

Article

Groundwater Hydrochemical Characteristics and Water Quality in Egypt's Central Eastern Desert

Ahmed Saleh ^{1,*} , Ahmed Gad ^{2,3} , Alaa Ahmed ², Hasan Arman ²  and Hassan I. Farhat ⁴ ¹ National Research Institute of Astronomy and Geophysics (NRIAG), Cairo 11421, Egypt² Geosciences Department, College of Science, United Arab Emirates University, Al Ain 15551, United Arab Emirates³ Geology Department, Faculty of Science, Ain Shams University, Cairo 11566, Egypt⁴ Geology Department, Faculty of Science, Suez University, El Salam City 43518, Egypt

* Correspondence: ahmed.saleh@nriag.sci.eg

Abstract: The rapid expansion of economic activities in Egypt's Central Eastern Desert has resulted in poorly coordinated groundwater development, having a negative impact on the resource. This study was conducted to assess the hydrochemical characteristics of the different aquifers in the Central Eastern Desert, with an emphasis on the impact of seawater intrusion and groundwater quality for different purposes. A total of 21 groundwater samples were collected representing the three main aquifers (Eocene Carbonate, Nubian Sandstone, and Fractured Basement) in the Central Eastern Desert, and analyzed for major ions and trace elements. The majority of the samples had electrical conductivity values that exceeded the salinity limit for natural water. Groundwater saline load is primarily influenced by sodium, calcium, chloride, and sulfate concentrations. The groundwater in the Central Eastern Desert mainly consists of Na-Cl, Ca-Cl, and Na-SO₄ water-types. Saltwater intrusion and water-rock interactions via cation exchange and minerals weathering are the primary controlling factors of groundwater hydrochemistry. The high salinity of this groundwater renders it unsuitable for irrigation or consumption. Additionally, it is unfit for domestic use based on total hardness values. Furthermore, the Al, Cd, Fe, Mn, and Ni concentrations in the investigated groundwater exceed the allowable limits for human consumption. Proper mitigation measures and adaptation strategies are required for groundwater sustainability in the Central Eastern Desert.

Keywords: groundwater; hydrogeochemistry; hydrochemical facies; seawater intrusion; water quality; Eastern Desert



Citation: Saleh, A.; Gad, A.; Ahmed, A.; Arman, H.; Farhat, H.I. Groundwater Hydrochemical Characteristics and Water Quality in Egypt's Central Eastern Desert. *Water* **2023**, *15*, 971. <https://doi.org/10.3390/w15050971>

Academic Editors: Imokhai Theophilus Tenebe and Domenico Cicchella

Received: 21 February 2023

Revised: 26 February 2023

Accepted: 27 February 2023

Published: 3 March 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In semiarid, arid climate, and coastal regions, communities rely mostly on groundwater as their source of drinking water [1,2]. Generally, groundwater is a finite natural resource of fresh water on Earth. The daily drinking and domestic water need of about 33% of the world's population are satisfied by groundwater [1,3,4]. Almost 2.1 billion people worldwide don't have access to safe drinking water [5]. Groundwater quality has received more attention in recent decades as a result of growing urbanization, intense agricultural activities, reclamation of new agricultural lands, and industrialization, which, in addition to an increasing population, pose an increased risk of groundwater and soil pollution [1,6–8]. Groundwater quality is affected by rainfall rates, the nature of recharge water, and surface-water resources, in addition to hydrogeochemical processes occurring in an aquifer [2,9]. Groundwater hydrogeochemistry is affected by geochemical natures for oxidation-reduction, ionic exchange, mineral weathering, authigenic mineral dissolution, and precipitation, in addition to groundwater abodes of time [1,9,10].

Intrusion processes are considered a major factor in influencing groundwater chemistry [11–14]. Salinization presents an outstanding problem threatening groundwater resources in coastal basins of arid and semi-arid climates [15]. Salinization process is

directly related to the effects of many factors (e.g., marine intrusion, climatic conditions, aquifers characteristics, and anthropogenic activities) that can exacerbate or decrease these problems [14,16–18]. The origin of the salinization of groundwater in coastal areas has been investigated by implementing many approaches [19,20]. The balance of groundwater discharge and recharge clarify how far saline water infiltrates, the aquifer–piezometric level, and the distance between the groundwater aquifer and the saline water sources, in addition to its geological structure [21]. Accordingly, it is indispensable to grasp the chemical processes leading to the salinity of coastal groundwater aquifers to create a valuable plan for the sustainable management of all vulnerable groundwater resources [20]. In addition, continuous groundwater extraction leads to a lowering in the groundwater table leading to increases in domestic water seepage and seawater intrusion, especially in the coastal areas [22,23].

A porous medium and permeable matrix are two terms that are frequently used to describe sandstone aquifers. Such aquifers, however, may be heavily fractured if the characteristics of the rock and the time of the deformation encourage brittle failure and crack opening [24–27]. Fractured carbonate aquifers are a common source of water supply [28,29]. In most sedimentary rocks, rapid solute transport of contaminants occurs within bedding plane fractures and joints rather than through intergranular porosity [24,28]. Groundwater availability in igneous and metamorphic rock is extremely rare and is directly controlled by geological processes (weathering and fracturing) [1]. The current consciousness is focused on preserving existing constrained drinking water resources in the context of rising demand [13,30]. So, continuous monitoring and assessment of both quantity and quality of existing limited water sources are extremely vital [30,31]. Effective continuous monitoring surveys are needed for discovering the mechanisms which control groundwater quality in coastal provinces. Considering the factors that contribute to groundwater quality deterioration will be critical for future management plans [32]. Many health and agriculture organizations establish standards used extensively comparing various components (major ions concentrations) and pollutants (e.g., potentially toxic elements and radionuclides) for irrigation and drinking water [5,33,34]. In addition, a lot of water quality indices and statistical analyses equally be utilized to reduce reliable data for assessing water-quality appropriateness within single and multiple–digit tools [32,35].

Nowadays, Egypt faces serious water shortage challenges coinciding with high population growth and climate change. Many focuses have recently been placed on agricultural developments and sustainable growth in the Egyptian deserts, and how they must meet most crucial objectives of the Governmental Strategy for Sustainable Agricultural Development 2030 [36,37]. Therefore, the resources of groundwater in Egypt play critical roles in satisfying part of water requirements for different uses, especially in coastal and arid provinces [8,37,38]. This study's main objectives are (i) to recognize the mechanisms governing groundwater chemistry in Egypt's Central Eastern Desert (CED), (ii) to evaluate the adequacy of groundwater quality for various uses.

2. Materials and Methods

2.1. The Study Area

The study area lies between 25°50'–27°00' N and 32°30'–34°25' E in the CED, Egypt (Figure 1). The geologic setting of the CED is represented mainly by the Precambrian basement rocks (igneous and metamorphic), which form the Red Sea Hills, and it is bordered on the eastern side along the coast by a narrow strip of sedimentary succession, and on the western side, it is also bounded by sedimentary rocks that extend up to Nile Valley. Basement rocks includes gneisses, serpentinites, metagabbros, and metabasalts that have been intruded by volcanic and younger granitic rocks and are overlain by molasse sediments (metasediments) [39,40]. After a long period of tectonic activity, the sedimentary rocks were deposited inside the subsidence blocks (basins) of the basement rocks near the coastal plain and on the western side until the Nile Valley [41]. The Nubian Sandstone Formation of Lower Cretaceous age, the oldest rock unit in the sedimentary succession, is

distinguished by fine- to coarse-grained sandstone with some shale and clay beds [42]. It is overlain by Late Cretaceous to Eocene shale and carbonate marine deposits [43]. The post-rift sediments are comprised of alluvial and alluvial fans deposits. The groundwater in the Central Eastern Desert is available at different depths and lithology. Based on the lithology, three main regional aquifer systems are distinguished; they are the Eocene Carbonate, the Nubian Sandstone (Upper Cretaceous sandstone, shale, and marl layers), and the underlying Fractured Basement aquifer (Precambrian igneous and metamorphic rocks).

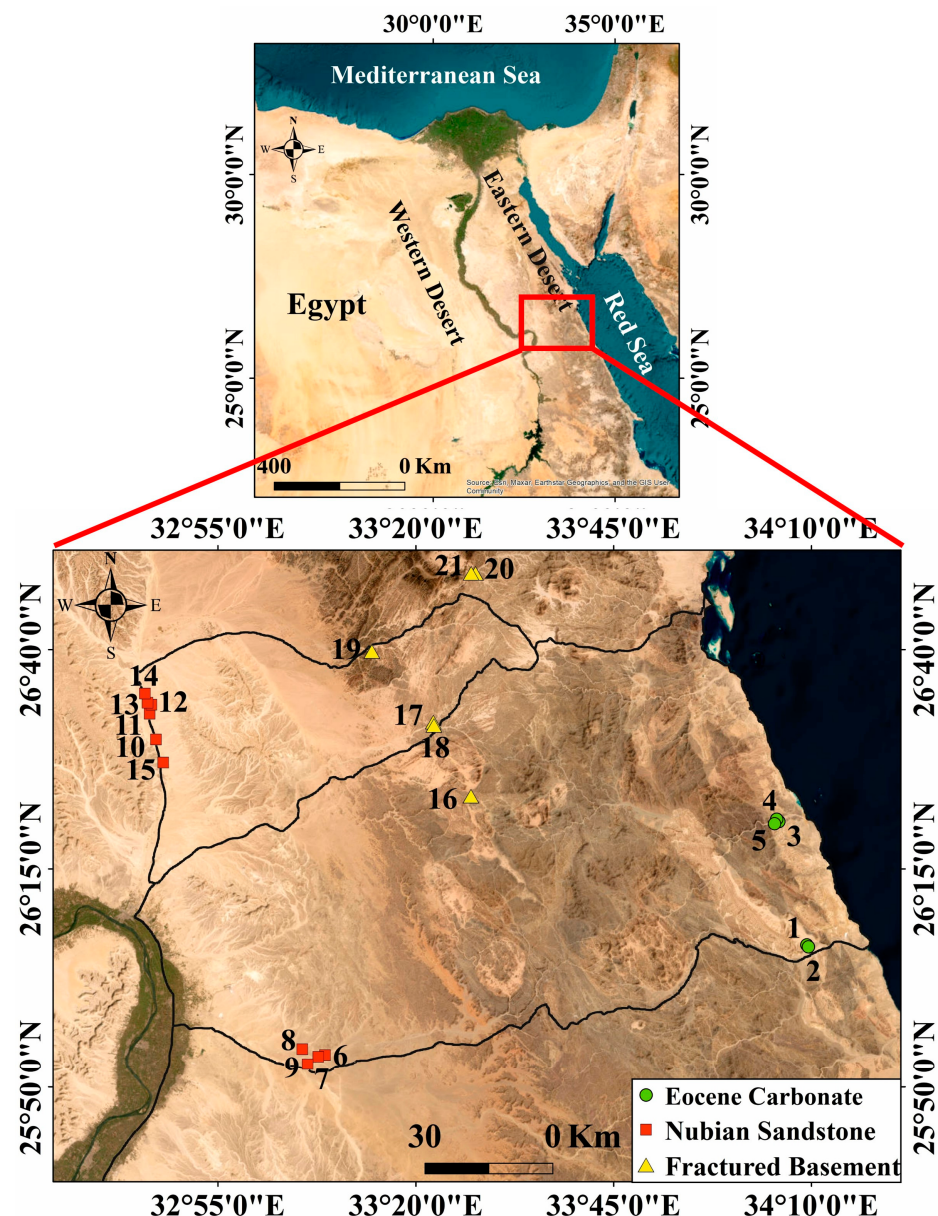


Figure 1. The study area and sampling site's locations.

2.2. Sampling and Analyses

Twenty-one groundwater samples in all were collected in 2019–2020 from the wells located throughout the Golden Triangle region of the CED (Figure 1). Samples were taken from the three main aquifers in the studied area Eocene Carbonate (EOC), Nubian Sandstone (NS), and Fractured Basement (FB) aquifers. To avoid the effects of static water, water was flushed for about 10 min before collecting samples. 1 Litre of water was collected in new and rinsed two polyethylene bottles for each sample. One bottle was filled with only fresh well water, while the other was acidified with HNO_3 to a $\text{pH} < 2$ in order to

reduce trace elements adsorption to bottle walls and biological activity. Titration with H_2SO_4 (0.01 N) was used to determine the concentrations of carbonate and bicarbonate. An ion chromatography system (Dionex, ICS-1100, Thermo Fisher Scientific Inc., Waltham, MA, USA) was used to measure Ca^{2+} , Mg^{2+} , Na^+ , K^+ , SO_4^{2-} , and Cl^- . The accuracy and reliability of the chemical analysis were examined by the Electrical Balance (EB%) between the cations and anions [44]. Trace elements (Al, Cd, Cr, Cu, Co, Fe, Mn, Mo, Ni, Pb, V, and Zn) were measured using inductively coupled plasma mass spectrometry (ICP, POEMSIII, thermo Jarrell elemental company, Waltham, MA, USA) with standard solutions containing 1000 mg/L (Merck). The major ions and trace elements were analyzed in the Desert Research Centre's hydro-geochemistry laboratories in Cairo, Egypt.

2.3. Groundwater Quality

The geochemical characteristic of water is an essential component in the process of evaluation of water quality. The current study attempted to determine the suitability of existing groundwater for various purposes. Chloride content, Electrical Conductivity (EC) [45], Soluble Sodium Percentage (SSP) [46], Sodium Adsorption Ratio (SAR) [47], Residual Sodium Carbonate (RSC) [47], Magnesium Adsorption Ratio (MAR) [47], TDS [48], Total Hardness (TH) [49], and Corrosivity Ratio (CR) [50], and toxic metal content are used to assess its suitability for irrigation, domestic uses, and drinking. Table S1 summarizes the formulae used to calculate the various indicators (in Supplementary Materials).

2.4. Data Treatment

The map of sampling locations in the study area was created using Google Earth and Arc-Map software (Arc-Map 10.3). Descriptive statistics and box and whisker plot charts (boxplots) have been presented by OriginLab (version OriginPro 2021). Bivariate X–Y plots (bivariate diagrams) between major ion have been presented by Excel (Microsoft Office 365) to precisely determine the origin of each element and separate different mechanisms that contribute to groundwater evolution. OriginLab, also, was used to calculate and present multivariate statistical analyses in the form of Pearson Correlation Coefficient (PCC) and R mode Hierarchical Cluster Analysis (HCA), to elucidate the interrelation between major ions and their effect in groundwater chemistry. Piper diagram is presented using OriginLab and HFE-Diagram is created using the spreadsheet software package, Microsoft Excel (Excel Macro) provided by Giménez-Forcada and Sánchez San Román [51].

3. Results and Discussion

3.1. General Hydrogeochemistry

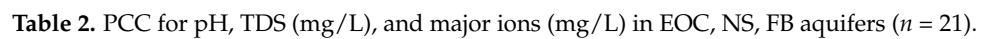
The physicochemical parameters (pH, EC, and TDS) and the major ion concentrations of investigated groundwater samples within the CED representing different aquifer types (EOC, NS, and FB) are presented in Table 1 and Figure 2. The EB% in this study was within 5%, indicating that the chemical analysis was accurate [4,6,13]. From Figure 2 it is evident that the groundwater in the investigated wells samples is characterized by a narrow range of pH values from slightly acidic to neutral (varied between 6 to 7.2). EC ranged from 4270.0–7980.0, 2730.0–12,550.0, and 690.0–5460.0 in the EOC, NS, and FB aquifers, respectively. These values exceeded the recommended EC limit for natural water (1300 $\mu\text{S}/\text{cm}$ at 25 °C; WHO [5]), except for FB aquifer (samples 16, 17, and 20). TDS, like EC, varied greatly, with the higher the value recorded in the NS aquifer and the least values recorded in the FB aquifer. The marked differences in the EC and TDS values reflect significant variation in the hydrochemical features in the EOC, NS, and FB aquifers. The concentration of the major ions in the groundwater samples varies significantly; Ca^{2+} (20.0–888.0), Mg^{2+} (9.11–214.8), Na^+ (105.0–1400.0), K^+ (2.0–17.0), HCO_3^- (108.6–791.8), SO_4^{2-} (50.0–1900.0), and Cl^- (55.0–2900.0 mg/L). Data suggested that the chemistry of groundwater was heterogeneous and governed by a variety of mechanisms, such as evaporation, water-rock interaction mixing processes, and saltwater intrusions [19,38,52]. In a recent study by Sherif et al. [53], groundwater mixing between different aquifers in Egypt's Eastern Desert was

proven utilizing ^{36}Cl abundances and $^{37}\text{Cl}/^{35}\text{Cl}$, $^2\text{H}/^1\text{H}$, and $^{18}\text{O}/^{16}\text{O}$ isotope ratios. In most cases, the three aquifers are dominated by Na^+ , followed by Ca^{2+} , Mg^{2+} , K^+ , and Cl^- , followed by SO_4^{2-} and HCO_3^- . Some fluctuations are observed between Ca^{2+} and Na^+ in NS and FB aquifers. The anionic distribution in the FB aquifer shows complex fluctuation between HCO_3^- , SO_4^{2-} , and Cl^- .

Table 1. Physicochemical parameters and major ions concentrations (mg/L) in EOC, NS, and FB aquifers.

NO.	Aquifer	pH	EC uS/cm	TDS mg/L	Ca^{2+} mg/L	Mg^{2+} mg/L	Na^+ mg/L	K^+ mg/L	HCO_3^- mg/L	SO_4^{2-} mg/L	Cl^- mg/L	EB %
1	EOC	6.4	7980.0	4734.0	557.4	141.5	860.0	14.0	207.2	1251.9	1800.0	−1.88
2		6.4	7330.0	4317.0	530.0	214.8	640.0	15.0	134.2	900.0	1950.0	−2.40
3		6.1	5340.0	3188.0	299.5	121.3	600.0	9.0	109.8	1028.1	1075.0	−2.16
4		6.1	4320.0	2523.0	310.8	116.3	380.0	7.0	195.2	736.8	875.0	−1.68
5		6.3	4270.0	2496.0	267.1	176.5	300.0	17.0	268.4	926.3	675.0	−1.68
Min.	EOC (N = 5)	6.1	4270.0	2496.0	267.1	116.3	300.0	7.0	109.8	736.8	675.0	−2.4
Max.		6.4	7980.0	4734.0	557.4	214.8	860.0	17.0	268.4	1251.9	1950.0	−1.7
6	NS	6.8	3770.0	2219.0	208.0	65.7	480.0	8.0	316.4	475.5	800.0	−1.03
7		6.9	12,550.0	7424.0	888.0	202.2	1400.0	13.0	194.4	1900.0	2900.0	−0.93
8		7.2	3810.0	2229.0	91.5	35.4	680.0	7.0	316.4	407.7	825.0	0.41
9		6.8	4730.0	2893.0	75.5	17.7	920.0	7.0	292.8	826.8	900.0	−2.13
10		6.0	9640.0	5699.0	609.9	165.8	1100.0	6.0	122.0	1556.6	2200.0	−2.30
11		6.2	4270.0	2521.0	358.1	85.9	360.0	5.0	134.2	794.7	850.0	−2.36
12		6.4	3010.0	1768.0	114.9	100.5	340.0	3.0	146.4	586.1	550.0	−2.14
13		6.2	3710.0	2209.0	279.0	75.9	360.0	9.0	134.2	688.1	730.0	−1.43
14		6.6	2730.0	1609.0	95.9	35.2	420.0	4.0	183.0	382.7	580.0	−2.38
15		6.8	3340.0	2078.0	45.6	30.3	640.0	5.0	292.4	698.8	500.0	−1.08
Min.	NS (N = 10)	6.0	2730.0	1609.0	45.6	17.7	340.0	3.0	122.0	382.7	500.0	−2.4
Max.		7.2	12,550.0	7424.0	888.0	202.2	1400.0	13.0	316.4	1900.0	2900.0	0.4
16	FB	7.1	1057.0	642.0	95.7	17.7	105.0	2.0	268.4	175.3	112.5	−1.67
17		7.0	690.0	405.0	20.0	9.1	120.0	2.0	243.6	65.0	55.0	0.84
18		6.8	3650.0	2255.0	235.0	20.0	500.0	5.0	280.7	804.2	550.0	−2.21
19		6.3	5460.0	3041.0	700.0	96.0	240.0	5.0	108.6	259.8	1650.0	−0.22
20		6.9	1128.0	638.0	28.0	13.0	200.0	2.0	390.0	50.0	137.5	−0.43
21		7.0	2595.0	1600.0	125.4	25.3	390.0	13.0	791.8	90.6	380.0	0.12
Min.	FB (N = 6)	6.3	690.0	405.0	20.0	9.1	105.0	2.0	108.6	50.0	55.0	−2.2
Max.		7.1	5460.0	3041.0	700.0	96.0	500.0	13.0	791.8	804.2	1650.0	0.8
Min.	All Samples (N = 21)	6.0	690.0	405.0	20.0	9.1	105.0	2.0	108.6	50.0	55.0	−2.4
Max.		7.2	12,550.0	7424.0	888.0	214.8	1400.0	17.0	791.8	1900.0	2900.0	0.8
Mean		6.6	4541.9	2689.9	282.6	84.1	525.5	7.5	244.3	695.5	956.9	−1.4

Table 2 displays R values of the PCC between physicochemical parameters and major ions of the investigated groundwater samples. The correlation matrix shows a significant positive correlation of TDS with Cl^- ($R = 0.937$), SO_4^{2-} ($R = 0.915$), Na^+ ($R = 0.880$), Ca^{2+} ($R = 0.879$), Mg^{2+} ($R = 0.794$), and K^+ ($R = 0.556$). Moreover, it was observed strong positive correlation of Cl^- with Ca^{2+} ($R = 0.930$), SO_4^{2-} ($R = 0.817$), Mg^{2+} ($R = 0.804$), Na^+ ($R = 0.797$), and K^+ ($R = 0.507$). likewise, SO_4^{2-} with Na^+ ($R = 0.848$), Mg^{2+} ($R = 0.755$), Ca^{2+} ($R = 0.716$), and K^+ ($R = 0.504$). Ca^{2+} exhibits a positive correlation with Mg^{2+} ($R = 0.798$), which is most likely owing to the dissolution of dolomite and calcite. HCO_3^- exhibits a negative and weak correlation with the other ions as well as TDS. This means that the majority of cations are strongly associated with Cl^- and SO_4^{2-} . It may indicate the impact of seawater intrusion on groundwater because the major anions in seawater are Cl^- and SO_4^{2-} . The R-Mode (variables) dendrogram created using HCA (Figure 3), supports the inferred relationship between TDS and the major ions.



	TDS	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ [−]	SO ₄ ^{2−}	Cl [−]
pH	−0.354	−0.455	−0.603	−0.065	−0.217	0.614	−0.439	−0.367
TDS		0.879	0.794	0.880	0.556	−0.355	0.915	0.973
Ca ²⁺			0.798	0.572	0.473	−0.437	0.716	0.930
Mg ²⁺				0.493	0.678	−0.473	0.755	0.804
Na ⁺					0.413	−0.151	0.848	0.797
K ⁺						0.137	0.504	0.507
HCO ₃ [−]							−0.441	−0.416
SO ₄ ^{2−}								0.817

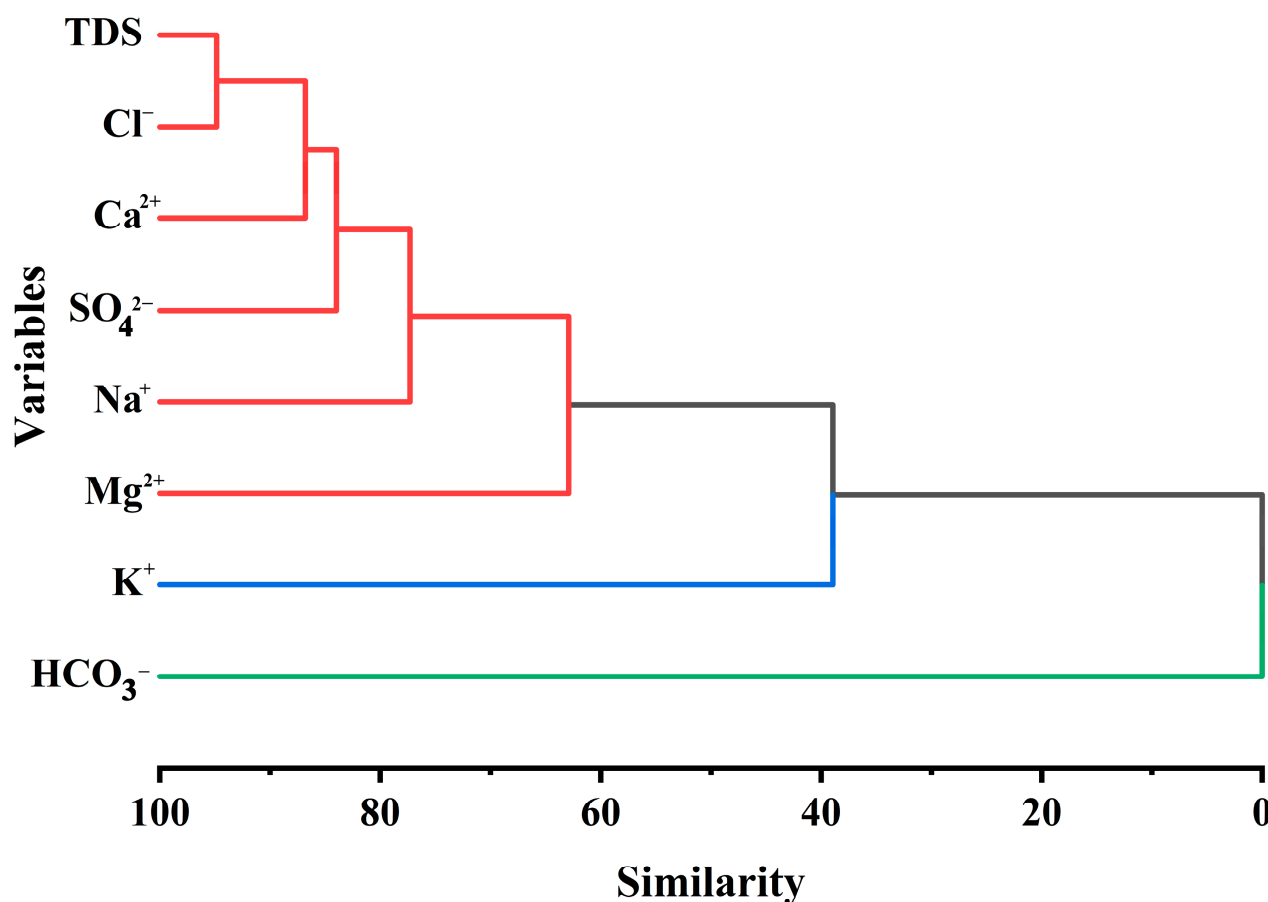


Figure 3. CA dendrogram in R-mode (Variables) for TDS, and major ions in EOC, NS, FB aquifers ($n = 21$).

3.2. Hydrochemical Facies

Many hydrogeochemical arithmetical diagrams may be used for distinguishing between differences and similarities in the composition of groundwater as well as for classifying them into specific chemical categories [54,55]. The hydrochemical components of studied aquifers groundwater were applied on a Piper Diagram (Figure 4) to highlight and clarify the main hydrochemical facies, and characteristics and for illustrating the different processes that control groundwater [52]. The excess of Cl⁻ type is clear in the anionic triangle for both EOC and NS aquifers while in FB aquifer bicarbonate type was dominant in most samples. Some samples exhibit sodium dominance in the cation's triangle, while others exhibit pole mixed calcium, except in FB (Sample 19) aquifers the calcium was dominant (Figure 4). In the anion's triangle, samples show a chloride predominance with a slight propensity sulfate pole (FB aquifer). The dominant water types in EOC and NS aquifers are Na-Cl type. The FB aquifer recorded many water types; Na-Cl (sample 18), Na-Ca-HCO₃ (samples 17 and 20), Ca-Mg-Cl (sample 16), and Ca-Cl (sample 19). The dominance of Na-Cl water type is confirmed by the HFE-Diagram [56] (Figure 5), indicating that this groundwater may be affected by seawater intrusion and leaching out of residual evaporative salts (i.e., gypsum/anhydrite and halite) during movement [53]. Generally, high values of Cl⁻, Na⁺, and SO₄²⁻ corresponding with seawater intrusion, and Ca²⁺, Mg²⁺, and K⁺ are not useful when distinguishing between different types of saline water.

The hydrogeochemical processes and hydrogeochemistry of groundwater vary depending on the mineralogy and geochemistry of the aquifer. The chemistry of groundwater is heavily influenced by the mineralogical composition of the aquifer through which it flows [38,57]. Groundwater major ion chemistry and interrelations are effective in determining solute sources and describing groundwater evolution [58,59]. The Na⁺ vs. Cl⁻ relationship has frequently been serves to identify the processes that cause water salinity

in arid and semi-arid regions [38,60]. The relationship between these two ions (Figure 6a) shows that most of the samples are near the 1:1 Line (halite dissolution line). Equal amounts of Na^+ and Cl^- are released into the solution when halite dissolves in water [61]. The recorded high Cl^- relative to Na^+ ion indicates the effect of saltwater intrusion [62], especially in EOC aquifer samples (Figures 5 and 6a). The decreasing trend in the concentration of Cl^- relative to the concentration of Na^+ in some NS aquifer samples likely reflects the cation exchange processes and weathering of the silicate minerals [62]. The additional Na^+ originates from the cation exchange in the clay minerals that present as shale intercalation of the NS aquifer leading to the adsorption of Ca^{2+} and the simultaneous releasing of Na^+ ions [38]; these expected cation exchange confirmed by plotting Na^+ vs. Ca^{2+} (Figure 6b), since the sampling points lie far below the uniline of Na^+ - Ca^{2+} . Regarding FB aquifer samples, the excess sodium may be ascribed to the dissolution of Na-Ca-Al-Silicates (albite-plagioclase).

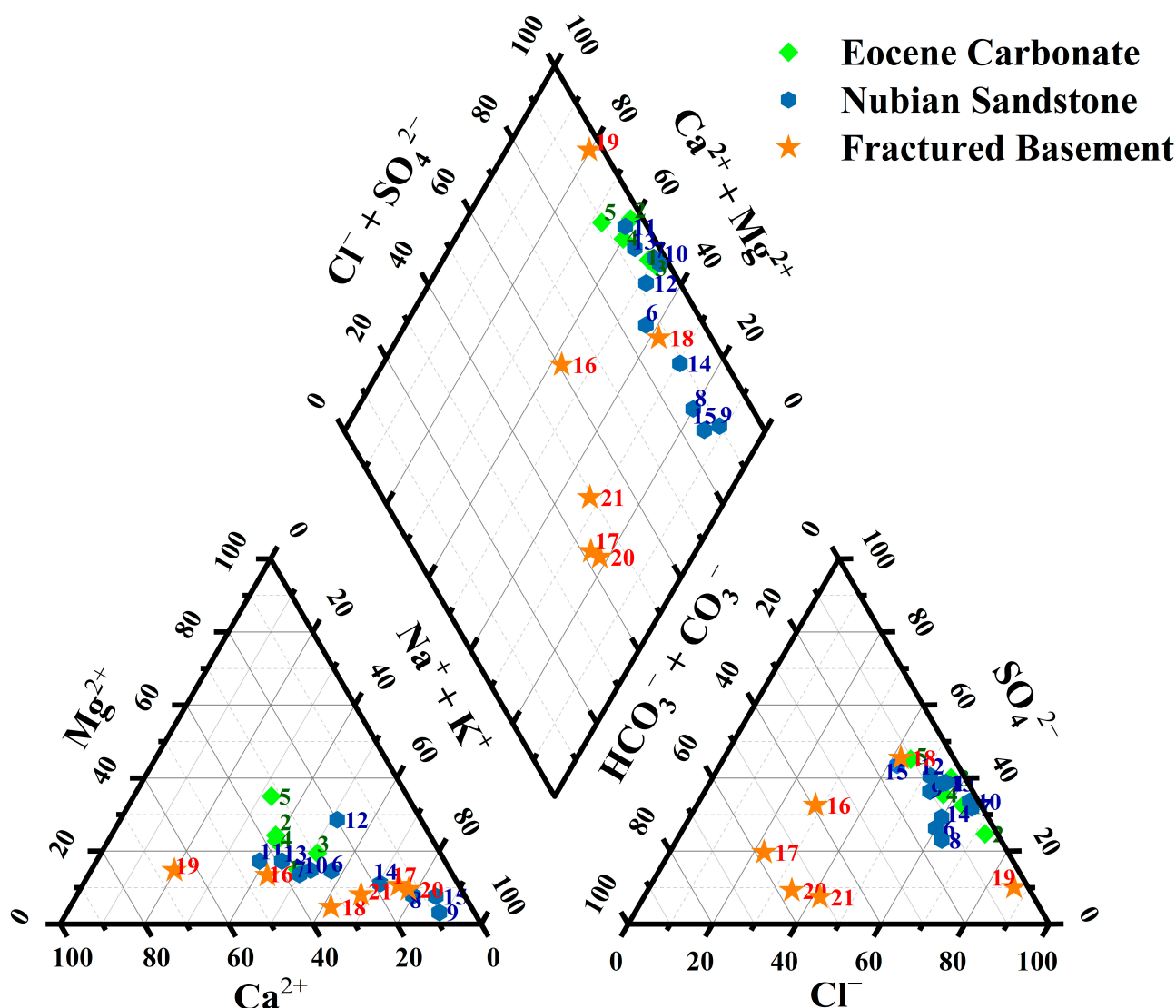


Figure 4. Piper plot of groundwater samples in EOC, NS, and FB aquifers.

The dissolution of carbonate minerals like calcite (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$) which are responsible for enriching of Ca^{2+} and Mg^{2+} was explored by $(\text{Ca}^{2+} + \text{Mg}^{2+})$ vs. $(\text{HCO}_3^- + \text{SO}_4^{2-})$ scatter diagram. Most of the NS and FB sample points lie below the equiline with few along it and above (Figure 6c), which indicates the predominance of silicate weathering. On the other hand, EOC sampling points lie above that line that

indicates the predominance of carbonate weathering. Given the abundance of carbonate and dolomite rocks in the EOC aquifer, it is likely that the groundwater will become much more Ca^{2+} and Mg^{2+} enriched as a result of the dissolution of these minerals. The effects of silicate weathering and carbonate mineral dissolution on groundwater hydrochemistry are well documented [27,37,38]. The relation between $(\text{Ca}^{2+} + \text{Mg}^{2+})-(\text{HCO}_3^- + \text{SO}_4^{2-})$ vs. $\text{Na}^+ + \text{K}^+ - \text{Cl}^-$ [61] referred to the effect of reverse ion exchange. Enrichment of Na^+ and K^+ when compared to the Ca^{2+} and Mg^{2+} in the FB aquifer and some samples of the NS aquifer is noted in Figure 6d (second quadrant negative ordinate and positive abscissa) [37]. As a result, the cation exchange sites preferentially absorb Ca^{2+} and Mg^{2+} while releasing Na^+ and K^+ (direct cationic exchange). In EOC aquifer samples, the relative depletion of Na^+ and K^+ regarding Ca^{2+} and Mg^{2+} is noted, which suggests reverse ion exchange (fourth quadrant positive ordinate and negative abscissa).

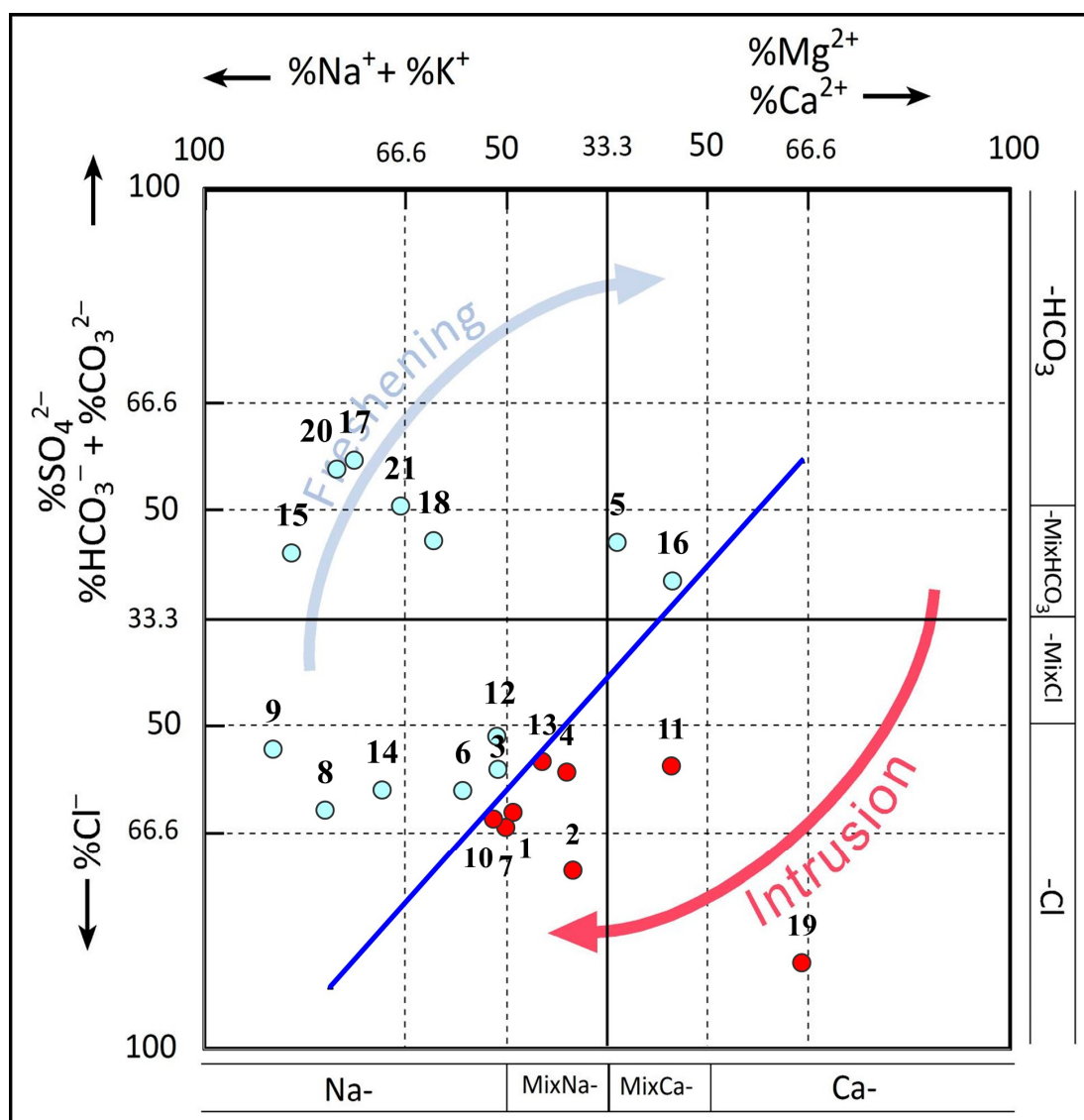


Figure 5. HFE-Diagram of the studied groundwater samples.

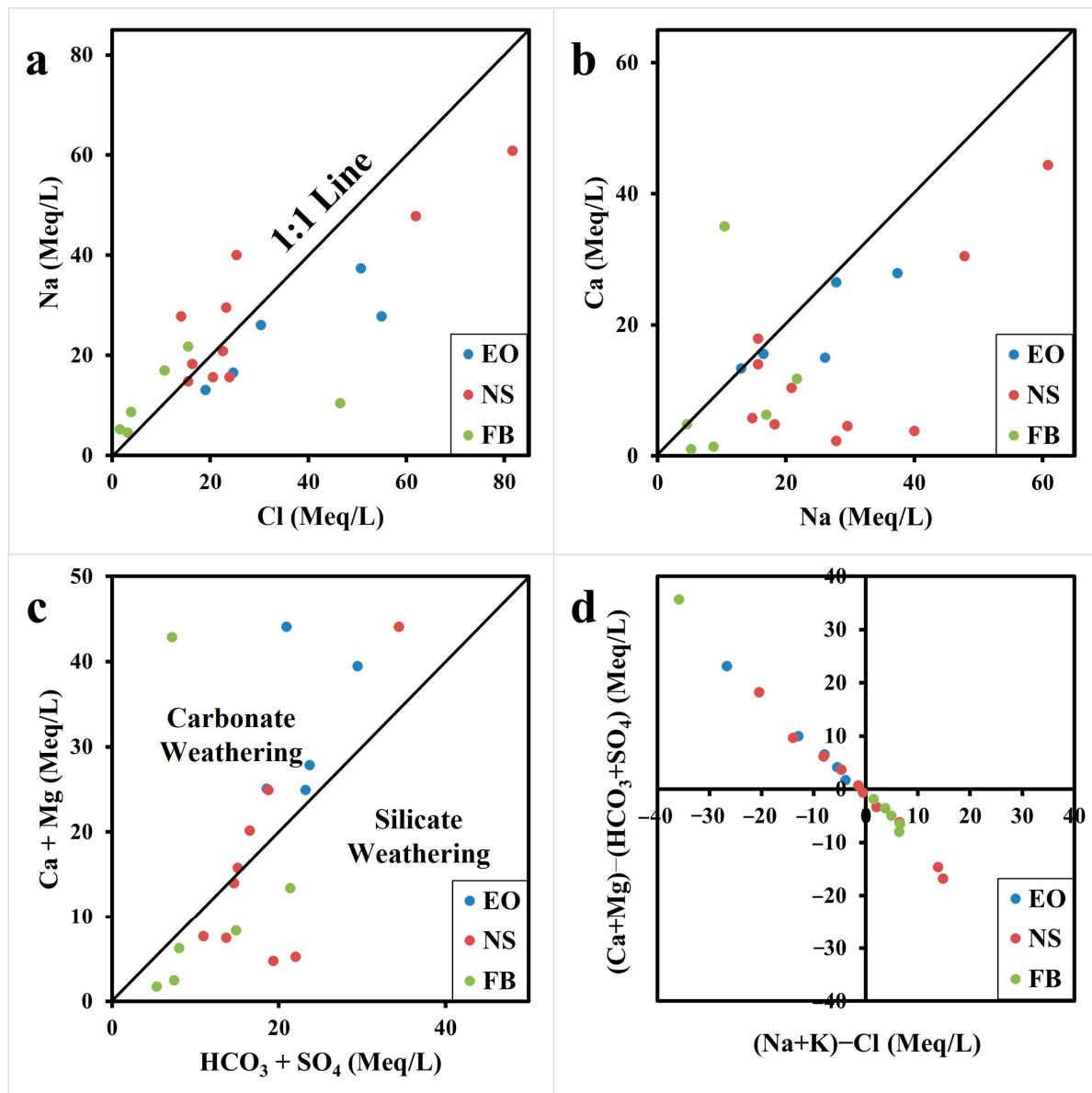


Figure 6. Plots of the EOC, NS, and FB groundwater samples on scatter diagrams: (a) Na^+ vs. Cl^- ; (b) Na^+ vs. Ca^{2+} ; (c) $(\text{Ca}^{2+} + \text{Mg}^{2+})$ vs. $(\text{HCO}_3^- + \text{SO}_4^{2-})$; (d) $(\text{Ca}^{2+} + \text{Mg}^{2+}) - (\text{HCO}_3^- + \text{SO}_4^{2-})$ vs. $\text{Na}^+ + \text{K}^+ - \text{Cl}^-$.

3.3. Trace Elements

Trace element concentrations clarify highly significant differences between the studied aquifers (Table 3). Overall, variations in the distribution of trace and heavy metals in groundwater are caused by a variety of factors such as cation exchange, evaporation, the leaching and disintegration of marine water seepage, climate, bedrock type, pH, redox potential, and mixing capacity [37,44]. Mostly, the monitoring results of the studied aquifers indicate that the rock type has a considerable impact on trace element distributions. EOC aquifer samples show the recorded maximum concentrations of Cd, Fe, Mn, Ni, V, and Zn. Particularly these may be owing to the anthropogenic impact of industrial and tourism activities near the coastline, reflecting the effects of water flows on trace elements allocation in these aquifers [63]. Both Fe and Mn are the most distributed metallic elements in Earth crust. Fe concentrations in groundwater is mostly regulated by many factors including flow rate, redox agents, dissolved organic matter, pH, leaching and disintegration of marine water seepage, and bedrock type [16,52]. The dissolution of Fe-bearing minerals commonly

found in aquifer sediments is one of its main sources in groundwater. As a result of industrialization progresses, the Ni presence in water systems increased, and many Ni compounds were introduced for industrial products [64].

Table 3. Trace element concentrations (mg/L) in EOC, NS, and FB aquifers.

NO.	Aquifer	Al	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	V	Zn
1	EOC	0.546	<0.0006	0.018	<0.01	<0.006	7.074	0.793	<0.001	0.070	<0.008	0.074	0.063
2		0.052	<0.0006	0.019	<0.01	<0.006	0.608	0.140	0.009	0.039	<0.008	<0.01	0.015
3		0.032	0.004	<0.001	<0.01	<0.006	<0.02	0.010	0.014	0.082	<0.008	<0.01	0.094
4		0.181	0.026	0.009	<0.01	<0.006	<0.02	<0.004	<0.001	<0.002	<0.008	<0.01	0.114
5		<0.01	<0.0006	<0.001	<0.01	<0.006	1.929	0.884	0.113	0.057	<0.008	<0.01	0.100
6	NS	<0.01	<0.0006	0.025	<0.01	<0.006	1.781	0.110	<0.001	0.073	<0.008	<0.01	0.017
8		<0.01	<0.0006	0.024	0.010	<0.006	<0.02	0.136	0.078	0.026	<0.008	<0.01	0.049
9		0.136	<0.0006	<0.001	<0.01	<0.006	0.696	0.168	0.028	0.011	<0.008	<0.01	<0.0005
10		0.354	0.013	0.073	<0.01	<0.006	0.065	0.007	<0.001	0.002	<0.008	<0.01	0.037
11		1.376	<0.0006	<0.001	<0.01	<0.006	4.384	0.091	<0.001	0.018	<0.008	<0.01	0.089
14		0.087	<0.0006	<0.001	<0.01	<0.006	<0.02	0.121	<0.001	0.022	<0.008	<0.01	<0.0005
15		1.078	<0.0006	0.032	<0.01	<0.006	0.454	0.093	<0.001	<0.002	<0.008	<0.01	0.099
17	FB	1.267	<0.006	<0.001	<0.01	<0.006	1.162	0.090	0.089	<0.002	<0.008	0.032	0.029
18		0.155	<0.006	<0.001	<0.01	0.006	<0.02	<0.004	0.126	0.060	<0.008	0.024	0.011
19		0.487	<0.006	<0.001	<0.01	<0.006	0.857	0.091	0.186	0.020	<0.008	<0.01	0.050
20		<0.01	0.009	0.010	<0.01	<0.006	0.281	0.046	0.203	0.028	<0.008	0.020	0.023
21		0.628	0.001	<0.001	<0.01	<0.006	0.637	0.197	0.015	<0.002	<0.008	<0.01	0.012
Min.	All Samples (N = 17)	0.032	0.001	0.009	0.010	0.006	0.065	0.007	0.009	0.002	-	0.020	0.011
Max.		1.376	0.026	0.073	0.010	0.006	7.074	0.884	0.203	0.082	-	0.074	0.114
Mean		0.491	0.010	0.026	-	-	1.661	0.198	0.086	0.039	-	0.038	0.053
WHO [5]		0.9	0.003	-	0.05	2	-	0.4	-	0.07	0.01	-	3
ESDW [34]		-	0.003	-	0.05	2	0.3	0.4	-	0.02	0.01	-	3
USEPA [65]		-	0.003	-	0.05	-	0.3	-	-	-	-	0.07	3
FAO [33]		5	0.01	-	0.1	0.2	5	0.2	-	0.2	-	0.1	2
CCME [66]		5	0.01	-	-	-	5	0.2	-	0.2	0.2	0.1	-

3.4. Assessment of Groundwater Quality for Different Purposes

3.4.1. Assessment for Irrigation Use

Irrigation water quality refers to its suitability for use in the irrigation of different crops. Under good soil and water management practices, good quality water has the potential to result in maximum yield [67]. The concentration and composition of dissolved constituents in water determine their quality and viability for irrigation. The results of the calculated indicators used for assessing the quality of groundwater samples for irrigation use are presented in Table 4. The studied groundwater samples have pH values within the permissible limit (6.5–8.8; FAO [33]). The measured values of EC indicate that the groundwater of EOC and NS and 50% of FB aquifers samples are unsuitable for irrigation. The main effect of high EC water on crop productivity is an increase in the osmotic pressure of the nutrient solution in the soil, which can result in reduced water uptake and nutrient deficiencies [33,68]. The combined SSP, SAR, RSC, and MAR computed results showed that there is no hazard with sodium and magnesium for irrigation use, except for a few samples which record high values for these indicators. The sodium hazards of irrigation water are significantly related to the degree to which the sodium is adsorbed by the soil. If the irrigation water contains an excessive concentration of Na^+ but little Ca^{2+} , the cation-exchange intricate could become saturated with sodium and destroy the soil structure [33,62]. Water infiltration is also influenced by SAR. Although Cl^- is crucial to crops at low levels, it can cause toxicity (leaf burns or leaf tissue deaths) in sensitive crops at elevated concentrations [69,70]. Only 50% of FB aquifer groundwater samples fall below the recommended chloride limit (140 mg/L; FAO [33]; Bouselsal and Saibi [70]) (Table 1),

and the rest of the samples fall above this limit and can cause Cl^- toxicity to crops if used in irrigation.

Table 4. Groundwater quality indicators for irrigation and domestic uses.

NO.	Aquifer	SSP		SAR		RSC		MAR		TH		CR	
1	EOC	48.9	Safe	8.4	Excellent	−36.07	Excellent	29.4	Suitable	1973.7	V. Hard	15.4	Unsafe
2		39.0	Safe	5.9	Excellent	−41.91	Excellent	39.9	Suitable	2205.7	V. Hard	24.0	Unsafe
3		51.4	Safe	7.4	Excellent	−23.12	Excellent	39.9	Suitable	1246.2	V. Hard	18.7	Unsafe
4		40.0	Safe	4.7	Excellent	−21.87	Excellent	38.0	Suitable	1253.6	V. Hard	8.3	Unsafe
5		32.6	Safe	3.5	Excellent	−23.42	Excellent	52.0	Unsuit.	1391.5	V. Hard	5.3	Unsafe
6	NS	57.2	Safe	7.4	Excellent	−10.60	Excellent	34.1	Suitable	789.4	V. Hard	4.3	Unsafe
7		50.1	Safe	11.0	Good	−57.79	Excellent	27.2	Suitable	3049.0	V. Hard	26.1	Unsafe
8		79.9	Unsafe	15.3	Good	−2.29	Excellent	38.8	Suitable	373.9	V. Hard	4.3	Unsafe
9		88.5	Unsafe	24.7	Doubtful	−0.43	Excellent	27.8	Suitable	261.3	Hard	5.8	Unsafe
10		52.1	Safe	10.2	Good	−42.08	Excellent	30.8	Suitable	2204.4	V. Hard	32.0	Unsafe
11		38.7	Safe	4.4	Excellent	−22.75	Excellent	28.2	Suitable	1247.5	V. Hard	12.0	Unsafe
12		51.5	Safe	5.6	Excellent	−11.58	Excellent	58.9	Unsuit.	699.4	V. Hard	7.4	Unsafe
13		44.1	Safe	4.9	Excellent	−17.97	Excellent	30.8	Suitable	1008.5	V. Hard	10.3	Unsafe
14		70.5	Unsafe	9.3	Excellent	−4.68	Excellent	37.5	Suitable	383.9	V. Hard	5.6	Unsafe
15		85.4	Unsafe	18.0	Good	0.03	Excellent	52.2	Unsuit.	238.4	Hard	3.7	Unsafe
16	FB	42.5	Safe	2.6	Excellent	−1.84	Excellent	23.3	Suitable	311.8	V. Hard	0.9	Safe
17		75.1	Unsafe	5.6	Excellent	2.25	Doubtful	42.7	Suitable	87.3	Moderately	0.5	Safe
18		62.0	Unsafe	8.4	Excellent	−8.79	Excellent	12.2	Suitable	669.5	V. Hard	4.3	Unsafe
19		19.8	Safe	2.3	Excellent	−41.09	Excellent	18.4	Suitable	2143.6	V. Hard	22.6	Unsafe
20		78.0	Unsafe	7.8	Excellent	3.93	Unsuitable	43.2	Suitable	123.3	Moderately	0.6	Safe
21		67.4	Unsafe	8.3	Excellent	4.64	Unsuitable	24.9	Suitable	417.2	V. Hard	0.7	Safe

When evaluating an irrigation water supply, the hazardous metal concentrations of the irrigation waters should be carefully examined [69]. A comparison with several international standards and guidelines for irrigation water [33,66] has been done to evaluate trace elements content in the investigated groundwater (Table 3). The results show that there is no problem with trace elements concentration for using this groundwater for irrigation except for some samples which contain elevated concentrations of Cd, Fe, and Mn.

3.4.2. Assessment for Domestic Use

High TDS values may be associated with excessive corrosion and scaling in pipes, fittings, and household appliances. Comparison between the TDS values of the investigated groundwater with the classification proposed by Bruvold and Daniels [48], disclosed that the majority of the samples can be classified as unacceptable for domestic use (Tables 1 and S1). According to Total Hardness (TH) values, this water is very hard and hard (Table 4). The presence of Ca^{2+} and Mg^{2+} in the aquifer rocks contributes significantly to the TH of groundwater. Hard water is not a health risk, but it can be infuriating in the home. Hard water is unfit for domestic use, and its industrial applications have been limited due to the degree of hardness of the water, which causes the scaling of pots, boilers, and irrigation pipelines [5]. Groundwater in the CED is unfit for domestic use on the basis of TH values.

3.4.3. Assessment for Drinking Use

Although the pH values of this groundwater are neutral to slightly acidic, and it is well within the acceptable WHO [5] range, the high TDS values render it invalid for drinking. Some of the major ions, including Na^+ , Ca^{2+} , Mg^{2+} , SO_4^{2-} , and Cl^- , have concentrations that are higher than that that are recommended for taste and aesthetics [5]. Furthermore, some samples recorded Al, Cd, Fe, Mn, and Ni concentrations exceeding the permissible limits in drinking water [5,34,65] (Table 3).

4. Conclusions

Findings of this study indicated that there were significant differences in the chemical composition between the studied three aquifers. The highest salinity values were recorded in the NS aquifer and the lowest values were recorded in the FB aquifer. Sodium, calcium, sulfate, and chloride concentrations are the main contributors to the elevated salinity of the groundwater in these aquifers. The cation contents are strongly associated with Cl^- and SO_4^{2-} through Na-Cl, Ca-Cl, and Na- SO_4 water types. The salinity of groundwater from the EOC, NS, and FB aquifers of the CED of Egypt is being regulated by two main factors. Seawater intrusion is the most important factor. The second factor is the water-rock interactions through direct and reverse cationic exchange and carbonate and silicate weathering. The groundwater of these aquifers is not safe and unsuitable for all purposes. Its very high salinity values prevent its use for irrigation, domestic, and drinking, with an exception for some FB samples. Groundwater resources in the CED are predicted to become more salinized as a consequence of increasing climate change effects, hence it is critical to prevent saltwater intrusion. These necessitate mitigation measures and adaptation strategies, which include actions such as regulating groundwater exploitation, monitoring groundwater quality, and better capacity to buffer heavy rainfall to diminish the effects of climate change and protect ecosystems from potential negative consequences.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w15050971/s1>, Table S1: Summary of the formulae used to calculate the water quality indicators.

Author Contributions: Conceptualization, A.S., A.G., A.A. and H.I.F.; methodology, A.S., A.G. and H.I.F.; software, A.S., A.G. and H.I.F.; validation, A.S., A.G., A.A., H.A. and H.I.F.; formal analysis, A.S. and A.G.; investigation, A.S., A.G. and H.I.F.; resources, A.S.; data curation, A.S., A.G., A.A., H.A. and H.I.F.; writing—original draft preparation, A.S., A.G. and H.I.F.; writing—review and editing, A.S., A.G., A.A. and H.A.; supervision, A.S., A.G. and H.A.; project administration, A.S.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This paper is part of the work supported by the Science, Technology & Innovation Funding Authority (STDF), Egypt, Under Grant Number: 30116.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This paper is part of the work supported by the Science, Technology & Innovation Funding Authority (STDF), Egypt, Under Grant Number: 30116. The authors thank El-Shlemly E. (Ain Shams University, Cairo, Egypt) for her valuable assistant.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Etikala, B.; Golla, V.; Li, P.; Renati, S. Deciphering groundwater potential zones using MIF technique and GIS: A study from Tirupati area, Chittoor District, Andhra Pradesh, India. *HydroResearch* **2019**, *1*, 1–7. [CrossRef]
2. Ma, Q.; Ge, W.; Tian, F. Geochemical Characteristics and Controlling Factors of Chemical Composition of Groundwater in a Part of the Nanchang Section of Ganfu Plain. *Sustainability* **2022**, *14*, 7976. [CrossRef]
3. Saana, S.; Martin, B.; Fosu, S.A.; Sebiawu, G.E.; Jackson, N.; Karikari, T. Assessment of the quality of groundwater for drinking purposes in the Upper West and Northern regions of Ghana. *SpringerPlus* **2016**, *5*, 2001. [CrossRef]
4. Iqbal, J.; Su, C.; Rashid, A.; Yang, N.; Baloch, M.Y.J.; Talpur, S.A.; Ullah, Z.; Rahman, G.; Rahman, N.U.; Earj; et al. Hydro-geochemical Assessment of Groundwater and Suitability Analysis for Domestic and Agricultural Utility in Southern Punjab, Pakistan. *Water* **2021**, *13*, 3589. [CrossRef]
5. WHO World Health Organization. *Guidelines for Drinking-Water Quality: First Addendum to the Fourth Edition 2017*; WHO: Geneva, Switzerland, 2017. [CrossRef]

6. Mansouri, Z.; Leghrie, Y.; Kouadri, S.; Al-Ansari, N.; Najm, H.M.; Mashaan, N.S.; Eldirderi, M.M.A.; Khedher, K.M. Hydro-Geochemistry and Groundwater Quality Assessment of Ouargla Basin, South of Algeria. *Water* **2022**, *14*, 2441. [\[CrossRef\]](#)
7. Chen, W.; Zhang, Y.; Shi, W.; Cui, Y.; Zhang, Q.; Shi, Y.; Liang, Z. Analysis of Hydrogeochemical Characteristics and Origins of Chromium Contamination in Groundwater at a Site in Xinxiang City, Henan Province. *Appl. Sci.* **2021**, *11*, 11683. [\[CrossRef\]](#)
8. Ramadan, R.S.; Dawood, Y.H.; Yehia, M.M.; Gad, A. Environmental and health impact of current uranium mining activities in southwestern Sinai, Egypt. *Environ. Earth Sci.* **2022**, *81*, 213. [\[CrossRef\]](#)
9. Awad, E.S.; Imran, N.S.; Albayati, M.M.; Snegirev, V.; Sabirova, T.M.; Tretyakova, N.A.; Alsahy, Q.F.; Al-Furaiji, M.H.; Salih, I.K.; Majdi, H.S. Groundwater Hydrogeochemical and Quality Appraisal for Agriculture Irrigation in Greenbelt Area, Iraq. *Environments* **2022**, *9*, 43. [\[CrossRef\]](#)
10. Kumar, L.D.; Dhakate, R.; Guguloth, S.; Srinivas, B. Hydrochemical appraisal of groundwater quality for drinking and agricultural utility in a granitic terrain of Maheshwaram area of Ranga Reddy district, Telangana State, India. *HydroResearch* **2021**, *4*, 11–23. [\[CrossRef\]](#)
11. Eissa, M.A.; Shawky, H.; Samy, A.; Khalil, M.M.H.; El Malky, M. Geochemical and Isotopic Evidence of Groundwater Salinization Processes in El Dabaa Area, Northwestern Coast, Egypt. *Geosciences* **2018**, *8*, 392. [\[CrossRef\]](#)
12. Bhagat, C.; Puri, M.; Mohapatra, P.K.; Kumar, M. Imprints of seawater intrusion on groundwater quality and evolution in the coastal districts of South Gujarat, India. *Case Stud. Chem. Environ. Eng.* **2021**, *3*, 100101. [\[CrossRef\]](#)
13. Dieu, L.P.; Cong-Thi, D.; Segers, T.; Ho, H.H.; Nguyen, F.; Hermans, T. Groundwater Salinization and Freshening Processes in the Luy River Coastal Aquifer, Vietnam. *Water* **2022**, *14*, 2358. [\[CrossRef\]](#)
14. Sarker, M.M.R.; Hermans, T.; Van Camp, M.; Hossain, D.; Islam, M.; Ahmed, N.; Bhuiyan, M.A.Q.; Karim, M.M.; Walraevens, K. Identifying the Major Hydrogeochemical Factors Governing Groundwater Chemistry in the Coastal Aquifers of Southwest Bangladesh Using Statistical Analysis. *Hydrology* **2022**, *9*, 20. [\[CrossRef\]](#)
15. Abu Salem, H.S.; Gmail, K.S.; Junakova, N.; Ibrahim, A.; Nosair, A.M. An Integrated Approach for Deciphering Hydrogeochemical Processes during Seawater Intrusion in Coastal Aquifers. *Water* **2022**, *14*, 1165. [\[CrossRef\]](#)
16. Bahir, M.; Ouazar, D.; Ouhamdouch, S.; Zouari, K. Assessment of groundwater mineralization of alluvial coastal aquifer of essaouira basin (Morocco) using the hydrochemical facies evolution diagram (HFE-Diagram). *Groundwater Sustain. Dev.* **2020**, *11*, 100487. [\[CrossRef\]](#)
17. Ouhamdouch, S.; Bahir, M.; Ouazar, D. Climate change impact assessment on a carbonate aquifer under semi-arid climate; example of the Cenomanian-Turonian aquifer within Meskala-Ouazzi region (Essaouira Basin, Morocco). *Arab. J. Geosci.* **2020**, *13*, 173. [\[CrossRef\]](#)
18. Sefelnasr, A.; Ebraheem, A.A.; Faiz, M.A.; Shi, X.; Alghafli, K.; Baig, F.; Al-Rashed, M.; Alshamsi, D.; Ahamed, M.B.; Sherif, M. Enhancement of Groundwater Recharge from Wadi Al Bih Dam, UAE. *Water* **2022**, *14*, 3448. [\[CrossRef\]](#)
19. Charfi, S.; Zouari, K.; Feki, S.; Mami, E. Study of variation in groundwater quality in a coastal aquifer in north-eastern Tunisia using multivariate factor analysis. *Quat. Int.* **2013**, *302*, 199–209. [\[CrossRef\]](#)
20. El Yousfi, Y.; Himi, M.; El Ouarghi, H.; Elgettafi, M.; Benyoussef, S.; Gueddari, H.; Aqnouy, M.; Salhi, A.; Alitane, A. Hydrogeochemical and statistical approach to characterize groundwater salinity in the Ghiss-Nekkor coastal aquifers in the Al Hoceima province, Morocco. *Groundwater Sustain. Dev.* **2022**, *19*, 100818. [\[CrossRef\]](#)
21. Kumar, B. Integrated hydrogeochemical, isotopic and geomorphological depiction of the groundwater salinization in the aquifer system of Delhi, India. *J. Asian Earth Sci.* **2015**, *111*, 936–947. [\[CrossRef\]](#)
22. Adepelumi, A.A.; Ako, B.D.; Ajayi, T.R.; Afolabi, O.; Omotoso, E.J. Delineation of saltwater intrusion into the freshwater aquifer of Lekki Peninsula, Lagos, Nigeria. *Environ. Geol.* **2009**, *56*, 927–933. [\[CrossRef\]](#)
23. Kura, N.U.; Ramli, M.F.; Sulaiman, W.N.A.; Ibrahim, S.; Aris, A.Z.; Mustapha, A. Evaluation of factors influencing the groundwater chemistry in a small tropical island of Malaysia. *Int. J. Environ. Res. Public Health* **2013**, *10*, 1861–1881. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Medici, G.; West, L.J.; Mountney, N.P. Characterizing flow pathways in a sandstone aquifer: Tectonic vs sedimentary heterogeneities. *J. Contam. Hydrol.* **2016**, *194*, 36–58. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Medici, G.; West, L.J. Review of groundwater flow and contaminant transport modelling approaches for the Sherwood Sandstone aquifer, UK; insights from analogous successions worldwide. *Q. J. Eng. Geol. Hydrogeol.* **2022**, *55*, 176. [\[CrossRef\]](#)
26. Tellam, J.H.; Barker, R.D. Towards prediction of saturated-zone pollutant movement in groundwaters in fractured permeable-matrix aquifers: The case of the UK Permo-Triassic sandstones. In *Fluid Flow and Solute Movement in Sandstones: The Onshore UK Permo-Triassic Red Bed Sequence*; Barker, R.D., Tellam, J.H., Eds.; Geological Society of London: London, UK, 2006; pp. 1–48. [\[CrossRef\]](#)
27. Worthington, S.R.; Davies, G.J.; Alexander, E.C., Jr. Enhancement of bedrock permeability by weathering. *Earth-Sci. Rev.* **2016**, *160*, 188–202. [\[CrossRef\]](#)
28. Medici, G.; West, L.J.; Banwart, S.A. Groundwater flow velocities in a fractured carbonate aquifer-type: Implications for contaminant transport. *J. Contam. Hydrol.* **2019**, *222*, 1–16. [\[CrossRef\]](#)
29. Terzić, J.; Frangen, T.; Borović, S.; Reberski, J.L.; Patekar, M. Hydrogeological Assessment and Modified Conceptual Model of a Dinaric Karst Island Aquifer. *Water* **2022**, *14*, 404. [\[CrossRef\]](#)
30. Kaur, T.; Bhardwaj, R.; Arora, S. Assessment of groundwater quality for drinking and irrigation purposes using hydrochemical studies in Malwa region, southwestern part of Punjab, India. *Appl. Water Sci.* **2017**, *7*, 3301–3316. [\[CrossRef\]](#)

31. Suneetha, N.; Gautam, G.; Rambabu, S.; Khan, T.; Vinit, C.E. Hydrogeochemical processes regulating the groundwater quality and its suitability for drinking and irrigation purpose in parts of coastal Sindhudurg district, Maharashtra. *J. Geol. Soc. India* **2021**, *97*, 173–185. [\[CrossRef\]](#)
32. Rao, N.S.; Das, R.; Gugulothu, S. Understanding the factors contributing to groundwater salinity in the coastal region of Andhra Pradesh, India. *J. Contam. Hydrol.* **2022**, *250*, 104053. [\[CrossRef\]](#)
33. FAO (Food and Agriculture Organization). *Water Quality for Agriculture*. FAO Irrigation and Drainage Paper 29; FAO: Rome, Italy, 1985.
34. ESDW (Egypt Standard for Drinking Water). *Standards and Specifications of Water for Drinking and Domestic Use*; Decision of the Minister of Health and Population No. 458 (2007); Ministry of Health and Population: Cairo, Egypt, 2007. (In Arabic)
35. Perera, T.A.N.T.; Herath, H.; Piyadasa, R.U.K.; Jianhui, L.; Bing, L. Spatial and physicochemical assessment of groundwater quality in the urban coastal region of Sri Lanka. *Environ. Sci. Pollut. Res.* **2021**, *29*, 16250–16264. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Saber, A.A.; Ullah Bhat, S.; Hamid, A.; Gabrieli, J.; Garamoon, H.; Gargini, A.; Cantonati, M. Chemical Quality and Hydrogeological Settings of the El-Farafrā Oasis (Western Desert of Egypt) Groundwater Resources in Relation to Human Uses. *Appl. Sci.* **2022**, *12*, 5606. [\[CrossRef\]](#)
37. Abd El-Wahed, M.; El-Horiny, M.M.; Ashmawy, M.; El Kereem, S.A. Multivariate Statistical Analysis and Structural Sovereignty for Geochemical Assessment and Groundwater Prevalence in Bahariya Oasis, Western Desert, Egypt. *Sustainability* **2022**, *14*, 6962. [\[CrossRef\]](#)
38. Yehia, M.; Baghdady, A.; Howari, F.M.; Awad, S.; Gad, A. Natural radioactivity and groundwater quality assessment in the northern area of the Western Desert of Egypt. *J. Hydrol. Reg. Stud.* **2017**, *12*, 331–344. [\[CrossRef\]](#)
39. Stern, R.J.; Johnson, P.; Kröner, A.; Yibas, B. Neoproterozoic Ophiolites of the Arabian Nubian Shield. In *Precambrian Ophiolites and Related Rocks*; Kusky, T.M., Ed.; Elsevier: Amsterdam, The Netherlands, 2004.
40. Fowler, A.; Baghdady, A.; Abdelmalik, K.; Gad, A. Remote sensing-guided stratigraphic dissection of an Ediacaran terrestrial molasse basin (Kareim basin, Egypt), with implications for sedimentary evolution. *Precambrian Res.* **2020**, *338*, 105589. [\[CrossRef\]](#)
41. Sultan, M.; Yousef, A.; Metwally, S.; Becker, R.; Milewski, A.; Sauck, W.; Sturchio, N.; Mohamed, A.; Wagdy, A.; El Alfy, Z.; et al. Red Sea rifting controls on aquifer distribution: Constraints from geochemical, geophysical, and remote sensing data. *GSA Bull.* **2011**, *123*, 911–924. [\[CrossRef\]](#)
42. Said, R. *The Geology of Egypt*; Balkema Publishers: Rotterdam, The Netherlands, 1990.
43. Montenat, C.; D'estevou, P.; Purser, B.; Burrollet, P.; Jarrige, J.; Sperber, F.; Philobos, F.; Plaziat, J.; Part, P.; Richert, J.; et al. Tectonic and sedimentary evolution of the Gulf of Suez and the Northwestern Red Sea. *Tectonophysics* **1988**, *153*, 161–177. [\[CrossRef\]](#)
44. Appelo, C.A.J.; Postma, D. *Geochemistry, Groundwater and Pollution*, 2nd ed.; CRC Press: London, UK, 2005.
45. Ragunath, H.M. *Groundwater*; Wiley Eastern Ltd.: New Delhi, India, 1987.
46. Eaton, F.M. Significance of carbonate in irrigation water. *Soil Sci.* **1950**, *69*, 123–134. [\[CrossRef\]](#)
47. Todd, D.K. *Groundwater Hydrology*, 2nd ed.; John Wiley and Sons: New York, NY, USA, 1980.
48. Bruvold, W.H.; Daniels, J.I. Standards for mineral content in drinking water. *J. Am. Water Works Assoc.* **1990**, *82*, 59–65. [\[CrossRef\]](#)
49. Sawyer, G.N.; McCarthy, D.L. *Chemistry of Sanitary Engineers*, 2nd ed.; McGraw Hill: New York, NY, USA, 1967.
50. Ryznre, J.W. A new index for determining amount of calcium carbonate scale formed by water. *J. Am. Water Works Assoc.* **1944**, *36*, 472–486. [\[CrossRef\]](#)
51. Giménez-Forcada, E.; Sánchez San Román, F.J. An Excel Macro to Plot the HFE-Diagram to Identify Sea Water Intrusion Phases. *Groundwater* **2015**, *53*, 819–824. [\[CrossRef\]](#) [\[PubMed\]](#)
52. Askri, B. Hydrochemical processes regulating groundwater quality in the coastal plain of Al Musanaah, Sultanate of Oman. *J. Afr. Earth Sci.* **2015**, *106*, 87–98. [\[CrossRef\]](#)
53. Sherif, M.I.; Sultan, M.; Sturchio, N.C. Chlorine Isotopes as Tracers of Solute Origin and Age of Groundwaters from the Eastern Desert of Egypt. *Earth Planet. Sci. Lett.* **2019**, *510*, 37–44. [\[CrossRef\]](#)
54. Selvam, S.; Jesuraja, K.; Roy, P.D.; Venkatramanan, S.; Chung, S.Y.; Elzain, H.E.; Muthukumar, P.; Nath, A.V.; Karthik, R. Assessment of groundwater from an industrial coastal area of South India for human health risk from consumption and irrigation suitability. *Environ. Res.* **2021**, *200*, 111461. [\[CrossRef\]](#)
55. Zolekar, R.B.; Todmal, R.S.; Bhagat, V.S.; Bhailume, S.A.; Korade, M.S.; Das, S. Hydrochemical characterization and geospatial analysis of groundwater for drinking and agricultural usage in Nashik district in Maharashtra, India. *Environ. Dev. Sustain.* **2021**, *23*, 4433–4452. [\[CrossRef\]](#)
56. Giménez-Forcada, E. Use of the Hydrochemical Facies Diagram (HFE-D) for the evaluation of salinization by seawater intrusion in the coastal Oropesa Plain: Comparative analysis with the coastal Vinaroz Plain, Spain. *HydroResearch* **2019**, *2*, 76–84. [\[CrossRef\]](#)
57. Lakshmanan, E.; Kannan, R.; Kumar, M. Major ion chemistry and identification of hydrogeochemical processes of ground water in a part of Kancheepuram district, Tamil Nadu, India. *Environ. Geosci.* **2003**, *10*, 157–166. [\[CrossRef\]](#)
58. Petrides, B.; Cartwright, I. The hydrogeology and hydrogeochemistry of the Barwon Downs Graben aquifer, southwestern Victoria, Australia. *Hydrogeol. J.* **2006**, *14*, 809–826. [\[CrossRef\]](#)
59. Petalas, C.P. A preliminary assessment of hydrogeological features and selected anthropogenic impacts on an alluvial fan aquifer system in Greece. *Environ. Earth Sci.* **2013**, *70*, 439–452. [\[CrossRef\]](#)
60. Abid, K.; Zouari, K.; Dulinski, M.; Chkir, N.; Abidi, B. Hydrologic and geologic factors controlling groundwater geochemistry in the Turonian aquifer (southern Tunisia). *Hydrogeol. J.* **2011**, *19*, 415–427. [\[CrossRef\]](#)

61. García, M.G.; Hidalgo, M.V.; Blesa, M.A. Geochemistry of groundwater in the alluvial plain of Tucumán province, Argentina. *Hydrogeol. J.* **2001**, *9*, 597–610. [[CrossRef](#)]
62. Yidana, S.M.; Yidana, A. An assessment of the origin and variation of groundwater salinity in southeastern Ghana. *Environ. Earth Sci.* **2010**, *61*, 1259–1273. [[CrossRef](#)]
63. Farhat, H.I.; Gad, A.; Saleh, A.; Abd El Bakey, S.M. Risks Assessment of Potentially Toxic Elements' Contamination in the Egyptian Red Sea Surficial Sediments. *Land* **2022**, *11*, 1560. [[CrossRef](#)]
64. Abdel-Satar, A.M.; Ali, M.H.; Goher, M.E. Indices of water quality and metal pollution of Nile River, Egypt. *Egypt. J. Aquat. Res.* **2017**, *43*, 21–29. [[CrossRef](#)]
65. USEPA (United States Environmental Protection Agency). *Drinking Water Standards and Health Advisories Table*; USEPA: San Francisco, CA, USA, 2007.
66. CCME (Canadian Council of Ministers of the Environment). *Canadian Environmental Quality Guidelines*; Publication No. 1299; Canadian Council of Ministers of the Environment: Ottawa, ON, Canada, 1999.
67. Jasmin, I.; Mallikarjuna, P. Evaluation of Groundwater Suitability for Irrigation in the Araniar River Basin, South India—A Case Study Using Gis Approach. *Irrig. Drain.* **2015**, *64*, 600–608. [[CrossRef](#)]
68. Subramani, T.; Elango, L.; Damodarasamy, S. Groundwater quality and its suitability for drinking and agricultural use in Chithar River Basin, Tamil Nadu, India. *Environ. Geol.* **2005**, *47*, 1099–1110. [[CrossRef](#)]
69. Simsek, C.; Gunduz, O. IWQ index: A GIS-integrated technique to assess irrigation water quality. *Environ. Monit. Assess.* **2007**, *128*, 277–300. [[CrossRef](#)]
70. Bouselsal, B.; Saibi, H. Evaluation of groundwater quality and hydrochemical characteristics in the shallow aquifer of El-Oued region (Algerian Sahara). *Groundwater Sustain. Dev.* **2022**, *17*, 100747. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.