DOI 10.7343/as-2024-757

ACQUE SOTTERRANEE
Italian Journal of Groundwater
journal homepage: https://www.acquesotterranee.net/

2024-AS51-757: 33 - 41

Water quality caracterization of drean-Annaba aquifer (NE Algeria): using hydrochemical and isotopic tools

Caratterizzazione della qualità delle acque dell'acquifero di Drean-Annaba (NE Algeria) attraverso strumenti idrochimici ed isotopici

Abderahmane YAHI[a,b], **Larbi DJABRI[b]**, **Rania REMMANI[e]**, **Hamza BOUGUERRA[b]**, **Salah Eddine TACHI[b,f]**, **Fehdi CHEMSEDDINE[c]**, **Hadji RIHAB[d]**, **Naziha MOKADEM[a]**, **Younes HAMED[a]**, **Salem BOURI[a]**

[a] Gafsa University, Tunisia
[b] Laboratoire de ressource en eau et développement durable REDD, Badji Mokhtar-Annaba University, Algeria
e-mail: *yahi_yayo@yahoo.com; abderrahmane.yahi@univ-annaba.org*
[c] Laboratoire Eau & Environnement. Larbi Tebessi University, Tebessa, Algeria.
[d] Mohamed Lamine Debaghine Setif 2 University, Setif, Algeria.
[e] Applied Chemistry Laboratory, University of Biskra, Biskra, Algeria
[f] Water Sciences Research Laboratory, National Polytechnic School, Algiers 16200, Algeria.

ARTICLE INFO

Ricevuto/*Received*: 9 March 2024
Accettato/*Accepted*: 5 September 2024
Pubblicato online/*Published online*: 30 December 2024

Handling Editor:
Chiara Sbarbati

Citation:
Yahi, A., Djabri, L., Remmani, R., Bouguerra, H., Tachib, S.E., Chemseddine, F., Rihabd, H., Mokadem, N., Hamed, Y., Bouria, S. (2024). Water quality caracterization of drean-Annaba aquifer (NE Algeria): using hydrochemical and isotopic tools Acque Sotterranee - *Italian Journal of Groundwater*, 13(4), 33 - 41
https://doi.org/10.7343/as-2024-757

Correspondence to:
Abderahmane Yahi
abderrahmane.yahi@univ-annaba.org

Keywords: *Annaba, aquifer, quality, PCA, surface water, dryness, hydrochemical analysis, isotopic signatures.*

Parole chiave: Annaba, acquifero, qualità, PCA, acque superficiali, siccità, analisi idrochimiche, firme isotopiche .

Riassunto

Nell'acquifero alluvionale di Drean-Annaba, la qualità dell'acqua è spesso variabile. Le interazioni acqua-roccia non possono essere la causa principale dei cambiamenti osservati. Invece, le prolungate condizioni di siccità che hanno interessato il Paese negli ultimi due decenni hanno avuto un forte impatto sull'alterazione della qualità delle acque. Durante questo periodo, sono state rilevate anomalie nei tempi e nella distribuzione delle precipitazioni. I cambiamenti idrochimici nelle acque sotterranee e di superficie, compresi gli uadi, sono stati analizzati statisticamente utilizzando l'analisi delle componenti principali (PCA). Dall'esame dei cambiamenti cationici è emersa una notevole competizione tra terre alcaline e alcali. Sul versante anionico, sono stati osservati spostamenti dai cloruri ai solfati e potenzialmente ai bicarbonati. L'analisi isotopica ha rivelato una nuova fonte di salinità, la cui origine rimane poco chiara. La ricerca è stata condotta in un'area ristretta, e ciò è stato utile per dimostrare la relazione tra l'aridità e la qualità delle acque sia nel sistema acquifero che nelle acque superficiali. Questo studio utilizza un approccio olistico integrando analisi idrochimiche, mappatura della mineralizzazione e indagini isotopiche per esaminare le complesse dinamiche della salinità delle acque nel bacino di Seybouse. I risultati rivelano l'intricata interazione di fattori quali l'intrusione marina, l'evaporazione e le formazioni geologiche nel modellare i gradi di salinità delle varie sorgenti d'acqua. Le variazioni spaziali, evidenziate attraverso la mappatura della mineralizzazione e il rapporto Br/Cl, evidenziano l'influenza dei fattori idrodinamici e delle caratteristiche geologiche. L'identificazione di famiglie di salinità distinte in base alla conducibilità e alle firme isotopiche sottolinea i diversi meccanismi che contribuiscono alla salinizzazione delle acque: dalle variazioni di conducibilità indotte dall'evaporazione agli effetti del riscaldamento recente. Questa ricerca offre spunti fondamentali per la gestione delle acque sotterranee e aiuta a sviluppare strategie per mitigare i rischi di salinità, promuovendo un uso sostenibile dell'acqua nel bacino di Seybouse e in aree simili.

Abstract

In the Drean-Annaba alluvial aquifer, the water quality often fluctuates. Water-rock interactions cannot be the main cause of the observed changes, but the country's dryness during the last two decades has played a significant role in water quality changes. During this time, abnormalities in the timing and distribution of rainfall events were detected. As a result, hydrochemical changes in groundwater and surface water, such as wadis, have a predictable pattern. To demonstrate these chemical effects statistically, principal component analysis (PCA) tools and a nickel diagram were used. The findings corroborate seasonal fluctuations in water quality between 1999 and 2000. The competition between alkaline and alkaline earths can be seen from a cationic standpoint. On the other hand, there is a shift from chlorides to sulfates and possibly to bicarbonates from an anionic standpoint. The isotopic technique revealed neo-salinity whose source was unknown. The current study was conducted in a small area, which was beneficial for demonstrating the relationship between dryness and water quality in both the aquifer system and surface water. This study investigated the complex dynamics of water salinity within the Seybouse Basin, offering insights into its distribution, origins, and implications for groundwater management. Through a multidisciplinary approach encompassing hydrochemical analyses, mineralization mapping, and isotopic investigations, we elucidate significant patterns governing groundwater quality in the region. Our findings reveal the intricate interplay of factors such as marine intrusion, evaporation, and geological formations in shaping salinity levels across various water sources. The spatial variations highlighted through mineralization mapping and Br/Cl ratio analysis underscore the nuanced nature of marine intrusion along the coast, which is influenced by hydrodynamic factors and geological features. The identification of distinct salinity families based on conductivity and isotopic signatures underscores the diverse mechanisms contributing to water salinity, from evaporation-induced conductivity changes to the effects of recent heating. This research underscores the importance of interdisciplinary approaches in understanding groundwater systems and informs critical considerations for water resource management and sustainability efforts in the Seybouse basin and similar regions. By leveraging the insights gleaned from our study, stakeholders can develop targeted strategies to mitigate salinity-related risks and ensure the sustainable utilization of water resources.

Introduction

The Mediterranean countries face problems with water quantity and quality (Benoit & Comeau, 2005). Batchi et al., (2014) mapped vulnerability to marine intrusion of the coastal aquifer of Mnasra (Gharb coast, Morocco, North West). Maruja & Mania (1997) reported the presence of a stratified salinity profile in the Triffa plain (Morocco). In Spain, López-Dóriga & Jiménez (2020) observed the variation in sea level rise in coastal areas of Catalonia. In the same country, Stein et al., (2020) observed the effects of long-term saline groundwater pumping for desalination on the fresh–saline water interface, and the samples used to carry out their work were collected from littoral zones. In Tunisia, Zghibi et al., (2013), works about assessmed of seawater intrusion and nitrate in the Korba coastal plain of Cap-Bon (NE of Tunisia). Zenati et al., (2010); Ikhlef et al., (2024) showed that the presence of highly salted water lake Fetzara could influence the salinity of groundwater in the superficial aquifer of Annaba. The water flows from the lake toward the aquifer, passing through Wadi Meboudja. Debieche (2002) underlines the salinity of Annaba deep aquifer waters, although their origin is not well defined. Aoun Sebaiti (2010) demonstrated the occurrence of seawater intrusion through the South–North oriented periphery. Djabri et al., (2014) highlighted the morphological factors influencing marine intrusion. Recently, Benchaib et al., (2018) used a hydrochemical tool to highlight the origins of the salinity of shallow water in the Annaba Plain.

According to physicochemical investigations of the Wadi-Lake-Sea aquifer system, this work presents the parameters that control groundwater salinity. Detailed data analysis reveals various factors affecting salinity levels, which are critical for understanding the hydrogeological dynamics of the region. By identifying these parameters, the study enables the modeling of the main aquifers, providing insights into the processes contributing to water salinity. The distribution of salinity across different hydrogeological zones is also explained, offering a comprehensive understanding of how natural and anthropogenic factors influence groundwater quality. This knowledge is essential for developing effective water management strategies and ensuring sustainable utilization of groundwater resources in the area.

Mediterranean countries face significant challenges concerning both water quantity and quality (Benoit & Comeau, 2005). Noteworthy studies by Batchi et al., (2014) have investigated the vulnerability mapping of the coastal aquifer of Mnasra along the Gharb coast of Morocco in the northwest. Similarly, Maruja & Mania (1997), along with El Mandour (1998), delineated the presence of a stratified salinity profile in the Triffa plain of Morocco.

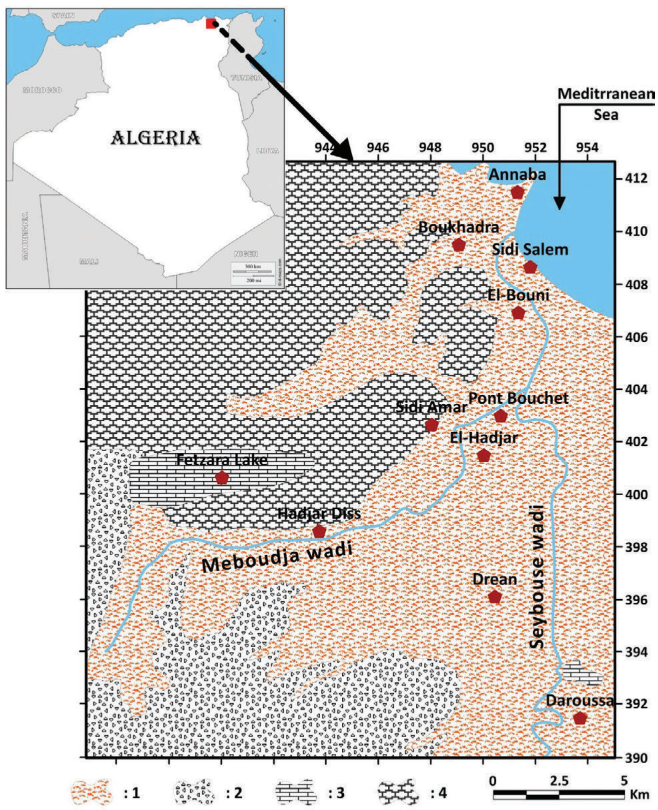
In Spain, López-Dóriga & Jiménez (2020) observed fluctuations in sea level rise along the coastal areas of Catalonia. Concurrently, Stein et al., (2020) investigated the long-term impacts of saline groundwater extraction for desalination on the fresh-saline water interface, with sample collection conducted in littoral zones. In Tunisia, Zghibi et al., (2013). conducted assessments of seawater intrusion and nitrate levels in the Korba coastal plain of Cap-Bon in the northeast. Similarly, in Algeria, Djabri's seminal works of Djabri (1987; 1996; 2008) contrasted water salinity in two aquifers with varying climates and geological compositions: the alluvial aquifer of Tebessa in the semiarid zone and the superficial aquifer of Annaba-Bouchegouf-Guelma in the Mediterranean area.

Geographic location and geological framework of the study area

The geological characteristics of the study area are shown in Figure 1. It is bounded by the Mediterranean Sea to the North, Drean town to the South, Oued Mafragh to the East and Fetzara Lake to the West. The plain is supplied in the West by the stream water coming from the Edough Mount and in the South by upstream supplies.

Studies carried out in the region show that there are two types of formations: metamorphic and sedimentary (Fig. 1). The geological formations are from the Paleozoic to the Quaternary Period.

The Dunar and alluvial formations characterize the Quaternary. We distinguished (i) the old Quaternary (high terraces) containing the alluvial aquifer, which is mostly composed of sands, clays, and gravels. (ii) the recent Quaternary, corresponding to low and medium terraces and



Legends: 1: Quaternary undifferentiated (clay, sand, silt, etc.); 2: high alluvial terraces; 3: Numidian sandstone and clay; 4: metamorphic rock formations (micaschist, gneiss and marble).

Fig. 1 - Geographic location and geological characteristics of the study area.

Fig. 1 - Ubicazione geografica e caratteristiche geologiche dell'area di studio.

 DOI 10.7343/as-2024-757

(iii) the current Quaternary, consisting primarily of sands and gravels (Djabri et al., 2014).

Research conducted in the region identifies two main formations: metamorphic and sedimentary (Fig. 2). These geological structures range from the Paleozoic to the Quaternary Period. The Quaternary formations include dunar and alluvial deposits, with high terraces representing old Quaternary layers that contain alluvial aquifers mainly composed of sands, clays, and gravels. In contrast, recent and current Quaternary formations are predominantly made up of sands and gravels, with recent Quaternary deposits marked by low and medium terraces (Joleaud, 1936 & Vila, 1980).

Local climate

The average annual precipitation in the whole Seybouse Basin varied between 400 mm and 700 mm, with a monthly maximum ranging between 90 and 120 mm in December and January. As far as the temperatures are concerned, the extremes are observed in winter and summer. The minima are observed in December-January (less than 10°C), and the maxima are observed in July or August (between 25°C and 30°C). The contrast between winter and summer is highly important far from the Mediterranean Sea. The potential evapotranspiration is closely linked to the temperature. The annual average evapotranspiration ranges from 1000 to 2000 mm. The Seybouse climate is Mediterranean but changes from the North to the South. Along the coast, the annual rainfall ranges between 700 and 900 mm.

Hydrogeology

The disposal of the geological formations shows the presence of two aquifers (Fig. 2), connected mainly by the Meboudja wadi, the shallow aquifer of Annaba and the alluvial aquifer of high terraces.

The piezometric map (Fig. 3) shows, in general, that the flow direction follows the topographic form of the studied zone in the south-north direction. However, at the Daghoussa elevation, we notice a change in the flow direction, which is from the sea toward the continent (Zenati et al., 2010).

This propensity, which is located in the northern section of the chart, implies that the aquifer may be supplied by the

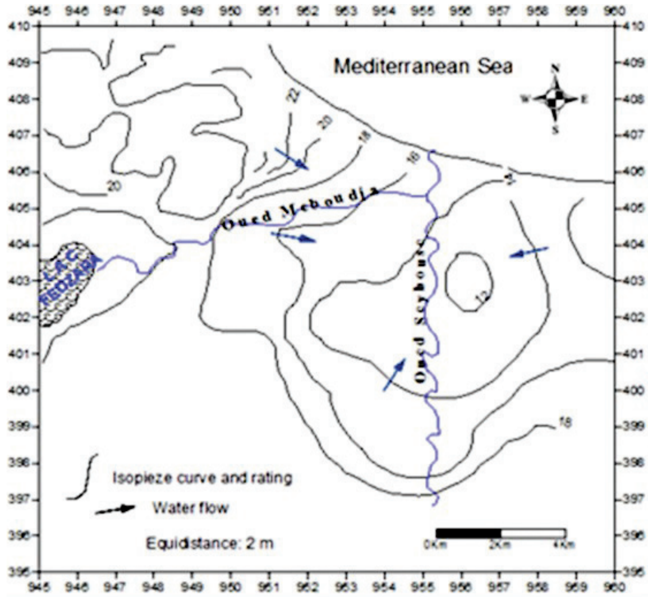
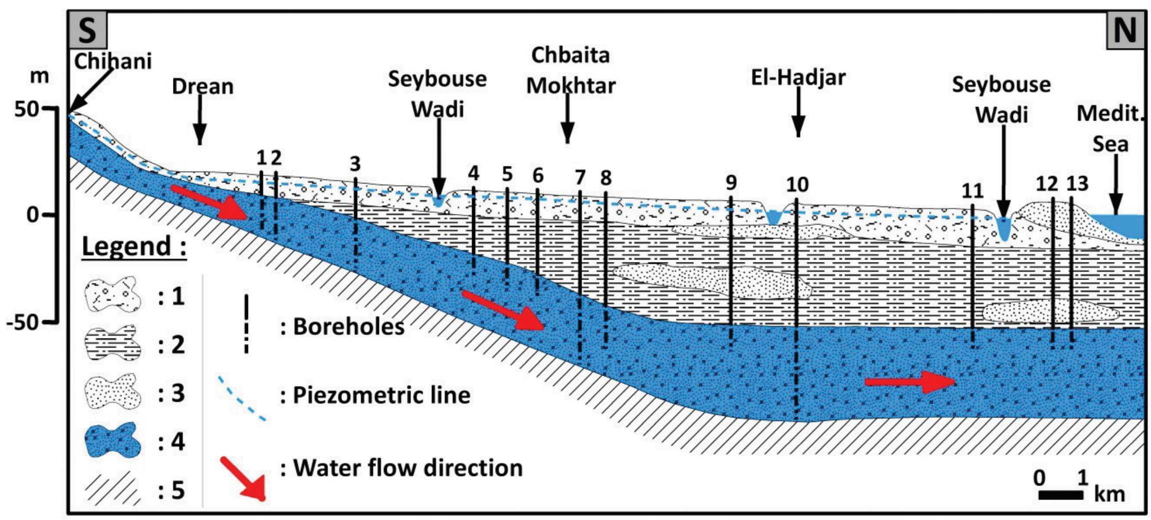


Fig. 3 - Piezometric map of the superficial aquifer of Annaba (2019).

Fig. 3 - Carta della piezometria dell'acquifero superficiale di Annaba (2019).



Legends: 1. Clayey Sand (shallow aquifer), 2. Detritus Clay from the Plio-Quaternary Period, 3. Sand, 4. Gravel and Pebbles (deep aquifer), 5. Numidian Clay.

Fig. 2 - Aquifer arrangements and a cross section through the plain of the Annaba Zone.

Fig. 2 - Disposizione degli acquiferi e sezione trasversale della piana della Zona di Annaba.

sea. Furthermore, the presence of depression emphasizes the impact of pumping, which can aid in the progression of the saltwater wedge. The alluvial aquifer of the high terraces is the second aquifer (NHT).

The piezometric map shows the existence of interactions between the various elements of the lake-wadi-aquifer system (Aoun Sebaiti, 2010). An excessive number of pumping wells (more than 150) in the studied zone affects the two aquifers (shallow and deep) and disturbs the water flow direction. This results in an imbalance of the salted water and fresh water interface. This deteriorates the quality of the water (increasing the salinity). The water chemistry indicates the state of the aquifer according to other constituent parameters of the system.

Material and methods

To achieve the goal of our study, 148 water samples were collected, each month during 8 months between September 2019 and May, 2020, from the study area. The extraction concerns the domestic wells of the unconfined groundwater located in Annaba-Drean zone (65 samples), the groundwater surrounding Fetzara lake (42 samples), the Seybouse (25 samples) and the Meboudja stream (16 samples).

The physicochemical parameters (pH, T°C and conductivity) were measured in situ using a WTW multiparameter device (Multilinear P3 PH/LF-SET) and a SEBA KLL-type probe for the measurement of the piezometric level. Chemical analysis was carried out by flame atomic absorption (PerkinElmer 11005) for cations. Anions and trace elements were measured using a spectrophotometer (PhotoLab WTW).

To measure the isotope ratios, we first converted the collected water samples into vapor, either by equilibrating them with a known gas or using another method. We determined the ratios of Oxygen-18 ($\delta^{18}O$) and Deuterium ($\delta^{2}H$) using mass spectrometry, reporting these values as per mil (‰) deviations from the Vienna Standard Mean Ocean Water (VSMOW).

Results

We were able to highlight the cause-and-effect links that exist between the sea and the aquifer, between the lake and the aquifer, and between the wadis and the aquifer through the chemical tests we conducted. The following tools will be built based on the representations: principal component analysis, Piper diagrams, and Tickle diagrams.

Principals Component Analysis

In our study, Principal Component Analysis (PCA) was employed to decipher the underlying factors affecting water quality in the Drean-Annaba aquifer. The PCA encompassed four seasonal phases, analyzing a total of 148 water samples for nine chemical elements. The first two principal components (F1 and F2) accounted for 68% of the total variance, indicating their significance in explaining the data's variability.

The PCA biplot (Fig. 4) illustrates a clear distinction between water samples with high mineral content and those with lower mineral concentrations along the F1 axis. This opposition is critical for understanding the primary sources of mineralization within the aquifer system. The F1 axis, which explains the majority of the variance, predominantly captures the influence of major ions such as sodium and chloride, indicative of marine intrusion and evaporation processes. In contrast, the F2 axis, which explains a smaller portion of the variance, highlights the seasonal variability and contributions from anthropogenic sources.

Further, the PCA loadings reveal that high levels of calcium and sulfate are associated with specific geological formations, suggesting gypsum dissolution as a significant process. The presence of bicarbonates correlates with samples influenced by surface water interaction, particularly in areas with extensive agricultural activities.

By visualizing the PCA results, we have enhanced the interpretation of hydrochemical data, providing a robust framework for identifying and quantifying the processes contributing to groundwater salinity. This improved illustration aids in distinguishing between natural and anthropogenic influences on water quality, thereby facilitating more effective groundwater management strategies.

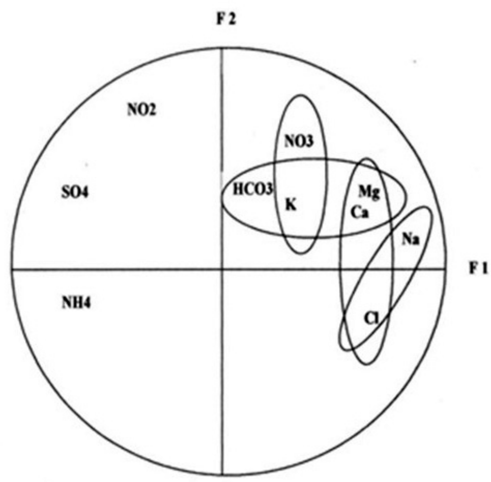


Fig. 4 - PCA circle of the superficial aquifer.

Fig. 4 - Cerchio della PCA per l'acquifero superficiale.

Piper diagrams

The samples are concentrated on the sodic and chlorinated poles, indicating that sodic chlorinated facies dominate, as shown by the Piper diagram of the shallow aquifer of Annaba (Fig. 5a). Some samples include high levels of calcium and chlorides, indicating the presence of a second calcic chlorinated water type. Three kinds of water appear to occur in the Fetzara Lake aquifer (Fig. 5b): water rich in chlorides and calcium (calcic chlorinated type); water rich in sulfates and calcium (calcic sulfate type); and water rich in bicarbonates and calcium (hydrocarbonated calcic type). Habes (2013) linked the occurrence of these three facies to the lake's supply sources (Oued Mellah, Oued El Hout, and Oued Zied).

 DOI 10.7343/as-2024-757

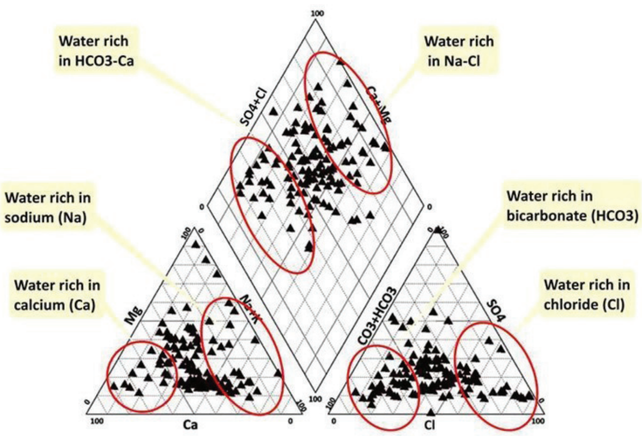


Fig. 5a - Piper diagram of the superficial aquifer of Annaba.

Fig. 5a - Diagramma di Piper per l'acquifero superficiale di Annaba.

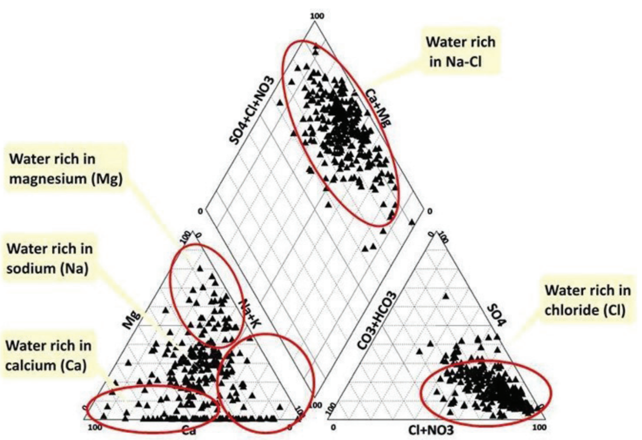


Fig. 5b - Piper diagram of the superficial aquifer of Fetzara Lake.

Fig. 5b - Diagramma di Piper per l'acquifero superficiale di Fetzara Lake.

On two major poles, the Piper diagrams demonstrate a variation in the chemical facies of dispersed water:

1. A saliferous pole characterizing the sodic chlorinated facies in deep geological layers, produced either by marine water or by the presence of evaporated formations;
2. A gypsiferous pole at the origin of the calcic sulphated facies, generated by the dissolution of gypsiferous formations;
3. A carbonated pole at the origin of the calcic bicarbonate facies, generated by the scrubbing and dissolution of meta.

The presence of two poles is shown by interpreting the Piper diagrams. This allows us to investigate the source of these components as well as their role in the rise in water salinity.

Mineralization map

To study the distribution and origins of the mineralization, we calculated and developed a TDS map (Fig. 6).

The observation of the mineralization map shows an alternation between strongly mineralized zones and zones of less mineralization. The zones of high mineralization are located on the coast of Annaba (6000 mg/L) and to the southeast of El Hadjar (7000 mg/L). These two zones are characterized by the presence of several wells and drillings during exploitation.

In the Annaba area, the Saline drilling battery is located near the sea; the overexploitation of these wells and drillings are at the origin of the imbalance of the freshwater-salt water interface.

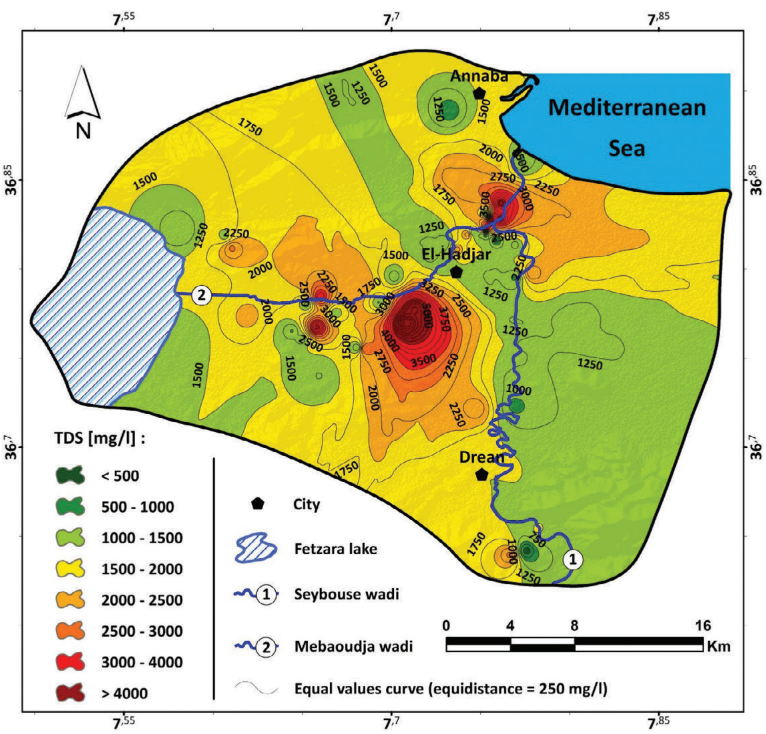


Fig. 6 - TDS variation map in the Annaba Plain.

Fig. 6 - Mappa delle variazioni di TDS nella piana di Annaba.

In the southeastern region of El Hadjar, the observed mineralization was facilitated by the tectonics that affected this area and contributed to the marine water flows, (Khaled-Khodja, et al., 2014). We can say that in Annaba Bay, marine intrusion seems to be evident; in the eastern zone, marine intrusion is caused by natural factors such as the elevation of Daroussa and Oued Mafragh. This could favor saltwater penetration toward the far zones.

To analyze the distribution and origins of mineralization, we constructed a total dissolved solids (TDS) map (Fig. 6).

Origins of water salinity

A Br/Cl ratio greater than certain values constitutes an intangible indicator of the marine origin of the observed salinity.

Variations in the Br/Cl ratio in the east-west direction

The calculated values of the Br/Cl ratio show that the latter exceeds 1.5‰ for the majority of the structures analyzed. This seems to indicate marine intrusion, which could be very evident, especially in the region of Sidi M'barek. In addition, the drilling in the Besbes region, which is located 25 km from the coast, has a ratio of 16.3‰, which indicates that marine intrusion does not occur in the same way along the coast.

Spatial variations in the Br/Cl ratio

Figure 7 shows the distribution of the Br/Cl ratio as a function of distance. We can observe two contradictory phenomena:

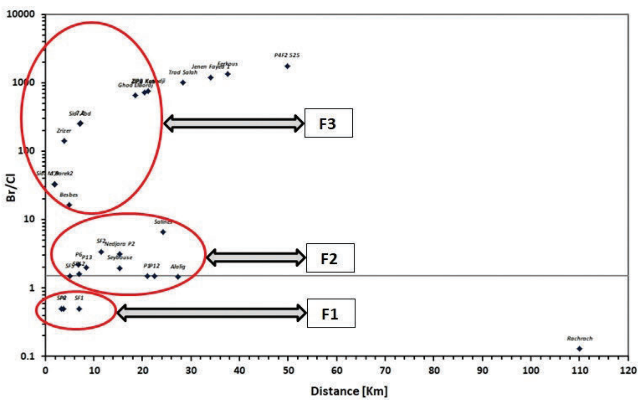


Fig. 7 - Variation in the Br/Cl ratio as a function of the distance from the sea.

Fig. 7 - Variazione del rapporto Br/Cl in funzione della distanza dal mare.

For the samples where the Br/Cl ratio changed with distance, both trends were the same. This is the case for water sampled at Sidi M'Barek, which is characterized by proximity to the sea and a high Br/Cl ratio of 33.3‰.

A divergence between the two parameters, in the case of the water collected from the Rachrach factory, which is located approximately 5 kilometers from the sea where the Br/Cl is approximately 0.13‰, does not indicate a marine influence. On the other hand, the water samples collected at Besbes, 25 km from the coast, indicate a ratio of approximately 16.3‰, showing the impact of the sea on water salinity. The values obtained could also be generated by sea spray or aerosols. To identify the different origins of the ratios and remove these ambiguities, we produced a graph of Br/Cl vs Cl meq/L (Fig. 8).

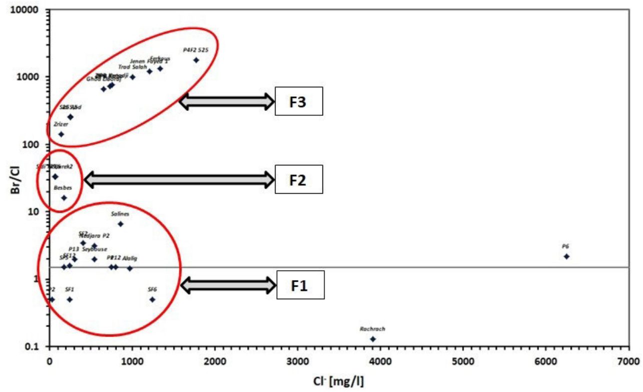


Fig. 8 - Variation in Br/Cl vs Cl mg/L.

Fig. 8 - Variazione in Br/Cl vs Cl mg/L.

Figure 8 shows three families of water with variable salinities:

The first includes 7 samples characterized by a Br/Cl ratio less than 1.5‰. In this case, the salinity could be due to the geological formations crossing by the water during its flow.

The second one, where the ratio is equal to or slightly greater than 1.5‰. Seven samples were also included. In this case, the salinity is generated by sea spray or aerosols.

The third sample, with 12 samples, is characterized by a Br/Cl ratio greater than 1.5‰. Similarly, the chloride concentrations remain high but lower than those of sea water. This could be explained by the mixing of freshwater and seawater. This suggests the presence of a marine intrusion.

The previous graphs show that marine intrusions are present in the region but do not occur in the same way along the coast. It remains influenced by hydrodynamic factors, mainly transmissivity. In fact, the map produced by Hani (2003) shows that this parameter remains high, reaching 4 to $5x10^{-3}$ m²/s on both sides of the Seybouse and Mafragh Oueds. Elsewhere, the values remain low. The elevation of Daghoussa acts as a brake on exchanges between fresh water and sea water. This generates preferential directions for the flows, resulting in the described marine contamination.

Marine intrusion, emphasized by hydrochemical tools, can be caused either by the effects of climate change, which is quite recent (less than 20 years), or by overexploitation generated by the industrial development of the region, which dates back to the end of the 1960s (creation of the steel complex in 1967). To answer these questions, the use of an isotopic tool is necessary.

Isotopic analysis

Tab. 1 - Results of isotope analyses and locations of the sampled points and their geological setting.

Tab. 1 - Risultati delle analisi isotopiche e ubicazione dei punti campionati e loro inquadramento geologico.

Sampling points	Waters origin	Aquifers	Conductivity µS/cm	$\delta^{18}O$ (‰) Smow	$\delta^{2}H$ (‰) Smow
Wells before Chihani	P W		1708	-5.85	-39.3
Wells at Chihani	P W	AS ASA	1678	-5.31	-35.2
Seybouse in Drean	O Wa		1724	-5.75	-30.1
Discharge ECOTEC	R		3630	-4.21	-27.6
Seybouse in Drean	O Wa		1872	-5.71	-38.7
Seybouse in Chbaïta	O Wa		1779	-6.0	-36.6
Seybouse in El-Hadjar	O Wa	GN NS	1736	-5.63	-34.5
Seybouse in Oasis	O Wa		1980	-5.55	-37.7
Meboudja Pont Bouchet	O Wa		2100	-2.24	-22.1
Seybouse in Sidi Salem	O Wa		6500	-4.54	-29.0
Discharge S.N. METAL	Ri Id		6250	-3.48	-23.0
Discharge ORELAIT	Ri Id		1020	-6.5	-42.6
Meboudja in Hadjar Diss	O Wa		2730	+0.12	-18.3
1st discharge S.N.S	R1		1350	-5.6	-50.3
2nd discharge S.N.S	Ri Id		2120	-1.82	-13.2
Meboudja after S.N.S	O Wa		2120	-2.26	-20.6
Industrial Zone - Sidi Amar	Ri Id	C	1588	-3.24	-20.18

Legend:

Aquifer types
AS: Alluvial Superficial Aquifer
C: Cipolin
CAL: Limestone
AR: Clay
T: Trias
GN: Numidiqn sandstone

Waters origin
O Wa: Wadi
Ri: Industrial discharge
Ru: Urbain discharge
P W: Wells

Contribution of isotope analyses

Relationship between Oxygen-18 and Conductivity

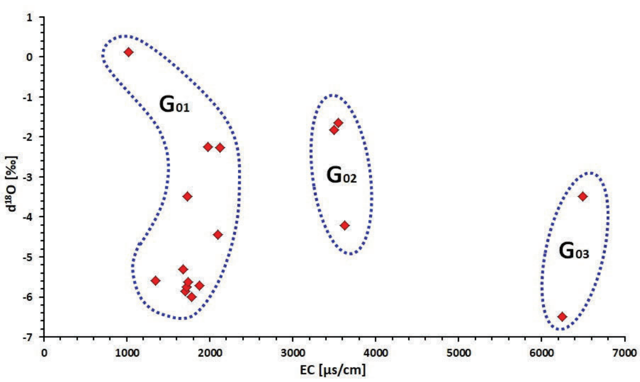


Fig. 9 - Relationship between Oxygen 18 (^{18}O) and Conductivity.

Fig. 9 - Relazione tra Ossigeno 18 (^{18}O) e Conducibilità.

The first family (G_{01}) is characterized by a relatively low conductivity, oscillating between 1000 and 2000 µs/cm. The oxygen-18 values range between –7‰ and +1‰. These waters belong to wells and wadis. This shows the influence of evaporation on the conductivity.

In the second family (G_{02}), the conductivity reaches 3000 µs/cm, and the oxygen-18 values are significant and vary from -2‰ to + 1‰, indicating recent heated waters.

The third family (G_{03}) is characterized by a high conductivity of up to 7000 µs/cm. The oxygen-18 exhibits values between -5‰ and -3‰. This family is characterized by heated and evaporated waters. The deuterium-oxygen 18 graph (Fig. 9) confirmed the presence of two families.

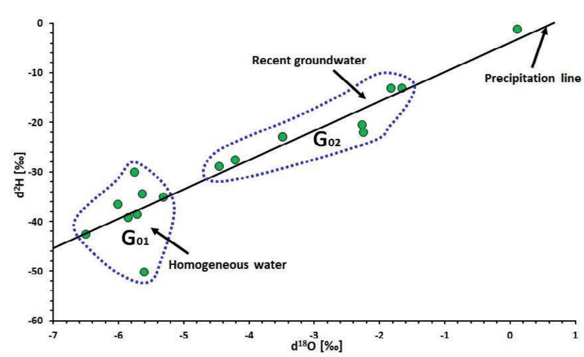


Fig. 10 - Deuterium vs Oxygen 18.

Fig. 10 - Deuterio vs Ossigeno 18.

Evaporated waters that align with the straight line of low slope; the homogeneous waters warmed, forming a cloud of points. The oxygen-18 is stable.

The isotopic tool reveals a neo-salinity where the origin is not well known. This is why the results of chemical analyses used.

Conclusions

This study, conducted in the region characterized by a Mediterranean climate, provides a detailed analysis of the water salinity dynamics within the Seybouse Basin. Over the last decade, an increase in temperature has been observed, contributing significantly to the salinity of the groundwater, particularly in the shallow aquifer. The study highlights seasonal variations in water quality, where sodium and chloride dominate in the first season, and calcium and carbonate prevail in the second season. This variation is attributed to the heterogeneity of geological formations influencing the deep aquifer.

The cartographic representations of different geochemical parameters illustrate the natural variability of groundwater quality, influenced by the geological and hydrogeological context. These maps are instrumental in identifying salinity anomalies across the region. The interplay between the sea, lake, wadi, and aquifer systems is evident from the chemical analyses conducted. The PCA, Piper diagrams, and Tickle diagrams used in this study effectively demonstrate the cause-and-effect relationships between these systems.

Principal Component Analysis (PCA) identified significant seasonal variations in the chemical composition of the water, accounting for 68% of the total data variability. The Piper diagrams revealed the dominance of sodic-chlorinated facies in the shallow aquifer of Annaba and three distinct water types in the Fetzara Lake aquifer: calcic-chlorinated, calcic-sulfated, and hydrocarbonated-calcic. These findings underscore the influence of different water sources, such as Oued Mellah, Oued El Hout, and Oued Zied, on the lake's water chemistry.

The TDS map indicated alternating zones of high and low mineralization, with significant salinity observed along the Annaba coast and southeast of El Hadjar. Overexploitation of wells near the sea and tectonic activities in El Hadjar were identified as major contributors to the salinity. The Br/Cl ratio analysis further confirmed marine intrusion, with spatial variations highlighting the impact of hydrodynamic factors and geological features on salinity distribution.

Isotopic analysis differentiated three families of water based on conductivity and oxygen-18 values, revealing the effects of evaporation and recent heating on water quality. The deuterium-oxygen 18 relationship supported these findings, showing stable oxygen-18 levels despite variations in other parameters.

This study provides a comprehensive understanding of the factors influencing water salinity in the Seybouse Basin. The findings highlight the critical role of interdisciplinary approaches in groundwater management, combining hydrochemical, isotopic, and geological analyses to address salinity issues. These insights are essential for developing targeted strategies to mitigate salinity-related risks and ensure sustainable water resource utilization in the Seybouse Basin and similar regions.

Acknowledgements

The authors would like to extend their sincere gratitude to Rania Remmani and Salah Eddine Tachi for their invaluable support and contributions throughout the course of this research. Their expertise and insights have significantly enriched the study and have been instrumental in achieving the outcomes presented.

Furthermore, we acknowledge the Badji Mokhtar Annaba University for providing the necessary resources and environment to conduct this research. The support from the university has been crucial in facilitating our study, enabling access to essential tools and fostering an encouraging academic atmosphere.

Funding source

This work received no external funding. All research activities were conducted using resources available to the authors and their affiliated institutions. The authors would like to note the absence of financial support from external sources.

Competing interest

The authors declare that there are no competing interests associated with this manuscript. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The statement of no financial resources reflects the authors' commitment to transparency and integrity in presenting their work.

Author contributions

All authors contributed significantly to the research and preparation of this manuscript, showcasing a collaborative effort throughout the process. The specific contributions of each author are as follows:

Writing, Analysis, and Confirmation of Results: all authors were equally involved in the writing process, analyzing the data, and confirming the results of the study. This collaborative approach ensured a comprehensive and unified presentation of the research findings.

Data Collection and Analysis: Abderahmane, Larbi, and Hamza contributed significantly more in the collection and analysis of data. Their efforts in gathering and interpreting the data were crucial in laying the foundation for the study's outcomes.

Each author's role was instrumental in the development and execution of this research. Their collective expertise facilitated a thorough examination of the subject matter, from initial data collection to the final confirmation of results.

Supervision and project administration were conducted collectively, with each author taking part in decision-making processes and overseeing the progression of the research project.

All authors have read and agreed to the published version of the manuscript, confirming their contribution and endorsement of the work presented.

Additional information

DOI: https://doi.org/10.7343/as-2024-757

Reprint and permission information are available writing to acquesotterranee@anipapozzi.it

Publisher's note Associazione Acque Sotterranee remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

Aoun Sebaiti, B. (2010). Study of the water's salinity and modelization of the aquifer system of Annaba. Master Degree Thesis. University of Annaba. 85p.

Batchi, M., Karkouri, A., El Maaqili, M., & Fenijiro, I. (2014). Cartographie de la vulnérabilité à l'intrusion marine de l'aquifère Côtier de Mnasra *"Mapping the vulnerability to marine intrusion of the Mnasra Coastal Aquifer"*. (littoral du Gharb, Maroc–Nord-Occidental). Mar Sci Coast Res J, 11.

Benchaib, A., Djabri, L., Hani, A., Chaffai, H., Boughrira, N. (2018). Hydrochemistry of groundwater salinity sources in the shallow aquifer: Case of Annaba plain (Ne Algeria). Journal of Biodiversity and Environmental Sciences (JBES), 13(5), 216-223.

Benoit, G., & Comeau, A. (2005). Méditerranée: les perspectives du Plan bleu sur l'environnement et le développement. Paris – France, Éditions de l'Aube, 428pp.

Debieche, H. (2002). Evolution of the water's quality (salt levels, azotes and heavy metals) influenced by industrial, agricultural and salt pollution: Application for the lower plains of Seybouse, Algerian NE. Doctoral dissertation, Doctorate Thesis, University of Franche-Comte. 200pp.

Djabri, L. (1987). Contribution to the hydrogeological study of the subsidence plain of Tebessa NE Algerie. Attempt of modelling. Doctoral dissertation, Doctorate Thesis, University of Franche Comté, France.

Djabri, L. (1996). Mechanism of Seybouse water pollution and vulnerability-geological, industrial, agricultural and urban origins. Doctoral dissertation, Doctorate Thesis, University of Annaba. 176pp.

Djabri, L., Bouhsina, S., Hani, A., Bosch, A., Mudry, J., & Cerif Djouamaa, M. (2014). Impacts of drought on water quality: the case of aquifers in eastern Algeria. Proceedings of the International Association of Hydrological Sciences, 364, 357-362.

Djabri, L., Rouabhia, A., Hani, A., Lamouroux, C., & Pulido-Bosch, A. (2008). Origin of water salinity in a lake and coastal aquifer system. Environmental geology, 54, 565-573. https://doi.org/10.1007/s00254-007-0851-2

El Mandour, A. (1998). Contribution à l'étude hydrogéologique de la plaine de Triffa: salinisation et modélisation *"Contribution to hydrogeological study of Triffa plain: salinisation and modeling"*. PhD, Faculty of Sciences of Oujda, Morocco.

Habes, S. (2013). Chemical characteristics of a lake belonging to wetland ecosystems in northern Algeria; Case: Lake Fetzara, North-East Algerian. Doctoral dissertation, PhD thesis. Annaba University. 211pp.

Hani, A. (2003). Methodological examination of anthropological structure and process, application for Mediterranean coastal basin water sources. Doctoral dissertation, PhD thesis. Annaba University. 213pp.

Ikhlef, N., Tachi, S. E., Bouguerra, H., Djabri L., & Arrar J. (2024). Classification of Groundwater Quality for Irrigation Purposes in Wetland Region by Irrigation Water Quality Index. Water Resources, 51, 322–331. https://doi.org/10.1134/S0097807823600493

Joleaud, L. (1936). Étude géologique de la région de Bône et de La Calle *"Geological study of the Bône and La Calle region"*, Alger, Bulletin du service de la Carte géologique de l'Algérie, 2(12), 436pp.

Khaled–Khodja, S., Samar, M. E., Ounissi, M., Saker, I. E., Kennouche, M., Laabed, S. & Gouiez, H. (2014). Impacts des activités anthropiques sur la qualité des eaux de l'oued Seybouse (Annaba, Algérie) *"Impacts of anthropogenic activities on the water quality of the Seybouse wadi (Annaba, Algeria)"*. Ouvrage Collectif aux éditions du Groupe Français des Pesticides, ISBN : 978–2–954611– 0–3, pp. 51–55.

López-Dóriga, U., & Jiménez, J. A. (2020). Impact of relative sea-level rise on low-lying coastal areas of Catalonia, NW Mediterranean, Spain. Water, 12(11), 3252. https://doi.org/10.3390/w12113252

Maruja, A., & Mania, J. (1997). Salinization origins of the Chaouia aquifer (Morocco). Hydrochemistry. IAHS publication, 224.

Stein, S., Sola, F., Yechieli, Y., Shalev, E., Sivan, O., Kasher, R., & Vallejos, A. (2020). The effects of long-term saline groundwater pumping for desalination on the fresh–saline water interface: Field observations and numerical modeling. Science of The Total Environment, 732, 139249. https://doi.org/10.1016/j.scitotenv.2020.139249

Vila, J. M. (1980). La chaîne Alpine d'Algérie orientale et des confins Algérotunisiens *"The Alpine chain of eastern Algeria and the Algerian-Tunisian borders"*. Sciences Thesis. Paris, Université Pierre et Marie Curie, France, 665pp.

Zenati, N., El Hadi, K., & Bouguemmat, A. (2010). Study of the hydrodynamic functioning of coastal aquifers and the impact of climatic and anthropogenic factors on the quality of their waters: Case of the Bou-Areg plain (Northeast of Morocco). Environmental Geology, 54, 1737-1749.

Zghibi, A., Tarhouni, J., & Zouhri, L. (2013). Assessment of seawater intrusion and nitrate contamination on the groundwater quality in the Korba coastal plain of Cap-Bon (North-east of Tunisia). Journal of African Earth Sciences, 87, 1-12. https://doi.org/10.1016/j.jafrearsci.2013.07.009