

Exploring the Hydrochemistry of the Tendirara Aquifer – A Comprehensive Analysis of Water Composition and Quality

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ABSTRACT

This study presents a comprehensive analysis of the hydrochemistry of the Tendirara aquifer in the Tendirara region of Morocco. The study encompasses various aspects of the region, including its geography, administration, relief, demography, economy, and climate, to establish a solid understanding of its water facies. Ten water sampling points have been chosen, and standard methods were used to analyze the physicochemical characteristics of the water, temperature, electrical conductivity, and concentrations of different ions and compounds. Descriptive statistics and hydrochemical classifications, including Piper's, Schoeller's, Wilcox's, and ternary classification, were applied to classify and identify different water facies. Additionally, principal component analysis (PCA) was conducted to explore the relationships between different water parameters. The results revealed distinct hydrochemical characteristics within the Tendirara aquifer, with predominantly alkaline water and varying concentrations of potassium, sodium, calcium, magnesium, chlorides, nitrates, bicarbonates, and sulfates. The numerical results indicated that the concentrations of major ions in the Tendirara aquifer varied within the following ranges: potassium (K⁺) 2.6–47 mg/l, sodium (Na⁺) 17–170 mg/l, calcium (Ca²⁺) 40.882–178 mg/l, magnesium (Mg²⁺) 33.534–159.72 mg/l, chlorides (Cl⁻) 22.865–244.201 mg/l, nitrates (NO³⁻) 2.806–237.85 mg/l, bicarbonates (HCO³⁻) 183–311.1 mg/l, and sulfates (SO⁴⁻²⁻) 40.392–336.6 mg/l. The electrical conductivity of the water ranged from 660 to 2640 μS/cm, indicating variations in mineral content and overall water quality analysis of the diagram shows that the Tendirara aquifer's subterranean waters are predominantly chloride-rich and sulfate-rich in calcium and magnesium. These findings contribute to a better understanding of the hydrochemistry of the Tendirara aquifer and have implications for water resource management in the region. The knowledge gained from this study can inform decision-making processes related to water treatment, conservation, and protection. It highlights the need for sustainable practices to ensure the availability of clean and safe water for the local population. Further research is recommended to investigate temporal variations, sources of contamination, and the long-term impacts of anthropogenic activities on the Tendirara aquifer's hydrochemistry.

Keywords: groundwater, Piper diagram, Wilcox diagram, Richards diagram, hydrogeochemical analysis.

INTRODUCTION

Access to clean and safe water is crucial for human well-being and sustainable development, especially in arid and semi-arid regions where water resources are limited [Whelan et al., 2007].

Africa faces significant challenges related to water scarcity, compounded by consecutive years of drought and escalating pollution threats. In this context, the Tendirara region in Morocco stands out as an area heavily reliant on the Tendirara aquifer to meet its water demands. However, the

aquifer's sustainability and water quality are at risk due to erratic rainfall and arid climatic conditions. To effectively manage and safeguard this vital resource, it is imperative to gain a comprehensive understanding of the aquifer's hydrochemistry [Castaño et al., 2018]. This knowledge plays a critical role in assessing spatial and temporal variations in water composition, identifying potential sources of contamination, and determining the overall suitability of the aquifer for diverse water need [Lavigne et al., 2010]. Previous studies have employed hydrochemical classifications, such as Piper's, Schoeller's, Wilcox's, and ternary classification, to categorize water facies and understand their distribution patterns. Additionally, statistical techniques like principal component analysis (PCA) have been utilized to unravel the relationships between different physicochemical parameters and decipher the dominant factors influencing water composition. However, while previous hydrogeological studies have primarily focused on the quantity and characterization of the Tendirra aquifer, a comprehensive analysis of its hydrochemistry is lacking [Yang et al., 2011]. To address this gap, this study aims to conduct a detailed analysis of water composition and quality in the Tendirra aquifer, considering various geographic, administrative, relief, demographic, economic, and climatic aspects of the region. The objectives of this study are: (1) to assess the physicochemical characteristics of the water, including pH, temperature, electrical conductivity, and concentrations of major ions and compounds; (2) to classify and identify water facies using hydrochemical classifications; (3) to analyze the interrelationships between different water parameters through multivariate statistical analysis; and (4) to provide valuable insights and recommendations for effective water resource management and sustainable utilization of the Tendirra aquifer.

The findings of this study will significantly contribute to the scientific understanding of the Tendirra aquifer's hydrochemistry. Moreover, they will inform decision-makers, water resource managers, and local communities about the water composition and quality in the region. This knowledge will guide the development of strategies for water treatment, conservation, and protection, ensuring a clean and safe water supply for the growing population of the Tendirra region while preserving the long-term sustainability of the aquifer [Wu et al., 2017].

MATERIALS AND METHODS

Study area

Tendirra, situated at the eastern boundary of the Kingdom of Morocco, serves as the administrative hub of the rural commune of Tendirra. Geographically, it occupies a strategic position within the region, located 70 kilometers north of Bouarfa and 164 kilometers south of Oujda. With geographic coordinates in the Lambert system of longitude $X = 817.000$ and latitude $Y = 277.660$, Tendirra falls under the Figuig province of the Oriental Tendirra region. It shares borders with the rural commune of Beni-Mathar in the Figuig Province and the rural commune of Oulad Sidi Abdelhakem in the Jerada Province to the north. At the same time, to the south lies the rural commune of Beni Guil. To the west, it is encompassed by the rural commune of Maatarka, and to the east, it extends up to the Morocco-Algerian borders (Fig. 1). Covering an expansive area of 8359 square kilometers, the commune's center is at an average altitude of approximately 1.400 meters and falls within the operational zone of MHBA (Moulouya Hydraulic Basin Agency).

Regarding relief (Fig. 2), Tendirra is positioned within the high plateaus region, characterized by a vast and undulating plain. The landscape boasts an average elevation exceeding 1.100 meters and showcases rounded reliefs, chotts (salt flats), dunes, and dayas (intermittent lakes). The pinnacle of Jbel Tendirra towers at 1679 meters, while the lowest point descends to 1254 meters, contributing to a diverse and contrasting topography.

Demographically, the population of Tendirra is sparsely distributed and primarily engaged in nomadic lifestyles revolving around sheep farming, limited cereal cultivation, and the collection of Alfa grass (*Stipa tenacissima*). As of the 2014 census (General Population and Housing Census GPHC 2014, Table 1), Tendirra is home to 15390 inhabitants, with a moderate average growth rate of around 2.47% since the 2004 census. The economic and social dynamics of Tendirra are significantly shaped by its arid climate and limited water resources. Water scarcity profoundly influences population distribution and agricultural practices, leading to the dominance of extensive livestock grazing, with vast expanses of Alfa grass-covered pastures serving as crucial grazing grounds. Despite the region's

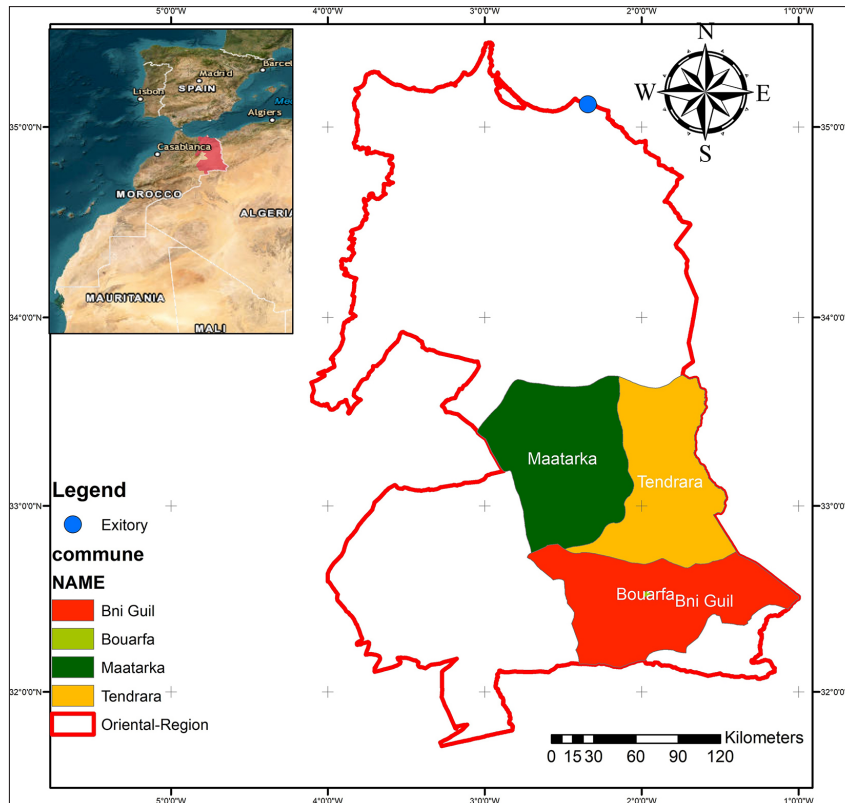


Figure 1. Location of the study area (map prepared with ArcMap 10.5 software)

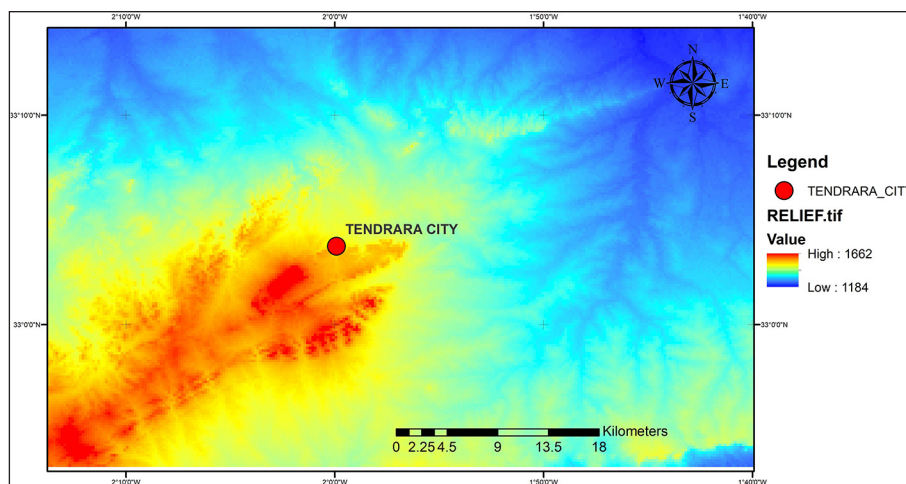


Figure 2. Relief map of the study area 1:150000 with ArcMap 10.5 software

agricultural potential, substantial portions of arable land remain uncultivated due to arid conditions, irregular rainfall patterns, and restricted access to irrigation water. Tendirara experiences a semi-arid climate characterized by cold winters, hot summers, and frequent winds throughout the year. This climatic pattern is influenced by the sub-desert environment extending toward the Mediterranean, with mountain ranges intensifying the continental climate in eastern Morocco.

A climate station positioned at an altitude of 1460 meters in the center of Tendirara provides invaluable meteorological data, with the Lambert coordinates of longitude = 817.500 meters and latitude = 277.700 meters [Yang et al., 2011].

Precipitation in the region is characterized by low and irregular rainfall, with an average annual precipitation of approximately 196.7 mm. The pronounced rainfall variability, as depicted in (Fig. 3) and the increasing demand for drinking water in

Table 1. Demographics of the study area (According to MHBA)

Specification	GPHC2004	GPHC2014	Population projections	
			2025	2030
Population	12057	15390	20130	22742

the center of Tendirra over the years (Tab.2) poses considerable challenges for water availability and management in Tendirra. These climatic characteristics underscore the importance of exploring groundwater resources, such as the Tendirra aquifer, to meet the region’s water needs effectively.

By delving into the geographic, administrative, relief, demographic, economic, and climatic aspects of the Tendirra region, we establish a comprehensive foundation for understanding its water resources. This scientific understanding serves as a vital catalyst for further research and strategic water management endeavors in Tendirra, fostering sustainable utilization and preservation of this invaluable groundwater resource for the foreseeable future [Moghaddam et al., 2020].

Sampling and chemical analysis

In our study area we selected for our study, 9 wells and one source were selected from three samples as showed in (Fig. 4). Sampling was carried out following guidelines for drinking water quality determined by the standards outlined by the World Health Organization (WHO) [World

Health Organization, 2017]. The samples were then labeled, placed in a cooler between 0°C and 4°C, and accompanied to the laboratory with a form containing the necessary information on the origin, date, and other remarks on the description. It should be noted that the pH, temperature, and electric conductivity (EC) measurements of each sample were performed on-site using a PCE-PHD 1 multimeter. The concentrations of principal cations and anions, namely Potassium (K⁺) and Sodium (Na⁺), are analyzed by using Flame photometer (Model: ELICO CL 378; accuracy ± 0.5 ppm), Calcium (Ca²⁺) and Magnesium (Mg²⁺) with titration with EDTA, Chlorides (Cl⁻) Titration with silver nitrate (0.1 N), Bicarbonates (HCO³⁻) Titration with hydrochloric acid (0.1 N), for Nitrates (NO³⁻), Sulfates (SO₄²⁻) using the colorimetric determination method using a UV-VIS Spectrophotometer (LANGE HACH DR-6000, precision ± 1 nm).

Data analysis

We had to use efficient and rapid tools and methods to analyze these data and extract as

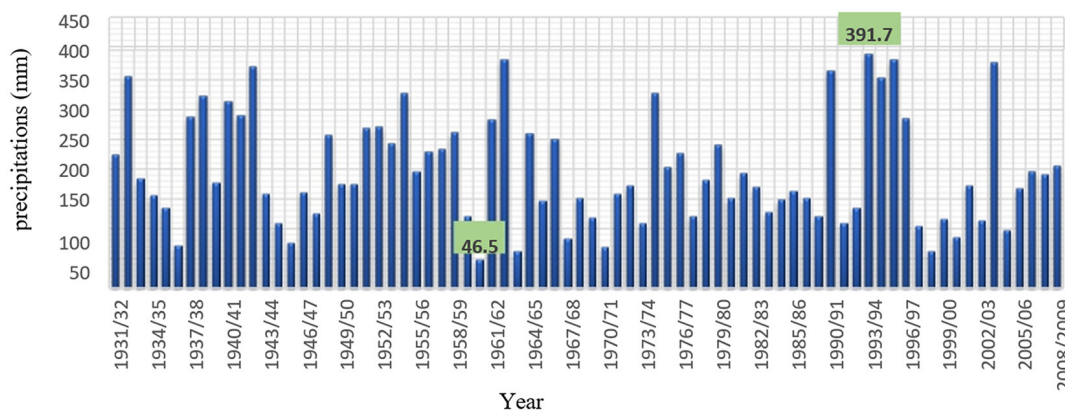


Figure 3. Evolution of annual precipitation recorded in the Tendirra station

Table 2. Drinking water needs of the center of Tendirra from 1994 to 2020 (according to NODW National Office for Drinking Water)

Years	1994	1997	2000	2010	2020
Population	5640	5900	6120	6930	7660
Average requirements in (l/s)	-	5.6	6.2	7.1	8.1
Peak requirements in (l/s)	-	7.3	8.1	9.2	11

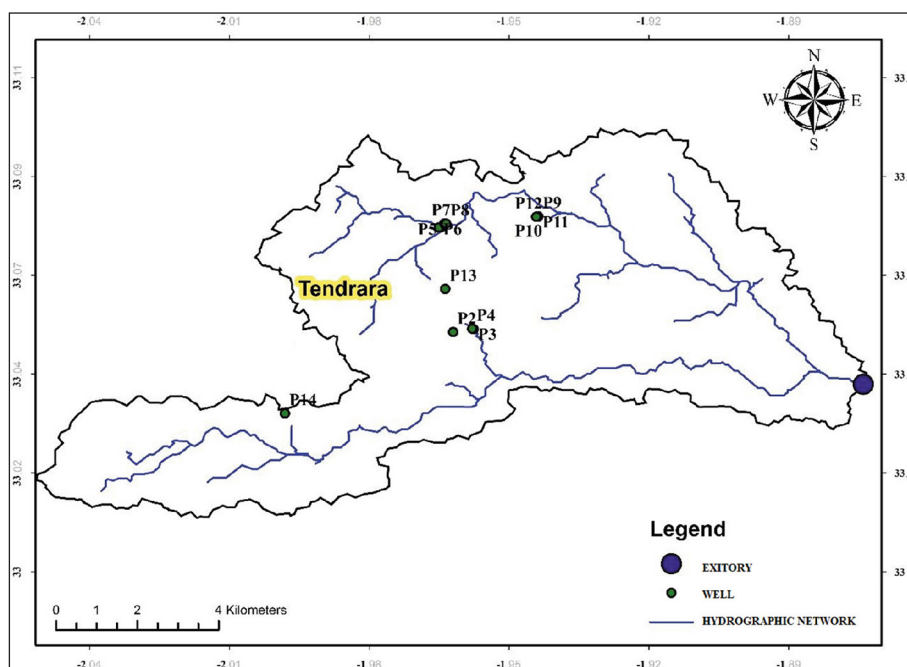


Figure 4. Wells and source location map with ArcMap 10.5 software

much information as possible in a short time. These included the Aquachem software, which helped us draw various diagrams and identify the type of water.

Hydrochemical water classification

To classify and identify the different facies, we have used the best-known main methods: Piper's, Schoeller's, Wilcox's and ternary classification. All these classifications are based on the chemical composition of the water [Suitte et al., 2005].

Descriptive statistics

A correlation matrix, and multivariate statistics (PCA using the rotated varimax method) were performed using RStudio (Version2023.3.0.386).

RESULTS AND DISCUSSION

Analyses of water data

Descriptive statistics

This table compares water quality parameters in 9 wells and one source (P1–P10) to evaluate their variations and potential implications. The results revealed distinct variations in the concentrations of these ions among the different forage sources. For instance, P8 exhibited

higher levels of K^+ (20 mg/l), Na^{2+} (110 mg/l), Ca^{2+} (178 mg/l), Mg^{2+} (137.94 mg/l), Cl^- (223.65 mg/l), NO_3^- (200.25 mg/l), HCO_3^- (250.1 mg/l), and electrical conductivity (2180 $\mu S/cm$). On the other hand, P10 had lower concentrations of most ions, such as Na^{2+} (3 mg/l), Ca^{2+} (25 mg/l), Mg^{2+} (100 mg/l), and NO_3^- (71 mg/l). P9 displayed relatively high concentrations of Na^{2+} (43 mg/l), Ca^{2+} (140 mg/l), and NO_3^- (237.85 mg/l). These variations could be attributed to differences in geological characteristics and land use practices surrounding the forage sources in Tendirara Region.

The conductivity measurements proved an effective parameter for assessing overall water quality. Higher conductivity values were observed in P4 (2640 $\mu S/cm$), P8 (2180 $\mu S/cm$), and P9 (2355 $\mu S/cm$), indicating a higher concentration of dissolved minerals. Conversely, lower conductivity values were recorded in P6 (660 $\mu S/cm$), P7 (1122 $\mu S/cm$), and P10 (1024 $\mu S/cm$), suggesting a lower mineral content in this source. These findings emphasize the importance of considering multiple water quality parameters when evaluating forage sources. The variations in ion concentrations and conductivity highlight the diverse nature of the water sources, which could impact their suitability for specific applications. It is important to analyze the values that exceed the norms and identify their potential sources. One parameter of concern is

potassium (K⁺), with measured values ranging from 2.6 mg/l to 47 mg/l, exceeding the standard range of 1–10 mg/l. The main sources of potassium in soils and waters can be attributed to agricultural activities and the use of potassium-based fertilizers.

Sodium (Na²⁺) levels range from 17 mg/l to 170 mg/l, surpassing the standard range of 20–200 mg/l. The excessive sodium content may arise from various sources, including irrigation practices, the presence of saline water, and the use of sodium-rich fertilizers. Calcium (Ca²⁺) concentrations vary from 40.882 mg/l to 178 mg/l, exceeding the standard range of 20–150 mg/l. Calcium can originate from geological formations and dissolution processes in the aquifer, but it can also result from human activities such as the use of calcium-containing fertilizers. Magnesium (Mg²⁺) values range from 33.534 mg/l to 159.72 mg/l, exceeding the standard range of 10–50 mg/l. Similar to calcium, magnesium can be sourced from natural geological formations and human activities like the use of magnesium-based fertilizers. Chloride (Cl⁻) concentrations vary from 22.865 mg/l to 244.201 mg/l, surpassing the standard range of 20–250 mg/l. The presence of high chloride levels can be attributed to natural processes like rock weathering, as well as anthropogenic sources such as the use of chloride-containing fertilizers and industrial activities. Nitrate (NO³⁻) levels in most of the measured samples fall below the detection limit, which is within the standard range (<10 mg/l). However, it is essential to monitor nitrate levels regularly due to its potential sources, including agricultural activities, excessive use of nitrogen fertilizers, and wastewater discharges. Bicarbonate (HCO³⁻) concentrations range from 183 mg/l to 311.1 mg/l, falling within the standard range of 0–200 mg/l. Bicarbonate ions can

originate from the dissolution of carbonate minerals and the carbon dioxide-carbonate equilibrium in water. Sulfate (SO₄²⁻) levels range from 40.392 mg/l to 585.6 mg/l, exceeding the standard range of 10–250 mg/l.

Sulfate ions can be sourced from natural geological formations, industrial discharges, and the use of sulfate-containing fertilizers. Temperature measurements fall within the standard range of 0–30°C, with values ranging from 22.5°C to 24°C. pH values range from 7.12 to 7.62, falling within the recommended range of 6.5–8.5. The pH level can be influenced by various factors, including geological characteristics, land use practices, and the presence of acidic or alkaline substances.

Electrical conductivity (EC) values range from 660 µs/cm to 2640 µs/cm, exceeding the recommended limit of <1000 µs/cm. High electrical conductivity suggests the presence of dissolved minerals in the water, which can originate from natural geological sources and anthropogenic activities such as agriculture and industrial discharges. To ensure the safety and quality of water resources, it is crucial to investigate the sources of these elements and implement appropriate measures to mitigate their impact. This may include adopting sustainable agricultural practices, regulating the use of fertilizers, improving wastewater treatment processes, and promoting responsible water resource management strategies (Table 3).

This study provides valuable insights into the variations in water quality parameters among different forage sources. The findings can contribute to effective water resource management in this study area, aiding decision-making processes related to water use and conservation. Future studies should focus on understanding the sources and causes of these variations and their long-term

Table 3. Descriptive statistics of the measured groundwater parameters in the present study

Parameter	K+	Na2+	Ca2+	Mg2+	Cl-	No3-	HCO3-	SO42-	T	pH	EC
Unit	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	°C	-	µs/cm
standard	1-10	20-200	20-150	10-50	20-250	<10	0-200	10-250	0-30°	6.5-8.5	<1000
Min.	2.6	17	40.88	33.53	22.86	2.806	183	40.39	22.5	7.12	660
1st Qu.	3.1	25.75	60.52	35.6	56.16	13.23	231.8	90.12	22.85	7.223	957.2
Median	3.4	45	86.47	54.3	87.34	57.558	256.2	154.5	23	7.485	1073
Mean	9.2	67	87.32	74.94	114.44	69.308	250.7	231.99	23.15	7.407	1415.4
3rd Qu.	5.85	100.5	100	114.33	191.75	104.129	273	335.58	23.38	7.548	2022.5
Max.	43	170	178	159.72	244.2	200.25	311.1	585.6	24	7.62	2640

implications for sustainable water management strategies [Qin et al., 2009].

Correlation of hydrochemical parameters

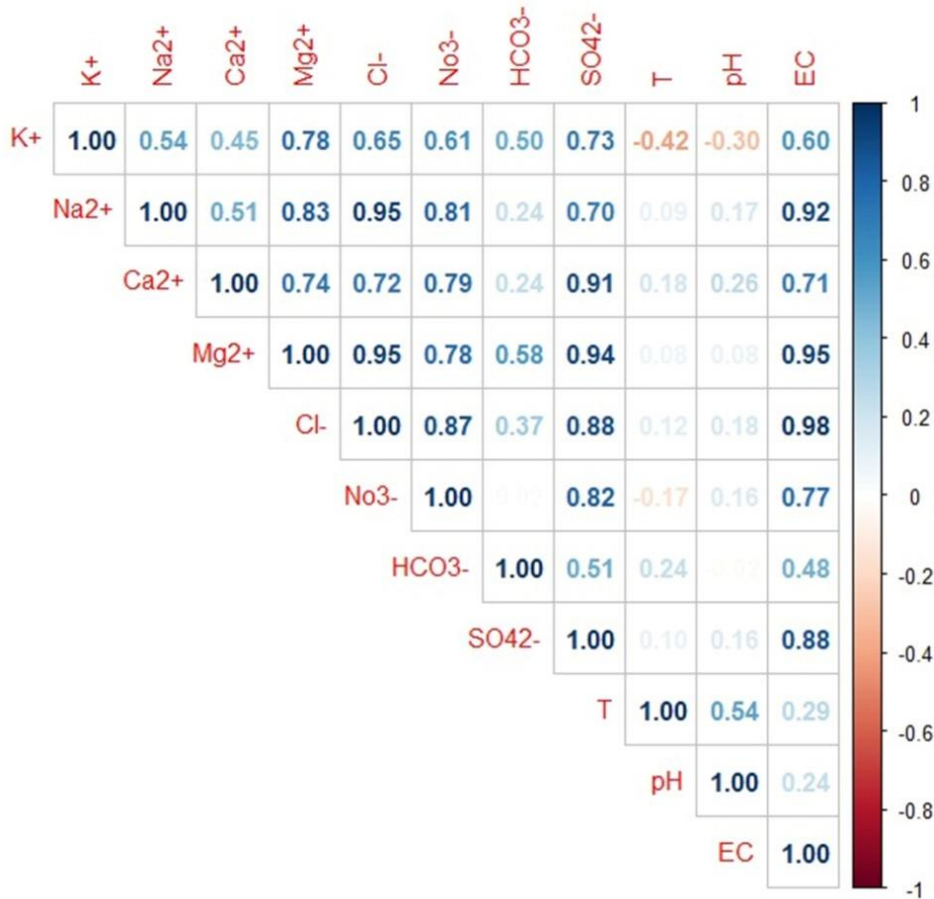
Correlation analysis was performed to explore further the relationships between different hydrochemical parameters [Howladar et al., 2016]. The Pearson correlation coefficient was calculated to determine the degree and direction of the linear relationship between pairs of variables.

The correlation analysis revealed several interesting relationships among the hydrochemical parameters. pH showed a positive correlation with temperature ($r = 0.54$) and electrical conductivity (EC) ($r = 0.58$). Furthermore, EC, Mg^{2+} and SO_4^{2-} are highly correlated with all chemical elements except HCO_3^- . This suggests that higher EC values were associated with increased levels of concentrations of different ions in the water. Ca^{2+} is positively correlate with all ions except K^+ and HCO_3^- , indicating a similar behavior and a possible common source for these ions in the aquifer. Also, NO_3^- and Cl^- are positively correlated

with all ions except HCO_3^- . While the latter element is correlated with K^+ and Mg^{2+} (Tab. 4). It is worth noting that the correlation coefficients between pH, temperature, and the analyzed ions were moderate, suggesting that other factors beyond these parameters might influence the hydrochemical characteristics of the Tendirra aquifer.

These correlation results provide valuable insights into the interrelationships between different hydrochemical parameters, indicating potential underlying processes and sources influencing water composition in the aquifer. However, further investigations, such as hydrogeological modeling and water source tracing, are required to fully understand these correlations' mechanisms and their implications for water quality management in the Tendirra region [McMahon et al., 2006]. In addition, this correlation is insufficient to identify the water facies; for this reason, PCA was adopted to facilitate the explanation of the elemental data and find groups of elements with the same derivation. According to the PCA, represented in (Fig. 5), the first two dimensions

Table 4. Pearson correlation matrix of hydrochemical parameters in the Tendirra aquifer. Significant correlations ($p < 0.05$) are indicated in bold



of analysis account for 86.9% of the total data-set inertia. This means that the plane formed by these dimensions captures a large proportion of the overall variability present in the individuals or variables studied. A high percentage like this indicates that the first plane is highly informative and represents a significant portion of the data's variability. Furthermore, the variability explained by this plane (86.9%) is greater than the reference value of 62.86%, reinforcing its significance.

All the variables included in the PCA are positively correlated, with a strong correlation observed between EC, SO_4^{2-} , Mg^{2+} , Cl^- , and Na^{2+} and a weak correlation between HCO_3^- and NO_3^- . The

analysis of the wells has revealed distinct clusters based on their characteristics. Cluster 1 consists of wells P1, P3, P5, P6, P7, and P10, which share similar features. These wells are characterized by low Ca^{2+} , NO_3^- , SO_4^{2-} , Mg^{2+} , Na^{2+} , HCO_3^- , and K^+ concentrations. This pattern suggests that Cluster 1 wells may have different geological or hydrological conditions than Cluster 2. The lower concentrations of these ions indicate a potential difference in the mineral composition and groundwater chemistry in Cluster 1 wells. The low levels of Ca^{2+} , NO_3^- , SO_4^{2-} , Mg^{2+} , Na^{2+} , HCO_3^- , and K^+ may be attributed to factors such as the type of bedrock, recharge sources, or groundwater flow paths.

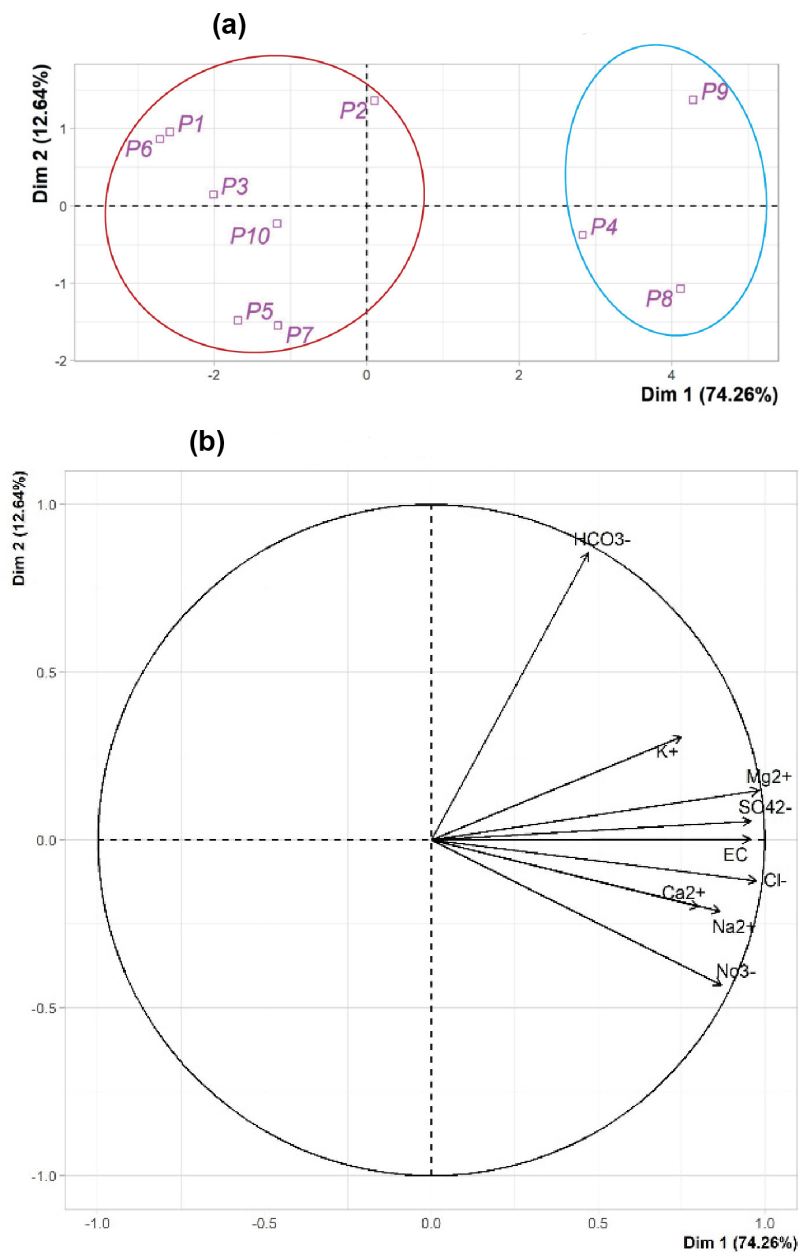


Figure 5. Individuals (a) and variables (b) factor map (PCA)

On the other hand, Cluster 2 comprises wells P8, P4, and P9, which characterised by a high concentration of Ca^{2+} , NO_3^- , SO_4^{2-} , Mg^{2+} , Na^{2+} , HCO_3^- , and K^+ . This indicates a different set of characteristics compared to Cluster 1. The elevated levels of these ions suggest a higher mineral content and potentially different hydrological conditions in Cluster 2 wells. Factors such as geological formations, proximity to pollution sources, or local land use practices could contribute to the increased concentrations of these ions.

The presence of drainage of rainwater towards artisanal wells can significantly impact the data obtained in hydrochemical studies. When rainwater infiltrates the ground, it can carry various contaminants and pollutants from the surface, such as fertilizers, pesticides, and other chemicals [Raju et al., 2007]. If the rainwater is not correctly managed or there are inadequate protective measures, these contaminants can seep into the groundwater, ultimately affecting the water composition in artisanal wells. This can lead to changes in the concentrations of various ions, compounds, and pollutants in the water, thus influencing the hydrochemical characteristics of the wells. The drainage of rainwater towards artisanal wells can introduce additional variables and sources of variability in the data, highlighting the importance of considering and monitoring the potential impacts of surface water drainage on groundwater quality in hydrochemical studies [Liu et al., 2013].

Hydrochemical water classification

Piper water classification

The Piper diagram (Fig. 6) represent several water samples simultaneously. It comprises two triangles representing the cationic and anionic facies of the water and a rhombus synthesizing the overall facies [D’amore et al., 1983]. The principle is to represent in each equilateral triangle the quantities reacting about the concentration of anions and cations, thus obtaining two representative points indicating the dominance of an anion or cation [Shrivastav et al., 2017]. Analysis of the diagram shows that the Tendrara aquifer’s subterranean waters are predominantly chloride-rich and sulfate-rich in calcium and magnesium.

Water classification by Schoeler-Berkaloff

The Schoeler-Berkaloff diagram (Fig. 7) allows us to represent the geochemical facies of several water samples and compare them simultaneously. This diagram shows that Tendrara aquifer water is chlorinated and sulfated with calcium and magnesium. The previous PIPER diagram confirmed the same results.

Water classification by ternary diagram

The ternary diagram comprises three poles (Na, Mg, Ca), allowing us to find the most abandoning chemical facies in the poles (Fig. 8).

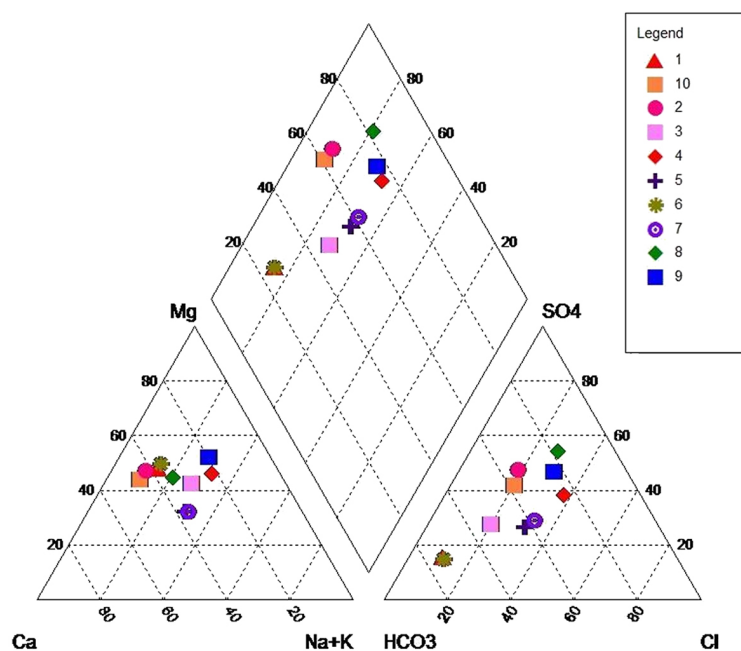


Figure 6. Hydrochemical facies according to Piper

Water classifications, according to Wilcox

According to WILCOX, water is classified according to its sodium content and electrical conductivity (Fig. 8). The 10 samples projected in WILCOX’s logarithmic diagram generally fall into three groups C2S1, C3S1 and C2S4 (Fig. 8). Samples 1 and 6 are in the C2S1 group and present a low risk of water salinization and alkalinization.

Most samples in group C3S1 also present a low salinization risk and meager alkalizing power. This implies that these waters are not loaded with sodium and are more suitable for consumption. As electrical conductivity is low, mineralization is also low [Akinyemi et al., 2011]. In the light of this WILCOX logarithmic diagram, we know that the SAR (Sodium Adsorption Ratio) is very low; in other words, the sodium content is low, and these

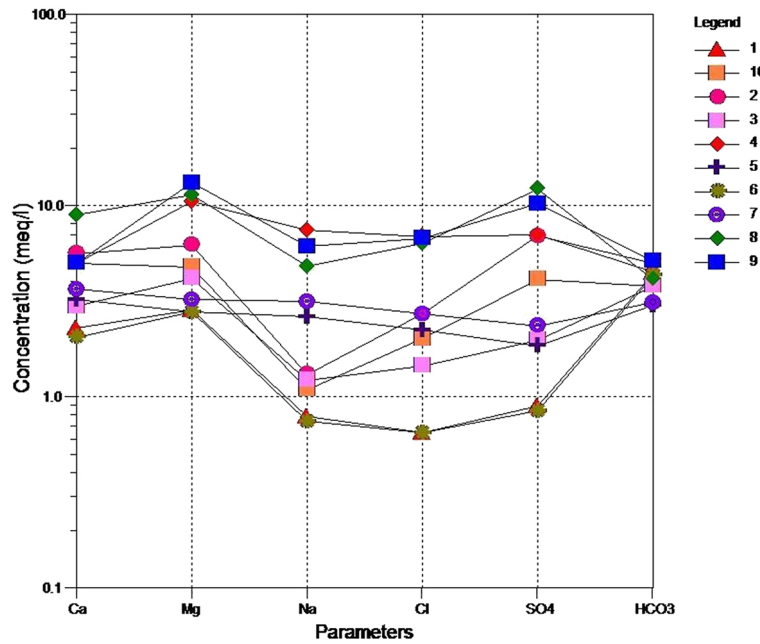


Figure 7. Schoeler-Berkaloff hydrochemical facies

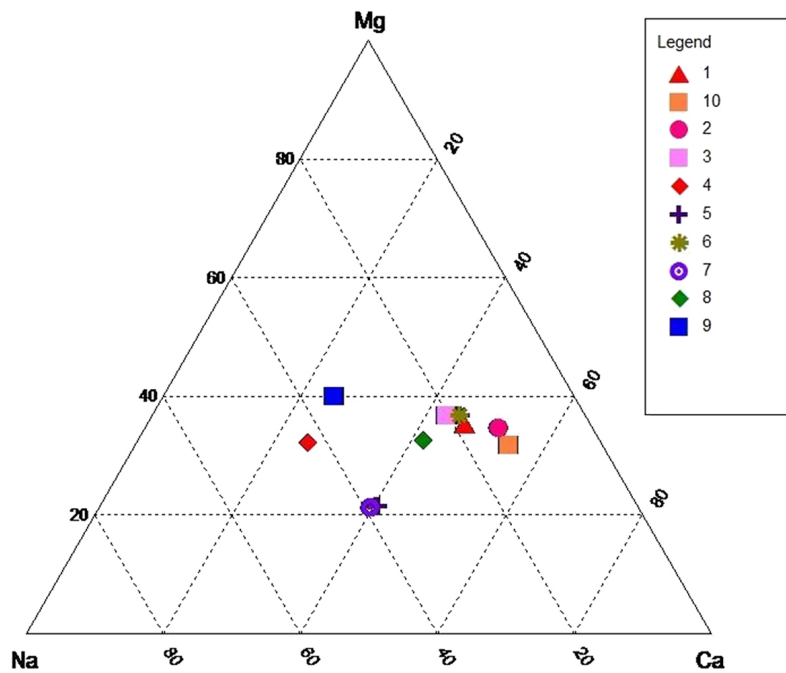


Figure 8. Mg, Na, Ca ternary diagram

waters can be used for irrigation, as their effect on the alkaline character of the soils in the study area is negligible. Agronomists should use this parameter for agricultural purposes [Gopinath et al., 2006]. This WILCOX logarithmic diagram is mainly used to assess the risk of soil salinization (Fig. 8).

Hydrochemical index (THT)

THT, or total hydrometric titer, measures water hardness based on calcium and magnesium ions. Magnesium ions were measured in the laboratory. It is expressed in (°F), (mg/l) or (mg/l). Water is classified according to the following ranges:

- 0 to 10°F: water is very soft;
- 10 to 20°F: water is soft;
- 20 to 30°F: water is moderately hard;
- 30 to 40°F: water is hard;
- Above 40°F: water is tough.

The hardness of the samples collected ranged from 24 to 77.4 °F, with an average value of 40.1 °F [Diehl et al., 1950]. THT, or Total Hydrocarbon Content, measures the concentration of hydrocarbon compounds. The THT indexes range from 24°F to 77.4°F across the samples, indicating varying levels of hydrocarbon content. These indexes provide insights into potential contamination or sources of hydrocarbon compounds in the samples. Further analysis is required to understand the extent and nature of hydrocarbon pollution in

each sample (Table 5). (Fig. 9) provides valuable insights into groundwater chemistry. In (Fig. 9a), the alignment of wells around the 1:1 line with an excess of Na suggests the contribution of halite dissolution, supported by negative saturation index values. (Fig. 9b) indicates the contribution of gypsum dissolution, with wells distributed around the 1:1 line and negative saturation index values for gypsum and anhydrite. (Fig. 9c) suggests the precipitation of calcite and dolomite, as indicated by aligned wells and positive saturation index values. Further analysis is needed for (Fig. 9d). Overall, these findings indicate ongoing halite dissolution, gypsum dissolution, and the precipitation of calcite and dolomite in the groundwater system, providing important information about the geochemical processes occurring in the studied area. (Fig. 10) provides insightful information on the saturation indices (SI) of halite, dolomite, calcite, and gypsum in relation to specific ion

Table 5. THT indexes

Sample	THT in °F
P1	25.6
P2	59
P3	35.6
P4	77.4
P5	29.8
P6	24
P7	34.2

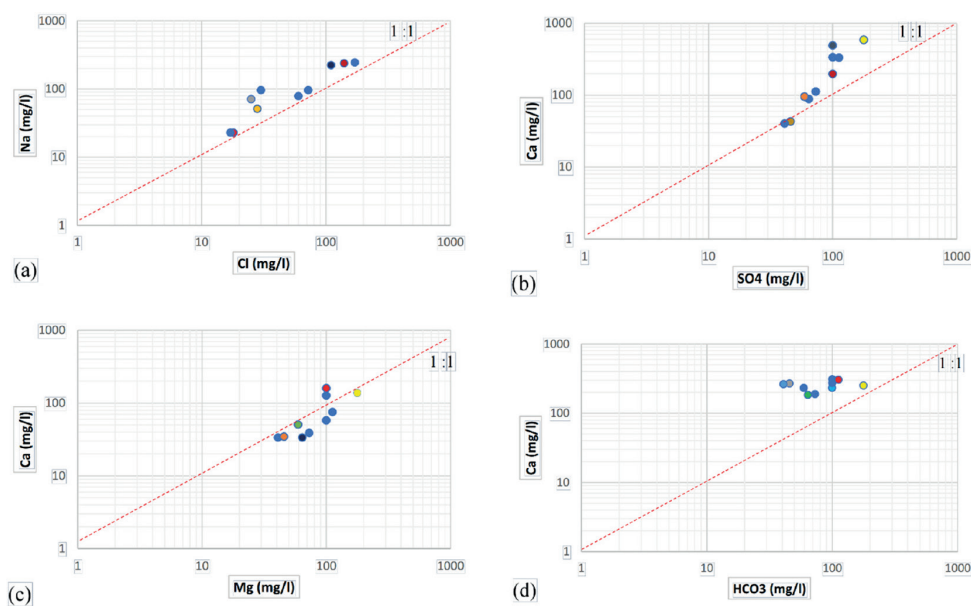


Figure 9. Correlation diagram: (a) Na vs Cl; (b) Ca vs SO4; (c) Ca vs Mg; (d) Ca vs HCO3; (e) SI (Halite) vs Na+Cl diagram

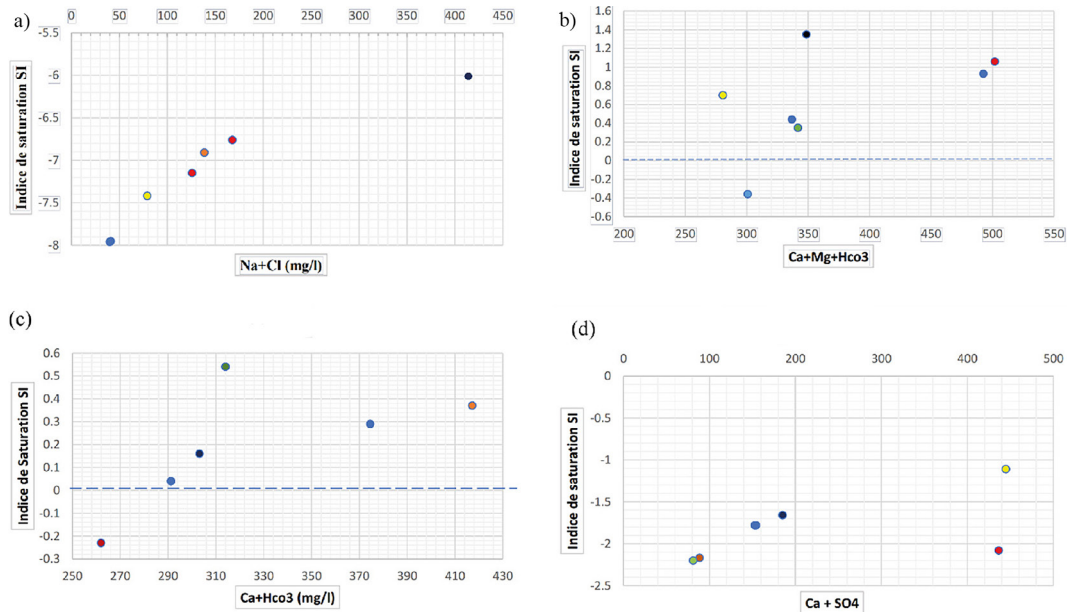


Figure 10. Correlation diagram: (a) SI (Halite) vs Na+Cl; (b) SI (dolomite) vs Ca+Hco3+Mg So4; (c) SI (calcite) vs Ca+Hco3; (d) SI(gypsum) vs Ca+So4

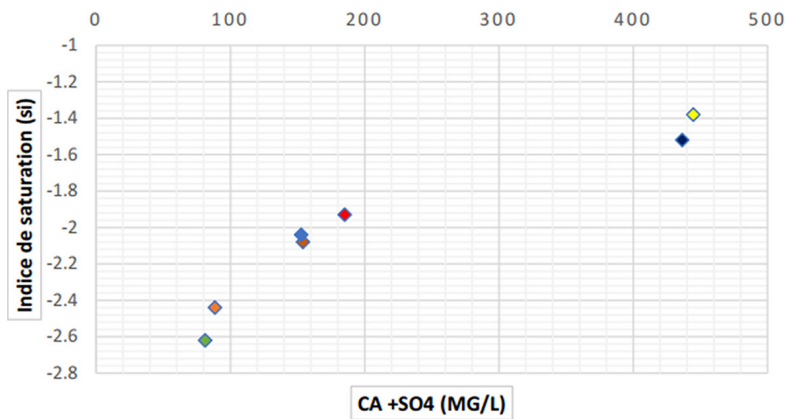


Figure 11. Saturation index SI (Anhydrite) vs Ca+So4

concentrations in groundwater. The alignment of data points in (Fig. 10a) reveals the SI of halite against Na+Cl concentration, where positive SI values indicate halite oversaturation, suggesting equilibrium with the groundwater, while negative SI values imply undersaturation and ongoing halite dissolution. (Fig. 10b) shows the SI of dolomite against combined Ca, HCO₃, Mg, and SO₄ concentrations, with positive SI values indicating dolomite oversaturation and negative values suggesting undersaturation or potential dissolution. (Fig. 10c) presents the SI of calcite against combined Ca and HCO₃ concentrations, where positive SI values indicate calcite oversaturation, and negative SI values suggest undersaturation or potential dissolution. Lastly, (Fig. 10d) represents

the SI of gypsum against combined Ca and SO₄ concentrations, where positive SI values indicate gypsum oversaturation, and negative values imply undersaturation or potential dissolution. In summary, (Fig. 10) provides valuable insights into the saturation indices of these minerals, revealing their equilibrium or disequilibrium status in the groundwater system. The saturation index (SI) of anhydrite plotted against the concentration of calcium and sulfate ions in groundwater provides valuable insights (Fig. 11). An SI less than zero indicates under-saturation with anhydrite, while an SI greater than zero suggests supersaturation. Additionally, comparing the SI values to dolomite and calcite, the data reveals that 91% of the waters are under-saturated with respect to dolomite, and

68% are under-saturated with respect to calcite. These findings highlight the limited ability of the groundwater to dissolve more dolomite and calcite due to insufficient concentrations of relevant ions. Such information aids in understanding groundwater dynamics and has implications for mineral exploration and resource management.

CONCLUSION

The detailed analysis of the hydrochemistry of the Tendirra aquifer in Morocco has provided valuable insights into the composition and quality of the water in the region. The study examined various physicochemical parameters, including pH, temperature, electrical conductivity, and concentrations of major ions and compounds, in order to assess the characteristics of the water and determine its suitability for different applications. The findings contribute to a comprehensive understanding of the aquifer's hydrochemistry and have important implications for sustainable water resource management in the Tendirra region.

The analysis of water composition revealed significant variations in the concentrations of dissolved ions and compounds among different forage sources in the aquifer. These variations indicate diverse hydrochemical characteristics and potential differences in the mineral composition and groundwater chemistry in different areas of the aquifer. For example, the concentrations of potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), and sulfate (SO_4^{2-}) showed notable variations across the sampled wells and sources. These variations can be attributed to geological characteristics, land use practices, and potential sources of contamination.

Hydrochemical classifications, including Piper's, Schoeller's, Wilcox's, and ternary classification, were employed to categorize the water facies and understand their distribution patterns. The classifications confirmed that the Tendirra aquifer water is predominantly chlorinated and sulfated, with calcium and magnesium as dominant ions. This information is crucial for assessing the overall hydrochemical facies and understanding the water's characteristics for different uses. It provides a basis for evaluating the water's suitability for drinking, agricultural, and industrial purposes and helps guide appropriate water treatment and management strategies. The correlation analysis revealed interesting relationships

between different hydrochemical parameters. The pH showed positive correlations with temperature and electrical conductivity, indicating potential interactions and influences between these parameters. Furthermore, significant correlations were observed among various ions, providing insights into the interrelationships and potential sources of these ions in the aquifer. These findings highlight the complex nature of the aquifer system and suggest the involvement of multiple processes and factors in shaping its hydrochemistry. The data analysis also included the assessment of water hardness using the Total Hydrometric Titer (THT) index. The THT indexes ranged from 24°F to 77.4°F, indicating varying levels of water hardness. The hardness of the water samples can have implications for different applications, such as domestic use and irrigation practices. Understanding the hardness of the water is important for determining appropriate treatment methods and ensuring its compatibility with intended uses.

The findings of this study have important implications for water resource management and sustainable utilization of the Tendirra aquifer. The knowledge gained from the comprehensive analysis of the aquifer's hydrochemistry can guide decision-makers, water resource managers, and local communities in developing effective strategies for water treatment, conservation, and protection. It provides a scientific basis for ensuring a clean and safe water supply for the growing population of the Tendirra region while preserving the long-term sustainability of the aquifer. Future studies should focus on further understanding the sources and causes of the observed variations in water quality parameters and their potential impacts on the aquifer's hydrochemistry. Additionally, conducting hydrogeological modeling and water source tracing can provide deeper insights into the aquifer's dynamics and facilitate more accurate predictions of future water quality trends. Continued monitoring and research efforts are essential for implementing sustainable water management practices and ensuring the long-term availability of clean and safe water resources in the Tendirra region. In summary, this study's comprehensive analysis of the hydrochemistry of the Tendirra aquifer contributes to the scientific understanding of this vital water resource. The findings enhance knowledge about the aquifer's characteristics, including its water composition, quality, and suitability for various uses. This scientific understanding serves

as a basis for informed decision-making and the development of strategies for effective water resource management, promoting sustainable utilization while preserving the long-term integrity of the Tendrara aquifer.

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