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Hydro-Chemical Characterization of Water Resources under Climate Change Pressure in Khenchela Province, North-Eastern Algeria

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Abstract. Water resources in semi-arid and arid regions are increasingly exposed to the combined pressures of climatic variability, drought, agricultural activity, urban growth, and water–rock interaction. Khenchela Province in north-eastern Algeria represents a climate-sensitive hydrogeochemical setting because it extends from relatively humid mountain and high-plain zones in the north to arid pre-Saharan areas in the south. This study evaluates the physicochemical and hydrochemical characteristics of 10 water resources sampled across Khenchela Province during June–August 2025. Field measurements included temperature, pH, electrical conductivity, and total dissolved solids, while laboratory analyses quantified Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, and NO_3^{-}. Spatial patterns were interpreted using GIS-based mapping, and hydrochemical facies were classified using Piper, Schoeller–Berkaloff, and Wilcox diagrams. Results show that water temperature ranged from 14 to 24 °C, pH from 6.75 to 7.91, EC from 702 to 3360 µS/cm, and TDS from 544 to 2579 mg/L. Northern and central sites generally showed lower mineralization, whereas southern sites exhibited brackish conditions and elevated Ca^{2+}, Na^{+}, Cl^{-}, SO_4^{2-}, and NO_3^{-} concentrations. The dominant hydrochemical facies were Ca–Mg–HCO_3, mixed Ca–Mg–Cl/Ca–Mg–SO_4, and Ca–Cl types, reflecting spatially variable carbonate dissolution, evaporitic influence, and longer water–rock interaction. Wilcox classification indicated that most samples were suitable for irrigation, but southern waters showed salinity and sodicity constraints requiring careful soil and irrigation management. The findings indicate that water quality in Khenchela Province is controlled by both natural hydrogeochemical processes and environmental stress associated with aridity. Although the dataset does not allow direct long-term attribution to climate change, the observed southward increase in salinity and mineralization highlights the vulnerability of regional water resources under conditions of warming, irregular rainfall, and reduced dilution. The study provides a valuable baseline for hydrochemical monitoring and supports the need for seasonal sampling, nitrate surveillance, salinity management, and integrated climate–water-resource planning in north-eastern Algeria.

1. INTRODUCTION

Freshwater resources in dryland regions are among the most vulnerable environmental systems because they are simultaneously controlled by climate, geology, land use, recharge dynamics, and human demand. In Mediterranean and North African regions, warming, rainfall irregularity, drought recurrence, and intense rainfall events increasingly affect both the quantity and quality of available water resources. Climate change can alter water quality directly through increasing water temperature and indirectly through changes in dilution, evaporation, runoff, soil erosion, pollutant mobilization, and groundwater recharge (IPCC, 2022; UN-Water, 2019). These pressures are particularly important in semi-arid and arid environments, where limited recharge and high evapotranspiration can concentrate dissolved ions and increase salinity hazards.

Algeria is recognized as a water-stressed country, with renewable water resources unevenly distributed between the relatively wetter northern basins and the arid southern territories. Previous studies have shown that Algeria's water sector is exposed to drought, declining rainfall, increasing evaporation, groundwater depletion, dam siltation, and salinization risks (Hamiche et al., 2015; Mohammed and Al-Amin, 2018). In north-eastern Algeria, where mountain, high-plain, steppe, and pre-Saharan landscapes occur over relatively short distances, water chemistry can change markedly from one zone to another. These spatial changes may reflect lithology, residence time, evaporation, agricultural return flow, domestic waste inputs, and interaction with carbonate or evaporitic formations.

Khenchela Province is a particularly relevant case because it extends from the Aurès Mountains and high plains toward arid southern depressions. Its topographic and climatic contrasts create a strong environmental gradient that can influence the hydrochemical composition of springs and groundwater resources. The study area elevations varied from the high Aurès Mountains, including peaks above 2300 m, to low-lying southern areas near El Mitta, with climate shifting from semi-arid conditions in the north to desert conditions in the south. This gradient creates an opportunity to examine whether water quality deteriorates spatially along the transition toward drier environments.

Hydrochemical assessment is a widely used approach for evaluating water origin, geochemical evolution, drinking suitability, and irrigation constraints. Major ions such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-}, and NO_3^{-} provide information on mineral dissolution, ion exchange, evaporite influence, anthropogenic inputs, and agricultural contamination (Hem, 1985; Freeze and Cherry, 1979). Piper diagrams help identify hydrochemical facies, Schoeller–Berkaloff diagrams allow comparison of ionic profiles, and Wilcox or salinity–sodicity diagrams support irrigation suitability classification (Piper, 1944; Schoeller, 1965; Wilcox, 1955). When combined with GIS mapping, these methods can reveal spatial patterns that are useful for water-resource management.

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Several studies in Algeria and comparable semi-arid regions have reported increasing concern over groundwater mineralization, nitrate contamination, and salinity hazards. Benrabah et al. (2016) investigated groundwater destined for drinking-water supply in Khenchela City, while Hamlat and Guidoum (2018) used water-quality indices in a semi-arid region of north-western Algeria. Mansouri et al. (2022) reported hydrogeochemical and groundwater-quality patterns in the Ouargla Basin, southern Algeria. Together, these studies show that water quality in Algerian drylands is shaped by both natural hydrogeochemical processes and human activities. However, additional site-specific assessments are needed because local geology, recharge conditions, and land use strongly control water chemistry.

The specific objectives of this study are to: (i) characterize the physicochemical and major-ion composition of selected water resources; (ii) identify spatial patterns in mineralization and key ions; (iii) classify hydrochemical facies using Piper and Schoeller–Berkaloff diagrams; (iv) evaluate irrigation suitability using Wilcox classification; and (v) discuss the implications of the observed patterns for water-resource management under semi-arid to arid conditions. The study is framed as a baseline hydrochemical assessment rather than a definitive causal attribution of climate-change effects, because the available water-quality dataset was collected during a single summer sampling period.

2. MATERIALS AND METHODS

2.1. Study Area

Khenchela Province is located in north-eastern Algeria, south-east of the Constantinian region, between approximately 35°07′–35°38′ N and 6°32′–7°34′ E (Figure 1). The province covers about 9715 km² and is bounded by Oum El Bouaghi to the north, Biskra and El Oued to the south, Tebessa to the east, and Batna to the west. The area includes strong topographic contrasts, ranging from the Aurès Mountains in the north and centre to pre-Saharan lowlands in the south. This relief variation is important because elevation, slope, drainage, lithology, and climate influence recharge, residence time, and groundwater mineralization.

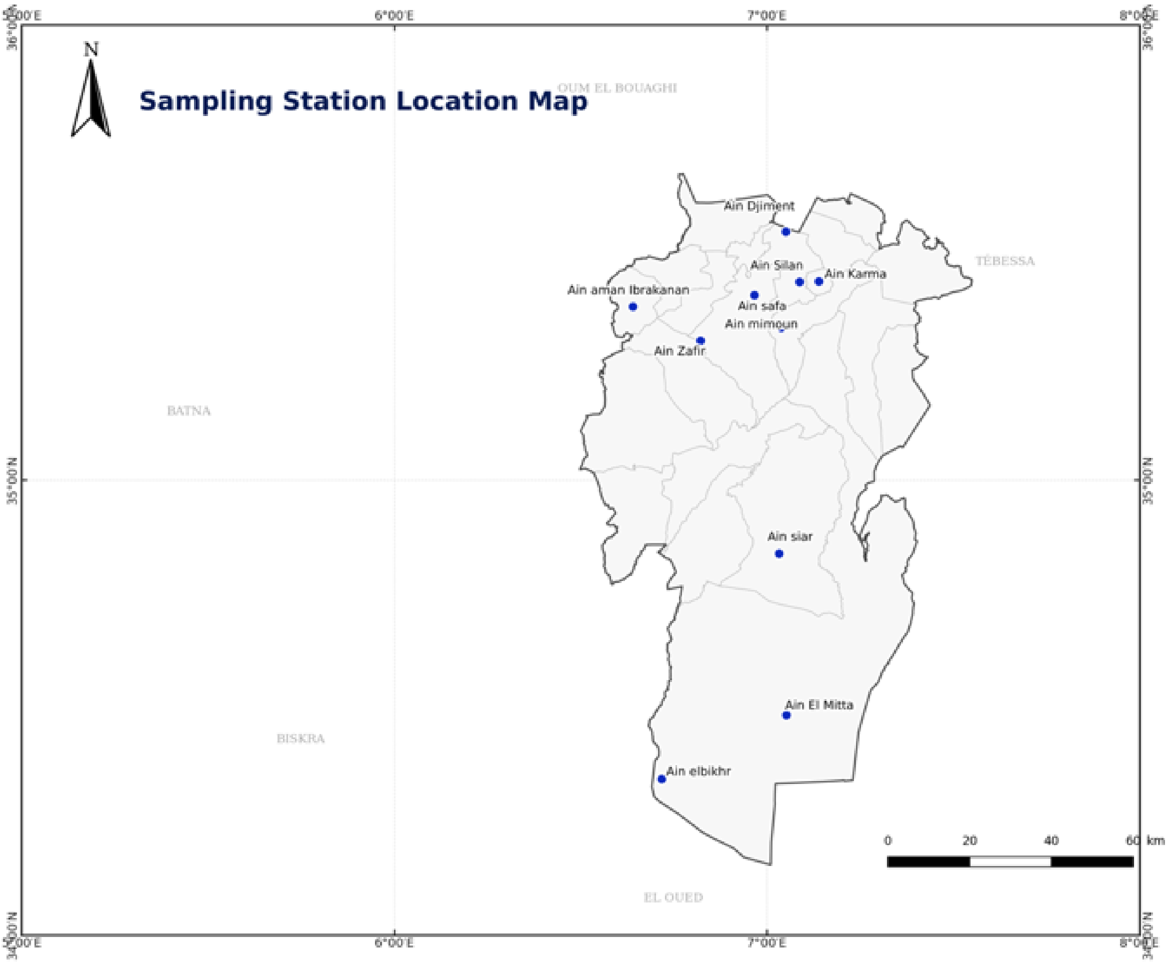
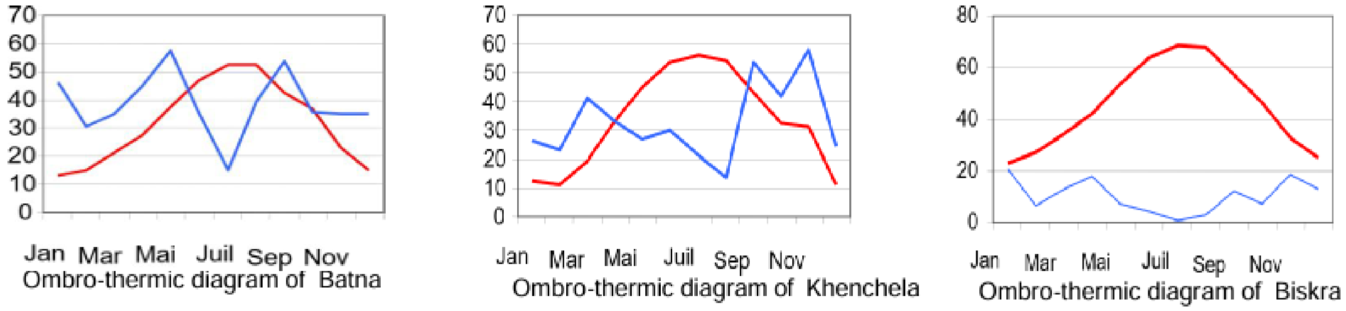


Figure 1. Study area and water-sampling locations in Khenchela Province, north-eastern Algeria.

2.2. Climatic Context

The study area has a marked climatic gradient. Climatic information from Batna, Khenchela, and Biskra meteorological stations for 1991–2023 indicates a transition from semi-arid conditions in the north toward arid or desert conditions in the south. The reports irregular precipitation and strong seasonal temperature contrasts, with hot dry summers and cooler winters in the northern highlands and more extreme aridity in the southern zone. Such conditions are expected to affect water availability and chemistry by influencing recharge, evaporation, dilution, and the concentration of dissolved salts.

Due to its geographical position and climatic characteristics, the climate in the study area is transitional, presenting a temperate continental climate in the northern part, which includes the coast and the Tell Atlas (hot and dry summers, wet and fresh winters); semi-arid with irregular and low precipitation on a high plateau in the center and arid desert with extremely low annual precipitation beyond the Saharan Atlas. The temperatures range from over 45 °C by day to − 5 °C by night, and annual rainfall ranges from some 200mm, over the entire southern, to levels of 700 to 1200mm in some restricted areas of the high mountains of the northwest massifs.



Ombro-thermic diagram of Batna

Ombro-thermic diagram of Khenchela

Ombro-thermic diagram of Biskra

Figure 2. Climatic context of the study area based on temperature and precipitation records from Batna, Khenchela, and Biskra meteorological stations for 1991–2023.

2.3. Geological and Hydrological Setting

The geology of Khenchela Province includes carbonate, marl, sandstone, conglomerate, and Quaternary formations. These geological units influence the chemical composition of water through mineral dissolution and water–rock interaction. Carbonate formations may contribute calcium, magnesium, and bicarbonate, while evaporitic or sulfate-bearing formations may increase sulfate, chloride, sodium, and total dissolved solids.

Hydrologically, the province is drained by several wadis and basins, including Oued El-Ma, Oued El-Arab, Oued Beni Barber, and the Chott Melghir basin. Many of these drainage systems are seasonal and strongly controlled by rainfall events. In arid and semi-arid settings, limited recharge and high evaporation can increase the mineralization of groundwater and spring water.

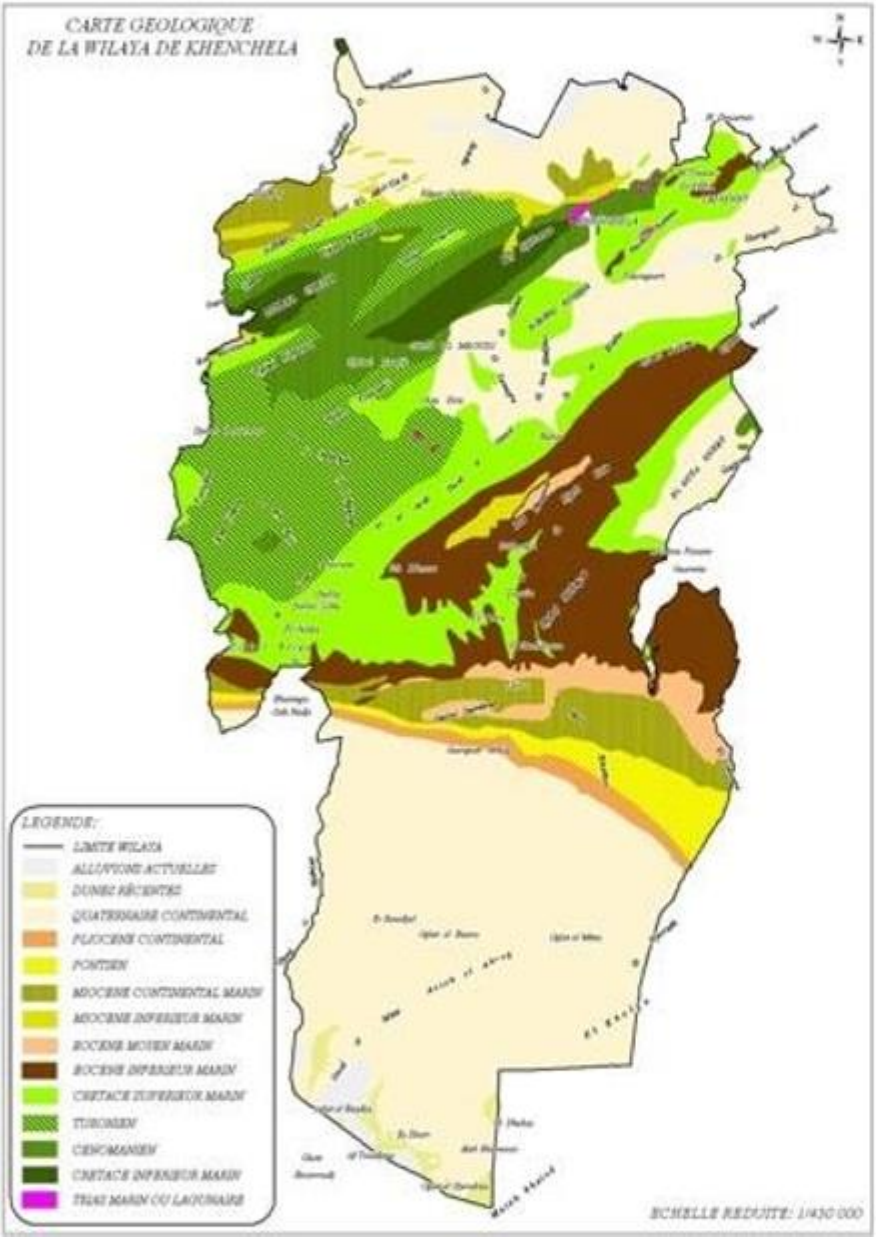


Figure 3. Geological map of Khenchela showing the major lithological formations that influence groundwater chemistry.

2.4. Sample Collection and Field Measurements

Ten water sampling sites were selected across Khenchela Province. The sites were chosen according to geographical location, climatic setting, physical characteristics, and lithological context. Sampling was carried out from June to August 2025. The selected sites were Ain Aman Ibrakanan, Ain Mimoun, Ain Zafir, Ain Djiment, Ain Silan, Ain Karma, Ain Safa, Ain Siar, Ain El Mitta, and Ain Elbikhr.

Water samples were collected in pre-cleaned polyethylene bottles. The bottles were washed with 2% nitric acid and rinsed with distilled water before use. Samples were stored in insulated coolers and refrigerated until laboratory analysis. Field measurements were taken directly at the sampling sites using a multiparameter instrument.

Field measurements included temperature, pH, electrical conductivity, and total dissolved solids. These parameters were measured in situ because they can change rapidly after sample collection. Temperature is important because it affects chemical reactions, dissolved oxygen, and biological activity. pH indicates the acidity or alkalinity of water and influences mineral solubility. Electrical conductivity and TDS provide a direct indication of water mineralization and salinity.

2.5. Laboratory Analysis

The collected water samples were analyzed for major cations and anions. Calcium and magnesium were measured by EDTA titration, sodium and potassium by flame photometry, chloride by silver nitrate titration, sulfate and nitrate by UV–visible spectrophotometry, and bicarbonate by hydrochloric acid titration. Before analysis, samples were filtered through 0.45 µm filter paper.

Table 1. Methods used for chemical analysis of water samples.

Chemical Variable	**Analytical Method**
Calcium, Ca^{2+}	EDTA titration
Magnesium, Mg^{2+}	EDTA titration
Sodium, Na^{+}	Flame photometry
Potassium, K^{+}	Flame photometry
Chloride, Cl^{-}	$AgNO_3$ titration
Sulfate, So_4^{2-}	UV–visible spectrophotometry
Nitrate, No_3^{-}	UV–visible spectrophotometry
Bicarbonate, HCo_3^{-}	Titration

2.6. GIS and Hydrochemical Diagram Analysis

GIS mapping was performed using ArcMap GIS 10.6 with the Spatial Analyst module. Kriging interpolation was used to visualize the spatial distribution of selected physicochemical parameters. Because the study included only ten sampling points, interpolation results should be interpreted as exploratory spatial patterns rather than definitive regional predictions.

Hydrochemical facies were interpreted using Piper and Schoeller–Berkaloff diagrams. These diagrams help identify dominant water types and compare ionic profiles between sites. Wilcox diagrams were used to evaluate irrigation suitability by considering salinity and sodium-related hazards.

3. RESULTS

3.1. Field Parameters and Mineralization

The measured physicochemical parameters showed clear spatial variability across the 10 sampling sites. Water temperature ranged from 14 °C at Ain Aman Ibrakanan to 24 °C at Ain El Mitta, with a mean of 18.1 °C. Lower temperatures were generally observed in northern or higher-elevation sites, while the highest values occurred in southern sites. This pattern is consistent with regional climatic variation and the seasonal timing of sampling during summer.

pH ranged from 6.75 at Ain Elbikhr to 7.91 at Ain Djiment, indicating neutral to slightly alkaline water. Most samples were within the normal pH range expected for natural waters influenced by carbonate lithology. Slightly lower pH values in the southern samples may reflect local geochemical conditions, residence time, or differences in dissolved carbon dioxide and mineral equilibria. However, without alkalinity speciation, dissolved CO_2, and saturation-index calculations, the controlling processes cannot be confirmed.

Electrical conductivity ranged from 702 µS/cm at Ain Zafir to 3360 µS/cm at Ain El Mitta. Total dissolved solids ranged from 544 mg/L at Ain Zafir to 2579 mg/L at Ain Elbikhr. The northern and central samples generally had lower EC and TDS, whereas Ain Siar, Ain El Mitta, and Ain Elbikhr had much higher mineralization. According to the results, about 70% of samples were classified as fresh water, while the three southern samples were brackish based on TDS values .

Table 2. Field Parameters and Mineralization.

Samples	**T**	**pH**	**EC µS/cm**	**TDS mg/L**
Ain aman Ibrakanan	14	7,51	742	562
Ain mimoun	17	7,38	751	569
Ain Zafir	15	7,22	702	544
Ain Djiment	19	7,91	801	610
Ain Silan	16	7,01	779	634
Ain Karma	17	7,34	806	717
Ain safa	15	7,58	902	684
Ain siar	21	6,80	2198	2301
Ain El Mitta	24	6,85	3360	2548
Ain elbikhr	23	6,75	2457	2579

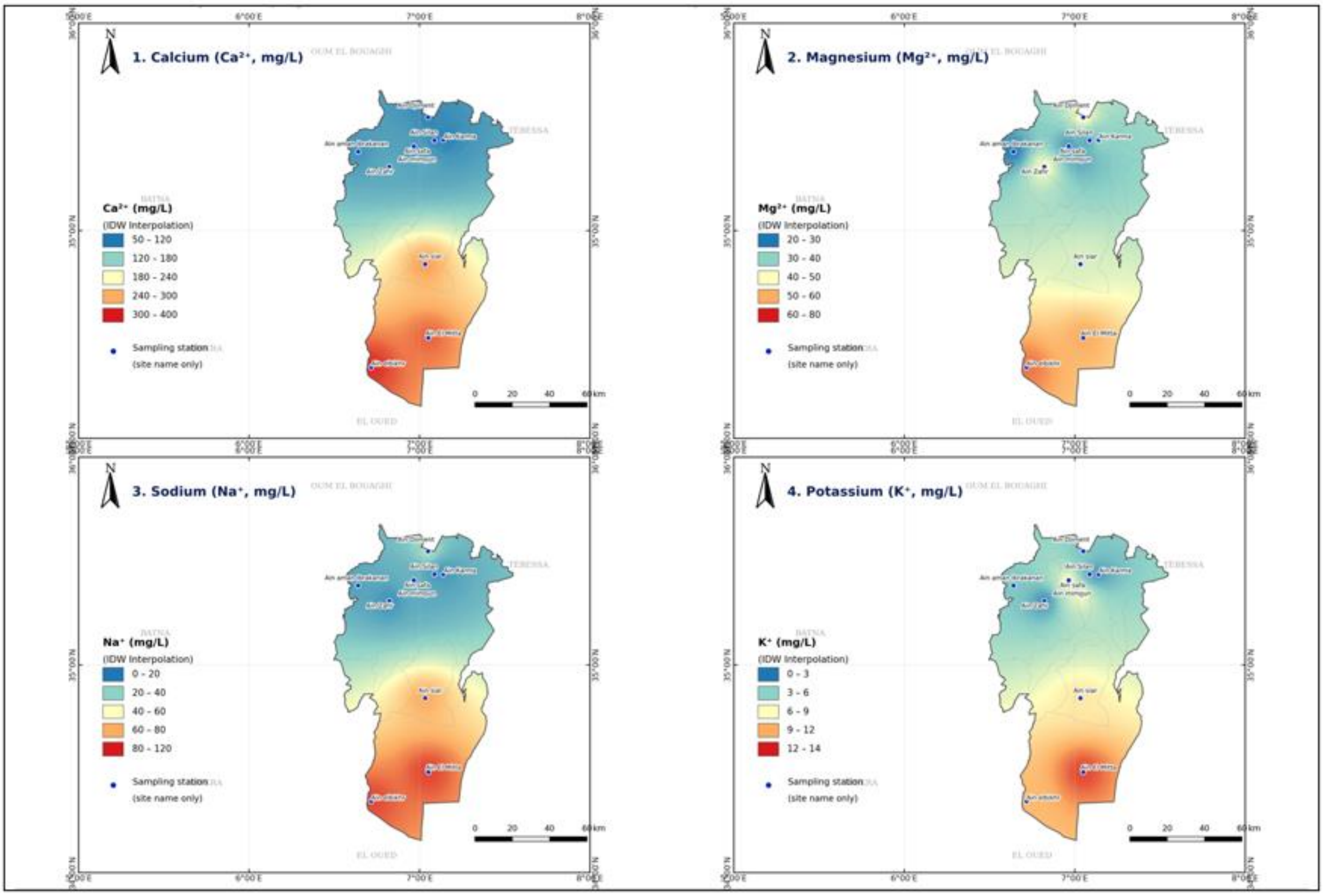


Figure 4. Spatial distribution of field parameters and mineralization indicators in Khenchela water samples: (1) temperature, (2) pH, (3) electrical conductivity and (4) TDS.

3.2. Major Elements

The hydrochemical composition of the sampled waters (Table 3) showed clear spatial variation in both major cations and anions across Khenchela Province. The analyzed cations included calcium, magnesium, sodium, and potassium, while the analyzed anions included bicarbonate, sulfate, chloride, and nitrate. Overall, the results indicate that the water chemistry is mainly controlled by carbonate dissolution, water–rock interaction, mineralization processes, and possible anthropogenic inputs, especially in the southern part of the study area.

Table 3. Chemical composition of sampled waters (mg/l).

Samples	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Cl^{-}	$So4^{--}$	$HCO3^{-}$	$NO3^{-}$
Ain aman Ibrakanan	76	21	14	3	36	92	244	25
Ain mimoun	87	25	20	7	52	110	231	18
Ain Zafir	98	51	8	1	13	55	339	11
Ain Djiment	62	52	39	3	62	288	288	9
Ain Silan	73	27	11	2	13	23	331	4
Ain Karma	53	37	9	1	15	22	339	16
Ain safa	97	28	16	7	55	140	244	29
Ain siar	322	45	90	8	209	350	270	33
Ain El Mitta	356	65	112	13	230	387	256	42
Ain elbikhr	389	71	111	10	245	401	312	55

3.2.1. Major Cations

Calcium was the dominant cation in most of the analyzed water samples. Calcium concentrations ranged from 53 mg/L at Ain Karma to 389 mg/L at Ain Elbikhr. The highest calcium values were recorded in the southern sites, especially Ain Siar, Ain El Mitta, and Ain Elbikhr. This increase may be related to the dissolution of carbonate minerals such as limestone and dolomite, which are common in the geological formations of the study area. The high calcium content also contributes to water hardness and reflects strong water–rock interaction.

Magnesium concentrations ranged from 21 mg/L at Ain Aman Ibrakanan to 71 mg/L at Ain Elbikhr. Similar to calcium, magnesium showed higher values in the more mineralized southern waters. The presence of magnesium may also be linked to carbonate rocks, particularly dolomitic formations. The combined dominance of calcium and magnesium indicates that alkaline-earth elements play an important role in the hydrochemical character of the sampled waters.

Sodium concentrations varied from 8 mg/L at Ain Zafir to 112 mg/L at Ain El Mitta. The highest sodium values were observed in Ain Siar, Ain El Mitta, and Ain Elbikhr, which also had the highest electrical conductivity and TDS values. This suggests stronger mineralization in the southern part of the province. Potassium was the least abundant cation, ranging from 1 mg/L to 13 mg/L. Its low concentration is expected because potassium is usually less mobile in groundwater and can be retained by clay minerals.

In general, the cationic composition shows the following dominant pattern:

$Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$

However, in the highly mineralized southern samples, sodium becomes more important, indicating a shift toward more evolved and saline water chemistry.

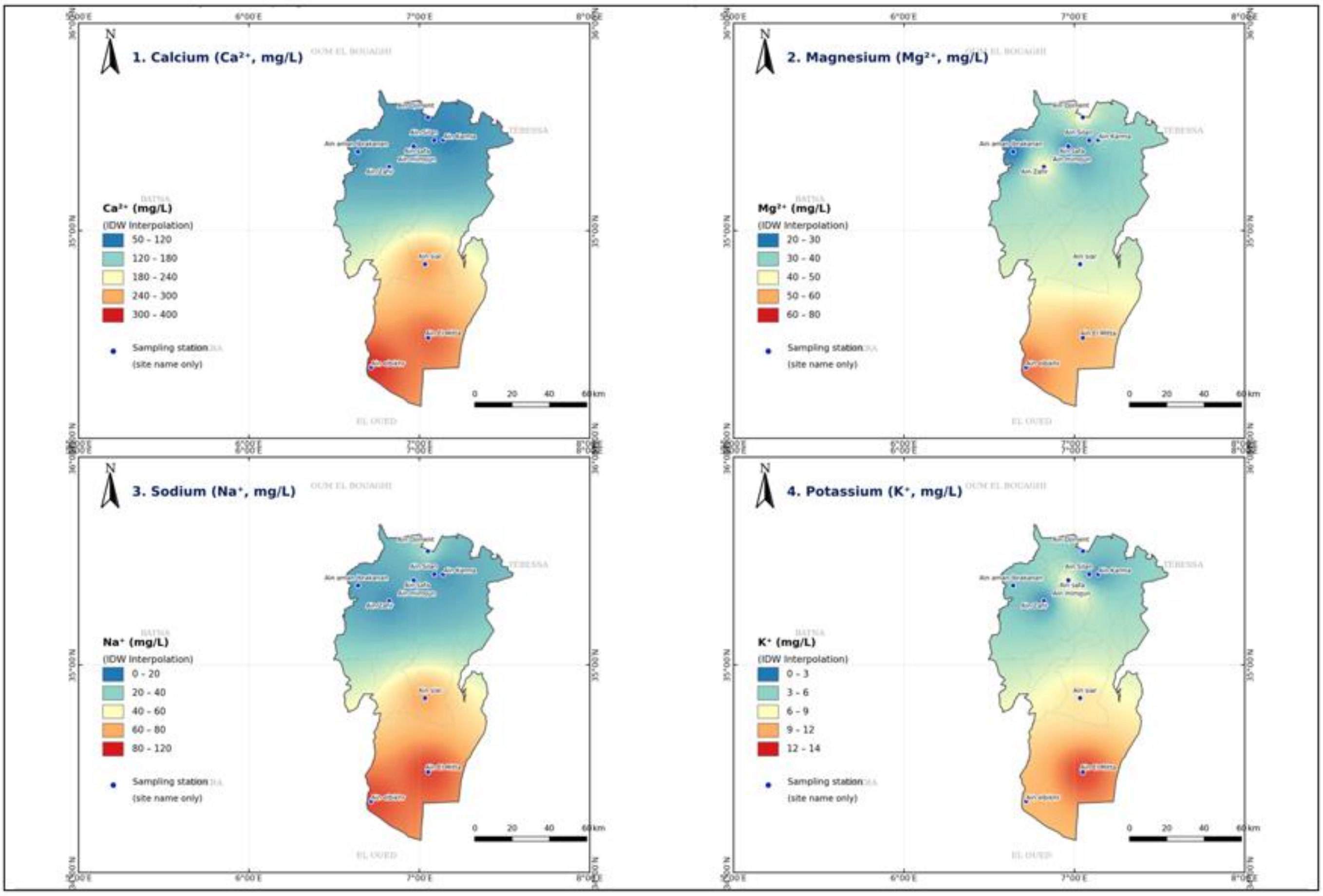


Figure 5. Site-wise variation of major cations in Khenchela water samples.

3.2.2. Major Anions

Bicarbonate was one of the dominant anions in the sampled waters, with concentrations ranging from 231 mg/L at Ain Mimoun to 339 mg/L at Ain Zafir and Ain Karma. The relatively high bicarbonate content reflects carbonate dissolution and confirms the influence of limestone, marl, and related geological formations in the study area. Bicarbonate-rich waters are generally associated with fresh recharge and carbonate aquifer systems.

Sulfate concentrations ranged from 22 mg/L at Ain Karma to 401 mg/L at Ain Elbikhr. The highest sulfate concentrations were recorded in the southern sites, especially Ain Siar, Ain El Mitta, and Ain Elbikhr. This enrichment may be associated with evaporitic minerals, sulfate-bearing formations, or increased evaporation under arid conditions. The rise in sulfate also corresponds with higher EC and TDS values, indicating stronger mineralization.

Chloride concentrations varied between 13 mg/L and 245 mg/L. The lowest values were observed at Ain Zafir and Ain Silan, while the highest value was recorded at Ain Elbikhr. Chloride enrichment in southern samples may reflect evaporation, longer residence time, or anthropogenic influence. Since chloride is a conservative ion, its increase is often a useful indicator of salinization processes.

Nitrate concentrations ranged from 4 mg/L at Ain Silan to 55 mg/L at Ain Elbikhr. The highest nitrate value exceeded the commonly used drinking-water guideline of 50 mg/L as NO_3^-, indicating possible contamination from agricultural activities, animal waste, or domestic wastewater. This result is important because nitrate contamination can affect drinking-water safety, especially for infants and vulnerable populations. However, repeated seasonal sampling is needed to confirm whether nitrate pollution is persistent or temporary.

Overall, the anionic composition shows that bicarbonate dominates in the less mineralized northern and central samples, while sulfate and chloride become more important in the southern samples. This pattern suggests a hydrochemical evolution from relatively fresh Ca–Mg–HCO_3 waters toward more mineralized waters enriched in SO_4^{2-} and Cl^-.

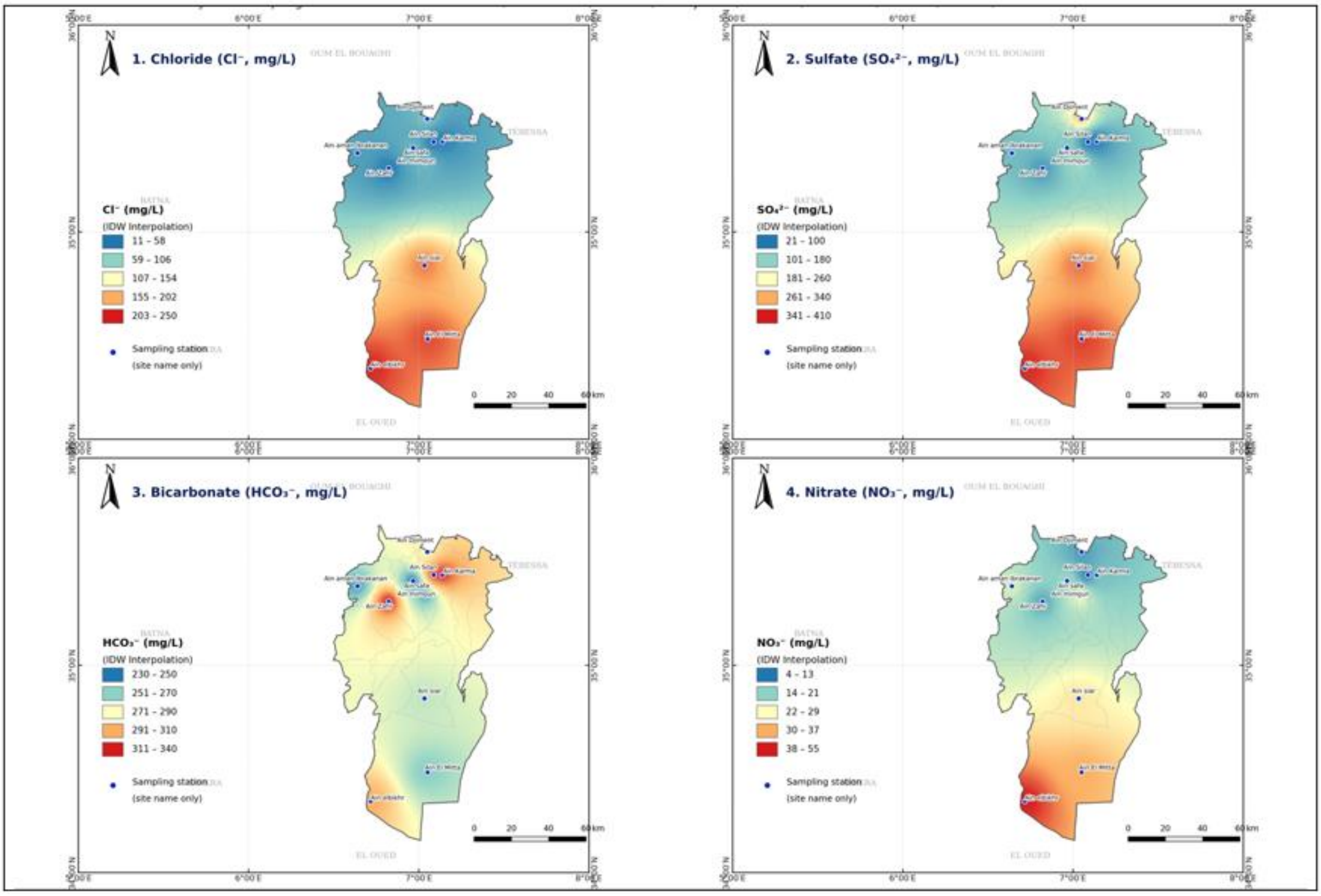


Figure 6. Site-wise variation of major anions in Khenchela water samples

3.4. Hydrochemical Facies

The Piper diagram classified the water samples into three main hydrochemical groups. The first group corresponds to Ca–Mg–HCO_3 facies and includes Ain Aman Ibrakanan, Ain Zafir, Ain Silan, and Ain Karma. This facies is typical of relatively fresh groundwater influenced by carbonate dissolution and shorter to moderate residence time. The second group includes mixed Ca–Mg–Cl and Ca–Mg–SO_4 facies represented by Ain Djiment, Ain Safa, and Ain Mimoun, indicating transitional water chemistry with increasing contribution from chloride and sulfate. The third group corresponds to Ca–Cl facies and includes Ain Siar, Ain El Mitta, and Ain Elbikhr, the southern samples with the highest mineralization.

The Schoeller–Berkaloff diagram confirmed similarities and differences in ionic profiles among the samples. The results reports that HCO_3^- generally dominated among anions, while Ca^{2+}, Mg^{2+}, and Na^+ were the principal cations. Calcium was dominant in most samples, whereas sodium became more important in the southern part of the study area. These profiles support the interpretation of spatially variable water–rock interaction, possible mixing, and progressive geochemical evolution along the north–south gradient.

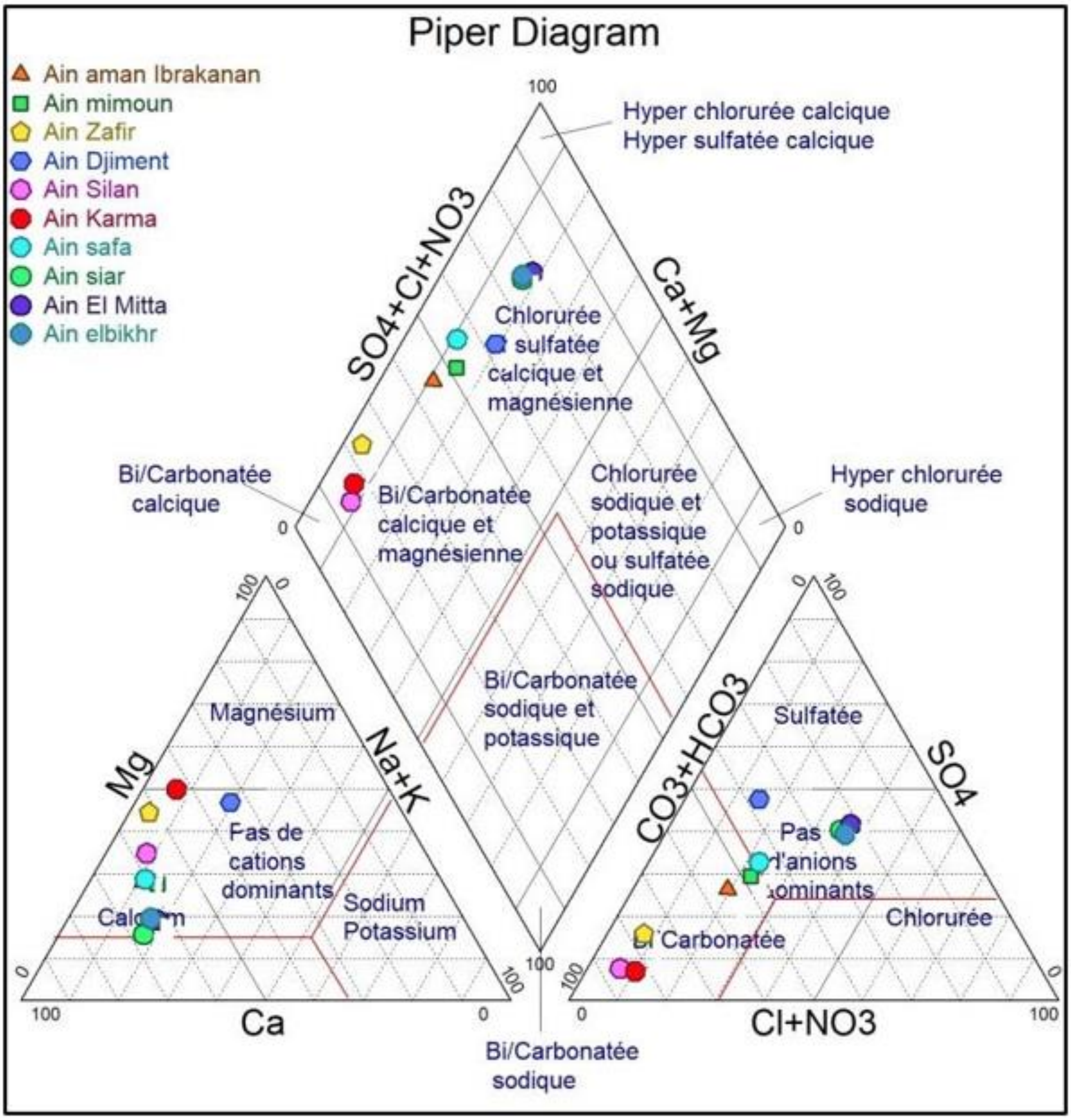


Figure 7. Piper diagram showing hydrochemical facies of the sampled waters in Khenchela Province.

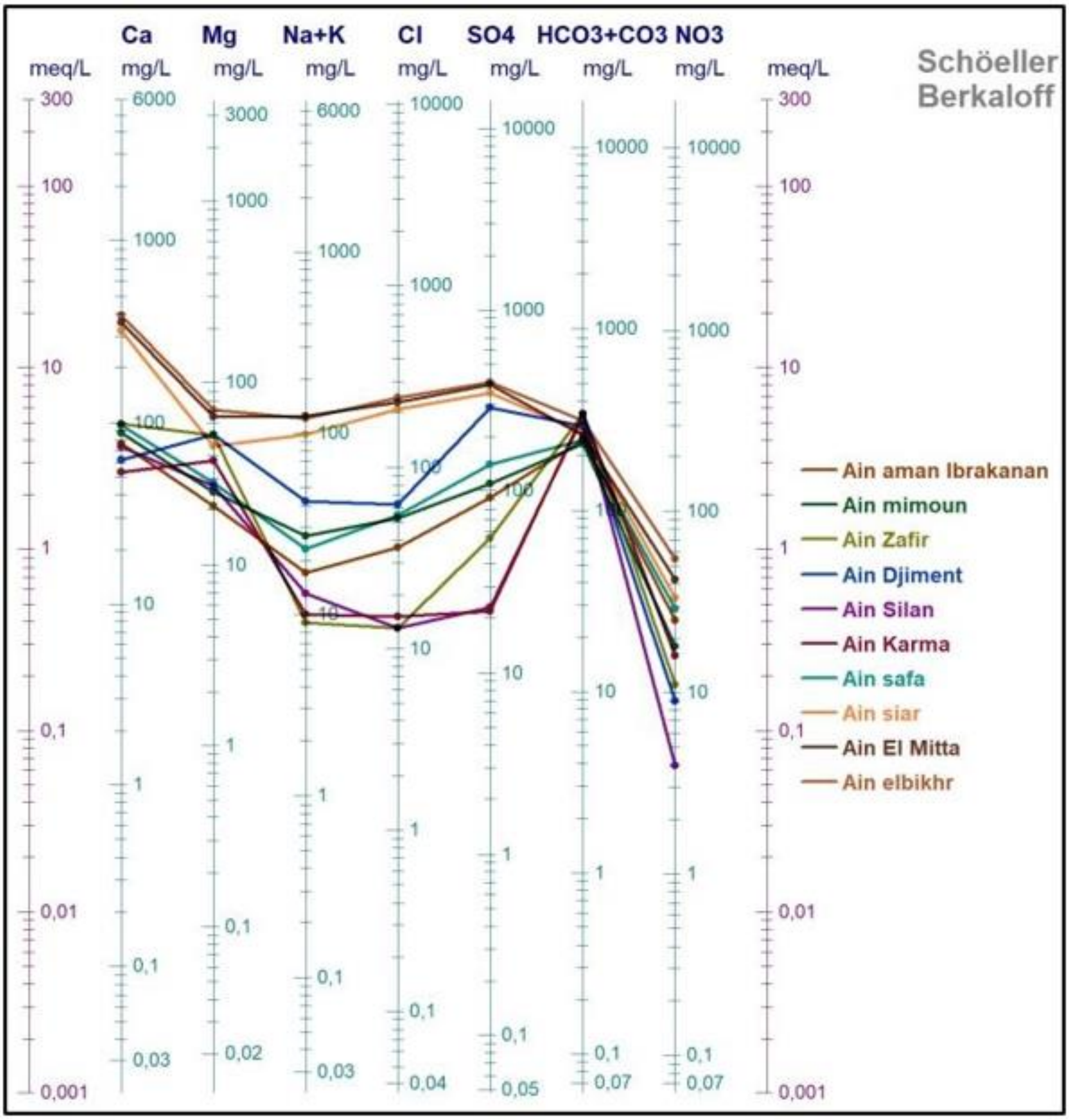


Figure 8. Schoeller–Berkaloff diagram of major-ion concentrations in water samples.

3.5. Irrigation Suitability

Wilcox diagram classification showed that a significant proportion of the groundwater samples was suitable for irrigation, with several samples falling in excellent to permissible categories. However, the southern samples showed higher salinity and sodium-related constraints. The results reports that approximately 70% of samples fell in low to medium–high salinity ranges, whereas the remaining 30% fell in very high salinity classes. These high-salinity waters may still be usable for salt-tolerant crops or under controlled irrigation conditions, but they require careful management of drainage, leaching fraction, soil texture, and crop selection.

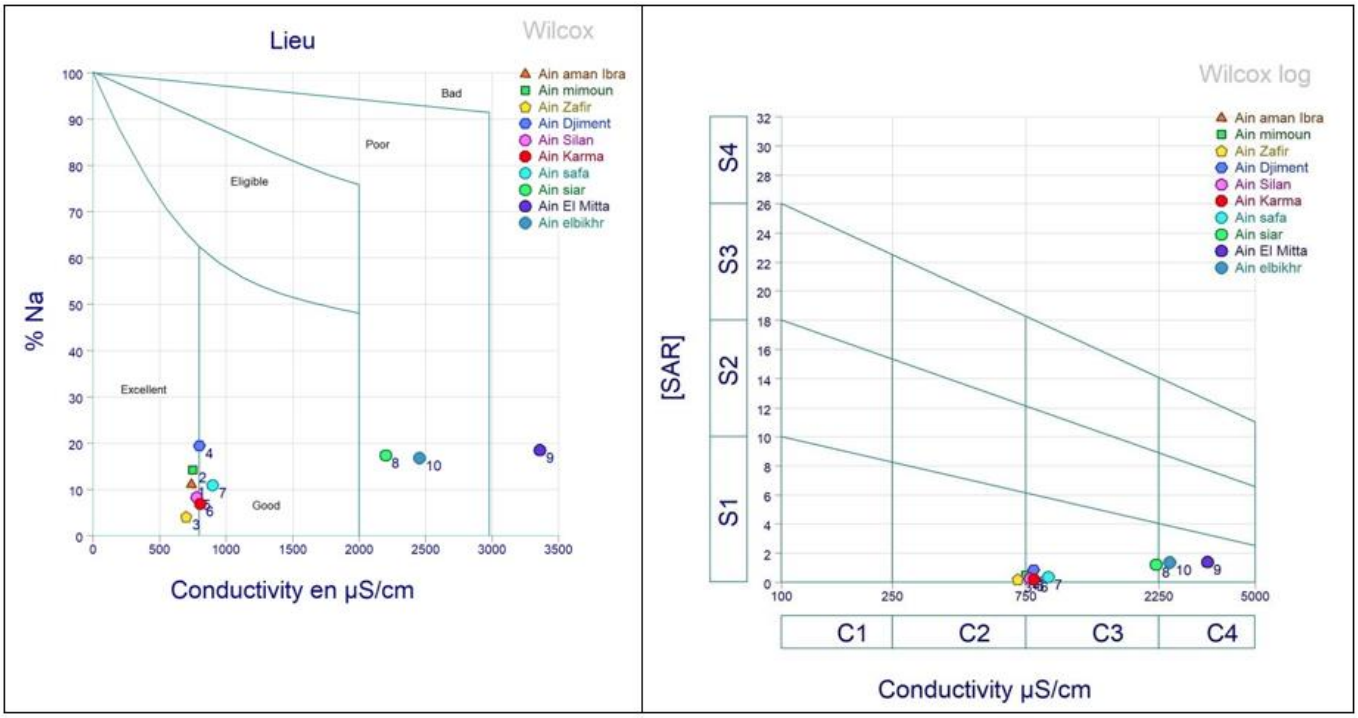


Figure 9. Wilcox diagram showing irrigation-water suitability of the Khenchela samples.

4. DISCUSSION

4.1. Spatial Hydrochemical Differentiation Across Khenchela Province

The results reveal a strong spatial contrast in water chemistry between northern/central and southern Khenchela. Northern and central sites generally show moderate mineralization, neutral to slightly alkaline pH, and Ca–Mg–HCO_3 or mixed facies. Southern sites show much higher EC, TDS, Ca^{2+}, Na^{+}, Cl^{-}, SO_4^{2-}, and NO_3^{-} concentrations. This pattern is consistent with the province's physiographic and climatic gradient, where increasing aridity, higher evaporation, reduced dilution, and potentially longer groundwater residence time can concentrate dissolved ions.

The hydrochemical evolution from Ca–Mg–HCO_3 water toward Ca–Cl and sulfate-rich compositions suggests that waters in the southern sector have undergone stronger geochemical modification. In carbonate-dominated aquifers, Ca^{2+}, Mg^{2+}, and HCO_3^{-} typically reflect dissolution of calcite and dolomite. As water moves through more arid environments or interacts with evaporitic minerals, sulfate and chloride may increase. Similar processes have been reported in semi-arid Algerian groundwater systems, where evaporation, water–rock interaction, lithological variability, and anthropogenic inputs control major-ion chemistry (Hamlat and Guidoum, 2018; Mansouri et al., 2022).

4.2. Mineralization, Salinity, and Drinking-Water Relevance

The TDS pattern is one of the most important findings. Water from the northern and central parts of the study area had TDS values between 544 and 717 mg/L, except Ain Safa at 684 mg/L and Ain Djiment at 610 mg/L, indicating moderate mineralization. In contrast, Ain Siar, Ain El Mitta, and Ain Elbikhr had TDS values above 2300 mg/L. Such brackish conditions may affect taste, domestic use, scaling potential, and suitability for sensitive consumers or uses. High EC and TDS also indicate limited dilution and greater dissolved-ion loads.

The southern salinity pattern may be explained by several interacting mechanisms. First, arid conditions increase evapoconcentration, especially where recharge is limited. Second, longer water residence time promotes water–rock interaction and mineral dissolution. Third, sulfate and chloride enrichment can reflect evaporitic formations or salt-bearing sediments. Fourth, agricultural return flow and domestic wastewater can add salts and nitrate. The dataset does not allow precise source apportionment, but the spatial co-occurrence of high TDS, chloride, sulfate, calcium, sodium, and nitrate in southern sites strongly indicates that these waters require closer monitoring before regular drinking use.

4.3. Nitrate Contamination and Anthropogenic Pressure

Nitrate is especially important because it can indicate agricultural or domestic contamination and has direct public-health relevance. In this study, nitrate ranged from 4 to 55 mg/L. The lowest value occurred at Ain Silan, while the highest occurred at Ain Elbikhr. The southern nitrate increase may be related to farming, fertilizer application, animal waste, septic tanks, or reduced dilution under arid conditions. The results also links higher nitrate levels in southern sites to farming and agricultural processes.

Ain Elbikhr exceeded the commonly used WHO guideline value of 50 mg/L for nitrate as NO_3^{-}. This result should be treated seriously, especially if the water is used for drinking by infants, pregnant women, or vulnerable groups. Nitrate contamination can also signal broader sanitary vulnerability of the water source. However, because the dataset represents a single sampling campaign, repeat sampling is essential before final risk classification. Seasonal variability may be important because nitrate concentrations can change after fertilizer application, rainfall events, recharge pulses, or drought periods.

4.4. Hydrochemical Facies and Water–Rock Interaction

The Piper and Schoeller–Berkaloff diagrams provide useful evidence of hydrochemical differentiation. Ca–Mg–HCO_3 facies in Ain Aman Ibrakanan, Ain Zafir, Ain Silan, and Ain Karma suggest relatively fresh recharge and carbonate-mineral influence. Mixed Ca–Mg–Cl/Ca–Mg–SO_4 facies in Ain Djiment, Ain Safa, and Ain Mimoun indicate transitional chemistry, possibly reflecting additional chloride and sulfate sources. Ca–Cl facies in Ain Siar, Ain El Mitta, and Ain Elbikhr points to greater mineralization and geochemical evolution.

This facies distribution can be interpreted as the result of changing lithological control, residence time, and aridity. Carbonate terrains commonly produce bicarbonate-rich waters, while evaporitic formations and concentration processes increase sulfate and chloride. In many semi-arid aquifers, the progression from bicarbonate facies to sulfate/chloride facies indicates longer flow paths, stronger evaporation, and greater interaction with soluble minerals. The Khenchela dataset fits this general model, although confirmation would require hydrogeological flow-path data, saturation-index modeling, isotope analysis, and more sampling points.

4.5. Irrigation Suitability and Agricultural Implications

The Wilcox diagram indicates that many sampled waters are suitable for irrigation, but southern samples require special caution due to salinity and sodicity hazards. High-salinity irrigation water can reduce crop water uptake by increasing osmotic stress. Sodium-rich water can degrade soil structure, reduce permeability, and affect infiltration, especially in clay-rich soils. These risks are particularly relevant in arid and semi-arid regions where evaporation is high and salts can accumulate in the root zone.

The practical implication is not that southern water resources must be abandoned, but that they should be managed carefully. Farmers using high-TDS or sodium-affected water should consider salt-tolerant crops, improved drainage, periodic leaching, blending with better-quality water where possible, and monitoring of soil electrical conductivity. Irrigation suitability should also be evaluated using sodium adsorption ratio, residual sodium carbonate, permeability index, magnesium hazard, and crop-specific tolerance thresholds. The results mention SAR values but does not provide the full calculated table in the extracted text; therefore, a revised manuscript should include all irrigation indices.

4.6. Climate-Related Interpretation and Limits of Attribution

The study is highly relevant to climate-change adaptation, but the available data do not prove a direct temporal impact of climate change on water chemistry. The water-quality dataset is spatial and single-season, while climate change is a long-term process requiring time-series analysis. Therefore, the most scientifically defensible interpretation is that the study documents current hydrochemical conditions across a climate-sensitive gradient and identifies water-quality constraints that may be exacerbated by warming, drought, declining recharge, and increased evaporation.

Climate change can reduce dilution, increase water temperature, intensify evaporation, alter recharge timing, and mobilize pollutants during extreme rainfall events (IPCC, 2022; UN-Water, 2019). In Khenchela, these mechanisms are plausible because the province already includes semi-arid and arid conditions, and Algeria has experienced drought and rainfall variability in recent decades (Sahnoune et al., 2013; Mohammed and Al-Amin, 2018). However, future research must combine repeated hydrochemical monitoring with climate records, groundwater-level data, and land-use information to quantify trends.

5. CONCLUSION

This study assessed the physicochemical and hydrochemical characteristics of 10 water resources in Khenchela Province, north-eastern Algeria, across a semi-arid to arid environmental gradient. The results show neutral to slightly alkaline water, moderate mineralization in northern and central sites, and substantially higher salinity in southern sites. TDS ranged from 544 to 2579 mg/L, EC from 702 to 3360 µS/cm, and nitrate from 4 to 55 mg/L. The highest salinity and nitrate values occurred in Ain Siar, Ain El Mitta, and Ain Elbikhr, indicating that southern water resources are more vulnerable to mineralization and possible anthropogenic contamination.

Hydrochemical classification identified Ca–Mg–HCO_3, mixed Ca–Mg–Cl/Ca–Mg–SO_4, and Ca–Cl facies. This facies evolution reflects spatial differences in lithology, water–rock interaction, residence time, and possibly evapoconcentration under arid conditions. Wilcox classification suggests that most samples are acceptable for irrigation, but the southern samples present salinity and sodicity constraints that require careful agricultural management.

The study provides a useful baseline for water-quality monitoring in Khenchela Province. Its main scientific value is the identification of spatial hydrochemical patterns across a climate-sensitive region. However, the study should not be presented as definitive proof of climate-change-driven water-quality degradation because the available water-quality data are single-season. Long-term monitoring, improved QA/QC, seasonal sampling, hydrogeological modeling, and stronger statistical analysis are required before causal climate impacts can be quantified.

The findings have direct implications for drinking-water surveillance, irrigation planning, and climate-adaptation policy in Khenchela Province. Southern sites with high TDS, sulfate, chloride, sodium, calcium, and nitrate require priority monitoring because they may pose constraints for drinking and irrigation. Ain Elbikhr requires particular attention because nitrate reached 55 mg/L, exceeding the commonly used WHO guideline for nitrate as NO_3^-. Before human consumption, such sources should be re-tested seasonally and assessed for microbiological quality.

For irrigation, southern waters should be used with caution. Soil salinity monitoring, crop selection, drainage management, and possible blending with lower-salinity water are recommended. Water managers should establish a hydrochemical monitoring network covering northern, central, and southern Khenchela to detect changes in salinity and nitrate over time. Integrating climate data, groundwater levels, land use, and chemical monitoring would support early warning of water-quality deterioration under drought and warming scenarios.

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