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Groundwater Quality Impacts on the Soils of Two Sites, NW Mosul, Iraq

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Abstract

This study evaluates the quality of groundwater from wells located in two areas on both sides of the Tigris River northwest of Mosul City in order to conduct a hydrochemical comparison and assess their impact on soil salinity. A total of 10 groundwater samples were collected from area (A), and 9 samples from area (B). Additionally, irrigated soil samples were taken from each well, along with three naturally rain-fed soil samples from each area. The water analyses include measurements of electrical conductivity (EC), pH, total hardness, and the major cations and anions. Soil analyses include salinity, pH, calcium carbonate content, and soil texture. The EC values of groundwater range from 3.51 to 7.49 dS/m in area (A), and from 1.02 to 5.23 dS/m in area (B). The average concentrations of salinity, sodium, potassium, calcium, sulfates, and chlorides in area (A) are approximately 1.5 times higher than those in area (B). The impact of irrigation with well water on soil is evident, as most irrigated soils in area (A) are saline soil. In contrast, only one saline soil sample is recorded in area (B). This difference is attributed to the lower salinity levels of well water in area (B). Long-term use of high-salinity groundwater in area (A) has led to soil salinization, especially when compared to rain-fed soils. Saturation indices for calcite, dolomite, gypsum, and halite minerals present in the aquifer are also calculated. Furthermore, hierarchical cluster analysis is applied to classify the wells in both areas.

Keywords:

Ground water, Water quality, Aquifer, Soil salinity, Irrigation.

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1. Introduction

Groundwater is one of the primary sources of fresh water on Earth and plays a vital role in sustainable development, especially in arid and semi-arid regions. It is considered a fundamental resource not only for drinking but also for irrigation and other uses. The quality and quantity of groundwater are both crucial, as they determine the potential for its utilization, particularly in agriculture (Kaur et al., 2017). In Iraq, groundwater has been excessively exploited for agricultural purposes, leading to a decline in water levels and a change in water quality. Water quality is no less important than its quantity; groundwater may be abundant in a given area but still unsuitable for use due to poor quality (Kateb and Al-Youzbakey, 2025). The occurrence of groundwater depends on several factors, including topography, drainage patterns, geological formations, slope, and land use (Nelly and Mutua, 2016). The chemical characteristics of groundwater play a crucial role in its classification, as these are determined by the concentration of dominant ions and the interactions between water, rocks, and soil. These interactions are influenced by rainfall chemistry, climatic conditions, types of minerals in the aquifer, and the interaction between surface and groundwater (Seeyan, 2020). The chemical composition of groundwater is primarily affected by its interaction with minerals present in the geological formations through which it flows (Sidhu and Chandel, 2023). Therefore, the factors influencing groundwater chemistry vary both spatially and temporally. The interactions between sediments, rocks and water, including redox reactions, ion exchange, aquifer residence time, dissolution of various minerals and aerobic or anaerobic conditions, all play a fundamental role in shaping groundwater chemistry. As a result, the groundwater in each location exhibits a unique chemical signature (Subramani et al., 2010). This study aims to evaluate the hydrochemical properties of groundwater in two areas on opposite sides of the Tigris River northwest of Mosul, and to assess its impact on soil salinity when used for irrigation by comparing it to adjacent rain-fed soils

2. Study Locations

The study is carried out at two sites in Nineveh Governorate, Iraq, between longitudes 42°48'.0" E - 43°3'.0"E and latitudes 36°30'.30"N - 36°23'.0" N. The first site (A) is located on the right bank of the Tigris River, in and around the villages of Al-Zanazel and Al-Buwair, approximately 38.1 km northwest of Mosul. The second site (B) is situated on the opposite left bank of the Tigris River, in and around the villages of Sheikh Mohammed and Alam Louk, approximately 29.7 km northwest of Mosul (Fig. 1). Both sites have intensive agricultural activity. Figure 2 shows the geological maps for both sites.

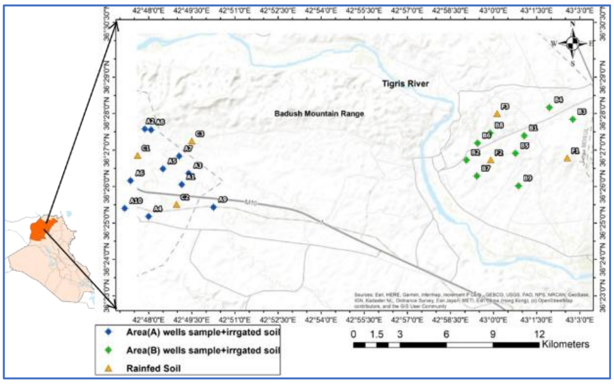

Fig. 1: Location of each well and associated soil samples in areas A and B.

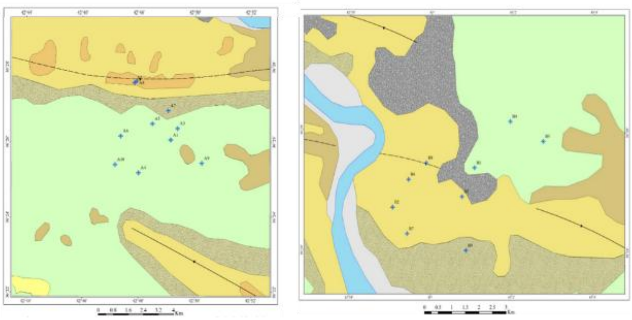

Fig 2: Geological map of the study area.

3. Materials and Methods

A total of 19 groundwater samples were collected in August 2024, which represent the end of the dry period; ten samples from area (A) and nine samples from area (B). Additionally, 24 surface soil samples (0–20 cm depth) were collected, twelve from each area, including nine irrigated soils (from lands irrigated with the studied well water) and three rained soils from each area for comparison. No soil sample was taken from well A8 due to the extremely high salinity of its water and the absence of any agricultural activity as observed during the field visit in this zone. Soil samples were collected in plastic bags and analyzed for salinity and pH using a 1:1 soil-water extract. Calcium carbonate content was determined by acid neutralization titration with hydrochloric acid following the method of Page et al. (1982). Soil texture was determined using the hydrometer method as described by Al-Zaghbi et al. (2013).

Groundwater samples were collected in clean plastic containers, which were thoroughly rinsed with well water before sampling. Samples were collected after operating the well for at least 15 minutes to ensure representative groundwater from the aquifer. Each sample was labeled, and relevant field data were recorded, including site name and coordinates using a GPS device to accurately plot on the map. The irrigated soil samples were located approximately 15–25 meters from the respective wells. Due to the map scale, soil points did not appear separately on the map and were represented by a single point corresponding to the well location.

Field measurements included pH, electrical conductivity (EC), and total dissolved solids (TDS) using an EC-pH meter. Laboratory analyses were conducted at the Soil Science Laboratory, Department of Soil and Water Resources Science, College of Agriculture and Forestry, University of Mosul. Total hardness was measured by titration with EDTA. The cations Na^+ and K^+ were measured using a flame photometer, while Ca^{2+} and Mg^{2+} were determined by titration with EDTA. The anions SO_4^{2-} and NO_3^- were analyzed using a spectrophotometer at wavelengths of 470 nm (for sulfates) and 220 and 275 nm (for nitrates). Chloride ions were determined by titration with silver nitrate, and bicarbonates were measured by titration with 0.01 N sulfuric acid following APHA (2017) procedures.

After completing the chemical analyses of the major ions, data accuracy was verified using the ionic balance equation as outlined by Hem (1989) using equation (1).

$$E\% = \frac{abs(\sum cat - \sum ani)}{\sum cat + \sum ani} \times 100 ......(1)$$

Where: ∑cat = sum of major cations (meq/l); ∑ani = sum of major anions (meq/l); abs = absolute value.

An ionic balance error ranging between 5% and 10% is generally considered acceptable for hydrochemical interpretations, while an error below 5% indicates a very high level of analytical accuracy (Stoodly et al., 1980). Based on the results, the highest calculated error among all samples is absolute (- 6.4%) (Table 1), indicating that the data are reliable and can be confidently used for hydrochemical interpretation.

4. Results and Discussion

Table (1) presents the laboratory analysis results for the groundwater samples. The average electrical conductivity (EC) ranges between 4942 µS/cm in area (A) and 3230 µS/cm in area (B). The average Total Dissolved Solids (TDS) ranges between 3493 mg/l in area (A) and 2068 mg/l in area (B). The salinity of well water in area (A) is approximately 1.5 times higher than in area (B). Most wells in area A exhibited higher salinity levels than those in area (B). EC values in all wells from area A exceeded 3 dS/m, which is the maximum permissible limit for irrigation according to the Food and Agriculture Organization (FAO) guidelines, while only 55% of the wells in area (B) exceeded this threshold. The average total hardness of water (TH) ranges between 1616 mg/l in area (A) and 1142 mg/l in area (B).

The average pH values are 6.44 and 6.67 in areas (A and B), respectively. The mean calcium (Ca^{2+}) concentrations are 467 mg/l in area (A) and 298 mg/l in area (B), indicating that calcium levels in area (A) are approximately 1.5 times higher, contributing to higher water hardness compared to area (B). The mean magnesium (Mg^{2+}) concentrations are 120 mg/l in area (A) and 102 mg/l in area (B). Sodium (Na^{+}) concentrations averaged 325 mg/l in area (A) and 179 mg/l in area (B). Potassium (K^{+}) concentrations averaged 9.2 mg/l in area (A) and 5.4 mg/l in area (B). The relatively low potassium concentrations in well water are attributed to its resistance to weathering compared to sodium, as well as its tendency to adsorb onto soil particles (Ibrahim and Nofal, 2020).

Chloride (Cl^{-}) concentrations average 552 mg/l in area (A) and 378 mg/l in area (B). Most of the chloride in groundwater originates from evaporite rocks, particularly halite (NaCl), which commonly occurs as lenses within the gypsum-bearing rocks of the Fatha Formation (Kateb and Al-Youzbakey, 2025). Sulfate (SO_4^{2-}) levels average 1360 mg/l in area (A) and 858 mg/l in area (B). Overall, most groundwater wells in area (A) show higher ion concentrations than those in area (B), with mean sulfate levels in area (A) exceeding those in area (B) by more than 1.5 times. The elevated sulfate concentrations can be attributed to the dissolution of gypsum and anhydrite rocks upon contact with groundwater within the Fatha Formation (Al-Youzbakey and Suleiman, 2020).

Bicarbonate (HCO_3^{-}) concentrations averaged 269 mg/l in area (A) and 307 mg/l in area (B). This was the only major ion that exhibited a reverse trend, with higher levels in area (B) than in area A. Nitrate (NO_3^{-}) levels averaged 22.4 mg/l in Area (A) and 6.6 mg/l in area (B). The elevated nitrate concentrations in area (A) are likely due to the excessive use of nitrogen-based and organic fertilizers in agricultural fields, with nitrate leaching through the soil into the underlying aquifers (Karyab et al., 2019).

Table 1: Laboratory analysis results of major ions in groundwater samples from both study areas.

Wells in area (A)

Well No.	EC	pH	TDS	TH	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	Cl^{-}	SO_4^{-2}	HCO_3^{-}	NO_3^{-}	E%
	dS/m		mg/l										
A_1	3.5	7.2	2247	1611.6	519.9	87.1	86.4	4.2	106.4	1322	219.6	13.9	3.7
A_2	5.9	6.4	4736	1620.6	424.0	145.4	551.4	15.5	1042.2	1439	329.4	2.3	-6.0
A_3	4.1	6.5	2650	1685.9	538.3	94.4	119.2	5.4	244.6	1579	219.6	22.4	-4.5
A_4	4.3	6.5	2787	1737.0	534.6	109.0	134.1	4.2	248.2	1346	219.6	19.5	3.3
A_5	3.8	6.5	2475	1529.6	394.5	140.6	149.0	3.6	109.9	1579.2	219.6	52.3	-3.3

A_6	4.3	6.5	2776	1721.0	505.1	122.3	152.0	3.7	148.9	1684	195.2	46.5	-1.4
A_7	4.8	6.2	3130	1691.5	519.9	106.5	283.1	11.2	432.5	1230	256.2	0.3	5.9
A_8	7.3	6.1	5840	1509.0	379.8	144.2	864.3	26.0	1701.6	957	439.2	19.8	-4.4
A_9	7.5	6.1	5992	1440.8	357.6	140.6	834.5	15.2	1382.6	1105	341.6	17.8	-1.3
A_{10}	3.6	6.1	2306	1673.2	497.7	115.0	80.4	3.0	106.4	1357	256.2	29.1	2.7
min	3.5	6.1	2247	1440.8	357.6	87.1	80.4	3.0	106.3	957	195.2	0.3	-1.3
max	7.5	7.2	5992	1737.0	538.3	145.4	864.3	26.0	1701.6	1684	439.2	52.3	-6.0
mean	4.9	6.4	3493.9	1616.5	467.1	120.5	325.5	9.2	552.3	1359.8	269.6	22.4	
Wells in area (B)													
B_1	5.2	6.7	3345	1455.7	390.8	124.8	447.0	8.7	886.2	1214.4	341.6	0.3	-6.1
B_2	1.0	7	652	468.4	103.2	53.3	43.2	2.3	88.6	168.0	329.4	1.1	0.3
B_3	3.6	6.8	2308	1619.4	427.7	143.0	77.5	5.8	141.8	1526.4	305.0	0.4	-5.4
B_4	3.9	6.4	2540	1748.2	497.7	133.3	98.3	5.7	194.9	1473.6	268.4	4.2	-0.5
B_5	3.9	6.4	2541	1225.9	324.4	107.8	253.3	6.9	549.4	879.0	317.2	16.7	-4.0
B_6	2.7	6.6	1779	815.3	195.4	83.6	192.2	5.3	407.6	567.0	305.0	0.4	-6.0
B_7	4.8	6.4	3085	1364.7	361.3	120.0	327.8	8.5	762.1	903.0	317.2	19.4	-3.9
B_8	1.5	6.3	977	743.7	184.3	72.7	59.6	2.4	124.0	333.6	329.4	1.0	5.9
B_9	2.1	7.2	1390	838.0	202.8	84.8	113.2	3.1	248.1	657.0	256.2	16.0	-6.4
min	1.0	6.3	652	468.4	103.2	53.3	43.2	2.3	88.6	168.0	256.2	0.3	0.3
max	5.2	7.2	3345	1748.2	497.7	143.0	447.0	8.7	886.2	1526.4	341.6	19.4	-6.4
mean	3.2	6.6	2068.5	1142.1	298.6	102.6	179.1	5.4	378.1	858.0	307.7	6.6	

Table 2: Some physical and chemical properties of the soil samples.

Area (A)							
soil samples	EC dS/m	pH	$CaCO_3$%	% sand	% silt	% clay	soil texture
A_1	6	6.8	33	15.8	40.75	43.45	silty clay
A_2	9.3	6.8	40	35.8	30.75	33.45	clay loam
A_3	3.5	7.2	30	20.8	39	40.2	clay
A_4	4	6.9	26	15.8	71.5	12.7	silty loam
A_5	6.2	6.7	31	20.8	64	15.2	silty loam
A_6	4.1	6.9	30.5	15.8	44	40.2	silty clay
A_7	6.6	6.8	32	21.55	45	33.45	clay loam
A_8	Without soil samples						
A_9	7	6.9	29.5	9.05	37.5	53.45	clay
A_{10}	3.1	6.8	27	10.8	40.75	48.45	silty clay
min	3.1	6.7	26	9.05	30.75	12.7	
max	9.3	7.2	40	35.8	71.5	53.45	
Rain-fed lands							
C_1	0.6	8.2	34	17.3	52.5	30.2	silty clay loam
C_2	0.5	8.3	35	12.3	55	32.7	silty clay loam
C_3	0.5	7.9	31.5	20.55	52.5	26.95	silt loam
(C) mean	0.53	8.13	33.5	16.72	53.33	29.95	Silty Clay Loam
Area (B)							
B_1	4.1	6.9	34	14.8	33.25	51.95	clay
B_2	1	7.1	38.5	12.3	33.25	54.45	clay
B_3	3.6	6.7	33	14.05	40.75	45.2	silty clay
B_4	3	6.9	24	7.3	35	57.7	clay
B_5	3.1	7.1	39.5	9.8	32.5	57.7	clay
B_6	2.8	7	37	17.3	37.5	45.2	clay
B_7	2.5	6.8	39.1	17.3	32.125	50.575	clay
B_8	3	6.9	35.5	14.8	31.75	53.45	clay
B_9	2	7.3	37.5	11.55	32.5	55.95	clay
min	1	6.7	24	7.3	32.1	45.2	
max	4.1	7.3	39.5	17.3	40.75	57.7	
Rain-fed lands							
F_1	0.5	8.1	24	8.05	46.13	45.83	silty clay
F_2	0.6	7.9	30	15.55	46.50	37.95	silty clay loam
F_3	0.6	8	24	13.8	55.00	31.20	silty clay loam
(F) mean	0.57	8	26	12.47	49.21	38.33	Silty Clay Loam

The relationship between sodium and chloride, as illustrated in Figure (3-b), shows that most of the groundwater samples lie on or close to the 1:1 line, indicating a strong positive correlation. This suggests that the source of these ions is predominantly the dissolution of secondary halite (NaCl) deposits present in the shallow subsurface layers, particularly in shallow wells (Al-Youzbakey and Suleiman, 2020; Sajil and James, 2016).

Similarly, the relationship between calcium and sulfate, shown in Figure (3-a), reveals that most samples fall along or close to the 1:1 line, reflecting a positive correlation. This indicates that the groundwater chemistry in the study areas is largely influenced by the dissolution of gypsum and anhydrite minerals. In general, calcium and sulfate concentrations in area (B) are lower than those in area (A). However, a few samples fall below the 1:1 line, suggesting lower calcium concentrations relative to sulfate. This deviation may be attributed to ion exchange processes (Omar, 2023).

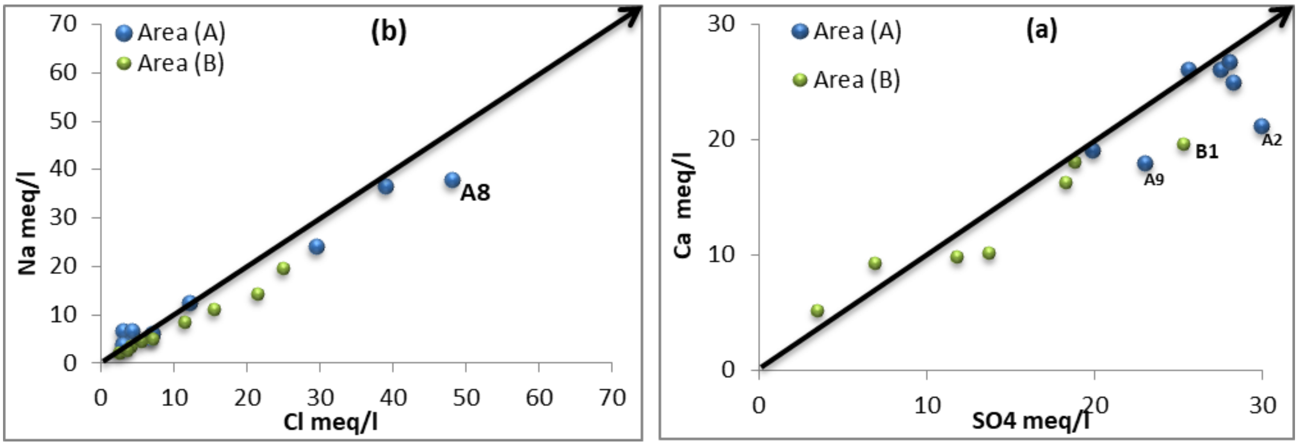

Fig. 3: Relationships between calcium and sulphate and sodium and chloride in groundwater samples from both study sites.

Based on Table (2), a clear difference is observed between rainfed soils and irrigated soils in terms of (EC) values. In area (A), EC values range between 3.1 and 9.3 dS/m for irrigated soils, compared to an average of 0.53 dS/m for rainfed soils. In area (B), EC values for irrigated soils range from 1 to 4.1 dS/m, while the average EC for rainfed soils is 0.57 dS/m. All irrigated soils in area (A) are classified as saline since their EC values exceed 4 dS/m according to Al-Zubaidi (1989), whereas in area (B), only one irrigated soil sample is classified as saline. Figure (4) illustrates a positive correlation between well water salinity and soil salinity, indicating the impact of irrigation with groundwater on increasing soil salinity. Regarding soil pH, its values in area (A) range from 6.7 to 7.2, while the average pH for rainfed soils is 8.13. In area (B), soil pH values range from 6.7 to 7.3, with rainfed soils averaging pH 8. Figure (5) shows an inverse relationship between soil salinity and soil pH. Calcium carbonate content in irrigated soils ranges between 26% and 40% in area (A), while in area (B) it ranges from 24% to 39.5%. As for soil, clay texture is predominant in area (B). In area A, soil samples are distributed as follows: 3 samples of Silty Clay, 2 samples of Clay Loam, 2 samples of Clay, and 2 samples of Silty Loam (Table 2).

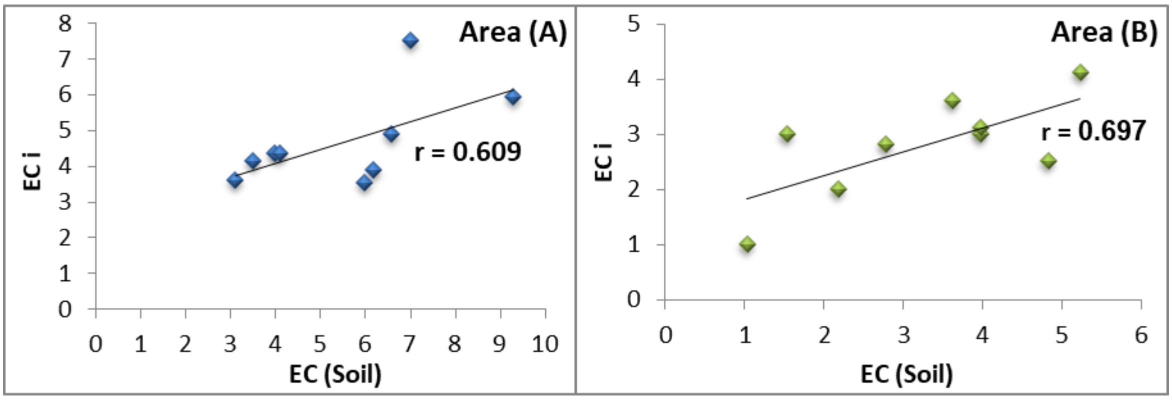

Fig. 4: Positive correlation between groundwater salinity and soil salinity.

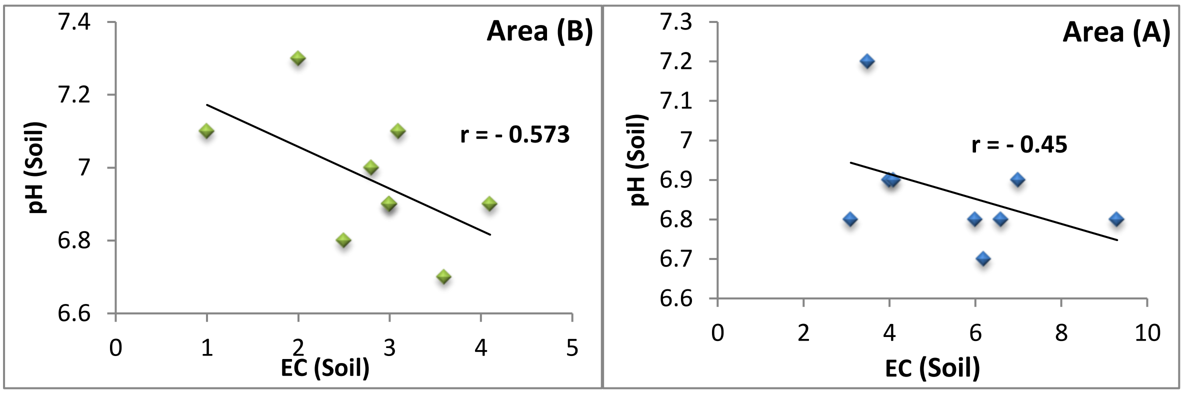

Fig. 5: Inverse correlation between salinity of soils and soil pH.

A. Hydrochemical Classification of Well Water

Water Hardness Classification

The total hardness (TH) and total dissolved solids (TDS) results are plotted as shown in Fig. 6. It is observed that all groundwater samples from both study sites (area A and area B) fall within the hard-brackish water category, except for two wells in Area B (B_2 and B_8), which are classified as hard-fresh water.

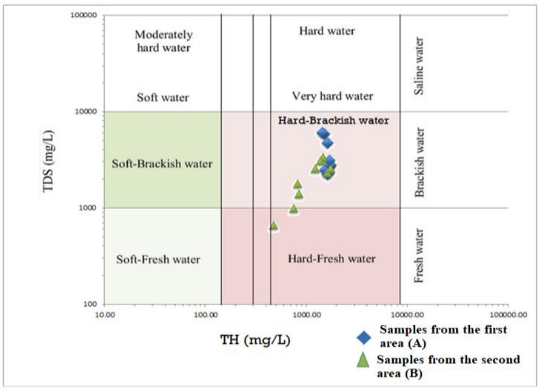

Fig. 6: Relationship between total hardness and total dissolved solids (Todd and Mays, 2004).

Piper Diagram

The Piper (1944) diagram is used to classify the groundwater samples. The results indicate that wells (A_1, A_3, A_4, A_5, A_6, A_7, A_{10}) in Area (A) correspond to the sixth type, classified as sulfuric groundwater of the Ca-SO_4 type. Well (A_2) is identified as from the third type, representing mixed water. Wells (A_8 and A_9) are classified as second-type saline groundwater of the Na-Cl type. In Area (B), wells (B_3 and B_9) are classified as from the sixth type (Ca-SO_4 type), while wells (B_1, B_4, B_5, B_6, B_7, and B_8) fall under the third type, mixed water. Only well (B_2) is categorized as from the first type, fresh carbonate water type of the Ca-HCO_3 type, as seen in Figure (7).

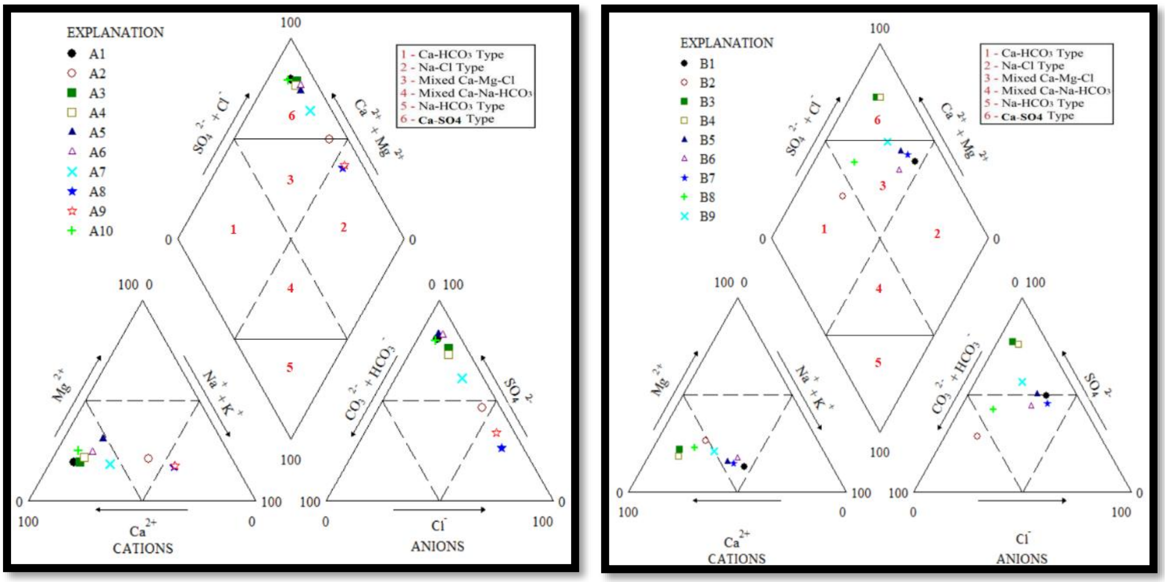

Fig.7: Piper plot illustrates the groundwater types in both study areas.

Ivanov Classification

This classification method is based on the percentage of major ions expressed in epm% (equivalents per million), considering only those exceeding 15% (Ivanov et al., 1968). Based on this system, the majority of groundwater samples from the first area (A) are classified as calcium-sulfate type ($Ca-SO_4$), representing 70% of the wells. Wells (A_8 and A_9) are classified as sodium-chloride (Na-Cl) saline water, while well (A_2) is categorized as sodium-sulfate ($Na-SO_4$) type. Similarly, in the second area (B), most wells are of the calcium-sulfate type ($Ca-SO_4$), constituting more than 75% of the samples. Well (B_2) is classified as calcium-bicarbonate ($Ca-HCO_3$), indicating fresh water, while well (B_7) is of calcium-chloride ($Ca-Cl_2$) type. Table (3) shows the dominance of sulfate-rich waters in both regions, attributed to the dissolution of gypsum and anhydrite rocks within the Fatha Formation, which is conformable from the outcrops of gypsum rocks in some areas as well as high concentrations of sulphate in most water wells.

Table 3: Ivanov (1968) classification of groundwater samples from both study sites.

Wells.	Hydrochemical Formula	Water Type
	First area samples (A)	
A_1	$TDS(2247)=\frac{SO4(80.13)}{Ca(70.16).Mg(19.38)}pH7.2$	Ca-Mg- Sulphate $CaSO_4$
A_2	$TDS(4736)=\frac{SO4(46.24).Cl(45.37)}{Na(41.71).Ca(36.80).Mg(20.80)}pH6.45$	Na-Ca-Mg-Cl- Sulphate $NaSO_4$
A_3	$TDS(2650)=\frac{SO4(75.17).Cl(15.78)}{Ca(67.24).Mg(19.43)}pH6.53$	Ca-Mg-Cl- Sulphate $CaSO_4$
A_4	$TDS(2787)=\frac{SO4(71.97).Cl(17.98)}{Ca(64.16).Mg(21.55)}pH6.55$	Ca-Mg-Cl- Sulphate $CaSO_4$
A_5	$TDS(2475)=\frac{SO4(81.34)}{Ca(52.04).Mg(30.57).Na(17.14)}pH6.57$	Ca-Mg-Na- Sulphate $CaSO_4$
A_6	$TDS(2776)=\frac{SO4(81.14)}{Ca(60.05).Mg(23.97).Na(15.75)}pH6.5$	Ca-Mg-Na- Sulphate $CaSO_4$
A_7	$TDS(3130)=\frac{SO4(60.95).Cl(29.04)}{Ca(54.83).Na(26.03).Mg(18.52)}pH6.2$	Ca- Na- Mg-Cl- Sulphate $CaSO_4$
A_8	$TDS(5840)=\frac{Cl(63.62).SO4(26.41)}{Na(54.43).Ca(27.43).Mg(17.18)}pH6.18$	Na-Ca-Mg-SO_4- Chloride NaCl

A_9	$TDS(5992)=\frac{Cl(57.44).SO4(33.89)}{Na(54.91).Ca(27.00).Mg(17.50)}pH6.13$	Na-Ca-Mg-SO4- Chloride	NaCl
A_{10}	$TDS(2306)=\frac{SO4(71.97)}{Ca(65.57).Mg(24.98)}pH6.11$	Ca-Mg- Sulphate	$CaSO_4$
Second area samples (B)			
B_1	$TDS(3345)=\frac{SO4(45.24).Cl(44.73)}{Ca(39.45).Na(39.33).Mg(20.77)}pH6.7$	Ca-Na-Mg- Sulphate	$CaSO_4$
B_2	$TDS(652)=\frac{HCO3(47.30).SO4(30.64).Cl(21.90)}{Ca(44.88).Mg(38.23).Na(16.37)}pH7$	Ca-Mg-Na-Cl-SO_4-HCO_3	$CaHCO_3$
B_3	$TDS(2308)=\frac{SO4(77.92)}{Ca(58.27).Mg(32.12)}pH6.8$	Ca-Mg- Sulphate	$CaSO_4$
B_4	$TDS(2540)=\frac{SO4(75.48)}{Ca(61.75).Mg(27.25)}pH6.46$	Ca-Mg-Sulphate	$CaSO_4$
B_5	$TDS(2541)=\frac{SO4(46.60).Cl(39.47)}{Ca(44.65).Na(30.39).Mg(24.47)}pH6.4$	Ca-Na-Mg-Cl-SO_4	$CaSO_4$
B_6	$TDS(1779)=\frac{SO4(41.69).Cl(40.62).HCO3(17.66)}{Ca(38.80).Na(33.27).Mg(27.38)}pH6.6$	Ca-Na-Mg-HCO_3-Cl-SO_4	$CaSO_4$
B_7	$TDS(3085)=\frac{Cl(46.93).SO4(41.04)}{Ca(42.55).Na(33.65).Mg(23.29)}pH6.48$	Ca-Na-Mg-SO_4- Chloride	$CaCl_2$
B_8	$TDS(977)=\frac{SO4(43.79).HCO3(34.04).Cl(22.07)}{Ca(51.58).Mg(33.54)}pH6.36$	Ca-Mg-HCO_3-Cl-SO_4	$CaSO_4$
B_9	$TDS(1390)=\frac{SO4(54.42).Cl(27.85).HCO3(16.71)}{Ca(45.77).Mg(31.58).Na(22.28)}pH7.2$	Ca-Mg-Na- HCO_3-Cl-SO_4	$CaSO_4$

Ion Exchange

Ion exchange reactions typically occur between the aquifer matrix particularly the clay minerals and the groundwater (Hossain et al., 2025). As groundwater remains in contact with or moves through the aquifer, the concentrations of dissolved ions may shift due to these interactions. The nature of ion exchange can be evaluated using the Chloro-Alkaline Indices (CAI) as proposed by Schoeller (1965) and described by Tarawneh et al. (2019). The phenomenon can be classified into:

A. Direct Ion Exchange

This process involves the replacement of Ca^{2+} and Mg^{2+} in groundwater with Na^+ and K^+ ions adsorbed on the surface of clay minerals, as shown in the following reaction:

$$(Ca_{1-x}\,Mg_x)\,CO_3 + Na\text{–}clays + H^+ \rightarrow HCO_3^- + 2Na^+ + (Ca_{1-x}\,Mg_x)\text{–}clays$$

B. Reverse Ion Exchange

In this case, Na^+ and K^+ in the groundwater are exchanged with Ca^{2+} and Mg^{2+} ions present on clay minerals:

$$HCO_3^- + 2Na^+ + (Ca_{1-x}\,Mg_x)\text{–}clays \rightarrow (Ca_{1-x}\,Mg_x)CO_3 + Na\text{–}clays + H^+$$

The CAI indices are calculated using the following equations (2 and 3), where ion concentrations are in meq/l:

$$CAI_1 = \frac{Cl^- - (Na^+ + K^+)}{Cl^-} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$CAI_2 = \frac{Cl^- - (Na^+ + K^+)}{So_4^{-2} + HCo_3^- + Co_3^{-2} + No_3^-} \quad \ldots\ldots (3)$$

As shown in Figure (8), all groundwater samples from area (B) exhibit positive CAI values indicating reverse ion exchange between Na^+ and K^+ in groundwater, and Ca^{2+}/Mg^{2+} in clay minerals. In area (A), half of the samples also show positive values (reverse exchange), while the other half (A_1, A_5, A_6, A_7, A_{10}) show negative CAI values suggesting direct ion exchange, where Ca^{2+} and Mg^{2+} in groundwater are exchanged with Na^+ and K^+ from the surrounding geological materials.

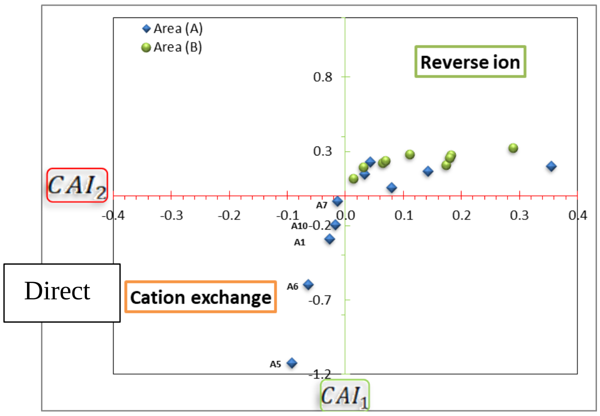

Fig. 8: Ion exchange and reverse ion exchange processes occurring in groundwater samples from both study sites.

Cluster Analysis

Cluster analysis is a statistical method used to categorize data into a limited number of groups. It helps in organizing data into clusters and presents results in a simplified form based on the proximity and similarity of variables (Danielsson et al., 1999; Chen et al., 2007). A hierarchical cluster analysis is performed using the SPSS statistical software, where the hydrochemical data of groundwater wells from each area are input. The results reveal that each area is divided into two clusters based on the hydrochemical characteristics of the groundwater. Each group includes several wells sharing similar hydrochemical properties, largely influenced by the nature of the geological formations the wells penetrate. In area (A), the first group, including wells (A_2, A_8, A_9), is characterized by high salinity levels ranging from 5920 to 7500 dS·m⁻¹, and elevated concentrations of Na^+ and Cl^-. This indicates that these wells likely penetrate geological layers rich in halite. The second group, including wells (A_{10}, A_7, A_6, A_5, A_4, A_3, A_1), exhibits lower salinity than the first group, and its values range from 3500 to 4900 $dS \cdot m^{-1}$ and higher concentrations of Ca^{2+} and SO_4^{2-}. This suggests that these wells were drilled through formations dominated by gypsum and anhydrite minerals. In area (B), the wells are also divided into two groups. The first group, including wells (B_4, B_3) and (B_7, B_5, B_1), is characterized by high salinity and elevated levels of Ca^{2+}, SO_4^{2-} , and Na^+. This indicates that these wells were drilled in evaporate formations rich in gypsum, anhydrite, and halite minerals. The second group, including wells (B_9, B_8, B_6, B_2), shows relatively lower salinity levels ranging from 1020 to 2780 $dS \cdot m^{-1}$ and comparatively lower ion concentrations. This suggests that these wells penetrate recent deposits composed of gravel, sand, clay, and silt (Fig. 9).

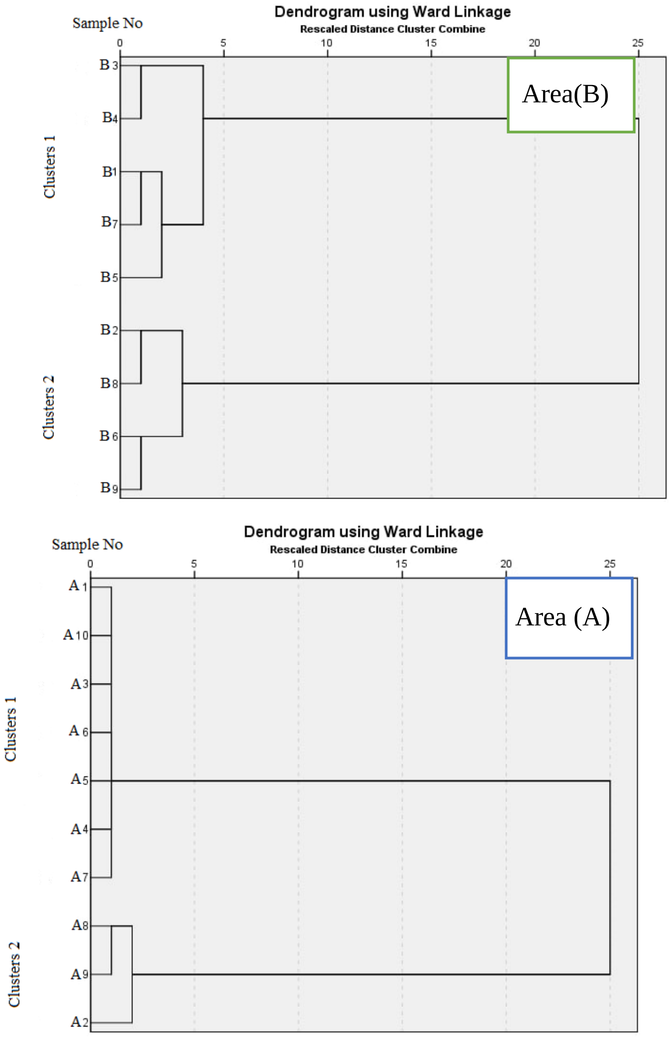

Fig. 9: Hierarchical dendrogram of the study wells in both areas.

6. Saturation Index (SI)

The Saturation Index describes the saturation state of various minerals that are in contact with groundwater. It helps in identifying the geochemical processes (dissolution, precipitation, or equilibrium) that govern groundwater quality (Kumar et al., 2015). SI negative values indicate that the mineral is undersaturated, meaning it is undergoing continuous dissolution or it is present in very low quantities. SI positive values indicate that the mineral is oversaturated, suggesting a tendency toward precipitation. SI values equal to or close to zero imply that the mineral is in a state of equilibrium (Kortatsi, 2006).

The Saturation Index is calculated using the following equations:

$$SI = Log\left(\frac{IAP}{K}\right) \ldots \ldots (4)$$

Where: *SI* = Saturation Index; *IAP* = Ion Activity Product; *K* = Solubility Product Constant for each mineral.

The saturation index (SI) is calculated for four minerals: gypsum, calcite, dolomite, and halite. The results, as illustrated in Figures (10 and 11), show that the saturation index for calcite in area (A) is under-saturated in all samples except one sample (A_1), which is oversaturated. In area (B), the results vary as follows: samples from wells (B_4, B_5, B_6, B_7, and B_8) are undersaturated, wells (B_1 and B_2) are in equilibrium, and wells (B_3 and B_9) are oversaturated.

For gypsum, samples (A_1, A_3, A_4, A_6, and A_{10}) in area (A) are oversaturated, while samples (A_2, A_5, and A_7) are in equilibrium. However, wells (A_8 and A_9) are undersaturated. In area (B), all samples are undersaturated except wells (B_3 and B_4), which are oversaturated. As for the dolomite and halite minerals, all samples in both areas are undersaturated because they have negative values in a state of continuous dissolution.

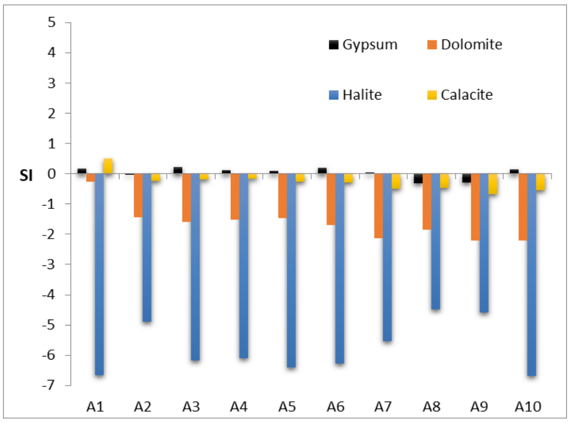

Fig. 10: Saturation index for some minerals in the first area (A).

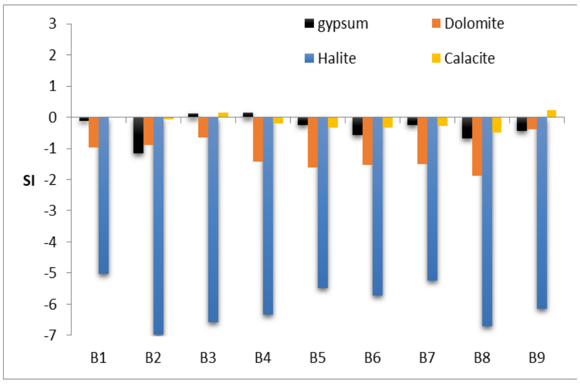

Fig. 11: Saturation index for some minerals in the second area (B).

5. Conclusion

A. All wells in area (A) penetrate the Fatha Formation, which consists of alternating layers of evaporate rocks and clay layers. In contrast, only some of the wells in area (B) penetrate the Fatha Formation, while the rest are in contact with recent alluvial deposits (Quaternary) having better water quality. As a result, the concentrations of major dissolved ions and salinity in area (A) are approximately 1.5 times higher than those in area (B).

B. According to the Piper classification, most groundwater samples in area (A) are of the Ca-SO_4 type, indicating the dominance of calcium sulfate water. In area (B), most of the samples fall under the mixed water type. Based on Ivanov's classification, the majority of groundwater in both areas is also classified as calcium sulfate type.

C. The saturation index (SI) is calculated for four minerals. The results indicate that halite and dolomite are undersaturated in both area. Gypsum is oversaturated in five wells in area (A) and undersaturated in seven wells in area (B). Calcite is undersaturated in nine wells in area (A) and in five wells in area (B).

D. The irrigation of agricultural lands using well water has had a noticeable impact on the soil's salinity, particularly in area (A), where most irrigated soil samples are classified as saline. In contrast, area (B) shows a lesser effect from well water, with only one saline soil sample identified compared to rain-fed soils.

E. Statistical cluster analysis is considered a good tool for classifying wells according to their similar hydrochemical properties and the type of aquifer they penetrate. The results are classified into two groups of wells for each area according to their salinity and the type of aquifer they were drilled into, whether it is a Fatha Formation aquifer or a Quaternary sediment aquifer.

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تأثير نوعية المياه الجوفية على الترب لموقعين في شمال غربي الموصل، العراق

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الملخص

تضمنت الدراسة تقييما لنوعية مياه الابار في منطقتين شمال غربي مدينة الموصل على جانبي نهر دجلة وذلك من اجل عمل مقارنة هيدروكميائية للمياه الجوفية ومعرفة تأثيرها على ملوحة التربة. تم جمع 10 عينات من مياه الابار من المنطقة (A) و 9 عينات من ابار المنطقة (B)، بالإضافة إلى جمع عينات تربة مروية من كل بئر وثلاثة تربة ديمية من كل منطقة. شملت تحاليل المياه قياس EC والـ pH،العسرة الكلية والايونات الرئيسة السالبة والموجبة. اما عينات التربة فشملتها تحاليل ملوحة ودرجة تفاعل التربة وكاربونات الكالسيوم ونسجة التربة. اذ تراوحت الـEC لمياه الابار مابين (3.51−7.49) dS m-1 في المنطقة الاولى A ومابين (1.02−5.23) dS m-1 في المنطقة الثانية B. كان معدل تراكيز الملوحة وايونات الصوديوم والبوتاسيوم والكالسيوم والكبريتات والكلوريدات في المنطقة الاولى اعلى بحدود 1.5 مرة من معدلها في المنطقة الثانية. كما ظهر تاثير الري بمياه الابار على التربة حيث كانت غالبية التربة مروية للمنطقة A وكانت تربة ملحية ، اما المنطقة B فقد كانت فقط تربة واحدة ملحية حيث كان التأثير اقل لانخفاض ملوحة مياه هذه الابار عن المنطقة A، أن الاستعمال طويل الأمد لمياه الابار عالية الملوحة في المنطقة (A) أدى إلى تملح التربة حيث لوحظت علاقة ارتباط جيدة بين ملوحة مياه الابار والتربة بالمقارنة بالأراضي الديمية. وتم حساب معامل التشبع لمعادن الكالسايت والدولومايت والجبسوم والهالايت ضمن معادن الطبقات الحاملة للمياه الجوفية. كما تم استخدام التحليل الاحصائي العنقودي لتصنيف الابار في كلتا المنطقتين.

الكلمات المفتاحية:

المياه الجوفية، نوعية المياه، الخزان الجوفي، ملوحة التربة، الري.

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