GLL

Geomatics, Landmanagement and Landscape No. 3 • 2024, 35–57

ISSN 2300-1496 http://dx.doi.org/10.15576/GLL/2024.3.03

Research paper

Received: 28.04.2024
Accepted: 28.05.2024
Published: 15.10.2024

Hydrochemical analysis and groundwater quality assessment for irrigation in the Remila Plain, Khenchela, Northeast Algeria

Abderrahim Bezai[1,✉] 0009-0004-4372-8146
Nafaa Brinis[1] 0000-0003-0897-5550
Azzeddine Reghais[2] 0000-0002-4968-9529
Samir Djenba[1] 0000-0002-4789-6866
Khadidja Bouzid[3] 0000-0003-1239-0117

[1] Department of Geology, Water Resources Mobilization and Management Laboratory (LMGRE), Batna 2 University, Algeria
[2] Departement of Earth and Universe Sciences, Geological Engineering Laboratory (LGG), University of Mohamed Seddik Benyahia, Algeria
[3] Scientific and Technical Research Centre on Arid Regions (CRSTRA), Algeria
✉ Corresponding author: a.bezai@univ-batna2.dz

Summary

Water resources are facing significant challenges in result of rapidly growing demand, deteriorating quality, and the effects of climate change. Today, water quantity and quality issues have become prevalent in various regions across the globe, affecting both northern and southern territories. Among the sectors reliant on this resource, irrigation stands out as the largest consumer of water. When surface water becomes inaccessible due to insufficient precipitation or other factors, the use of groundwater becomes the only viable alternative for irrigation. The Remila Plain (Khenchela) is located in an endorean watershed in northeastern Algeria and extends over 250 km^2 in a synclinal basin filled with water from the Mio-Plio Quaternary - the main aquifer of the region, widely used for irrigation. The aim of this work is to study the hydrochemistry of these waters, as well as the evolution of mineralisation, the identification of the origin of the chemistry, and the suitability of these waters for irrigation. Initial results indicate an evolution of mineralisation in the direction of groundwater flow, with electrical conductivity values varying between 1000μS/cm in the recharge zones, and 2700μS/cm at the outlet. This mineralisation is mainly due to the dissolution of evaporitic minerals and the alteration of silicates. In addition, the various water quality indices used indicate that the water can be used for irrigation without major risk to plants and soils.

Keywords

hydrochemistry • mineralisation • Remila plain • Mio-Plio-Quaternary aquifer • suitability for irrigation

1. Introduction

A reliable and healthy water supply is crucial for improving the quality of life, maintaining ecosystem stability and promoting social and economic development in both rural and urban areas [Reghais et al. 2023]. Currently, groundwater serves as a dependable alternative to meet the water needs of industry, households, and agriculture in regions where surface water resources are insufficient. This is especially true for arid and semi-arid countries, where climatic conditions significantly affect the quality and quantity of water [Adimalla et al. 2020]. Algeria is highly dependent on groundwater for irrigation, as this source accounts for about 67% of total water consumption [Zektser and Everett 2004], which has confronted the country with a major water pollution crisis in recent decades. This crisis has necessitated the conduct of numerous studies [Khelifa et al. 2024, Zahi et al. 2021, Khedidja et al. 2023] in order to assess the quality of groundwater and determine the extent of its suitability for drinking and irrigation throughout the country. In fact, the quality of groundwater resources in arid and semi-arid regions is influenced by a number of factors. These factors include local hydrogeology, geological structures, topography, precipitation, evaporation, rock-water interactions, weathering, irrigation and cultivation methods, industrial effluents and anthropogenic activities [Adimalla and Venkatayogi 2018, Kumari and Rai 2020]. According to FAO and UNESCO reports, more than half of the world's irrigation systems are affected by secondary salinisation due to the intensive use of water resources [Eulenstein et al. 2016]. So, monitoring and measuring the quality of groundwater is crucial today for maximising its efficient use. The quality of groundwater is determined by various physical, chemical, and biological parameters, which directly impact its acceptability and usefulness for domestic, irrigation, and industrial purposes. Therefore, understanding the chemical composition of groundwater is essential for assessing its suitability for different uses [Ahmad and Khurshid 2019, Panaskar et al. 2016].The endorheic (closed) Remila basin, located in northern Algeria between the Tellian Atlas and the Saharan Atlas, is the subject of this study. It is a typical closed basin with an area of 250 km^2, of which 800 ha are irrigated. It is also one of the semi-arid regions where groundwater is exploited on a large scale (through more than 500 boreholes) for urban water supply (serving more than 47,000 people) and irrigation [Aouidane and Belhamra 2017, Aouidane et al. 2021].

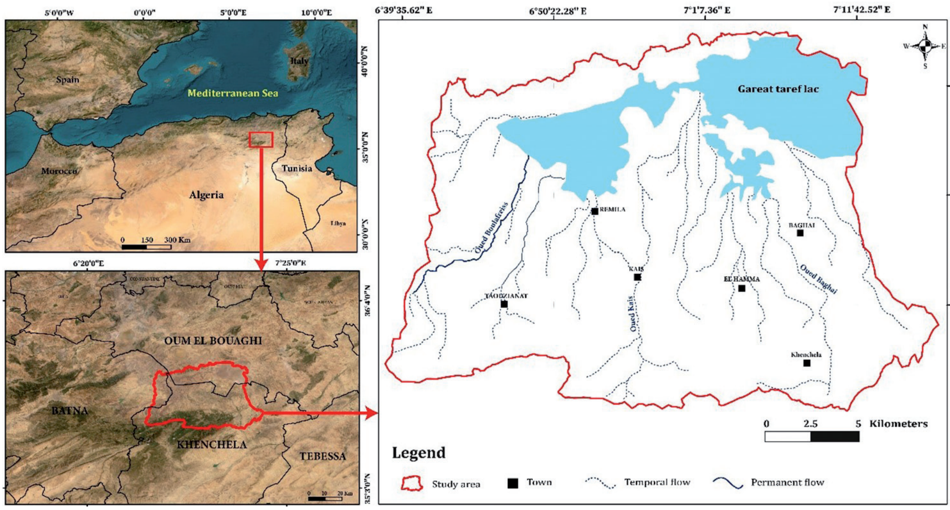
In this context, our study aims to improve the quality management of water resources in this area based on 25 water samples taken from the groundwater of the plain. The objectives of our study are as follows:

1) to conduct a comprehensive hydrochemical characterisation,
2) to determine the water facies and to monitor the mineralisation evolution,
3) to identify the chemical origin and to assess the suitability of the water for irrigation using diverse evaluation methods, such as SAR, RSC, KR, MH, PI, the Wilcox diagram, and the USSL diagram.

2. Features of study area and sampling

2.1. Location and climate

The study area is located in the northern region of the province of Khenchla, Algeria, surrounded by the Tell Atlas to the north and the Sahara Atlas to the south. It lies approximately between latitudes 35°25´N and 35°40´N and longitudes 06°30´E and 07°05´E. This vast area includes numerous towns, including Remila, Kais, El-Hamma, Taouzianat, Ain-Ziatoun, Baghai, and M'Toussa (Fig. 1). It is a part of the Constantine Plateau, which is an extensive endorheic depression. It has a uniform topography, which is between 800 and 1000 m above sea level and covers an area of 250 km^2. The study area is bounded to the north by the Djbel Fdjoudj massif, to the east by the saline depressions of Sabkha Gareat Et Tarf, and to the south and west by the northern slopes of the Aures Mountains (Fig. 1) [CPH 1977].



Source: Authors' own study

Fig. 1. Geographical map of Remila plain

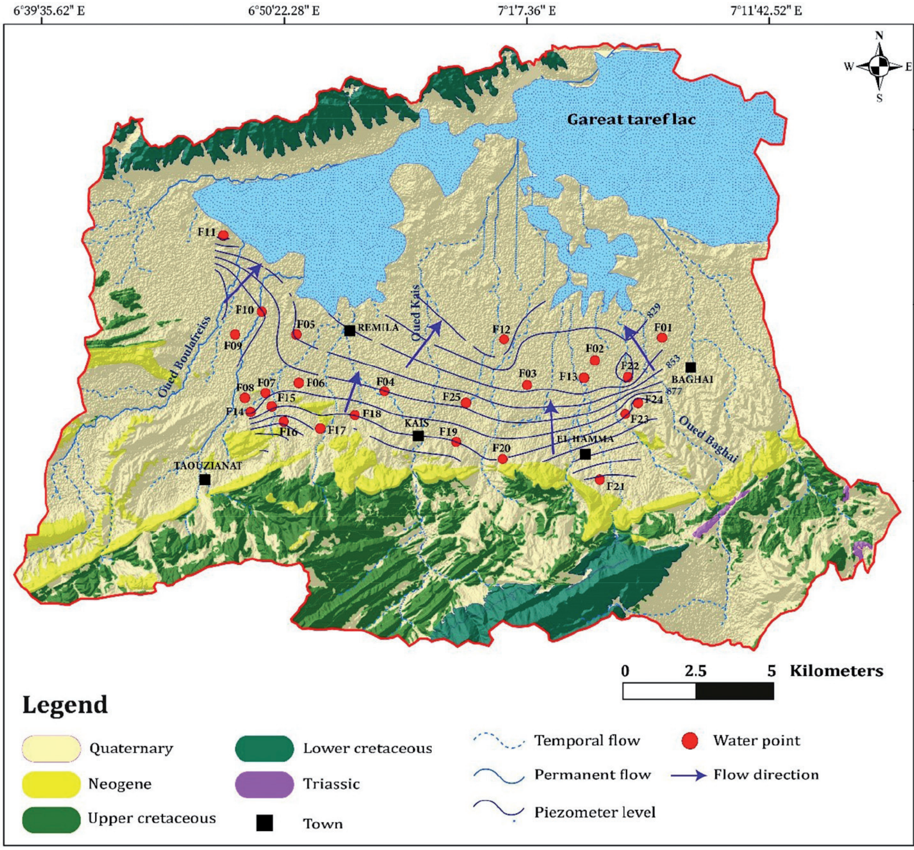
The region is characterised by its sprawling dense forests, particularly in the higher areas, composed of holm oaks, Aleppo pines, junipers, yews, and various conifers. The population of the region amounts to approximately 60,000, mainly concentrated in the municipalities and mechtas (villages). Agriculture and logging shape the traditional economy in the region. In contrast, industrial activities are nearly non-existent, with only a handful of wood processing plants, mills, and milk collection and processing facilities [Houha 2007].

The region has a semi-arid climate with an annual rainfall of less than 400 mm. The average annual temperature is 17°C, with the lowest temperatures occurring in January

(6°C) and the highest temperatures in August (30°C). The annual potential evapotranspiration is 1050 mm [SMK 2014]. Due to the scarcity and periodic nature of surface water in the study area, it strongly relies on groundwater to meet the needs of a rural population of 47,000 inhabitants and to irrigate an 800 ha area [Aouidane and Belhamra 2017].

2.2. Geological and hydrogeological setting

Our understanding of the geological setting of the study region (Fig. 2) is mainly based on regional research, studies, and overviews of the Aures massif, the high steppe, and wetlands [Laffitte 1939]. These studies have predominantly focused on the stratigraphic, geomorphologic, sedimentologic, and structural features. The Remila Plain consists of thick stratigraphic series. It is composed of a Mesozoic basement at its base, which is unconformably overlain by a sedimentary layer originating from the Upper Triassic to the Quaternary [Laffitte 1939].



Source: Authors' own study

Fig. 2. Geological and piezometric map with location samples

Quaternary soils exhibit a wide range of facies and characteristics, resulting from the heterogeneity of the underlying lithology and structure (Fig. 2). These features are especially prominent in the areas situated between the Cretaceous reliefs of the Aures Mountains to the south and the central depression of the Remila Basin. Most of these formations originated during the Neogene age [Aouidane 2017, Houha 2007]. Additionally, the study area is delimited by Middle Cretaceous (Aptian) or Upper Cretaceous (Cenomanian, Turonian, and Senonian) formations, which occupy the northern and southern sectors of the region. In the north-west, the Miocene is characterised by the deposition of calcareous sandstones and limestones (Burdigalian) that overlie the Cretaceous and Pontian red marl. Meanwhile, the eastern parts of the floodplain are encompassed by an endorheic salt depression (Fig. 2), commonly referred to as the Sabkha Great Etarf [Vila 1977].

2.3. Sampling and analytical procedures

Twenty-five functional groundwater sampling points (Fig. 2) were carefully chosen within the Remila aquifer system during the February 2022 field campaign. The authors followed the sampling and analysis techniques suggested by [Rodier et al. 2009] to limit any potential errors arising from sample processing. In addition, the authors considered crucial aspects of the hydrogeology of the study area to ensure that each sample effectively represented the entire study area. These aspects included the orientation of groundwater flow, spatial evolution of aquifer rocks, and human activities [Azzeddine et al. 2024].

The Garmin Etrex 10 GPS device was used to accurately determine the sampling locations. Sampling and measurements were carried out after the wells had been pumped at least twice. Subsequently, the collected samples were stored in pre-cleaned and rinsed 1-L polyethylene bottles through a membrane filter of 0.45 um and sealed immediately after collection to prevent exposure to air. Afterwards, the samples were stored at a temperature of 4°C until the completion of the analysis. Each bottle was properly labelled and sent to the Laboratory of Algerian waters (ADE) Batna, Algeria, where chemical analyses were performed. The pH value, temperature (T; °C), electrical conductivity (EC; μS/cm) and total dissolved solids (TDS) were all measured on site using a Hanna 98130 digital multimeter. A spectrophotometer was used to measure the concentrations of cation species such as Ca^{2+}, Mg^{2+}, K^+ and Na^+ in the samples, while the concentrations of anions such as SO_4^{2-}, HCO_3^-, Cl^- and NO_3^- were determined using a digital titration method.

The analytical error verification of the concentration of the analysed ions was conducted through the assessment of electroneutrality, also known as the charge-balance error (CBE) [Reghais 2023], which can be determined using the following equation:

$$CBE = \frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{cations} + \sum \text{anions}} \cdot 100 \tag{1}$$

where:

∑ cations – represents the sum of cations (expressed by meq/L),

∑ anions – represents the sum of anions (expressed by meq/L), it is understood that the charge-balance error should be kept within ± 5% in order to ensure accurate measurements.

In the present study, all samples showed a %CBE within the prescribed range of ±5%.

Metallic trace elements were filtered before being preserved with ultrapure 6N nitric acid at pH < 2 in 100 ml vials. The stabilised samples are intended for the analysis of cademium (Cd), copper (Cu), lead (Pb), zinc (Zn). Each sample is analysed three times, then an average value is used. Analyses are performed by flame atomic spectrophotometer type PinAAcle 900 AA Series (Scientific and Technical Research Centre on Arid Regions laboratory).

3. Methodology

3.1. Hydro-geochemical assessment of groundwater

The population of the Remila Plain Khenchela relies heavily on groundwater for irrigation. Consequently, there is a notable concern regarding the contamination of groundwater and the deterioration of water quality.In this context, the hydrogeochemistry of groundwater was studied using data from samples to better understand the quality of groundwater for agriculture in the Remila aquifer.

The objective of this study was to evaluate groundwater quality parameters through the use of the usual range in irrigation water and recommended maximum concentrations of trace elements in irrigation water [Ayres and Cat 1985]. Several indices were used, such as the percentage of sodium (% Na), residual sodium carbonate (RSC), the sodium adsorption ratio (SAR), magnesium hazard (MH), and the permeability index (PI). Additionally, the US salinity diagram (USDA/Salinity Laboratory Staff) and the Wilcox diagram were employed to classify the water samples and comprehend the combined impact of the percentage sodium (%Na) and electrical conductivity (EC), respectively [Singh et al. 2020].

Table 1 shows the limits used for salinity, nutrients, pH, and SAR to characterize the quality of water used for irrigation [Ayres and Cat 1985].

Table 1. Laboratory determinations required for the assessment of common problems with the quality of irrigation water

Water parameter		Symbol	Unit	Usual range in irrigation water	
Salinity	Electrical conductivity	ECw	dS/m	0–3	dS/m
	Total dissolved solids	TDS	mg/L	0–2000	mg/L

Cations and anions	Calcium	Ca	meq/L	0–20	meq/L
	Magnesium	Mg	meq/L	0–5	meq/L
	Sodium	Na^+	meq/L	0–40	meq/L
	Carbonate	CO	meq/L	0–0.1	meq/L
	Bicarbonate	HCO_3	meq/L	0–10	meq/L
	Chloride	Cl	meq/L	0–30	meq/L
	Sulphate	SO_4	meq/L	0–20	meq/L
Nutrients	Nitrate-Nitrogen	NO_3-N	mg/L	0–10	mg/L
	Ammonium-Nitrogen	NH_4-N	mg/L	0–5	mg/L
	Phosphate-Phosphorus	PO_4-P	mg/L	0–2	mg/L
	Potassium	K^+	mg/L	0–2	mg/L
Miscellaneous	Acid/Basicity	pH	1–14	6.0–8.5	
	Sodium adsorption Ratio3	SAR	(meq/L)	0–15	meq/L

Table 2. Recommended maximum concentrations of trace elements in irrigation water

Element	Symbol	Recommended maximum concentration (mg/L)
Cadmium	Cd	0.01
Copper	Cu	0.20
Lead	Pd	5.0
Zinc	Zn	2.0

Source: adapted from National Academy of Sciences [1972] and Pratt [1972].

Table 3 presents detailed information regarding the calculation methods employed for the aforementioned indices. This includes the groundwater classes assigned to each index, with all ions expressed in milliequivalents per litre (meq/L).

Table 3. Classification of Irrigation Water Parameters

Index	Equation	Index range	Groundwater class	Reference
SAR	$SAR = \frac{Na^+}{\left[\frac{Ca^{2+} + Mg^{2+}}{2}\right]^{1/2}}$	0–10	Excellent	Richards [1954]
		10–18	Good	
		18–26	Fair/Doubtful	
		> 26	Poor/Unsuitable	

Table 3. cont.

Index	Equation	Index range	Groundwater class	Reference
%Na	$\%Na = \frac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} \cdot 100$	< 20	Excellent	Wilcox [1955]
		20–40	Good/Safe	
		40–60	Permissible/Safe	
		60–80	Doubtful/Unsafe	
		> 80	Unsuitable/Unsafe	
PI	$PI = \frac{Na^{+} + \sqrt{HCO_3^{-}}}{Ca^{2+} + Mg^{2+} + Na^{+}}$	< 75	Unsuitable	Das and Nag [2015]
		25–75	Good	
		> 75	Suitable	
MH	$MH = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \cdot 100$	< 50	Suitable	Raghunath [1987]
		> 50	Unsuitable	
RSC	$RSC = HCO_3^{-} - (Ca^{2+} + Mg^{2+})$	< 2.25	Good	Eaton [1950]
		1.25–2.25	Doubtful	
		> 2.25	Unsuitable	

4. Results and discussion

The hydrochemical parameters measured and the results of statistical processing (minimum, maximum, And mean standard deviation and coefficient of variation) are shown in Table 4.

Firstly, it should be noted that the maximum magnesium values (7.35/5 meq/L), and the mean (13/10 meq/L) and maximum (38.83/10 mg/L) nitrate-nitrogen values exceed the guide values for water quality for irrigation [Ayres and Cat 1985].On the other hand, the rest of the parameters indicate water that can be used for irrigation without risk. All the minimum values are below the limit recommended by FAO.

Trace elements are not all toxic. On the contrary, in small quantities several are essential for plant growth (Fe, Mn, Mo, Zn). However, excessive quantities will cause undesirable accumulations in plant tissues and limit their growth. Research has established toxic limits, particularly for irrigation water.

As part of this study, five elements were monitored (Cd, Cu, Pb, Zn), and a comparison of the results with the recommended maximum values (Table 2) [Ayres and Cat 1985] shows that copper levels are sometimes considerably too high, with the maximum value recorded exceeding the recommended maximum limit by 30 times, while the average value is 9 times.

Table 4. Statistical description of the physicochemical results of the samples studied

Parameters			Unit	Min	Mean	Max	SD	CV%	Irrigation Water quality
Salinity	Electrical conductivity	EC	dS/m	1.00	1.68	2.68	408.58	24.37	**0–3**
	Total dissolved solids	TDS	mg/L	617	1018.44	1589	261.49	24.37	**0–2000**
Cations and anions	Calcium	Ca	meq/L	2.44	7.55	12.55	49.65	32.79	**0–20**
	Magnesium	Mg	meq/L	2.97	4.92	**7.35**	14.95	24.98	**0–5**
	Sodium	Na	meq/L	1.58	5.79	17.26	95.06	71.37	**0–40**
	Bicarbonate	HCO_3	meq/L	3.16	4.06	5.29	35.9	14.50	**0–10**
	Chloride	Cl	meq/L	1.73	6.32	16.66	141.04	62.97	**0–30**
	Sulphate	SO_4	meq/L	2.99	5.47	7.90	65.29	24.86	**0–20**
Nutrients	Nitrate-Nitrogen	NO_3-N	mg/L	0.00	**12.95**	**38.83**	8.95	69.11	**0–10**
	Potassium	K	mg/L	0.03	0.06	0.16	1.42	62.56	**0–2**
Miscellaneous	Acid/Basicity	pH		6.95	7.39	7.69	0.21	2.84	**6–8.5**
	Sodium adsorption ratio	SAR	meq/L	0.64	2.42	7.72	1.88	77.60	**0–15**

Source: Irrigation quality values adapted from Ayers and Westcot [1985]

Furthermore, it is accepted that a deviation above 50% from the mean for a parameter indicates a significant variation between the maximum and minimum values, which is linked either to geology (natural ions) or to human activity (pollution parameters) [Brinis et al. 2021, Brahmia et al. 2018].

Calculation of the CV% shows that it is high (CV > 70%) for Mg^{2+} and SAR (71% and 77%), chlorides, nitrogen-nitrate and potassium (63%; 69% and 62.5%), which may be a result of heterogeneity in the distribution of these parameters in the groundwater of the Remila Plain – the amplitude between minimum and maximum values is considerable. For natural parameters (cations and anions), this can be explained by the geology, and for pollution parameters, such as nitrates, by localised contamination. For the rest of the parameters, the CV% does not exceed 30%, so the variation indicates a relative homogeneity in the waters studied.

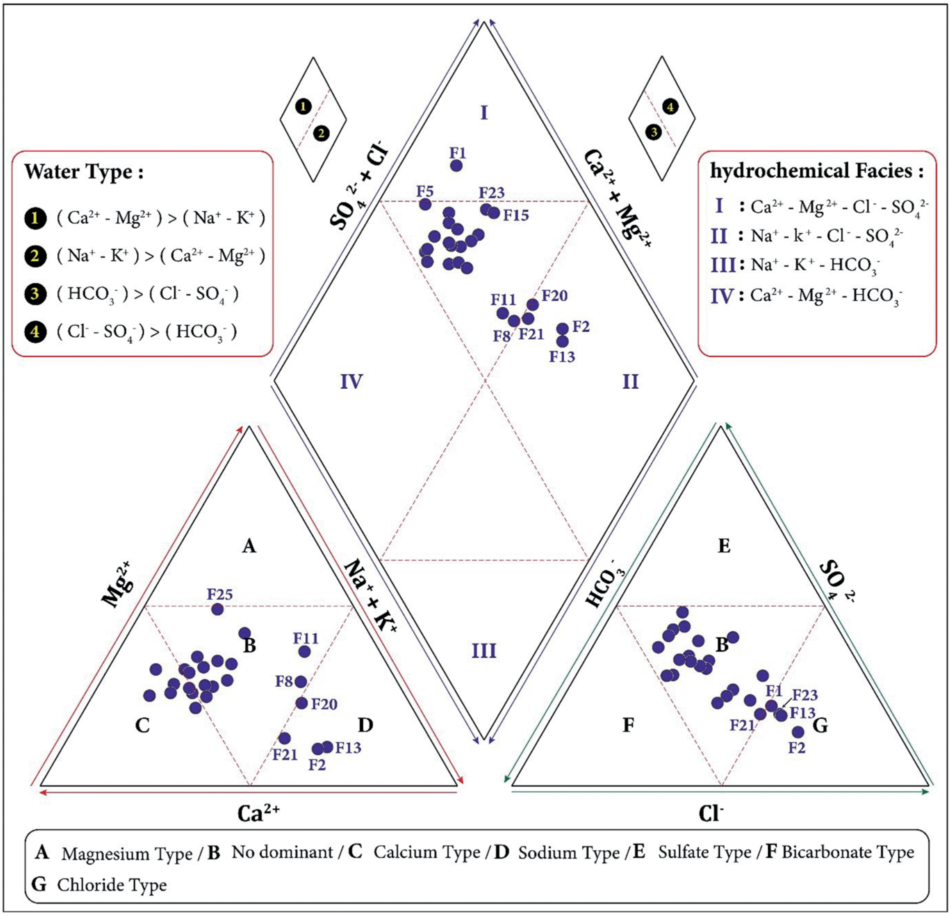
The calculated coefficients of variation (CV%) for trace elements vary between 52% and 270%, indicating a significant heterogeneity in the spatial distribution of the levels of these elements in the waters studied. This heterogeneity may be the result of contamination from human activity.

Table 5. Statistical description of the results of the trace elements of the analysed samples

Parameters		Unit	Min	Mean	Max	SD	CV%	Recommended maximum concentrations
Trace elements	Cd	mg/L	0.001	0.014	**0.04**	0.012	85.71	**0.01**
	Cu	mg/L	**0.585**	**1.799**	**5.917**	1.15	63.92	**0.20**
	Pb	mg/L	0.042	0.193	0.52	0.117	60.62	**5.0**
	Zn	mg/L	0.002	0.054	0.712	0.146	270.37	**2.0**

4.1. Identification of the chemical characteristics of water

The analyses are plotted on the Piper diagram (Fig. 3), and the samples are divided into two families: calcium and magnesium sulphated chlorinated waters and sodium/potassium chlorinated or sodium sulphated waters. In the anion triangle, the majority of points are located in the part where there are no dominant anions, although some points tend towards the chloride pole. Whereas in the cation triangle, one part of the point cloud shows a tendency towards sodium, the other towards calcium, and the rest in the non-dominant anion part. The dominance of Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, and SO_4^{2-} indicates mineralisation of either evaporitic origin or the alteration of silicate minerals such as clays. The bicarbonate facies are not the dominant component. Ca^{2+}, Mg^{2+}, Na^{+}, SO_4^{2-}, and Cl indicate the dissolution of several types of evaporitic minerals such as halite (Na, Cl), gypsum ($CaSO_4$), epsomite (Mg SO_4), mirabilite (Na_2SO_4) etc.... [Brinis et al. 2015].



Source: Authors' own study

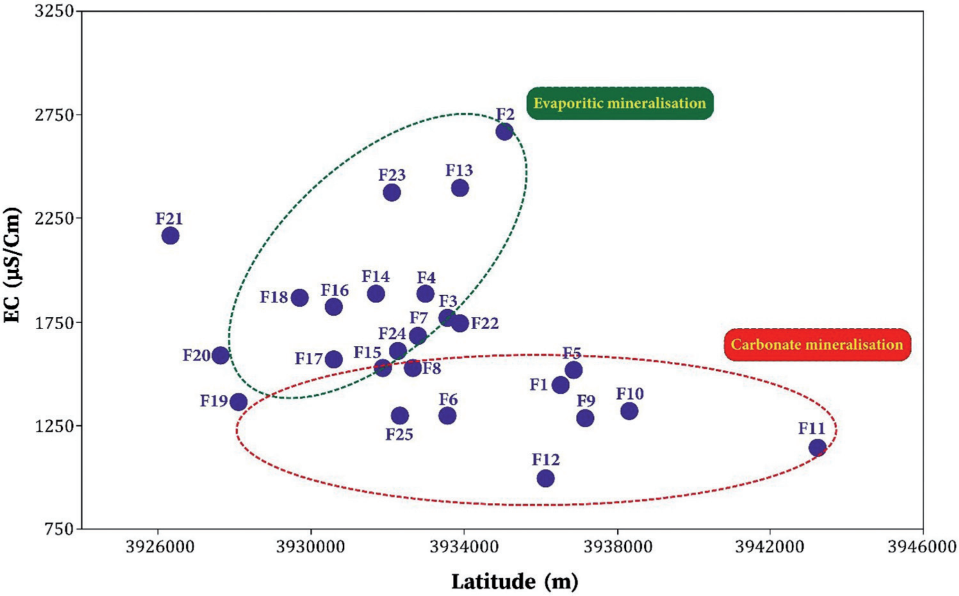
Fig. 3. Graphical representation of the results of the chemical analysis in the Piper diagram

4.2. Origin and evolution of water mineralisation

Evolution of electrical conductivity

The graph in Figure 4 represents electrical conductivity as a function of latitude (direction of flow), indicating an overall pattern of slight decrease in mineralisation. However, the scatter plot can be interpreted as having a double trend; a first trend showing no or little increase in the flow direction (positive direction of latitude), which would probably be related to carbonate ions, with a variation between 1000 and 1500 μS/cm. The second trend indicates a significant increase in conductivity, ranging between 1500 and 2750 μS/cm, which is probably related to the dissolution of evaporitic minerals or silicate weathering (Fig. 5). The correlations between the different ions (rNa/Cl = 0.7,

$rCa/SO_4 = 0.3$, $rMg/SO_4 = 0.7$) can be explained by a dual influence on mineralisation: the dissolution of evaporites and the weathering of silicates.

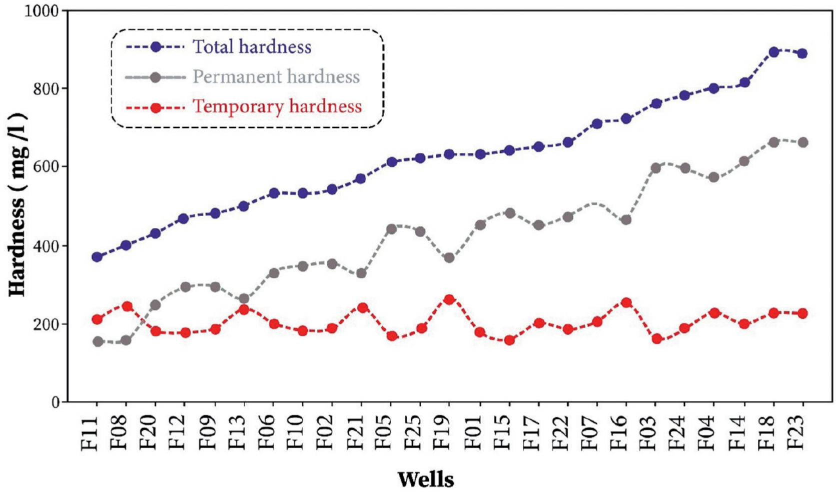


Source: Authors' own study

Fig. 4. Monitoring evolution of electrical conductivity in a South-North direction

Evolution of hardness (mg/L de Ca CO3)

Tracking the different types of hardness in the same graph, from the least concentrated to the most concentrated waters, shows that the carbonate hardness represents 34% of the total hardness of the water (Fig. 5). The evolution of the latter in the study area shows a certain stability and does not follow the evolution of the total hardness ($r = 0.12$), which can be interpreted as a relatively stable HCO_3 concentration over the entire Plain. The coefficient of variation (CV) is approximately 14%, indicating that the HCO_3 contents do not deviate significantly from the average content. On the other hand, the graph of the permanent hardness due to chloride and sulphate anions increases significantly, and follows perfectly the evolution of the total hardness of the water ($r = 0.98$), representing over 66% of it. This indicates the dominance of the ions from evaporitic minerals. However, the deviation from the average chloride content is quite significant, with a CV% reaching 63%.

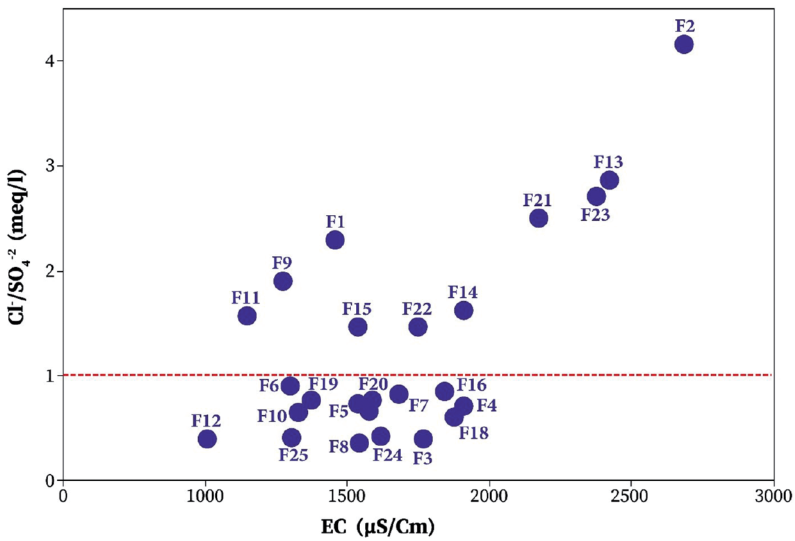


Source: Authors' own study

Fig. 5. Monitoring changes in temporary and permanent hardness in the water

Relation Cl/SO_4 vs EC

The combination of Cl/SO_4 with electrical conductivity in the same graph shows that high values of electrical conductivity are more influenced by the dissolution of chloride salts, which varies between 1200 µS/cm and 3000 µS/cm (Fig. 6).



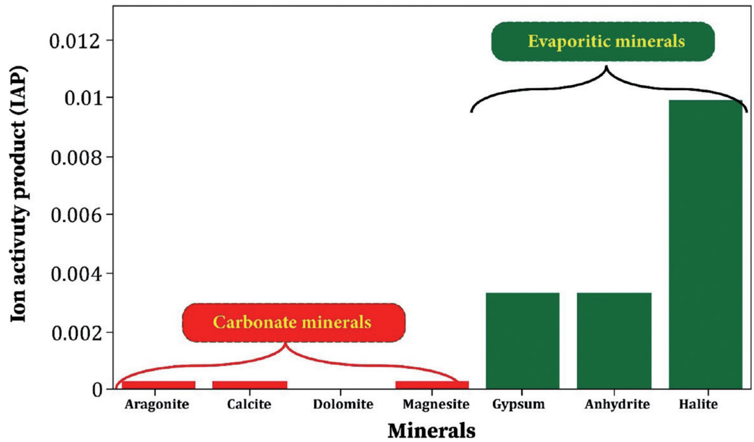
Source: Authors' own study

Fig. 6. Evolution of the Cl/SO_4 ratio as a function of electrical conductivity

The evolution of electrical conductivity influenced by the dissolution of sulphate salts is between 1000 μS/cm and 2000 μS/cm. This is undoubtedly linked to the difference in solubility between the two salts (chloride salts are more soluble than sulphate salts).

Monitoring the ionic activity of minerals dissolved in water

The simulation of the state of the dissolved minerals in the waters studied by the 'Phreeq.C' software indicates that the estimated ionic activity product (P.I.P.) of evaporitic minerals is higher. This means that the minerals are undersaturated and have more capacity to dissolve. On the other hand, the estimated P.I.P. of carbonate minerals is approaching zero, indicating that they are close to the steady state (Fig. 7).

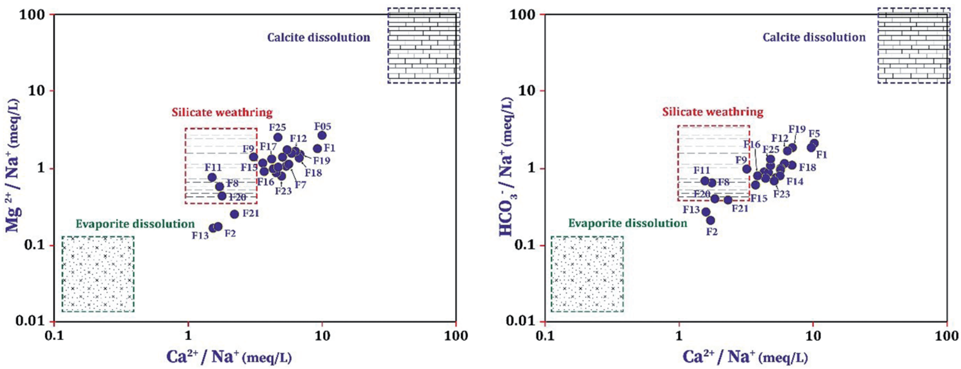


Source: Authors' own study

Fig. 7. The significance of the ionic activity of mineral ions dissolved in water

Origin of ions dissolved in water

The concentration of mineral salts in groundwater is a result of atmospheric precipitation inputs, chemical weathering of rocks and minerals and anthropogenic inputs. Previous studies have shown that the impact of rock weathering on the composition of major elements in water can be interpreted in terms of mixing between three main end-members: the weathering products of carbonates, silicates and evaporites [Négrel et al. 1993, Cao et al. 2016, Ollivier et al. 2010]. Figure 8 confirms that the salts dissolved in the water come from two sources: the alteration of silicates and evaporite formations. The hydrochemical facies of the water are caused by the dissolution of these formations.



Source: Authors' own study

Fig. 8. Mixing diagrams using Na-normalised molar ratios: a. Mg^{2+}/Na^{+} vs Ca^{2+}/Na^{+} and b. HCO_3^{-}/Na^{+} vs Ca^{2+}/Na^{+} for the Remila Plain

4.3. Indexes of groundwater quality

Five different indices (SAR, RSC, %Na, PI and MH) were used to evaluate the suitability of groundwater for irrigation based on different ionic parameters measured in meq/L. Table 6 illustrates the classification of groundwater into different categories based on results of groundwater quality indicators for the Remila aquifer.

Table 6. Results of the water quality indices calculated for irrigation in the Remila Plain

Categories	Index	Groundwater class	Number of samples	% of Wells
1	SAR	Excellent	25	100
2		Good	0	0.00
3		Fair/Doubtful	0	0.00
4		Poor/Unsuitable	0	0.00
1	% Na	Excellent	7	28.00
2		Good/Safe	12	48.00
3		Permissible/Safe	4	16.00
4		Doubtful/Unsafe	2	8.00
5		Unsuitable/Unsafe	0	0.00
1	PI	Unsuitable	1	4.00
2		Marginally suitable	24	96.00
3		Suitable	0	0.00

Table 6. cont.

Categories	Index	Groundwater class	Number of samples	% of Wells
1	MH	Suitable	21	84.00
2		Unsuitable	4	16.00
1	RSC	Good	25	100
2		Doubtful	0	0.00
3		Unsuitable	0	0.00

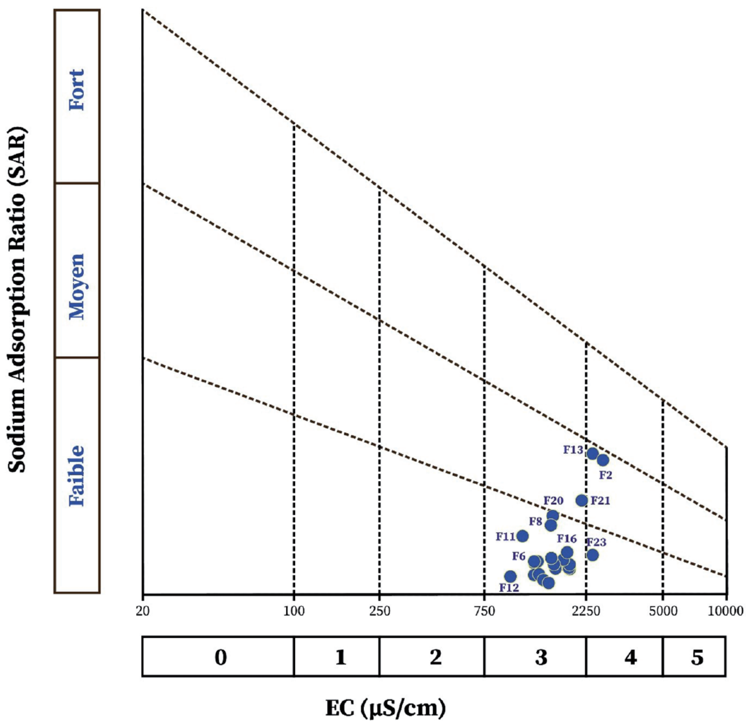
The sodium adsorption ratio (SAR) index plays a crucial role in evaluating the suitability of groundwater for agricultural purposes. It helps identify risks related to alkali/sodium that may affect crops by defining cation exchange reactions within the soil, particularly when sodium displaces absorbed magnesium and calcium [Chen et al. 2019, Wilcox 1955]. According to the SAR classification designed by [Richards 1954], as illustrated in Table 3, SAR values below 18 indicate water suitability for irrigation with minimal sodium-related threats. The SAR values of the groundwater examined ranged from 0.64 to 7.72 (Table 7), with an average value of 2.42 (all samples were less than 10), making it suitable for irrigation. Sodium poses no risk, and the area's water can irrigate a wide variety of soils and crops.

Table 7. Statistics of water quality indices for irrigation

	Min	Max	Mean	SD
SAR	0.64	7.72	2.42	1.88
%Na	11.76	63.53	30.17	14.69
RSC	−13.29	−3.05	−8.42	2.93
MH	28.11	67.11	40.51	10.59
PI	24.93	71.33	41.49	14.01

The excessive presence of salt in water has a detrimental effect on soil properties, with high levels of sodium, often coupled with calcium, leading to increased sodium adsorption ratio (SAR) levels [Adimalla and Venkatayogi 2018, Ali Khan et al. 2018]. For these reasons, this study also used the US salinity diagram for groundwater classification (Fig. 9), applying electrical conductivity to represent salinity hazards and sodium absorption ratio (SAR) to describe sodium hazards.According to the diagram:

- The majority of the samples (84%) are classified in the C3-S1 category, indicating a low SAR risk and a very high salinity risk (Fig. 9). Consequently, these values indicate a moderate suitability for irrigation purposes.



Source: Authors' own study

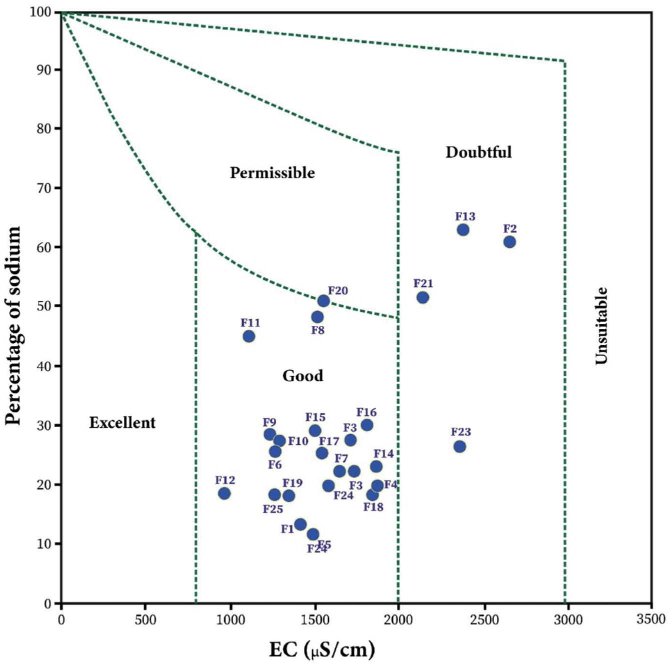
Fig. 9. USSL diagram for assessing irrigation water quality

- Two of the samples (8%) are categorised in the C4-S2 group, which means an increased salinity with moderately alkaline water. This classification could be deemed appropriate for irrigating salt-tolerant and semi-tolerant plant species, assuming favourable drainage conditions are in place.
- Two samples are classified in the C3-S2 and C4-S1 groups, respectively, reflecting high salinity levels and moderate sodium content in the former, and very high salinity levels and low sodium content in the latter.

The sodium percent (% Na) index is another method for determining the concentration of soluble sodium in irrigation water. It is used to identify the sodium hazard to crops [Panaskar et al. 2016].According to [Fipps 2003], water with a sodium level over 60% might create sodium buildup and threaten soil permeability – the soil becomes dry and compacted, lowering water and air infiltration rates into the soil structure. The sodium percentage values ranged from 11.76 to 63.53, with an average of 30.17. Based on the Na values, the majority of the water samples (76%) fall into the excellent and good irrigation classes. While 16% of the samples are categorised in the permissible irrigation class. With the exception of two groundwater samples, F2 and F13, the groundwater in the study area is generally suitable for irrigation.

The Wilcox diagram is also used in this research to assess the suitability of groundwater for irrigation by plotting the percentage of sodium (Na^{+}) against the electrical conductivity (EC). According to this diagram (Fig. 10), the majority of samples (84%) of the groundwater samples fall into the 'good to acceptable' category, while the remaining 16% (4 samples) are in the 'doubtful to unsuitable' range.

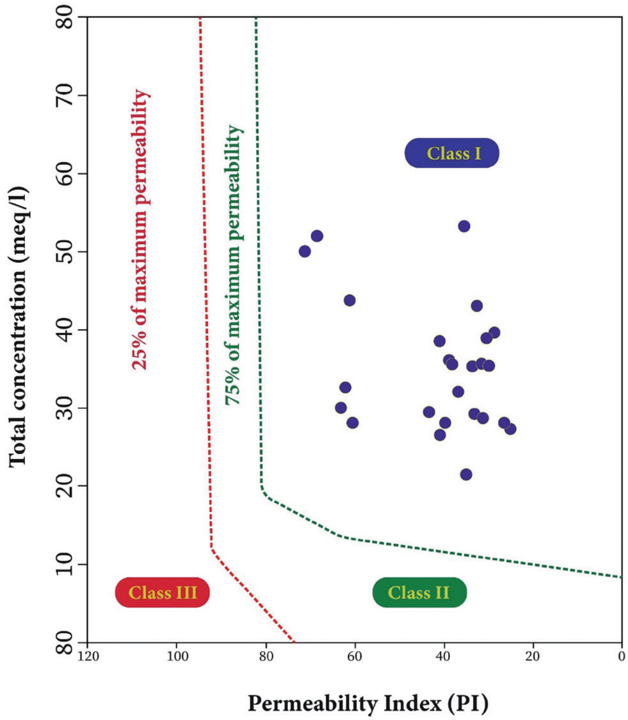
Equally significant is the residual sodium carbonate (RSC), which serves as a valuable tool for detecting the presence of sodium carbonate in water. The precipitation of Ca^{2+} and Mg^{2+} as carbonates is triggered by elevated concentrations of CO_3^{2-} and HCO_3^{-} [Merani et al. 2014]. The estimation of residual sodium carbonate is crucial for gaining insights into the detrimental impact of carbonate and bicarbonate on the quality of agricultural water. Prolonged use of water with high RSC levels leads to leaf burn in plants and reduces crop yields [Eaton 1950, Ramesh and Elango 2012]. Based on RSC values, all the samples examined in the study were found to be suitable for irrigation (all samples were in the good class).



Source: Wilcox's [1948]

Fig. 10. Irrigation water suitability of Remila Plain

Although magnesium is found in a wide range of minerals, it is primarily dissolved in dolomitic rocks. In the majority of groundwater sources, calcium ions (Ca^{2+}) and magnesium ions (Mg^{2+}) maintain a state of equilibrium. The more Mg^{2+} is in groundwater at the state of equilibrium, the worse the soil quality, which becomes alkaline, and so has a reduced crop productivity [Hem 1985, Wilcox 1955]. According to [Raghunath 1987], water is classified into two categories: suitable (MH < 50) and unsuitable (MH > 50), The results of magnesium adsorption ratio obtained show that the MH of the water samples ranges from 28,11 to 67,11 (Table 7), with a mean of 40,51, 84 % of the analysed water samples are classified as suitable water (21 samples), and 16% (4 samples) as unsuitable water.



Source: Authors' own study

Fig. 11. Classification of irrigation water in the Remila Plain based on the permeability index

Similarly, the long-term consumption of irrigation water affects soil permeability, a factor that is influenced by the salt, calcium, magnesium and bicarbonate content of the soil. The permeability index is another adapted criterion used to assess the quality of agricultural water and focuses on salt solubility and cation exchange reactions within the soil solution. According to the classification of Doneen [1964], the permeability index (PI) is divided into three categories: class I (PI < 25 permeability), class II (PI = 25–75) and class III (PI > 75%). Classes I and II are considered suitable for irrigation, while class III – with a maximum permeability of 25% – is considered unsuitable. In the current study, the permeability index (PI) values varied between 25 and 71.32 meq/L. These results indicate that all samples fall into the 'good quality' range (Fig. 11). According to the classification of Doneen [1964], several factors, including ion exchange, dolomite and calcite dissolution, may contribute to the elevated permeability index (PI) values.

5. Conclusion

In addition to analysing the hydrochemical composition of the water, the aim of this study was to evaluate the feasibility of utilising the Plio-Quaternary subterranean aquifer located in the Remila Plain, Khenchela for agricultural purposes. The findings indicate that:

- The groundwater quality in the examined area is suitable for fulfilling agricultural water requirements. Instances of anthropogenic contamination were limited, with only a few cases involving nitrates (maximum concentration of 170 mg/L).
- High levels of chlorides (maximum 590 mg/L), sodium (maximum 396 mg/L), and sulphates (maximum 370 mg/L), along with high electrical conductivity (maximum 2680 μS/cm), are the primary limitations identified by the analyses of monitored sample. However, it should be noted that these exceedances only affect a limited number of water sources. Therefore, crops adapted to relatively mineralised water can be grown in the affected areas. As far as trace elements are concerned, we note that copper exceeds the recommended maximum levels and needs to be monitored regularly.
- The influence of geology, specifically the dissolution of evaporitic rocks and the alteration of silicates, influences the fundamental factors governing water mineralisation. Additionally, agricultural activity exerts a significant impact on water quality, resulting in elevated nitrate levels.
- The water exhibits characteristics consistent with a chloride-sulphate/calcium-sodium composition, with variations in mineralisation observed along the flow path. Lower values are indicative of recharge areas, while higher values progressively emerge closer to the outlet. Monitoring of water hardness and ionic activity further substantiates the prevalence of chlorides and sulphates.

The assessment of water quality for agricultural purposes takes into account various factors related to the quality of irrigation water. Water from the Remila aquifer is classified as follows:

- 100% of samples are of excellent quality for SAR.
- 28% as excellent, 48% as good and 16% as acceptable in relation to % Na.
- For MH, 84% were considered suitable and 16% unsuitable.
- Finally, 96% are marginally appropriate and 4% inappropriate for PI.

This study's findings suggest that the groundwater within the aquifer is viable for irrigation. Nevertheless, it is crucial to exercise strict control over the application of fertilizers in order to mitigate nitrate levels and prevent potential deterioration of the utilized groundwater.

References

Adimalla N., Dhakate R., Kasarla A., Taloor A.K. 2020. Appraisal of groundwater quality for drinking and irrigation purposes in Central Telangana, India. Groundwater for Sustainable Development, 10, 100334.

Adimalla N., Venkatayogi S. 2018. Geochemical characterization and evaluation of groundwater suitability for domestic and agricultural utility in semi-arid region of Basara, Telangana State, South India. Applied Water Science, 8. http://dx.doi.org/10.1007/s13201-018-0682-1.

Ahmad S., Khurshid S. 2019. Hydrogeochemical assessment of groundwater quality in parts of the Hindon River basin, Ghaziabad, India: implications for domestic and irrigation purposes. SN Applied Sciences, 1, 2, 151.

Ali Khan M. Department of Geoscience, Faculty of Earth Science, Universiti Malaysia Kelantan, Campus Jeli, Locked Bag No. 100, 17600 Jeli, Kelantan, Malaysia.

Aouidane L. 2017. Origines de la salinisation des eaux et des sols d'une zone à climat semi-aride: Cas de Remila (W. Khenchela). http://thesis.univ-biskra.dz/3074/.

Aouidane L., Belhamra M. 2017. Hydrogeochemical processes in the Plio-Quaternary Remila aquifer (Khenchela, Algeria). Journal of African Earth Sciences, 130, 38–47.

Aouidane L., Belhamra M., Kheddouma A. 2021. Integrated statistical and hydro-geochemical approach to identify the origin and process of saline contamination of Remila plain groundwater (Khenchela, Algeria). Earth and Environmental Science Transactions of the Royal Society of Edinburgh, 112, 2, 89–99.

Ayres R.S., Cat D.W.W. 1985. Water Quality for Agriculture, FAO, Irrigation and Drainage paper.

Azzeddine R., Abdelmalek D., Ewuzie U., Faouzi Z., Taha-Hocine D. 2024. Compositional data analysis (CoDA) and geochemical signatures of the terminal complex aquifer in an arid zone (northeastern Algeria). Journal of African Earth Sciences, 210, 105162.

Brahmia A., Brinis N., Nouar T. 2018. Statistical and hydrogeochemical characteristics of the M'Daourouch-Drea Plain's groundwater, North-East of Algeria. Journal of Water and Land Development, 38, 1, 19–26.

Brinis N., Boudoukha A., Ahmed Hamel A. 2015. Analyse Statistique et Geochimique de la Dynamique des Parametres Physico-Chimiques des Eaux Souterraines du Synclinal de Ghassira Algerie Orientale. Larhyss Journal, 22, 123–137.

Brinis N., Brahmia A., Hamel A., Benhamida S. 2021. Origine et dynamique des ions controlant la mineralisation des eaux des sources dans la partie amont de la vallee de L'oued Labiod, (W) Batna, Algerie. Regions: Ichemoul, Arris, T'kout et Ghassira. LHB 107, 1, 1–10.

Cao Y., Tang C., Cao G., Wang X. 2016. Hydrochemical zoning: natural and anthropogenic origins of the major elements in the surface water of Taizi River Basin, Northeast China. Environmental Earth Sciences, 75, 9.

Chen J., Huang Q., Lin Y. et al. 2019. Hydrogeochemical Characteristics and Quality Assessment of Groundwater in an Irrigated Region, Northwest China. Water, 11, 1, 96.

C.P.H. 1977. Proposition de réalisation d'étude et projets d'aménagement hydro agricole de la plaine de Rémila. Rapport de Consortium Projectum-Hidroesb, Rio de Janeiro Janvier, 100 p.

Doneen L.D. 1964. Notes on water quality in agriculture. Department of Water Science and Engineering, University of California, Davis.

Eaton F.M. 1950. Significance of Carbonates in Irrigation Waters. Soil Science, 69, 2, 123.

Eulenstein F., Tauschke M., Schindler U. et al. 2016. Agricultural Land Use Systems and Groundwater Quality: Impact Assessment Using Nutrient Balances for Evaluation, Monitoring and Conservation of Natural Resources. Agriculture and Agricultural Science Procedia, 11, 49–58.

Fipps G. 2003. Irrigation water quality standards and salinity management strategies. https://gfipps.tamu.edu/files/2021/11/EB-1667-Salinity.pdf

Guiraud R. 1073. Évolution post-Triasique de l'Avant pays de la chaine alpine en Algérie d'aprés l'étude du bassin du Hodna et des régions voisines, Thèse Sci. Univ. Nice, 270 p.

Hem J.D. 1985. Study and Interpretation of the Chemical Characteristics of Natural Water. Department of the Interior, U.S. Geological Survey.

Houha B. 2007. Etude du fonctionnement hydrogéochimique et salin d'un bassin semi-aride. Remila, Khenchela. Doctoratethesis, University of Annaba, Algeria.

Khedidja A., Drias T., Reghais A. 2023. Assessment of groundwater vulnerability to pollution using DRASTIC and the SI methods: case of the alluvial aquifer in Tadjenanet-Chelghoum laid (East Algeria). Acque Sotterranee - Italian Journal of Groundwater, 12, 2, 37–47.

Khelifa M., Khedidja A., Mansour H., Azzeddine R. 2024. Water resources and physicochemical properties of the Mio-Pliocene aquifer complex in the M'leta Plain, Western Algeria. Journal of Water and Land Development, 11–20.

Kumari M., Rai S.C. 2020. Hydrogeochemical Evaluation of Groundwater Quality for Drinking and Irrigation Purposes Using Water Quality Index in Semi Arid Region of India. Journal of the Geological Society of India, 95, 159–168. http://dx.doi.org/10.1007/s12594-020-1405-4.

Laffitte R. 1939. Etude géologique de l'Aurès. Service de la carte géologique de l'Algérie.

Mardhiya A., Ainul Kamal Z., Mansor H.E., Mathialagan K.R.P. 2018. Evaluating the suitability of shallow aquifer for irrigational purposes in some parts of Kelantan, Malaysia. Buletin Persatuan Geologi Malaysia, 66, 1, 57–64.

Merani B.N., Sheikh S.A., Channa M.J., Panhwar A.A., Soomro A.H. 2014. Estimation spatial distribution of Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC) in groundwater of Tando Muhammad Khan Pakistan. Journal of Pharmacy and Nutrition Sciences, 4, 2, 162–169.

Négrel P., Allègre C.J., Dupré B., Lewin E. 1993. Erosion sources determined by inversion of major and trace element ratios and strontium isotopic ratios in river water: The Congo Basin case. Earth and Planetary Science Letters, 120, 1–2, 59–76.

Ollivier P., Hamelin B., Radakovitch O. 2010. Seasonal variations of physical and chemical erosion: A three-year survey of the Rhone River (France). Geochimica et Cosmochimica Acta, 74, 3, 907–927.

Panaskar D.B., Wagh V.M., Muley A.A., Mukate S.V., Pawar R.S., Aamalawar M.L. 2016. Evaluating groundwater suitability for the domestic, irrigation, and industrial purposes in Nanded Tehsil, Maharashtra, India, using GIS and statistics. Arabian Journal of Geosciences, 9, 13, 615.

Raghunath H.M. 1987. Ground Water: Hydrogeology, Ground Water Survey and Pumping Tests, Rural Water Supply and Irrigation Systems. New Age International.

Ramesh K., Elango L. 2012. Groundwater quality and its suitability for domestic and agricultural use in Tondiar river basin, Tamil Nadu, India. Environmental Monitoring and Assessment, 184, 6, 3887–3899.

Reghais A. 2023. Study of the hydrodynamic and hydrochemical functioning of the aquifer of the Terminal Complex in the Biskra region (Southeast Algeria). https://rgdoi.net/10.13140/RG.2.2.34729.36967/1.

Reghais A., Drouiche A., Zahi F., Debieche T.H. 2023. Hydrogeochemical evaluation of the Terminal Complex aquifer system in an arid area: a case study from the Biskra region, northeast Algeria. Environmental Earth Sciences, 82, 7, 182.

Richards L.A. 1954. Diagnosis and Improvement of Saline and Alkali Soils. Handbook.

Rodier J., Legube B., Merlet N. et al. 2009. L'analyse de l'eau-9e éd. Eaux naturelles, eaux résiduaires, eau de mer. Dunod, 564–571.

Singh G., Rishi M.S., Herojeet R., Kaur L., Priyanka, Sharma K. 2020. Multivariate analysis and geochemical signatures of groundwater in the agricultural dominated taluks of Jalandhar district, Punjab, India. Journal of Geochemical Exploration 208, 106395.

S.M.K. 2014. Service des statistiques, les données climatiques de la wilaya de Khenchela. Station Métrologique de la Wilaya de Khenechela.

Vila J.M. 1977. Notice explicative de la carte géologique, au 1/50.000, Touffana (feuille n° 202). Editée par Sonatrach en 1977. 6 p.

Wilcox L.V. 1955. Classification and Use of Irrigation Waters. U.S. Department of Agriculture.

Zahi F., Medjani F., Djidel M., Drouiche A. 2021. Groundwater quality and its suitability for different uses in lower Djendjen Watershed, Northest Algeria. Asian Journal of Research in Chemistry, 179–185.

Zektser I.S., Everett L.G. 2004. Groundwater Resources of the World and Their Use, IHP-VI Ser. Groundwater6, UN Educ., Sci. Cult. Organ., Paris.