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# MINERALIZATION AND RECHARGE PROCESSES OF THE TURONIAN AQUIFER IN AN ARID REGION (SOUTHWESTERN ALGERIA)

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## Abstract

Region of Béchar, located in southwestern Algeria, is characterized by an arid climate with a Saharan tendency and faces increasing water demand due to economic and demographic growth. This study aims to characterize the Turonian aquifer system, which represents a crucial economic water resource for drinking water supply and irrigation. The interpretation of hydrogeological and hydrochemical data has provided insights into the functioning of this aquifer system. The piezometric map reveals a groundwater flow direction from the northeast to the southwest, with an increasing hydraulic gradient towards the Djorf Torba dam. The recharge of the aquifer occurs through meteoric water infiltration and lateral contributions from Atlas aquifers. Hydrochemical analysis has identified dominant chemical facies and assessed water quality for human consumption and agricultural use. Principal Component Analysis (PCA) was applied to determine the mineralization processes, mainly influenced by the dissolution of evaporitic formations.

***Keywords:*** *Hydrochemistry, Principal component analysis (PCA), Arid zone.*

## 1. Introduction

Water-related issues are closely tied to sustainable development, as water resources must meet both current and future generational needs [1]. In arid regions, particularly in the Maghreb, water resources hold critical economic and environmental significance due to prevailing water stress [2,3]. Various factors, including population growth, climate change, expansion of irrigated areas, and industrial development, contribute to increased pressure on these resources, making them vulnerable to contamination [4]. The Turonian aquifer in the Béchar region, part of the Cretaceous Er Rachidia-Béchar Basin, is the primary groundwater resource, supplying approximately 20% of the potable water demand for a population of over 192,900 inhabitants (as of 2007). This aquifer is influenced by both anthropogenic factors and unfavorable climatic conditions [5-7].

Previous studies (SONAREM, 1976; ANRH, 1994; Mekideche et al., 1995) have indicated that the aquifer holds substantial reserves, primarily sourced from major springs like Boukais and Djorf Torba. Effective water resource management necessitates a thorough understanding of the aquifer's hydrogeological and hydrochemical characteristics. This study aims to evaluate the hydrogeological potential and determine the physicochemical quality of the groundwater in the Béchar region.

## 2. Methods

### 2.1. Study Area

Béchar region lies at the foothills of the southern flank of the Pre-Saharan Atlas, approximately 950 km southwest of Algiers. It belongs to the vast Cretaceous Er-Rachidia-Boudenib Basin, covering around 8,000 km². It is bordered to the north by the Djebel Antar (1,960 m) and Djebel Horriet (1,461 m) massifs, to the south by Chebket Mennouna, to the east by Djebel Béchar (1,512 m), and to the west by the Algerian-Moroccan border (Figure 1). The region experiences an arid climate with Saharan tendencies, characterized by irregular annual precipitation averaging 72 mm (1988–2008). Minimum recorded temperatures drop to 4°C in January, while peak temperatures reach 40°C in July, with an annual average of 27°C [8, 9]. The mean evaporation rate is 306 mm, significantly exceeding precipitation levels, leading to persistent drought conditions [7, 9].

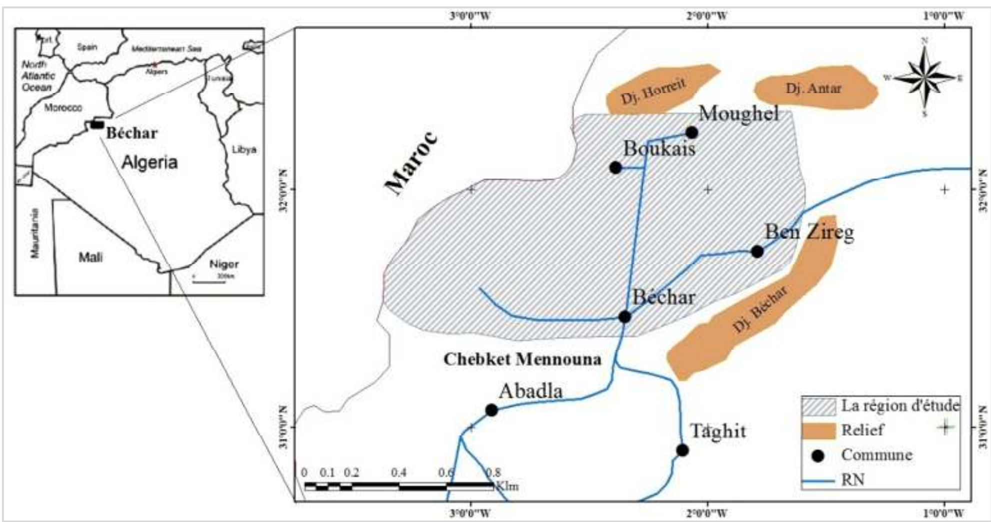


***Figure 1*** *Geographical location of the study area*

### 2.2. Geological and Hydrogeological

Béchar is part of the stable, cratonized Saharan platform, offering a diverse and well-exposed geological landscape. Previous geological studies have identified formations ranging from the Precambrian to the Quaternary [10, 11]. The lithological profile includes thick limestone banks, alternating with shale and marl sequences, forming prominent cliffs along the Béchar-Kénadsa-Djorf Torba route (Figure 2) [12]. The Turonian aquifer, a key regional water source, consists of thick limestone and dolomitized formations [13, 14]. Its base comprises low-permeability Cenomanian marls (15–50 m thick), while it's upper boundary is formed by Senonian marls with gypsum and anhydrite layers (Figure 3) [15, 16]. The aquifer is unconfined at the periphery but transitions to a confined system towards the basin center [17]. The most exploited capture field is in Ouakda, where nine wells collectively produce about 116 l/s [18, 19].

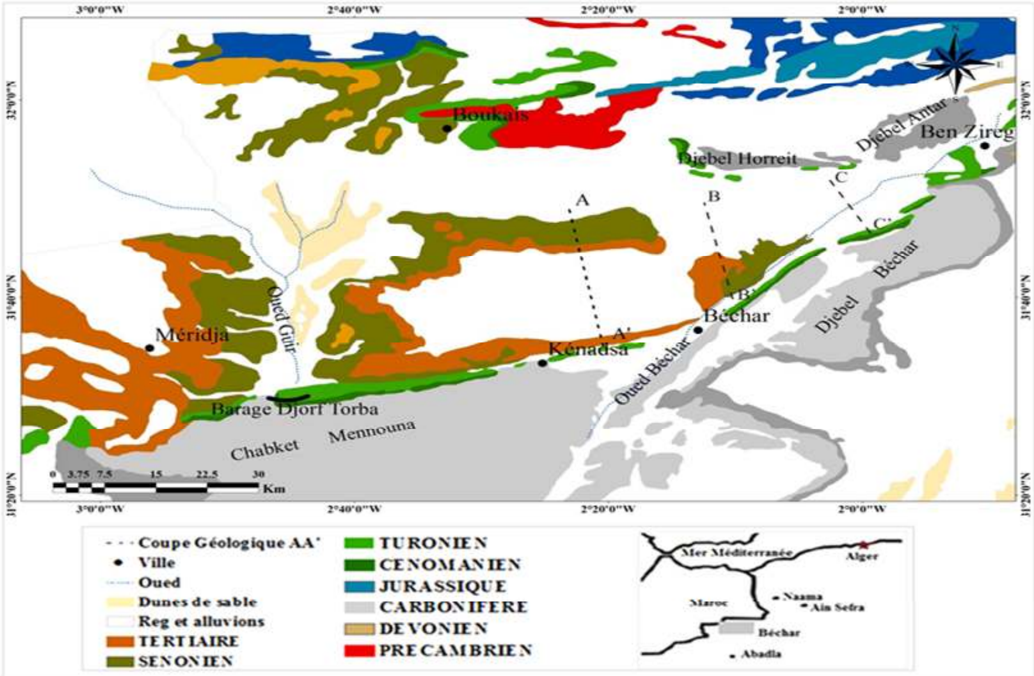


***Figure 2** Geological map of the Béchar region*

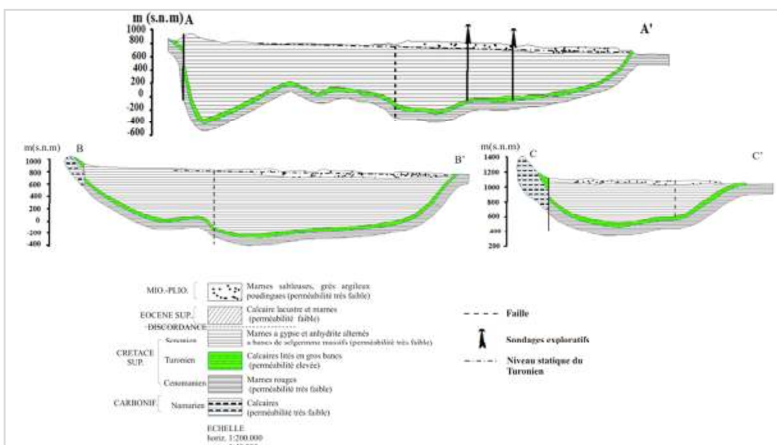


***Figure 3** Interactive transverse hydrogeological cross-section of the Turonian aquifer*

## 2.3. Hydrogeological Conditions and Water Sampling

Hydrogeological assessments indicate that the Turonian aquifer is primarily recharged by direct rainfall infiltration in exposed areas and secondary recharge through lateral inputs from overlying and adjacent aquifers. Pumping tests conducted by ANRH in 2014 (at wells PZ01–PZ04 in Ouakda) [19] revealed transmissivity values ranging from $10^{-3}$ to $10^{-4}$ m²/s [20], permeability between $10^{-4}$ and $10^{-3}$ m/s, and a storage coefficient of approximately $10^{-4}$ [21].

Water samples were collected from 20 groundwater points across the Béchar-Kénadsa Basin in May 2014. These samples underwent laboratory analysis at ANRH, focusing on major ion concentrations ($Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $SO_4^{2-}$, $HCO_3^{-}$, $NO_3^{-}$) and physicochemical parameters such as electrical conductivity, mineralization, and pH.

## 3. Results and discussion

### 3.1. Piezometry

Piezometric map of the Turonian aquifer (Figure 4), established in May 2014, was created based on measurements taken by agents of the National Agency for Water Resources of Adrar (ANRH) during a campaign to measure the piezometric levels of this aquifer. This effort led to the development of a new piezometric map (Figure 4). Due to the very limited number of water points, the piezometric reconstruction was constrained by a lack of information in the central part of the basin, where the piezometry was drawn based on data from a single borehole (Saf-Saf1) (Figure 4). This new map highlights the flow configuration of groundwater in the Turonian aquifer. The general flow direction is from the northeast to the southwest. The map reveals piezometric altitudes ranging from 697 to 850 meters. The highest values are located in the eastern part of the study area, gradually decreasing towards the west until reaching the natural outlet of the dam source (S-DJT), situated at the Djorf Torba dam. This configuration indicates a convergent flow pattern for this aquifer. The hydraulic gradient, calculated from the May 2014 piezometry, shows variations from east to west towards the Djorf Torba dam, with values ranging between 0.33% and 0.4%. These variations may be influenced by the lithological nature of the basin or by qualitative and quantitative variations in fracturing.

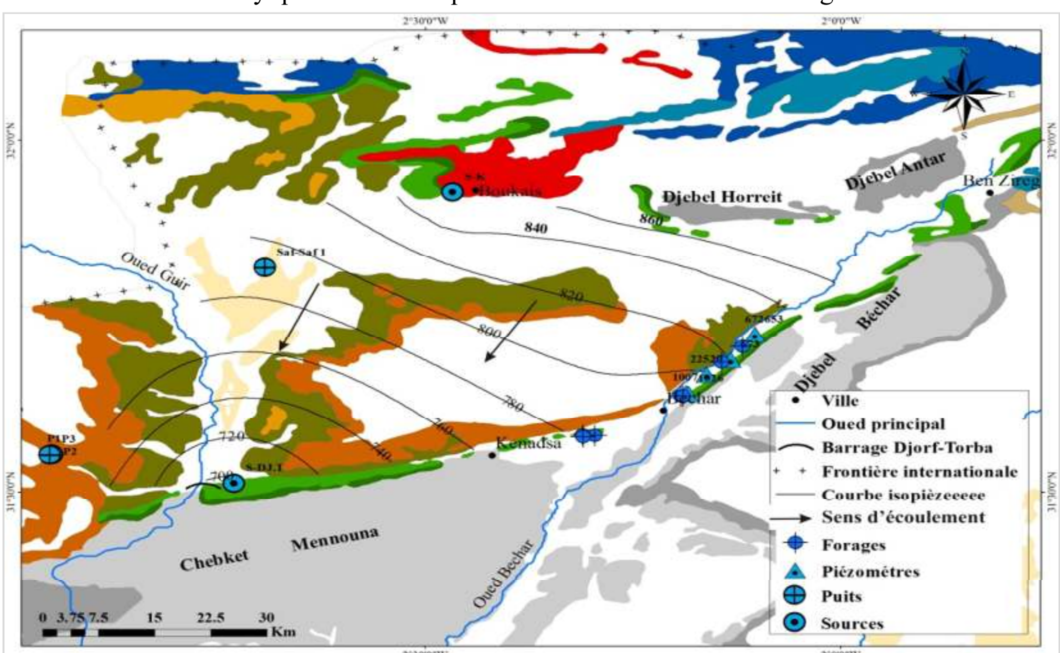


***Figure 4** Piezometric map of the Turonian aquifer, May 2014*

### 3.2. Hydrochemistry

Water temperatures of the Turonian aquifer range between 20°C and 26°C. The high temperature observed in some water points is attributed to the presence of nitrates ($NO_3^-$). The pH of the groundwater in this aquifer has an average value of 7.19. The chemical analysis of groundwater data reveals a wide variation in chemical composition. The recorded electrical conductivity values range from 0.98 to 35 mS/cm, with an average of approximately 4.24 mS/cm, indicating that the water in the study area exceeds WHO standards. The spatial distribution map of groundwater mineralization in the Turonian aquifer (Figure 5) shows a logical increase along the flow direction. Generally, the aquifer presents values ranging between

615 and 9542 mg/L, with the highest values characterizing water in the extreme southern part of the study area.

This high mineralization is mainly linked to the lithological nature of the terrain. Low mineralization values, not exceeding 1000 mg/L, are observed in the Boukais region and the center of Béchar. These lower values may be influenced by the infiltration of rainwater and/or runoff from the Dj. Horreit and Dj. Antar mountains, which act as recharge zones.

The results of the major element representation on the Piper diagram [22] indicate that the groundwater of the Turonian aquifer exhibits a similar chemical facies of the chloride and sulfate-calcium-magnesium type (Figure 6). The spatial distribution of these chemical facies is primarily influenced by the lithological nature of the aquifer and recharge conditions.

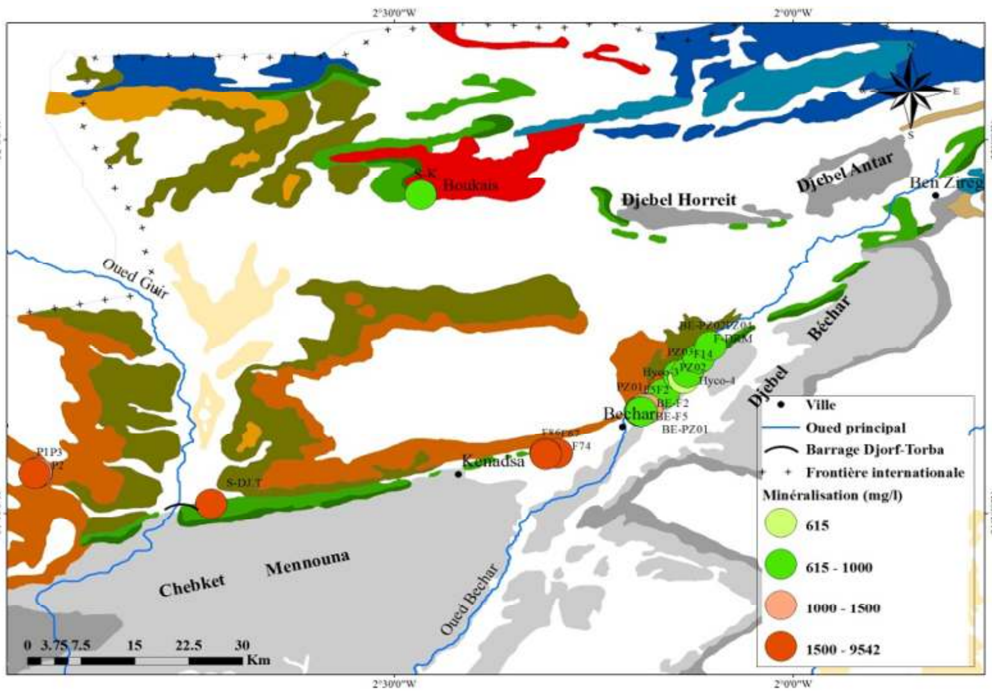


***Figure 5*** *Mineralization of the Turonian aquifer waters*

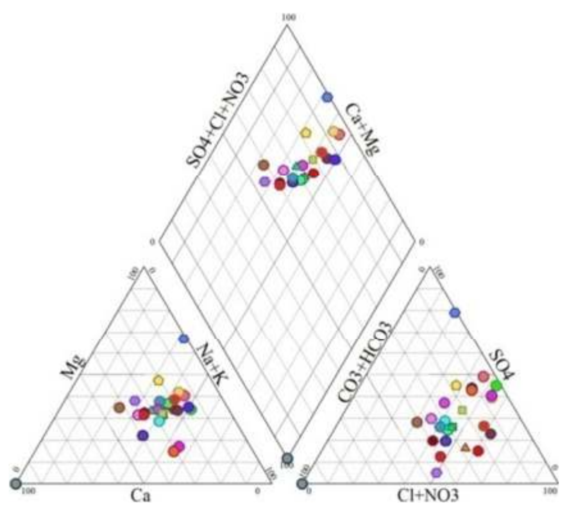


***Figure 6*** *Piper diagram of the Turonian aquifer waters*

### 3.3. Principal Component Analysis (PCA)

Numerous studies have focused on analyzing water chemistry data using multivariate statistical techniques, among which Principal Component Analysis (PCA) is widely employed. This method helps clarify the relationships between variables and the underlying processes driving these associations [23-25]. A statistical study using PCA was conducted on 10 variables and 20 sampling points from the Turonian aquifer in the study area during the year 2014. The analysis of the factorial plane (F1/F2) indicates that more than 75% of the total variance is explained, confirming the reliability of this approach. Strong correlations ($0.51 < R < 0.93$) were observed among $Mg^{2+}$, $Na^{+}$, $Cl^{-}$ , $SO_4^{2-}$, and $Ca^{2+}$ ions (Table 1). These elements are positioned in the same direction along the F1 axis, which accounts for over 46% of the total variance (Figure 7). This axis reflects the mechanisms responsible for groundwater mineralization, primarily linked to the geological origin through the dissolution of evaporitic formations and dolomitic limestone. Positive correlations were also observed between pH, electrical conductivity, and $HCO_3^{-}$ ($0.81 < R < 0.95$) (Table 1), grouping these elements along the F2 axis, which explains over 29% of the total variance (Figure 7). This result suggests that the high electrical conductivity of the water is influenced by the dissolution of Upper Cretaceous formations. Factor 3 of the PCA, defined by $K^{+}$ and $NO_3^{-}$, indicates that surface water infiltration is primarily driven by the degradation of organic matter, likely due to agricultural fertilizer inputs.

***Tableau1*** *Pearson correlation matrix between the chemical elements of the Turonian aquifer*

| | pH | CE | $Ca^{2+}$ | $Mg^{2+}$ | $Na^{+}$ | $K^{+}$ | $Cl^{-}$ | $SO_4^{2-}$ | $HCO_3^{-}$ | $NO_3^{-}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **PH** | **1** | | | | | | | | | |
| **CE** | **0.95** | **1** | | | | | | | | |
| **$Ca^{2+}$** | 0.29 | -0.23 | **1** | | | | | | | |
| **$Mg^{2+}$** | -0.37 | 0.45 | **0.63** | **1** | | | | | | |
| **$Na^{+}$** | -0.05 | 0.11 | **0.91** | **0.86** | **1** | | | | | |
| **$K^{+}$** | 0.01 | 0.01 | -0.06 | -0.01 | -0.14 | **1** | | | | |
| **$Cl^{-}$** | 0.01 | 0.07 | **0.93** | **0.84** | **0.99** | -0.06 | **1** | | | |
| **$SO_4^{2-}$** | -0.47 | **0.54** | **0.51** | **0.98** | **0.78** | 0.05 | **0.75** | **1** | | |
| **$HCO_3^{-}$** | **0.81** | -0.81 | 0.13 | -0.34 | -0.19 | 0.31 | -0.12 | -0.40 | **1** | |
| **$NO_3^{-}$** | 0.21 | -0.05 | 0.20 | 0.28 | 0.24 | -0.36 | 0.23 | 0.22 | 0.03 | **1** |

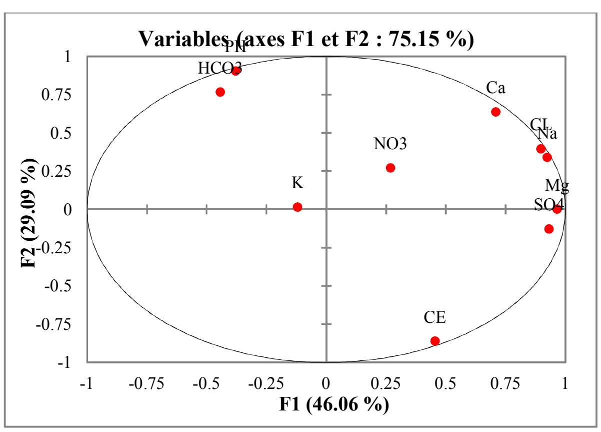


***Figure** 7 Projection of variables on the factorial plane 1-2 (Mai 2014)*

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### 3.4. Origin of the Main Chemical Elements

The examination of the gypsum saturation index in relation to $Ca^{2+} + SO_4^{2-}$ (Figure 8-a) explains the dissolution of this mineral, showing a moderate correlation with a coefficient of determination R2 = 0.589. This saturation index varies from -2.17 to 0.39 across all analyzed samples. This confirms that the waters of the Turonian aquifer are undersaturated with respect to gypsum, which primarily originates from the Senonian formation. Moreover, the absence of correlation between the saturation index of water with respect to dolomite, based on $Ca^{2+} + Mg^{2+} + HCO_3^-$ (Figure 8-b), contradicts the dissolution of these carbonate minerals, despite the state of undersaturation, which is also attributed to the Senonian formation. The correlation of $Ca^{2+}$ as a function of $SO_4^{2-}$ (Figure 9-a) highlights an excess of calcium ($Ca^{2+}$). This enrichment in $Ca^{2+}$ is due to the Turonian aquifer's origin and the dissolution of the Senonian formation. Furthermore, this suggests that the source of the latter is not sulfate-based (Figure 9-a). The relationship between $Na^+$ and $Cl^-$ shows that most samples are close to the reference line with a slope of 1 (Figure 9-b), with an excess of $Na^+$ ions compared to $Cl^-$ ions. This result is attributed to the dissolution of halite and/or anhydrite, as confirmed by the strong positive correlation between these two ions, displaying a coefficient of determination R2=0.979 (Figure 9-b). The proportional evolution between $Ca^{2+} + SO_4^{2-}$ and $Ca^{2+} + HCO_3^-$ confirms that the primary source of $Ca^{2+}$ is mainly linked to the dissolution of carbonate formations in the Turonian aquifer (Figure 10-a). These ion exchanges are further highlighted by the relationship $(Ca^{2+} + Mg^{2+}) - (HCO_3^- + SO_4^{2-})$ as a function of $(Na^+ + K^+ - Cl^-)$ [26, 27], represented in Figure 10-b. These exchanges are characterized by a slope of -1, as indicated by the positioning of the samples. In the absence of such exchanges, all sample points should be located near the original reference point [28]. However, in the waters of the Turonian aquifer, Figure 10-b illustrates an increase in $Ca^{2+} + Mg^{2+}$ accompanied by a deficit in $Na^+ + K^+$.

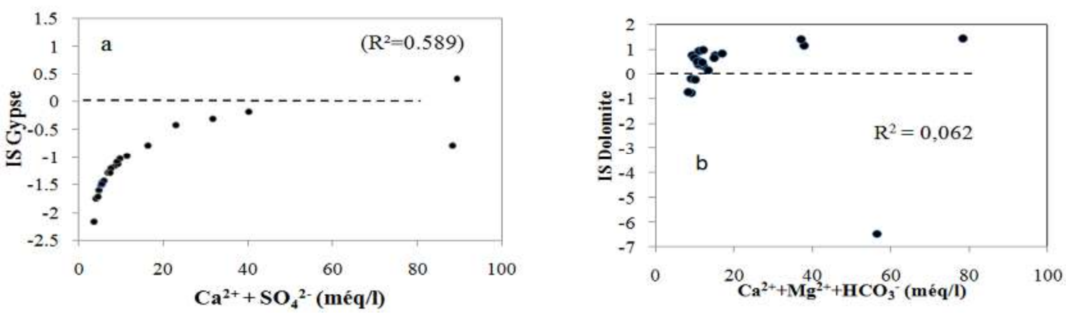


***Figure 8*** *Correlation of the gypsum saturation indices as a function of $Ca^{2+} + SO_4^{2-}$, ($R^2$ : Coefficient of determination) , relation between $Ca^{2+}$ / $SO_4^{2-}$*

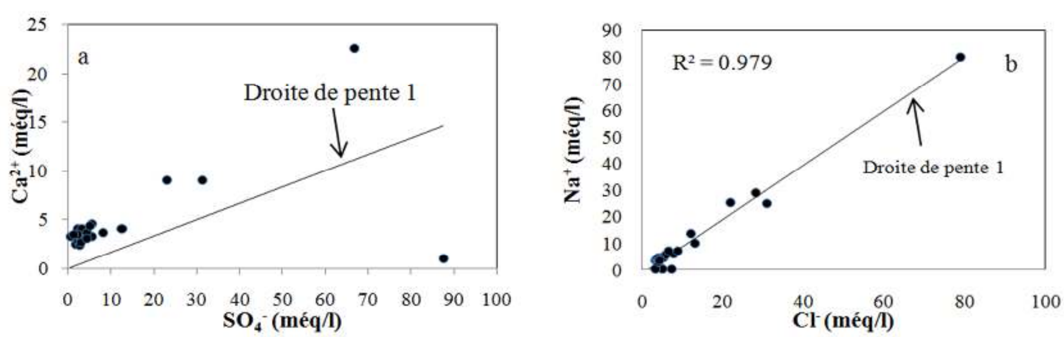


***Figure 9*** *Relation between $Ca^{2+}$ / $SO_4^-$ , relation de $Na^+$ / $Cl^-$*

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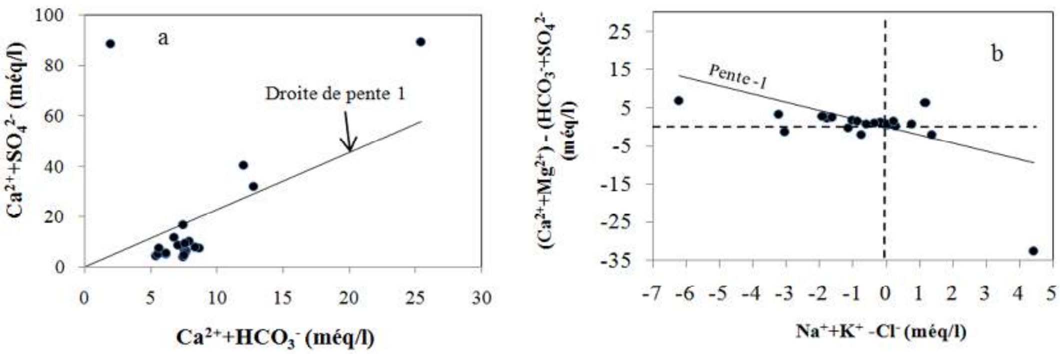


***Figure 10*** *Relation between* $(Ca^{2+} + Mg^{2+}) / (HCO_3^- + SO_4^{2-})$ , $(Ca^{2+}+Mg^{2+})-(HCO_3^-+SO_4^{2-}) / (Na^++K^+-Cl^-)$

## 4. Conclusion

A hydrogeological and hydrochemical characterization of groundwater was conducted on the Turonian aquifer in the Er Rachidia-Béchar basin. This aquifer is distinguished by a significant water storage capacity. Groundwater flow generally occurs from the northeast to the southwest, with variable hydraulic gradients from upstream to downstream. The hydrodynamic properties of the Turonian aquifer also vary, with calculated transmissivities ranging between $10^{-3}$ and $10^{-4}$ m²/s. The hydrochemical study of the Turonian aquifer reveals considerable chemical variability, which helps to clarify the functioning of the aquifer and the different lithostratigraphic variations. The groundwater of this aquifer is characterized by a chloride- and sulfate-calcium-magnesium facies, with electrical conductivity values ranging from 0.98 to 35 mS/cm. The waters of the Turonian aquifer are highly mineralized, mainly due to the dissolution of Upper Cretaceous formations. Overall, the groundwater quality is good in the Ouakda plain to the east. However, in the Méridja area to the west, the water quality is unsuitable for drinking purposes but remains adequate for irrigation. The dissolution of gypsum, halite, and/or anhydrite contributes to the salinization of the aquifer's water. This is in full agreement with the state of undersaturation of the water with respect to these minerals. Sodium ($Na^+$) and chloride ($Cl^-$) ions primarily originate from the dissolution of halite and/or anhydrite, while calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), and bicarbonate ($HCO_3^-$) ions mainly result from the dissolution of dolomitic formations. To build upon the findings of this study, future research could focus on applying isotopic techniques to better quantify recharge sources and mechanisms within the Turonian aquifer. Additionally, modeling tools could be used to simulate the impacts of climate change and increased anthropogenic activities on groundwater quality and availability. A comparative analysis with other aquifers in similar arid environments may also enhance regional water management strategies.

## 5. Conflict of interest

The authors declare that they have no conflict of interest.

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