

# Physicochemical quality and irrigation suitability of groundwater resources in the Feija aquifer (southeastern Morocco)

Hamid Nadi<sup>1)</sup> , Fathalah Elwahab<sup>\*2), 3)</sup> , Hicham Ouhakki<sup>1)</sup> ,  
Mehdi Boudraïne<sup>1), 4)</sup> , Hanae Marjaa<sup>5)</sup> , Nabila Auajjar<sup>1)</sup> ,  
Naima Dohou<sup>6)</sup> , Khalid Yamni<sup>7)</sup> , Moulay Laarbi Ouahidi<sup>1)</sup> 

<sup>1)</sup> Ibn Tofail University, Faculty of Sciences, Department of Biology, Laboratory of Biology and Health,  
B.P. 133, 14000, Kenitra, Morocco

<sup>2)</sup> Ibn Tofail University, Faculty of Sciences, Laboratory of Botany, Biotechnologies, and Plant Protection,  
B.P. 133, 14000, Kenitra, Morocco

<sup>3)</sup> Regional Center of Agricultural Research of Kenitra, B.P. 257, 14000 Kenitra, Morocco

<sup>4)</sup> Ministry of National Education, Preschool and Sports, Place Al-Nasr, Bab Rouah – Rabat, Morocco

<sup>5)</sup> Ibn Tofail University, Faculty of Science, Laboratory of Natural Resources and Sustainable Development, B.P. 133,  
14000 Kenitra, Morocco

<sup>6)</sup> Ibn Zohr University, Faculty of Sciences, Laboratory of Plant Biotechnologies, B.P. 8106, Cité Dakhla, 80000 Agadir, Morocco

<sup>7)</sup> Regional Centre for Education and Training (CRMEF), Natural Sciences and Didactic Innovation Team,  
Rabat-Salé-Kénitra, Avenue Allal El Fassi, B.P. 6210, 10000 Rabat, Morocco

\* Corresponding author

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**Abstract:** Groundwater is the primary water resource in the arid Feija plain (Zagora, Morocco), but its quality is increasingly threatened by climate change and intensive agriculture. This study assessed the physicochemical quality and irrigation suitability of the Feija aquifer. Over three years (2022–2024), 96 groundwater samples were collected from eight wells (P1–P8) in all four seasons to assess spatial and temporal variability. Physicochemical parameters, including pH, electrical conductivity (EC), and major ions, were analysed. The results indicate high mineralisation, with a mean EC of 2934.14  $\mu\text{S}\cdot\text{cm}^{-1}$  and significant spatial heterogeneity. Correlation analysis and principal component analysis (PCA) identified two dominant processes: a salinity gradient driven by natural water–rock interactions and evaporative concentration, and a pollution gradient linked to diffuse agricultural inputs (nitrates and bicarbonates). Seasonal box plots identify summer as a critical period, with nitrate concentrations frequently exceeding the 50  $\text{mg}\cdot\text{dm}^{-3}$  drinking-water threshold and EC values peaking in autumn. High sodium and chloride concentrations indicate a sodium–chloride hydrochemical facies, with agricultural intensification contributing to groundwater degradation. Irrigation-suitability indices calculated from the mean ionic composition (sodium adsorption ratio, SAR  $\approx 3.4$ ; permeability index, PI  $\approx 67\%$ ) indicate a high to very high salinity hazard (Richards' USSS classes C3–C4, based on measured EC), a low sodium hazard (class S1) and a permissible to good permeability class (Doneen class II). Salinity, rather than sodicity, is therefore the main constraint on irrigation use.

**Keywords:** Feija aquifer, groundwater quality, irrigation suitability, multivariate statistics, nitrate contamination, physicochemical quality

## INTRODUCTION

Groundwater is a vital natural resource in arid and semi-arid regions worldwide, providing a primary source of freshwater for domestic, industrial, and agricultural purposes. In these water-scarce environments, where surface water is often ephemeral, aquifers provide an important buffer against prolonged droughts and shifting precipitation patterns (Wada *et al.*, 2010). However, rapid population growth and the intensification of agricultural practices have increased pressure on these reserves, leading to severe depletion and deteriorating water quality (Li *et al.*, 2021).

In Morocco, water scarcity is a serious challenge exacerbated by climate change and recurrent drought cycles (Schilling *et al.*, 2012; Hssaisoune *et al.*, 2020). The southeastern part of the country, particularly the Drâa River basin and the Zagora region, is among the most vulnerable arid areas (Karmaoui *et al.*, 2019). Within this area, the Feija aquifer supports the regional economy by sustaining domestic water supply and an expanding agricultural sector dominated by date palm oases and intensive watermelon cultivation (Lamqadem, Saber and Pradhan, 2019; Nadi *et al.*, 2025). The sustainability of these activities is closely linked to the physicochemical quality of the available groundwater.

Despite its importance, the Feija aquifer is increasingly threatened by anthropogenic impacts and natural hydrogeochemical constraints (Bouchaou *et al.*, 2008). High evaporation rates, low annual rainfall, and excessive groundwater pumping accelerate salinisation (Bouchaou *et al.*, 2008). Furthermore, intensive use of chemical fertilisers and plant-protection products in modern agriculture has led to the leaching of nitrates and other contaminants into the water table, a pattern already documented in other intensively cultivated Moroccan plains such as the Saïss and the Gharb (Berni *et al.*, 2021; El Bouzaidi *et al.*, 2022).

Continued use of highly mineralised or sodic groundwater for irrigation can alter soil permeability and structure, ultimately reducing crop yields and threatening regional food security (Richards, 1954; Wilcox, 1955).

Although the wider Drâa basin has been investigated, detailed local assessments of the Feija aquifer's hydrochemical facies and suitability for irrigation under intensive farming remain scarce. Understanding the processes that govern groundwater chemistry in the plain, including water-rock interactions, ion exchange and evaporation, is essential for implementing effective management strategies (Appelo and Postma, 2005).

This study therefore aims to assess the physicochemical quality of the groundwater in the Feija aquifer. The objectives are to (1) determine the hydrochemical facies and the main geochemical processes controlling water mineralisation using multivariate statistics, an approach increasingly applied to Moroccan agri-environmental datasets (cf. Elwahab *et al.*, 2025); (2) evaluate the spatial distribution of water quality parameters; and (3) classify groundwater suitability for irrigation using established hazard indices, including the sodium adsorption ratio (SAR) and permeability index (PI) (Richards, 1954; Wilcox, 1955). The findings provide a baseline to inform sustainable agricultural and water management practices in southeastern Morocco.

## MATERIALS AND METHODS

### STUDY AREA

The Feija plain (Zagora Province, eastern Morocco) lies in the arid pre-Saharan zone, which has a desert climate with low rainfall and high evaporation (Fig. 1). Groundwater is therefore

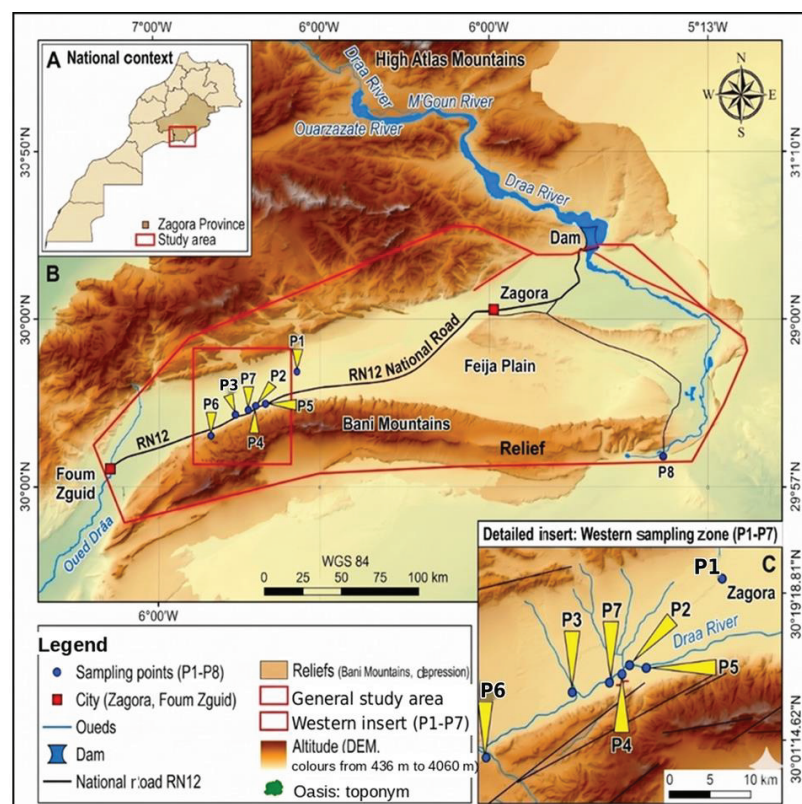


**Fig. 1.** Geological map of the Feija plain: A) national context showing the location of Zagora Province and the study area within Morocco, B) general study area with sampling points (P1–P8), the Drâa River, Zagora dam, and the RN12 national road, C) detailed inset of the western sampling zone (P1–P7); source: own elaboration

essential for irrigation and domestic use. The plain lies within the Drâa watershed and contains sand, silt and gravel alluvium through which groundwater circulates. It covers approximately 1,000 km<sup>2</sup> on the right bank of the Drâa River (Oued Drâa), south of Zagora. Figure 1 shows the Feija aquifer boundary, the investigated wells (P1–P7) and the reference well (P8).

The plain is a synclinal depression underlain by schist. It extends approximately 80 km from west to east and is bounded by mountains on both sides. Its upper part measures approximately 8–12 km and extends eastwards to the Drâa Valley, the main drainage system of the plain. Sediment deposition has shifted the course of the Feija slightly southwards. The terrain slopes gently southwards at approximately 0.7% and eastwards at 0.3% along the RN12 road connecting Zagora and Fom Zguid.

### SAMPLING AND ANALYTICAL PROCEDURES

Groundwater sampling was conducted over three consecutive years (2022, 2023, and 2024) to assess spatial and temporal variability in water quality. Eight sampling wells (P1–P8) were selected, with well P8 designated as a control site as a reference for interpreting variation at the other sites. The sampling sites were chosen to represent spatial variation and the main hydrochemical conditions across the study area. Sampling was conducted in all four seasons: winter (S1), spring (S2), summer (S3), and autumn (S4). Each year  $\times$  season  $\times$  well combination (P1–P8, including the reference well) was analysed to characterise groundwater hydrochemistry. Well selection was guided by three criteria: (i) year-round accessibility and operational status over the full 2022–2024 monitoring period; (ii) spatial coverage of the main land-use gradient across the plain, from zones under intensive irrigated date-palm and watermelon cultivation to areas with comparatively limited agricultural pressure; and (iii) the selection of well P8, outside the main irrigated area, as a hydrochemical reference for the least disturbed groundwater conditions.

### ANALYSED PARAMETERS

The groundwater quality assessment was based on the analysis of physicochemical parameters grouped into three main categories.

#### *In situ* physicochemical parameters

*In situ* physicochemical parameters were measured in the field at sampling to avoid changes during transport or storage. Hydrogen potential (pH), water temperature (*T*), dissolved oxygen (DO), and electrical conductivity (*EC*) were determined using portable multiparameter instruments calibrated according to the manufacturers' recommendations. The probes were rinsed with site water prior to each measurement to ensure the accuracy of the results.

#### Major ions

Major ions were analysed in the laboratory in water samples collected in clean bottles and stored at 4°C. Chloride (Cl<sup>−</sup>), bicarbonate (HCO<sub>3</sub><sup>−</sup>), and total hardness were determined by titrimetry according to standard methods for the analysis of natural waters. The concentrations of sodium (Na<sup>+</sup>), calcium (Ca<sup>2+</sup>), magnesium (Mg<sup>2+</sup>), potassium (K<sup>+</sup>), and sulphate (SO<sub>4</sub><sup>2−</sup>) were measured using chemical or spectrophotometric methods, in accordance with standardised protocols.

#### Nutrient and aggregate parameters

Nutrient parameters, including ammonium (NH<sub>4</sub><sup>+</sup>), nitrate (NO<sub>3</sub><sup>−</sup>), and nitrite (NO<sub>2</sub><sup>−</sup>), were determined by spectrophotometry following appropriate sample preparation. Total alkalinity (*TA*) and total hardness (*TH*) were evaluated by titrimetry using specific indicators and standard solutions. Concentrations are expressed in mg·dm<sup>−3</sup>, whereas *EC* is expressed in  $\mu$ S·cm<sup>−1</sup> and ionic balance parameters expressed in meq·dm<sup>−3</sup>, where applicable.

### ANALYTICAL METHODS

Analyses were conducted in accordance with standard protocols for the examination of natural waters. The *in situ* parameters (pH, temperature, *EC*, and DO) were measured directly in the field using calibrated portable instruments. Major ions and nutrient parameters were determined in the laboratory following standardised analytical methods, including titrimetry for bicarbonates and total hardness, spectrophotometry for nitrates, nitrites, and ammonium, as well as conventional chemical methods for the other ions. Quality control included regular instrument calibration, duplicate measurements, and the use of analytical blanks.

### STATISTICAL DATA ANALYSIS

Statistical analyses were performed using RStudio (v4.4.0). Descriptive statistics (minimum, maximum, mean, median and standard deviation) and box plots were used to evaluate the spatiotemporal variability of groundwater quality across wells, seasons, and years, as well as to identify exceedances of established quality standards. Correlation analysis and principal component analysis (PCA) were used to examine the relationships between physicochemical parameters and to identify the primary natural and anthropogenic factors governing groundwater hydrochemistry.

## RESULTS

### DESCRIPTIVE STATISTICS OF GROUNDWATER PHYSICOCHEMICAL PARAMETERS

The descriptive statistics for the physicochemical parameters of the groundwater are presented in Table 1. The results show substantial spatial and temporal variability in the hydrochemical characteristics of the studied groundwater.

Water temperature ranged from 15.3 to 32.28°C, with a mean of 24.61°C, reflecting the direct influence of local climatic conditions. The pH values were slightly alkaline (mean = 7.46), indicating generally stable pH conditions.

Electrical conductivity (*EC*) varied widely (850–8,113  $\mu$ S·cm<sup>−1</sup>; CV  $\approx$  64.81%), reflecting the heterogeneous mineralisation of the groundwater. This variability may be associated with evaporation processes, mineral dissolution, and anthropogenic inputs.

Regarding major ions, the results show a predominance of sodium (Na<sup>+</sup>) and calcium (Ca<sup>2+</sup>), with mean concentrations of 155.42 and 88.46 mg·dm<sup>−3</sup>, respectively. Chloride (Cl<sup>−</sup>) showed very high variability (CV  $\approx$  271.09%), indicating pronounced salinisation in some areas. Bicarbonate (HCO<sub>3</sub><sup>−</sup>) was also abundant (mean = 624.04 mg·dm<sup>−3</sup>), reflecting significant

**Table 1.** Descriptive statistics for the physicochemical parameters of the groundwater

| Parameter                                             | N  | Min.  | Max.    | Mean     | Median | Standard deviation | Variance     | CV (%) |
|-------------------------------------------------------|----|-------|---------|----------|--------|--------------------|--------------|--------|
| $T$ (°C)                                              | 96 | 15.3  | 32.28   | 24.61    | 24.32  | 3.905              | 15.247       | 15.87  |
| $EC$ ( $\mu\text{S}\cdot\text{cm}^{-1}$ )             | 96 | 850   | 8113    | 2,934.14 | 1982.5 | 1901.53            | 3,615,807.18 | 64.81  |
| $\text{Na}^+$ ( $\text{mg}\cdot\text{dm}^{-3}$ )      | 96 | 54    | 480     | 155.42   | 114    | 106.00             | 1,1236.84    | 68.21  |
| $\text{Ca}^{2+}$ ( $\text{mg}\cdot\text{dm}^{-3}$ )   | 96 | 40    | 457.22  | 88.46    | 80     | 60.35              | 3,642.26     | 68.23  |
| $\text{Mg}^{2+}$ ( $\text{mg}\cdot\text{dm}^{-3}$ )   | 96 | 19.25 | 80      | 44.54    | 44     | 17.66              | 311.96       | 39.65  |
| $\text{K}^+$ ( $\text{mg}\cdot\text{dm}^{-3}$ )       | 96 | 5     | 20      | 12.12    | 12     | 3.70               | 13.70        | 30.55  |
| $\text{NH}_4^+$ ( $\text{mg}\cdot\text{dm}^{-3}$ )    | 96 | 0.001 | 0.16    | 0.025    | 0.012  | 0.032              | 0.001        | 127.60 |
| $\text{NO}_3^-$ ( $\text{mg}\cdot\text{dm}^{-3}$ )    | 96 | 8.07  | 95      | 49.14    | 50     | 23.79              | 566.17       | 48.42  |
| $\text{NO}_2^-$ ( $\text{mg}\cdot\text{dm}^{-3}$ )    | 96 | 0.001 | 0.286   | 0.061    | 0.034  | 0.069              | 0.005        | 113.08 |
| $\text{Cl}^-$ ( $\text{mg}\cdot\text{dm}^{-3}$ )      | 96 | 12.91 | 6,097.9 | 247.35   | 88.37  | 670.55             | 449,637.62   | 271.09 |
| $\text{HCO}_3^-$ ( $\text{mg}\cdot\text{dm}^{-3}$ )   | 96 | 195.2 | 1,244   | 624.04   | 613.56 | 269.19             | 72,464.48    | 43.14  |
| $\text{SO}_4^{2-}$ ( $\text{mg}\cdot\text{dm}^{-3}$ ) | 96 | 50.33 | 441.3   | 180.62   | 177.5  | 77.30              | 5975.60      | 42.80  |
| $TH$ ( $\text{meq}\cdot\text{dm}^{-3}$ )              | 96 | 3.549 | 26.2    | 8.07     | 7.66   | 3.33               | 11.11        | 41.33  |
| $TA$ ( $\text{meq}\cdot\text{dm}^{-3}$ )              | 96 | 3.2   | 20.39   | 10.41    | 9.87   | 5.00               | 25.04        | 48.10  |
| pH (-)                                                | 96 | 7     | 8.16    | 7.46     | 7.45   | 0.226              | 0.051        | 3.03   |
| DO ( $\text{mg}\cdot\text{dm}^{-3}$ )                 | 96 | 2     | 5.9     | 3.00     | 2.4    | 1.205              | 1.452        | 40.14  |

Explanations:  $T$  = temperature,  $EC$  = electrical conductivity,  $TH$  = total hardness,  $TA$  = total alkalinity, pH = potential of hydrogen, DO = dissolved oxygen.

Source: own study.

water–rock interactions, particularly carbonate dissolution. Sulphate ( $\text{SO}_4^{2-}$ ) was present at moderate concentrations, associated with geological weathering processes.

Nutrient concentrations, particularly nitrate ( $\text{NO}_3^-$ ), varied considerably (mean =  $49.14 \text{ mg}\cdot\text{dm}^{-3}$ ;  $CV \approx 48.42\%$ ), suggesting the influence of agricultural activities and the application of nitrogen fertilisers. Nitrite ( $\text{NO}_2^-$ ) and ammonium ( $\text{NH}_4^+$ ) also varied widely, indicating nitrogen transformation processes within the aquifer system.

Overall, these findings reveal high mineralisation and significant spatial heterogeneity within the groundwater. These patterns are primarily influenced by water–rock interactions, intense evaporation, and anthropogenic pressures, particularly from agriculture. The high variability of critical parameters ( $EC$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ) highlights the risk of progressive degradation of groundwater quality in specific areas of the study region.

#### GROUNDWATER QUALITY PARAMETERS – CORRELATION MATRIX

The correlation matrix of the main physicochemical parameters analysed in the groundwater of the Feija–Zagora area is presented in Figure 2. It shows relationships among major ions and water-quality parameters that help identify the dominant hydrochemical processes in the aquifer.

The results show a strong positive correlation between electrical conductivity ( $EC$ ) and several dissolved ions, particularly chloride ( $\text{Cl}^-$ ), sodium ( $\text{Na}^+$ ), and sulphate ( $\text{SO}_4^{2-}$ ). This relationship reflects the contribution of these ions to the overall mineralisation of the groundwater. The strong correlation

between  $\text{Na}^+$  and  $\text{SO}_4^{2-}$ , as well as between  $\text{Na}^+$  and  $\text{K}^+$ , suggests a common geochemical origin related to the dissolution of evaporitic formations or water–rock interactions.

Chloride also exhibits a positive correlation with  $EC$  and sodium, consistent with its contribution to salinity. This association may reflect natural salinisation associated with evaporation and the dissolution of saline minerals within the aquifer.

Nitrate ( $\text{NO}_3^-$ ) shows a moderate correlation with  $EC$  and bicarbonate ( $\text{HCO}_3^-$ ), which could indicate an anthropogenic influence, particularly from agriculture and wastewater infiltration. In contrast,  $\text{NO}_3^-$  exhibits weak correlations with several major cations, suggesting an origin distinct from natural mineralisation processes.

Dissolved oxygen (DO) generally showed negative or weak correlations with salinity parameters ( $\text{Cl}^-$ ,  $EC$ , and  $\text{Na}^+$ ), reflecting a decrease in water oxygenation as mineralisation increases.

Nitrite ( $\text{NO}_2^-$ ) showed mainly negative correlations with several parameters, particularly  $\text{Cl}^-$  and total hardness ( $TH$ ), consistent with its low stability in the aquifer and transient role in nitrification.

#### SPATIAL VARIABILITY OF GROUNDWATER PHYSICOCHEMICAL PARAMETERS

Physicochemical parameters varied considerably among the wells studied in the Feija–Zagora area (Fig. 3). Well P8, used as a reference well, provides a basis for comparing the other sampling sites and the regional mean.

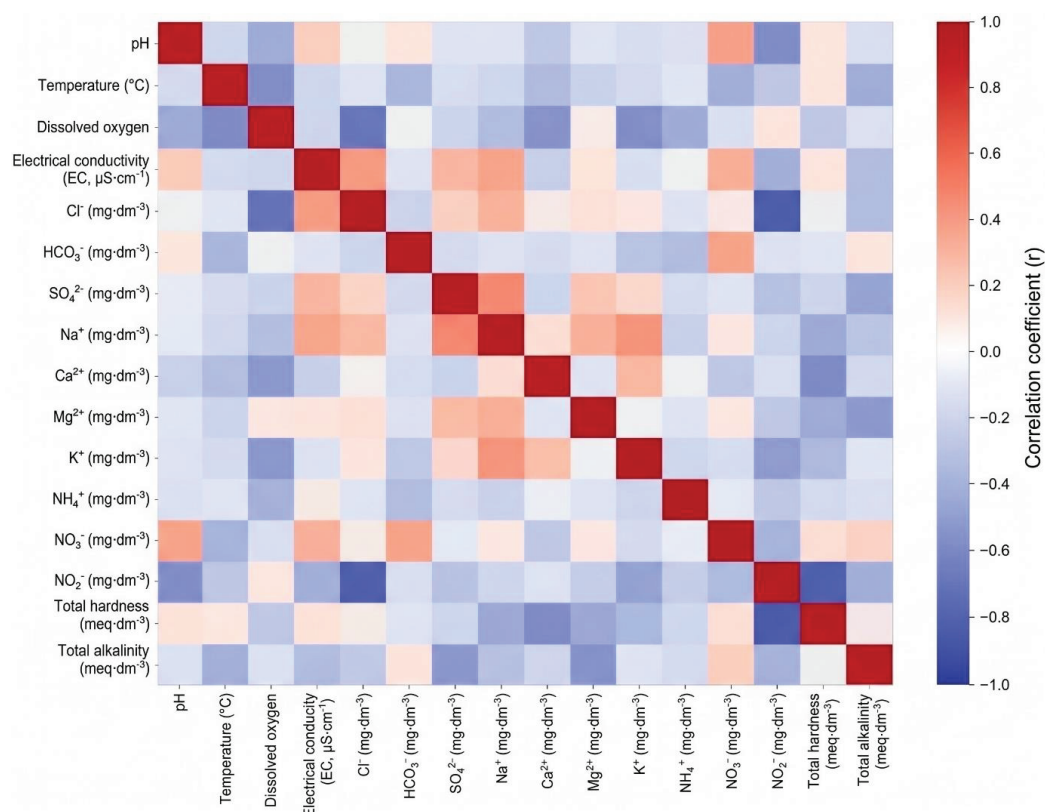


Fig. 2. Pearson correlation matrix of the physicochemical parameters of groundwater in the Feija aquifer; source: own study

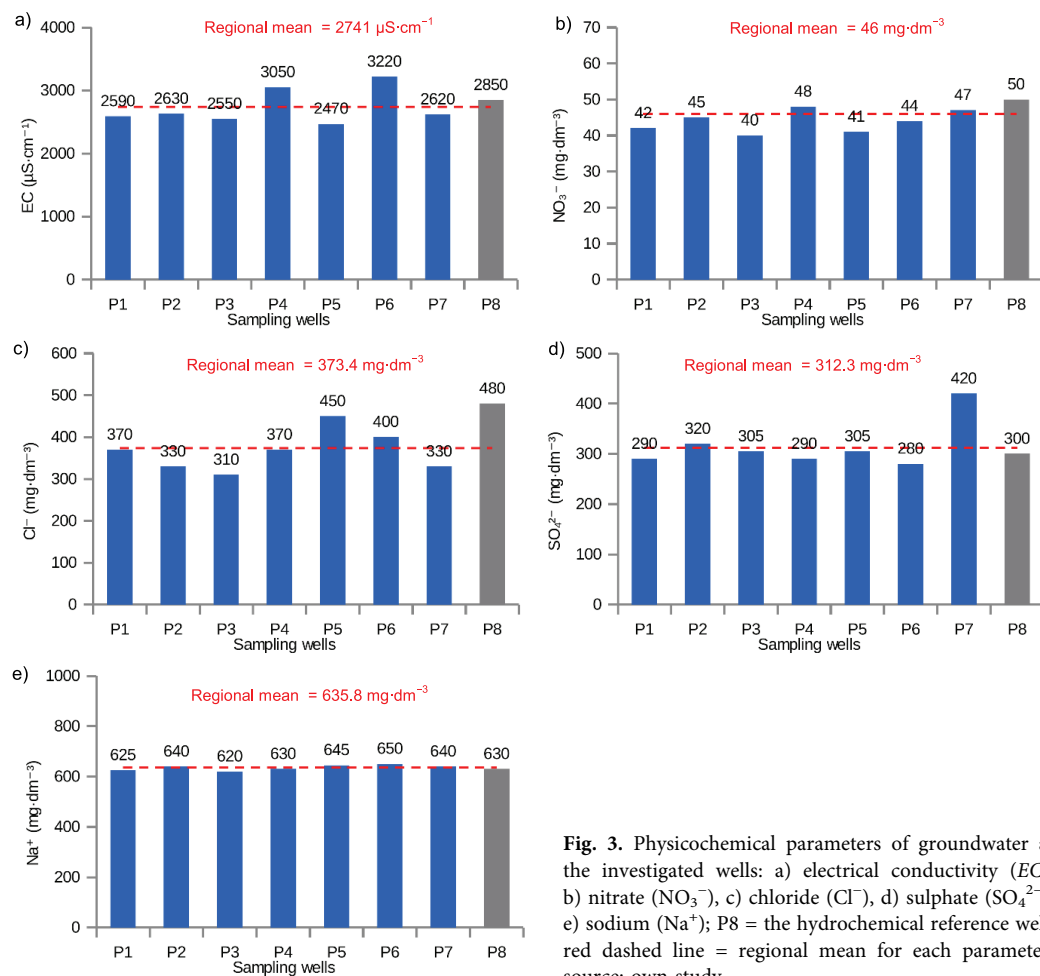


Fig. 3. Physicochemical parameters of groundwater at the investigated wells: a) electrical conductivity (EC), b) nitrate ( $\text{NO}_3^-$ ), c) chloride ( $\text{Cl}^-$ ), d) sulphate ( $\text{SO}_4^{2-}$ ), e) sodium ( $\text{Na}^+$ ); P8 = the hydrochemical reference well; red dashed line = regional mean for each parameter; source: own study

EC was generally high across the wells, reflecting significant groundwater mineralisation. Reference well P8 had an EC of approximately  $2,850 \mu\text{S}\cdot\text{cm}^{-1}$ , close to the regional mean ( $2,741.2 \mu\text{S}\cdot\text{cm}^{-1}$ ), indicating a hydrochemical background signature representative of the aquifer. The highest values were recorded in wells P6 and P4, suggesting locally more mineralised zones, likely influenced by intensified evaporation processes, the dissolution of geological formations, or anthropogenic inputs.

Chloride ( $\text{Cl}^-$ ) concentrations varied markedly across sites, with higher values in certain wells, and the concentration in reference well P8 was approximately  $480 \text{ mg}\cdot\text{dm}^{-3}$ . This distribution primarily reflects natural mineralisation and water-rock interactions, but it can also be locally amplified by inputs related to agricultural activities and irrigation, which promote the progressive accumulation of salts in the aquifer.

Sodium ( $\text{Na}^+$ ) levels were relatively uniform across all wells, with values close to the regional mean ( $635.8 \text{ mg}\cdot\text{dm}^{-3}$ ), suggesting a common geochemical origin for the groundwater, associated with dissolution of silicate and evaporitic minerals.

In reference well P8, nitrate ( $\text{NO}_3^-$ ) concentrations were close to  $50 \text{ mg}\cdot\text{dm}^{-3}$ , slightly above the regional mean ( $46.0 \text{ mg}\cdot\text{dm}^{-3}$ ), reflecting the background level of the study area. Variation among the other wells suggests a combined influence of natural conditions and anthropogenic activities, particularly the use of nitrogen fertilisers and intensive agricultural practices, which are likely to facilitate nitrate infiltration into the unconfined aquifer.

Sulphate ( $\text{SO}_4^{2-}$ ) was present at moderate concentrations in well P8 ( $\approx 300 \text{ mg}\cdot\text{dm}^{-3}$ ), close to the regional mean ( $312.3 \text{ mg}\cdot\text{dm}^{-3}$ ), whereas well P7 had the highest concentrations. These differences reflect spatial variation associated with local geological conditions, the dissolution of sulphate-bearing minerals, and variations in groundwater flow processes.

Overall, these results show spatial gradients in mineralisation and contamination across the aquifer. This spatial heterogeneity reflects the combined influence of local geological conditions, groundwater flow dynamics, and surface-based anthropogenic pressures, particularly those related to intensive agricultural activities. Well P8 therefore serves as a hydrochemical reference for comparing the other sampling sites with the regional background and identifying departures from assumed natural conditions.

The designation of P8 as a reference well does not imply an absence of anthropogenic influence; it indicates a site selected to represent average or background aquifer conditions. In aquifer systems subject to high agricultural pressure and sustained human activity, even reference wells may exhibit a modified chemical signature, including measurable concentrations of dissolved salts, nitrates, or other elements originating from human activities. This is particularly common in arid environments, where low aquifer recharge limits the dilution of contaminants and favours their progressive accumulation.

The reference well therefore provides a basis for comparison: it enables the identification of spatial deviations, the quantification of the extent of hydrochemical degradation, and the localisation of areas most affected by salinisation processes, evapoconcentration, and diffuse agricultural pollution. This comparison can inform assessments of aquifer vulnerability and groundwater management.

#### SEASONAL VARIABILITY OF GROUNDWATER PHYSICOCHEMICAL PARAMETERS

Groundwater chemistry in the Feija area varied substantially by season (Fig. 4). The seasonal distribution of pH, EC, and concentrations of  $\text{NO}_3^-$  and  $\text{Cl}^-$  is shown in box plots,

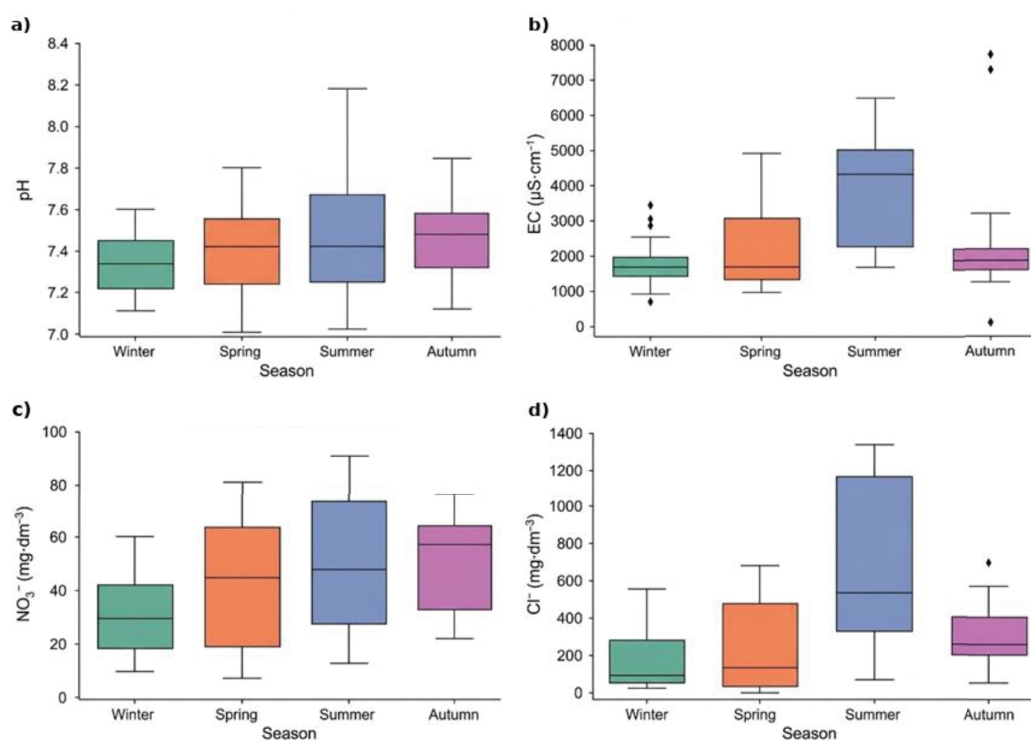


**Fig. 4.** Seasonal variations of physicochemical parameters in groundwater: a) potential of hydrogen (pH), b) electrical conductivity (EC), c) nitrate ( $\text{NO}_3^-$ ), d) chloride ( $\text{Cl}^-$ ); source: own study

highlighting the primary hydrochemical dynamics of the studied aquifer. The plots represent the median, interquartile range, and potential outliers for each season (winter, spring, summer, autumn), illustrating seasonal variation in groundwater quality under climatic and anthropogenic pressures.

pH remained generally stable across all seasons, with slightly alkaline values ranging from 7.0 to 8.2, consistent with buffering by the aquifer geology. In contrast, *EC* varied markedly by season, with significantly higher values recorded in summer, reaching medians exceeding  $4,000 \mu\text{S}\cdot\text{cm}^{-1}$ , and peaks nearing  $8,000 \mu\text{S}\cdot\text{cm}^{-1}$  in autumn. This pattern indicates pronounced groundwater mineralisation during periods of low recharge.

Overall, these results highlight that summer is the most critical period for groundwater quality, marked by an intensification of natural mineralisation and an increase in anthropogenic inputs. This pattern reflects the combined influence of climatic factors and agricultural activities on the degradation of the studied aquifer's quality. Nitrate ( $\text{NO}_3^-$ ) concentrations increased from spring to autumn, frequently exceeding the drinking-water threshold of  $50 \text{ mg}\cdot\text{dm}^{-3}$  during summer and autumn, suggesting contamination primarily of agricultural origin. Similarly,  $\text{Cl}^-$  concentrations followed a seasonal pattern similar to that of *EC*, with maximum values recorded in summer (median of approximately  $550 \text{ mg}\cdot\text{dm}^{-3}$  and peaks exceeding  $1,200 \text{ mg}\cdot\text{dm}^{-3}$ ), reflecting high salinity dominated by a sodium-chloride signature.

#### PRINCIPAL COMPONENT ANALYSIS BIPLLOT

Principal component analysis (PCA) was performed to explore the relationships between physicochemical parameters and their seasonal variability. The first two axes explained 36.3% (F1) and 19.1% (F2) of the total variance, or 55.4% combined (Fig. 5).

Axis F1 was primarily associated with high positive loadings for major ions, notably  $\text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Mg}^{2+}$ , and *EC*. This axis

represents a salinity gradient, highlighting an increase in water mineralisation. Samples corresponding to the summer season were mainly located on the positive side of this axis, indicating increased salinisation linked to evaporative processes characteristic of hot periods.

Axis F2, explaining 19.1% of the variance (Fig. 5), separates two hydrochemical signatures. On one side,  $\text{NO}_3^-$  and  $\text{HCO}_3^-$ , associated with agricultural inputs and diffuse pollution, are projected on the negative side of the axis. On the other,  $\text{Ca}^{2+}$  is positioned on the positive side, reflecting a carbonate signature of natural geological origin. This axis thus reflects a pollution and biogeochemical process gradient. The seasonal distribution was clear: summer samples were distinguished by their position on the positive side of axis F1, confirming their high mineralisation. In contrast, winter and spring samples cluster on the negative side of this axis, indicating lower salinity, suggesting a dilution effect linked to precipitation and reduced evapotranspiration.

Autumn samples occupy an intermediate position, reflecting a transition between these two hydrochemical states. Furthermore, the relationships between variables reveal a strong correlation between  $\text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , and *EC*, indicating a common origin linked to mineralisation. Conversely, the separation of  $\text{NO}_3^-/\text{HCO}_3^-$  from  $\text{Ca}^{2+}$  highlights the coexistence of two distinct processes: diffuse anthropogenic pollution and natural geochemical influence.

#### IRRIGATION SUITABILITY ASSESSMENT

To address the third study objective, the irrigation suitability of the Feija groundwater was evaluated using the sodium adsorption ratio (SAR), the permeability index (PI), the percentage of soluble sodium (Na%), and Kelly's ratio (KR), calculated from the major ion concentrations in Table 1 (ionic units converted to  $\text{meq}\cdot\text{dm}^{-3}$ ) following Richards (1954), Wilcox (1955), Doneen (1964), and Kelley (1963):

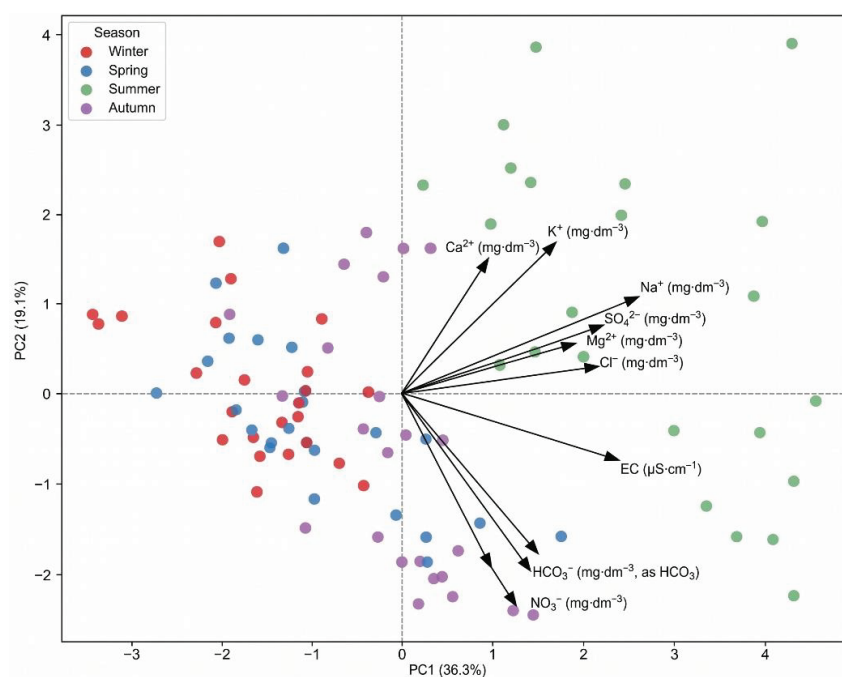


**Fig. 5.** Principal component analysis (PCA) biplot illustrating the hydrochemical dynamics of groundwater across seasons; *EC* = electrical conductivity; source: own study

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \quad (1)$$

$$PI = \frac{[Na^+] + \sqrt{[HCO_3^-]}}{[Ca^{2+}] + [Mg^{2+}] + [Na^+]} 100 \quad (2)$$

$$Na\% = \frac{[Na^+] + [K^+]}{[Ca^{2+}] + [Mg^{2+}] + [Na^+] + [K^+]} 100 \quad (3)$$

$$KR = \frac{[Na^+]}{[Ca^{2+}] + [Mg^{2+}]} \quad (4)$$

where:  $[Na^+]$  = concentration of sodium,  $[Ca^{2+}]$  = concentration of calcium,  $[Mg^{2+}]$  = concentration of magnesium,  $[HCO_3^-]$  = concentration of bicarbonate,  $[K^+]$  = concentration of potassium.

The indices calculated from the mean ionic composition of the 96 samples, together with the corresponding hazard classes, are summarised in Table 2.

**Table 2.** Irrigation-water quality indices for the Feija aquifer, computed from the mean ionic composition (see Tab. 1), with hazard/permeability classification

| Index                                                  | Value                                                                      | Class                       | Interpretation                                                                                                        |
|--------------------------------------------------------|----------------------------------------------------------------------------|-----------------------------|-----------------------------------------------------------------------------------------------------------------------|
| Electrical conductivity ( <i>EC</i> , salinity hazard) | mean = 2,934 $\mu S \cdot cm^{-1}$ ; range 850–8,113 $\mu S \cdot cm^{-1}$ | C3–C4 (high to very high)   | salinity is the principal irrigation constraint; risk of soil-salinity build-up, especially in summer/autumn (Fig. 4) |
| Sodium adsorption ratio ( <i>SAR</i> – sodium hazard)  | $\approx 3.4$                                                              | S1 (low)                    | sodium hazard to soil structure is low at the mean composition; $Ca^{2+}$ and $Mg^{2+}$ largely balance $Na^+$        |
| Permeability index ( <i>PI</i> )                       | $\approx 67\%$                                                             | class II (good-permissible) | long-term irrigation use is generally permissible; periodic monitoring recommended                                    |
| Soluble sodium percentage ( <i>Na%</i> )               | $\approx 47\%$                                                             | permissible                 | consistent with the low <i>SAR</i> -based sodium hazard                                                               |
| Kelly's ratio ( <i>KR</i> )                            | $\approx 0.84$                                                             | suitable ( $KR < 1$ )       | confirms the water is not sodium-dominated despite the Na-Cl hydrochemical facies                                     |

Source: own study.

The values in Table 2 represent only the mean composition of the dataset. Because *EC*, *SAR* and *PI* vary by well and season (Figs. 3–4), the sample-level ranges may be wider. In particular, *SAR* and *PI* may be highest at the most saline wells and during the most saline seasons (e.g. wells P4 and P6 in summer and autumn; Sections 3.3–3.4), when elevated  $Cl^-$  and  $Na^+$  coincide with reduced dilution.

## DISCUSSION

The physicochemical analysis of the Feija aquifer indicates highly mineralised groundwater, with electrical conductivity (*EC*) values exceeding 2,500  $\mu S \cdot cm^{-1}$ . The dominance of  $Na^+$ ,  $Cl^-$ , and  $SO_4^{2-}$  identifies a sodium–chloride hydrochemical facies, typical of groundwater in arid environments where evaporation rates significantly exceed precipitation (Wada *et al.*, 2010). The strong association between *EC*,  $Na^+$ , and  $Cl^-$  (Fig. 2) indicates that salinity is governed primarily by natural water–rock interactions, specifically the dissolution of evaporitic formations prevalent in

the Zagora region. This is consistent with observations in similar Moroccan contexts, where evaporative concentration is a primary driver of groundwater salinisation (Bouchaou *et al.*, 2008).

The spatial distribution of parameters (Fig. 3) highlights distinct hydrochemical gradients. Using well P8 as a reference helps identify deviations from background hydrochemistry. The elevated *EC* and nitrate ( $NO_3^-$ ) levels in wells P6 and P4, relative to P8, indicate localised zones of degradation. This spatial heterogeneity is a common feature in semi-arid aquifers, reflecting both geological complexity and the impact of irrigation practices that facilitate the migration of salts (Li *et al.*, 2021). Similar spatial patterns of salinity and nitrate enrichment linked to irrigation return flow and fertiliser leaching have recently been documented in Central Tunisian aquifers, where elevated *EC* and  $NO_3^-$  concentrations coincide with intensively cultivated zones (Missaoui *et al.*, 2026). This is consistent with earlier work on fractured aquifers in arid Central Tunisia, which attributed comparable hydrochemical heterogeneity to the combined influence of aquifer structure and agricultural water use (Msaddek *et al.*, 2023). At the regional scale, such anthropogenic

pressure on groundwater quality is compounded by climatic variability across North Africa (Hamed *et al.*, 2018).

The seasonal box plots (Fig. 4) demonstrate that summer is the most critical period for groundwater quality. The sharp increase in *EC* and  $NO_3^-$  concentrations during summer and autumn aligns with the “evapoconcentration effect”, exacerbated by reduced recharge and high abstraction rates. The  $NO_3^-$  concentrations, which frequently exceed the 50  $mg \cdot dm^{-3}$  threshold, are consistent with diffuse pollution linked to intensive use of nitrogen fertilisers, a major concern in the Drâa Valley (Karmaoui *et al.*, 2019). This trend confirms that water scarcity in semi-arid regions limits the dilution capacity of the aquifer, worsening the chemical impact of agricultural intensification (Schilling *et al.*, 2012).

The principal component analysis (PCA) results (Fig. 5) provide a framework for disentangling natural geochemistry from human-induced degradation, an approach widely applied to characterise seasonal and spatial sources of groundwater contamination (Guo *et al.*, 2018). The F1 axis (36.3% variance) confirms that salinity is the primary driver of hydrochemical variability,

linked to summer evaporation, a pattern consistent with other semi-arid Maghrebien aquifers where evaporation and water–rock interaction dominate the first factorial axis (Bradai *et al.*, 2022; Ghodbane *et al.*, 2022). Conversely, the F2 axis (19.1%) isolates the pollution gradient, with  $\text{NO}_3^-$  and  $\text{HCO}_3^-$  associated with anthropogenic inputs, distinct from the  $\text{Ca}^{2+}$  signature of natural carbonate dissolution (Yang *et al.*, 2015). The intermediate position of autumn samples in the biplot illustrates a seasonal transition in which precipitation reduces the high salinity observed in summer (Wakida and Lerner, 2005; Yang *et al.*, 2015), a shift comparable to the seasonal PCA reorganisation documented for other semi-arid North African aquifers subject to similar recharge–dilution cycles (Ghodbane *et al.*, 2022).

In hydrochemical studies, PCA is widely recognised as a robust tool for aggregating the effects of multiple variables to interpret the underlying geochemical structure (Yang *et al.*, 2015). The association of nitrates with anthropogenic activities such as agricultural runoff, intensive fertiliser use, and inadequate domestic wastewater management is a well-documented driver of groundwater quality degradation in shallow aquifers (Wakida and Lerner, 2005; Rivett *et al.*, 2008).

When evaluating the suitability of these waters for irrigation (Tab. 2), the Richards diagram (Richards, 1954) classifies the Feija groundwater predominantly as C3–C4 (high to very-high salinity hazard), reflecting the same evaporative concentration and water–rock interaction processes that drive the F1 axis of the PCA (Fig. 5). By contrast, the sodium adsorption ratio (SAR)-based sodium hazard is low (S1), because the elevated  $\text{Na}^+$  is largely balanced by co-dominant  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , consistent with the carbonate-dissolution signature identified on the PCA F2 axis; this is corroborated by the moderate permeability index (class II, Doneen 1964),  $\text{Na}\%$  ( $\approx 47\%$ , permissible), and Kelly's ratio ( $\approx 0.84$ , suitable) reported in Table 2. Practically, this means the Feija aquifer poses a greater risk of soil salinisation (via accumulation of soluble salts) than of sodicity/permeability loss, particularly where irrigation coincides with the high-EC summer and autumn periods (Fig. 4) and at the most mineralised wells (P4, P6; Fig. 3). This distinction has direct management implications, since salinity-related risk is primarily mitigated through leaching fractions and drainage management, whereas sodicity risk would instead call for gypsum amendment or calcium-based soil conditioners; the latter appear less urgent here.

The Feija aquifer is clearly under dual pressure from natural arid-zone geochemistry and agricultural intensification. To ensure sustainable groundwater use, water management strategies must prioritise: (1) precision agriculture to reduce nitrate leaching (Sigua *et al.*, 2017); (2) regular hydrochemical monitoring programmes (Sanad, 2024); and (3) regulated pumping rates, especially during the critical summer months, to mitigate salinisation (Jafary and Bradley, 2018; Singh, 2021).

This study has several limitations that should be considered when interpreting its findings. First, the statistical approach is primarily descriptive; correlation and PCA results were used to identify hydrochemical gradients and associations, but formal inferential testing (e.g. significance of correlation coefficients, ANOVA/Kruskal–Wallis comparisons across wells and seasons) was not performed and should be incorporated in future analyses. Second, the irrigation-suitability indices (SAR,  $PI$ ,  $\text{Na}\%$ ,  $KR$ ) reported here were derived from the mean ionic composition of the dataset rather than from every individual sample; classifica-

tion of each well and season (Batarseh *et al.*, 2021) would provide a more spatially and temporally resolved picture of irrigation hazard. Third, the eight-well network, while capturing the main spatial gradient of the plain, cannot fully resolve fine-scale heterogeneity, and no isotopic or geophysical tracers were used to confirm the inferred sources of salinity and nitrate. Future work should combine the existing hydrochemical dataset with statistical significance testing, sample-level irrigation indices, stable-isotope tracing (Xue *et al.*, 2009), and direct soil/crop-response monitoring to more precisely quantify the agronomic impact of groundwater quality on oasis agriculture in the Feija plain.

## CONCLUSIONS

The hydrochemical assessment of the Feija aquifer indicates that groundwater quality is influenced by natural geological weathering and anthropogenic pressures. The observed mineralisation, dominated by sodium and chloride, is primarily driven by the region's arid climate and high rates of evapotranspiration, which concentrate salts within the aquifer. The identification of well P8 as a hydrochemical reference highlights that even baseline conditions in the Feija plain are subject to significant mineralisation, while other wells show further degradation due to agricultural activities. The seasonal monitoring established that summer and autumn are the most critical periods, characterised by a marked increase in salinity and nitrate levels that frequently exceed potability thresholds. For irrigation suitability, the Feija groundwater falls predominantly within the high-to-very-high salinity hazard classes (C3–C4) of the Richards' diagram, while the low sodium adsorption ratio (SAR, S1), moderate permeability index (class II), and permissible percentage of soluble sodium ( $\text{Na}\%$ ) and Kelly's ratio values indicate that sodicity is not a major concern; salinity management (leaching, drainage, and crop selection) should therefore take priority over sodicity-focused amendments. Given these findings, regional authorities should implement stricter management of nitrogen-based fertilisers and monitor groundwater pumping rates to safeguard this critical resource for the long-term sustainability of oasis agriculture.

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## CONFLICT OF INTERESTS

All authors declare that they have not conflict of interests.

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