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Assessment of Groundwater Quality for Potable and Agriculture Uses in Southeast Dead Sea, Jordan

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Abstract

This study assesses the suitability of groundwater for potable and agricultural purposes of southern Jordan to evaluate the water's appropriateness for drinking and irrigation as well as the degree of ionic toxicity present. Between August 2024 and August 2025, samples of groundwater were taken from thirty-one groundwater resources. Temperature, dissolved oxygen, pH, conductivity, main ions (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}), (HCO_3^-, Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, F^-), and heavy metals (Fe^{2+}, Al^{3+}, Cu^{2+}, Ni^{2+}, Zn^{2+}, Pb^{2+}, Mn^{2+}) were all measured in the samples. Due to prolonged contact with rocks, the water quality in the research region was found to be highly salinized. The research found that bicarbonate and chloride were the predominant ions in groundwater samples, which were classed as alkaline earth fluids. The average ion concentrations were as follows: $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$, and $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > PO_4^{3-} > F^-$. Comparing these data to WHO and Jordan's drinking water guidelines helped determine the groundwater's acceptability for consumption. In addition, different metrics, such as the (SAR), (Na%), (RSC), and utilized to evaluate whether the water is appropriate for agricultural use. Most samples were classed as C2-S1, indicating medium salinity and low sodium threat, according to the US Salinity Laboratory's figure, that plotted SAR values against electrical conductivity (EC) for each sample. According to this study, groundwater trace metals often don't provide any environmental or health risks. Furthermore, the water sample measurements show that irrigation uses water in a good to acceptable manner. Future research is required to analyze and appraise the characterization of organic compounds in groundwater quality, according to the study's recommendations.

Keywords

Drinking and Irrigation Water Quality, Groundwater, Dead Sea, Jordan, Saturation Indices

1. Introduction

In regions that are dry or semi-arid, groundwater (GW) supplies are a significant problem. For human, economic, social, and sustainable development, they are essential [1]-[4]. In both urban and rural areas of the world, GW is a highly valuable natural resource for irrigation and drinking. Groundwater quality is critical to rural socioeconomic development since it directly affects human health, plant and food growth, and the ecological system [5] [6]. To avoid harmful impacts on human health and environment, managers, planners, policy makers, and users must evaluate, monitor, and assess water resources for various uses. This includes addressing appropriate GW management and protection solutions, such as technological treatment or alternative water resources [7]-[11]. The quality of GW is measured by various processes and reactions that effect water from the time it is collected until it is stored in a well, which are typically governed by numerous physicochemical features [12] [13]. Jordan's water quality is heavily influenced by the country's freshwater deficit and rising demand. Jordan's water resources include of fossil water and GW, which are located throughout the country in aquifers of varied depths. Groundwater is water stored subsurface the Earth's surface, supplying subsurface and deep water. In Jordan, it serves as primary water supply drinking water, making increasing contamination from industrial and agricultural pollutants a serious and growing concern [14]-[16]. Jordan's primary wet season is winter, which lasts from late October until April. Rainfall is Jordan's principal water source, although it varies widely. In addition, the observed population increase has created intense water consumption [16] [17].

The country's two biggest problems are pollution and water shortages. The second issue is caused by arid to semiarid climates, a lack of sewage systems, and rapid population expansion (the average annual growth rate is about 3.5 percent). As a result, wastewater seeps into groundwater and spring water supplies [16] [18]. In the present research, a one-year monitoring work was conducted with the aims of measured degree ionic toxicity in water samples, classifying waters according to their quality, and determining whether water is suitable for uses in potable and agriculture in relation to recommended levels in accordance with WHO and Jordanian guidelines.

2. Materials and Methods

2.1. Study Area Description

Investigated area is located southeast Dead Sea along the highlands (**Figure 1**). It comprises a large part of the south region of Jordan extended between Latitude

30˚15 to 30˚55 N and Longitude 35˚10 to 36˚50 E. It has a total area of about 5100 km^2 [19]. The area is characterized by low population density and major industries such as cement factory in Al-Tafila area, phosphate mines in Al-Hasa, Al-Abied areas and potash production in the west of investigated area. Besides wastewater treatment plants that treat around 4000 m^3/day in Al-Tafila and Al-Karak governorates. The study area receives different types of pollutants such as anthropogenic remains of solid and liquid wastes, industrial liquid and solid wastes, fertilizers, pesticides and irrigation return flows. On the other hand, the rainfall is low in the area. Intensive farming activities started in the early 1980's especially at Al-Shoubak area where large amounts of good quality freshwater are consumed for irrigation purposes and excessive amounts of pesticides and fertilizers were added to the soil [20].

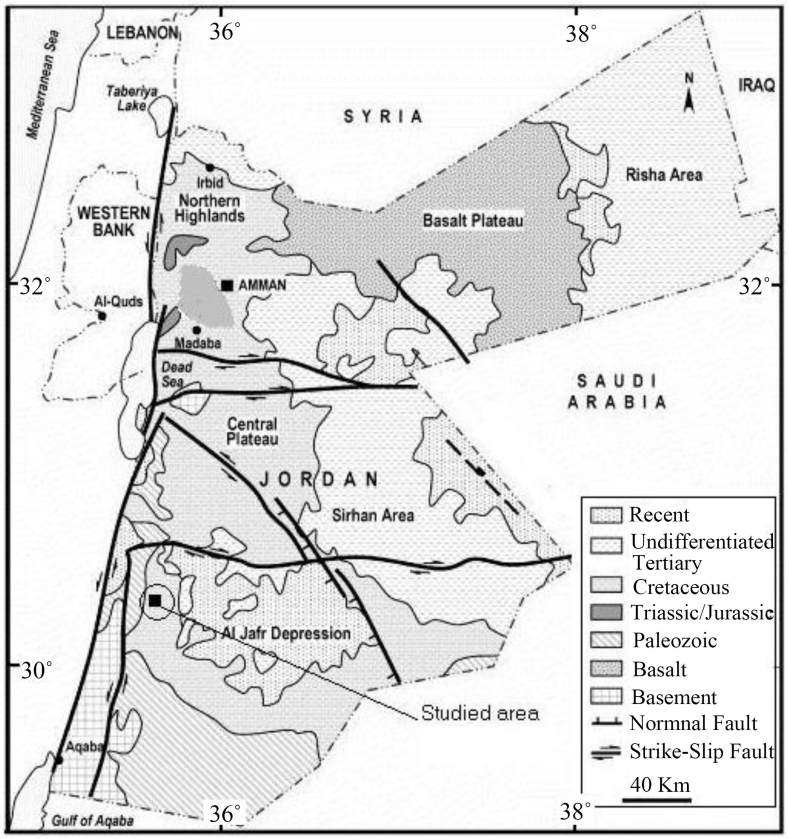

Figure 1. Geological map of Jordan. The study area location is highlighted.

2.2. Climate

The difference between a wet season and arid, hot summer conditions is one of the most significant aspects of the Mediterranean climate found in the studied area. The study area's center highlands get 350 mm of rainfall annually, whereas the southeastern desert and west side that borders the Wadi Araba escarpment receive less than 50 mm [19] [21]. During the winter, snowfall is common in the highlands, which are located between 1000 and 1600 meters above sea level. In the

Al-Shoubak region, which is 1365 meters above sea level, the maximum recorded annual snowfall is 35 cm, and the average number of snowy days is around five [22]. According to Al-Khashman and Jaradat [15] (2014), the potential for evaporation in the region varies from around 1788 mm/year in the Al-Shoubak area to 3467 mm/year in Ma'an area. While relative humidity varies from 40% to 80%, the study region's sunlight hours range from 9.0 hours per day in Al-Shoubak to 9.8 hours per day on average in the Ma'an area [22].

2.3. Geological Setting

Geological setting of the study area is characterized by rock outcroppings that range in age from the Cambrian period to the present day. The Kurnub Group is predominantly consisting of sandstone, primarily found along portions rift side such as Tafila, Karak, and Shoubak. While the lithology of this group is consistent across Jordan, it becomes slightly more terrestrial to the south and east of area [23]. Rainwater is primary source of GW recharge in area, it plays good recharging the entire catchment area and serving as the main exploitable water resource. Groundwater moves both eastward and westward toward the central region of Wadi Araba, where the Dead Sea to the north and the Red Sea to the south serve as the two base levels [24]. The lithological units in the area consist of sedimentary rocks with thicknesses ranging from 40 to 480 meters, including layers from the Cretaceous and Tertiary periods. These layers are consisting of chalky limestone with chert intercalations, marl, limestone, and chert [25] (**Figure 1**).

2.4. Hydrogeology

Groundwater serves as primary water source in area, primarily recharge by precipitation throughout the catchment. It serves as most heavily used and dependable water resources in many areas valued for its consistent availability and quality. In the study area, the primary aquifer system from the Cretaceous period comprises several subsystems:

1) Lower Aquifer Systems: These consist of sandstone (Kurnub Sandstone) and limestone from the Lower Cretaceous period. The Kurnub Sandstone aquifer is made up of massive, white, and multi-colored sandstone with a total thickness of approximately 300 meters [25] [26]. Found primarily along the rift side of the study area, the Kurnub group is dominated by sandstone. It is well-cemented, friable, and highly permeable sequences make it an excellent aquifer, offering favorable conditions for water storage and movement.

2) Systems of middle aquifers made up of the Amman, Wadi Al-Sir, and Hummar hydraulic complexes, which make up the Upper Cretaceous rock units. The primary aquifers in this system are A_1/A_2, A_3, A_4, A_5/A_6, A_7/B_2, B_2, and B_4. The A_1/A_2 is a decent aquifer made up of marl limestone, dolomitic limestone, grey mudstone that contains plant remnants, and gypsum lamina [24] [25]. The A_3 is regarded as a poor aquifer and is made up of strata of laminated fibrous and locally nodular gypsum interbedded with marl, limestone, and mudstone. The A_4 is made

up of gray limestone, crystalline dolomite limestone, and a lot of micrite and chert nodules. When broken and reunited, this deposit is thought to be extremely permeable, creating an excellent aquifer [26]. Due to its high jointing nature, the A_5/A_6 formation consists of marly limestone and marl, interspersed comprises occasional layers of dolomitic limestone, dolomite, and limestone, which collectively constitute an excellent aquifer. One of the most significant GW reservoirs in area is A_7/B_2 formation, which consists of chalk, dolomite, and thin marly limestone interbedded with chert layers [26].

3. Sampling and Analytical Review

Groundwater (GW) samples were collected monthly from 31 monitoring wells over a 12-month period, yielding a total of 372 samples. GW sampling actually began in August 2024 and ended in July 2025. Wells in the southeastern Dead Sea area are typically drilled to depths ranging from approximately 200 in Shoubak area to more than 500 m, depending on the target aquifer and local geological conditions. These wells primarily tap confined (artesian) carbonate aquifers within the Kurnub Group, Ajlun Group, and Belqa Group, with groundwater commonly occurring under confined conditions due to overlying low-permeability marl and shale units. The principle sources of GW are classified A7/B2 (upper cretaceous aquifer) [25]. The majority of the samples were obtained from locally accessible wells. The extensive data matrix used in this study was gathered over the course of a year-long monitoring system. Chemical and physical properties of the water samples were analyzed in accordance with methodologies outlined by Eaton *et al.*, [27] and Al-Khashman [20]. To minimize air entrapment, polypropylene vials were filled with groundwater and rinsed multiple times with clean groundwater [28]. For samples intended for metal analysis, nitric acid was used as a preservative. Field measurements, consisting of temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO), were conducted on-site. Before collecting samples, all plastic container and glassware were treated in 20% HNO_3 for one day followed by through rinsing with deionized water. The pH-meter Model JENWAY-370 was used to measure pH levels on site, and conductivity meter Model JENWAY-470 with temperature correction was utilized to measure electrical conductivity. Calibration was performed before measurement using standard buffer solutions with pH values ranging from 4.00 to 7.00. Dissolved oxygen meter (WTW equipment) was utilized for measuring dissolved oxygen concentrations in situ. Total dissolved solids (TDS) were measured using an Oakton Control Co. meter (USA). Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} are the main cations that were analyzed utilizing an 800 Varian Flame Atomic Absorption Spectrophotometer and 100 Dionex Ion Chromatography apparatus with an AG4A-SC guard column, AS4ASC separating column, and SSR1 anion self-regeneration support. By titrating 0.01 hydrochloric acid, the bicarbonate value was ascertained using methyl orange as an indicator. Using GTA 100 equipment, metals (Fe^{2+}, Al^{3+}, Mn^{2+}, Cu^{2+}, Ni^{2+}, Zn^{2+}, and Pb^{2+}) were investigated in a graphite furnace. The GF-AAS was

calibrated using the standard addition method. Both blank samples and standard solutions of the ions, and metals prepared at different concentrations. 0.01 M HNO_3 [29] was used daily to dilute the stock solutions. This solution was made from the analytical grade HNO_3 that Merck provided. As a result, all standard solutions may be developed. A quality control procedure that comprised recovery testing of standard reference material, duplicate sample analysis, and equipment recalibration was used to manage the quality of the data (see Al-Khashman [14]). All substances and reagents utilized were of laboratory grade, unless stated otherwise. Deionized water (Milli-Q, 18.2 μS/cm) was utilized for dilution processes to ensure the purity of the solutions. To avoid contamination with metals, all glassware, Pyrex, and plastic vessels were thoroughly cleaned using soap and deionized water multiple times. Afterward, the containers were subsequently exposed to 0.01 M HNO_3 and flushed with ultra-pure water. Precision of guidelines used in analysis was maintained within ±7%, ensuring reliable results. The analytical quality of the hydrochemical data was assessed through a comprehensive Quality Assurance/Quality Control (QA/QC) program. Calibration standards, procedural blanks, certified reference materials, and duplicate samples were routinely analyzed throughout the analytical campaign. The recovery percentages for major cations and anions ranged from 95% to 105%, indicating satisfactory analytical accuracy. Duplicate analyses showed a relative percent difference (RPD) of less than 5% for major ions, demonstrating good analytical precision. The method detection limits (MDLs) were 0.05, 0.02, 0.05, and 0.05 mg L^{-1} for Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}, respectively, and 0.10, 0.10, 1.0, and 0.05 mg L^{-1} for Cl^{-}, SO_4^{2-}, HCO_3^{-} and NO_3^{-}, respectively. All reported concentrations exceeded their respective detection limits. The PHREEQC software (v. 3.3.7) is very useful for measuring the SI of minerals in water samples. The calculations incorporated the measured field parameters (pH, temperature, and electrical conductivity) together with the laboratory-determined major-ion concentrations. The selected database provides thermodynamic constants suitable for groundwater geochemical modeling under the hydrochemical conditions encountered in the study area.

4. Results

4.1. Chemical Characteristics of Water

The volume-weighted averages of different physical and chemical characteristics, derived from the samples and analyzed statistically, are presented in **Table 1**.

Table 1. Statistical analysis of physical and chemical parameters of groundwater samples, n = 372 samples.

Parameters	Units	Min	Max	Mean	St.Dev
T	(˚C)	16.81	24.75	20.18	0.94
pH	-	6.65	8.25	7.82	0.28
EC	μS/cm	518.10	1220.70	765.00	167.20

Continued

DO	mg/L	3.18	7.10	4.51	0.59
TDS	mg/L	313.25	749.41	485.20	108.08
TH	mg/L	200.10	485.10	316.30	53.62
Ca^{2+}	mg/L	52.30	149.20	83.77	19.00
Mg^{2+}	mg/L	17.50	39.50	26.20	4.05
Na^{+}	mg/L	15.00	40.15	28.53	5.31
K^{+}	mg/L	1.10	14.50	6.03	1.78
HCO_3^-	mg/L	119.90	321.06	197.66	48.41
Cl^-	mg/L	51.00	148.00	97.63	33.60
NO_3^-	mg/L	28.10	132.10	80.05	25.65
SO_4^{2-}	mg/L	40.00	173.50	90.18	21.82
F^-	mg/L	0.65	4.12	1.58	0.84
PO_4^{3-}	mg/L	0.60	6.15	3.26	1.18
B	mg/L	0.02	0.67	0.21	0.14
SAR	-	0.33	1.95	1.73	0.27
% Na		9.76	28.65	19.76	4.62
RSC	meq/L	−5.19	−1.65	−2.49	1.17
PI	%	21.33	34.51	29.83	3.59
SI calcite	-	0.21	0.50	0.40	0.05
SI dolomite	-	1.27	1.51	1.34	0.15
SI gypsum	-	−3.15	−1.42	−2.23	0.21
SI anhydrate	-	−2.94	−2.51	−2.49	0.17

EC: Electrical conductivity; TH: Total hardness; TDS: Total dissolved solids; SAR: Sodium adsorption ratio; RSC: Residual sodium carbonate; SI: Saturation index; PI: Permeability Index.

The accuracy of the obtained parameter was demonstrated by the ratio of total ions [30]. It was found that the average total of cations was equivalent to that of the anions 0.85 ± 0.28. Additionally, a variance R^2 of 0.87 was achieved from the linear regression of the cation sum on the anion sum for the samples included in this study, indicating that data quality very good. Temperature measured in field which had a mean value of 20.18˚C ± 0.94, with temperatures recorded at 16.81˚C during the rainy season for Bir El Harir No.1 and 24.75˚C during the dry season for Hasa well No.21. The depth of the water sources was the main factor contributing to the temperature differences observed for each well in the study area [19].

The pH readings from the average sample sites during the rainy season ranged from 6.65 at Hasa well No. 12 to 8.25 at Oran well. In the dry season, the average pH was 7.82 ± 0.28, with Hasa No. 19 showing a pH of 7.20 and Bir El Harir at 7.88. The main reason for the differences in pH values across various wells was

the increase in bicarbonate concentrations in water aquifers. Table 2 shows median pH levels of the water samples met the standards set by WHO [31] and JSMO (2015) regulations.

Table 2. Jordanian Standards and WHO guidelines for drinking water quality.

Parameters	Units	JSMO [32]	WHO [31]
T	(˚C)	12 - 25	12 - 25
pH	-	6.50 - 8.5	6.5 - 8.5
EC	μs/cm	400	1500
Na^+	mg/L	200 - 400	200
Ca^{2+}	mg/L	75 - 200	50
Mg^{2+}	mg/L	50 - 150	50
K^+	mg/L	10 - 50	20
HCO_3^-	mg/L	200 - 400	200
Cl^-	mg/L	200 - 500	250
SO_4^{2-}	mg/L	200 - 500	250
NO_3^-	mg/L	70	50
TDS	mg/L	500 - 1500	500 - 1000
TH	mg/L	500	500
Fe^{2+}	mg/L	0.3 - 1.0	0.3
Mn^{2+}	mg/L	0.1 - 0.2	0.1 - 0.5
Zn^{2+}	mg/L	5 - 15	0.01 - 3
Al^{3+}	mg/L	0.2 - 0.3	0.2
Pb^{2+}	mg/L	0.05	0.01
Cu^{2+}	mg/L	-	2
Cd^{2+}	mg/L	-	0.003

During the wet season, the electrical conductivity (EC) of the water at Bir El-Harir was measured at 518.10 μs/cm, while Umurg well No. 2 recorded a much higher value of 1220.70 μs/cm. The mean EC value was 765.00 ± 167.4 μs/cm at 25˚C, with variations in the dry season ranging from 460 μs/cm in Fujaj well No. 4 to 1920 μs/cm in Umurg well No. 2. The high conductivity measured in samples from wells in Al-Tafila area corresponded to highest levels of major ions, likely due to ion exchange and the dissolution of minerals in aquifer [29] [33]. The measured electrical conductivity (EC) values are slightly higher than the guideline value recommended by the World Health Organization (WHO) (400 μS/cm). The elevated EC observed in the groundwater samples is primarily attributed to the increased concentrations of major dissolved ions, including Ca^{2+}, Mg^{2+}, HCO_3^-, and SO_4^{2-}. These ions originate predominantly from water-rock interactions, particularly mineral dissolution and ion-exchange processes occurring within the aquifer system. The average calcium concentration across the different wells was

83.77 ± 19.00 mg/L, with values varied from 52.30 mg/L to 149.20 mg/L. Notably, highest concentration was recorded in winter, attributed to precipitation that allowed calcium to leach from carbonate rocks and soil materials into the groundwater [34]. There was no significant difference in calcium levels between samples collected during the wet and dry seasons. The elevated calcium levels at Quaternary aquifer were linked to overexploitation.

The water samples showed average salinity levels of 28.53 ± 5.31 mg/L—as indicated from major ionic values such as Ca^{2+}, with a range from 15.00 mg/L at the Q'A Ma'an 1 well to 40.15 mg/L at the Tahouneh 1 well. The summer measurements were particularly informative. Major ions present in GW samples show similar trend in their distribution (increase in summer and decrease in wet seasons). The increase in salinity content during summer is primarily due to agricultural water use and reuse. In contrast, the decrease in salinity levels during the dry and wet seasons suggests that rainfall has diluted groundwater (**Figure 2**). The reduction in salinity concentrations from the dry to rainy seasons indicates that rainfall has effectively diluted the groundwater. When comparing the contribution of sodium ions to that of calcium and magnesium, it is relatively minor.

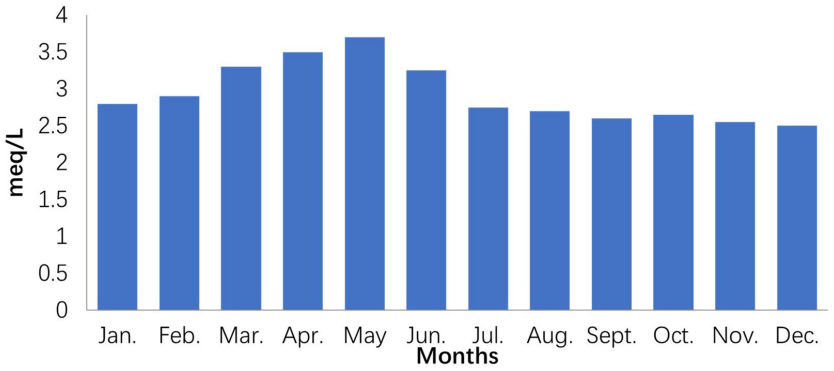

Figure 2. Monthly mean value of Ca^{2+} ionic values in GW samples.

Mercado [23] and Al-Khashman [20] suggest that the reduced Na^+:Cl^- ratio in water samples is due to interactions with clay minerals, which swap sodium for calcium and magnesium ions near groundwater outflows. The median Na^+:Cl^- ratio recorded was 1. The composition of the aquifer, consisting of alternating layers of marl and limestone, further supports this idea, as the clay in the marl likely acts as the exchange medium. The average bicarbonate concentration in the water samples was 197.66 ± 48.41 mg/L, with values ranging from 119.90 mg/L in the Q'A Ma'an 1 well to 321.06 mg/L in the Tahouneh1 well. There was a noticeable increase in Cl^-, K^+, Na^+, NO_3^-, and HCO_3^- from the summer to winter season. The levels of potassium, fluoride, and bromide were all significantly below the allowable limits. A common method for evaluating the relationship between two variables is the relationship. The statistical analysis revealed that Ca^{2+} has a strong positive correlation with Mg^{2+}, Cl^-, and SO_4^{2-} (R^2 = 0.813, 0.740, and 0.741, respectively) with $p < 0.01$. In contrast, sodium showed a positive relationship both

Cl^- and SO_4^{2-} with (R^2 = 0.729 and 0.691) with $p < 0.01$, while Mg^{2+} demonstrated a significant strong correlation with Cl^- and SO_4^{2-} (R^2 = 0.832 and 0.744). Additionally, Cl^- ions showed a greater affinity for HCO_3^- and SO_4^{2-} with (R^2 = 0.837 and 0.824) with $p < 0.01$.

4.2. Chemistry of Water

Water chemistry is influenced by interactions between groundwater and the minerals and dissolved gases present within the aquifer through processes such as mineral dissolution and precipitation [35]. To evaluate mineral-water equilibrium, the saturation index (SI) is commonly used. According to Aghazadeh and Mogaddam [36], the saturation index is calculated using Equation (1):

$$SI = \log(IAP/Kt) \quad (1)$$

where, K is the equilibrium solubility product of a mineral at a given temperature, and IAP is the ion activity product of the dissolved species in solution. The saturation index indicates the equilibrium state between groundwater and a mineral. An SI value of 0 indicates equilibrium (saturation), SI < 0 indicates undersaturation and a tendency **for** mineral dissolution, whereas SI > 0 indicates supersaturation and a tendency for mineral precipitation [20] [35] [37]. A summary of the saturation index statistics for the groundwater samples is presented in **Table 1**. Calcite and dolomite exhibited positive (or near-zero, if applicable) saturation indices, indicating that the groundwater is at or above equilibrium with these carbonate minerals and that precipitation is thermodynamically favored. In contrast, gypsum and anhydrite showed negative saturation indices in all samples, indicating that the groundwater is undersaturated with respect to these minerals and that they tend to dissolve rather than precipitate if present. These results suggest that carbonate mineral equilibria largely control the groundwater chemistry, whereas sulfate minerals remain undersaturated. The trilinear diagram developed by Piper (1953) illustrates the ionic composition of the groundwater samples, while the classification of Langguth (1966) (**Figure 3**) aids in hydrochemical interpretation. The groundwater samples were classified as alkaline earth waters dominated by bicarbonate or as alkaline earth waters containing both bicarbonate and chloride. Based on the hydrochemical composition, the dominant ions are sodium, potassium, magnesium, bicarbonate, chloride, sulfate, nitrate, phosphate, fluoride, and calcium. Overall, the groundwater chemistry is primarily controlled by the dissolution of carbonate rocks and is characteristic of freshwater conditions.

Chemistry of water is influenced by interacts with ions and dissolved gases present within the aquifer due to processes such as mineral precipitation and dissolution [35]. To evaluate the mineral-water balance, saturation indicators are utilized. Aghazadeh and Mogaddam [36] propose that Equation (1) can be used to determine saturation index of mineral.

The potassium level reflects the equilibrium solubility product of a compound at a specific temperature, whereas the ion activity product (IAP) describes the effective activity of the dissolved ionic species present in the solution. Minerals will

dissolve when the saturation index (SI) is less than 1 and will precipitate when SI is greater than 1 [20]. The saturation index can be used to indicate the concentration levels of minerals present in the analyzed water samples. Specifically, when saturation index is less than 1, minerals dissolve, and when SI is greater than 1, they precipitate [35] [37]. A summary of the saturation index statistics for the water samples is presented in **Table 1**. Calcite and dolomite were present in all groundwater samples, while the indices for gypsum and anhydrate were negative across all samples. This suggests that the water samples below the saturation limit for gypsum and anhydrate may contain higher levels of dissolved gypsum and anhydrate.

The trilinear diagram created by Piper in 1953 illustrated the ion proportions in groundwater samples, while Langguth's classification from 1966 (**Figure 3**) helped interpret the results. The water samples were categorized as alkaline earth waters high in bicarbonate, or as alkaline earth waters content in both bicarbonate and chloride. Based on the water sample chemistry, the ionic ratios ranked from highest to lowest are sodium, potassium, magnesium, bicarbonate, chloride, sulfate, nitrates, phosphate, fluoride, and calcium. The water's chemistry is mainly governed by the dissolution of carbonate rocks. Despite this, it is generally considered to have freshwater conditions.

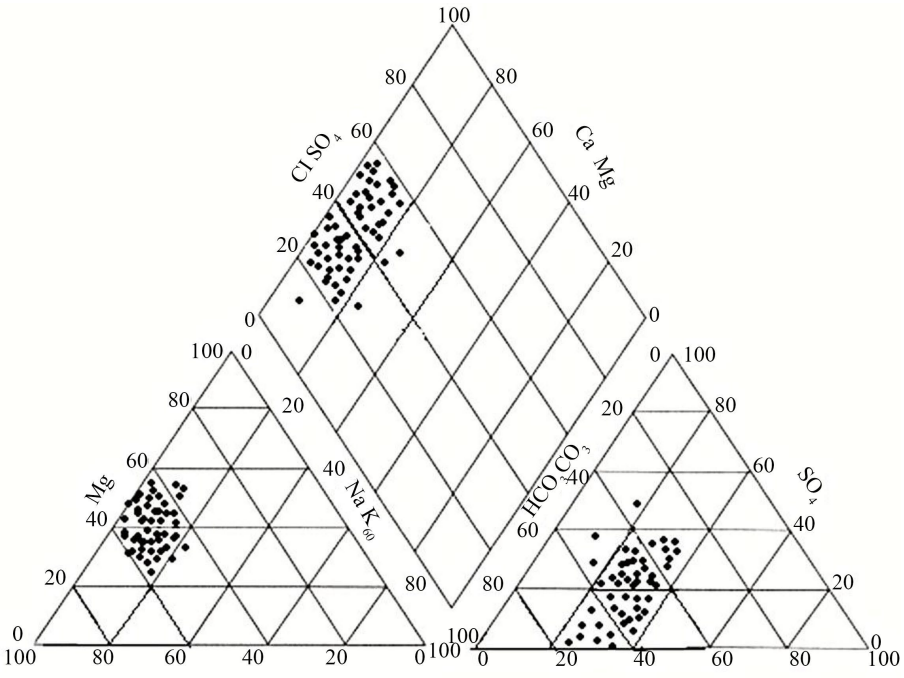

Figure 3. Piper diagram of GW in studied area (values in % meq/L).

4.3. Assessment for Drinking

To assess drinking water quality, TDS and TH measurements are compared against JSMO [32] and WHO [31] guidelines (**Table 2**). Overall, the TDS levels in water parameters are within acceptable limits set by JSMO [32] and WHO [31].

Most GW samples were categorized as very hard water (Table 3), according to Sawyer and McCarty [38] for assessing their suitability of water samples for uses.

Table 3. Classification of the water samples on the basis of the total hardness.

Hardness (mg/L)	Water class	No. of samples
0 - 75	Soft	-
75 - 150	Moderately hard	22
150 - 300	Hard	150
Over 300	Very hard	200

Measured average hardness of water samples was 316.30 mg/L, ranging from 200.10 mg/L to 485.10 mg/L. Notably, Q'A Ma'an 1 well had the highest recorded value. The total hardness (TH) of drinking water can reach up to 500 mg/L, while the minimum acceptable level is 100 mg/L [31] [39] [40].

The average nitrate value was 80.05 ± 25.65 mg/L, varied from 28.10 mg/L to 132.10 mg/L. Elevated nitrate concentrations in the groundwater (GW) samples, particularly during the summer season, are primarily attributed to intensified agricultural activities, including the application of nitrogen-based fertilizers for irrigation, enhanced biological nitrogen fixation, and the infiltration of untreated domestic wastewater from cesspools widely distributed throughout the villages within the study area [15]. Despite these seasonal increases, only 3% of the analyzed groundwater samples exceeded the maximum permissible nitrate concentration of 50 mg/L established by the World Health Organization for drinking water, whereas approximately 95% of the samples remained within the recommended guideline value, indicating generally acceptable groundwater quality with respect to nitrate contamination. Fluoride is a key trace ion found in groundwater and can occur in substantial quantities because the bedrock contains fluoride-bearing minerals [25] [40] [41]. Groundwater samples exhibited an average fluoride level of 1.58 ± 0.84 mg/L, with individual measurement varying between 0.65 mg/L to 4.12 mg/L. The results indicate that the fluoride values in all water samples comply with Jordan's drinking water standards and fall within the acceptable range.

4.4. Water Suitability for Irrigation

Influence of GW ions and nutrient levels on plants and soil has is essential for evaluating irrigation suitability [5] [6] [13] [42]. Amount of water assigned for agricultural uses depends on availability of water resources. Various parameters, including pH, EC, SAR, Sodium Percentage (SP), and RSC, are utilized to evaluate suitability of water for agricultural uses [40] [43].

Electrical conductivity (EC), a proxy for TDS in GW, is a key indicator of salinity. Elevated salinity concentration in water used for irrigation lowers osmotic pressure in root zone, restricting water absorption and impairing plant growth [15] [35] [44]. In addition, EC is a useful tool for assessing water quality and pro-

vides a dependable measure of the salt threat to plants and crops. The EC values for the water samples varied between 518.10 μs/cm to 1220.70 μs/cm, with a mean of 765.00 ± 167.20 μs/cm. According to the results, nearly all water samples fell inside the acceptable permissible values for irrigation water quality [5] [6] [40] [45]. The TDS levels showed value of 485.20 mg/L, between 313.25 mg/L to 749.41 mg/L that is below the suggested limit of 2000 mg/L, suggesting that GW are suitable for irrigation and not affected by osmotic pressure of soil solution [40] [43]. The TDS value generally below the threshold set by JSMO [32]. The data showed that, excluding April, when TDS levels exceeded those of June, TDS values tended to rise during dry seasons compared to rainy ones.

The average boron content in samples was 0.21 mg/L, varied from 0.02 mg/L to 0.67 mg/L (**Table 4**). For semi-sensitive crops, all groundwater samples were below the allowable limits. Most vulnerable crops can tolerate only 0.5 - 1.0 mg/L, as noted by Todd [46]. The SAR is used as a key indicator to assess sodium threat on crops and GW suitability for agricultural use. The later parameter can be calculated by applying formula below [47].

$$SAR = Na^{+}/(Ca^{2+} + Mg^{2+})^{0.5}/2 \quad (2)$$

All values are expressed in meq/L.

Table 4. Permissible limits of boron in irrigation water for several types of crops.

	Semi-sensitive crops			Semi-tolerant crops			Tolerant crops		
Boron class	Range (mg/L)	No. of wells	Wells (%)	Range (mg/L)	No. of wells	Wells (%)	Range (mg/L)	No. of wells	Wells (%)
Excellent	<0.3300	350	94	<0.67	372	100	<1.00	372	100
Good	0.33 - 0.67	22	6	0.67 - 1.33	Nil	0	1.0 - 2.0	Nil	0
Permissible	0.67 - 1.00	Nil	0	1.33 - 2.00	Nil	0	2.0 - 3.0	Nil	0
Doubtful	1.10 - 1.25	Nil	0	2.00 - 2.50	Nil	0	3.0 - 3.75	Nil	0
Unsuitable	>1.25	Nil	0	>2.50	Nil	0	>3.75	Nil	0

Average value of SAR was 1.730, with a range from 0.33 to 1.95. The classification of low sodium (S1) applies to the 27 samples collected the area. Majority of these samples are categorized as C3S1, which signifies high salinity and low sodium risk, making them suitable for irrigation across nearly all soil types, based on the data plotted on the US salinity diagram [48] (**Figure 4**). All samples showed Na percentages below 40% (**Figure 5**), suggesting that the water is almost adapted to irrigation conditions [49]. RSC denotes the abundance of carbonate and bicarbonate [50]. The RSC is measured using Equation (3).

$$RSC = (CO_3^{2-} + HCO_3^{-}) - \left(Ca^{2+} + Mg^{2+}\right) \quad (3)$$

All values are present in meq/L.

The classification of irrigation water based on RSC values results is presented in **Table 1**. RSC is used to classify different types of water for agricultural purposes [1] [4]. The mean RSC level was −2.49 ± 1.17, with a range from −5.19 meq/L to

−1.65 meq/L. All samples showed satisfactory water quality, as RSC levels were below 1.25 meq/L.

Elevated HCO_3^- levels of irrigation water can lead to increased toxicity and negative impacts on plant nutrition. However, as discussed later, PI levels of the samples revealed their suitability for irrigation [45]. The PI value serves as an indicator of the appropriateness of irrigation water, assessing the salt hazards associated with it.

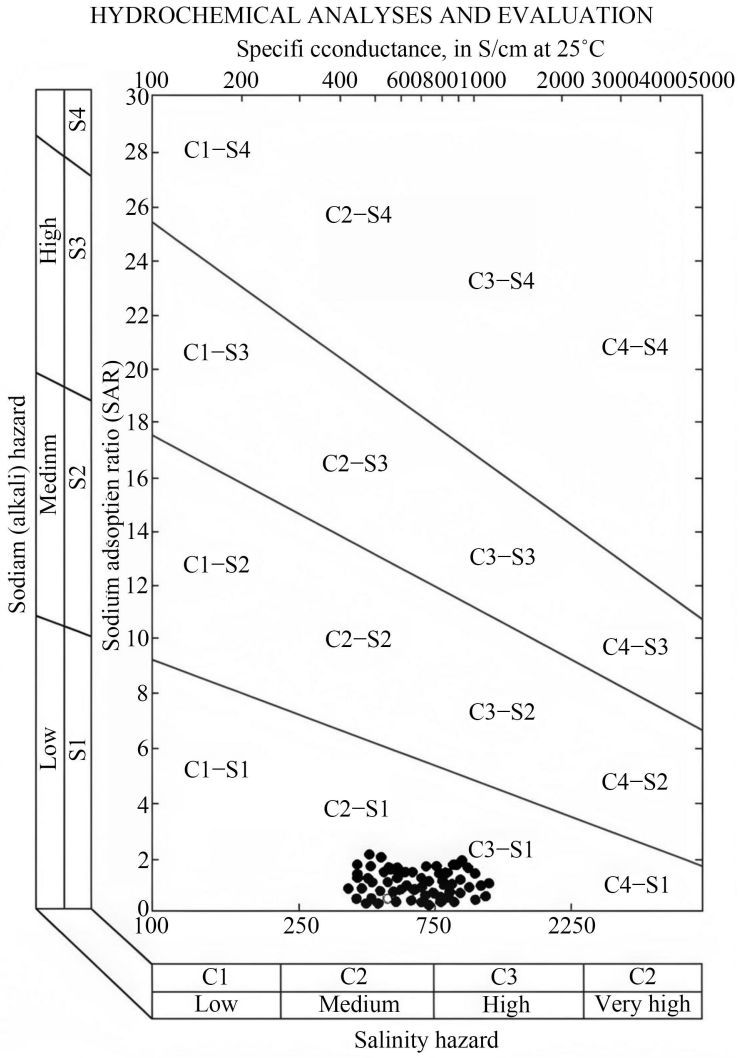

Figure 4. Rating of GW samples in relation to salinity (EC) and sodium hazard (SAR) based on USSL diagram.

The Permeability Index (PI) of the groundwater samples varied from 21.33 to 34.51**,** with a mean value of 29.83. The majority of the samples were distributed within Class I and Class II of the permeability index classification, reflecting favorable to moderately favorable conditions for irrigation use across the study area. Approximately 35% of the groundwater samples were categorized as good, while 63% were classified as suitable for irrigation, indicating that most groundwater

resources possess acceptable permeability characteristics for sustained agricultural application [40] [51].

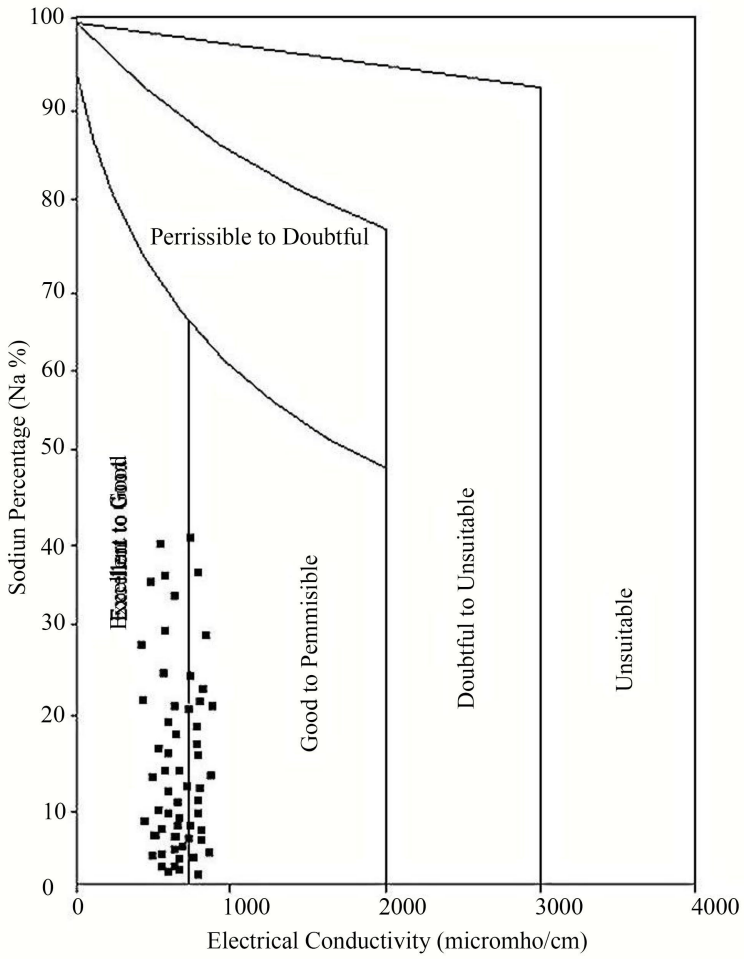

Figure 5. Rating of GW samples on the basis of EC and Na% (after Wilcox [49]).

4.5. Trace Metals

Historically, trace metals have been associated with both natural and human activities, and they can be found in surface water as well as groundwater. The two main natural processes that leads to the higher values of metals in water are chemical alteration of rocks and soil nutrient depletion [14] [52]. The release of metals from soils and similar materials greatly affects their stability in water. Factors including co-precipitation, hydration, pH, and adsorption are all involved in this process [37] [52]. **Table 5** provides analytical evaluation of elemental values of samples. Across the majority of water samples trace metals values are relatively low, likely due to high pH (above 7.0) which either promotes metals concentration or inhibits leaching host rock [18] [53]. The iron content in the water samples averaged 112.35 μg/L ± 42.29, having levels varied between 65.23 μg/L to 198.12 μg/L.

Groundwater contains low concentrations of iron because iron forms a strong

bond with oxygen, which only break apart when there is no oxygen. The detected iron concentration in water was significantly lower than thresholds suggested by the WHO potable water. As presented in Table 5, lead content in samples varied between 10.00 μg/L to 54.10 μg/L, with a mean value of 24.53 μg/L. Based on JSMO [32], all tested samples fell within the permitted range and were under tolerance levels (0.05 mg/L).

Mean value of manganese (Mn) was 17.50 μg/L ± 4.96, with values between 8.10 μg/L and 24.80 μg/L. Nevertheless, every water samples had Mn concentrations that were below the acceptable threshold for drinking water quality. Zn levels varied from 9.50 μg/L to 41.00 μg/L, with a mean value of 23.56 μg/L ± 7.83. All groundwater samples contained zinc levels below the recommended threshold set by the Jordanian Standard (2001). Levels of other trace metals were also below levels considered safe for drinking.

Table 5. Statistical analysis of trace metals of groundwater samples.

Parameters	Units	Minimum	Maximum	Mean	St.Dev
Fe^{2+}	μg/L	65.23	198.12	112.35	42.29
Al^{3+}	μg/L	54.10	170.00	89.50	23.84
Cu^{2+}	μg/L	9.51	32.15	18.41	7.58
Ni^{2+}	μg/L	9.65	31.05	16.95	5.40
Pb^{2+}	μg/L	10.00	54.10	24.53	12.11
Zn^{2+}	μg/L	9..50	41.00	23.56	7.83
Mn^{2+}	μg/L	8.10	24.80	17.50	4.96

5. Conclusions

This study focused on characterization of GW to assess its suitability for potable and agricultural uses, and to determine the source of expected pollution. Over a one-year period, water quality indicators of GW from southern Jordan were analyzed. The results indicated that the collected samples exhibited generally alkaline conditions. Major contributors to salinity were Cl^{-}, Na^{+}, Ca^{2+}, HCO_3^{-} and Mg^{2+}. The values of these ions increased relative to precipitation as a result of carbonate dissolution in aquifers.

Trace metal levels in samples were minimal, attributed to water's mildly alkaline characteristics. The metals levels were significantly under the acceptable limits of WHO and JSMO guidelines for drinking water. According to measured levels of EC, SAR, RSC, Na%, PI, Boron, beside salinity diagram, it determined that all suitable for drinking and irrigation. Hydrochemical analysis indicated that most samples fell into the Ca-Mg-HCO_3 category, followed by Ca-Mg-Cl-SO_4 and Na-K-HCO_3 hydrochemical facies. Therefore, water samples considered suitable for long-term use in both drinking and irrigation. However, continuous monitoring and protective measures are necessary to mitigate the impacts of household waste, sewage water, and chemical fertilizers used in agricultural practices in study

area. Additional study is also needed to assess inorganic, biological and organic parameters for monitoring the quality of GW and springs.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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