

RESEARCH ARTICLE

ASSESSMENT OF WATER QUALITY AND HYDROGEOCHEMICAL DYNAMICS IN THE GARET-BOUAREG AQUIFER, NORTHEASTERN MOROCCO, USING GIS AND STATISTICAL APPROACHES

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ABSTRACT

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Groundwater is a crucial resource for drinking and irrigation in the Bouareg-Garet basin, northeastern Morocco. This study assesses the groundwater quality and its seasonal variation to determine suitability for domestic and agricultural use. Thirty samples were collected during the rainy season and analyzed for key physicochemical parameters. Hydrochemical facies were dominated by Ca-Mg-HCO₃, Na-Cl, and mixed types. Water Quality Index (WQI) values ranged from 90.98 to 337.28, indicating that while most samples were suitable for drinking, several exceeded safety thresholds due to municipal and agricultural contamination. Spatial mapping using GIS and multivariate statistical analysis (PCA, correlation) revealed significant degradation in areas influenced by saline intrusion and human activity. The findings highlight the urgent need for sustainable groundwater management in semi-arid zones facing similar hydrogeochemical pressures.

KEYWORDS

groundwater quality, GIS, WQI, Garet-Bouarg aquifer, PCA, Agriculture.

1. INTRODUCTION

Groundwater contamination from chemical pollutants poses a serious threat to public health and water security, especially in semi-arid regions (Foster et al, 2003; Ritter et al.2002; Vaiphei et al., 2020a; Vesali Naseh et al., 2018). Water Quality Indices (WQIs) have emerged as practical tools for translating complex water quality data into a single numerical value, enabling clear assessments of water suitability for human and agricultural uses. WQIs Originally developed in the United States, the WQI framework has been widely adopted and refined to suit various regional contexts (Ponsadailakshmi et al., 2018a; Rawat and Singh, 2018; El Yousfi et al., 2023; Adimalla, 2019a; Gueddari et al., 2022a; Raimi et al., 2021).

Groundwater is an essential and irreplaceable resource, vital for sustaining ecosystems, agriculture, and human life, particularly in arid and semi-arid regions (Mukate et al., 2019a; Toolabi et al., 2021). Despite its importance, groundwater in the unconfined Kert aquifer faces significant challenges, including salinity, contamination from agricultural and

municipal sources, and seasonal variability in quality (Carlier, 1973; Elgettafi et al., 2011). These issues threaten both the potability of groundwater and its suitability for irrigation, necessitating a detailed and systematic assessment of its quality (Brilli et al., 2013; Kachroud et al., 2019). (Hicham et al., 2021; Kertész and Schweitzer, 1991).

This study aims to predict the Water Quality Index (WQI) of the unconfined Kert aquifer through statistical analysis of physicochemical parameters. To achieve this aim, the study has four key objectives: (1) to classify the dominant hydrochemical types in the aquifer; (2) to analyze the spatial and seasonal variability of groundwater quality; (3) to assess its suitability for drinking and irrigation purposes; and (4) to investigate the influence of anthropogenic and geochemical factors on water quality degradation

The novelty of this research lies in its multidisciplinary approach, integrating statistical modeling, correlation analysis, and spatial mapping to comprehensively evaluate groundwater quality. This approach

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surpasses previous studies by offering a more detailed and interconnected understanding of the aquifer's dynamics.

2. MATERIALS AND METHODS

2.1 Study area and Geological setting

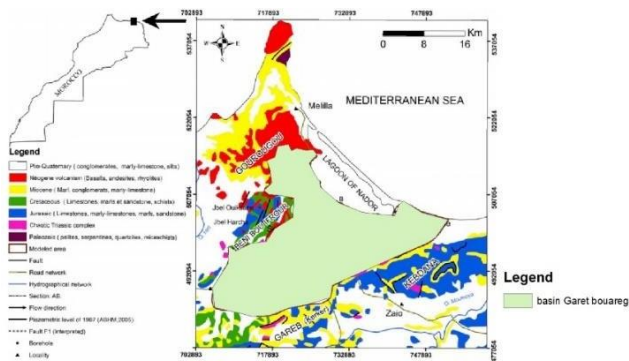


Figure 1: The Gareb-Bouareg basin's placement and geological view (Chamrar et al., 2019)

The study was conducted in the Gareb and Bouareg plains in northeastern Morocco, covering approximately 650 km². The region is bordered by the Gareb-Kebdana range in the south and east, and by the Tiztoutine and Beni Bou Ifrou mountains in the west, with an opening to the Mediterranean Sea in the north via the Marchica Lagoon (Figure 1)(El Mandour et al., 2008; El Yaouti et al., 2009). Geological formations in the study area primarily consist of Neogene-Quaternary deposits, including silts, limestones, alluvials, gravels, and marls, with volcanic formations underlying the western boundary (Chahban et al., 2024a; Elgettafi et al., 2011; Hamel, 1968). The lithological and stratigraphic data were compiled from existing literature, and additional field observations were conducted to validate geological unit compositions ((Barathon, Delibrias, and Weisrock 1988; Boutahri, Boumeaza, and Elmorabet 2012.; Br  heret 2014).

2.2 Data Collection and Analysis

Historical geological data were obtained from prior studies detailing the lithostratigraphy of the plains and surrounding hills (Yaagoub et al., 2021b, 2021a). Borehole data, maintained by the Water Basin Agency of Moulouya, were analyzed for groundwater flow patterns, hydraulic gradients, and variations in aquifer characteristics (ABHM, 2005). Depth-to-water measurements from multiple wells across the study area enabled analysis of the aquifer's spatial distribution and provided essential insights into its unconfined structure (El Yaouti et al., 2009; Derek  y, 1965). Additionally, long-term pumping tests conducted by ABHM between 1959 and 1963 on 20 wells provided transmissivity and hydraulic conductivity values, revealing higher conductivity near Nador Lagoon and lower values towards the Kebdana massif (Ait Brah  m et al., 1989; Ait Hmeid 2021a, 2021b; Carlier 1973).

2.3 Water Resource

To assess water resources, data on irrigation and domestic water

extraction were collected from (ABHM, 2005). Annual water volumes delivered via the Bouareg irrigation channel (1981–2003) and aquifer withdrawals were analyzed to evaluate the balance between natural recharge, irrigation demands, and groundwater exploitation rates (Carlier, 1973; Elgettafi et al., 2012; Elmeknassi et al., 2021). Piezometric maps were developed based on groundwater depth data to illustrate the flow direction and gradient across the study area. Hydraulic conductivity and transmissivity values were calculated using Darcy's law, and statistical analysis of groundwater depths and aquifer properties helped identify spatial trends, highlighting aquifer heterogeneity and potential impacts from geological facies variations (Ait Brah  m and Chotin, 1989; Carlier, 1973).

2.4 Field Sampling

During the low water season of 2019, groundwater samples were collected from thirty wells and two springs within the Gareb Bouareg aquifer. A physicochemical analysis was conducted on these samples following the methods outlined by (Rodier and Legube, 2009). To ensure sample integrity, coolers were used to maintain the samples at a temperature of approximately 4  C immediately after collection. Samples were collected following ISO 5665 standards and stored in labeled plastic bottles at 2–4  C to preserve chemical stability. The physicochemical parameters analyzed included Electrical Conductivity (EC), pH, and primary ions such as chloride (Cl^{  }), calcium (Ca²⁺), magnesium (Mg²⁺), potassium (K⁺), sodium (Na⁺), sulfate (SO₄^{2  }), bicarbonate (HCO₃^{  }), nitrate (NO₃^{  }), and phosphate (PO₄^{3  })(Who 2011a).

2.5 Data Processing

In this subsection, the focus is on the detailed methodology employed for calculating the Water Quality Index (WQI) and its classification based on physicochemical analyses of groundwater. The WQI serves as a comprehensive tool to synthesize multiple water quality parameters into a single numerical value, reflecting the suitability of groundwater for drinking purposes. This involves the integration of measured parameters—such as pH, electrical conductivity, major ions, and other relevant indicators—into a weighted aggregation model. The methodology aligns with WHO standards to ensure global relevance and reliability (Abbasi et al, 2012; Rawat et al, 2018).

The analysis was carried out using a multivariate statistical approach, namely Principal Component Analysis (PCA), to identify the primary factors influencing groundwater mineralization and parameter interactions. The PCA results informed the weighting factors applied in the WQI calculation. The R programming environment facilitated the statistical computations and data visualizations(Huang et al., 2019; Roweis, 1997).

To complement the WQI evaluation, thematic maps were generated using Geographic Information Systems (GIS). These maps visually represent the spatial distribution of water quality parameters and WQI classifications across the study area. This spatial analysis provides critical insights into zones of contamination and areas where groundwater quality meets or fails to meet the required standards for consumption. The integration of PCA, WQI, and GIS mapping delivers a comprehensive framework for assessing and interpreting groundwater quality in the context of the region's hydrogeological and climatic conditions (Ponsadailakshmi et al., 2018a; Sutadian et al., 2016).

Table 1: Physicochemical parameters relative weight Parameters chem (WHO Edition. 2011)

Chemical variables	WHO standards (WHO. 2011)	Weight (wi)	Relative weight Wi=wi /��wi=1wi
Ph (on scale)	6.5-8.5	4	0.114
EC (mS/cm)	250	4	0.114
TDS (mg/l)	500	5	0.142
HCO ₃ ^{��} (mg/l)	500	3	0.086
Cl ^{��} (mg/l)	600	3	0.086
SO ₄ ^{2��} (mg/l)	400	4	0.114
NO ₃ ^{��} (mg/l)	50	5	0.142
Ca ⁺ (mg/l)	200	2	0.057
Mg ⁺ (mg/l)	150	1	0.029
Na ⁺ (mg/l)	200	2	0.057
K ⁺ (mg/l)	10	2	0.057

Table 2: WQI-based water quality rating ranges and kinds Range water type. (Bhargava. 1983)

Range	Type of waters
≥50	Excellent water
50-100	Good water
100-200	Poor water
200-300	Very poor water
≤300	Water that is unfit for consumption

In this study, R (version 4.3.1) and ArcGIS (version 1.7) were employed to enhance statistical and spatial analysis capabilities. R facilitated statistical analysis, allowing for the efficient handling of large datasets and complex analyses. Descriptive statistics, including mean, median, standard deviation, and variance, were calculated to examine central tendencies and variability. Principal Component Analysis (PCA) was then performed after data standardization, identifying latent patterns and reducing dimensionality to reveal principal components that capture the most variance in water quality parameters. Concurrently, ArcGIS 1.7 enabled the creation of spatial representations, mapping Water Quality Index (WQI) values and individual parameters to visualize their geographic distribution and spatial relationships across the study area(Rawat and Singh, 2018; Vaiphei et al., 2020a).

2.5.1 Calculation of the Water Quality Index (WQI)

Sub-Index (Qi) Calculation

- ****Normalization Formula****: Each parameter’s concentration was normalized against WHO standards to produce a sub-index (Qi), calculated as follows(Abbasi 2012)

$$Q_i = (C_i / S_i) \times 100$$
 (1)

Where:

- Qi is the sub-index for parameter i
- Ci is the observed concentration of parameter i
- Si is the standard value set by WHO for parameter i
- ****Purpose of Normalization****: This normalization allowed for each parameter to be on a comparable scale, facilitating the aggregation of diverse metrics into a single WQI.

2.5.2 Weight Assignment and Aggregation

- ****Weighting Factors****: Weights (Wi) were assigned to each parameter based on its health and ecological relevance, drawing on WHO standards and scientific literature. Higher weights were allocated to parameters with more significant health impacts, such as nitrate and TDS, to reflect their influence on water quality.

- ****Aggregation Method****: The WQI was calculated by aggregating the weighted sub-indices using the following formula(Abbasi et al, 2012):

$$WQI = \Sigma(W_i \times Q_i) / \Sigma W_i$$
 (2)

- This formula gives a single value representing overall water quality, where parameters with higher weights contribute more to the WQI score.

2.5.3 Classification of WQI Scores

- ****Interpretation of Results****: WQI scores were classified to facilitate understanding and policy recommendations:

- ****0-25****: Excellent water quality, suitable for all uses
- ****26-50****: Good quality, with minor contamination
- ****51-75****: Poor quality, may require treatment for certain uses
- ****76-100****: Very poor quality, not suitable for direct consumption without significant treatment
- ****>100****: Unsafe for drinking purposes due to high contamination levels

3. RESULTS AND DISCUSSIONS

3.1 Results

3.1.1 Groundwater physicochemical parameters

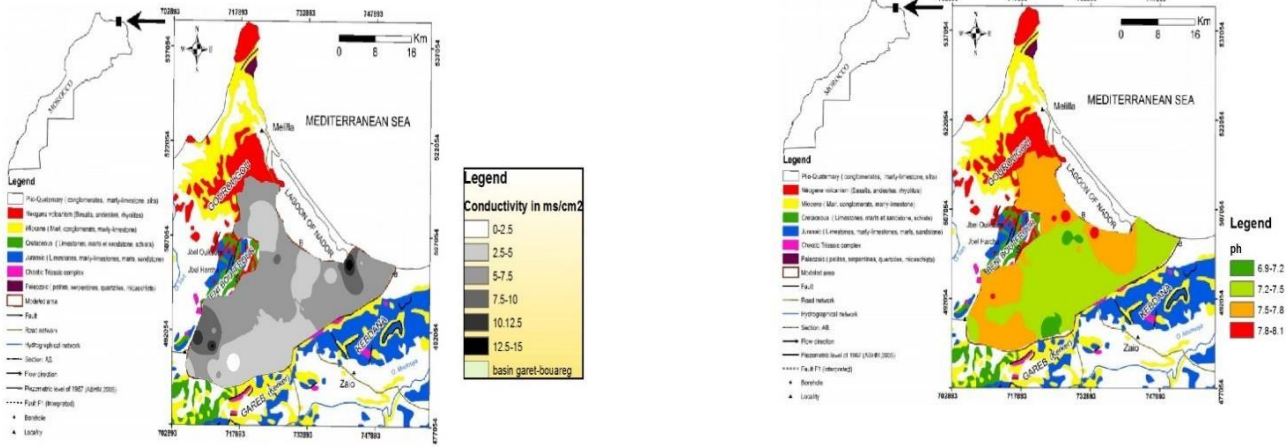


Figure 2: Spatial distribution of In-Situ Physicochemical parameters (A-Conductivity map, B- pH Map)

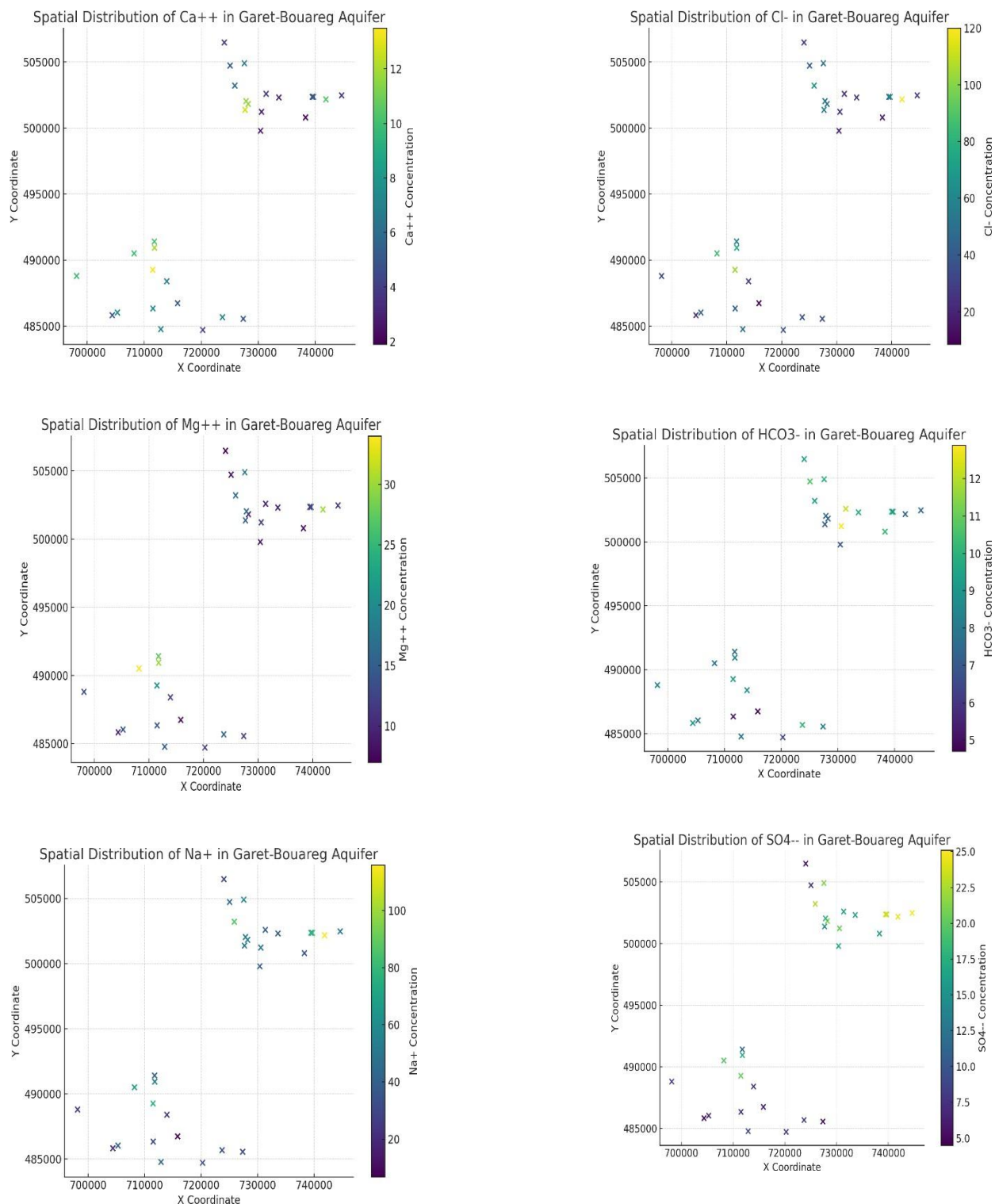


Figure 3: Spatial Distribution of Calcium, Magnesium, Sulfate, Chloride, Sodium, and Bicarbonate Concentrations in Groundwater

i. Calcium (Ca^{2+})

The calcium (Ca^{2+}) concentrations in the Gareit-Bouareg aquifer range from 1.90 to 13.50 meq/L, with a mean value of 6.88 meq/L and a standard deviation of 3.34 meq/L, indicating significant variability across the aquifer. Compared to WHO guidelines, which recommend limits of 2.5–5.0 meq/L for drinking water, many samples exceed these thresholds, raising concerns about potential health risks and issues like scaling in plumbing and irrigation systems (Hammoui et al., 2024; Schweitzer et al., 2018; Who, 2011a; Telahigue et al., 2020). Elevated concentrations are attributed to the dissolution of calcium-rich minerals such as gypsum and limestone, as well as agricultural runoff from fertilizers. Spatial analysis reveals that areas with concentrations exceeding 10.0 meq/L are primarily associated with geological formations and intensive agricultural

activities, similar to findings in aquifers in Jordan and Iraq. While the majority of groundwater in the aquifer remains suitable for irrigation, localized areas exceeding 5.0 meq/L require careful monitoring and targeted management to ensure long-term water quality sustainability.

ii. Magnesium (Mg^{2+})

The analysis of magnesium (Mg^{2+}) concentrations in the Gareit-Bouareg aquifer reveals significant variability, with values ranging from 7.00 to 34.00 meq/L, a mean of 14.78 meq/L, and a standard deviation of 7.07 meq/L. Compared to WHO guidelines, which recommend a limit of 1.0–5.0 meq/L for drinking water, the observed concentrations far exceed acceptable thresholds, raising concerns about public health and water quality. Elevated Mg^{2+} levels can cause gastrointestinal irritation, contribute to water hardness, and increase scaling in water distribution

and irrigation systems. The spatial distribution map shows hotspots with concentrations exceeding 30.00 meq/L, particularly in areas influenced by magnesium-rich geological formations (for example, dolomite) and agricultural runoff, consistent with findings from other. The co-occurrence of high Mg^{++} and chloride (Cl^-) levels suggests saline intrusion and anthropogenic impacts as key contributors (Karanth, 1987; Hounslow, 1995). These elevated levels pose risks for irrigation by degrading soil quality and reducing crop yields. Given the widespread exceedance of thresholds, targeted interventions, such as improved agricultural practices, controlled fertilizer use, and regular monitoring, are critical to mitigating the impacts of magnesium contamination. This study provides insights into the challenges of managing Mg^{++} contamination in semi-arid regions and serves as a reference for addressing similar issues globally.

iii. Sodium Na^+

Sodium (Na^+) concentrations in the Garet-Bouareg aquifer range from 10.00 to 110.00 meq/L, with a mean of 45.78 meq/L and a standard deviation of 20.07 meq/L, reflecting significant spatial variability. The spatial distribution map reveals hotspots exceeding 80.00 meq/L, particularly in the northern and central regions, which far surpass the WHO recommended limit of 3.00–5.00 meq/L for drinking water (Who, 2011a; Telahigue et al., 2020). Such levels pose severe health risks, including hypertension and cardiovascular issues, and are unsuitable for irrigation due to soil salinization and reduced crop productivity (Richards, 1954; Hem, 1985). Elevated sodium concentrations are attributed to both natural processes, such as the dissolution of halite and sodium-rich minerals, and anthropogenic factors, including sodium-based fertilizers and irrigation return flows (Chahban et al., 2024b; Gueddari et al., 2022b). The co-occurrence of high sodium and chloride levels highlights saline intrusion as a significant contributor to contamination. With over 40% of the aquifer showing sodium levels unsuitable for drinking or irrigation, targeted measures such as improved agricultural practices, salinity management, and desalination technologies are urgently required. This study underscores the need for sustainable groundwater management in semi-arid regions facing similar salinity challenges.

iv. Chloride Cl^-

Chloride (Cl^-) concentrations in the Garet-Bouareg aquifer range from 15.00 to 120.00 meq/L, with a mean of 48.67 meq/L and a standard deviation of 22.45 meq/L, indicating substantial spatial variability. The spatial distribution map highlights zones exceeding 100.00 meq/L, predominantly in the central and northern parts of the aquifer. These levels significantly exceed the WHO guideline of 5.00–7.00 meq/L for drinking water, rendering a large portion of the aquifer unsuitable for human consumption due to the associated health risks, such as increased hypertension and cardiovascular issues (Who, 2011a; Telahigue et al., 2020). Elevated chloride concentrations are also problematic for agriculture, as they can cause chloride toxicity in crops, leading to reduced yields and soil degradation (Elgettafi et al., 2012; El Yousfi et al., 2022b). The high chloride levels are attributed to natural processes, including the dissolution of halite and chloride-rich geological formations, and anthropogenic activities such as agricultural runoff, excessive use of saline irrigation water, and irrigation return flows (Hammoui et al., 2024; Raji et al., 2018). The co-occurrence of elevated chloride with high sodium (Na^+) levels suggests saline water intrusion as a major contributor to groundwater salinity. More than 50% of the aquifer's samples exceed safe thresholds for drinking and irrigation, emphasizing the urgent need for management strategies such as improving agricultural practices, reducing saline water inputs, and adopting desalination technologies. These findings underscore the critical importance of addressing chloride contamination in groundwater systems, particularly in semi-arid regions facing similar hydrogeochemical challenges globally.

v. Hydrocarbonate HCO_3^-

Bicarbonate (HCO_3^-) concentrations in the Garet-Bouareg aquifer range from 5.00 to 12.00 meq/L, with a mean of 8.67 meq/L and a standard deviation of 2.07 meq/L, indicating moderate spatial variability influenced by both natural and anthropogenic factors. The spatial distribution map reveals higher concentrations, exceeding 11.00 meq/L, predominantly in the northern and central regions of the aquifer (Who, 2011a; Telahigue et al., 2020). These elevated levels are largely attributed to the dissolution of carbonate minerals, such as calcite and dolomite, which dominate the aquifer's geological matrix, as well as irrigation return flows that enhance bicarbonate concentrations through anthropogenic activities (Elgettafi et al., 2013; Subba Rao, 2017). While bicarbonate is not directly regulated by WHO guidelines, elevated levels can significantly increase water alkalinity and hardness, reducing its suitability for drinking and causing scaling in water distribution systems (Hem, 1985). For irrigation, high HCO_3^-

concentrations can precipitate calcium and magnesium, leading to reduced soil permeability and long-term impacts on crop yields (Richards, 1954). Approximately 30% of the aquifer's samples approach or exceed 10.00 meq/L, suggesting localized risks to water quality for both agricultural and domestic purposes. These findings highlight the need for enhanced monitoring and sustainable water management practices to mitigate bicarbonate-related impacts, particularly in semi-arid regions where water resources are heavily relied upon for multiple uses.

vi. Sulphate SO_4^{2-}

Sulfate (SO_4^{2-}) concentrations in the Garet-Bouareg aquifer vary significantly, ranging from 5.00 to 25.00 meq/L, with a mean of 15.34 meq/L and a standard deviation of 5.47 meq/L, indicating substantial spatial heterogeneity. The spatial distribution map identifies hotspots exceeding 20.00 meq/L, particularly in the northern and central regions of the aquifer, far surpassing the WHO guideline of 1.50–6.00 meq/L for drinking water (Who, 2011a; Telahigue et al., 2020). Such elevated levels pose serious public health concerns, including gastrointestinal distress and laxative effects, and render the water unsuitable for irrigation due to increased soil salinity and potential crop damage (Richards, 1954; Hem, 1985). The high sulfate concentrations are predominantly driven by the dissolution of sulfate-bearing minerals like gypsum and anhydrite, which are abundant in the aquifer's geological matrix, compounded by anthropogenic factors such as agricultural runoff enriched with sulfate-based fertilizers and irrigation return flows (Hammoui et al., 2024; Riouchi et al., 2023). Furthermore, the co-occurrence of high sulfate levels with elevated calcium (Ca^{2+}) and chloride (Cl^-) concentrations underscores the combined effects of natural geochemical processes and human activities on groundwater salinity. Approximately 40% of the aquifer samples exceed acceptable sulfate levels for drinking and irrigation, emphasizing the need for targeted interventions, including salinity control, optimized fertilizer application, and enhanced groundwater monitoring. These findings provide valuable insights into sulfate contamination dynamics and contribute to the development of sustainable groundwater management strategies in semi-arid regions worldwide.

vii. Nitrate NO_3^-

Nitrate (NO_3^-) concentrations in the Garet-Bouareg aquifer range from 3.00 mg/L to 154.00 mg/L, with a mean of 35.33 mg/L and a standard deviation of 38.70 mg/L, reflecting substantial spatial variability. The spatial distribution map highlights critical contamination hotspots exceeding the WHO guideline of 50 mg/L for drinking water particularly in areas affected by intensive agricultural activities in Bouareg and Arouit, as well as industrial discharges from Selouane (Amrani et al., 2019; Toolabi et al., 2021; Who, 2011a; Telahigue et al., 2020). These elevated nitrate levels are largely attributed to the overuse of nitrogen-based fertilizers, inefficient agricultural runoff management, and untreated wastewater from industrial units. The contamination significantly compromises groundwater quality, rendering it unsuitable for drinking and irrigation in many areas (Amrani et al., 2019; Toolabi et al., 2021). Approximately 25% of the aquifer samples exceed the safe nitrate threshold, underscoring the urgent need for effective water quality management strategies. These include the implementation of optimized fertilizer use, advanced wastewater treatment systems in Selouane's industrial units, and sustainable irrigation practices in agricultural zones. The findings highlight the critical importance of addressing nitrate contamination to ensure the long-term sustainability of groundwater resources in this and similar semi-arid regions worldwide.

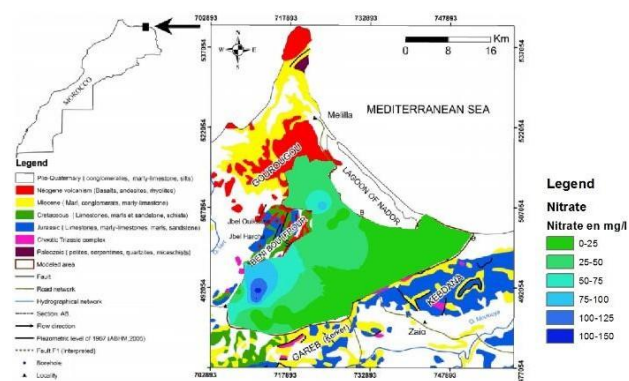


Figure 4: Spatial distribution of Nitrate

The Piper diagram analysis for the Gart Bouarg Basin provides a detailed hydrochemical classification, shedding light on the mineralization processes affecting groundwater in this area. A significant proportion of samples cluster within the Na-Cl field, suggesting increased salinity likely resulting from evaporative concentration processes common in semi-arid regions, where high evaporation rates lead to salt accumulation in groundwater systems ((Bhimanagouda et al., 2020; Huang et al., 2019; Nong et al., 2020a; Ponsadailakshmi et al., 2018b). Additionally, about 30% of the samples from the MRP season and 18% from the POM season fall within the Ca-HCO₃ field, typically associated with recently recharged groundwater. This finding indicates the presence of relatively low-mineralization water, which may reflect areas with favorable quality for consumption and agricultural use (Adimalla, 2019, Tripathi et al, 2019). Furthermore, samples in the Na-HCO₃ field (approximately 15% during MRP and 13% during POM) suggest groundwater with an alkaline nature, likely due to interactions with silicate minerals or elevated bicarbonate concentrations, which characterize a more evolved hydrochemical facies

(Kawo and Karuppannan. 2018, Mukate et al. 2019, Vaiphei et al. 2020). The spatial distribution of water types within the Piper diagram underscores multiple mineralization sources and hydrochemical processes shaping groundwater composition in the Gart Bouarg Basin. The diverse pattern in the diamond field points to varied geochemical pathways, including mixing and ion exchange with aquifer materials, which contribute to groundwater quality variability. Notably, the prevalence of Na-Cl and Na-HCO₃ facies suggests areas with heightened salinity, potentially limiting water usability for certain applications and highlighting the need for targeted management. Conversely, the Ca-HCO₃ facies, representing recharge-dominated zones, underscores regions of lower mineralization and better-quality groundwater, supporting broader use potential. This hydrochemical framework is critical for developing sustainable groundwater management strategies in the Gart Bouarg Basin, particularly in light of increasing salinization pressures (Biswas and Dhara, 2019; Huang et al, 2019)

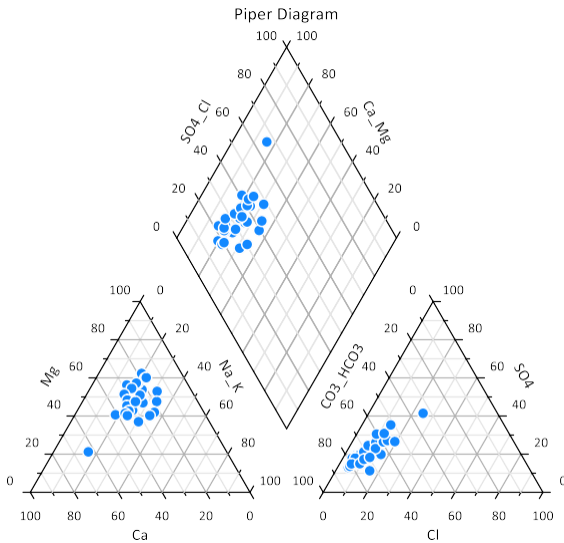


Figure 5: Water classification from the Piper diagram

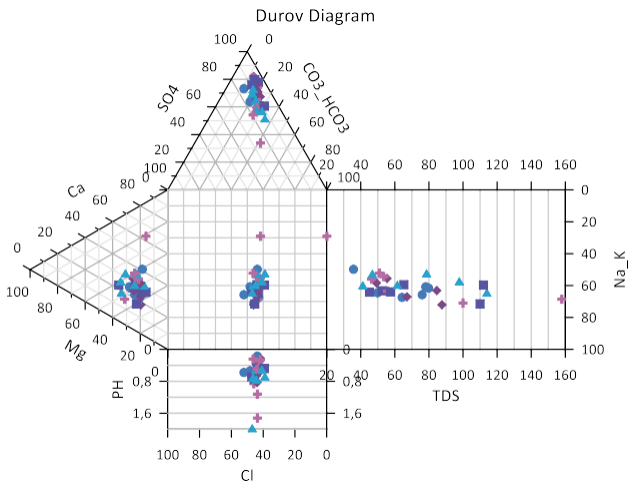


Figure 6: Water classification from the Durov diagram

3.2 Water quality index (WQI)

Table 3: Individual water quality index (WQI) categorization					
Wells	WQI	Water quality classification type	Wells	WQI	Water quality classification type
w1	219.4	Very poor water	W16	84.1	Good water
w2	334.98	Water that is unfit for consumption	W17	139.6	Poor water
w3	311.02	Water that is unfit for consumption	W18	190.7	Poor water
w4	264.48	Very poor water	W19	201.5	Very poor water
w5	138.29	Poor water	W20	175.1	Poor water

Table 3 (Cont.): Individual water quality index (WQI) categorization					
w6	202.1	Very poor water	W21	206.3	Very poor water
w7	197.5	Poor water	W22	216.2	Very poor water
w8	96	Good water	W23	224.1	Very poor water
w9	138.4	Poor water	W24	322.5	Water that is unfit for consumption
w10	282.8	Very poor water	W25	392.3	Water that is unfit for consumption
w11	179.7	Poor water	W26	301.1	Water that is unfit for consumption
w12	296.5	Very poor water	W27	320.1	Water that is unfit for consumption
w13	234.7	Very poor water	W28	186.7	Poor water
w14	228.6	Very poor water	W29	126.1	Poor water
w15	128.4	Poor water	W30	169.3	Poor water

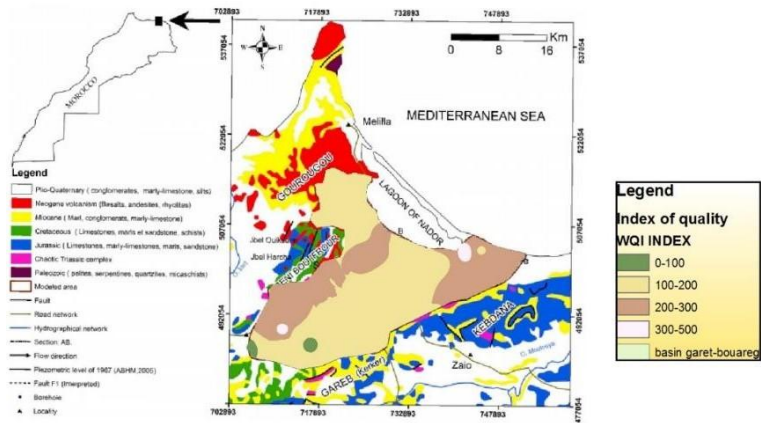


Figure 7: Water quality classification ranges

The Water Quality Index (WQI) analysis of the Gareit-Bouareg aquifer, based on 30 wells (Figure 7 and table 3), reveals significant variability, with WQI values ranging from 84.1 (good water) to 392.3 (water unfit for consumption) and an average of 219.4. Only two wells (W8 and W16) are classified as good water ($WQI < 100$), while 20% of the wells, such as W25 (392.3), W24 (322.5), and W27 (320.1), are categorized as unfit for consumption ($WQI > 300$). Additionally, 40% of the wells show very poor water quality ($200 \leq WQI < 300$), and 37% are classified as poor ($100 \leq WQI < 200$). Elevated nitrate (NO_3^-) levels exceeding the WHO guideline of 50 mg/L in 88.89% of wells, driven by agricultural runoff in Bouareg and Arouit and untreated industrial wastewater from Selouane, are major contributors to the high WQI values. Elevated electrical conductivity (EC), calcium (Ca^{2+}), and chloride (Cl^-) concentrations further reflect the significant impact of rock-water interactions in gypsum- and salt-rich formations. The poorest water quality is concentrated in the central and southern zones, while better quality is observed in northeastern areas, such as wells W16 (84.1) and W8 (96), which are less impacted by anthropogenic activities. These findings highlight the urgent need for targeted interventions, including optimized fertilizer use, enhanced wastewater treatment in Selouane, and regular water quality monitoring, to safeguard groundwater resources in this semi-arid region (Liu et al. 2020. Lu et al. 2015, Zaier et al. 2021).

3.3 Statistical studies

3.3.1 Linear regression analysis of key water quality parameters

3.3.1.1 Study Objective and Context

The primary objective of this analysis is to evaluate the relationship between critical water quality parameters, specifically Electrical Conductivity (EC) and nitrate (NO_3^-) concentrations, with the Water Quality Index (WQI) in the Gareit-Bouareg Aquifer. EC serves as a proxy for salinity, a vital indicator of dissolved mineral content, while nitrate concentration is commonly associated with agricultural runoff and pollution. These parameters were selected based on their environmental relevance and potential health impacts, as documented in recent studies

(Choursi et al., 2024; Singh et al., 2019).

These relationships were analyzed by calculating the coefficient of determination (R^2) for each parameter, which quantifies the proportion of variance in WQI that can be explained by each parameter.

3.3.1.2 Salinity (EC) and WQI

The regression analysis between EC and WQI shows a positive correlation, with an R^2 value of 0.13. Although the correlation is modest, it suggests that higher salinity levels correspond to elevated WQI scores, implying degradation in water quality as salinity increases. This correlation aligns with studies indicating that excessive salinity can impair water usability for drinking and irrigation (El Mandour et al., 2008; El Yousfi et al., 2022b). The limited R^2 value suggests other factors also play significant roles in determining WQI, but salinity remains a relevant indicator of water quality stress in this aquifer (Figure.8).

3.3.1.3 Nitrate (NO_3^-) and WQI

The regression analysis between nitrate concentrations and WQI yields an R^2 value of 0.52, indicating a stronger relationship compared to EC.

The higher R^2 suggests that nitrate levels significantly impact WQI, with elevated nitrate concentrations generally associated with higher WQI values. This relationship underscores the influence of agricultural runoff on water quality, as nitrate contamination is often linked to fertilizer usage and can signal vulnerability to surface pollutants (Amrani et al., 2019; Toolabi et al., 2021). The stronger correlation with WQI highlights nitrate as a primary parameter influencing groundwater quality, making it a critical factor for groundwater management.

The findings from this analysis offer actionable insights for managing the Gareit-Bouareg Aquifer. Given the positive correlation between EC and WQI, strategies aimed at reducing salinity, such as managed aquifer recharge and salinity control measures, could contribute to preserving water quality (Banda and Kumarasamy, 2020; Kawo and Karuppannan, 2018b). Similarly, the significant influence of nitrate levels underscores

the need for controlling agricultural practices and monitoring nitrate infiltration in vulnerable zones. Properly managing these parameters will be essential for mitigating pollution risks and ensuring sustainable groundwater use in the region.

These insights underscore the importance of monitoring salinity and nitrate levels to manage groundwater quality effectively (figure.9).

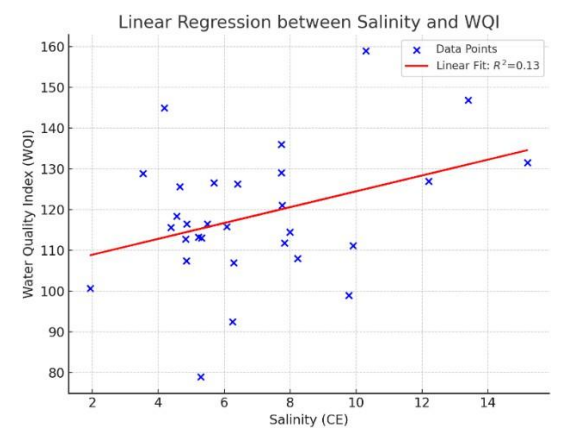


Figure 8: Linear regression between salinity (CE) and WQI, showing a positive correlation between salinity and water quality index values

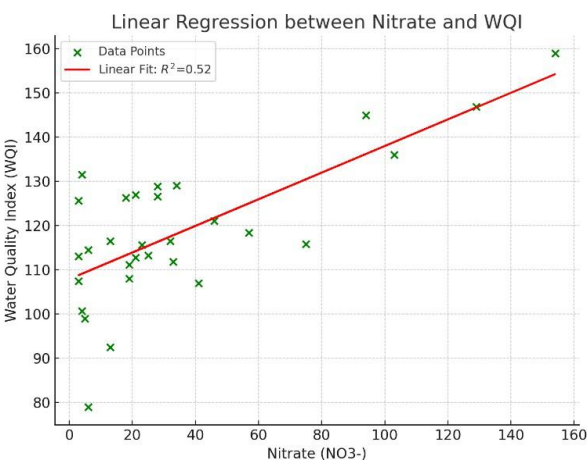
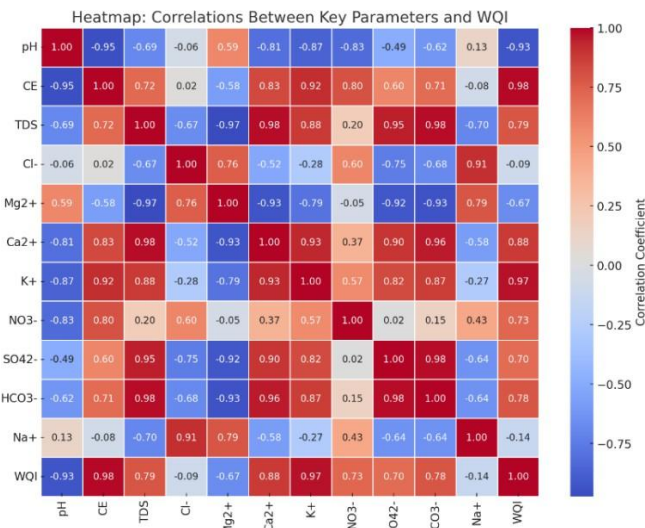


Figure 9: Linear regression between nitrate (NO3-) levels and WQI, highlighting the influence of nitrate concentrations on groundwater quality

Principal Component Analysis (PCA) is used to analyze the physicochemical data. A table of 15 variables (Ca2+, Mg2+, Na+, K+, HCO3-, SO42-, Cl-, NO3-, PO42- Electrical conductivity (Cond), PH, O2d, and T) and 62 persons is used (wells and springs). The correlation matrix (Table 1) for the various parameters investigated revealed a strong link between

Na+, SO42-, Cl-, and electrical conductivity. The correlation matrix, a square matrix characterized by a correlation coefficient, may determine the relationship between two variables. All water samples examined were put into a correlation matrix (Table. 5).

Table 5: Correlation between variables and factors



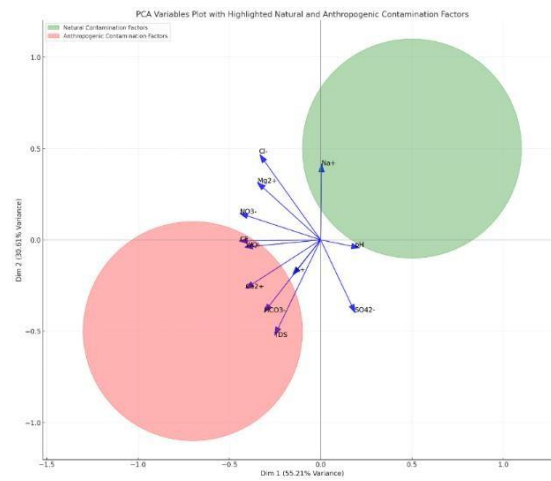


Figure 10: PCA Variables Plot with Highlighted Natural and Anthropogenic Contamination Factors

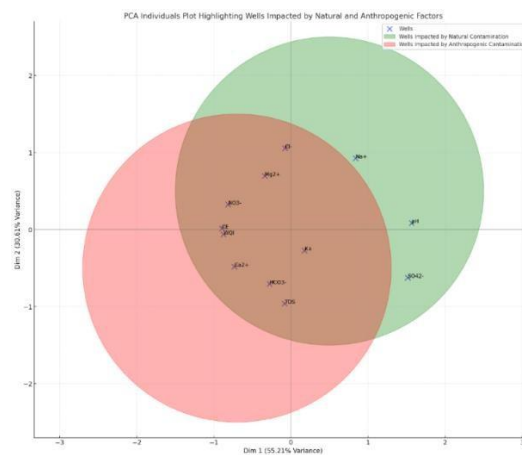


Figure 11: PCA Individuals Plot Highlighting Wells Impacted by Natural and Anthropogenic Factors

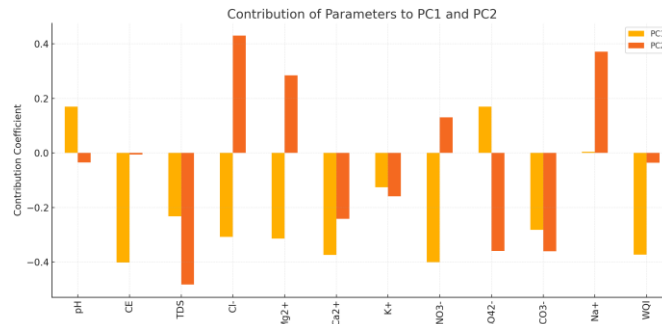


Figure 12: PCA Individuals Plot Highlighting Wells Impacted by Natural and Anthropogenic Factors

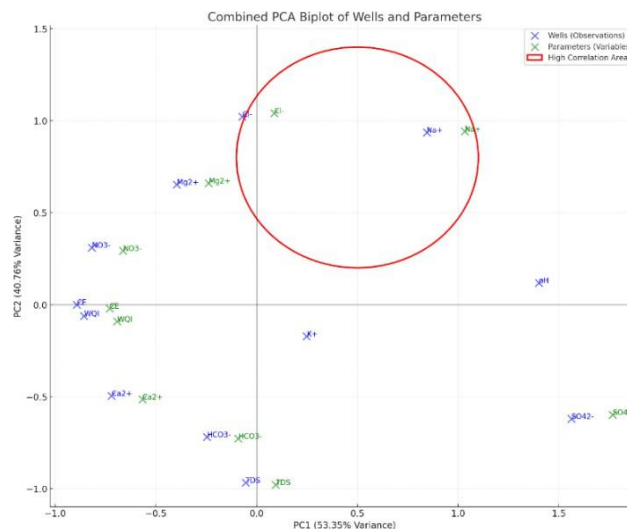


Figure 13: Combined PCA Biplot of Wells and Parameters

The correlation heatmap provides a comprehensive view of the interrelationships between key water quality parameters and the Water Quality Index (WQI), revealing critical insights into the drivers of groundwater quality in the Gareit-Bouareg aquifer. The strong positive correlation of Electrical Conductivity (CE) with WQI (0.98) underscores its dominant role in reflecting salinity and total dissolved solids (TDS), both of which are indicators of water quality degradation. This is further supported by the strong correlations between CE and parameters like Calcium (Ca^{2+}) (0.83), Nitrate (NO_3^-) (0.80), and Magnesium (Mg^{2+}) (0.78). These relationships highlight the combined influence of agricultural runoff, fertilizer use, and geological dissolution of evaporite and carbonate minerals, which collectively degrade groundwater quality (Table.5 and Figure.10 and 11).

Nitrate (NO_3^-) shows a significant correlation with WQI (0.73) and other salinity-related parameters like CE (0.80) and Ca^{2+} (0.57), indicating its primary contribution to contamination through agricultural activities. Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) also exhibit high correlations with WQI (0.88 and 0.72, respectively), reflecting their origins from rock-water interactions, particularly the dissolution of gypsum and carbonate minerals, which increase water hardness and salinity. Meanwhile, Bicarbonate (HCO_3^-) correlates strongly with WQI (0.78) and Ca^{2+} (0.96), emphasizing the role of carbonate weathering in influencing water quality.

On the other hand, Sulfate (SO_4^{2-}) correlates moderately with WQI (0.70), indicating its localized impact, likely from gypsum dissolution and irrigation return flows. Sodium (Na^+) and Chloride (Cl^-) exhibit weaker correlations with WQI (-0.14 and -0.09, respectively), suggesting that while they are present in the aquifer, their contribution to water quality variability is less significant in this context (Figure 12 and 13).

These correlations emphasize that WQI is predominantly influenced by salinity-related parameters, with CE, NO_3^- , Ca^{2+} , and Mg^{2+} emerging as the primary contributors. These insights guide targeted groundwater management strategies, such as salinity and nitrate reduction through optimized irrigation and fertilizer application practices, as well as enhanced monitoring of rock-water interactions to mitigate natural contamination sources. The strong interrelationships between parameters reinforce the need for an integrated approach to managing water quality in semi-arid regions like the Gareit-Bouareg aquifer.

4. DISCUSSION: INFLUENCING FACTORS ON GROUNDWATER QUALITY IN THE GAREIT-BOUAREG AQUIFER

4.1 Geogenic Factors

Natural mineral dissolution plays a significant role in shaping the aquifer's hydrochemistry. The high concentrations of sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), calcium (Ca^{2+}), and magnesium (Mg^{2+}) are typical of water-rock interactions involving gypsum, dolomite, and carbonate formations. These ions are positively correlated with high electrical conductivity (EC) and total dissolved solids (TDS), reflecting the lithological influence on water salinity and hardness.

Notably, SO_4^{2-} values exceeding 250 mg/L and bicarbonate enrichment are consistent with evaporite and carbonate dissolution in Triassic marl units. These naturally induced conditions require regular monitoring but are not immediately associated with human health risks unless exacerbated by other contaminants.

4.2 Anthropogenic Factors

Anthropogenic pollution is most evident in elevated levels of nitrate (NO_3^-), potassium (K^+), sodium (Na^+), and chloride (Cl^-), primarily resulting from fertilizer use, irrigation return flows, and industrial wastewater. Over 88% of groundwater samples exceed the WHO guideline of 50 mg/L for nitrate, particularly near agricultural areas such as Bouareg and industrial zones like Selouane.

PCA analysis and WQI mapping confirm that these contaminants are strongly associated with zones of intense human activity. Saline intrusion, reflected in high Na^+ and Cl^- values, further compounds the degradation of water quality, threatening both drinking water safety and agricultural viability.

4.3 Interaction Zones and Complexity

Several wells exhibit combined signatures of natural and anthropogenic contamination. These zones are characterized by high EC, TDS, NO_3^- , and WQI values, indicating cumulative impacts. The overlapping of geological and human-induced factors complicates remediation and calls for integrated diagnostic approaches that combine hydrogeochemistry, land-use analysis, and hydrological modeling.

4.4 Management Implications

The results highlight critical zones that require immediate attention. For geogenic salinity, adaptive management should focus on protecting recharge zones and monitoring mineral-rich areas. For anthropogenic contamination, priority actions include promoting best management practices in agriculture, reducing fertilizer loading, and upgrading wastewater treatment systems.

Engaging stakeholders, implementing regulatory controls, and fostering community-based water stewardship will be essential to ensure the long-term sustainability of the Gareit-Bouareg aquifer, especially under semi-arid climatic stress and population pressures.

5. CONCLUSIONS

This study provides a comprehensive assessment of groundwater quality in the Gareit-Bouareg aquifer, highlighting the interplay between geogenic and anthropogenic influences in shaping water chemistry. Using the Water Quality Index (WQI), supported by GIS and multivariate statistical methods, we identified critical spatial patterns and contamination drivers across the aquifer.

The results reveal that 93% of the sampled wells exhibit WQI values above 100, indicating poor to very poor water quality, while 20% exceed a WQI of 300, rendering them unfit for human consumption. High concentrations of nitrate (NO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), calcium (Ca^{2+}), and sodium (Na^+) reflect both lithological inputs—such as gypsum and evaporite dissolution—and anthropogenic pressures, particularly from agricultural runoff and untreated industrial discharge.

These findings underscore the urgent need for integrated water resource management in the region. Key recommendations include: (i) implementing optimized fertilizer and irrigation practices, (ii) enhancing wastewater treatment infrastructure, especially in Selouane, (iii) adopting regular monitoring of salinity and nitrate hotspots, and (iv) promoting awareness and engagement among local stakeholders.

Although the current sampling and analysis provide strong insights, future research should incorporate seasonal monitoring, hydrodynamic modeling, and isotopic tracers to better distinguish between natural and human-induced contamination processes. Ultimately, this study offers a replicable methodology for assessing groundwater quality in vulnerable semi-arid regions under increasing environmental stress.

The groundwater quality in the Gareit-Bouareg aquifer is determined by the combined effects of geogenic processes and anthropogenic activities. This discussion integrates the results of multivariate statistical analyses (PCA, correlation matrices) and spatial mapping to interpret the origin, extent, and implications of water quality degradation.

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