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A GEOCHEMICAL STUDY ON THE USABILITY OF WELLS WATER SOUTH SINJAR MOUNTAIN, NORTHERN IRAQ

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EXTENDED ABSTRACT

Nei luoghi privi di acque superficiali, le falde acquifere sono un requisito fondamentale per il mantenimento della vita, in particolare nelle aree con climi semiaridi o desertici, dove la profondità, la quantità e la qualità delle acque sotterranee che i residenti possono usare è correlata alle attività domestiche e agricole.

Il tipo di rocce serbatoio e i tipi di rocce e terreni attraverso cui l'acqua passa e si infiltra nelle falde acquifere sono gli elementi più significativi che influenzano la qualità delle falde acquifere, oltre all'impatto delle acque provenienti dalle vicine attività domestiche e agricole, che si combina con le precipitazioni e si infiltra nelle falde acquifere superficiali.

L'area studiata, che si estende per 60 km in lunghezza e 30 km in larghezza verso la città di Al-Baaj a sud, è situata a nord-ovest della regione di Al-Jazera, nell'Iraq settentrionale, a sud del Monte Sinjar. L'area riceve circa 350 mm di pioggia all'anno. Di conseguenza, il bacino idrografico che alimenta i bacini idrici sotterranei della zona è rappresentato dal versante meridionale del Monte Sinjar. A causa della scarsità di acqua superficiale, la popolazione locale fa affidamento principalmente sull'acqua di pozzo per uso domestico e agricolo.

La principale caratteristica geologica della regione, l'anticlinale di Sinjar, è rappresentata dal Monte Sinjar. Il suo asse di piega orientato est -ovest è lungo circa 75 km e largo 12 km. L'anticlinale di Sinjar e il suo lembo meridionale rivelano le seguenti formazioni geologiche: la Formazione Shiranish (Cretaceo) di calcare e marne si trova al centro dell'anticlinale, le Formazioni di Aliji e Sinjar (Paleocene superiore-Eocene inferiore) costituiscono la maggior parte del Monte Sinjar e sono dominate da calcari. Ai piedi del Monte Sinjar, affiorano le formazioni di: Jaddala e Avanah (Eocene medio e superiore), composte da calcari e marne; Serikagni e Dhiban (Miocene inferiore), composte da calcari e gessi; Eufrate e Jeribe (Miocene inferiore e medio), contenenti calcari, marne e dolomiti; Fat'ha (Miocene Medio), composta da alternanze di gessi, marne e calcari. Questa formazione è considerata una roccia serbatoio a causa dell'elevata solubilità del gesso e della formazione di canali di fusione che immagazzinano acqua; tuttavia, le sue acque contengono tipicamente alte concentrazioni di solfati. La formazione Injana (Miocene Superiore) è composta da alternanze di arenarie, siltiti e mudstone, mentre la formazione Muqdadiya (Pliocene) è composta da arenarie ghiaiose, siltiti e mudstone.

Le formazioni suddette, sono ricoperte da depositi quaternari (Pliocene e Olocene) costituite da depositi di versante e conoidi allo sbocco di alcune valli principali. Questi depositi contengono frammenti di roccia derivanti principalmente dall'erosione dei calcari di Sinjar, nonché affioramenti di altre formazioni ai piedi del Monte Sinjar. Queste aree sono ricoperte da terreni gessosi e calcarei trasportati contenenti frammenti di roccia di gesso e carbonato, il cui spessore aumenta verso sud.

L'indice di qualità dell'acqua potabile (WQI) è stato stimato utilizzando analisi chimiche (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO^{3-}, SO_4^{2-}, Cl^{-}, NO^{3-}) e test fisici come la conduttività elettrica (E.c.) e i sali totali disciolti (TDS). I pozzi disseminati lungo il versante meridionale del monte Sinjar, nella parte superiore dell'area di studio, indicano la presenza di riserve di acqua sotterranea in strati calcarei. La loro acqua presenta una bassa concentrazione di sali disciolti ed è stata classificata come "buona" per uso potabile e domestico, incoraggiando lo sviluppo di complessi residenziali nelle vicinanze. I pozzi a sud dei precedenti indicano la presenza di riserve di acqua sotterranea in strati evaporitici o di riserve superficiali condizionate dall'infiltrazione d'acqua che trasporta i prodotti della disintegrazione di frammenti di roccia carbonatica e gessosa. Presentano un'elevata concentrazione di sali, in particolare solfati, e sono stati classificati come "scarsi - non adatti" per il consumo umano. L'acqua nella maggior parte dei pozzi contiene solfato di calcio e magnesio, ad eccezione di alcuni pozzi che contengono cloruro di sodio a causa del loro elevato contenuto di sodio e cloro, e bicarbonato essendo contenuta negli strati calcarei.

L'acqua per l'irrigazione è stata classificata utilizzando diversi parametri: rapporto di adsorbimento del sodio (SAR), percentuale di sodio (SSP), percentuale di magnesio (MAR), indice di permeabilità (PI) e indice di Kelly (KR). Questi risultati suggeriscono che l'acqua dei pozzi è generalmente adatta all'irrigazione. Di conseguenza, nella regione può essere utilizzata per irrigare i campi tutto l'anno e per integrare l'irrigazione delle principali colture come grano e orzo durante i periodi di siccità. In alcune aree, è possibile passare dall'agricoltura arida a quella umida, raggiungendo la sostenibilità agricola e soddisfacendo al contempo il fabbisogno idrico della regione e rinnovando l'attività agricola.

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ABSTRACT

Groundwater is critical in countries with arid to semi-arid climates and limited surface water availability. Groundwater use is strongly related to its quality. The most important elements influencing groundwater quality are the type of underlying rock, the amount of rainfall, and the type of soil through which surface water seeps into subsurface layers.

The study area extends south of Sinjar Mountain and toward the town of Baaj. It is around 60 kilometers long and 30 km wide. The water catchment region on Sinjar Mountain's southern flank replenishes groundwater. Residents in this area rely on well water to support their civil and agricultural needs due to a lack of surface water and poor rainfall, which can fall below 350 mm/year on average.

Chemical analyses (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-}, NO_3^{-}) and physical tests (electrical conductivity (E.c.) and total dissolved salts *(TDS)*) were used to estimate the drinking water quality index (*WQI*) and irrigation water classification parameters (percentage of sodium adsorption, *SAR*; percentage of sodium, *SSP*; percentage of magnesium, *MAR*; Permeability Index, *PI*, and Kelly's Ratio, *KR*). The upper part of the investigated area represents an underground water reservoir in limestone strata, which are designated as good for drinking purposes, encouraging the development of many residential complexes in the region. The lower section depicts groundwater reservoirs in the evaporite strata, as well as the influence of infiltrated water containing the dissolving products of gypsum and carbonate rock fragments, which are classed as poor to unsuitable for drinking. Most wells indicated that their water was appropriate for irrigation. This serves to revitalize agricultural operations in the region, whether through supplementary irrigation or irrigation of farms distributed around the region.

Keywords*: water assessment, water index, Sinjar, hydrogeochemistry, Sinjar Mount, Al-Jazera region*

INTRODUCTION

Groundwater is a crucial resource for sustaining life in areas without surface water, particularly in arid to semi-arid climates, where domestic and agricultural activity is dependent on the depth, quantity, and quality of groundwater available for use (Medler & Eldridge, 2021; Kateb & Al-Youzbakey, 2022). Groundwater frequently does not require purification or filtration (Awadh *et alii*, 2021). The quality of groundwater is determined by several factors, the most important of which are the type of stored rocks, the characteristics of the rocks and soils through which the water flows before infiltrating into the aquifer (Aqrawi & Al-Mallah, 2021; Kateb & Al-Youzbakey, 2022), and the geochemical interactions between water and soluble minerals (Aghazadeh *et alii*, 2010; Kapoor *et alii*, 2016). Water from household and agricultural operations also mixes with rainwater and infiltrates shallow groundwater (Dikeogu *et alii*, 2018; Al-Youzbakey & Sulaiman, 2021).

The studied area is located northwest of the Al-Jazera region in northern Iraq, reaching 60 kilometers along Mount Sinjar's southern limb and 30 kilometers south to the town of Al-Baaj. The region has a Mediterranean climate with an annual rainfall rate of 350 mm (Kateb & Al-Youzbakey, 2025). The main catchment for the groundwater reservoirs is the southern flank of Mount Sinjar and the network of valleys that extends southward. Local populations primarily rely on well water, with certain wells being utilized by farmers for supplementary irrigation and irrigation of scattered agricultural fields.

Many researchers who have studied groundwater in the Sinjar region concur that the quality of water is mostly influenced by the host rock. As a result, they stated that the groundwater in the reservoir within the Injana Formation is acceptable for both home and agricultural purposes. The groundwater in the Fat'ha formation is not drinkable due to its high salinity, particularly sulfate concentrations (Al-Mohsen, 1985; Al-Jubouri, 2007; Faisal, 2013).

Geological settings

Mount Sinjar occupies the main geological structure in the region Sinjar anticline, with a length of about 75 km and a width of about 12 km and its fold axis extends in an east-west direction (Sissakian, 1993).

Several geological formations alternate throughout the studied region. Shiranish Formation (Cretaceous) occupies the center of the Sinjar anticline and is not visible from the fold's southern limb. It is composed of limestone and marl. It is followed by the Aaliji and Sinjar formations (Upper Paleocene-Lower Eocene), which make up the majority of Mount Sinjar and are composed primarily of limestone.

The formation outcrops at the foot of Mount Sinjar are Jaddala and Avanah (Middle-Upper Eocene), which consist of limestone and marl, followed by Serikagni and Dhiban (Lower Miocene), which consist of limestone and gypsum, Euphrates and Jeribe (Lower-Middle Miocene), which contain limestone, marl, and dolomite. They are followed by the Fat'ha Formation (Middle Miocene), which consists of cycles of gypsum, marl, and limestone. The Injana Formation (Upper Miocene) is composed of cycles of sandstone, siltstone, and claystone, whereas the Muqdadiya Formation (Pliocene) is made up of pebbly sandstone, siltstone, and claystone (Sissakian, 1993), (Fig. 1).

The Fat'ha Formation is classified as a reservoir rock because of the high solubility of gypsum and the creation of dissolution channels that store water; nonetheless, its waters typically contain significant quantities of sulphates. The Injana

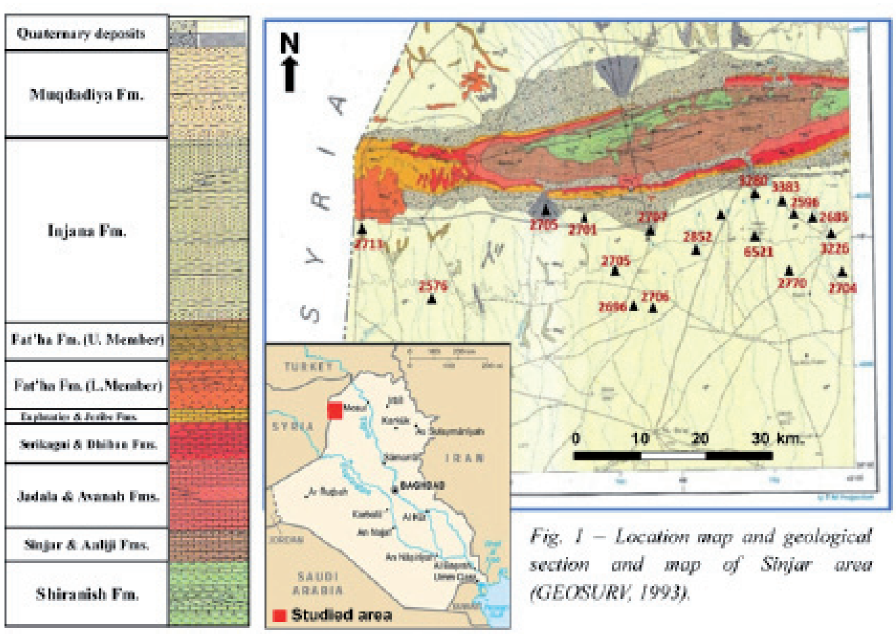

Fig. 1 – Location map and geological section and map of Sinjar area (GEOSURV, 1993).

Fig. 1 - Location and Geological map and section of Sinjar area, (Geosurv, 1993)

and Muqdadiya Formations are distinguished by the presence of sandstone, which can hold water due to its high porosity and permeability, and the absence of the effect of the type of rocks on water quality due to its insolubility (Faisal, 2013).

Previous formations covered by quaternary deposits (Pliocene and Holocene) consisted of slope deposits containing rock fragments resulting from erosion of Sinjar limestone primarily, as well as outcrops of other formations at the foot of Mount Sinjar, and alluvial fan deposits at the end of some major valleys as a result of the accumulation of erosion products caused by heavy rains. In addition to the transported gypsiferous soil and calcareous soils containing gypsum and carbonate rock pieces, which cover the area and increase in thickness towards the south (Fig. 1).

The southern limb of Mount Sinjar resulted in the construction of a series of parallel valleys that fell from the mountain towards the south, transferring the products of weather and erosion. The region is often characterized by a gently undulating component, which aids in water infiltration into the subsurface reservoir via sediment and soil.

The study's goal is to analyze the quality of well water distributed between Mount Sinjar's southern limb and Al-Baaj town in order to determine its potential applications.

MATERIALS AND METHODS

The chemical and physical parameters of eighteen water samples were obtained from the report (Hydrogeological and hydrochemical research of a region Singer Plate (16-37-NJ), scale 1:250000), which was published by the General Company for Geological Survey and Mining's Mineral Investigation Department (Table1).

Well No.	E	N
2576	41° 19' 12.83"	36° 08' 51.87"
2596	41° 56' 15.31"	36° 18' 31.24"
2685	41° 59' 10.18"	36° 17' 42.40"
2696	41° 40' 45.43"	36° 12' 33.54"
2701	41° 55' 37.55"	36° 16' 59.50"
2704	41° 59' 35.31"	36° 12' 15.82"
2705	41° 39' 18.37"	36° 14' 48.30"
2706	41° 41' 30.86"	36° 12' 45.95"
2707	41° 44' 03.69"	36° 16' 46.60"
2713	41° 16' 38.52"	36° 16' 20.71"
2770	41° 55' 18.75"	36° 13' 03.46"
2773	41° 48' 43.05"	36° 15' 31.36"
2852	41° 36' 27.28"	36° 14' 02.30"
3226	41° 58' 40.98"	36° 15' 03.64"
3280	41° 52' 49.20"	36° 19' 11.45"
3383	41° 55' 15.18"	36° 19' 15.59"
6521	41° 52' 08.40"	36° 14' 16.00"

Tab. 1 - Geographic coordinates of the studied wells

The water quality index (*WQI*) was estimated using the Gupta & Misra (2016) equation, employing (Ca^{2+}, Mg^{2+}, Na^{+},

K^+, HCO^{3-}, SO_4^{2-}, Cl^-, NO_3^-, EC and *TDS*) and WHO standard values (2006).

$$WQI = \sum_{i=1}^{n} \left(Q_i * W_i / \sum W_i \right) \qquad (1)$$

where:

Qi: *100x(Vm-Vi)/(Vs-Vi)* ……for each parameter;

Qi: The quality rating of the ith parameter for a total of n water quality parameters;

Vm: Measured value of the water samples for quality parameters estimated from analysis;

Vi: Ideal value of that water quality parameter can be obtained from the standard tables. The ideal value is equal to zero for most parameters except for pH=7;

Vs: standard values for the parameter according to the standards of the World Health Organization (WHO, 2006) for drinking water (Table 2);

Wi= K/Vs (*K*=Proportionality constant=1);

Wi: Relative unit weight of nth parameter.

The water balance was calculated using the concentrations of cations and anions in (m_{eq}/l) that reflect the accuracy of chemical analysis data, as well as to estimate the water classification parameters for irrigation purposes, such as the percentage of sodium adsorption (*SAR*), percentage of sodium (*SSP*), amount of residual sodium carbonate (*RSC*), percentage of magnesium (*MAR*), the Permeability Index (*PI*), and Kelly's Ratio (*KR*) (Leizou *et alii*, 2017):

$$SAR=Na^+/\sqrt{[(Ca^{2+}+Mg^{2+})/2]} \qquad (2)$$

$$SSP=Na^+ \times 100/(Ca^{2+}+Mg^{2+}+Na^++K^+) \qquad (3)$$

$$RSC=(CO_3^{=}+HCO_3^-)-(Ca^{2+}+Mg^{2+}) \qquad (4)$$

$$MAR=Mg^{2+} \times 100/(Ca^{2+}+Mg^{2+}) \qquad (5)$$

$$PI=(Na^++\sqrt{HCO_3^-})/(Ca^{2+}+Mg^{2+}+Na^+) \times 100\% \qquad (6)$$

$$KR=Na^+/(Ca^{2+}+Mg^{2+}) \qquad (7)$$

RESULTS AND DISCUSSION

Table 2 shows the results of the chemical analyses, in addition to the electrical conductivity and the total amount of dissolved salts in the studied well water. The results allow the wells in the study region to be divided into two main categories based on the concentration of the major ions. The best ion classification is sulfates, which vary from 96 to 706 mg/L in wells with low ion concentrations and from 1008 to 4174 mg/L in wells with high concentrations. This categorization also holds true for calcium ions, which range from 58 to 264 mg/L and 160 to 626 mg/L, respectively, and magnesium ions, which vary from 12 to 60 mg/L and 53 to 354 mg/L, respectively. In addition, the dissolved ion content of the water is indicated by the EC and *TDS* values, which are lower in wells with low concentrations than in wells with high concentrations. In wells with low and high concentrations, electrical conductivity values vary from 520 to 2500 µs/cm and from 2500 to 9093 µs/cm, respectively. Similarly, the range of *TDS* values is 319 to 1762 mg/L and 2369 to 7943 mg/L, respectively.

The host rock type, which is mostly composed of carbonate rocks from the Sinjar, Avanah-Jaddala, Serikagni-Dhiban, and Euphrates formations, is largely responsible for the difference in concentrations between the two groups. Rock outcrops can be found in these formations, especially near the foot of Mount Sinjar. The Fatha Formation has wells with significant sulfate concentrations (Aqrawi & Al-Mallah, 2021; Kateb & Al-Youzbakey, 2022). Additionally, Table 2 shows that, with the exception of a few wells, sulfate concentrations are often higher than bicarbonate concentrations in both groups.

	Well No.	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3	SO_4^{2}	Cl	NO_3	EC	TDS
High Sulphates	2576	430	138	301	1	68	1750	210	50	3480	2947
	2596	160	140	406	1	134	1008	521	1	2500	2369
	2707	588	84	29	1	126	1660	35	1	3312	2458
	2713	626	53	17	1	139	1586	27	1	3203	2377
	3226	528	354	442	1	137	2600	515	205	5000	4800
	6521	600	267	1606	1	137	4174	1154	1	9093	7943
Low Sulphates	2685	216	43	108	1	250	422	245	1	1905	1157
	2696	82	35	56	1	200	216	54	4	810	601
	2701	86	15	8	1	176	111	12	2	640	319
	2704	151	51	402	1	298	336	612	1	2500	1762
	2705	264	60	44	1	239	706	30	1	1646	1222
	2706	68	17	61	1	212	144	35	4	596	442
	2770	64	39	31	1	150	256	15	1	1000	950
	2773	77	32	21	1	153	142	17	1	900	700
	2852	58	30	39	1	195	96	36	29	520	398
	3280	70	19	14	1	92	160	36	1	546	364
	3383	108	12	296	1	183	270	382	7	1737	1135
WHO, 2006		75	50	200	55	400	400	250	50	1400	1000

Tab. 2 - *The chemical properties, Ec and TDS of selected well water in south Sinjar Mount area; in addition the standard values for the parameter, according to the World Health Organization (WHO, 2006), for drinking water*

While the concentrations of other cations and anions vary without sorting, this is most likely due to their generally low concentrations as well as the influence of other factors such as topography and surface water infiltration into the soil.

The soil and Quaternary deposits, which include slope deposits and alluvial fans containing rock fragments, are erosional consequences of several types of exposed rock on Mount Sinjar. When these fragments are exposed to chemical weathering from rainwater and streams, the water, along with erosion byproducts, seeps into the near-surface aquifer, increasing ion concentrations, particularly highly soluble ions such as sulfates, sodium, and chlorides (Kateb & Al-Youzbakey, 2022; Kateb & Al-Youzbakey, 2025), as well as having localized effects at each well.

Figure 2 illustrates the strong correlation between calcium and sulfate (r^2=0.74), reflecting that the primary source of these two ions is the gypsum in the evaporates of the Fat'ha Formation. This is supported by the weak correlation between calcium and bicarbonate in Fig. 3, which represents a low influence of carbonate minerals in the limestone rocks.

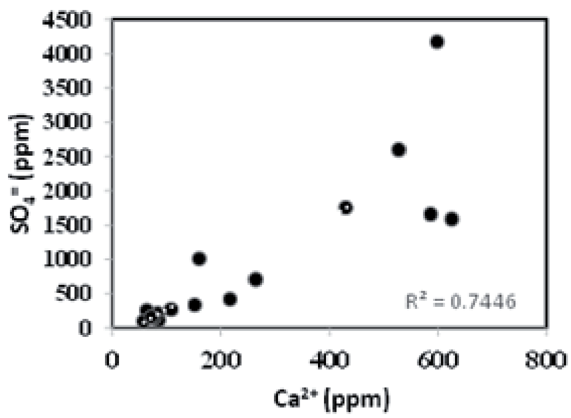

Fig. 2 - The relationship between Ca^{2+} and SO_4^{2-}, reflects the effect of evaporite rock type

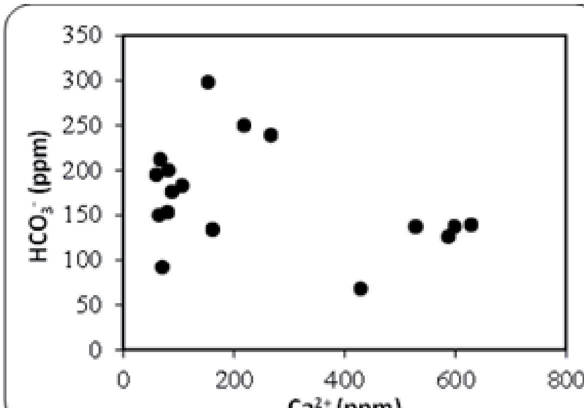

Fig. 3 - The weak relationship between Ca^{2+} and HCO_3^- reflects a lower effect of limestone rocks compared to evaporate rocks on water quality. in the studied wells

Figures 4 and 5, do not show strong or clear relationships between magnesium and either calcium or bicarbonate, indicating the low impact of the carbonate minerals on water quality. The impact of ion exchange between rocks and water is also shown in this relationship. The concentrations of calcium and magnesium rise as a result of ion exchange between sodium and potassium in the water and calcium and magnesium in the rocks. Because calcium and bicarbonate are less soluble than magnesium and sulfate, some calcium migrates to the solid phase in the form of $CaCO_3$. As a result, as Table 2 illustrates, there is a correlation between the rise in magnesium and the rise in sulfate in well water.

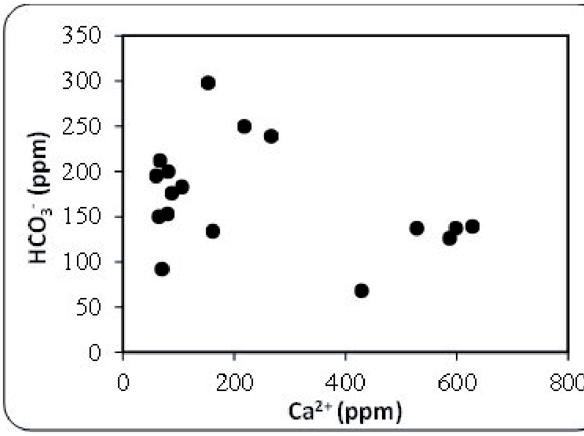

Fig. 4 - The random relationship between Ca^{2+} and Mg^{2+} that reflects both the effects of evaporates and carbonates on water quality

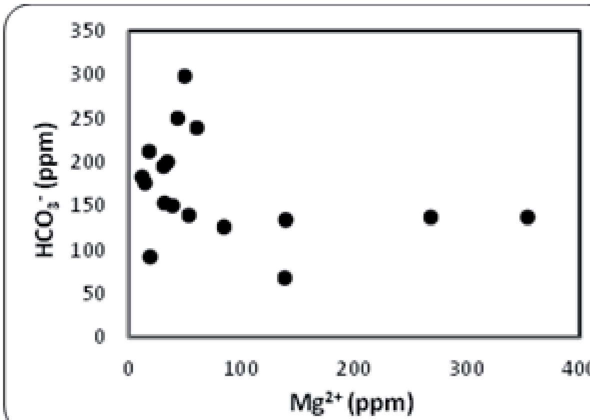

Fig. 5 - The random relationship between HCO_3^- and Mg^{2+} that shows the combined effect of calcite and dolomite in carbonate on the water quality

Figures 6 and 7, illustrate the strong relationship between sodium and chloride (r^2=0.91), indicating the presence of the mineral halite, either as salts transported from several locations and redeposited as secondary halite within the weathering and erosion products of the area's rocks, and/or the presence of halite as a primary mineral associated with gypsum in the evaporated rocks of the Fat'ha Formation.

Groundwater classifications

The drinking water quality index (*WQI*) was estimated based on chemical, Ec and *TDS* analyses. Table 3 indicates

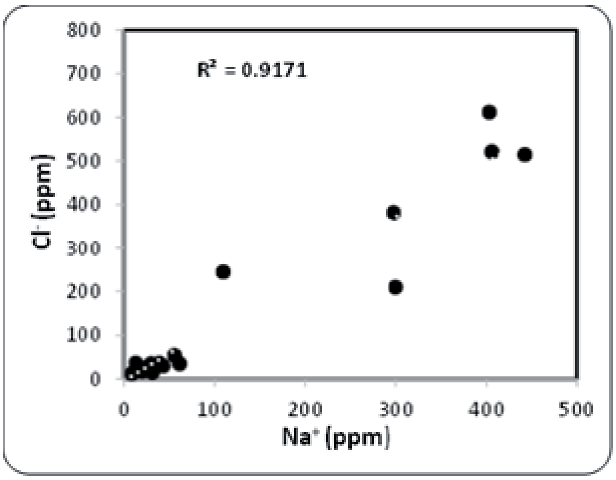

Fig. 6 - The strong relationship between Na^+ and Cl^-, indicating the effect of halite mineral

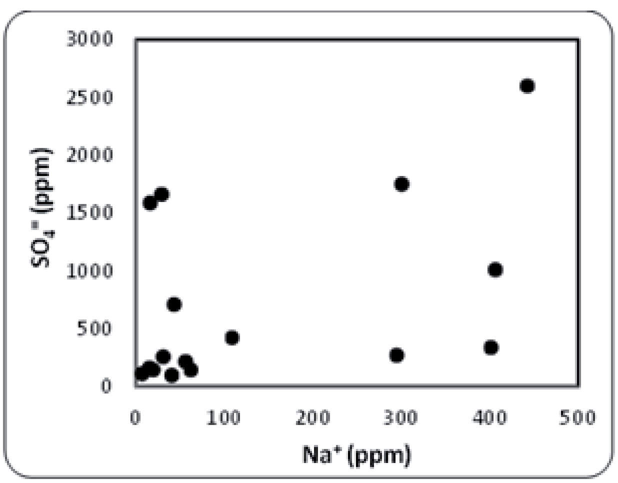

Fig. 7 - Most Na^+ comes from secondary halite, in addition to the relatively small contribution of halite found within evaporites

Well No.	WQI	Class	location
3280	27	good	near the mount
2701	29	good	near the mount
2706	30	good	near the mount
2773	36	good	near the mount
2770	38	good	within the sinjar Fn.
2696	42	good	within the sinjar Fn.
2852	44	good	within the sinjar Fn.
3383	52	poor	within euphrates Fn.
2685	79	very poor	within euphrates Fn.
2704	86	very poor	within euphrates Fn.
2705	93	very poor	within euphrates Fn.
2596	131	unsuitable	within euphrates Fn.
2713	171	unsuitable	far from the mount
2707	178	unsuitable	within euphrates Fn.
2576	205	unsuitable	far from the mount
6521	358	unsuitable	far from the mount
3226	414	unsuitable	far from the mount

Tab. 3 - Water Quality Index (WQI) of the studied well

Well No.	Ca^{2+}	Mg^{2+}	Na^+	K^+	total	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	total
2576	21.46	11.35	13.09	0.03	**45.92**	1.11	36.43	5.92	0.81	**44.27**
2596	7.98	11.51	17.65	0.03	**37.17**	2.20	20.98	14.69	0.02	**37.89**
2685	10.78	3.54	4.70	0.03	**19.04**	4.10	8.78	6.91	0.02	**19.81**
2696	4.09	2.88	2.43	0.03	**9.43**	3.28	4.50	1.52	0.06	**9.36**
2701	4.29	1.23	0.35	0.03	**5.90**	2.88	2.31	0.34	0.03	**5.57**
2704	7.53	4.19	17.48	0.03	**29.23**	4.88	6.99	17.26	0.02	**29.15**
2705	13.17	4.93	1.91	0.03	**20.05**	3.92	14.70	0.85	0.02	**19.48**
2706	3.39	1.40	2.65	0.03	**7.47**	3.47	3.00	0.99	0.06	**7.52**
2707	29.34	6.91	1.26	0.03	**37.54**	2.07	34.55	0.99	0.02	**37.62**
2713	31.24	4.36	0.74	0.03	**36.36**	2.28	33.01	0.76	0.02	**36.07**
2770	3.19	3.21	1.35	0.03	**7.77**	2.46	5.33	0.42	0.02	**8.23**
2773	3.84	2.63	0.91	0.03	**7.41**	2.51	2.96	0.48	0.02	**5.96**
2852	2.89	2.47	1.70	0.03	**7.08**	3.20	2.00	1.02	0.47	**6.68**
3226	26.35	29.11	19.22	0.03	**74.70**	2.25	54.12	14.52	3.31	**74.20**
3280	3.49	1.56	0.61	0.03	**5.69**	1.51	3.33	1.02	0.02	**5.87**
3383	5.39	0.99	12.87	0.03	**19.27**	3.00	5.62	10.77	0.11	**19.51**
6521	29.94	21.96	69.83	0.03	**121.75**	2.25	86.89	32.54	0.02	**121.69**

Tab. 4 - The chemical properties in epm

that the water of wells drilled near Sinjar Mountain into limestone layers was good due to its low ion content, while the water of wells drilled into evaporation layers or rocks affected by seepage of water carrying products of dissolution of rock fragments from Quaternary sediments were very poor and unsuitable for drinking. According to Davis & Dewiest (1966), which depends on the values of *TDS*, the water that is classified as good (*WQI*) falls into the freshwater category, because *TDS* < 1000 ppm (Table 2), while the rest of the wells are classified as medium salinity.

Table 4 shows the concentrations of main ions in milliequivalents/litter, and the ionic balance of cations and anions. Figure 8 and Table 5 show the type of water in the study wells, most of which are calcium and magnesium sulphate, with the exception of wells (2704, 3383 and 6521), which were classified as sodium chloride due to their high sodium and chlorine content. Table 6 shows the water facies of the studied wells, most of which are sulfurous, with the exception of wells (2701, 2706 & 2852), which are described as bicarbonate due to their presence within the limestone layers.

Table 7 presents well water classification parameters for irrigation. (SAR) values indicated that the well waters were generally of a low-sodium category (0-10) and are suitable for irrigating most crops and for almost all soils except for very sensitive crops to sodium (according to the American Salinity Laboratory classification).

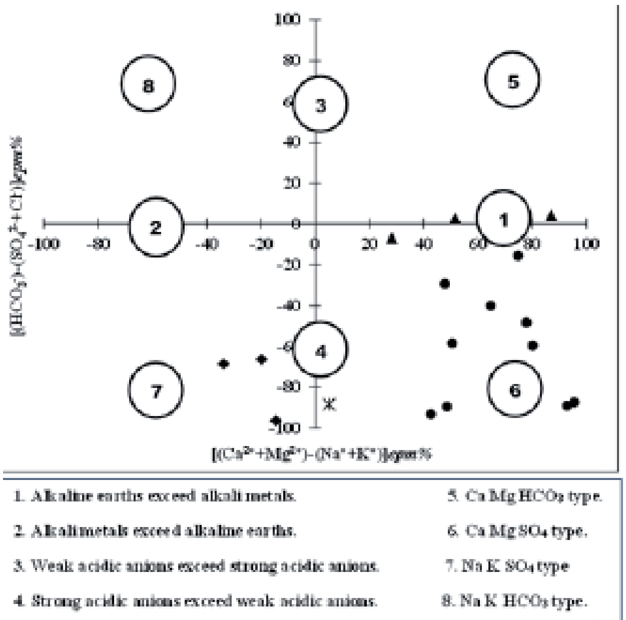

Fig. 8 - The (Chadha, 1999) classification diagram developed from the Piper diagram showing the water types in the studied wells

Well No.	*class*	*type*
2576	**6**	*Ca Na SO_4 type.*
2596	**4**	*Na SO_4 type & Na Cl type.*
2685	**6**	*Ca Mg SO_4 type.*
2696	**6**	*Ca Mg SO_4 type.*
2701	**1**	*Ca HCO_3 type.*
2704	**7**	*Na Cl type.*
2705	**6**	*Ca Mg SO_4 type.*
2706	**1**	*Ca HCO_3 type.*
2707	**6**	*Ca Mg SO_4 type.*
2713	**6**	*Ca Mg SO_4 type.*
2770	**6**	*Mg Ca SO_4 type.*
2773	**6**	*Ca Mg SO_4 type.*
2852	**1**	*Ca HCO_3 type.*
3226	**6**	*Mg Ca SO_4 type.*
3280	**6**	*Ca Mg SO_4 type.*
3383	**7**	*Na Cl type.*
6521	**7**	*Na SO_4 type & Na Cl type.*

Tab. 5 - The water types of the studies wells

Well No.	water facies			
	Anions	Cations	Family	Group
2770 & 3226	$SO_4 > HCO_3$	$Mg^{2+} > Ca^{2+}$	Mg – Ca – SO_4	SO_4
2685, 2696, 2705, 2707, 2713, 2773 & 3280	$SO_4 > HCO_3$	$Ca^{2+} > Mg^{2+}$	Ca - SO_4	SO_4
2576		$Ca^{2+} > Na^+$	Ca - Na - SO_4	
6521 & 2596		$Na^+ > Ca^{2+}$	Na - SO_4 & Cl	
2704 & 3383	$Cl > HCO_3$	$Na^+ > Ca^{2+}$	Na - Cl	Cl
2701, 2706, & 2852	$HCO_3 > SO_4$	$Ca^{2+} > Mg^{2+}$	Ca - HCO_3	HCO_3

Tab. 6 - The water facies of the studied wells

Well No.	*SAR*	*SSP*	*RSBC*	*PI*	*MAR*	*KR*
2576	3.23	28.50	-31.69	2.59	34.59	0.40
2596	5.65	47.48	-17.30	4.46	59.05	0.91
2685	1.76	24.67	-10.22	10.90	24.70	0.33
2696	1.30	25.82	-3.69	19.51	41.29	0.35
2701	0.21	5.90	-2.64	28.98	22.33	0.06
2704	7.22	59.79	-6.84	8.17	35.76	1.49
2705	0.64	9.54	-14.19	9.98	27.25	0.11
2706	1.71	35.51	-1.32	25.40	29.18	0.55
2707	0.30	3.36	-34.18	3.86	19.06	0.03
2713	0.18	2.03	-33.32	4.17	12.24	0.02
2770	0.75	17.34	-3.94	20.41	50.11	0.21
2773	0.51	12.32	-3.97	21.56	40.65	0.14
2852	1.04	23.94	-2.17	25.57	46.02	0.32
3226	3.65	25.73	-53.21	2.26	52.49	0.35
3280	0.38	10.70	-3.55	21.79	30.91	0.12
3383	7.21	66.78	-3.38	9.67	15.48	2.02
6521	13.71	57.35	-49.65	1.80	42.31	1.35

Tab. 7 - Water classification parameters for irrigation

This corresponds to the values of (*SSP*) and (*RSBC*), which were less than 75% and less than 1.25, respectively, for all wells, and which also indicate their suitability for irrigation.

The permeability index values (*PI*) also indicate that they were in the class (I) which are good for irrigation for almost all wells, because they fall within the range 0-25%.

Kelley's ratio (*KR*) represents the ratio of sodium ion concentration in water to the sum of calcium and magnesium concentrations. This parameter reflects the chemical balance between sodium solubility and the solubility conditions of both calcium and magnesium. The values of (*KR*) in Table 5 are generally less than (1.0), and the percentages of magnesium (*MAR*) in almost all wells are close to and below 50%, which indicates that wells water is suitable for irrigation.

CONCLUSIONS

Wells distributed along the foot of the southern limb of Mount Sinjar represent an underground water reservoir in limestone layers, it is characterized by a low content of dissolved salts, and therefore they are suitable for drinking purposes. This encourages the establishment of housing complexes in the region. By contrast wells distributed to the south of the previous wells represent groundwater reservoirs in the layers of evaporites or in reservoirs close to the surface affected by the infiltration of the water carrying the dissolving products of gypsum and carbonate rock fragments. These waters are characterized by their high content of salts, especially sulfate, and therefore they are classified as poor to unsuitable classes for drinking.

Water classification parameters for irrigation (*SAR*, *SSP*, *RSBC*, *PI*, *MAR* and *KR*) indicated that the well waters are generally suitable for irrigation. Therefore, the area's well water can be used for farm irrigation during the year, and for supplementary irrigation of the main crops, such as wheat and barley, during the periods of rainfall receding. In some locations, it is possible to change to wet agriculture instead of dry agriculture and achieve agricultural sustainability for the region's requirements.

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