Assessing Spatial Distribution and Quality of Phreatic Water for Sustainable Supply: A Study of the Tebessa Aquifer System

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Abstract

Groundwater quality plays a vital role in addressing freshwater demands, especially in semiarid regions with water scarcity. This study focuses on assessing groundwater quality in the Tebessa aquifer system, a primary water source for various needs. The investigation is prompted by challenges like hydric stress, aridity, urbanization, and population growth, which impact water demand and quality. Factors such as intensive agriculture and industrial activities contribute to declining groundwater quality. The study employs the Water Quality Index (WQI) method, which combines multiple parameters to evaluate water health comprehensively. Geographic Information Systems (GIS) technology aids in analysing spatial relationships, crucial for hydrogeological processes. The study incorporates a multiparameter approach to create maps of water quality, with parameters including pH, Total Dissolved Solids (TDS), and various ions. These maps reveal spatial variations and priority classes ranging from 'Excellent' to 'Very Poor' in groundwater quality. The main objective is to enhance understanding of groundwater quality dynamics in semiarid regions and identify management strategies. The Tebessa-Morsott Plain in Algeria serves as the study area, characterized by a semi-arid climate. Field and laboratory investigations were conducted to analyse hydrochemical characteristics. The results show diverse ranges of parameters, indicating alkalinity, salinity, and elevated concentrations of ions. By analysing interrelationships and spatial variability, the study contributes to both scientific understanding and informed water resource management. Geospatial mapping and the generation of a groundwater quality index map illustrate varying levels of water quality across the study area, guiding strategic decisions for sustainable water resource management.

1. Introduction

The quality of groundwater assumes paramount significance as an indispensable source of potable water, particularly in semiarid regions. These areas, characterized by scarce and unpredictable precipitation, heavily rely on groundwater to meet their freshwater demands. The intrinsic resilience of groundwater reserves in semi-arid zones offers a lifeline to communities facing water scarcity. However, the sustained viability of this vital resource hinges upon its quality. Ensuring the purity and safety of groundwater is imperative to safeguard public health and well-being. Contaminants, both natural and anthropogenic in origin, can compromise the suitability of groundwater for consumption, potentially leading to a range of adverse health effects. As such, a comprehensive understanding of groundwater quality is essential to implement appropriate management strategies that preserve its potability. By comprehensively assessing the quality of groundwater and instituting effective monitoring and safeguarding mechanisms, semiarid regions can ensure a sustainable and reliable source of drinking water, thereby addressing a critical facet of water security in these challenging environments. Numerous researchers have conducted rigorous investigations into the water-related challenges within both the study area and its neighboring regions, as highlighted by the studies of Drias et al. (2015), Hamad et al. (2018a, b, 2021a, b), Nekkoub et al. (2020), and Brahmi et al. (2021). These studies have underscored the issues of water availability, quality, and sustainability.

The comprehensive assessing the groundwater quality within the Tebessa aquifer system, as the primary source for drinking, domestic, industrial, and agricultural needs is essential. The imperative for such an investigation arises from a confluence of challenges, including hydric stress, climatic aridity, rapid urbanization, and population growth. These factors have accentuated the demand for freshwater resources, leading to the overexploitation of groundwater. In recent years, the degradation and deterioration of aquifer quality have emerged as critical concerns, attributed to multifarious influences. Among these influences are intensified agricultural practices characterized by elevated utilization of chemical pesticides, as well as intricate interactions between the aquifer and surrounding soil and lithological features. Additionally, the distinctive climatic attributes and the inherent vulnerability of groundwater to pollution, stemming from industrial activities, have compounded the issue. This study, by focussing on the factors contributing to groundwater quality decline, contributes to a more profound scientific understanding of the phenomenon. It is through such rigorous analysis that sustainable solutions can be devised to preserve and restore the quality of this indispensable resource in the face of mounting challenges.

The Water Quality Index (WQI) method stands as a pivotal tool within the realm of environmental science, facilitating a comprehensive and quantitative assessment of water quality. This method synthesizes diverse water quality parameters into a single index, offering a concise representation of overall water health. By amalgamating physical, chemical, and biological variables, the WQI method provides a holistic perspective on the condition of a water body, allowing for effective comparison and interpretation. Through a systematic scoring system, each parameter's significance is weighted, aligning with its ecological relevance and potential impact on human health. The resultant index score serves as a valuable diagnostic metric, enabling policymakers, scientists, and resource managers to gauge the extent of water pollution, track trends over time, and allocate resources for remediation strategies. This approach fosters a standardized framework for evaluating water quality, aiding in data-driven decision-making and fostering a more resilient and sustainable management of water resources within the context of complex and dynamic environmental systems (Cotruvo, 2017; Elubid et al. 2019; Li et al. 2019).

Geographic Information Systems (GIS) technology emerges as a foundational instrument within the domain of hydrogeological modeling and environmental assessments, including methodologies like the Water Quality Index (WQI). Renowned for its capacity to systematize and analyze a diverse spectrum of geographical data, GIS serves as a potent facilitator in the understanding of intricate spatial relationships that underlie hydrogeological processes. By integrating various data types, such as geology, hydrochemistry, topography, land use, and climatic variables, GIS offers a powerful platform for holistic analysis and visualization. The incorporation of diverse datasets aids in unveiling nuanced patterns and trends critical to effective resource management. Furthermore, when coupled with hydroenvironmental approaches such as the WQI, GIS transcends the mere compilation of information to provide a dynamic framework for assimilating water quality parameters into comprehensive spatial analyses. This synergy empowers researchers and decision-makers to navigate complex hydrogeological landscapes, unravel causal relationships, and prioritize interventions aimed at preserving water quality and environmental integrity. The incorporation of GIS technology into hydroenvironmental investigations thus signifies a potent marriage of data-driven precision and analytical depth, propelling scientific inquiry and policy formulation toward a more nuanced and sustainable management of aquatic ecosystems.

The challenge of water scarcity in the semi-arid region of North Africa has garnered considerable attention from a multitude of researchers, as evidenced by the comprehensive body of work from Hamed et al. (2018, 2023), Bensoltane et al. (2021), Benmarce et al. (2021, 2023), and Ncibi et al. (2021). These scholarly endeavors collectively underscore the urgency and complexity of addressing water scarcity issues in this ecologically sensitive region. By delving into various aspects of water availability, utilization, and conservation, these authors have contributed significantly to the scientific understanding of the intricate interplay between environmental conditions and human activities, providing essential insights for formulating sustainable solutions. The study entails a multiparameter approach encompassing the preparation, interpretation, and interpolation of water quality maps, coupled with the modeling of spatial distributions for a spectrum of vital water quality attributes. The parameters in focus encompass a comprehensive array including pH, Total Dissolved Solids (TDS), as well as crucial ions such as calcium, sodium, potassium, chloride, sulfate, and bicarbonates, all pivotal in reflecting the intricate quality nuances of the groundwater system. Leveraging the capabilities of Geographic Information Systems (GIS), these disparate datasets were adeptly synthesized and assimilated, culminating in meticulously constructed maps capturing the spatial dynamics of water quality across the study area. The resultant maps unveil a nuanced portrayal of spatial variations, providing insights into the intricate interplay of geological, hydrological, and anthropogenic factors. Notably, the culmination of this endeavor is a unified integrated map, meticulously stratified into five distinct priority classes (ranging from 'Excellent' to 'Very Poor') representing a pragmatic depiction of groundwater quality across the studied region. This systematic and comprehensive approach underscores the scientific rigor and robustness of the methodology, equipping stakeholders and decision-makers with essential insights for effective water resource management and policy formulation.

The overarching objective of this study is to comprehensively assess and enhance the understanding of groundwater quality, particularly within the challenging context of semiarid regions. In these regions, groundwater assumes critical significance as a primary source of potable water, serving as a lifeline for communities grappling with the complexities of water scarcity. The primary aim is to decipher the intricate interplay between hydrological, climatic, anthropogenic, and geological factors that influence groundwater quality in such arid environments. Specifically, this study endeavors to Evaluate Groundwater Quality; Identify Key Influences; Integrate Spatial and Analytical Approaches; formulate Management Strategies. By achieving these objectives, this study seeks to contribute substantively to the scientific understanding of groundwater quality dynamics in Tebessa semiarid region. The findings and insights are expected to inform evidence-based policies, interventions, and strategies that mitigate risks associated with water scarcity and promote the preservation of water resources critical for human well-being in these environmentally sensitive areas.

2. Study area

The geological context of North Africa forms an integral segment within the broader framework of African geology. This intricate geological setting holds paramount significance in unraveling the geological history and dynamics of the African continent (Rouabhia et al. 2004; Bagwan et al. 2023; Sankar et al. 2023; Orabi). In the border region between Algeria and Tunisia, all the collapse trenches intersect atlas structures of the Late Lutetian age. The extensional phase of the Miocene is evidenced by the formation of the Oulad Soukies, Foussana-Kasserine trenches, and the EL Ma Labiod basin. The substrate of the Tebessa and Hammamet trenches is composed of a mosaic of horsts and grabens. Four successive stages have been identified during the development of the Tébessa trench: The first stage occurred during the Lower Villafranchian (Upper Pliocene). The second stage occurred during the Upper Villafranchian. The third stage occurred at the end of the Middle Pleistocene. And the fourth stage occurred at the end of the Upper Pleistocene. The subsidence process is still ongoing, as evidenced by three seismic events in 1995. This is parallel to the uplifting of the graben margins, where the subsurface sank in the central part during the final collapse stage. This ongoing geodynamic activity sheds light on the complex tectonic evolution of the region.

The Tebessa-Morsott plain (35°24' to 35°35'N latitude and 7°50' to 8°10' E longitude) is situated in the northeastern region of Algeria at 28 km from the international border, and 230 km from the Mediterranean Sea. Spanning an area of 974.4 km², this basin stands as a host to significant aquifers that play a crucial role in the region (Fig. 1). The region is marked by a semi-arid climate featuring hot and arid summers, contrasting with cold winters. The annual precipitation ranges from 200 mm to 350 mm, indicative of the region's arid nature. The summer temperatures can surge to 45°C.

The Tebessa-Morsott plain belongs to the Merdja subwatershed and is drained by the Oued Ksob stream. It boasts an elongated North-West to South-East orientation and encompasses a vast depression hemmed in by mountainous terrain. The altitudinal variation spans from 1712 meters to 700 meters, adhering to the geological structure of the North Auresian (Aures Nememcha) region within the Saharan Atlas.

Numerous researchers have diligently explored the geological context of the study region, as evidenced by the works of Mouici et al. (2017), Tamani et al. (2019), Boulemia et al. (2021), Zerzour et al. (2020, 2021), Taib et al. (2022, 2023), Mahleb et al. (2022), Chibani et al. (2022), Benyoucef et al. (2023), and Zighmi et al. (2023). The region is characterized by the Triassic diapirs of Jebel Jebissa, constituting the oldest geological outcrop in the Tebessa region. These formations consist of sandstone clay passing to gypsum limestone. A substantial Plio-Quaternary infill within the Tebessa Collapse Ditch substantiates the existence of a considerable groundwater reservoir in the region. It consists of sand, alluviums, and limestone pebbles. The Maastrichtian carbonate formations outcrop in the South-West and North-East edge of the basin, whereas the Turonian limestone appears in the East (Fig. 2). These serve as important karstic reservoirs of the region. Because of their significant depth in the center of the basin, the potential of these reservoirs remains untapped within the plain.

3. Materials and Methods

3.1. Field and Laboratory Investigations

In February 2019, a comprehensive groundwater sampling campaign was executed across three distinct locations: Merdja, featuring 17 wells, Bek-karia with 6 wells, and Hammamet encompassing 3 wells. This operation aimed to assess the hydrochemical characteristics of the sampled groundwater. The collected groundwater samples underwent an analysis to ascertain their chemical composition and properties. The measurement of temperature, conductivity, and pH values was executed directly in the field utilizing a portable platinum electrode conductivity meter and pH meter.

Analytical scrutiny was conducted in the laboratory setting, employing standardized methodologies outlined by the American Public Health Association (APHA) in the year 1995. The range of eight key parameters was meticulously investigated in each groundwater sample. Calcium (Ca^{+2}), total dissolved solids

(TDS), bicarbonate (HCO3-), chloride (Cl-), sulfate (SO4-2), potassium (K+), sodium (Na+), and major cations (Ca+2, Na+, and K+) formed the focal points of the investigation. The determination of major cations (namely calcium, sodium, and potassium) was achieved via the utilization of the ICP-Mass spectrometer method.

The quantification of bicarbonate (HCO3) content involved a volumetric titration process employing hydrochloric acid (HCl) as the reagent. For the assessment of sulfate (SO4), a spectrophotometric turbidimetry method was employed, while chloride (Cl-) content was quantified using a volumetric titration procedure involving silver nitrate (AgNO3) and potassium dichromate (K2Cr2O7). Moreover, bicarbonate (HCO3) and carbonate (CO3) concentrations were evaluated through Portamess analysis using titration with hydrochloric acid (HCl), alongside the utilization of phenolphthalein and methyl orange as indicator reagents (Selvam et al. 2013). This method yielded a dataset that enhances our understanding of the hydrochemical composition of the sampled groundwater across these locations.

3.2. Geospatial Data Collection, Integration, and Interpolation

The accurate determination of sampling points, encompassing their precise latitude, longitude, and elevation coordinates, was achieved through the utilization of the GARMIN 12-Channel GPS device in the fieldwork. These geographical coordinates, once established, were combined with the groundwater parameters following preparation within the Excel-pro Program. This dataset was subsequently imported into a GIS platform, serving as the foundation for further analytical and digitization processes. The dataset, now in the form of point data, was integrated into the ArcGIS 10.8 software, where it constituted a distinct point layer. To facilitate advanced analyses and visualization, a geo-database was established. This facilitated the generation of spatial distribution maps that depicted the prevalence of selected water quality parameters across the studied region (Bairu et al. 2013). Spatial interpolation, a technique pivotal in environmental sciences, involves predicting values at unknown points based on known values at neighbouring points. Among the plethora of interpolation methods, two widely employed ones are Inverse Distance Weighting (IDW) and Ordinary Kriging (OrK). Both methods fundamentally rely on the concept of spatial autocorrelation, wherein samples that are spatially proximate tend to exhibit similar characteristics.

The implementation of IDW and OrK necessitates the determination of observation quantities for predictions. In this context, the search window's scope should encompass these observations, thus encapsulating an area surrounding the point of prediction. The configuration of this search window is determined based on empirical knowledge pertaining to the phenomenon being investigated (Zarco-Perello, & Simões, 2017). IDW method estimates data values for unknown locations by averaging the available values from sampled data points (Setianto, & Triandini, 2013).

3.3. Calculation of Water Quality Index (WQI)

To assess the water quality of the basin, the WQI is a valuable tool that summarizes multiple water parameters into a concise numerical representation. This index method is particularly aligned with the guidelines for drinking water quality established by the World Health Organization (WHO). By converting an array of complex variables into a singular one- or two-digit number, the WQI simplifies the interpretation of extensive monitoring data. Water quality indices offer a streamlined means of monitoring and managing water quality. They serve as a convenient instrument for assessing trends in regional water quality and aiding decision-makers in evaluating the efficacy of specific interventions aimed at improving water quality (Li et al. 2019).

The computation of the Water Quality Index involves four sequential steps. In the initial step, each of the nine water quality parameters is assigned a weight (wi) based on its relative significance in determining the overall quality of water for drinking purposes. Notably, the assignment of weights was informed by their individual importance, with the highest weight of 5 attributed to TDS. Parameters such as pH, chloride, sulfate, electrical conductivity, and sodium were assigned a weight of 3, while calcium, bicarbonate, and potassium were assigned a weight of 2 (Table 1).

The subsequent step involves the calculation of the relative weight (Wi) according to the (Eq. 1) :

$$w_i = \frac{w_i}{\sum_{i=1} w_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where "Wi" represents the relative weight, "wi" is the weight of each parameter, and "n" is the number of parameters.

Following this, a quality rating scale (qi) is assigned to each parameter (Eq. 2). This scale is derived by dividing the concentration (Ci) of each chemical parameter in a water sample by its corresponding standard (Si) as outlined by WHO guidelines.

qi = (Ci / Si) x 100…………..(2)

Equation (2) captures this rating, with qi signifying the quality rating, Ci representing the concentration of each chemical parameter in milligrams per liter (mg/L), and Si denoting the WHO drinking water standard for each parameter according to WHO guidelines.

The Sub-Index (SI) for each parameter (i) is subsequently computed using the (Eq. 3) :

SIi = Wi qi……………(3)

The overall Water Quality Index (WQI) is obtained by summing the individual SIi values (Eq. 4) :

WQI = Σ SIi …………. (4)

The calculated WQI values are generally categorized into five distinct classes: excellent, good, poor, very poor, and unfit for drinking purposes (Table 2). This classification aids in communicating the quality of groundwater samples, thus supporting informed decision-making (Tiwari et al. 2014).

4. Results and Discussions

The characterization of groundwater quality is a pivotal aspect of environmental assessment. Chemical analyses have facilitated the compilation of key statistics for 26 groundwater samples, (Table 3). Moreover, the correlation matrix analysis, (Table 4), sheds light on the intricate relationships among various groundwater quality parameters.

In the study area, the pH values of groundwater samples exhibit a range from 5 to 8.6, signifying a moderate alkaline nature within the Merdja aquifer. The Total Dissolved Solids (TDS) measurements span a spectrum from 1948 to 263 mg/l, with an average of 952.11 mg/l. Among the ions examined, namely HCO^{-3}, $SO4^{-2}$, Ca^{2+}, K^{+}, and Na^{+}, a noteworthy observation is the relatively low variability exhibited by their concentrations. Specifically, the bicarbonate content fluctuates between 21 to 0.6 mg/l, sulfate ranges from 323.7 mg/l to calcium at 68.14 to 6.41 mg/l, potassium varying from 13.9 to 0.3 mg/l, and sodium spanning 200 to 31.2 mg/l. Of particular significance is the elevated concentration of chloride, demonstrating a wide variability from 5538 to 124 mg/l.

Examining the interrelationships between parameters, it is notable that TDS displays strong correlations with both calcium (R = 0.68) and chloride (R = 0.62). These correlations underscore augmented groundwater salinity, indicative of the intertwined influence of calcium and chloride on the overall salinity levels. Such findings provide valuable insights into the complex hydrochemical interactions at play within the Merdja aquifer region.

By juxtaposing statistical analyses, correlation evaluations, and parameter concentrations, this study offers a comprehensive understanding of the groundwater quality dynamics within the investigated area. These insights contribute not only to the scientific understanding of the aquifer's hydrochemistry but also to the broader objectives of water resource management and environmental protection.

4.1. Spatial Variability Physicochemical Parameters

pH:

The pH parameter stands as a critical indicator of water quality, delineating the acidic or alkaline nature of water. It holds significance within water chemistry for its role in chemical interactions. The designated maximum contaminant level (MCL) for pH in drinking water, ranging from 6.5 to 8.5 mg/L, is prescribed by authoritative bodies such as WHO. The observed pH values spanning 11.5 to 8.6 in the study area surpass the recommended limit. This deviation is attributed to mineral precipitation and heightened salinity. The spatial distribution map depicting pH variations is presented in Figure 3a.

Electrical Conductivity (EC):

Electrical Conductivity (EC) emerges as a paramount parameter, serving as an indicator of salinity hazard and suitability for irrigation. The stipulated MCL for EC in drinking water is 2000 μS/cm. The EC values observed range between 1858 to 2.43 μS/cm. This parameter's significance lies in its manifestation of dissolved salts and its utility as a marker of water pollution. A spatial map illustrating the distribution of EC has been generated and is showcased in Figure 3b.

Total Dissolved Solids (TDS):

Total Dissolved Solids (TDS) stand as a valuable indicator of water's suitability for various applications. It encompasses inorganic salts and trace amounts of organic substances, varying based on regional mineral solubility disparities. The established MCL for TDS in drinking water is 1000 mg/l. The measured TDS values span from 1948 to 263 mg/l. This elevated TDS concentration arises due to salt leaching from soil and anthropogenic influences. The spatial map delineating TDS variations has been produced and is presented in Figure 3c.

Calcium:

Calcium's presence in groundwater arises from the dissolution of carbonate formations bordering the aquifer, as well as the contribution of gypsum marl, dolomite minerals, and evaporative deposits. The MCL for Ca+2 in drinking water is 75 mg/l. Observed Ca+2 concentrations range from 68.14 to 6.41 mg/l. The spatial distribution map portraying calcium concentrations has been formulated and is illustrated in Figure 3d.

Sodium:

Sodium content holds significance in evaluating groundwater quality for irrigation, primarily due to its impact on soil hardness and permeability. Higher sodium levels lead to increased soil hardness and decreased permeability. The MCL for Na+ in drinking water is set at 200 mg/l. The measured Na+ concentrations range from 200 to 31.2 mg/l. A spatial map depicting the spatial variability of sodium concentrations has been generated and is presented in Figure 3e.

Potassium:

Potassium's presence in groundwater finds its origin in nearby agricultural lands where fertilizers are employed. The MCL for K+ in drinking water is defined as 12 mg/l. The observed K^{+} concentrations range from 13.9 to 0.3 mg/l. A spatial map illustrating potassium concentration variations has been formulated and is exhibited in Figure 3f.

Sulphate:

Sulphate sources encompass atmospheric deposition, industrial discharges, contact with geological formations like pyrite, lignite, and coal, along with the dissolution of gypsum and evaporites. The MCL for SO4-2 in drinking water is set at 250 mg/l. The observed SO4-2 concentrations span from 32 to 3.7 mg/l.

A spatial map depicting the distribution of sulphate concentrations has been constructed and is presented in Figure 3g.

Chloride:

Chloride content originates from the leaching of evaporites, along with sand, clay, and gypsum deposits covering a substantial basin area. Additionally, industrial activities contribute to chloride concentrations. The MCL for Cl^- in drinking water is established at 250 mg/l. The observed Cl^- concentrations range from 5538 to 124 *mg/l*. A spatial map portraying the spatial distribution of chloride concentrations has been formulated and is displayed in Figure 3h.

Bicarbonate:

Bicarbonate presence results from the dissolution of carbonate formations bordering the aquifer. The MCL for HCO_3^- in drinking water is specified as 120 mg/l. Observed HCO_3^- concentrations span from 21 to 0.6 mg/l. A spatial map outlining the spatial distribution of bicarbonate concentrations has been developed and is exhibited in Figure 3i.

4.2. Mapping Groundwater Quality index

The generation of the groundwater quality map (Fig. 4) entailed is based on the classification process framework outlined in Table 5, and executed using ArcGIS software. The intricate spatial distribution of groundwater quality is a product of various interacting factors, including lithological characteristics, hydrodynamic behaviour of groundwater, prevailing climatic conditions, influx of wastewater, and potential sources of pollution.

Integral to this endeavour is the creation of a water quality index (WQI) map, a visual representation that encapsulates a comprehensive synthesis of water quality parameters. This is due to the Kriging geostatistical technique renowned for its ability to yield spatial interpolations of complex datasets. The WQI values were judiciously classified into four distinct ranges, namely excellent water (50), good water (50-100), poor water (100-200), and very poor water (200-300).

Upon scrutinizing the groundwater quality distribution map, discernible patterns manifest. Locations characterized by excellent water quality, as indicated by WQI values below 50, stand out prominently in wells 6, 9, 23, and 24. The bulk of the samples align with good water quality, reflecting WQI values within the 50-100 range. In contrast, the next tier, embodying poor water quality, is exemplified by wells 8, 14, and 15. Distinctively, the classification of very poor water quality, representing WQI values spanning the 200-300 range, is discernable in well 4.

This insightful geospatial analysis accentuates the intricate interplay of myriad factors influencing groundwater quality distribution. Such revelations hold far-reaching implications, particularly in the realms of resource management and environmental safeguarding. The synergy of water quality indices, advanced geostatistical methodologies, and GIS tools culminate in a holistic understanding that guides strategic decision-making processes and contributes to the sustainable management of vital water resources.

5. Conclusion Recommendations and Outlook Perspectives

The preservation of groundwater quality is pivotal for sustaining life in semiarid regions heavily reliant on this precious resource. This study underscores the intricate interplay of factors impacting groundwater quality within the Tebessa-Morsott plain of Northeastern Algeria. The aquifer's vulnerability to contamination, coupled with escalating demands, compels a comprehensive assessment to ensure its sustainability.

Groundwater quality is not only a product of natural processes but is also profoundly influenced by anthropogenic activities. Increased agricultural practices, accentuated by chemical pesticide use, contribute to the degradation of water quality. Complex interactions between the aquifer and surrounding soil, lithology, and climatic conditions further exacerbate the challenge. Understanding these dynamics is essential for crafting effective management strategies.

The Water Quality Index (WQI) serves as a powerful tool for quantifying water quality. This method simplifies complex data into a single numerical value, allowing for easy interpretation and informed decision-making. Integrating GIS amplifies this approach, enabling spatial analyses that unveil trends and patterns, aiding resource management and policy formulation.

Results underscore the significance of pH, Total Dissolved Solids (TDS), calcium, sodium, potassium, sulphate, chloride, and bicarbonate concentrations in groundwater. Strong correlations reveal intricate relationships, shaping the hydrochemical landscape. By mapping these parameters, spatial nuances become apparent, guiding targeted interventions.

Crucially, the Water Quality Index map reflects the intricate web of influences on groundwater quality. Wells with excellent water quality (WQI 50) are identified, while those with poor and very poor quality signal intervention needs. This geospatial understanding supports resource allocation and decision-making processes.

The study's objective to enhance understanding aligns with sustainable management aspirations. Its findings inform policies, interventions, and strategies vital for navigating the challenges of water scarcity. By synergizing scientific rigor, geospatial analysis, and multidisciplinary insights, this study paves the way for safeguarding groundwater quality in semiarid regions, ensuring the continued availability of this invaluable resource for generations to come.

Addressing the multifaceted challenges of water scarcity and declining groundwater quality in semiarid regions necessitates a comprehensive approach. Integrated management strategies, involving collaboration between government agencies, local communities, and scientific institutions, should encompass regulatory measures to control pollution sources while promoting sustainable practices. A robust groundwater monitoring network is crucial for tracking water quality changes over time, fostering transparency and informed decision-making. Incorporating climate resilience strategies, education on sustainable water practices, economic incentives, and cross-border collaboration can enhance groundwater preservation efforts. Sustained research and innovation are vital to understanding complex interactions and developing effective solutions. Policy integration across sectors ensures holistic management, ensuring equitable and sustainable use of groundwater resources while considering environmental protection and land use. By embracing these recommendations, stakeholders can navigate the challenges posed by water scarcity and safeguard the availability of safe water for current and future generations.

Declarations

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Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest. No participating authors have a financial or personal relationship with a third party whose interests could influence by the article's content. The corresponding author ensures that the descriptions are accurate and agreed upon by all authors.

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Tables

Table 1: Relative weight of chemical parameters

Chemical parameters	WHO Standard	Weight(wi)	Relative weight(Wi)
Na^{+}	200	3	0.115
Ca^{2+}	75	2	0.076
K^{+}	12	2	0.076
Cl^{-}	250	3	0.115
SO_4^{-2}	250	3	0.115
HCO_3^{-}	120	2	0.076
Ph	8.5	3	0.115
TDS	1000	5	0.192
Electrical conductivity	2000	3	0.115
Total		**Σwi = 26**	**ΣWi=0.995**

Table 2: Classification of WOI range and category of water

WQI Range	Category of water
<50	Excellent water
50-100	Good water
100-200	Poor water
200-300	Very Poor water
>300	Unfit for drinking purpose

Table 3: Normal statistics of water quality parameters of groundwater samples.

STATISTICS	K(mg/l)	pH	CEµ.cm^{-1}	TDS (mg/l)	Ca (mg/l)	Na(mg/l)	Cl(mg/l)	SO_4(mg/l)	HCO_3 Meq /l
Maximum	13.9	11,5	1858	1948	68,14	200	5538	32	21
Minimum	0.3	8,6	2,43	263	6,41	31,2	124	3,7	0,6
Average	5.37	9,93	702,95	952,11	32,45	82,93	826,26	11,53	5,49
Standard deviation	4.10	0,74	768,51	443,71	17,41	43,28	1194,44	8,34	3,67
Median	3.55	9,8	262,73	862,5	26,85	70,3	297	8,15	5,05

Table 04: Correlation matrix analysis result of the groundwater quality parameters.

parameters	pH	TDS	K^+	Ca^{+2}	Na^+	SO_4^{-2}	HCO_3^-	Cl^-
pH	1							
TDS	-0,40	1						
K^+	-0,08	-0,24	1					
Ca^{+2}	0.44	**0,68**	-0,02	1				
Na^+	0,18	-0,20	**0,50**	0,12	1			
SO_4^{-2}	0,15	-0.11	0,32	0.18	0,20	1		
HCO_3^-	0,40	0,03	-0,07	-0,19	0,10	-0.002	1	
CL^-	0,01	**0.62**	0,49	0.27	0,18	-0,02	-0,26	1

Table 5: Quality rating (Qi), Sub index of each chemical parameter (SIi), WQI and water classification of each groundwater samples of Study areas.

Sample code	Na^+		Ca^{+2}		K^+		pH		TDS		Cl^-		SO_4^{-2}		HCO_3^-	
	Qi	SLi	Qi	SLi	Qi	SLi	Qi	SLi	Qi	SLi	Qi	SLi	Qi	SLi	Qi	SLi
W1	25,05	2,88	36,86	2,80	15	1,14	105,88	12,17	171,1	32,85	305,3	35,10	2,88	0,3312	6,13	0,46
W2	45,25	5,20	32,06	2,43	2,5	0,19	110,58	12,71	80,5	15,45	106,5	12,2	2,88	0,33	4,91	0,37
W3	24,75	2,84	31,3	2,38	5,83	0,44	108,23	12,44	93,4	17,93	191,7	22,04	2,2	0,253	4,58	0,34
W3 BIR	26,15	3,00	53,44	4,06	19,16	1,45	104,70	12,04	146,2	28,07	262,7	30,21	3,12	0,35	4,25	0,32
W4	28,45	3,27	34,73	2,63	115,83	8,80	122,35	14,07	0	0	2215,2	254,74	4,4	0,50	0,5	0,03
W5	100,5	11,5	33,66	2,55	77,5	5,89	114,11	13,12	125,6	24,11	191,7	22,04	3,4	0,391	3,5	0,26
W6	40,45	4,65	51,29	3,89	17,5	1,33	101,17	11,63	0	0	58,22	6,69	3,84	0,44	2,08	0,15
W7	50,4	5,79	71,06	5,40	10,83	0,82	105,88	12,17	0	0	333,7	38,37	4,36	0,5	5,86	0,44
W8	62,6	7,19	90,85	6,90	13,33	1,01	112,94	12,98	0	0	805,7	92,65	2,88	0,33	4,75	0,361
W9	85	9,77	14,42	1,09	95,83	7,28	123,52	14,20	26,3	5,04	71,2	8,18	5,16	0,59	1,66	0,12
W10	56	6,44	8,54	0,64	63,33	4,81	130,58	15,01	95,8	18,39	191,6	22,03	3,4	0,39	5	0,38
W11	73	8,39	64,01	4,86	114,16	8,67	115,29	13,25	0	0	362	41,63	11,8	1,357	2,5	0,19
W12	21,25	2,44	84	6,38	17,16	1,30	111,76	12,85	194,8	37,40	124	14,26	2,88	0,33	1,66	0,12
W13	36	4,14	88	6,68	57,5	4,37	115,29	13,25	0	0	454,4	52,25	12,8	1,47	3,33	0,25
W14	51,3	5,89	70,66	5,37	85,83	6,52	117,64	13,52	0	0	1164,4	133,906	3,76	0,43	4,16	0,31
W15	97,75	11,24	49,33	3,74	73,33	5,57	116,47	13,39	0	0	894,8	102,90	2,56	0,29	4,16	0,31
W16	27,35	3,14	38,66	2,93	35,83	2,72	127,05	14,61	64	12,28	99,6	11,45	1,52	0,174	3,33	0,25
W17	23	2,64	14,66	1,11	28,33	2,15	115,29	13,25	82,8	15,897	113,6	13,06	1,48	0,170	4,16	0,31
W18	18,45	2,12	49,33	3,74	29,16	2,21	117,64	13,52	66,3	12,72	92,4	10,62	2,2	0,253	5	0,38
W19	23,75	2,73	29,33	2,22	68,33	5,19	114,11	13,12	71,9	13,80	92,4	10,62	2,24	0,25	5	0,38
W20	57,25	6,58	20	1,52	72,5	5,51	135,29	15,55	89,7	17,22	99,6	11,45	6,72	0,7728	17,5	1,33
W21	31,4	3,61	30,66	2,33	10,83	0,82	117,64	13,52	94	18,08	56,8	6,532	2,24	0,256	5,83	0,44
W22	56,45	6,49	53,33	4,05	55,83	4,24	132,9	15,28	136,8	26,26	92,4	10,66	7,52	0,86	7,5	0,57
W23	15,6	1,79	24	1,82	22,5	1,71	128,2	14,74	38,5	7,392	92,4	10,626	2,24	0,25	5	0,38
W24	24,9	2,86	24	1,82	25,83	1,96	121,17	13,93	55	10,56	49,6	5,704	10,92	1,25	3,33	0,25
W25	35,15	4,04	26,66	2,02	30	2,28	114,11	13,12	81,1	15,57	71,2	8,18	10,6	1,219	3,33	0,25

Figures

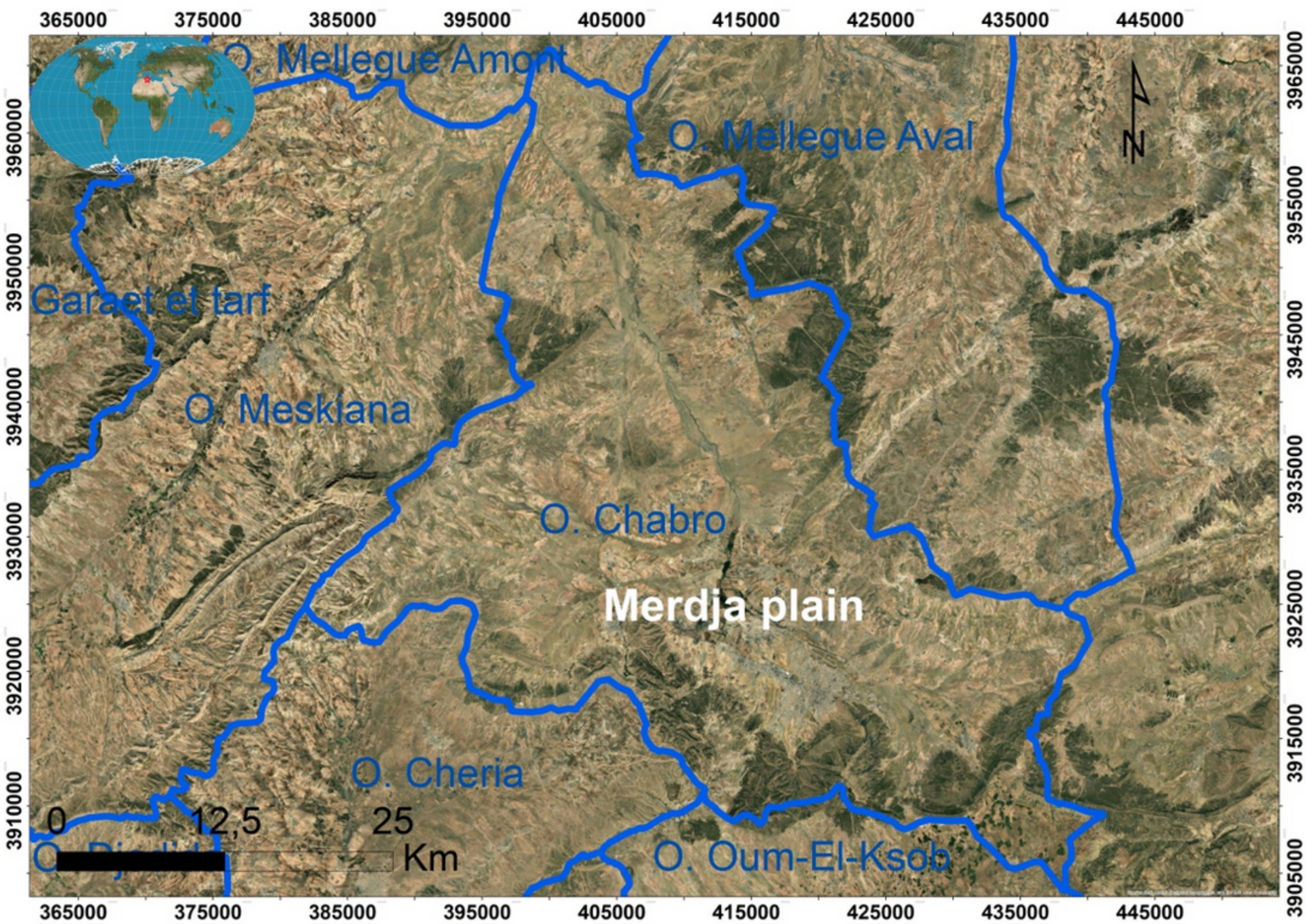

Figure 1

Geographic location of the study area.

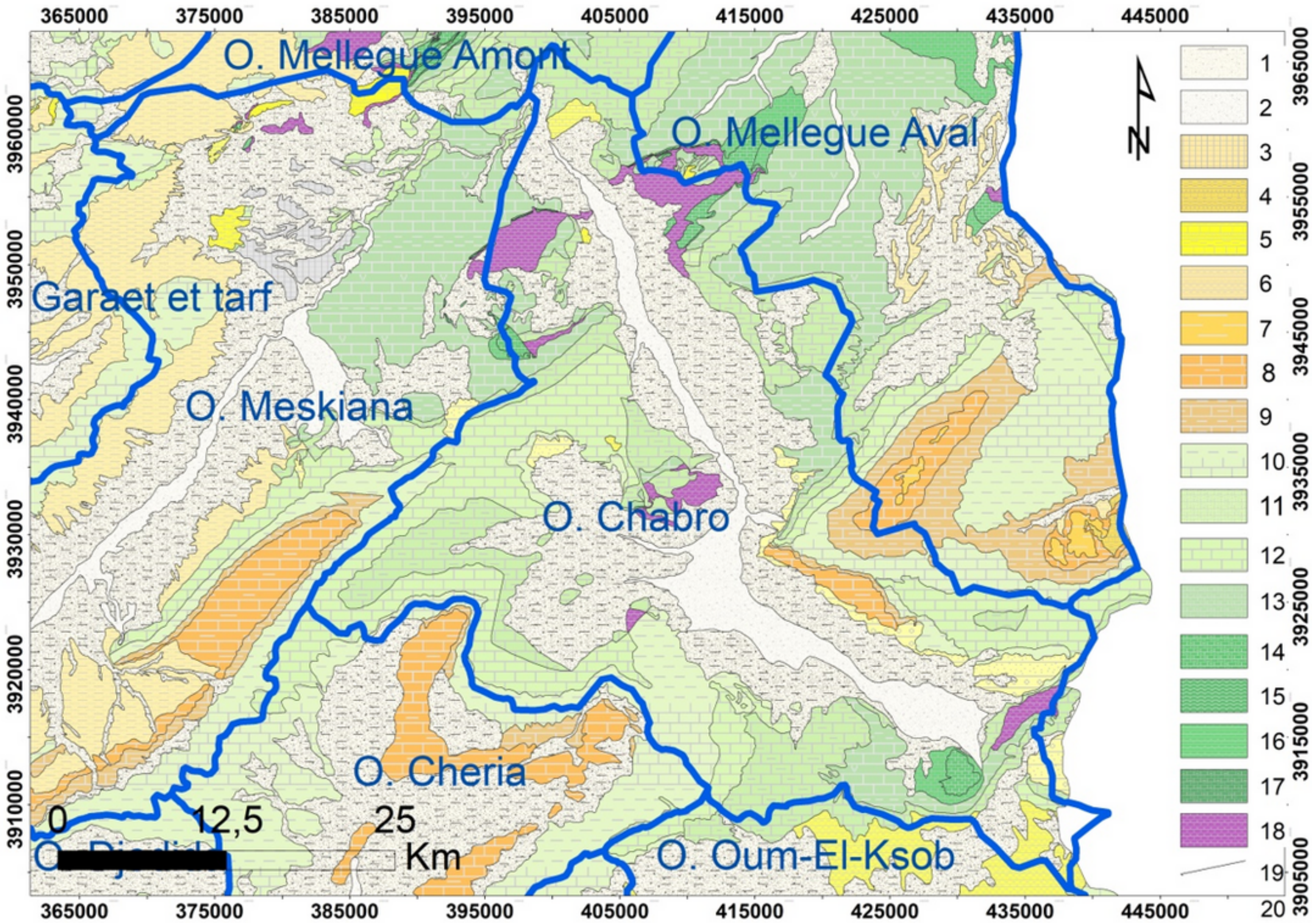

Figure 2

Simplified geological map of study area.

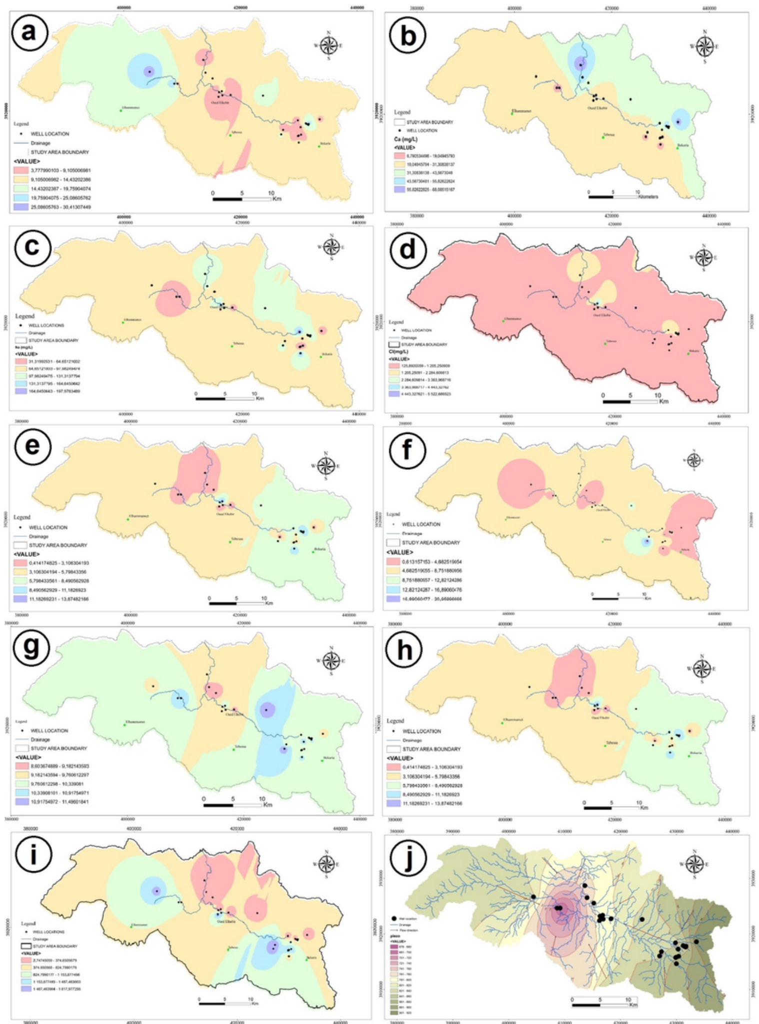

Figure 3

Spatial distribution of physiochemical parameters such SO_4^{-2}, Ca^{+2}, Na^{+}, Cl^{-}, K^{+}, HCO_3^{-},pH, EC, TDS and stream network map of the study area.

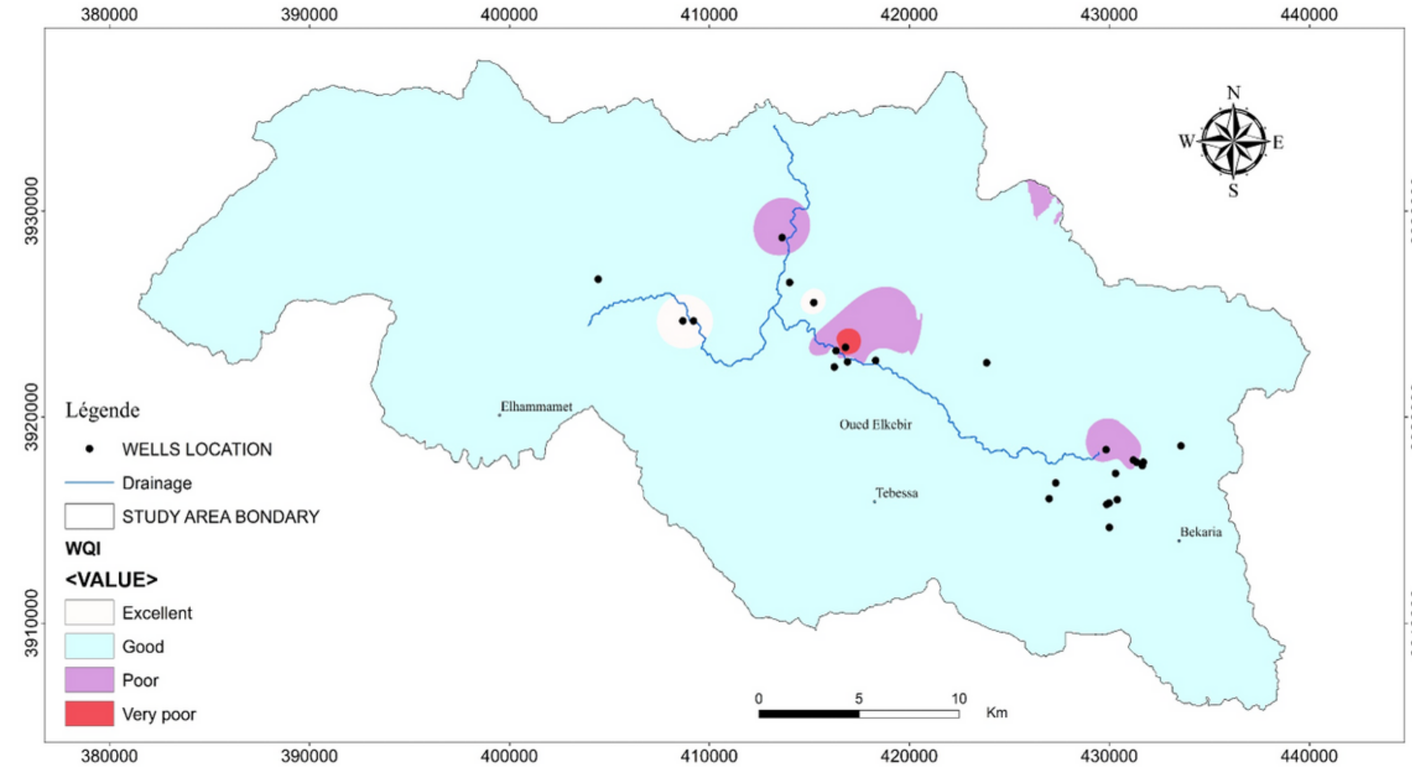

Figure 4

Spatial distribution map of water quality index in Merdja plain.