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*Research Article*

# Groundwater availability for irrigation purposes: Case of Middle Cheliff aquifer Algeria

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**Abstract**

The Middle Cheliff Plain faces persistent difficulties in managing its limited groundwater reserves. This region, covering 321 km$^2$ in a semi-arid climate, is subjected to a detailed study of groundwater quality for irrigation purposes. In this context, twelve samples were carefully collected and analyzed. Nine essential parameters were evaluated, including physicochemical parameters and irrigation indices  It is noted that the waters have an average conductivity of 4231 µs.cm$^{-1}$ and a significant chloride content of 23.33 meq/l which has an unacceptable category for irrigation also the majority of the indices present fairly acceptable and permissible values for irrigation SAR and RSC (100%) of the samples respectively, also the PI 75% of the piezometers are suitable for irrigation These criteria were used to assess the suitability of groundwater for irrigation. In most of the plain, the Groundwater Quality Index for Irrigation (GWQII) indicates both acceptable and poor quality. These results show that most of these chemical constituents are above the FAO standards. Therefore, irrigation water poses a danger to the region's vast fields and its fragile crops. The proposed approach has demonstrated efficacy in the assessment of groundwater quality for irrigation purposes, exhibiting versatility in application and adaptability across diverse geographical regions, including humid, arid, and semi-arid settings worldwide.

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## 1. Introduction

Groundwater plays a crucial role in meeting water needs for domestic, agricultural, and industrial uses in arid and semi-arid regions. The only water source in the studied area, the study area aquifer, offers significant potential. It is essential to adopt a collaborative and comprehensive management approach to preserve this vital resource. However, the diminishing capacity of aquifer reserves due to an imbalance between renewal and exploitation exacerbates pollution problems (Ali and Armanuos, 2023; Bouderbala & Merouchi, 2023; Samal et al 2023). Groundwater quality is particularly affected by agricultural practices, mainly due to contamination by inputs. Monitoring the quality of water used for irrigation is essential to reduce adverse effects on soil and plant health (Bouderbala et al., 2019a).

According to Mattauer (1958) and Abdel Baki and Boukli (2007), demographic growth and agricultural development already endanger the scarcity of this groundwater source.In Morocco's Souss-Massa region, overexploitation of groundwater for agriculture has led to aquifer depletion and pollution (Mansir et al., 2018). Similarly, Tunisia's Mahdia region faces water scarcity due to rapid urban growth and improper resource management, resulting in groundwater overexploitation (Soula et al., 2020). The Arab region, one of the world's most water-scarce areas, heavily relies on groundwater, with unsustainable extraction rates exceeding natural recharge (Khiyat, 2022). In Ethiopia, despite significant groundwater potential, rapid urban population growth and agricultural development have increased pressure on this resource (Gaikwad et al., 2019; Mengistu et al., 2019).

In Algeria, groundwater is a vital resource, particularly in regions with limited surface water availability, serving as the primary source of human consumption of potable water for municipalities and supporting agricultural activities (Bouderbala et al., 2019a; Djema & Mebrouk, 2022). However, excessive exploitation has led to the depletion and contamination of groundwater reserves, highlighting the need for accurate and reliable assessments of groundwater quality according to Food and Agriculture Organization FAO (2016). The socioeconomic development of Algeria is heavily reliant on groundwater resources, yet these are increasingly threatened by both natural and anthropogenic factors, including environmental changes and human activities (Hamed, 2022; Bouderbala et al., 2019b).

Numerous studies have employed groundwater quality indicators both globally and within Algeria. For example, In the course of their investigation, researchers in the Sichuan Basin and the Sahara aquifer made use of a range of indices, to assess the suitability of groundwater for drinking and irrigation, including the Irrigation Water Quality Index (IWQI) and the Sodium Adsorption Ratio (SAR) (Singaraja, 2017; Gaagai et al., 2023).

In Algeria's Ziban region, studies focused on physicochemical parameters to assess groundwater quality for irrigation, revealing unsuitability in certain areas based on hydrochemical facies and graphical analyses (Chellouai et al., 2023). Research in the Algerian desert has also involved the use of water quality indices and geographic information systems (GIS) to evaluate groundwater quality for agricultural purposes, utilizing Support Vector Machine Regression (SVMR) models to generate robust estimates of various IWQIs. These studies underscore the importance of such tools in managing groundwater resources in arid regions (Eid et al., 2023). Research in El-Oued regions found that while groundwater was deemed unsuitable for drinking due to mineralization and anthropogenic impacts, it remained viable for irrigation based on evaluations of SAR, sodium percentage (Na%), Magnesium Risk (MR), Permeability Index (PI), and Residual Sodium Carbonate Index (RSC) (Eid et al., 2022)

The aquifer in the study area in northern Algeria has a number of challenging hydrogeological conditions, which have led to a number of impacts, including problems of groundwater degradation. The degradation of groundwater quality is due to rapid urbanisation, industrial expansion and reckless irrigation practices. In view of these difficulties, A thorough assessment of aquifer characteristics is required to ensure an environmentally sound utilization of subsurface resources in the decades to come. Having region-specific hydrogeochemical information is vital for improving groundwater management approaches, ensuring sustainability, and preventing degradation. (Barick & Ratha, 2014; Nagaraju et al., 2014; Bari et al., 2021; Guettaf et al., 2017; Masood et al., 2022). Researchers have emphasized the water chemistry of samples studied aquifer by evaluating its quality over time and space for irrigation (Madene et al., 2022). Another research group proposes a hydrogeochemical analysis using statistical methods and binary diagrams (Hennia et al., 2022). It should be noted that multivariate analysis and geostatistical modelling have proved to be effective in the assessment of groundwater irrigation resources and the identification of both natural and anthropogenic influences on water quality in the Middle Cheliff aquifer (Belouchrani et al., 2019; Bradai et al., 2022).

It is crucial to evaluate the physico-chemical characteristics of groundwater to determine its suitability for various situations. Groundwater quality can be affected by factors such as industrialization, urbanization, and agricultural practices (Prasad & Rao, 2018; Vohra, 2023). Parameters like pH, turbidity, conductivity, and ion concentrations are essential for assessing water quality (Vohra, 2023; Das et al., 2019). This requires considering maximum allowable concentrations, which play an important role in assessing groundwater quality. Furthermore, this process serves as an invaluable tool for elucidating the chemical composition of groundwater and identifying the principal control mechanisms. Groundwater in the region presents high mineral concentrations, requiring regular monitoring for irrigation and evaluating its capacity for use with or without treatment (Bounab et al., 2022). Various tools and indices are used to assess the suitability of groundwater for drinking and irrigation, including water quality indices (WQIs), nitrate contamination indices (NCIs) and irrigation water quality indices (IWQIs) (Behera & Baliarsingh, 2017; Behera & Mishra, 2017; Panneerselvam et al., 2020). Moreover, researchers frequently employ a range of parameter indicators (Bouderbala, 2017a, b; Sadick et al., 2017; Gad et al., 2020; Bounab et al., 2022; Gautam et al., 2023).

The aim of this study is to assess the groundwater quality capacity in the study area Plain for irrigation with many mathematic tools index and its impact on agricultural production. The objective is to guide decision-makers towards preventing contamination and facilitating the safe selection of future development in semi-arid areas.

## 2. Materials and methods

### *2.1 Region field study*

The study area region, situated in the central part of Cheliff Province in northwestern Algeria (Figure 1). Covering an area of 321 km$^2$, it had an estimated population of 480,000 as of 2010, according to data from the National Statistics Office (2011). The climate is semi-arid with an average annual rainfall of about 365 mm. The primary function of the study area aquifer is the provision of potable water. agriculture, and industry. However, in recent years, economic growth in agriculture has led to increased water demand and a decline in its quality (Gayar, 2020).

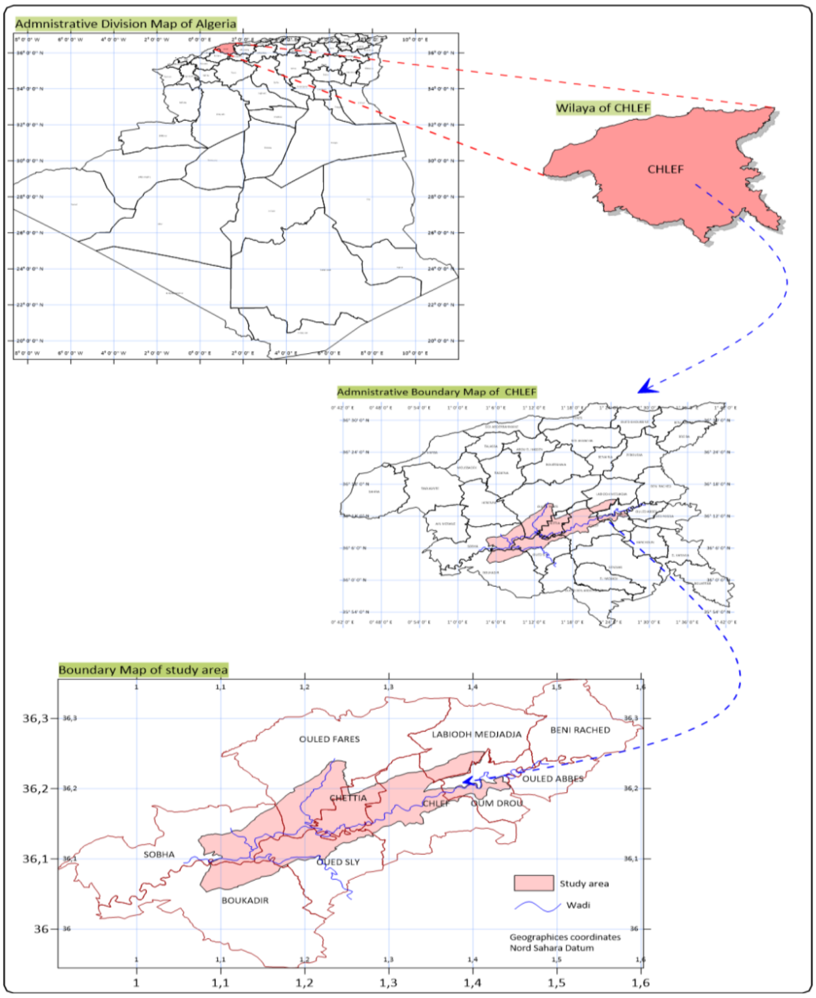


*Figure 1: Situantion region reseach.*

According to Mattauer (1958), the study area comprises two different lithological sequences (Figure 2). The pre-Neogene formations consist mainly of sedimentary rocks (marls, clays, marly limestones, shales, sandy clays). The Neogene formations include lower Miocene conglomerates, clayey sandstones, upper Miocene blue marls, gypsum formations, limestone with lithothamniums, and Pliocene blue marls and limestones.

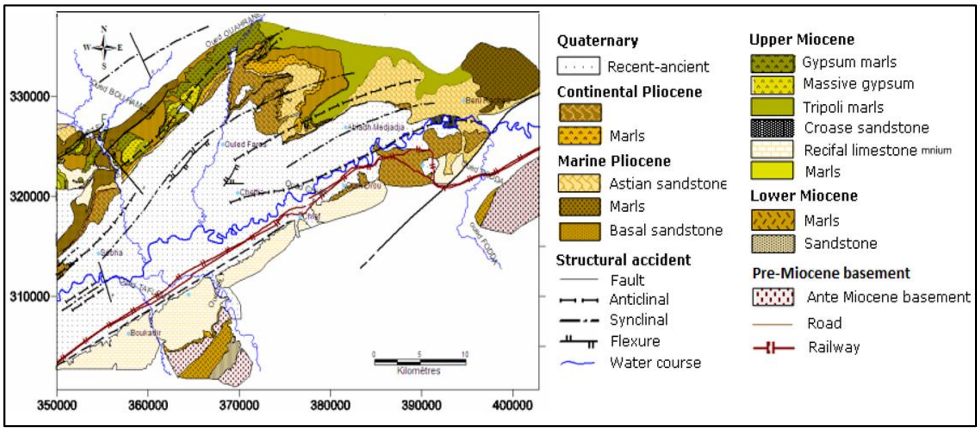


*Figure 2: The study area geology basin map (Scet- Agri, 1985)*

Quaternary formations consist of ancient Quaternary conglomerates, gravels, pebbles, and clays, as well as recent Quaternary sediments mainly present along watercourses and their tributaries. Three main aquifers in the basin have distinct hydrogeological potentials (Figure 3): a. Upper Miocene limestones along the southern edge of the valley, underlying alluvium; b. Pliocene sandstones (Astian) between the hills of El Kherba downstream from Sobha and Oued Ouahran, partially covered by Quaternary formations; c. Pleistocene and Quaternary alluvial sediments forming the valley fill. The studied aquifer has an average annual abstraction of about 155 $hm^3$, with 64 % for drinking water supply, 31 % for agricultural purposes, and 5 % for industrial uses.

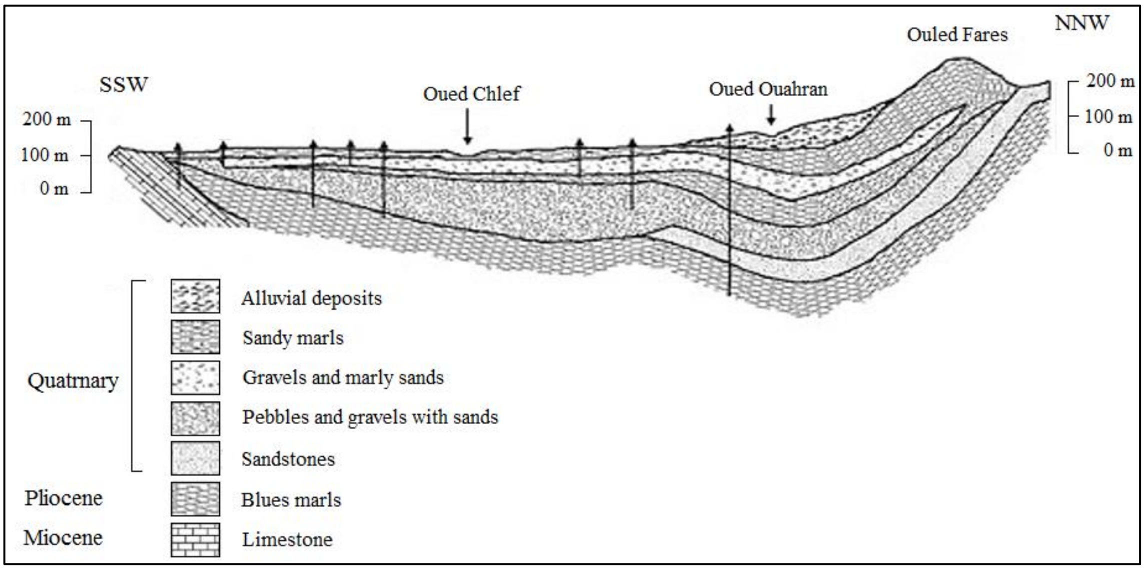


*Figure 3: Hydrogeological cross-section showing the different aquifers (Scet- Agri, 1985).*

A strategic selection and sampling of a network of 12 representative piezometers throughout the study area ensured sufficient spatial coverage to characterise groundwater quality in the aquifer, despite the limited number of monitoring points. Field measurements of four key physicochemical parameters (temperature (T°C), pH, and electrical conductivity (EC)) were carried out using a Multi340i multiparameter kit (WTW). The analysis of major ions ($Ca^{2+}$, $Mg^{2+}$, $Na^+$, $K^+$, $Cl^-$, $SO_4^{2-}$, and $HCO_3^-$), including nitrates ($NO_3^-$), was conducted. The ion balance error remained within the acceptable threshold of ±5% (Table 1).

Soil characteristics are significantly influenced by irrigation water quality, with a consequent effect on agricultural yields. An appreciation of the quality of irrigation water and the potentially detrimental effects it can have on crop growth is of paramount importance. The Water Quality Index also assesses irrigation water quality, providing a comprehensive assessment of the overall impact of each parameter. This is crucial for monitoring groundwater resources and implementing the study area aquifer action plan. Irrigation water quality directly influences soil properties, which in turn affects agricultural productivity.

### 2.2 *Water quality irrigation methodology assay*

It is vital for evaluating the hygiene of irrigation water and identify any possible dangers to crop productivity. A common assessment method is the Water Quality Index (WQI), which integrates the effects of various water quality parameters into a comprehensive assessment. In this study, the irrigation water quality was evaluated using several key indices and parameters. These parameters were analyzed to decide the proper use of water for irrigation in the research area (Adagba et al., 2022; Alsahli, 2023)

### *2.2.1 Ground Water quality irrigation indexes*

The Water Quality Index (WQI) method was used to enhance water quality assessment and provide an effective method for classifying water suitability for irrigation. WQI is calculated based on recommended standards for various uses, considering ten water quality parameters (pH, EC, $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $HCO_3^-$, $Cl^-$, $SO_4^{2-}$, $NO_3^-$).

Initially, a value of w_i is attributed to each parameter based on its relative importance in assessing the quality of irrigation water. Parameters considered most critical, such as EC, $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $Cl^-$, and $SO_4{}^{2-}$, are given the highest weight of 5. Medium weights of 3 are assigned to pH and $K^+$, whereas $NO_3$ and $HCO_3$ have the lowest weight of 2 (Table 1). The following equation is then used to calculate the relative weight (rWi):

$$rWi = \frac{wi}{\sum_{i=1}^{n} wi}$$

Where (rWi) represents the relative weight, (wi) is the assigned weight of each parameter, and nnn is the total number of parameters. The calculated values of (rWi) are presented in Table 1. In the third step, each parameter is assigned a Quality Rating (QR) scale. This is determined by dividing the measured concentration of the parameter by its corresponding standard concentration, as defined by Ayers & Westcot (1985), multiplied by 100%.$qi = \frac{Ci}{Si} * 100$
where (qi) is the quality index, (Ci) is the concentration of each chemical parameter in each water sample in mg/L, and (Si) is the permissible concentration of water for irrigation for each chemical parameter in mg/L.

*Table 1: Assigned Weights (wi) and Corresponding Relative Weights (rWi) for Each Chemical Parameter*

| Parameters | | EC (µS/cm) | pH | $Cl^-$ (mg/l) | $SO_4^{2-}$ (mg/l) | $HCO_3^-$ (mg/l) | $Na^+$ (mg/l) | $Ca^{2+}$ (mg/l) | $Mg^{2+}$ (mg/l) | $NO_3^-$ (mg/l) | $K^+$ (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Irrigation water | Ayers &Westcott (1985) | 2250 | 8.5 | 350 | 250 | 400 | 200 | 200 | 100 | 50 | 10 |
| | Weight (wi) | 5 | 3 | 5 | 5 | 2 | 5 | 5 | 5 | 2 | 3 |
| | Relative weight (rwi) | 0.125 | 0.075 | 0.125 | 0.125 | 0.05 | 0.125 | 0.125 | 0.125 | 0.05 | 0.075 |

Finally, to calculate the Groundwater Quality Index (GWQII), (SLi) is first determined for each parameter, and the sum of the SLi values provides the water quality index for each sample according to Table 2:

$$SLi = rWi \times qi$$
$$GWQII = \sum SLi$$

*Table 2: Suggested Irrigation classes for GWQII. (Sahu and Sikdar, 2008)*

| Type Classes | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| Range of GWQII for irrigation purposes | < 50 | 50 - 100 | 100 - 200 | 200 - 300 | > 300 |
| Categories | Class Excellent | Class Good | Class Permissible | Class Doubtful | Class Unsuitable for irrigation uses |

### *2.2.2 Water quality index for irrigation purposes*

The potential for groundwater to be used for irrigation is contingent upon a number of factors, including the texture and composition of the soil, the specific crop types being cultivated, the techniques employed for irrigation, and the chemical properties of the water in question. High-quality irrigation water is typically characterized by acceptable values for several key indices illustrate in Table 3.

*Table 3: Irrigation suitability assessment of groundwater.*

| QI | Equation | Range | Class |
|---|---|---|---|
| Electrical Conductivity (EC) (Richards, 1954) | *In situ* | < 250 | Excellent |
| | | 250 – 750 | Good |
| | | 750 – 2250 | Permissible |
| | | 2250 - 5000 | Doubtful |
| | | > 5000 | Unacceptable |
| Chloride (meq/L) (Srinivasamoorthy et al, 2011) | *Anlaysis and coversion to meq/l* | < 4 | Excellent |
| | | 4 – 7 | Good |
| | | 7 – 12 | Permissible |
| | | 12 - 20 | Doubtful |
| | | > 20 | Unacceptable |
| (SAR)Sodium adsorption ratio (Richards, 1954) | $SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$ | <2 | Excellent |
| | | 2–12 | Good |
| | | 12–22 | permissible |
| | | 22-32 | Fair |
| | | >32 | Poor |
| (Na%) Percent sodium (Wilcox, 1967) | $\%Na = \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} * 100$ | 0–20 | Excellent |
| | | 20–40 | Good |
| | | 40–60 | permissible |
| | | 60–80 | doubtful |
| | | >80 | Unacceptable |
| (PI) Permeability index (Doneen,1964) | $PI = \frac{Na^+ + \sqrt{(HCO_3^-)}}{Ca^{2+} + Mg^{2+} + Na^+} * 100$ | <25.0 | Unsuitable |
| | | 25–75 | Good |
| | | >75 | Suitable |
| (KR) Kelley's ratio (Kelly, 1963) | $KR = \frac{Na^+}{Ca^{2+}+Mg^{2+}}$ | >1 | Unsuitable |
| | | <1 | Suitable |
| (MHR) Magnesium hazard ratio (Raghunath, 1987) | $MHR = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} * 100$ | <50 | Suitable |
| | | >50 | Unsuitable |
| (SSP) Soluble sodium percentage (Todd, 1981) | $SSP = \left(\frac{Na^+}{Ca^{2+} + + Mg^{2+} + Na^+}\right) * 100$ | <50 | Good |
| | | >50 | Unsuitable |
| (RSC) Residual Sodium Carbonate (Eaton,1950; Richards, 1954) | $RSC = (HCO_3^- + CO_3^-) - (Ca^{2+} + Mg^{2+})$ | <1.25 | Permissible |
| | | ≥1.25 | Unsuitable |

| QI | Equation | Range | Class |
|---|---|---|---|
| (PS) Potential Salinity (Doneen,1964) | $PS = Cl^{-} + \sqrt{SO_4^{2-}}$ | <3 | Excellent |
| | | 3–5 | Good |
| | | >5 | Unsuitable |

## 3. Results

Natural interactions with geological materials influence the composition of groundwater, As do people's and ecosystem processes which influence the integrity of groundwater. In the defined study area defined, groundwater quality was assessed to determine its suitability for suitability for irrigation.

### *3.1 Groundwater quality*

The study of the quality of groundwater reveals hydro-chemical uniformity with significant variations in $Ca^{2+}$, $Mg^{2+}$, $Cl^{-}$, $HCO_3^{-}$, $SO_4^{2-}$, and $NO_3^{-}$ ions (Table 3). The pH ranges from 6.9 to 8.3, indicating slight alkalinity within potable water standards. The mean electrical conductivity is 4231 µS/cm, indicating the combined impact of both geologic and anthropogenic factors. Elevated concentrations of calcium, magnesium, and sodium often exceed WHO limits, primarily due to geological weathering and anthropogenic activities such as domestic waste and fertilizers (Table 3). Approximately 70% of samples exceed WHO limits for $HCO_3^{-}$ ions, attributed to carbonate deposits and nitrogen fertilizer use. More than 95% of samples show high sulfate concentrations, often linked to evaporation, untreated wastewater, and gypsum dissolution. Elevated chloride levels indicate contamination from wastewater and the return of irrigation water. Lastly, over 80% of samples exhibit nitrate concentrations exceeding WHO standards, largely due to agricultural pollution from intensive pesticide and fertilizer use (Table 4).

*Table 4: Variation of physicochemical parameters.*

| Parameters | Max | Min | Mean | SD | WHO standards |
|---|---|---|---|---|---|
| Bicarbonate (mg/l) | 436 | 46 | 241 | 156.13 | 200 |
| Sulfate (mg/l) | 1670 | 35 | 655 | 498.35 | 250 |
| Total dissolved salts(mg/l) | 4626 | 366 | 2546.5 | 1292.68 | 500 |
| Chloride (mg/l) | 2400 | 137 | 827 | 615.68 | 250 |
| Calcium (mg/l) | 353 | 24 | 166 | 111.83 | 75 |
| Magnesium (mg/l) | 306 | 6 | 137 | 99.47 | 45 |
| Sodium (mg/l) | 875 | 86 | 465 | 245.81 | 200 |
| Potassium (mg/l) | 8 | 1 | 5 | 2.21 | 12 |
| Nitrate (mg/l) | 280 | 1 | 50 | 83.47 | 50 |
| Hydrogen potential | 8.1 | 6.9 | 8 | 0.43 | 8.5 |
| Electric Conductivity (µS/cm) | 8250 | 570 | 4231 | 2174.19 | 500 |

According to the Piper diagram (Figure 4), the aquifer predominantly displays two hydro-chemical types: chlorinated and sulfate-rich calcareous waters, with an additional facies of chlorinated sodium and potassium waters. The observed variance is most likely caused by the dissolution of evaporitic formations, such as alluvial deposits.

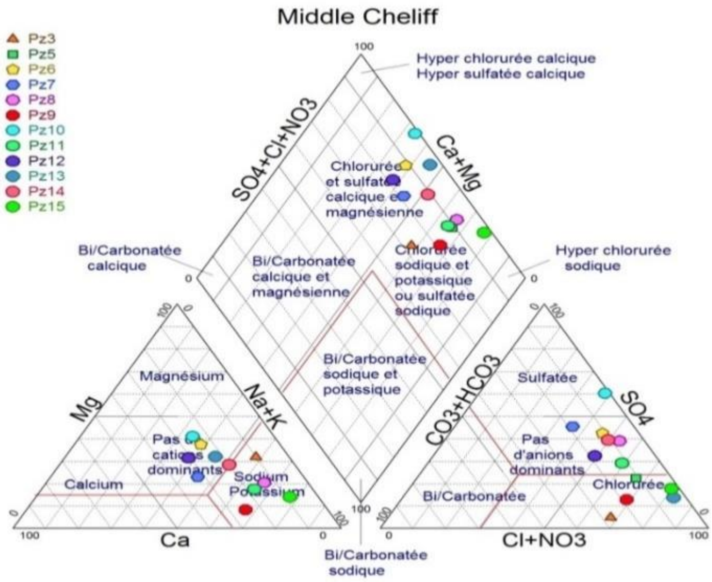


*Figure 4: Diagram Illustrating the Hydrochemical Facies of Groundwater in the study area.*

### *3.2 Water Quality Index for Irrigation*

This evaluation employed the Groundwater Quality Index for Irrigation (GWQII), a critical tool for comparing various quality parameters against established irrigation standards. Nine key parameters were analysed to evaluate the aptitude of water use in the studied area. The water quality index includes the relative weights of these parameters in recommending irrigation practice. The analysis of twelve samples collected during the dry season of 2021 revealed the following classifications, as shown in Table 5. The groundwater quality index map for irrigation (Figure 5) indicates that the central and western regions of the study area exhibit questionable to unsuitable water quality zones, whereas the eastern region, towards Medjadja and Ouled Fares, generally demonstrates better water quality. To evaluate irrigation water quality, the study area's analytical results included measurements of physical and chemical parameter and calculates indices irrigation (Asadi et al., 2020; Maman and Arzu, 2022) (Table 6).

*Table 5: Classification of groundwater quality for irrigation purposes*

| Samples | GWQII | Categories class |
|---|---|---|
| PIEZ 3 | 78.47 | Class-Good |
| PIEZ 5 | 41.36 | Class-Excellent |
| PIEZ 6 | 232.75 | Class-Doubtful |
| PIEZ 7 | 152.72 | Class-Permissible |
| PIEZ 8 | 171.08 | Class-Permissible |
| PIEZ 9 | 37.92 | Class-Excellent |
| PIEZ 10 | 321.18 | Class-Unsuitable |
| PIEZ 11 | 141.99 | Class-Permissible |
| PIEZ 12 | 189.69 | Class-Permissible |
| PIEZ 13 | 307.43 | Class-Unsuitable |
| PIEZ 14 | 262.99 | Class-Doubtful |
| PIEZ 15 | 193.97 | Class-Permissible |

PIEZ:Piezometer; GWQII : Ground water quality irrigation index
PIEZ :Piozometer; GWQII : Ground water quality irrigation index; Ind: Indice

*Table 6: Statistical Summary of Irrigation Water Quality Criteria*

| Samples | EC -Ind (µs/cm) | Cl-Ind (meq/l) | %Na - Ind | SAR - Ind | RSC - Ind | PI - Ind | MAR - Ind | KR- Ind | PS- Ind | GWQII- Ind | Catego-ries |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PIEZ 3 | 2210 | 15.30 | 57.96 | 5.80 | -2.73 | 63.73 | 75.90 | 1.37 | 16.72 | 78.47 | C4S2 |
| PIEZ 5 | 1292 | 6.38 | 66.43 | 4.92 | -2.06 | 71.88 | 62.26 | 1.97 | 7.84 | 41.36 | C3S1 |
| PIEZ 6 | 5940 | 26.80 | 38.41 | 5.20 | -28.25 | 40.60 | 60.86 | 0.62 | 31.88 | 232.75 | C5S2 |
| PIEZ 7 | 3790 | 13.33 | 44.70 | 5.25 | -14.28 | 47.95 | 41.56 | 0.80 | 17.50 | 152.72 | C4S2 |
| PIEZ 8 | 4550 | 23.77 | 66.14 | 10.27 | -10.60 | 68.24 | 60.86 | 1.94 | 27.94 | 171.08 | C4S3 |
| PIEZ 9 | 570 | 3.86 | 66.75 | 3.79 | -0.90 | 74.71 | 24.81 | 1.92 | 4.72 | 37.92 | C2S1 |
| PIEZ 10 | 5830 | 17.63 | 34.11 | 4.43 | -36.58 | 34.65 | 62.26 | 0.51 | 23.53 | 321.18 | C5S2 |
| PIEZ 11 | 3520 | 18.69 | 64.79 | 8.82 | -7.93 | 67.52 | 49.74 | 1.82 | 21.73 | 141.99 | C4S3 |
| PIEZ 12 | 3840 | 17.63 | 37.81 | 3.95 | -14.41 | 41.47 | 50.65 | 0.60 | 21.14 | 189.69 | C4S2 |
| PIEZ 13 | 8270 | 67.70 | 45.58 | 7.71 | -39.69 | 46.57 | 58.84 | 0.83 | 71.08 | 307.43 | C5S3 |
| PIEZ 14 | 5420 | 25.25 | 51.71 | 7.65 | -19.67 | 53.93 | 58.84 | 1.07 | 29.90 | 262.99 | C5S3 |
| PIEZ 15 | 5540 | 43.72 | 77.21 | 16.02 | -10.03 | 78.27 | 61.82 | 3.37 | 46.84 | 193.97 | C5S3 |

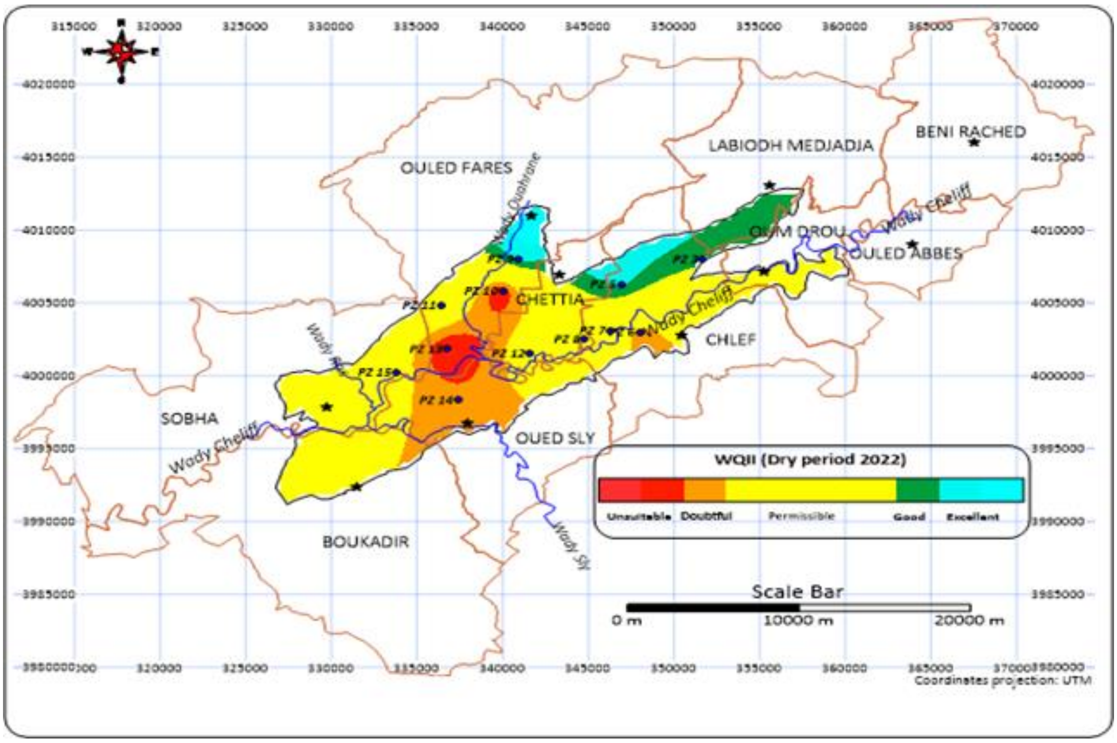


*Figure 5: Spatial variability of WQII in the study area*

### *3.2.1 Electrical Conductivity (EC)*

Water chemistry details suggests that piezometers have values above the usual level of 3 mS/cm. (Table 5; Figure 6). High EC impacts crop productivity and soil structure, causing a physiological drought that decreases water availability to plants even when the soil appears moist. The yield potential of irrigation water with high EC decreases (Qiu et al., 2017; Wang et al., 2023).

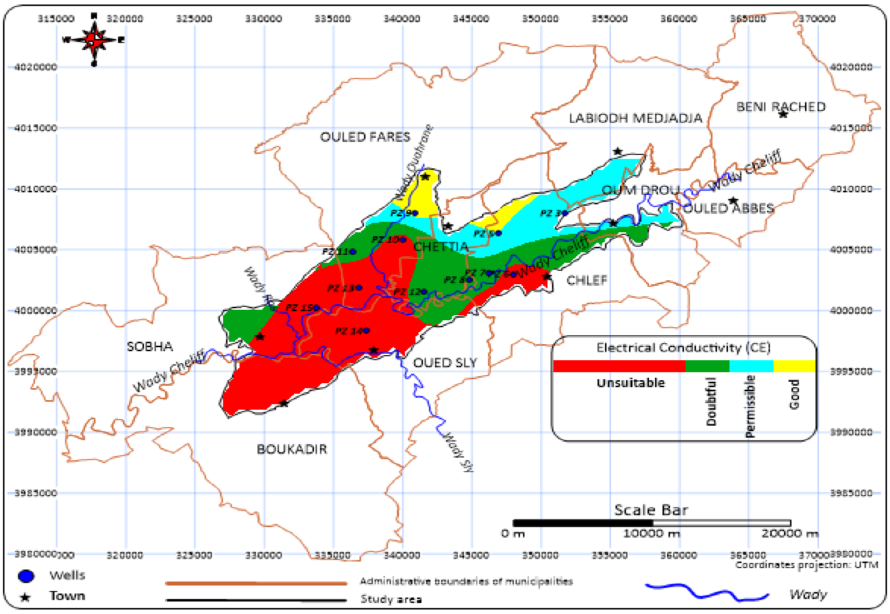


Figure 6: Electrical Conductivity (EC)

### 3.2.2 Chlorides ($Cl^-$)

Unlike other elements, chloride ion is an effective pollution indicator as it is not absorbed and remains mobile. High chloride concentrations in leaves can cause damage signs such as burns, tissue desiccation, and leaf yellowing. Additionally, over 90% of the samples have chloride values exceeding the standard (Ayers & Westcot, 1985) (Table 6; Figure 7). This high concentration can be explained by salt deposit dispersion, agricultural fertilizer use, wastewater discharge, and infiltrated irrigation water runoff. Groundwater can be locally contaminated by each of these pollution sources.

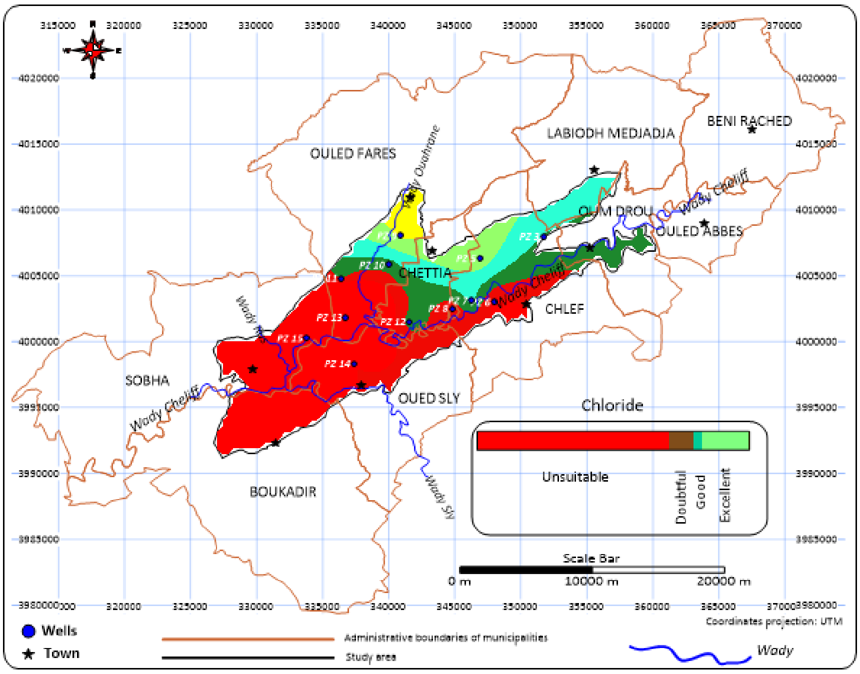


Figure 7: Electrical Conductivity (EC)Chlorides ($Cl^-$)

### *3.2.3 Sodium Percentage (% Na)*

The sodium percentage is a critical indicator for evaluating the quality of irrigation water, as it signifies the potential hazards posed by soluble sodium in the water, which may render it unsuitable for irrigation purposes Birhane & Hagos (2021) It should be noted that a progress in the sodium content of the soil can affect on the physic deposition soil. This is due to reduced permeability and aeration, which affects plant growth. In the study area, sodium levels range from 30% to 70%, with an average of 50%. The predominant classification is the moderate category, with 75% of samples falling into this group. Conversely, the acceptable, marginal, and excellent categories each account for 8% of the samples, with only one sample per class (Table 6; Figure 8).

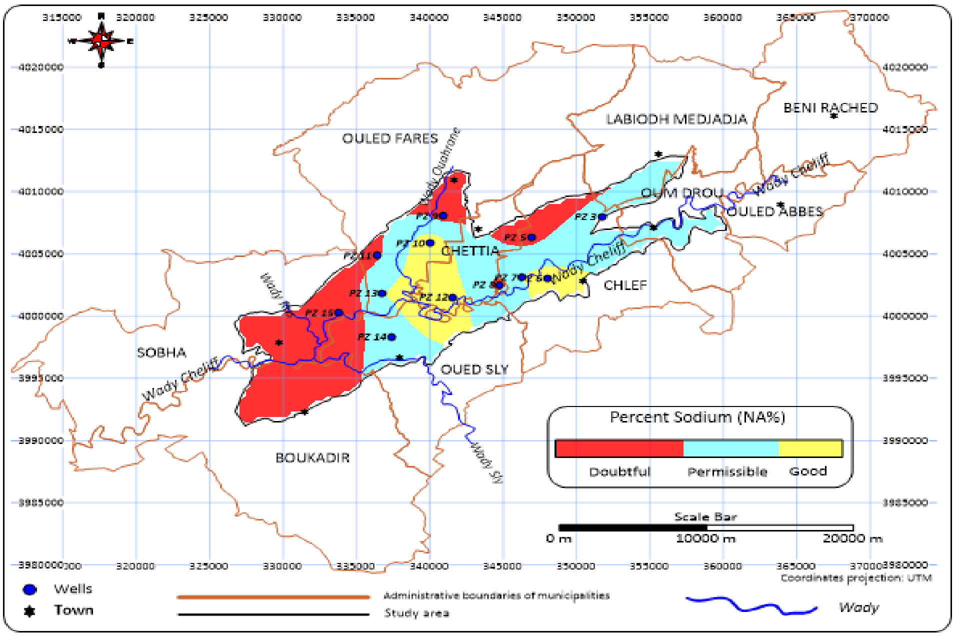


*Figure 8: Percentage of Sodium (% Na)*

### *3.2.4 Sodium Adsorption Ratio (SAR)*

The Sodium Adsorption Ratio (SAR) assesses the ability of sodium ions to displace calcium and magnesium ions in the soil. Such displacement can have a detrimental impact on soil structure, as it results in the dispersion of clay particles and the disruption of soil aggregates., leading to compacted and impermeable soil. Such changes decrease pore size, thereby restricting water infiltration to plant roots. In this study, the SAR classification shows that approximately 90% of the samples are categorized as excellent, while the remaining 10% fall into the good category (Table 6; Figures 9 and 10)

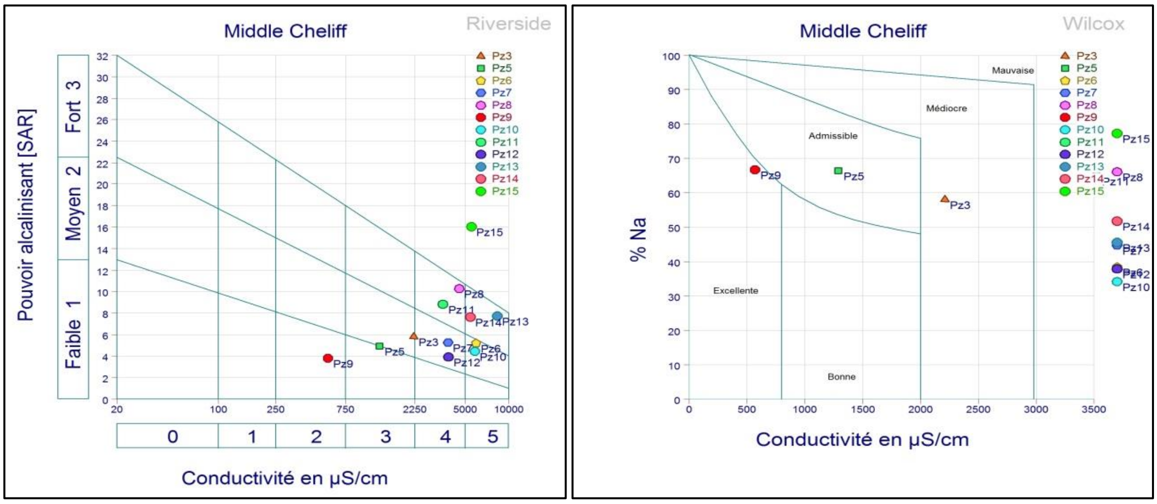


*Figure 9: The irrigation diagrams provide a classification of groundwater in the study area region.*

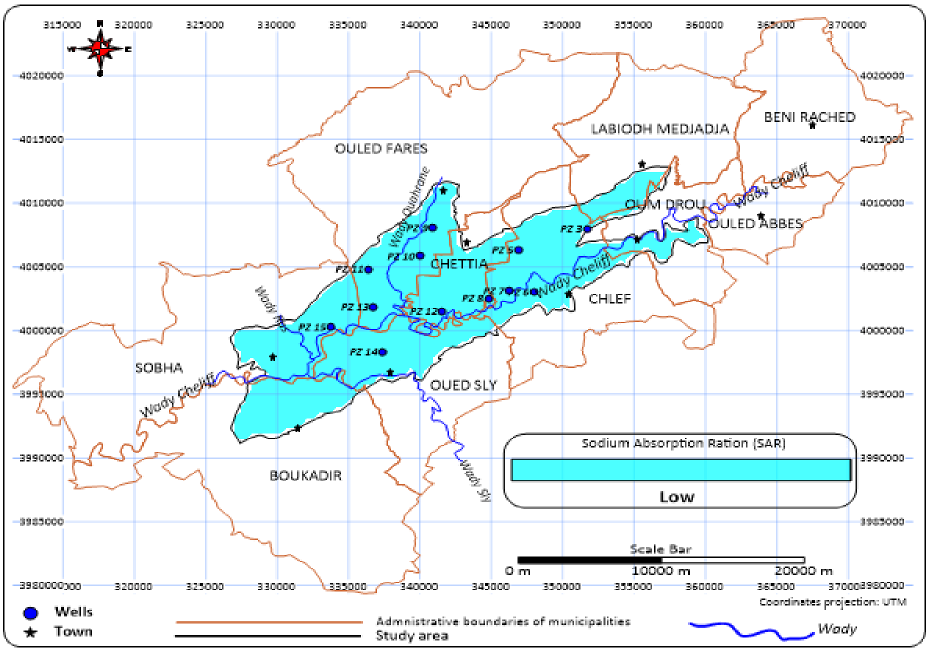


*Figure 10: Sodium Absorption Ratio (SAR).*

### *3.2.5 Magnesium Hazard (MH)*

To assess the danger of high magnesium levels, the MH ratio was used, with a threshold value of 50%. Values exceeding this threshold indicate danger. Results show that groundwater is free of magnesium hazards, except for a few cases. Analysis shows that 10% of the samples belong to the dangerous class, while the rest are classified as safe. (Table 6; Figure 11)

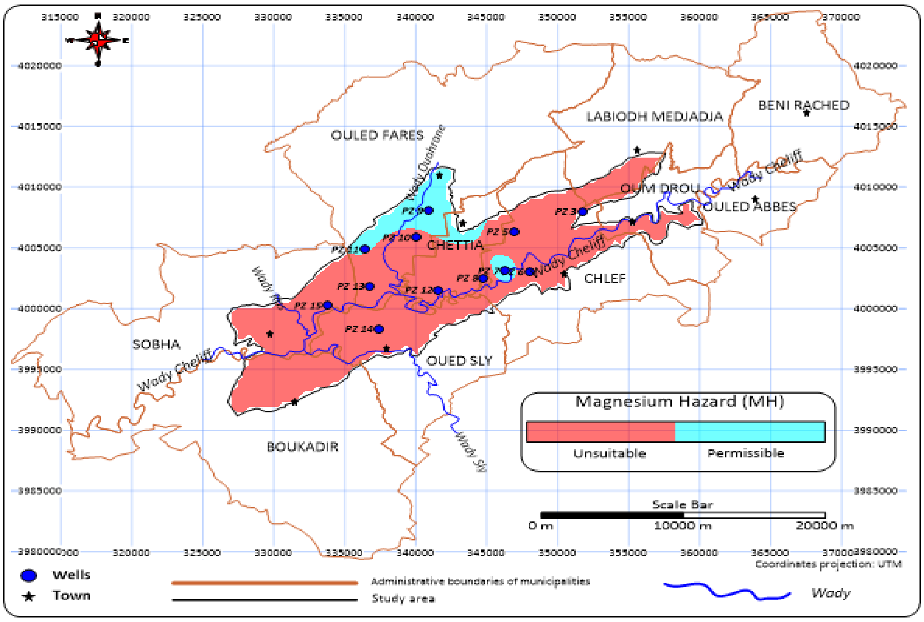


*Figure 11: Magnesium Hazard (MH)*

### *3.2.6 Kelly's Ratio (KR)*

KR is an important parameter used to classify irrigation water quality. When the KR value exceeds 1, The use of water for irrigation is not recommended. In the event that the values are found to be below 1, the water in question is deemed suitable for irrigation purposes. In the context of the study area, the average value is around 1. Most values are within the limit, indicating the safe category. Some values exceeding this threshold are considered unsuitable for irrigation (Table 6; Figure 12).

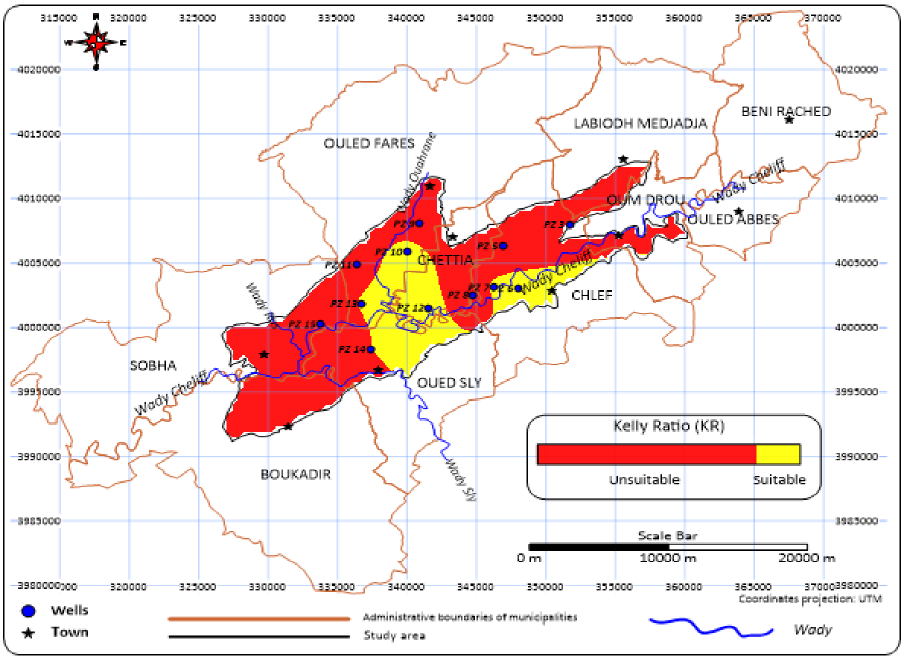


*Figure 12: Kelly Ratio (KR)*

### *3.2.7 Permeability Index (PI)*

The permeability index assesses irrigation water's suitability based on its effect on soil permeability. Results show that values range from 30% to 70%, indicating varying degrees of suitability. In the study area, PI values show acceptable to poor classifications for irrigation water quality (Table 6; Figure 13).

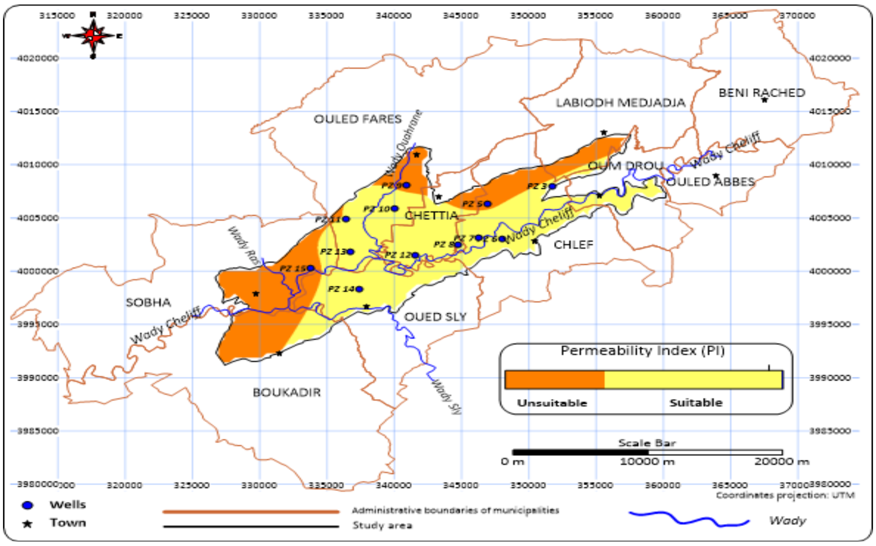


*Figure 13: Permeability Index (PI)*

### *3.2.8 Potential Salinity (PS)*

The potential salinity represents water salinity in terms of dissolved solids and ions. It is calculated using the sum of chloride concentration and half the sulphate concentration ($Cl^- + 1/2SO_4^{2}$). In the study area, potential salinity values indicate significant challenges for irrigation purposes. Most values exceed standard thresholds, highlighting the need for treatment before use (Table 6; Figure 14).

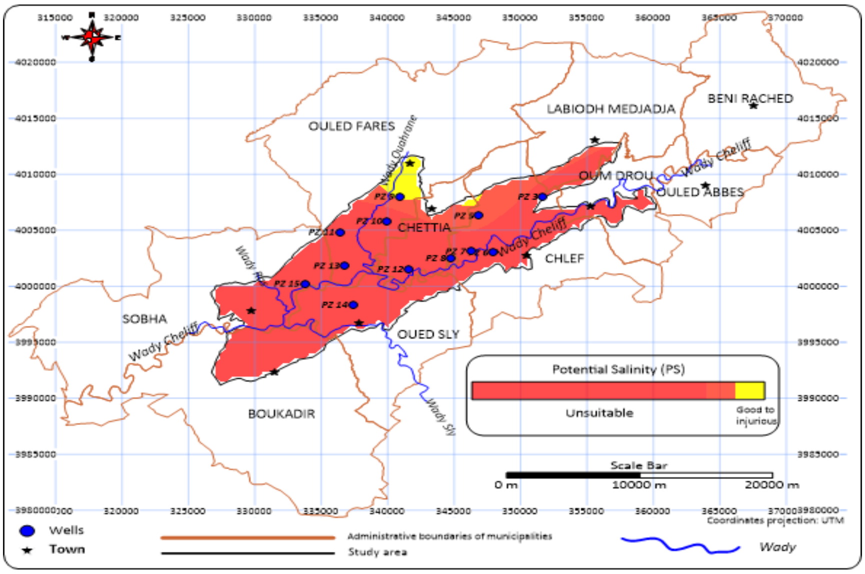


*Figure 14: Potential Salinity (PS)*

### *3.2.9 Residual Sodium Carbonate (RSC)*

RSC values indicate the potential for carbonate and bicarbonate ions to precipitate as sodium carbonate when calcium and magnesium are removed from water. High RSC values can adversely affect soil structure by promoting the precipitation of sodium carbonate. However, in the study area, RSC values are generally within acceptable limits, implying that there is no significant risk to irrigation practices (Table 6; Figure 15).

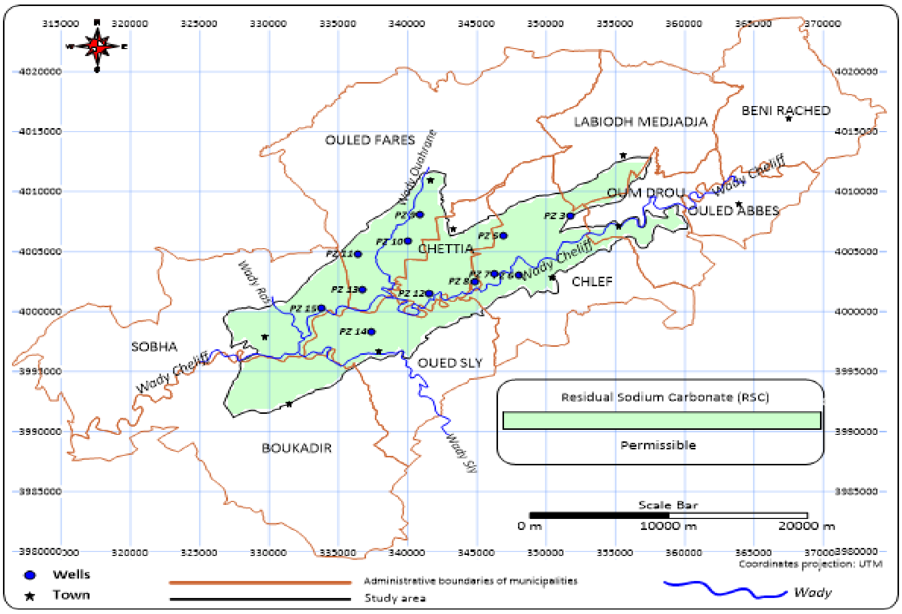


*Figure 15: Residual Sodium Carbonate (RSC)*

A correlation coefficient exceeding 0.7 suggests a robust relationship between WQII values.and those of electrical conductivity (EC), chlorides (Cl), Residual Sodium Carbonate (RSC), and Potential Salinity (PS). This high correlation implies that WQII classifies irrigation quality. In view of this relationship, it is not necessary to distinguish between the different forms of salt, as the measurable parameters are already correlated to overall salinity of the irrigation water. (Table 7). The following table, Table 8, presents a summary of the groundwater suitability data for irrigation in the study area plain.

*Table 7: Correlation between the Water Quality Index, WQII, and the parameters used to assess water quality*

| Parameters | Relationship with | R correlation |
|---|---|---|
| *Elecctric Conductitvity (µs/cm)* | WQII | 0,94 |
| *Chloride (meq/l)* | | 0,65 |
| *Sodium %Na--Ind* | | -0,61 |
| *SAR-Ind* | | 0,16 |
| *RSC-Ind* | | -0,93 |
| *PI-Ind* | | -0,70 |
| *MAR-Ind* | | 0,29 |
| *KR-Ind* | | -0,46 |
| *PS-Ind* | | 0,71 |

*Table 8: Classification of groundwater quality in the study area*

| Parameters | Class | Value | Station (%) |
|---|---|---|---|
| Electrical Conductivity (EC) (Richard, 1954) | C1- Excellent.. | < 250 | - |
| | C2- Good.. | 250 - 750 | 1 (8.33) |
| | C3-Permissible.. | 750 - 2250 | 2(16.67) |
| | C4-Doubtful. | 2250 - 5000 | 4 (33.33) |
| | C5- Unsuitable.. | > 5000 | 5(41.67) |
| Chloride (meq/L) (Srinivasamoorthy et al, 2011) | C1- Excellent. | < 4 | 1 (8.33) |
| | C2- Good.. | 4 - 7 | 1 (8.33) |
| | C3-Permissible. | 7 - 12 | - |
| | C4-Doubtful. | 12 - 20 | 5(41.67) |
| | C5- Unsuitable. | > 20 | 5(41.67) |
| Percent Sodium (% Na) (Richard, 1954) | C1- Excellent. | 0 - 20 | - |
| | C2- Good. | 20 - 40 | 3 (25) |
| | C3-Permissible. | 40 - 60 | 4 (33.33) |
| | C4-Doubtful. | 60 - 80 | 5(41.67) |
| | C5- Unsuitable. | > 80 | - |
| Sodium Absorption Ratio (SAR) (Gupta and Gupta,1987) | C1-Very low. | < 2 | - |
| | C2-Low. | 2 - 12 | 12 (100) |
| | C3-Medium. | 12 - 22 | - |
| | C4-High. | 22 - 32 | - |
| | C5-Very high. | > 32 | - |
| Per Ind (PI) (Doneen, 1964) | C1- Suitable. | < 75 | 9 (75) |
| | C2-Unsuitable. | ≥ 75 | 3 (25) |
| Res Sod Car (RSC) (meq/L) (Eaton, 1950; Richard, 1954) | C1-Permissible. | < 1.25 | 12 (100) |
| | C2-Unsuitable. | ≥ 1.25 | - |
| Magnesium hazard (MH) (Raju,2007) | C1-Permissible. | < 50 | 3 (25) |
| | C2-Unsuitable. | ≥ 50 | 9 (75) |
| Kelly's ratio (Kelly, 1940) | C1- Suitable. | < 1 | 5(41.67) |
| | C2-Unsuitable. | ≥ 1 | 7 (58,33) |
| Potentialsalinity (PS) (Doneen,1964) | C1- Excellent . | < 3 | - |
| | C2- Good . | 3 - 5 | 1 (8.33) |
| | C3- Injurious . | > 5 | 11 91,67) |

## 4. Discussion

In our study, the groundwater quality was evaluated using various physic-chemical parameters and irrigation indices, for the electrical conductivity, high mineralization from sedimentary and marl formations contributes to increased electrical conductivity (EC) in groundwater. Studies have demonstrated a positive correlation between groundwater level fluctuations and EC, with falling water levels potentially leading to increased salinity and mineral content (John & Das, 2020). A significant linear correlation between EC and both TDS and sodium concentrations exists (Cetin et al., 2020). In areas with shallow mineralized groundwater, EC values ranging from 600 to 2100 µS/cm have been reported, indicating a high risk of soil salinization (Burger &Čelková, 2018). Additionally, intensive use of fertilizers and saline irrigation water significantly contributes to high conductivity levels. In particular, studies conducted in arid and semi-arid area have revealed that, have found that subterranean water in these regions often has high EC values, ranging from 2.24 to 3.86 dS/m, which can lead to severe soil salinity problems if not managed properly (Abdel-Mageed et al., 2018). The use of potassium chloride fertilizers has been identified as a significant source of groundwater salinization, contributing up to 60% of chloride in some cases

(Buvaneshwari et al., 2020). However, traditional irrigation practices can mitigate these effects. For instance, a study in Morocco found that traditional irrigation systems led to lower EC values and nitrate concentrations compared to non-irrigated areas, highlighting the potential benefits of ancestral hydro-agro systems in maintaining groundwater quality (Bouimouass et al., 2022). The region's calcareous and marl formations, such as Miocene marls and limestones, contribute to elevated bicarbonate levels. Studies in Lebanon and Morocco have shown that limestone aquifers typically produce calcium bicarbonate-rich water with moderate alkalinity (Bahir et al., 2018; Khadra et al., 2022; Elgettafi et al., 2022). In Egypt's limestone aquifer, bicarbonate concentrations ranged from 62 to 124 ppm (Saad et al., 2023). Anthropogenic activities, particularly irrigated agriculture, can enhance silicate weathering and increase bicarbonate concentrations in groundwater. In California's San Joaquin Valley, bicarbonate showed the greatest increase among major ions over a century, primarily due to enhanced silicate weathering caused by irrigation water enriched in $CO_2$ (Hansen et al., 2018). Gypsum formations significantly increase sulfate levels in water, with gypsum dissolution potentially leading to sulfate concentrations as high as 190 mg/L, and theoretical maximum values reaching 879 mg/L (Thornton, 1997). Gypsum amendments on agricultural fields can cause temporary increases in sulfate concentrations in nearby water bodies, potentially affecting aquatic biota (Rantamo et al., 2021). Certain fertilizers can also elevate sulfate concentrations. Similar high TDS values were recorded in Algeria by Bouderbala (2014). In reservoir systems, gypsum formations can influence water quality parameters such as TDS (Sajadian & Heidarzadeh, 2022). In semi-arid regions, evaporation and irrigation practices lead to salt accumulation in soil profiles, resulting in groundwater TDS concentrations as high as 46,000 mg/L (Barica, 1972). High chloride values are initially sourced from marl formations and saltwater intrusions from ancient marine aquifers (Suhartono et al., 2019; Vallejos et al., 2020). Additionally, the use of poor-quality irrigation water rich in chlorides and certain fertilizers can elevate chloride levels in soil and plants. Irrigation with saline or brackish water can cause soil salinization, reducing soil fertility and crop yields (Alvarez et al., 2014; Bouderbala & Hadj Mohamed, 2020). Nitrogen fertilization can help mitigate chloride accumulation in plant tissues, but excessive nitrogen application may result in increased leaching of both nitrogen and chloride (Bar-Tal et al., 2020). High sodium concentrations result from the leaching of sodium minerals from marl and sedimentary formations (Bouderbala et al.,2016; Öztürk et al., 2023). The concentration of beneficial minerals, including calcium, magnesium, and iron, in groundwater from sedimentary aquifers is often higher than in groundwater from karstic aquifers. However, it may also contain excessive levels of sodium, which can contribute to health issues such as hypertension and cardio-metabolic diseases when combined with dietary intake. The lack of clear health-based guideline values for sodium in drinking water is a concern that requires further attention (Nwankwo et al., 2020). Agricultural activities also play a role, as certain fertilizers and irrigation water with high sodium content increase sodium concentrations; sodium concentrations in soil can increase by up to 70% with reclaimed wastewater irrigation (Manalang et al., 2020). The assessment of the different Quality Index for Irrigation Purposes (GWQII) in our study area indicates that most of the water is suitable for irrigation. However, areas with high GWQII values falling into the poor category are primarily due to elevated groundwater salinity. This salinity is largely influenced by water-rock interactions and evaporation processes. Additionally, the infiltration of surface water into the aquifer can impact groundwater quality, as observed in Nekor-Ghiss (Morocco) (Elkhalki et al., 2023) and the Ouargla region (Algeria) (Boussaada et al., 2023), where groundwater quality was found to be very poor and unsuitable for drinking or irrigation. When compared to the study by Kayemah et al. (2021) in Sharjah (UAE), our findings suggest that the GWQII in our study area has remained relatively stable over time. The excellent and good results for Sodium Absorption Ratio (SAR), Percent Sodium (Na%), Permeability Index (PI), and Residual Sodium Carbonate (RSC) suggest that the irrigation water has a favourable balance of sodium relative to calcium and magnesium. This indicates good water quality concerning sodium's impact on soil structure and permeability. These metrics demonstrate low sodium hazards, appropriate permeability, and balanced cation ratios, beneficial for soil health, as shown in studies by Farahani et al. (2018) and Pandao et al. (2024). However, the unsatisfactory results for kelly's ratio (KR), Magnesium Hazard Ratio (MHR) and Potential Salinity (PS) highlight significant issues with high magnesium levels and overall salinity. High MHR indicates that excessive magnesium is likely causing soil dispersion, degrading soil structure, and reducing permeability, independent of sodium-related parameters, leading to a decrease in agricultural crop yields (Bouderbala & Gharbi, 2017; Qadir et al., 2018). Furthermore, high PS suggests that total salinity, including salts other than sodium, High enough to pose a potential risk to soil and plant health. This combination implies that while sodium levels are well managed, the adverse effects of high magnesium and overall salinity dominate, leading to poor soil conditions despite favourable readings in other metrics. Addressing high magnesium and salinity levels is crucial for improving soil quality and agricultural productivity, as demonstrated in the studies by Senbayram et al, (2015) and Bhat et al. (2016).

## 5. Conclusion

In the study area plain, the quality of groundwater has been thoroughly studied, mainly to assess its suitability for irrigation to mitigate potential risks. However, the findings have shown that most of the chemical components studied exceeded the standards established by the World Health Organization (WHO). These values were primarily due to high levels of electrical conductivity, chlorides, sulphates, nitrates, bicarbonates, and magnesium, caused by direct discharges of urban waste and agricultural fertilizers, exacerbated by low precipitation. According to the results obtained using various parameters, classifications, and indices such as EC, Cl, SAR, RSC, %Na, KR, MAR, PI, PS, as well as the Riverside and Wilcox classifications. It has been shown that the quality of the groundwater for irrigation purposes ranges from good to poor. According to the Groundwater Quality Index for Irrigation (GWQII), the reservoir is completely unsuitable for irrigation. The GWQII maps were spatially analysed, emphasizing the importance of taking measures when using groundwater for crop irrigation. Moreover, the continuity of sampling and the increase in the number of wells in the study area are essential to provide critical data for effective groundwater management and the preservation of sustainability in this semi-arid region.

For irrigation purposes, indicators such as SAR, Na%, PI, KR, MH, SSP, RSC, and PS were considered. The results showed that the majority of the samples were considered suitable for irrigation in the sampling period However, elevated levels of salinity and magnesium led to increased PS and MHR, indicating a potential risk to the soil and agricultural practices in the area. The study suggests that to maintain groundwater quality in the National Irrigation and Drainage Program area, it is imperative to strengthen the monitoring program. Based on the research findings, the following recommendations are proposed: Implement measures to improve water quality, including strategies for nutrient reduction and sustainable agricultural and waste management practices to decrease pollution entering the aquifer. Establish a regular monitoring program to track groundwater quality changes and identify potential pollution sources. Ensure recreational facilities are maintained and clean through routine programs. Raise public awareness about groundwater preservation and eco-friendly practices, and encourage community involvement in conservation efforts. Strengthen existing regulations, develop new ones if needed, and enforce strict zoning and land-use policies to manage and mitigate potential pollution sources.

## Conflict of Interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content, and (c) approval of the final version.

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## References

Abdel-Mageed, Y., Hassan, H., Abdel-Rahim, A., Abd EL- Azeim, M., &Matouk, M. (2018). Evaluation of groundwater quality for irrigation and its effects on some soil chemical properties in the western desert of El-minia governorate, Egypt. *Journal of Soil Sciences and Agricultural Engineering,* 9(8), 283–294. CrossRef

Adagba, T., Kankara, A. I., & Idris, M. A. (2022). Evaluation of groundwater suitability for irrigation purpose using gis and irrigation water quality indices. *Fudma journal of sciences*, 6(2), 63–80. CrossRef

Ali, S., & Armanuos, A. M. (2023). Introduction to "groundwater in arid and semi-arid areas. *groundwater in arid and semi-arid areas*, 3–9.

Alsahli, A. (2023). Evaluation of groundwater quality utilizing integrated physicochemical parameters and indexing approaches. *International Journal of Environmental Studies and Researches*, 2(2), 89–98. CrossRef

Alvarez, M. del P., Dapeña, C., Bouza, P. J., Ríos, I., & Hernández, M. A. (2014). Groundwater salinization in arid coastal wetlands: a study case from Playa Fracasso, Patagonia, Argentina. *Environmental Earth Sciences*, 73(12), 7983–7994. CrossRef

Arveti, N., Sarma, M. R.S., Aitkenhead-Peterson, J.A., Sunil, K. (2011). Fluoride incidence in groundwater: a case study from Talupula, Andhra Pradesh, India. *Environmental monitoring and assessment*, 172: 427-443. CrossRef

Asadi, E., Isazadeh, M., Samadianfard, S., Ramli, M. F., Mosavi, A., Nabipour, N., & Chau, K. W. (2019). Groundwater quality assessment for sustainable drinking and irrigation. *Sustainability*, *12*(1), 177.

Ayers, R. S., & Westcot, D. W. (1985). Water quality for agriculture Rome, *Food and Agriculture Organization of the United Nations-FAO*. 29(1), pp 37-70.p.174.

Bahir, M., Ouhamdouch, S., & Carreira, P. M. (2018). Geochemical and isotopic approach to decrypt the groundwater salinization origin of coastal aquifers from semi-arid areas (Essaouira basin, Western Morocco). *Environmental Earth Sciences*, 77(13). CrossRef

Bari, J. A., Perumal, K., & Muthuramalingam, S. (2021). Evaluation of Groundwater quality and suitability for irrigation using hydro-chemical process in Bhavani taluk, Erode District, Tamilnadu, India. CrossRef

Barica, J. (1972). Salinization of groundwater in arid zones. *Water Research*, 6(8), 925–933. CrossRef

Barick, S. R., & Ratha, B. K. (2014). Hydro-chemical analysis and evaluation of groundwater quality of Hial area, Bolangir district, Odisha, India. *Journal of Geosciences and Geomatics*, *2*(5), 22-28.

Bar-Tal, A., Kiwonde, E., Kanner, B., Nitsan, I., Shawahna, R., & Kurtzman, D. (2020). Nitrogen fertilization of plants irrigated with desalinated water: a study of interactions of nitrogen with chloride. *Water*, 12(9), 2354. CrossRef

Behera, S. M., & Baliarsingh, Dr. F. (2017). Hydrogeochemical analysis and quality evaluation of groundwater for irrigation purposes in Puri District, Odisha. *International Journal of Trend in Scientific Research and Development*, 1 (6), 1286–1295. CrossRef

Behera, S., & Mishra, S. (2017). Hydrogeochemical analysis and quality apraisal of groundwater for irrigation, puri district, odisha, India. *International Journal of Advanced Research*, 5(9), 1534–1544. CrossRef

Belouchrani, A. S., Bouderbala, A., & Hocine, M. (2019). Participatory approaches to sustainable development and management of soil resources in arid zones of Algeria. water resources in Algeria - Part I, 269–292. CrossRef

Bhat, M. A, Mir, S.H, Qureshi, M.A. (2016).Assessment of groundwater quality for irrigation purposes using chemical indices. *Journal of Environmental Management*, 183. 565-574. CrossRef.

Birhane, H., Hagos, M. (2021). Impacts of soil salinity/sodicity on soil-water relations and plant growth in dry land areas: a review. *Journal of Natural Sciences Research*. CrossRef

Bouderbala, A. (2014). Groundwater salinization in semi-arid zones: an example from Nador plain (Tipaza, Algeria). *Environmental Earth Sciences*, 73(9), 5479–5496. CrossRef

Bouderbala, A. (2017a). Assessment of water quality index for the groundwater in the upper Cheliff plain, Algeria. *Journal of the Geological Society of India*, *90*(3), 347-356.

Bouderbala, A. (2017b). Effects of climate variability on groundwater resources in coastal aquifers (Case of Mitidja Plain in the North Algeria). *Groundwater and Global Change in the Western Mediterranean Area*, 43–51. CrossRef

Bouderbala, A. (2019a). The human impact of septic tank effluent on groundwater quality in the rural area of ain soltane (ain defla), Algeria. *Environmental & Socio-economic Studies*, *7*(2), 1-9. CrossRef

Bouderbala, A. (2019b). The impact of climate change on groundwater resources in coastal aquifers: case of the alluvial aquifer of mitidja in Algeria. *Environmental Earth Sciences*, 78(24). CrossRef

Bouderbala, A., & Gharbi, B. Y. (2017). Hydrogeochemical characterization and groundwater quality assessment in the intensive agricultural zone of the upper cheliff plain, Algeria. *Environmental Earth Sciences,* 76(21). CrossRef

Bouderbala, A., & Hadj Mohamed, N. (2020). Water resources in coastal aquifers of algeria face climate variability: case of alluvial aquifer of mitidja in Algeria. Water Resources in Algeria - Part I, *Assessment of Surface and Groundwater Resources*, 203–224. CrossRef

Bouderbala, A., & Merouchi, H. (2023). Impact of climate change and human activities on groundwater resources in the alluvial aquifer of upper Cheliff, Algeria. *Indian Journal of Ecology*, *50*(3), 575-583.

Bouderbala, A., Remini, B., Saaed Hamoudi, A., & Pulido-Bosch, A. (2016). Application of multivariate statistical techniques for characterization of groundwater quality in the coastal aquifer of Nador, Tipaza (Algeria). *Acta Geophysica,* 64(3), 670–693. CrossRef

Bouimouass, H., Fakir, Y., Tweed, S., Sahraoui, H., Leblanc, M., & Chehbouni, A. (2022). Traditional irrigation practices sustain groundwater quality in a semiarid piedmont. *Catena*, 210, 105923. CrossRef

Bounab, S., Khemmoudj, K., & Sedrati, N. (2022). Assessment and physicochemical characterization of groundwater quality for irrigation and drinking purposes in bazer sakhra (Eastern Area of Algeria). Journal of Ecological Engineering, 23(8), 118–131. CrossRef

Boussaada, N., Boualem, B., Benhamida, S. A., Hammad, N., & Kharroubi, M. (2023). Geochemistry and Water Quality Assessment of Continental Intercalary Aquifer in Ouargla Region (Sahara, Algeria). Journal of Ecological Engineering, 24(2), 279–294. CrossRef

Bradai, A., Yahiaoui, I., Douaoui, A., Abdennour, M. A., Gulakhmadov, A., & Chen, X. (2022). Combined modeling of multivariate analysis and geostatistics in assessing groundwater irrigation sustenance in the middle Cheliff Plain (North Africa). *Water*, 14(6), 924. CrossRef

Burger, F., & Čelková, A. (2003). Salinity and sodicity hazard in water flow processes in the soil. *Plant, Soil and Environment*, 49(7), 314–320. CrossRef

Buvaneshwari, S., Riotte, J., Sekhar, M., Sharma, A. K., Helliwell, R., Kumar, M. S. M., Braun, J. J., & Ruiz, L. (2020). Potash fertilizer promotes incipient salinization in groundwater-irrigated semi-arid agriculture. *Scientific Reports*, 10(1). CrossRef

Çetin, M., Gölpınar, M. S., & Erkan Can, M. (2020). Deriving mathematical relationships between electrical conductivity and concentrations of some minerals in groundwater: a case study in the mediterranean region of Turkey. *International Journal of Innovative Approaches in Agricultural Research*, 4(3), 318–327. CrossRef

Chellouai, N., Masmoudi, A., Messameh, A. (2023). Hydrogeochemical quality of groundwater used for irrigation in ziban region, Algeria. Al-Qadisiyah *Journal For Agriculture Sciences* , 13(1), 23-35. CrossRef

Das, J., Dr, A., Dr, R., & Murali, A. (2019). Hydro-geochemical evaluation of groundwater for its suitability to various uses; a case study of a small mountainous river basin in western ghats, South India. *International Journal of Research in Advent Technology*, 7(5), 665–676. CrossRef

Das, R., Subba Rao, N., Sahoo, H. K., & Sakram, G. (2023b). Nitrate contamination in groundwater and its health implications in a semi-urban region of Titrol block, Jagatsinghpur district, Odisha, India. *Physics and Chemistry of the Earth*, Parts A/B/C, 132, 103424. CrossRef

Djema, M., & Mebrouk, N. (2022). Groundwater quality and nitrate pollution in the Nador plain, Algeria. *Environmental Earth Sciences*, 81(18). CrossRef

Doneen, L.D. (1964). Notes on water quality in agriculture. published as a water science and engineering paper 4001, department of water science and engineering, university of California, Davis.

Eaton, F.M. (1950). Significance of carbonates in irrigation waters. *Soil science*, 69(2). 123-134. CrossRef.

Eid, M. H., Elbagory, M., Tamma, A. A., Gad, M., Elsayed, S., Hussein, H., Moghanm, F. S., Omara, A. E.-D., Kovács, A., & Péter, S. (2023). Evaluation of groundwater quality for irrigation in deep aquifers using multiple graphical and indexing approaches supported with machine learning models and GIS techniques, Souf Valley, Algeria. *Water*, 15(1), 182. CrossRef

Eid, M.H., Tamma, A.A., Péter, S., Kovács, A. (2022). Hydrogeochemical evaluation of groundwater and its suitability for drinking and irrigation using water quality index, statistical and geochemical modelling, Debila and El-Oued regions, Algeria. CrossRef.

Elgettafi, M., Elmeknassi, M., Elmandour, A., Himi, M., Lorenzo, J. M., & Casas, A. (2022). δ34S, δ18O, and δ2H-δ18O as an approach for settling the question of groundwater salinization in neogene basins: the north of Morocco in Focus. *Water*, 14(21), 3404. CrossRef

Elkhalki, S., Hamed, R., Jodeh, S., Ghalit, M., Elbarghmi, R., Azzaoui, K., Lamhamdi A. (2023). Study of the quality index of groundwater (GWQI) and its use for irrigation purposes using the techniques of the geographic information system (GIS) of the plain Nekor-Ghiss (Morocco). *Frontiers in Environmental Science*; 11. 1179283. CrossRef

Food and Agriculture Organization FAO. (2016). Aquastat: FAO's information system on water and agriculture. Food and Agriculture Organization of the United Nations

Farahani, E., Emami, H., & Keller, T. (2018). Impact of monovalent cations on soil structure. Part II. results of two swiss soils. *International Agrophysics*, 32(1), 69–80. CrossRef

Fehdi C, Rouabhia A, BaaliF, Boudoukha A. (2009). The hydrogeochemical characterization of Morsott-El Aouinet aquifer. northeastern Algeria. Environmental Geology; 58. 1611-1620. CrossRef.

Gaagai, A., Aouissi, H.A., Bencedira, S., Hinge, G., Athamena, A., Heddam ,S., Ibrahim, H. (2023). Application of water quality indices, machine learning approaches, and GIS to identify groundwater quality for irrigation purposes: A case study of Sahara Aquifer, Doucen Plain, Algeria. *Water* 15(2), 289. CrossRef

Gad M, El-Hendawy S, Al-Suhaibani N, Tahir MU, Mubushar M, Elsayed S. Combining hydrogeochemical characterization and a hyperspectral reflectance tool for assessing quality and suitability of two groundwater resources for irrigation in Egypt. Water 2020;12(8):2169. CrossRef.

Gaikwad, H., Shaikh, H., &Umrikar, B. (2019). Evaluation of groundwater quality for domestic and irrigation suitability from upper bhima basin, western india: a hydro-geochemical perspective. *Hydrospatial Analysis*, 2(2), 113–123. CrossRef

Gautam, V. K., Pande, C. B., Moharir, K. N., Varade, A. M., Rane, N. L., Egbueri, J. C., &Alshehri, F. (2023). Prediction of sodium hazard of irrigation purpose using artificial neural network modelling. *Sustainability*, 15(9), 7593. CrossRef.

Gayar, A. E. (2020). A study on water's green economy for development in agriculture. *International Journal of Agricultural Invention*, 5(02), 218–232. CrossRef

Guettaf, M., Maoui, A., &Ihdene, Z. (2017). Assessment of water quality: a case study of the Seybouse River (North East of Algeria). *Applied water science*, *7*(1), 295-307.

Gupta, S.K, Gupta, I. C. (1987). Management of saline soils and waters. Oxford and IBH Publishing Company, New Delhi. 52:1067-1074. CrossRef

Hamed Y. (2022). Vulnerability characterization for multi-carbonate aquifer systems in semiarid climate. case of Algerian–Tunisian transboundary basin. *International Journal of Energy and Water Resources,* 6(1). 67-80. CrossRef

Hansen, J. A., Jurgens, B. C., & Fram, M. S. (2018). Quantifying anthropogenic contributions to century-scale groundwater salinity changes, San Joaquin Valley, California, USA. *Science of The Total Environment*, 642, 125–136. CrossRef

Hennia, K., Saaed Hamoudi, A., & Bouderbala, A. (2022). Hydrogeochemical characterization and groundwater quality assessment: a case study of the alluvial aquifer in the middle western cheliff (Algeria). *International Journal of Environmental Analytical Chemistry*, 104(9), 2075–2095. CrossRef

John, B., & Das, S. (2020). Role of electrical conductivity on salinity and mineralization due to groundwater level fluctuations in Kolkata City. IOP Conference Series: *Earth and Environmental Science*, 505(1), 012021. CrossRef

Kayemah, N., Al-Ruzouq, R., Shanableh, A., & Gokhan Yilmaz, A. (2021). Evaluation of groundwater quality using groundwater quality index (GWQI) in Sharjah, UAE. E3S Web of Conferences, 241, 01005. CrossRef

Kelley, W.P. (1963). Use of saline irrigation water. Soil Sci, 95, 385–391. CrossRef

Kelly, W.P. (1940) Permissible composition and concentration of irrigated waters. proceedings of the American society of civil engineers 66, 607-613.

Khadra, W.M., Elias, A. R., & Majdalani, M. A. (2022). A systematic approach to derive natural background levels in groundwater: application to an aquifer in north lebanon perturbed by various pollution sources. *Science of The Total Environment*, 847, 157-586. CrossRef

Khiyat, Z. (2022). Groundwater in the arab region: making the invisible visible. *Desalination And Water Treatment*, 263, 204–206. CrossRef

Madene, E., Boufekane, A., Meddi, M., Busico, G., & Zghibi, A. (2022). Spatial analysis and mapping of the groundwater quality index for drinking and irrigation purposes in the alluvial aquifers of upper and middle Cheliff basin (north-west Algeria). *Water Supply*, *22*(4), 4422-4444.

Maman Hassan, A., &Firat Ersoy, A. (2022). Hydrogeochemical and isotopic investigations on the origins of groundwater salinization in Çarşamba coastal aquifer (North Turkey). *Environmental Earth Sciences*, 81(4). CrossRef

Manalang, M. F. P., Tala, R. L., Dizon, P. D., David., K. C. E., & Villar, M. J. M. (2020). Reclaimed water project: effects of high na concentration in soil and plant tissues. *International Journal of Engineering and Advanced Technology*, 9(4), 1181–1187. CrossRef

Mansir, I., Bouchaou, L., Choukr-allah, R., Chebli, B., & El Otmani, M. (2017). Groundwater resources scarcity in souss-massa region and alternative solutions for sustainable agricultural development. groundwater and global change in the western mediterranean area, 189–197. CrossRef

Masood, A., Aslam, M., Pham, Q. B., Khan, W., & Masood, S. (2022). Integrating water quality index, GIS and multivariate statistical techniques towards a better understanding of drinking water quality. *Environmental Science and Pollution Research*, 1-17. CrossRef

Mattauer, M. (1958). Etude géologique de l'ouarsenis oriental (Algérie). Geological study of the eastern Ouarsenis (Algeria). *PublServ Carte Géol Algérie, Alger. Bull, 17.*

Mengistu, H.A., Demlie, M.B. & Abiye, T.A. (2019). Review: Groundwater resource potential and status of groundwater resource development in Ethiopia. *Hydrogeoly*, 27, 1051–1065 CrossRef

Nagaraju, A., Sunil Kumar, K., & Thejaswi, A. (2014). Assessment of groundwater quality for irrigation: a case study from bandalamottu lead mining area, guntur district, andhra pradesh, south India. *Applied Water Science*, *4*, 385-396.

Nwankwo, C. B., Hoque, M. A., Islam, M. A., & Dewan, A. (2020). Groundwater constituents and trace elements in the basement aquifers of africa and sedimentary aquifers of asia: medical hydrogeology of drinking water minerals and toxicants. *Earth Systems and Environment*, 4(2), 369–384. CrossRef

Öztürk, H. S., DevirenSaygın, S., Copty, N. K., İzci, E., Erpul, G., Demirel, B., Saysel, A. K., & Babaei, M. (2023). Deterioration of physical and hydraulic properties of a calcareous clay-rich soil in central Anatolia, Turkey, By Sodic Water. CrossRef

Pandao, Manish, R., Akshay, A., Thakare, Rupeshkumar, J,. Choudhari, Nagesh, R., Navghare, Dhananjay, D., Sirsat, and Sindhu, R. Rathod. (2024). "Soil health and nutrient management". *International Journal of Plant & Soilcience,*36(5):873-83. CrossRef.

Panneerselvam, B., Karuppannan, S., &Muniraj, K. (2020). Evaluation of drinking and irrigation suitability of groundwater with special emphasizing the health risk posed by nitrate contamination using nitrate pollution index (NPI) and human health risk assessment (HHRA). *International Journal Human and Ecological Risk Assessment*, 27(5), 1324–1348. CrossRef

Prasad, Y. S., & Rao, B. V. (2018). Monitoring and assessment of groundwater quality in a khondalitic terrain, Andhra Pradesh, India. *Environmental Monitoring and Assessment*, 190(7). CrossRef

Qadir, M., Schubert, S., Oster, J. D., Sposito, G., Minhas, P. S., Cheraghi, S. A. M., Murtaza, G., Mirzabaev, A., & Saqib, M. (2018). High-magnesium waters and soils: Emerging environmental and food security constraints. *Science of The Total Environment*, 642, 1108–1117. CrossRef.

Qiu, R., Jing, Y., Liu, C., Yang, Z., & Wang, Z. (2017). Response of hot pepper yield, fruit quality, and fruit ion content to irrigation water salinity and leaching fractions. *Hort Science*, 52(7), 979–985. CrossRef

Raghunath, I. I. M. (1987). Groundwater. second ed., Wiley Eastern Ltd., New Delhi. India, pp. 344–369.

Raju, N.J. (2007) Hydrogeochemical parameters for assessment of groundwater quality in the upper gunjanaeru river basin, cuddapah district, andhra pradesh, South India. *Environmental Geology*

Rantamo, K., Arola, H., Aroviita, J., Hämälainen, H., Hannula, M., Laaksonen, R., Laamanen, T., Leppänen, M. T., Salmelin, J., Syrjänen, J. T., Taskinen, A., Turunen, J., & Ekholm, P. (2021). Risk assessment of gypsum amendment on agricultural fields: effects of sulfate on riverine biota. *Environmental Toxicology and Chemistry*, 41(1), 108–121. Portico. CrossRef

Richards, L.A. (1954). Diagnosis and improvement of saline and alkali soils. vol. 160. u. s. department of agriculture handbook. Washington USA DC, 7-53., CrossRef

Saad, A., Fattah, M., & Gad, M. (2023). Groundwater quality evaluation for the limestone aquifer utilizing hydrochemical characteristics and imitative techniques, eastern nile valley, Egypt. *International Journal of Environmental Studies and Researches*, 2(3), 118–131. CrossRef

Sadick, A., Asante, P., Dugan, E., &Asaana, J. (2017). Correlation analysis of Irrigation water quality parameters from lake bosomtwe in the ashanti Region of Ghana.

Sahu, P., & Sikdar, PK. (2008). Hydrochemical Framework of the aquifer in and around east kolkata wetlands, west bengal, India. *Environmental Geology*, 55: 823-835. CrossRef

Sajadian, A., & Heidarzadeh, N. (2022). The effect of the gypsum formation on the water quality of reservoirs: A case study of Kosar dam basin, Iran. *Journal of Geochemical Exploration*, 243, 107107. CrossRef

Samal, P., Mohanty, A. K., Khaoash, S., & Mishra, P. (2023). Hydrogeochemical characteristics and spatial analysis of groundwater quality in a semi-arid region of Western Odisha, India. *Arabian Journal of Geosciences*, 16(1). CrossRef

Senbayram, M., Gransee, A., Wahle, V., & Thiel, H. (2015). Role of magnesium fertilisers in agriculture: plant–soil continuum. *Crop and Pasture Science*, 66(12), 1219. CrossRef

Singaraja, C. (2017). Relevance of water quality index for groundwater quality evaluation: thoothukudi district. Tamil Nadu. India. *Applied water science*,7. 2157-2173. CrossRef.

Soula, R., Chebil, A., McCann, L., &Majdoub, R. (2021). Water scarcity in the mahdia region of tunisia: are improved water policies needed. *Groundwater for Sustainable Development*, 12, 100-510.CrossRef

Srinivasamoorthy, K., Nanthakumar, C., Vasanthavigar M., Vijayaraghavan, K., Rajivgandhi, R. (2011) Groundwater quality assessment from a hard rock terrain, salem district of tamilnadu, India. *Arabian Journal of Geosciences,* 4: 91–102. CrossRef

Srinivasamoorthy, K., Vijayaraghavan, K., Vasanthavigar, M., Sarma, V. S., Rajivgandhi, R., Chidambaram, S., Anandhan, P., & Manivannan, R. (2010). Assessment of groundwater vulnerability in Mettur region, Tamilnadu, India using drastic and GIS techniques. *Arabian Journal of Geosciences*, 4(7–8), 1215–1228. CrossRef

Subba Rao, N., Das R., Sahoo, H.K., Gugulothu, S. (2024b).Hydrochemical characterization and water quality perspectives for groundwater management for urban development. *Groundwater for Sustainable Development*, 24, 101071. CrossRef

Subba Rao, N., Sunitha, B., Das, R., & Anil Kumar, B. (2022). Monitoring the causes of pollution using groundwater quality and chemistry before and after the monsoon. *Physics and Chemistry of the Earth*, Parts A/B/C, 128, 103228. CrossRef

Suhartono, E., Isgandhi, R., Sulaiman, S., Rahardjo, P., & Satriyadi, L. (2019). Analysis of the effect of soil water taking on potential of soil water pollution in semarang. *Bangun Rekaprima*, 5(2), 29. CrossRef

Thornton, E. C. (1997). Origin of increased sulfate in groundwater at the ETF disposal site. *Office of Scientific and Technical Information* (OSTI). CrossRef

Todd, D.K., DoJ, W.L. (1981). Groundwater hydrology. 2nd edition. xiii + 535 pp., new york. chichester. brisbane. toronto: john wiley. ISBN 0 471 87616 X.. *Geological Magazine* .118(4). 442–442. CrossRef

Vallejos, A., Daniele, L., Sola, F., Molina, L., & Pulido-Bosch, A. (2020). Anthropic-induced salinization in a dolomite coastal aquifer. hydrogeochemical processes. *Journal of Geochemical Exploration*, 209, 106438. CrossRef

Vohra, P. (2023). Review on physicochemical characteristics of ground water and their health effects. *Journal of Mechanical and Construction Engineering (JMCE*), 3(1), 1–8. CrossRef

Wang, X., Tian, W., Zheng, W., Shah, S., Li, J., Wang, X., & Zhang, X. (2023). Quantitative relationships between salty water irrigation and tomato yield, quality, and irrigation water use efficiency: A meta-analysis. *Agricultural Water Management*, 280, 108213. CrossRef

Wilcox, L. V., & Durum, W. H. (1967). Quality of Irrigation Water. Irrigation of Agricultural Lands, 104–122. CrossRef

World Health Organization WHO. (2017). Guidelines for Drinking-Water Quality, 2nd edition. Geneva. *Chronicle*, *38*(4), 104-8.