical current it can carry. It differs from one material to another depending on the ability to let the electricity flow through them. It is an intrinsic feature of a material and is also known as specific conductance. The unit of electrical conductivity is mho/m or Siemens per meter (S/m). In the Quaternary Deltaic deposits aquifer, the electrical conductivity ranges from 3213 µS/cm to 23500 µS/cm, with an average of 10599.95 µS/cm. Figure 4a shows spatial distribution of EC in the Quaternary Deltaic deposits aquifer that the higher values of EC are represented in the west and north-west, while the values decrease towards the east near the main Wadi channel. This enormous rise in EC could be linked to saltwater intrusion and the impact of sabkha deposits. The EC of groundwater in Wadi Sudr is classified according to (Handa, 1969) as described in Table 3.

Table 3: The classification of groundwater in the region based on EC in (µS/cm) according to (Handa, 1969).

EC (µS/cm)	Water salinity	Number of samples	Percentage of samples
0-250	Low	Nil	Nil
251-750	Medium	Nil	Nil
751-2250	High	Nil	Nil
2251-6000	Very high	9	15
6001-10000	Extensively high	18	30
10001-20000	Brine weak	30	50
20001-50000	Brine moderate	3	5
50001-100000	Brine high	Nil	Nil
>100000	Brine extremely high	Nil	Nil

Total hardness

The total hardness values of the Quaternary aquifer range between 423.17 ppm in Well 58 and 4638.54 in Well 1 with a mean value of 2131.02 ppm. The spatial distribution of TH in the Quaternary Deltaic deposits aquifer is shown in Figure 4b.

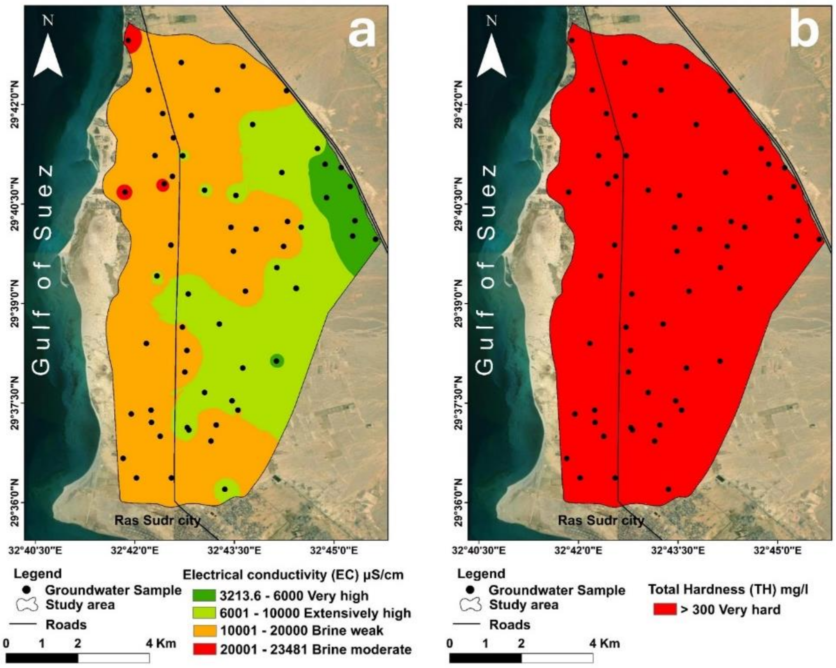

Fig. 4: Spatial GIS distribution in the Quaternary Deltaic deposits aquifer: **a**) EC; **b**) TH.

According to Sawyer and McCarthy, 1967, total hardness can be categorized in (Table 4) and all water samples are classified as very hard water types. The TH distribution map (Fig. 4b) highlights the impact of seawater intrusion, particularly in the western parts of the region, and the leaching and dissolution of salts rich in Ca^{2+} and Mg^{2+} ions within the water-bearing formations. Also, it is observed that the higher values of hardness are represented by the wells tapping the Quaternary aquifer in the western and northwest parts of the study area, while the values decrease in the eastern parts near the main Wadi channel due to dilution effect because of recharge of such aquifer from surface and subsurface runoff. This means that the total hardness increases with water salinity increase.

Table 4: The Classification of groundwater hardness in the region according to (Sawyer and McCarthy, 1967).

Hardness ppm as $CaCO_3$	Water class	Number of samples	Percentage of samples
0-75	Soft	Nil	Nil
75–150	Moderately hard	Nil	Nil
150–300	Hard	Nil	Nil
>300	Very hard	60	100

Chloride

The average chloride concentration in the study region is 2884.63 ppm, with well 1 having the highest value (7098.9 ppm) and well 60 having the lowest value (416 ppm). According to the chloride ion distribution map in deltaic deposits (Fig. 5a), the TDS and the chloride content follow a similar pattern. The concentrations of chloride rise in western and northwestern directions where seawater intrusion is a major problem and reduce in eastern regions where the aquifer is refilled by runoff from the main wadi channel. Chloride content can be classified according to (Taylor and Oza, 1954), into four classes as in (Table 5).

Table 5: Chloride content classification, according to (Taylor and Oza, 1954):

Class	Chloride content	Chloride range (ppm)	Number of samples	Percentage of samples
First class	Low chloride	<200	Nil	Nil
Second class	Medium chloride	200-500	2	3
Third class	High chloride	500-1000	4	7
Fourth class	Very high chloride	>1000	54	90

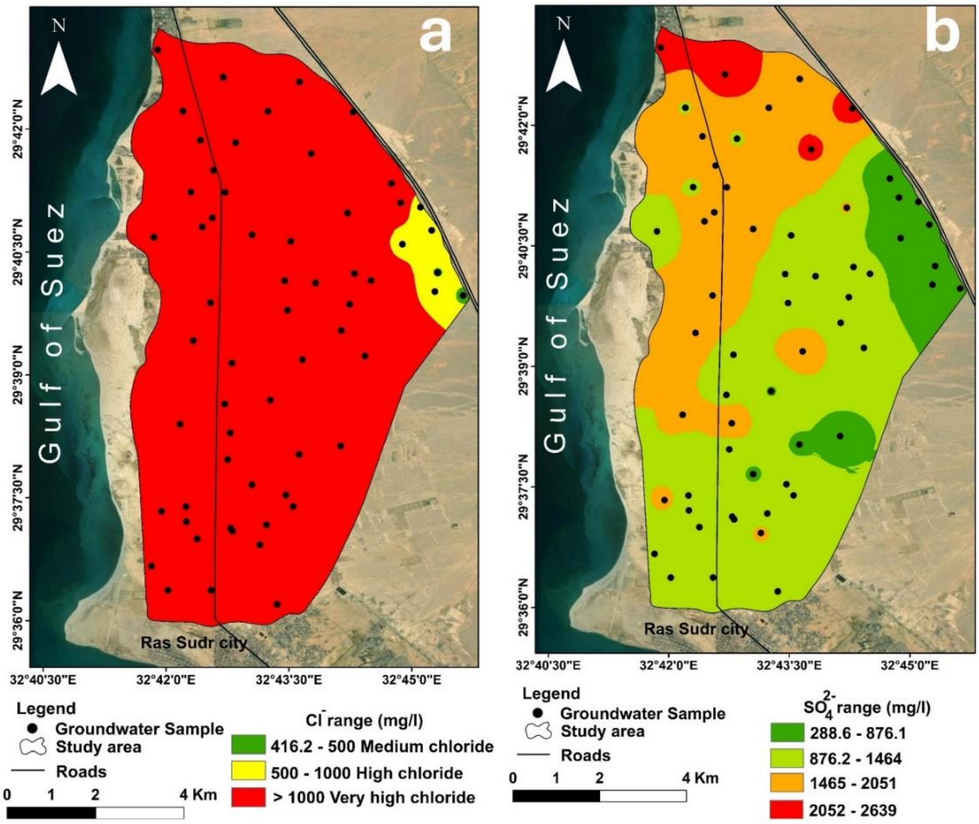

Fig. 5: Spatial GIS distribution in the Quaternary Deltaic deposits aquifer: **a**) Cl; **b**) SO_4.

Sulphate

Sulfate ions are found in all tested samples, ranging from 288.5 ppm to 2639 ppm, with an average of 1271.2 ppm. A map for sulfate ions distribution in Deltaic deposits is constructed as in Figure 5b, showing that highest values of sulfate ions are recorded at the northwestern and western parts of the area of study and reflecting the precipitation of widespread evaporites (gypsum, halite, and anhydrites) and the intrusion of seawater. Sulfate ions also increase in some wells of the study area, which are attributed to the effect of over-pumping and seawater invasion. While the lowest sulfate values were encountered in the wells tapping the Quaternary aquifer at eastern parts of the area of study near to main wadi channel.

Calcium

Calcium is either derived as cyclic salt from saltwater or the calcareous rocks dust, and emissions from industry (EL Fayoumy, 1968). Calcium concentrations range between 105.2 ppm and 915 ppm with an average of 442.73 ppm. The calcium distribution map in the Deltaic deposits (Fig. 6a) shows that the calcium values increase to the west and northwest and decrease toward the east and some sites.

Magnesium

Magnesium ions vary from 23 ppm and 572 ppm with an average of 249.22. Spatial distribution map of Magnesium in the Quaternary Deltaic deposits aquifer is illustrated in Figure 6b, where the highest values were recorded in wells located in the northwest parts. The least magnesium content is generally recorded in the east which is mainly recharged from the main Wadi channel of both wadi Sudr and Lahata.

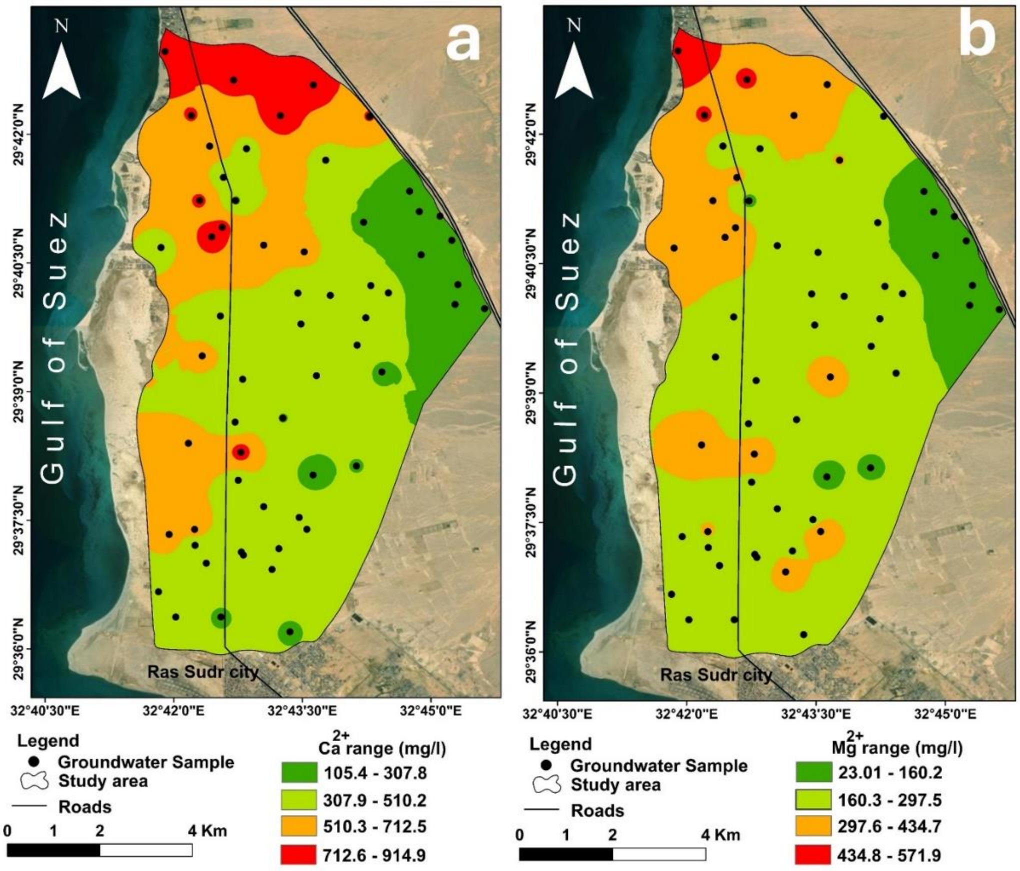

Fig. 6: Spatial GIS distribution in the Quaternary Deltaic deposits aquifer: **a**) Ca; **b**) Mg.

Hydrochemical facies of the Sudr area aquifer

Pattern diagram was initially introduced by (Hill, 1940) and later improved by (Piper, 1944) and major cations and anions were further analyzed. It offers a graphical representation that enables the classification of water based on its geographical location, geological formation, or origin (Jiao and Post, 2019). Based on the cationic triangle illustrated in Figure 7, it can be observed that 65% of the water samples were categorized under the (Na + K), indicating a prevalence of sodium-type water within the aquifer. In the anionic triangle, all water samples analyzed were found to fall under the chloride type category. The distribution of these samples can be visualized in the form of a diamond-shaped plot. It reveals that zone 3 accounted for 66.67% of the samples, while zones 1 and 5 comprised 28.33% and 5%, respectively. This pattern suggests that the main water types in the study area are Na-Cl, Ca-Cl, and Ca-Mg-Cl. Notably, in the Sudr area, the Na-Cl water type is primarily influenced by marine facies, whereas the Ca-Cl and Ca-Mg-Cl water types are influenced by continental facies (Said, 2004).

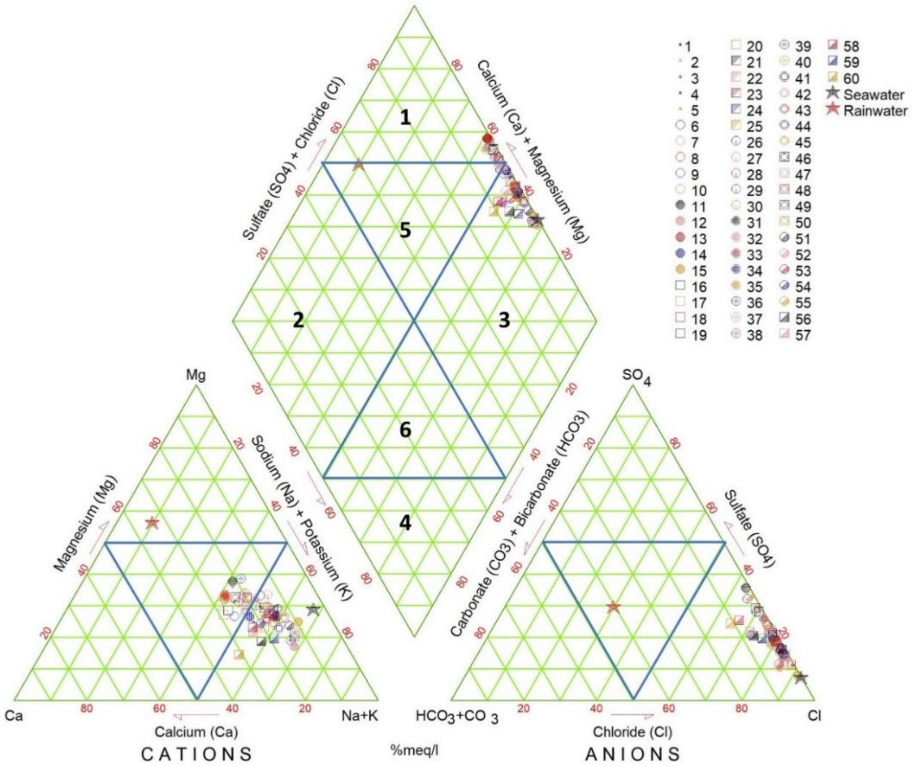

Fig. 7: Piper diagram representing the hydrogeochemical facies observed in the groundwater samples. 1. Ca-Cl type, 2. Ca-HCO_3 type, 3. Na-Cl type, 4. Na-HCO_3 type, 5. Ca-Mg-Cl type, and 6. Ca-Na-HCO_3 type.

Evaluation of groundwater quality for irrigation uses

The quality of groundwater significantly influences plant health and the conditions of agricultural soil through its impact on irrigation (Gugulothu et al., 2022). The elevated levels of dissolved ions in groundwater can lead to both physical and chemical impacts on plants and soil, including the decrease in osmotic pressure within plant cells, ultimately impeding water uptake and leading to diminished irrigation efficiency (Sarkar et al., 2022).

Sodium adsorption ratio

The groundwater samples have been classified according to the sodium adsorption ratio, as outlined in by USSL staff (Hide, 1954). The US Salinity Diagram (USSL) (Fig. 8) was introduced by USSL staff (Hide, 1954) for evaluating the suitability of irrigation water by analyzing the EC and SAR of groundwater samples. The classification of groundwater can be based on salinity hazard (EC) and sodium hazard (SAR) into four categories each, namely C1, C2, C3, C4 for salinity hazard and S1, S2, S3, S4 for sodium hazard.

The SAR values range from 6.40 to 31.95 with an average of 15.47. Results show that 68.33% of samples have sodium content acceptable for irrigation purposes. Figure 8 demonstrates that 6.67% of the groundwater samples gathered belong to the C4S2 category, signifying very high salinity and moderate sodium hazard, which may be applicable for plant species with high salt tolerance but may limit their suitability for irrigation in poorly drained soils (Mohan et al., 2000). Moreover, 5% of the samples fall within the C4S3 category while 86. 67% belong to the C4S4 classification, both of which exhibit high levels of salinity and alkalinity for agricultural purposes. Sample 15 is out of range of USSL.

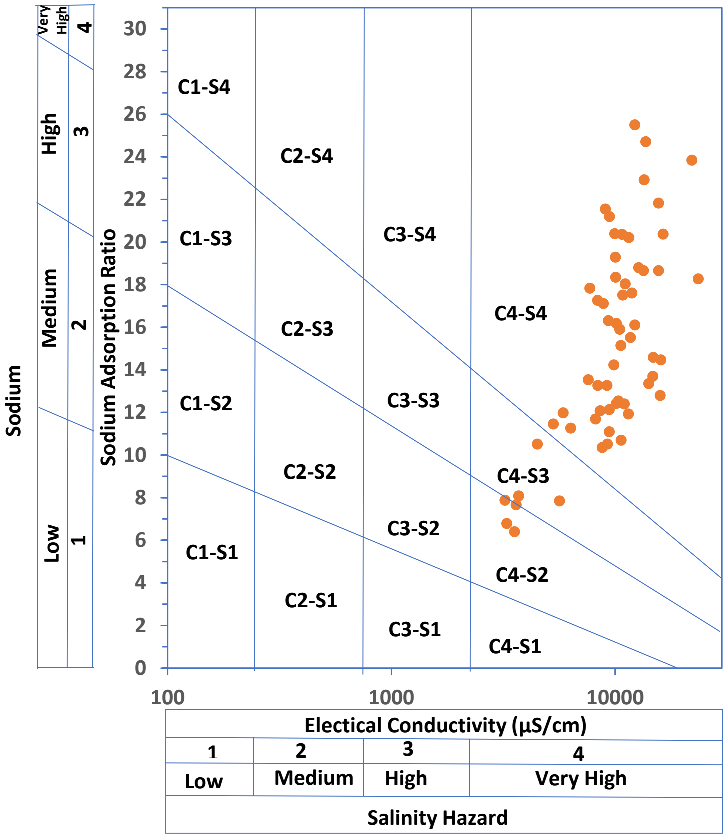

Fig. 8: USSL staff diagram (Hide, 1954) for classification of irrigation water.

sodium Percent

The Na % values vary from 49.91 to 76.25 with an average of 62.83 that most samples are doubtful class (Table 6).

Table 6: Irrigation quality of groundwater based on sodium percentage (Na%) (Wilcox, 1955).

Na%	Water class	samples number (percentage)
<20	Excellent	Nil
20-40	Good	Nil
40-60	Permissible	20 (33.33%)
60-80	Doubtful	40 (66.67 %)
>80	Unsuitable	Nil

Permeability index

According to (Doneen, 1964), waters falling under class I and class II categories are excellent and appropriate for irrigation purposes. On the other hand, class III water is unsuitable for irrigation. Doneen's diagram created to classify the quality of irrigation water. This classification is based on two factors: the total ion concentration and the PI (permeability index). The purpose of this diagram is to estimate the level of soil permeability.

The PI value exhibited a range from 50.79 to 77.49% with an average of 64.5%. The analysis of the diagram indicates that most water samples (90%) belong to class I, which signifies their suitability for irrigation purposes. Only six samples fall into class II, denoting a marginal suitability (Fig. 9).

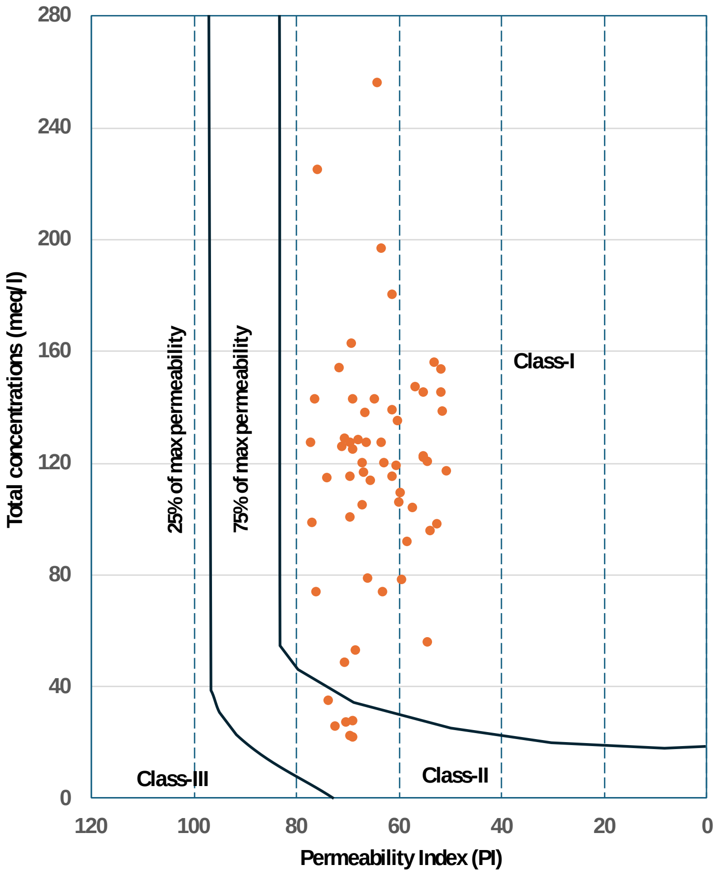

Fig. 9: Doneen's plot is based on total ion concentrations and permeability index.

Potential salinity (PS)

The PS level of less than 3 meq/l is appropriate for irrigation purposes, while it becomes unsuitable when it exceeds 3 meq/l (Doneen, 1964). According to the findings, the PS values exhibited a range between 14.74 and 225.96, with an average of 94.61. These could be attributed to the raised levels of Cl^- and SO_4^{2-} in all the water samples. The obtained results suggest that the water in this study area is appropriate in irrigation for high salt tolerance plants.

Residual Sodium Carbonate (RSC) /Residual Alkalinity (RA)

According to (Eaton et al., 1995), the RSC is safe and favorable for irrigation when it is less than 1.25 meq/L (<2.5), a value of RSC between 1.25 and 2.5 meq/L is moderate of marginal quality, whereas a value greater than 2.5 meq/L (>2.5) is not appropriate for irrigation. The RSC values range from -90.33 to -5.12 with a mean -40.14. These findings suggest that all groundwater samples are deemed safe for irrigation.

Kelly's Ratio (KR) Kelly's Index (KI)

Samples are considered unsuitable for agriculture activities if KR is greater than 1, while samples are considered suitable if KR is less than 1 (Kelley, 1963). The results demonstrate that all the water samples in the region are suitable for irrigation applications for plant species with high salt tolerance. This could be attributed to the prevailing high presence of Na^+ in the water.

Magnesium Hazard (MH) or Magnesium Adsorption Ratio (MAR)

According to (Ayers and Westcot, 1985), an MH below 50% is considered appropriate for irrigation, while a MH exceeding 50% is deemed unsuitable for irrigation purposes. The MH values vary from 22.19 to 61.24, with an average of 47.39. Results reveal that water samples in the region are appropriate for irrigation purposes with plant species that have a high tolerance to salt.

IV. CONCLUSION

This study assesses of groundwater quality for irrigation in an arid coastal aquifer: Sudr area, South Sinai, Egypt using hydrochemical indicators and GIS. The order of the ionic compositions in groundwater is as Na^+> Ca^{2+}>Mg^{2+}>K^+ and Cl^- >SO_4^{2-} >HCO_3^-. The high salinity values in the west and north-west region are primarily attributed to seawater encroachment, leaching and dissolution processes of Sabkha and playa, and excessive withdrawal in comparison to the current recharge. While the low salinity values in the East are primarily attributed to the recharge sources resulting from the direct percolation of surface runoff water through flash floods, which typically occur during the autumn and winter seasons. Based on the cationic triangle in Piper diagram, 65% of the water samples were categorized under the (Na + K), indicating a prevalence of sodium-type water within the aquifer. In the anionic triangle, all water samples analyzed were found to fall under the chloride type category.

The SAR values vary between 6.40 and 31.95 that 6.67% of the groundwater samples collected fall under the C4S2 category. Additionally, 5% of the samples are classified under the C4S3 category, while the majority, accounting for 86.67%, belong to the C4S4 classification. The Na % values vary from 49.91 to 76.25, most samples (66.67 %) are doubtful class, while the remaining (33.33%) is in permissible class. The analysis of the Doneen's diagram indicates that most water samples (90%) belong to class I, which signifies their suitability for irrigation purposes. Only six samples fall into class II, denoting a marginal suitability. The PS values range from 14.74 to 225.96, likely due to elevated Cl^- and SO_4^{2-} levels in all water samples. The results of RSC indicate that all groundwater samples are considered suitable for irrigation use. The findings indicate that the water samples in the area are suitable for irrigation use with plant species that exhibit a high resistance to salt. Regular Monitoring of seawater intrusion in coastal aquifers is crucial for sustainable groundwater quality.

Data availability statement

The data will be provided on request.

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