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Research Article

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Impact of Hydrochemical Processes on The Groundwater Quality Southwest Sinai Egypt.

By

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Abstract

The evolutionary mechanisms and potentiality development of the five aquifers in the southwestern Sinai Peninsula were detected using the hydrogeochemical, isotopic, and water quality characteristics. Hydrochemical and isotopic data reveal distinguishing between shallow, evaporation-dominated resources and deep, rock-water interaction regimes. Highly mineralized brackish waters have been produced in the shallow Quaternary Aquifer by kinetic evaporation and agricultural return flows. Mineral dissolution, silicate weathering and structurally mediated fault mixing control the Nubian Sandstone, Carboniferous Sandstone, Cambrian-Ordovician and fractured Basement aquifers. Sustained by unevaporated paleo recharge from ancient humid climates, the Nubian Sandstone represents the freshest, most viable reservoir for domestic supply and agricultural irrigation. While the fresher aquifers demonstrate major-ion suitability for agricultural expansion, active geogenic weathering across all five stratigraphic units causes pervasive exceedance of World Health Organization (WHO, 2022) drinking water thresholds for Pb, Cd, and Cr. Consequently, a stratified management strategy is recommended, prioritizing the Nubian Sandstone for municipal utilization while mandating

targeted remediation technologies to mitigate heavy metal toxicity prior to domestic consumption.

Keyword: Hydrochemistry; hydochemical process; heavy and trace elemts, environmental stable isotopes.

Introduction

Aquifer lithology and mineral assemblage are the most factors controlling the groundwater characteristics. The mineralogical composition of the aquifer materials influences geochemical reactions such as dissolution-precipitation, ion-exchange and redox reactions. Hydrogeochemical studies are the tools for identification and detection of the interaction processes between groundwater and the minerals of the aquifer (Jeevanandam, et al. 2006).

The inland area of the Sinai Peninsula suffers from a severe shortage of traditional water resources, this significant challenge requires conducting studies to evaluate existing water resources, such as groundwater and surface water resources, is crucial for developing sustainable water management strategies. Optimizing the use of available resources through water conservation measures, and possibly exploring alternative water sources like desalination or wastewater reuse can help address the water scarcity issue in these areas. Additionally, promoting community involvement and awareness about water conservation practices can also contribute to maximizing water utilization and ensuring long-term water security in the region.

This area is characterized by the presence of many economic ore deposits especially cupper, manganese and uranium ores (Hussein, et al. 1992). This study includes four main wadis (Wadi Nasib, Wadi ElSeih, Wadi Baba, and W. Asahu) (Fig. 1). These wadis are inhabited by Bedouin communities that used natural materials and available resources in their living system.

The existence of valuable ore deposits and the reliance of Bedouin communities on natural resources, there is a need to balance economic development with conservation and sustainable resource management. Responsible mining practices should be adopted to mitigate these adverse effects and to ensure the long-term sustainability of the environment and local communities. The region's natural resources and ecosystems must be protected by conducting environmental impact assessments, implementing effective waste management practices, and monitoring and mitigating potential environmental risks. By integrating environmental considerations into mining activities and promoting responsible resource extraction practices, it is possible to support economic development while preserving the unique biodiversity and ecological balance of the Sinai Peninsula.

The limited previous hydrogeochemical investigations in the study area highlight the need for further research in this area to better understand the quality and sustainability of aquifers in the study region. While studies on geological features, aquifer potentiality mapping, radioactive elements, and flash flood hazard mapping are valuable for understanding the physical characteristics and potential risks associated with water resources, a comprehensive understanding of hydrogeochemical factors is essential for assessing water quality and potential contamination sources (Hussein et al. 1992; El-Fiky, 2010; Aly and Ragab 2013; El-Aassy et al. 2015; Ali et al. 2016; Arnous and Omar. 2018; Randa et al. 2022; Mosad et al. 2024.).

This study is concerned with identifying the hydrochemical factors influencing the quality of potential aquifers in the study area to ensure their sustainable use and protect them from deterioration, as well as evaluating the quality of these aquifers and evaluate their suitability for different uses. In addition to ultimately, to provide valuable information for decision-makers and stakeholders to make informed choices regarding the management and protection of the aquifers in the study area.

Site Description:

Geographic location, land use, and climate

The study area is situated in the South eastern part of Sinai Peninsula in the east region of South Sinai about 35 km east of Abu Zeneima city between longitude 33° 19' 51.6" –33° 28' 42.6" E and latitude 28° 57' 18"–29° 8' 24" N with approximately area of about 300 km^2. The topography of study area varies from low to moderate relief with a flat sand sheet, for example, Gabal (G.) Um Rinna (600 m) above sea level. The basement rocks are rough and moderately high mountains at the Southwestern part of the area which attains 693 m above sea level, whereas to the south, G. Abu Trifia (1105 m), is located. High topographic Paleozoic sedimentary rocks are clearly shown at G. Um Reglain (1037 m), G. Sarabit El-Khadim (1096 m) These highlands landforms serve as high runoff zones and rank as low potentiality for groundwater occurrences except the structural hills that have well-developed joints, fractures and faults. The area dissected by many wadis, such as Wadi (W.) Baba trending NE-SW (about 13.8 km long). Wadi Baba is one of the major drainage basins of south west Sinai with an intricate network of tributaries and stream channels, formed by the erosive forces of water over millions of years, originates at the joining of W. El-Seih from the east and W. Nasib from the south. W. Lehian trending N-S to NNW-SSE (about 9.5 km long), W. Nasib trending NNW-SSE (6.4 km long), W. El-Sahu is trending ENE-WSW to WNW-ESE (10.6kmlong) (Fig. 2) (Arnous and Omar. 2018 and Mosad et al. 2024).

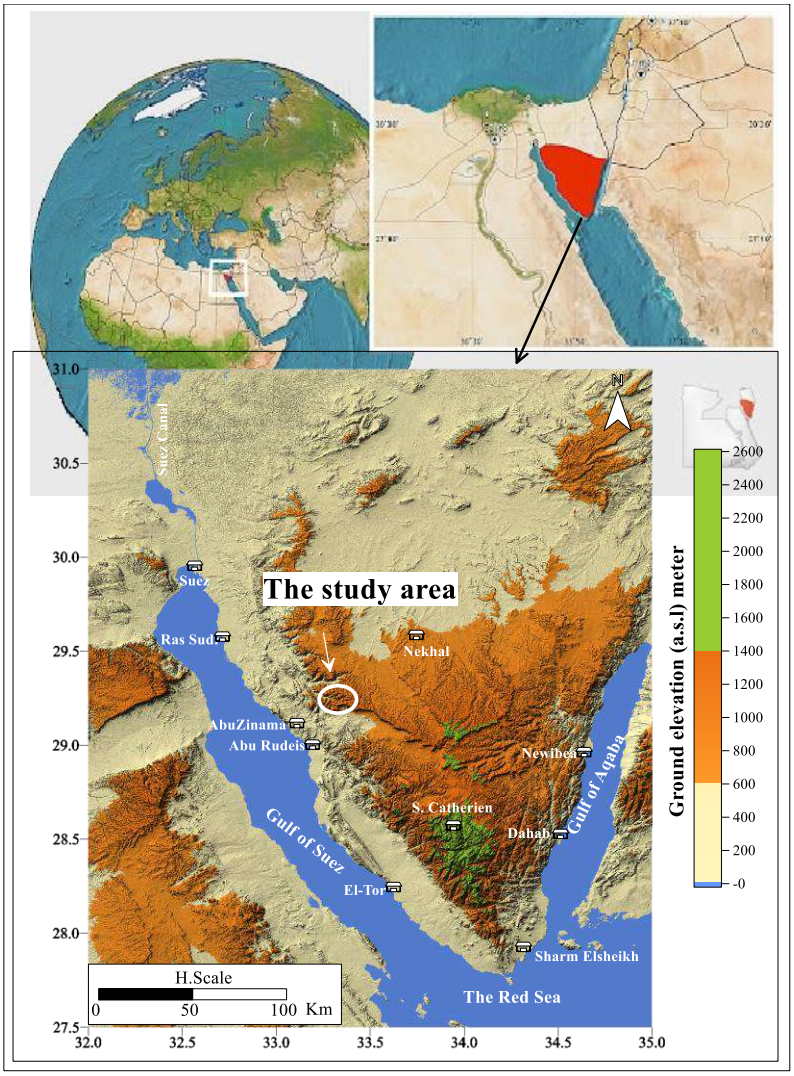


Fig. 1. Location map of the study area.

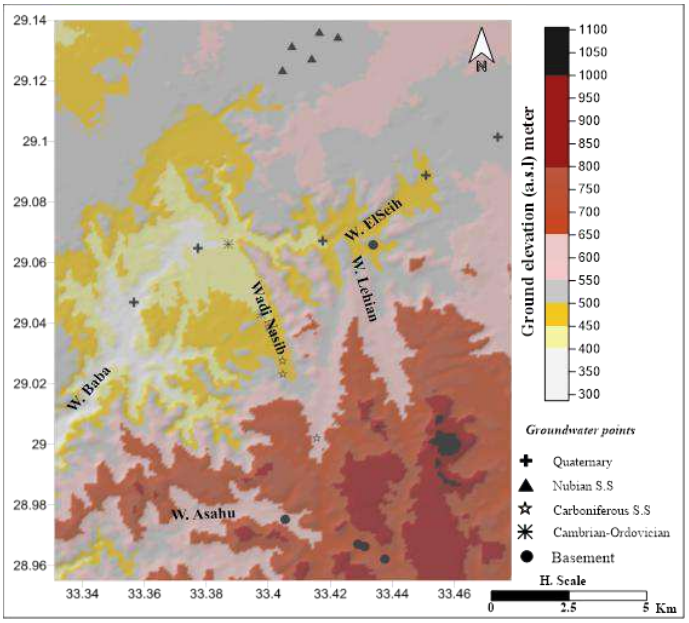


Fig. 2. Topographic map of the study area with digital elevation model (DEM).

The area under investigation lying within the arid region characterized by low precipitation, high evaporation, and temperature with hot long summer and mild short winter (Ali et al. 2016). South western Sinai area receives heavy rain storms every two or four years (El Shamy 1983) causing destructive floods that runoff towards the Gulf of Suez. The annual precipitation varies from 16.4 to 64.3 mm, the average temperature ranges between 9.8°C in January and 32.9°C in July, with mean relative humidity varied from 49% to 62% (Mosad et al. 2024).

2.2. Geology and hydrogeological setting

Geologically, south western Sinai belongs to the Suez Gulf rift, the geological outcrops of the study area are ranging in ages from Precambrian basement rocks to Quaternary deposits. The lithostratigraphic units in the investigated area are: ***(a) Precambrian basement rocks:*** It cover large areas of the surface of the study area consists mainly of old granite rocks, schist, gneisses and younger granites rocks.

(b) Paleozoic rocks: These rocks comprise several formations contains the Fe–Mn, Cu, and U mineralization (Hussein et al. 1992). consists of sandstone rocks of the Cambrian-Ordovician age Naques Formation (Cross bedded sandstone of fluviatile origin interbedded with shallow marine sand) and Carboniferous age Abu Durba Formation (Dark shale silt and sandstone, some marl and limestone intercalation).

(c) Mesozoic rocks: consists of sandstone rocks of the Permo–Triassic Qiseib Formation (Interbedded friable sand stone and mudstone and Cretaceous Duwi Formation. ***(d) Quaternary deposits:*** It covers the streams of valleys and low-lying areas, and consists of alluvial fans, gravel and sand. Faults make an important control in the inclination of the sedimentary blocks in the study area (Allam and Khalil, 1989; Said, 1990; Patton et al., 1994; Moustafa, 2004; Aggour and Gomaa, 2008) (Fig. 3).

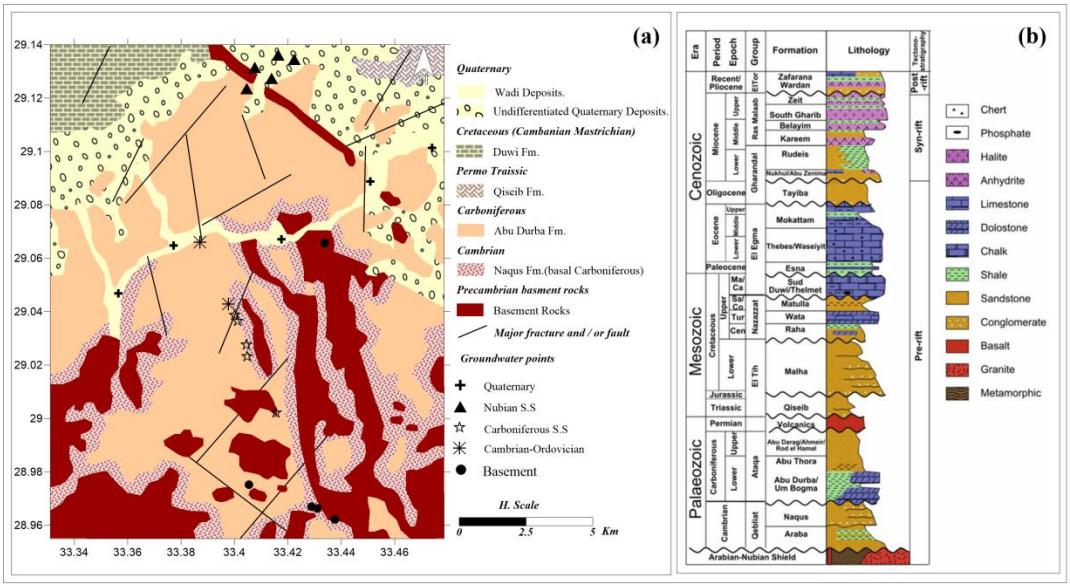


Fig. 3. (a) (Geological map showing the outcropping rocks and well locations (CONOCO, 1987). (b) Generalized stratigraphic column for the Gulf of Suez (*El Tahlawi. 2014; Pivnik et al. 2003*)

The hydrogeological aspects were studies by many authors, the water samples were collected from five aquifers: **(a) The Quaternary aquifer:** The Quaternary aquifer is one of the main aquifers in south Sinai region; Due to the ease and affordability of drilling shallow wells in these aquifers, the Quaternary aquifers are used for irrigation and domestic uses. This aquifer has good to moderate potentiality of considerable thicknesses (Mosad et al. 2024). The water-bearing deposit of this aquifer is primarily constituted of sand and gravels, with boulders and cobbles made up of foundation rocks, limestone, and sandstone, the groundwater occurs under unconfined conditions (Kassem, 1981; Afandy et al., 2016). This aquifer tapped by 5 samples, the depth to water varies from 8 to 30 meters. **(b) Nubian sandstone aquifer:** This aquifer represented by Lower Cambrian-Lower Cretaceous rocks as a thick clastic sequence covered by sandstones, limestones and shales (Allam and Khalil, 1989). Regionally extending from the crystalline rocks of central Sinai westward to the Suez Gulf with a thickness varying from 70 to 130 m (Mohamed, 2020). The groundwater wells tapping to the Nubian sandstone aquifer have good to moderate potentiality of considerable thicknesses (Mosad et al. 2024). This aquifer tapped by 5

samples, the depth to water rages from 50 to 75m, these wells exiting in El-Ramla area. **(c) The Carboniferous sandstone aquifer:** The aquifer formation belongs to Abu Thora Formation of Lower Carboniferous age; This Formation consists of sandstone with intercalations of carbonaceous clay. The groundwater in this aquifer exists under unconfined conditions (El-Fiky, 2010). This aquifer is tapped by 5 samples, the depth to water rages from 3.7 to 5m, these wells exiting in W. Lehian, W. Nasib and Alouga.

(d) Cambrio-Ordovician sandstone aquifer: This aquifer locally tapping to the Adedia Abu Hamata and Sarabit El-Khadim formations (Lower Sandstone unit). Thes formations are hydraulically connected with overlying carbonate unit (UmBogma formation). The recharge of this aquifer is mainly from the rainwater from high mountains area at El-Tih plateau in addition to might be occur by leakage from the basement aquifer as subsurface inflow, especially at the low land areas (El-Rayes and Arnous. 2015). This aquifer is tapped by 2 samples, the depth to water rages from 20.2 to 23.6m, these wells exiting in W. Nasib.

(e) Fractured basement aquifer: The sinuosity, dikes and fractures are the main factors that control the occurrence of the groundwater in this aquifer, which is the fractures (faults-joints) is the water bearing formation (Aggour and Gomaa, 2008). Porosity may be occupied 2% of the total rock volume and the porosity of the weathered igneous and metamorphic rocks exceeds than 10% (Afandy et al., 2016; El- Shamy et al. 1989; El –Shamy, El- Rayes. 1992). This aquifer is tapped by 5 samples, the depth to water rages from 20.2 to 23.6m, these wells exiting in W. Asahu and Elseih.

Materials and methods

Sample collection and analysis

Twenty-two groundwater samples were collected from groundwater wells tapping for five aquifers (5 water samples for Quaternary, 5 for Nubian sandstone, 5 for Carboniferous, 2 for Cambrian - Ordovician and 5 for Basement aquifers) in the area under investigation. The

water points were recorded using global positioning system (GPS) model etrex 10. The water samples were collected and analyzed during May 2023. The samples were gathered in 100 ml bottles for anion measurements. After acidification to pH < 2 with HNO_3, a 50 ml of water samples were stored for cations, heavy and trace element analysis, and 50 ml were stored for stable isotopes, all samples were stored in clean, tight-capped high density polyethylene bottles (HDPE) bottles wrapped in strips to ensure no leakage and stored at 4 C in iceboxes.

Field measurements were carried out such as EC, Temperature and pH were measured using portable meters (For E.C and T Hach model EC5, after calibrated with 147- 1413 - 12188 µS/cm solutions and for pH HANNA HI83141). All chemical analyses were performed in the hydrogeochemistry department, Desert Research Center, Egypt. Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_2^{-4}, Cl^{-} and NO_3^{-} were determined using ion chromatography system (Dionex, ICS-1100). CO_2^{-3} & HCO^{-3} were measured titrimetrically. Heavy metals and trace constituents (Al^{3+}, B^{3+}, Cd^{2+}, Cr^{6+}, Cu^{2+}, Fe^{2+}, Mn^{2+}, Mo^{2+}, Ni^{3+}, Pb^{2+}, and Zn^{2+}) were carried out using inductive coupled plasma mass spectrometry (ICP, POEMSIII, thermo Jarrell elemental company USA), using 1000 mg/l (Merck) Stock solution for standard preparation.

For stable isotopes measurements of oxygen and hydrogen (^{18}O, ^{2}H) were carried out at the Water-Quality Lab in Desert Research Center, Cairo, Egypt, by Picarro's unique Cavity Ring-Down Spectroscopy (CRDS).

The total dissolved solids (TDS) were calculated by summing the main ionic species (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_2^{-4}, Cl^{-} and NO_3^{-}) with total alkalinity.

In ordered to evaluation of analysis accuracy charge balance errors (CBE) were calculated for all samples using the following formula (Deutsch 1997):

$$CBE = \frac{\sum Cation - \sum Anion}{\sum \text{Cation} + \sum \text{Anion}} \times 100 \ (unite: meq/l)$$

All samples exhibited CBE below ±5%, indicating acceptable analytical precision.

Hydrochemical methods

The groundwater samples were classified according to its chemical composition. Piper plot is an important diagram which show the groundwater evolution (Fig. 6).

Piper (1944) diagram can be used to determine the relationships between dissolved major ions and classify the predominant water types in a region. The groundwater chemistry is influenced by several factors, including aquifer lithology, geochemical conditions as well as pH and redox potential and water-rock interactions over time. Groundwater evolution mainly evolves from Ca-HCO_3 to Na-Cl with increasing salinity and residence time (Qi and Harris, 2017). The relative amounts of sodium and calcium in groundwater are influenced by the mineral composition of the surrounding rock thus carbonate-rich rocks tend to produce groundwater with lower sodium levels, while silicate-rich rocks can result in higher sodium concentrations (Banks and Frengstad, 2006). Groundwater chemistry can be visually represented on a Gibbs diagram (Gibbs, 1970) (Fig. 7). This diagram shows that groundwater composition can vary widely, unlike surface water. Based on that study, the main governing processes include evaporation, precipitation, and water-rock interaction. For discriminating the origin of groundwater, Sulin diagram was used (Sulin, 1946) (Fig. 8). The Sulin diagram serves as a fundamental hydrogeochemical tool for discriminating meteoric, marine, and connate groundwater origins through the graphical representation of relative Na^+, K^+, Mg^{2+}, Cl^-, and SO_4^{2-} ionic proportions.

The stable isotope approach enables a multidisciplinary investigation to identify the recharge and the source of salinization of the groundwater for different aquifers in the study area. Stable isotope ratios of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) were reported in per mil deviation from the international Standard Mean Ocean Water (SMOW) standard, with analytical uncertainties of ±1‰ and ±0.1‰, respectively (Table, 4).

Results and discussion

Groundwater chemistry

The pH of the groundwater samples ranged from 7.03 to 7.8 in the groundwater samples reflecting slightly alkaline nature. The electrical conductivity of the groundwater samples of the Quaternary aquifer ranged from 1680 to 4200, for the Nubian S.S ranged from 569 to 1100, Carboniferous S.S from 917 to 2540, Cambrian-Ordovician from 1957 to 3600 and for the Basement aquifers from 1284 to 6500 µmohs/cm reflecting that 71% of the groundwater sample classified as low salts enrichment, and 29% of samples high salts enrichment (Rao et al. 2002) (Table, 1., Fig 4).

Table 1. Statistical summary of hydrochemical components in the area under investigation.

Parameter		Quaternary (N=5)	Nubian Sandstone (N=5)	Carboniferous (N=5)	Cambrian (N=2)	Basement (N=5)
pH	Mean	7.58	7.48	7.40	7.50	7.59
	Min	7.2	7.3	7.2	7.2	7.03
	Max	7.9	7.7	7.6	7.8	7.8
EC *(µS/cm)*	Mean	3330	877.8	1812	2779	2871
	Min	1680	569	917	1957	1284
	Max	4200	1100	2540	3600	6500
TDS *(mg/L)*	Mean	2059.6	565.4	1104.3	1595.5	1704.8
	Min	1041.6	366.8	553.8	1128.4	738.7
	Max	2604.0	708.4	1594.7	2062.7	3947.9
Ca *(mg/L)*	Mean	175.8	52.4	107.2	160.0	161.2
	Min	94.8	43.0	60.0	148.0	60.0
	Max	220.0	59.0	198.0	172.0	304.0
Mg *(mg/L)*	Mean	82.7	20.5	55.0	74.1	76.1
	Min	48.8	16.9	41.7	46.2	29.2
	Max	98.9	23.1	82.6	102.1	136.1
Na *(mg/L)*	Mean	451.5	73.1	212.0	310.0	338.0
	Min	*257.5*	*60.0*	*85.0*	*200.0*	*130.0*
	Max	*550.0*	*82.3*	*280.0*	*420.0*	*880.0*
K *(mg/L)*	Mean	9.0	4.9	14.0	8.0	19.4
	Min	*5.2*	*4.0*	*3.0*	*6.0*	*6.0*
	Max	*11.0*	*5.5*	*48.0*	*10.0*	*48.0*
HCO_3 *(mg/L)*	Mean	296.3	147.0	308.4	302.6	360.7
	Min	*105.6*	*120.8*	*78.1*	*283.0*	*273.3*
	Max	*429.4*	*165.7*	*644.2*	*322.1*	*468.5*
SO_4 *(mg/L)*	Mean	394.3	143.6	167.	294.9	310.5
	Min	*259.2*	*117.9*	*67.1*	*185.9*	*58.2*
	Max	*503.2*	*161.8*	*265.8*	*404.0*	*977.9*
Cl *(mg/L)*	Mean	796.3	78.7	329.2	573.2	634.9
	Min	*454.2*	*64.7*	*123.5*	*352.7*	*235.2*
	Max	*970.0*	*88.7*	*458.6*	*793.7*	*1528.5*

Total dissolved solids (TDS) of the groundwater samples of the Quaternary aquifer ranged from 1041.6 to 2604, for the Nubian S.S ranged from 367 to 708, Carboniferous S.S from 554 to 1595, Cambrian-Ordovician from 1128 to 2063 and for the Basement aquifers from 739 to 3948 mg/l reflecting that 36% of the groundwater sample classified as fresh water and 64% of samples classified as Brackish water (Freeze and Cherry, 1979) (Table, 1., Fig 5).

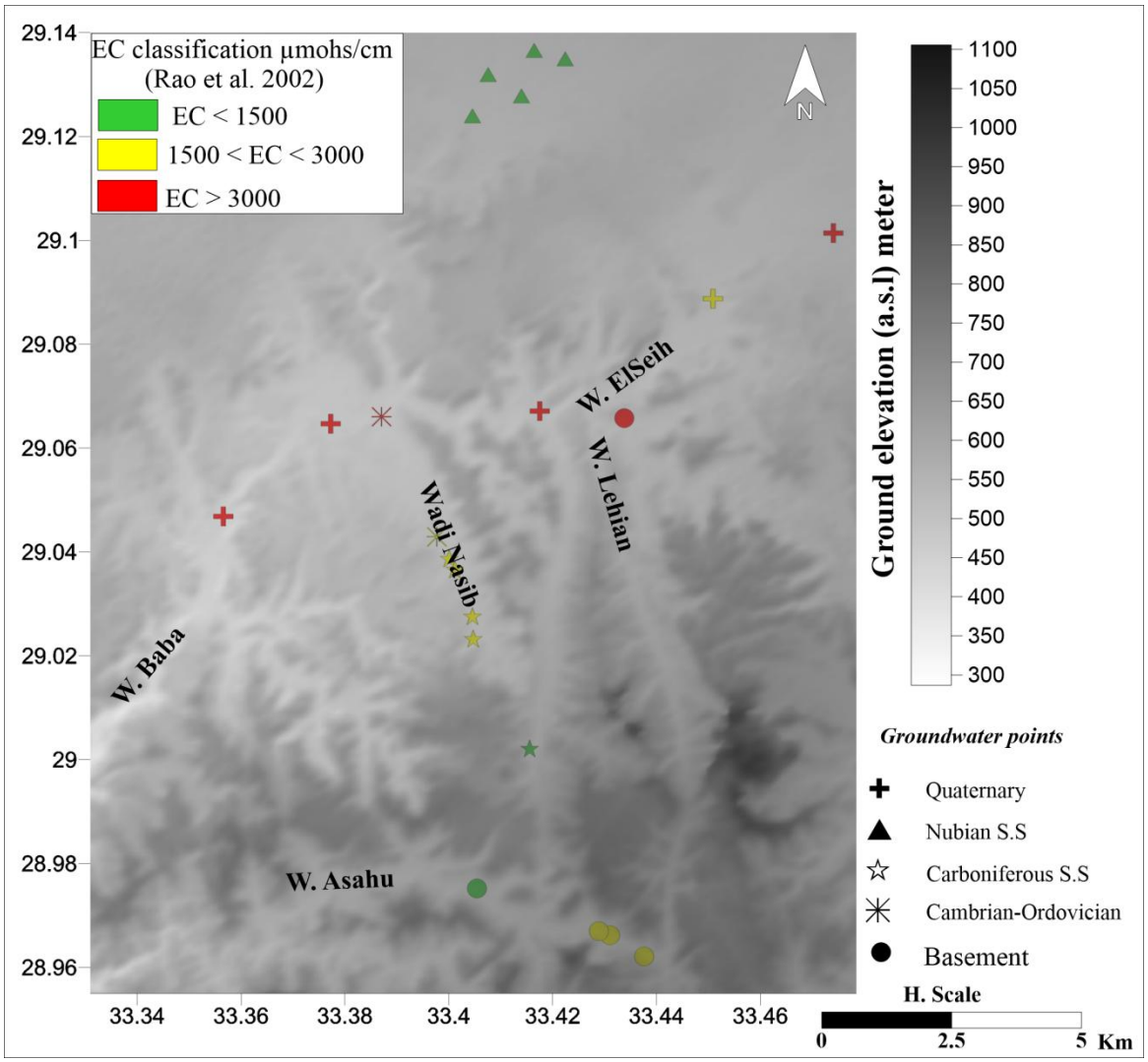


Fig. 4. Electrical conductivity classification map for the groundwater samples in Southwester Sinai.

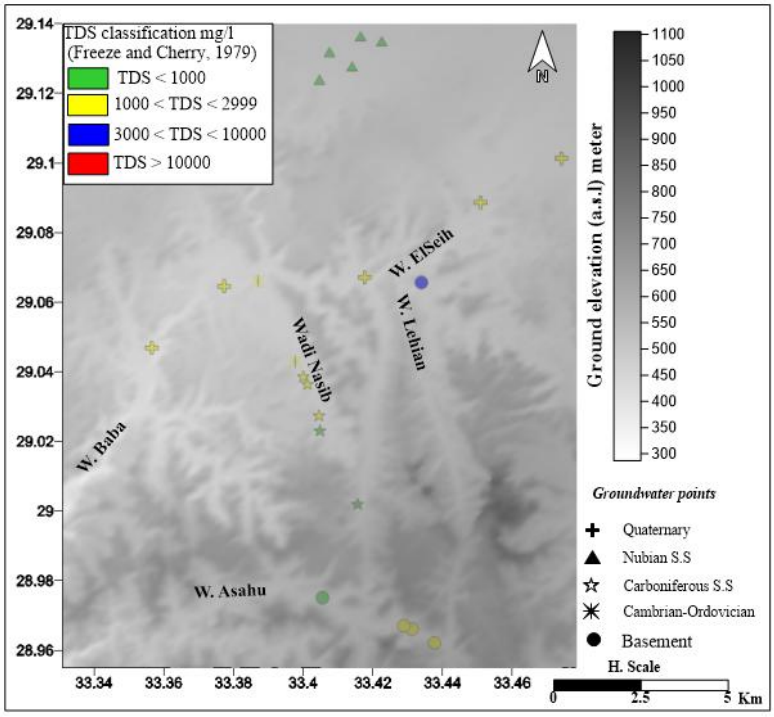


Fig. 5. Total dissolved solids classification map for the groundwater samples in Southwester Sinai.

Hydrochemical classification and water type

In general, we can categorize water types the groundwater samples (aquifers) (Table, 2) according to the relative concentrations of major ions. Table 2 shows that the Quaternary Aquifer system facies ranging from Na–Cl to Na–Ca–Cl–SO_4 reflecting the influence of evaporite dissolution, marine salts, or prolonged residence time, leading to saline enrichment. The presence of Ca^{2+} and Na^{+} suggests cation exchange or mixing with fresher recharge. The Nubian Sandstone Aquifer shows Na–Ca–SO_4–HCO_3 facies which characteristic of intermediate evolutionary stages, where silicate weathering, carbonate dissolution, and sulfate reduction or gypsum dissolution collectively contribute to the ionic dominance.

Carboniferous Aquifer shows Na–Ca–Cl–HCO_3 water type suggests a transitional environment, where carbonate dissolution and evaporite influences (contributing Cl^{-}). The near-equivalence of Ca^{2+} and Mg^{2+} may reflect dolomitic sources or dissolution of mixed carbonate minerals. Cambrian Aquifer shows a clear sodium–chloride dominance, with

sulfate as the secondary anion and bicarbonate the least abundant. The Na–Cl–SO_4 facies indicate a more advanced saline environment, probably under the influence of water–rock interaction. The hydrochemical signature of the Basement Aquifer is transitional between a relatively fresh Mg–Na–HCO_3–Cl type and a saline Na–Cl–SO4 end-member, suggesting the influence of both shallow, recently recharged waters with dominant carbonate weathering and Mg–HCO3 signatures and deeper saline brines (Na–Cl–SO_4) via fracture-controlled flow pathways or different mixing levels.

Table 2. Aquifers water type, dominance anions and cations in the area under investigation.

Aquifer Group	Dominant Cations (in meq/L order)	Dominant Anions (in meq/L order)	Primary Hydrochemical Facies (Water Type)
Quaternary	$Na^+ > Ca^{2+} > Mg^{2+}$	$Cl^- > SO_4^{2-} > HCO_3^-$	Na–Cl to Na–Ca–Cl–SO_4
Nubian Sandstone	$Na^+ > Ca^{2+} > Mg^{2+}$	$SO_4^{2-} \approx HCO_3^- \approx Cl^-$	Mixed Na–Ca–SO_4–HCO_3
Carboniferous	$Na^+ > Ca^{2+} \approx Mg^{2+}$	$Cl^- \approx HCO_3^- > SO_4^{2-}$	Mixed Na–Ca–Cl–HCO_3.
Cambrian	$Na^+ > Ca^{2+} > Mg^{2+}$	$Cl^- > SO_4^{2-} > HCO_3^-$	Na–Cl–SO_4
Basement	$Na^+ > Ca^{2+} \approx Mg^{2+}$	$Cl^- > HCO_3^- \approx SO_4^{2-}$	Mg–Na–HCO_3–Cl *(fresh)* to Na–Cl–SO_4 *(saline)*

Trace and heavy metals

The concentrations of trace and heavy metals in the studied aquifers (Table 3) were compared with the standards of drinking water of the World Health Organization (WHO, 2022). The Quaternary Aquifer water samples show exceed permissible limits for Al (0.21–0.54 mg/L vs. 0.2 mg/L threshold). Samples BW14 and 26 H show elevated levels of Cd (0.02 vs. 0.003 mg/L), Fe (0.33 vs. 0.3 mg/L), Mo (0.11–0.13 vs. 0.07 mg/L), and severe Pb contamination (0.21 vs. 0.01 mg/L). The Nubian Sandstone Aquifer showed that all samples exceed the WHO limits for Cr (0.07 vs. 0.05 mg/L), Ni (0.11–0.14 vs. 0.07 mg/L), and Pb (0.20 - 0.25vs. 0.01 mg/L).

The Carboniferous Aquifer, exceedances were recorded in sample NW1 for Al (0.43 mg/L); samples AL7, NW8, and NW9 for Cd (0.01–0.03 mg/L); sample NW8 for Cr (0.12 mg/L); and samples LW6 and NW9 for Ni (0.11–0.12 mg/L). Significant Pb contamination is

present in LW6, AL7, NW1, and NW9 (0.04–0.19 mg/L). The Cambrian-Ordovician Aquifer recorded that both NW10 and NW11 exceed the limit for Cr (0.09–0.11 mg/L), while NW11 also surpasses the thresholds for Cd (0.01 mg/L) and Ni (0.10 mg/L). The Basement Aquifer samples EW2 and SbW13 exceed the Cd limit (0.02 mg/L), and EW4 and SbW13 surpass the Cr threshold (0.09–0.11 mg/L). The majority of samples (EW3, EW4, EW5, and SbW13) consistently exceed the reference values for both Mo (0.13–0.17 mg/L) and Ni (0.09–0.12 mg/L). Notable Pb exceedances occur in EW3, EW2, and SbW13 (0.06–0.25 mg/L).

The pervasive exceedance of toxic heavy metals most notably Lead, Cadmium, and Chromium across all stratigraphic units reflected active geochemical weathering and rock dissolution. Consequently, these groundwater resources are unsuitable for domestic drinking purposes without treatment.

Table 3. Trace and heavy metals constituents for groundwater samples in the area under investigation.

Code / aquifer		Al	B	Cd	Cr	Cu	Fe	Mn	Mo	Ni	Pb	Zn
SbW12	Quaternary	0.21	0.41	<0.003	<0.01	<0.009	<0.02	0.004	0.05	<0.002	<0.008	0.01
BW14		0.54	0.36	0.02	0.05	0.01	0.33	0.16	0.13	0.04	0.21	0.14
26 H		0.32	0.34	0.02	<0.01	0.01	0.33	0.11	0.13	0.04	0.21	0.01
37 H		0.27	0.42	<0.003	<0.01	<0.009	<0.02	0.004	0.05	<0.002	<0.008	0.01
28 H		0.39	0.35	<0.003	<0.01	<0.009	<0.02	0.004	0.05	<0.002	<0.008	0.01
RW15	Nubian sandstone	0.05	0.06	<0.003	0.07	<0.009	<0.02	<0.002	0.04	0.11	0.23	0.03
32 H		0.05	0.06	<0.003	0.07	<0.009	<0.02	<0.002	0.04	0.14	0.25	0.03
33 H		0.05	0.06	<0.003	0.07	<0.009	<0.02	<0.002	0.04	0.12	0.2	0.03
34 H		0.05	0.06	<0.003	0.07	<0.009	<0.02	<0.002	0.04	0.12	0.24	0.03
35 H		0.05	0.06	<0.003	0.07	<0.009	<0.02	<0.002	0.04	0.12	0.21	0.03
LW6	Carbonefrous	<0.01	0.27	<0.003	0.05	0.02	<0.02	<0.002	0.15	0.12	0.19	0.01
AL7		<0.01	<0.007	0.03	<0.01	<0.009	<0.02	<0.002	0.04	0.06	0.09	0.12
NW1		0.43	0.31	<0.003	0.04	0	<0.02	<0.002	0.07	0.02	0.08	<0.009
NW8		<0.01	0.23	0.01	0.12	0.08	<0.02	<0.002	0.07	<0.002	<0.008	0.06
NW9		<0.01	0.06	0.02	0.04	0.06	<0.02	<0.002	0.11	0.11	0.04	<0.009
NW10	Ca	<0.01	0.08	<0.003	0.11	0.08	<0.02	<0.002	0.01	0.04	<0.008	0.06
NW11		0.06	0.1	0.01	0.09	0.06	<0.02	<0.002	<0.001	0.1	<0.008	<0.009
EW2	Basement	<0.01	0.02	0.02	0.05	<0.009	<0.02	<0.002	0.04	0.03	0.11	<0.009
EW3		<0.01	0.32	<0.003	<0.01	0.06	0.21	0.02	0.13	0.1	0.25	<0.009
EW4		0.05	0.24	<0.003	0.11	0.05	<0.02	<0.002	0.17	0.11	<0.008	<0.009
EW5		<0.01	0.22	<0.003	<0.01	<0.009	<0.02	<0.002	0.15	0.12	<0.008	<0.009
SbW13		<0.01	0.51	0.02	0.09	0.03	<0.02	<0.002	0.15	0.09	0.06	0.14

Processes controlling groundwater chemistry

The triangular anionic zone of Piper diagram (Fig. 6) shows that the Quaternary Aquifer constitutes Na-Cl hydrochemical evolution end-member. Its high salinity is due to evaporite dissolution and evaporative concentration under hyper-arid conditions, with secondary

salinization from irrigation returns further accentuating the Na-Cl dominance. Nubian and Carboniferous Sandstone Aquifers are in a transitional evolution between Ca-Mg-Cl and Na-Cl facies.

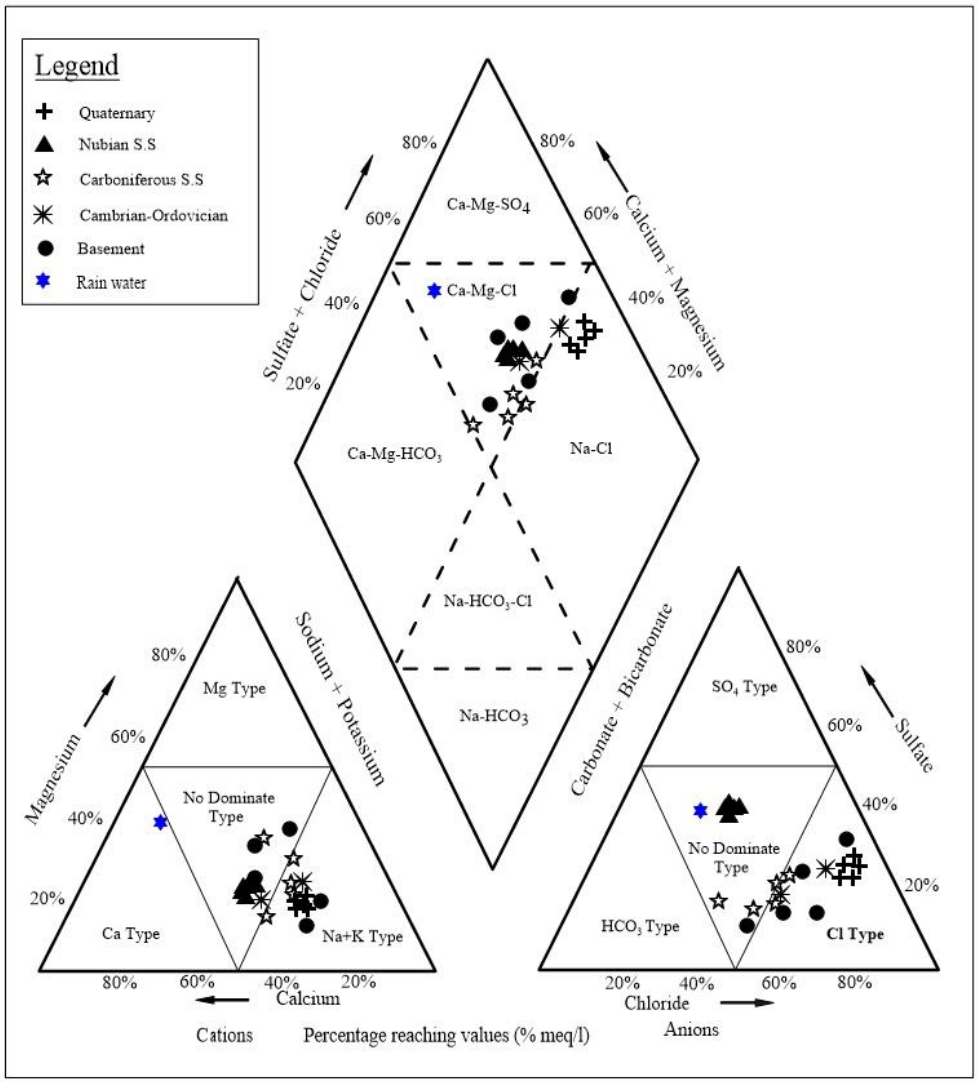


Fig. 6. Piper's trilinear diagram (1944) showing the relationship between dissolved ions and water type in the Southwester Sinai area.

Their chemistry is representative of rock-matrix interaction in deep paleo-groundwater systems. The Cambrian-Ordovician and Basement Aquifers are also in a transitional evolution such as Nubian and Carboniferous Sandstone Aquifers but exhibit a scattered vertical distribution within the Ca-Mg-Cl sub-field, possibly suggestive of heterogeneous, structurally compartmentalized flow systems. Mineralization is structurally controlled, with water-rock interactions in fractured crystalline bedrock and basal sedimentary sequences.

Gibb's plot shows two main hydrochemical processes controlling the groundwater mineralization in the study area, with a clear division between shallow evaporitic systems and deep rock-dominated systems. The Quaternary Aquifer is apparently in the evaporation-dominance field, where the hyper-arid climate leads to intensive evapotranspiration, concentrating dissolved solutes and enriching the residual brine in Na^+ and Cl^-.

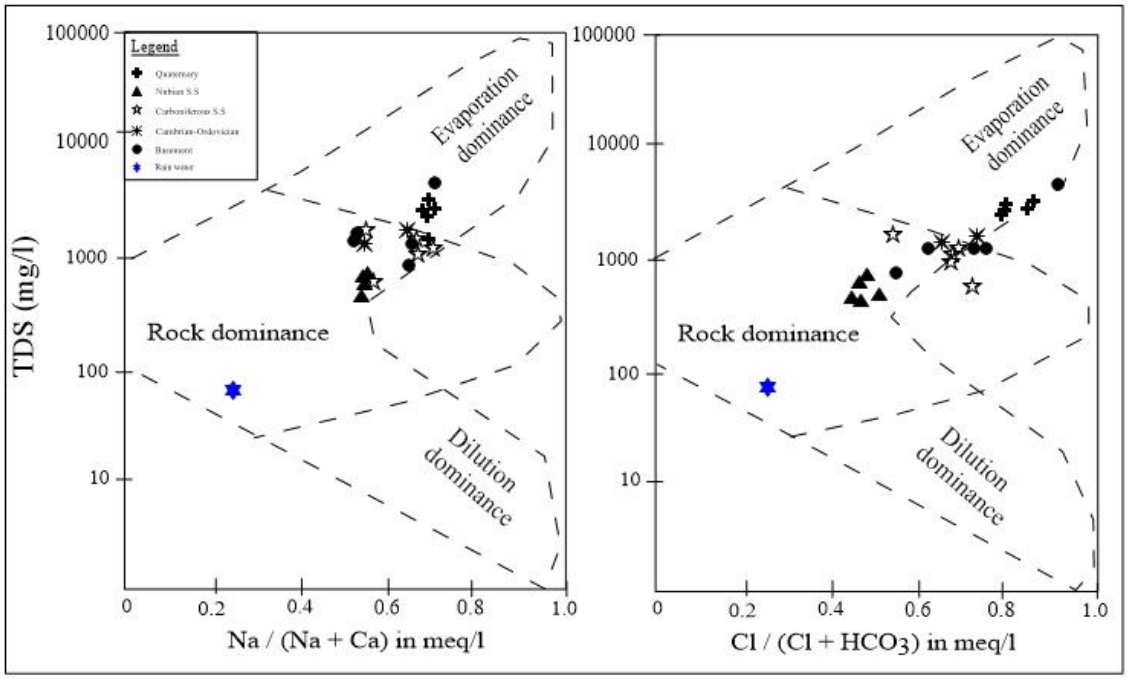


Fig. 7. Gibbs (1970) diagram showing the origin of salinity in the Southwester Sinai area.

This evaporation process is further enhanced by irrigation return flows, and the aquifer is further supported as the ultimate evolutionary endpoint by anthropogenic secondary salinization. The Nubian, Carboniferous, Cambrian-Ordovician and Basement aquifers lie in the rock-water interaction field. The transitional state between rock dominance and dilution in the Nubian and Carboniferous sandstones point to water-rock interactions in sandstones with silicate weathering. The Cambrian-Ordovician and Basement aquifers have rock-dominated signatures with structural constraints (Fig. 7).

Sulin genetic classification diagram (Fig. 8) shows that the Quaternary aquifer shows a $MgCl_2$ Facies with the recent marine domain, strongly indicative of active salinization processes such as evaporite dissolution reveals that the dissolution of marine salts from the host rocks.

The Cambrian-Ordovician aquifer, despite plotting similarly in the $MgCl_2$ marine field, is attributed to deep connate marine waters fossil, reflecting long-term geochemical equilibration with ancient sedimentary environments. The fractured Basement aquifer exhibits a dual signature, with the majority of samples falling into the marine $MgCl_2$ domain, implying upward migration of mineralized saline fluids through fault networks, while a single outlier in the meteoric Na_2SO_4 field underscores the inherent heterogeneity of fractured systems, likely representing a locally isolated recharge-fed fracture pathway. In contrast, the Na_2SO_4 facies in the Nubian S.S aquifer in the meteoric realm indicate long term water rock interaction, cation exchange and sulfate dissolution under deep paleo-recharge conditions. Carboniferous Sandstone aquifer is predominantly meteoric Na_2SO_4 type but extend well into the marine field indicating the presence of transitional mixing zones between ancient meteoric waters and saline end-members. Collectively, these patterns delineate a spectrum from ancient meteoric end-members to connate and recent dissolution of marine salts from the host rocks is a predominant process, with transitional and structurally controlled mixing governing the hydrochemical variability observed across the different aquifer lithologies.

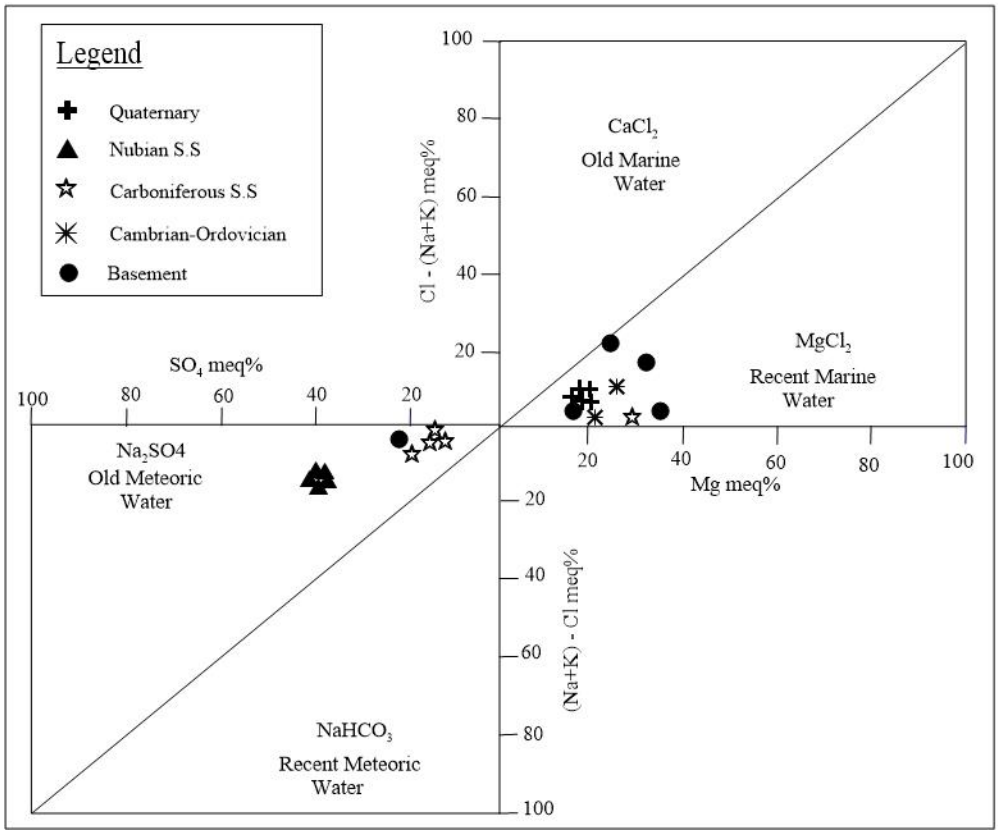


Fig. 8. Genetic types of groundwater by applying Sulin's diagram.

According to the isotopic data ($\delta^{18}O$ and $\delta^{2}H$) and its relations (Table, 4) (Figs. 9,10), the groundwater aquifers in the study area exhibits different evolutionary trends. The isotopic data show a bifurcated recharge regime with primordial non-evaporated meteoric waters and modern recharge that has undergone substantial surface evaporation.

The first is direct meteoric and Paleo-Recharge: The Nubian Sandstone aquifer together with selected samples from the Basement (Ew5) and Carboniferous Sandstone (Lw6) show significantly depleted isotopic signatures with $\delta^{18}O$ ‰ values ranging from -5.38‰ to -4.82‰. These samples are located close to the Global Meteoric Water Line (G.M.W.L) and the Mediterranean Meteoric Water Line (M.M.W.L). Moreover, they have high d-excess values (12.54-17.76) that are close to the local precipitation signal (d-excess = 18.55). This suggests that these groundwaters are the product of direct, non-evaporated meteoric rainfall, probably reflecting deep paleo-recharge during cooler and more humid times in the past.

The second is e**vaporated Recharge,** conversely samples from the Quaternary aquifer (well Sbw12), certain Carboniferous Sandstone wells (Nw1), and specific Basement fractures (well Sbw13) show distinct isotopic enrichment, with $\delta^{18}O$ values greater than -3.0‰. These samples plot along a characteristic evaporation line that deviates to the right of the meteoric water lines. This trajectory signifies that the recharge waters were subjected to significant kinetic evaporation prior to, or during, infiltration into the shallow or fractured aquifer systems.

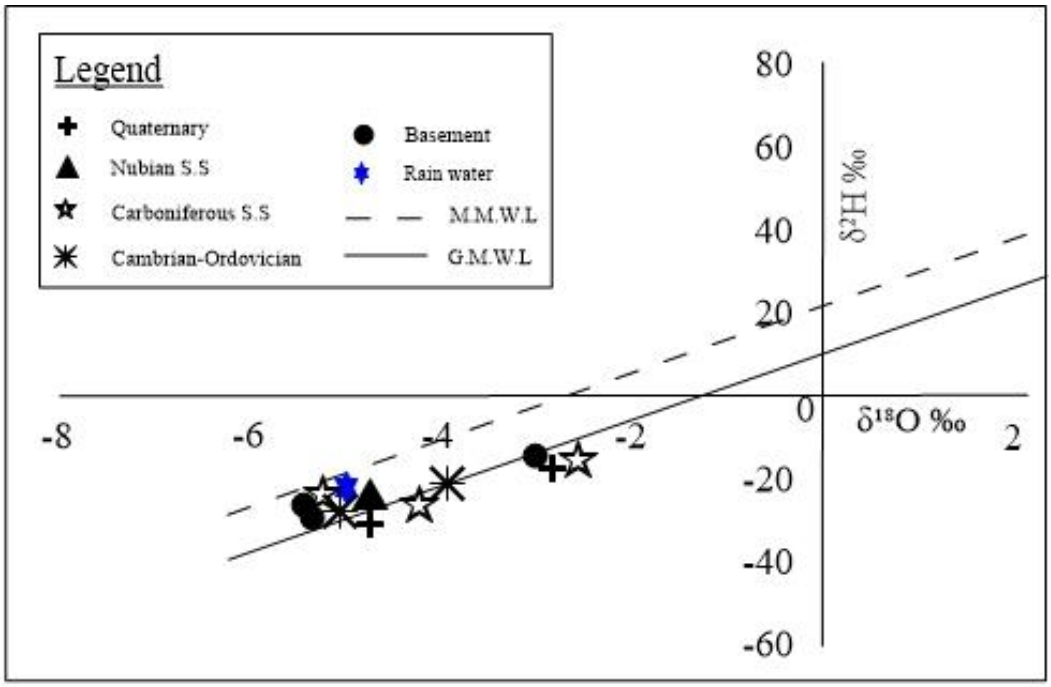


Fig. 9. Relationship Between $\delta^{18}O$ and $\delta^{2}H$ in the Studied Aquifer Systems South western Sinai.

The IAEA (1981) standards on the relationship of oxygen-18 and chloride (Fig. 10) show the different processes responsible for salinization of groundwater in the studied aquifers. The first mechanism is evaporative concentration. A positive correlation between $\delta^{18}O$ and Cl^-, and a negative correlation between δ 18 O and d excess clearly indicates kinetic evaporation. This is evidenced in the Quaternary Aquifer, where high chloride concentrations and strong isotopic enrichment indicate active recycling of irrigation water, leaching from the surface, and evaporative concentration typical of unconfined agricultural

systems, and some saline samples from the Basement (Sbw13, TDS = 3947.92 mg/L; Cl^- = 1528.54 mg/L) and (Sbw12), which show higher salinity, $\delta^{18}O$ enrichment, and lower d excess values of 8.04 and 5.96, respectively.

The second mechanism is water-rock interaction (mineral dissolution) which causes a horizontal displacement on the Cl-versus-δ18O diagram with large salinity increases, but no concomitant isotopic enrichment. This regime of dissolution is exemplified by the Cambrian–Ordovician Aquifer (e.g., well Nw11) and some of the Quaternary samples (e.g., well Bw14), which show depleted isotopic signatures ($\delta^{18}O$ between –4.84 ‰ and –3.99 ‰) and high chloride concentrations, consistent with salinization by evaporite leaching and long-term rock-water interactions during deep circulation rather than surface evaporation. In contrast, the Nubian Sandstone Aquifer preserves a primary recharge signature with low Cl- concentrations and δ18O values of approximately -4.8 ‰, similar to that of modern precipitation, indicative of deep confined fresh water. The Carboniferous Sandstone Aquifer is characterized by moderate Cl- concentrations and significant enrichment of δ18O (up to -2.3 ‰), indicative of evaporation prior to infiltration or isotopic exchange with carbonate minerals. The Basement Aquifer salinity influenced only by fracture leaching and silicate weathering, without evaporative influence.

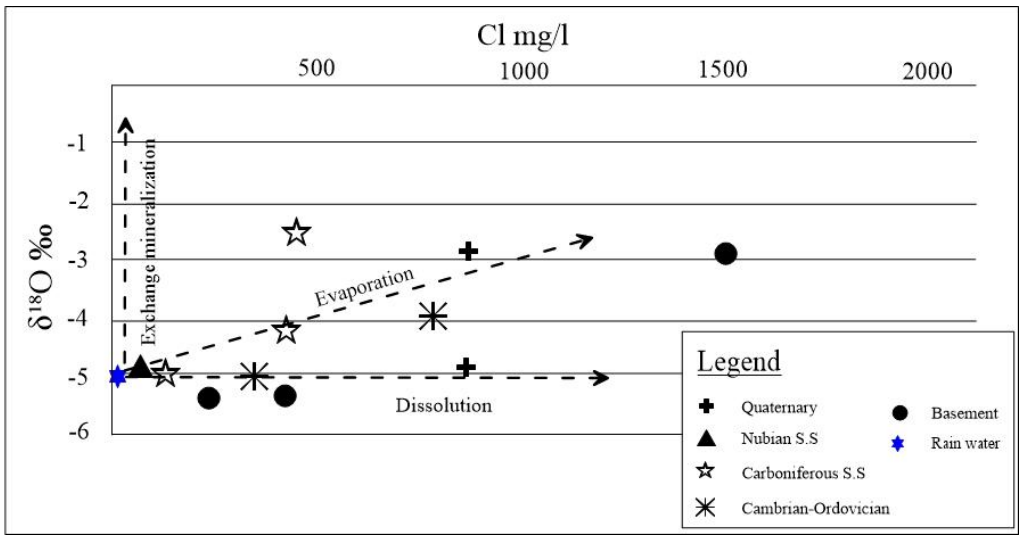


Fig. 10. Change of isotopic composition of water associated with different salinization processes (I.A.E.A., 1981)

Table 4: Stable isotopes result of groundwater samples in the area under investigation.

Code	**aquifer**	**$\delta^{18}O$ ‰**	**$\delta^{2}H$‰**	**d-excess**
Sbw12	Quaternary	-2.81	-16.52	5.96
Bw14		-4.84	-29.89	8.83
Rw15	Nubian Sandstone	-4.82	-26.02	12.54
Lw6	Carboniferous	-4.97	-22.2	17.56
Nw1		-2.57	-15.26	5.3
Nw8		-4.24	-23.18	10.74
Nw10	Camberian - Ordovician	-5.01	-25.94	14.14
Nw11		-3.99	-21.33	10.59
Ew2	Cambrian	-5.3	-29.59	12.81
Ew5		-5.38	-25.28	17.76
Sbw13		-2.93	-15.4	8.04
Rain		-4.99	-21.37	18.55

Conclusion

This research using the hydrogeochemical, isotopic, and water quality attributes of twenty-two groundwater samples from five aquifer systems, indicated a significant distinction between shallow resources impacted by evaporation and deeper systems shaped by rock-water interactions in the southwestern Sinai Peninsula. All groundwater is slightly alkaline, but salinity gradients and hydrochemical classification show that the shallow Quaternary Aquifer contains highly mineralized brackish waters, driven by kinetic evaporation, agricultural recycling, and modern evaporated recharge, while the deeper Nubian Sandstone, Carboniferous Sandstone, Cambrian-Ordovician, and fractured Basement aquifers are controlled by mineral dissolution, silicate weathering, and structurally mediated fault mixing.

Among these, the Nubian Sandstone represents the fresh water, most viable reservoir, sustained by direct, un-evaporated paleo-recharge from ancient, humid climatic regimes, whereas the transitional and fractured aquifers exhibit moderate-to-high salinity and extreme spatial heterogeneity. However, despite the major-ion suitability of the fresher aquifers for agricultural development, active geogenic weathering across all five stratigraphic units has resulted in the pervasive exceedance of World Health Organization (WHO, 2022) thresholds for toxic heavy metals specifically lead (Pb), cadmium (Cd), and

chromium (Cr) rendering the groundwater universally unsuitable for raw domestic drinking purposes without targeted remediation.

Recommendations for sustainable development

To sustainable manage these groundwater resources for drinking water supply and agricultural expansion, a stratified utilization strategy is recommended based on aquifer potentiality, and water quality:

Promising Aquifers for Drinking Water Supply

The Nubian Sandstone Aquifer represented the primary candidate aquifer, which recorded the highest water quality aquifer due to deep paleo-recharge source free from surface evaporation and anthropogenic contamination reflecting the most promising reservoir for municipal and domestic water supply. Treatment requirement due to removal of toxic heavy metals (specifically Pb, Cd, and Cr).

Promising Aquifers Agricultural Development

High-Potential Agricultural Zones represented by the Nubian Sandstone and the Carboniferous Sandstone aquifers provide optimal salinity levels for irrigation without risking immediate soil salinization. The Quaternary aquifer used for irrigation purposes under controlling due to its high salinity, this source should be restricted to salt-tolerant crops. Strict irrigation efficiency approach and soil drainage systems must be enforced.

Author Statement

The Author declares that this work described has not been published previously at any form. The article is not under consideration for publication elsewhere. The article's publication is approved by author and tacitly or explicitly by the responsible authorities where the work was carried out.

A clinical trial: The author declares that the current study is not a clinical trial.

Author contributions statement

All work that was carried out in this research was done by Dr. Ehab Zaghlool, who is the sole author of this article, and it includes: Writing- review & editing, Data curation, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Field and laboratory work, Writing – original draft, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

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

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Authorship

The corresponding author confirm he have read the journal policies and is submitting his manuscript in accordance with those policies

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Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

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