Euro-Mediterranean Journal for Environmental Integration
https://doi.org/10.1007/s41207-023-00400-3

ORIGINAL PAPER

Modeling groundwater recharge mechanisms in semi-arid regions: integration of hydrochemical and isotopic data

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Received: 6 March 2023 / Accepted: 14 July 2023

Abstract
Groundwater management is crucial, particularly in arid and semi-arid regions, where it is influenced by the climate and human activities. The Gabès region in southeastern Tunisia is known for its significant groundwater resources, which are mainly associated with the Continental Intercalary (CI) and Djeffara aquifers as well as interlayers from the Ceno-Turonian and Miocene-Pliocene aquifer systems. The Cretaceous and Quaternary aquifer systems are the most exploited in this region. This study aimed to assess the hydrochemistry of these aquifer systems and contribute to understanding the recharge mechanisms. To achieve this, 44 groundwater samples were collected and analyzed for major ions and the isotopes oxygen-18 and deuterium. The results indicate that the total dissolved solids concentration ranges from 300 to 7200 mg/L, with temperatures varying from normal (19 °C) to extremely high (> 70 °C). Cluster analysis revealed two main groups (A and B) with distinct chemical and isotopic characteristics. The isotopic ratios of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) were used to identify the recharge mechanism. The findings suggest relatively depleted ^{18}O and ^{2}H isotopic ratios, indicating a mixing of groundwater from the Djeffara aquifer with deep thermal groundwater from the CI. However, groundwater depth and local geological structures also influence the mixing pattern. The results highlight the need for detailed structural characterization in the future to identify the spatial distribution and dominant properties of fractures. This information is crucial for understanding their contribution to regional groundwater recharge. Integrating hydrogeochemical data and the isotopic groundwater composition will enhance our understanding of the geochemical processes governing groundwater hydrochemistry and recharge in the Gabès region as well as in similar hydrogeological and structural settings.

Responsible Editor: Abdelazim Negm.

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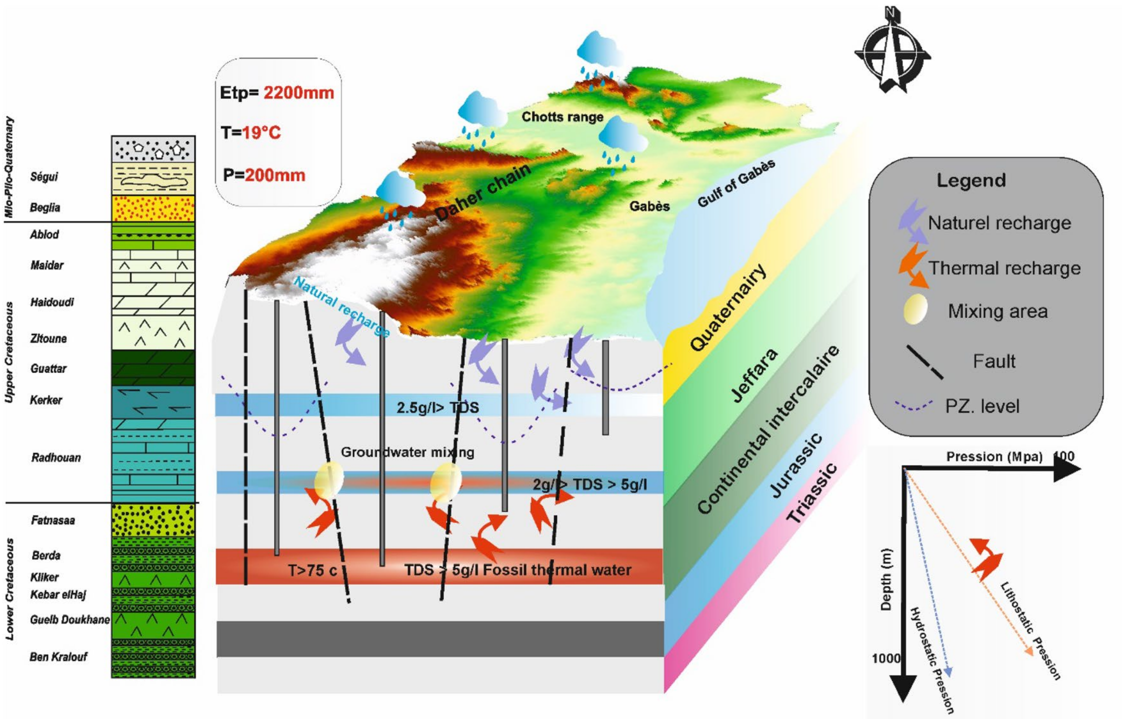
Graphical Abstract



Keywords Hydro-geochemistry · Isotopic data · Groundwater recharge mechanism · Arid region · Tunisia

Introduction

Water, a fundamental natural resource, is essential for the development of both urban and rural areas. However, various factors such as climate change, population growth, and complex economic activities have significantly increased the pressure on water resources, leading to adverse effects on water availability and quality. These factors have resulted in compromised runoff and a decline in the quality of freshwater ecosystems worldwide (Grafton et al. 2013; Mattos et al. 2018, Abdelkarim et al. 2023, Mnassri et al. 2023).

Water scarcity arises when the demand for water exceeds the available supply (FAO 2012). It is characterized by unmet demand, overexploitation of groundwater resources, and vulnerability of natural resources (Vairavamoorthy et al. 2008; Kharraz et al. 2012; Acharyya 2014; Selby and Hoffmann 2014; Mattos et al. 2018, Missaoui et al. 2023a, b). This scarcity of water resources poses significant challenges in arid and semi-arid regions, where the supply and quality of water are already major concerns. Societies in these regions are particularly vulnerable to climate variability and fluctuations in water availability, making them highly susceptible to the impacts of climate change (Krol and Bronstert 2007).

Arid and semi-arid regions often experience periods of below-average rainfall and severe droughts, exacerbating water shortages. The Gabès region in southern Tunisia, for example, has recently faced severe water shortages, and this situation is expected to worsen until 2030 (Agoubi et al. 2018; Abdelkarim et al. 2022a, b). Consequently, there has been an increasing reliance on the exploitation and consumption of groundwater to meet the growing water demands of agriculture, industry, and various human activities (Marques et al. 2021; Missaoui et al. 2022, 2023a, b, Ben Abdelkarim et al. 2023).

In these regions, semi-arid conditions characterized by high evapotranspiration rates and irregular rainfall patterns associated with climate change are prevalent and have a significant impact on groundwater recharge processes. Therefore, effective strategies and management approaches are necessary to sustain groundwater resources (Sher et al. 2016; Hamed et al. 2018; Besser et al. 2018; Ouhamdouch et al. 2019; Rasheed et al. 2020, 2022). In the Gabès region, with its dry climate, understanding groundwater recharge mechanisms is crucial to ensure long-term viability, minimize overexploitation, and assess groundwater vulnerability to pollution (Abdelkarim et al. 2022a, b).

To address these issues, numerous studies have focused on investigating groundwater flow mechanisms in aquifer systems within semi-arid regions. The aims of those studies were to estimate potential groundwater recharge zones (Abdelkarim et al. 2022a), assess groundwater suitability (Madhav et al. 2018; Liu et al. 2020; Pazalja et al. 2021; Rasheed et al. 2021), and evaluate groundwater quality. Investigating the groundwater hydrogeochemistry, which includes analyzing environmental isotopes such as ^{18}O and ^{2}H, has proven to be a valuable approach for understanding groundwater recharge sources, water migration, and mixing from various sources. This integration of groundwater data has been applied in studies conducted globally, including in Egypt, China, Iran, Italy, Brazil, and Algeria (Masoud and El-Magd 2022; Wang et al. 2017; Daneshian et al. 2021; Grappein et al. 2021; Sacchi et al. 2021; Silva et al. 2021).

The groundwater spatial distribution plays a crucial role when identifying and delineating water recharge processes. The estimation of groundwater potential recharge relies on various criteria, including the geology, topography, and climatic conditions (Yeh et al. 2016; Abdelkarim et al. 2022c). To assess and identify potential groundwater recharge areas, researchers have employed different methodologies, such as geographic information systems (GIS) and remote sensing techniques (Yeh et al. 2016; Nadiri et al. 2019).

The primary objective of this research was to propose a parametric model that defines groundwater recharge mechanisms through the integration of hydrochemical and isotopic approaches. The identified groundwater recharge zones will be mapped using remote sensing techniques and the Kohonen self-organization algorithm (a machine learning process). This defined methodology will generate realistic maps, contributing significantly to the understanding of lateral variations in groundwater recharge mechanisms in the Gabès region. It will also serve as a valuable tool for obtaining more suitable solutions to ensure the sustainability of groundwater resources in this arid region, thus addressing water security concerns.

The outcomes of this research have the potential to aid local and regional authorities in making informed decisions regarding groundwater availability management, encompassing both quantity and quality aspects. By providing a comprehensive understanding of groundwater recharge mechanisms, the research findings will contribute to the development of effective strategies and policies to sustainably manage and protect groundwater resources in the Gabès region. This research will be instrumental in enhancing water security and facilitating responsible decision-making processes related to groundwater resources for the benefit of the local communities and the environment.

Study region

The area of the study region is approximately 7116 km^2, and it is located in the Gabès region on the Mediterranean coast of southeastern Tunisia (Fig. 1). The region is bordered to the west by the Tebaga and Dahar chains, to the north-east by the Zemlet el Bidha structure, and to the east by the coastal zone (the Gulf of Gabès; Fig. 1). The coastal section has a Mediterranean climate with an annual average rainfall of 200 mm/year^{-1}, but the western half has an arid climate with dry and hot summers, rainy and chilly winters, and an average annual rainfall of less than 150 mm/year^{-1} (Ben Alaya et al. 2013; Agoubi 2018). Moreover, most of the study region consists of a landform with an average altitude of 150 m above sea level. There are no permanent rivers in the Gabès area. Nevertheless, large storms may cause surface runoff, which is discharged via wadis, including Oued El Akarit, Oued Jir, and Oued El Hamma.

Geological setting

The study area is located at the eastern boundary of the Tunisian Meridional Atlas. The sedimentary series that are outlined in the area range from the Lower Cretaceous to the Quaternary, while Paleocene-Eocene sediments are lacking (Fig. 1). The important and thought-provoking series of the Triassic-Jurassic, Neocomian-Barremian, Aptian-Senonian, and Neogene-Quaternary comprise four major sedimentary cycles in the Chotts basin (Bouaziz 1995; Abaab et al. 2021).

The geology of the area presents a lateral variation of different lithologies such as sand, clay, gypsum, and carbonate (Abdeljaouad and Zargouni 1981; Bouaziz 1995; Ben Youssef and Peybernes 1993; Boukhalfa et al. 2015; Li et al. 2017; Abaab et al. 2021). The thicknesses of the geological layers vary spatially from the west to the Mediterranean coast as a result of the various tectonic events that govern the study area (Zouaghi et al. 2011). The Gabès region is dominated by horst and graben series, since the multidirectional faults that have affected the region are controlled by the atlas phase and the alpine phase (Abdeljaouad and Zargouni 1981; Mamou 1990; Bouaziz 1995; Gharbi et al. 2013; Gharbi et al. 2014). In this area, the lithostratigraphic unit is composed of a stratigraphic series extending from the Triassic to the Quaternary (Fig. 1). The Triassic rocks consist of highly soluble evaporites, including gypsum, halite, and anhydrite, while the Jurassic series is represented by carbonates.

Otherwise, the Cretaceous series is composed of a Lower Cretaceous unit that starts with detrital materials and ends with carbonate deposits and an Upper Cretaceous unit characterized by dominant carbonate deposits with clay intercalations. The Mio-Pliocene deposits are mainly composed of alluvial marls and limestones near the coastal area

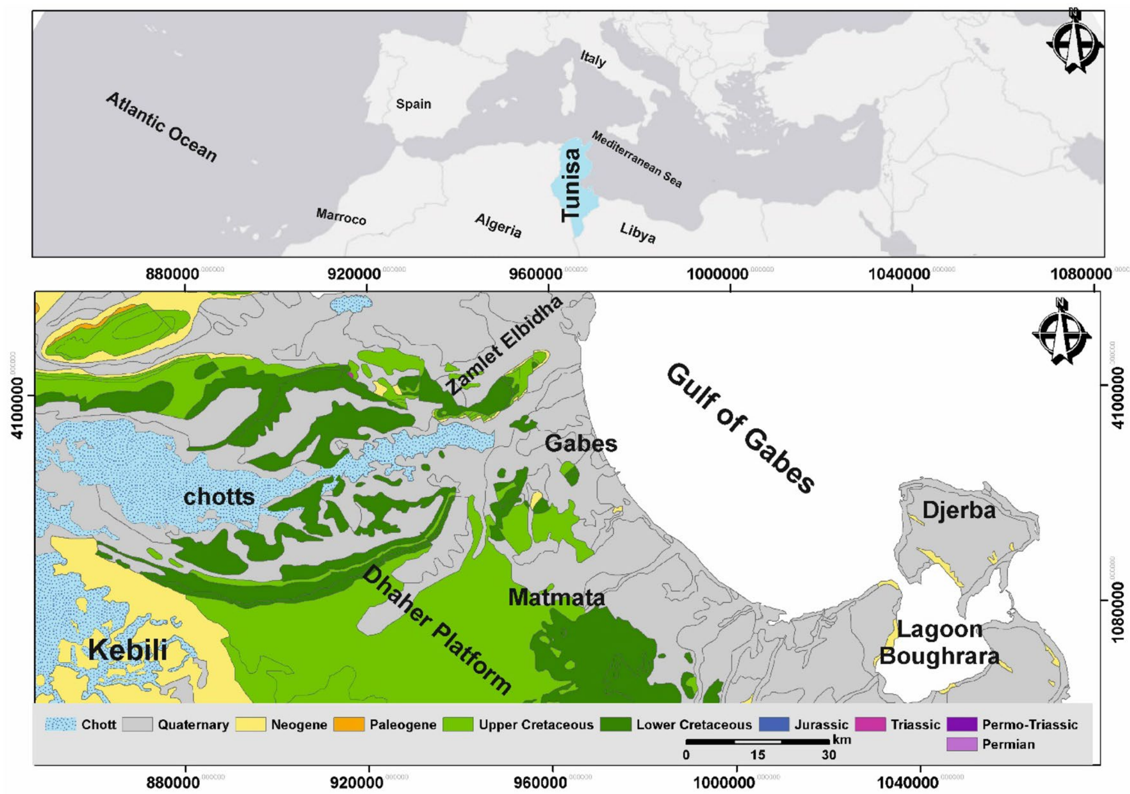


Fig. 1 The study area

(Abdeljaouad and Zargouni 1981; Louhaïchi and Tlig 1993; Lazzez et al. 2008; Gharbi et al. 2013; Boukhalfa et al. 2015; Li et al. 2017; Abaab et al. 2021). These rocks are characterized by different sedimentation processes (Abdeljaouad and Zargouni 1981; Louhaïchi and Tlig 1993). The deposits are of fluvial origin, mostly detrital, and have high permeability (Fig. 1).

Hydrogeological setting

As presented in the lithostratigraphic log (Fig. 2), three remarkable detrital formations can be considered and/or could represent a reservoir for old and/or recent fluids: (i) Lower Cretaceous formations such as the sandstones of Benkralouf, the Sidi Aich formation, the dolomitic stones of the Kebar El Haj formation, and the Guattar formation (Fig. 2); (ii) Upper Cretaceous formations formed by the dolomitic stones of the Hidoudi, Maider, and Abiod formations (Fig. 2); (iii) the sandstones of the Beglia formation and the conglomerate of the Segui formation, which cover the Neogene age, whereas the Quaternary aquifers are lodged in the alluvium deposits (Fig. 2). All of those aquifer systems occur as a multi-layered aquifer in the Gabès region. The deposited materials with good permeability or semi-permeability are considered productive aquifers, similar to fissured and fractured aquifer systems. The impermeable layers are considered a substratum and are dominated by clay, gypsum, and dolomite (Ben Alaya et al. 2013). Most of those aquifer systems are highly exploited in the study area (GDWR 2018). In the region of Gabès, the aquifer systems are formed by three major groundwater reservoirs. The first level is lodged in the alluvium material, with the depths of wells ranging from 15 to 50 m, corresponding to the phreatic water table. The semi-deep aquifer is exploited by wells with depths varying between 80 and 250 m, whereas the deep aquifer is lodged in the Lower Cretaceous formations and is exploited by deep wells (more than 600 m) (GDWR 2018).

With the exception of some wadis that use the Fejij chotts as a downline, the dominant groundwater flow is from SW to NE, to the coastal Mediterranean zone. The study region is affected by a network of faults that control the geometry and the geomorphology of the hydrogeological system; as a consequence, the groundwater circulation drives ascending drainage phenomena, ensuring mixing between the hot deep water and the surface water in the CI aquifers and the Djeffara aquifers, especially in the El Hamma region. The most important structural fault affecting the region is the Gafsa-Mednine fault system, which frustrates the Cretaceous deposits by ameliorating the groundwater flow in the dolomite materials and favoring water drainage. In a section

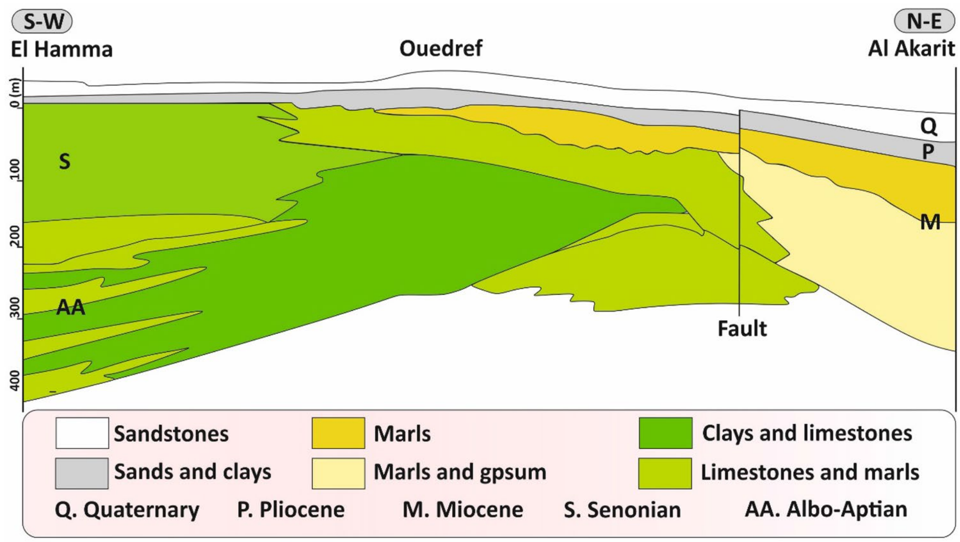


Fig. 2 Hydrogeological setting and the potential aquifers associated with the lithological formations in the study area

oriented SW–NE across the study area (Fig. 2), a significant horst and graben structure occurs, which is associated with the faults in the El Hamma region (south-west of Gabès). Fault ramification affects the whole series in the region, from the Lower Cretaceous series to the surface (Trabelsi 2006; Ben Alaya et al. 2013). The progressive thinning of the number of faults may imply vertical intercommunication between the Cretaceous and Neogene aquifer systems—between the Lower Cretaceous aquifer (CI) and the Djeffara aquifer. The contact between these superimposed aquifers could also occur through the ramification of the Gafsa-Mednine fault system. Indeed, the water in the Cretaceous aquifer system flows into the detrital complex of the Neogene aquifer. The detrital aquifer from Mio-Plio-Quaternary complexes could function as a water collector and promote water drainage to deep Cretaceous layers (Ben Alaya et al. 2013).

Material and methods

Sampling

Fifty-six groundwater samples (hand-pumped, drilled well, and surface water samples) were taken throughout the Gabès basin in March 2020. The sample bottles were rinsed three times before being used. After 30 min of water pumping, the samples were obtained. To ensure proper handling and analysis, all groundwater samples were stored at a temperature of 4 °C prior to laboratory testing. The sample locations were determined using a global positioning system (GPS) for accurate spatial referencing. However, certain parameters, including hydrogen ion concentration (pH), electrical conductivity (EC), total dissolved salts (TDS), and temperature, were assessed in situ using a portable multiparameter device. Additionally, a piezometric sound probe was employed to measure the water depth in each well. In the laboratory, the total alkalinity of each sample was determined a few hours after collection. This analysis was conducted at the Gabès High Institute of Water Research and Technologies' Geosciences and Environment Laboratory. To evaluate alkalinity, a titration technique utilizing a 0.1 M HCl solution was employed. Chemical studies were performed to analyze various components such as chloride (Cl^-), nitrate (NO_3^-), bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). The analytical data for cation and anion concentrations as well as the overall charge balances exhibited uncertainties that were within 10%. Analytical data quality, specifically that pertaining to the cation–anion balance, was assessed using the following equation:

$$E = \frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{anions} + \sum \text{cations}}. \quad (1)$$

Here, the total cations and anions are expressed in meq/L, and E represents the calculated ionic balance as a percentage. In this research, the ion charge balance errors obtained for the analyzed groundwater samples were found to be less than 5%.

Data interpretation

In numerous studies conducted worldwide, a combination of multivariate statistical analysis and hydrogeochemical correlation was employed to evaluate water quality and discuss its degradation. These methods aim to reduce and summarize the extensive database while providing insights into the source of water mineralization. Principal component analysis (PCA) and geochemical methods are among the most widely used and fundamental techniques for analyzing correlations between multiple variables arranged in descending order of importance. This analysis incorporates data collected from field surveys, field measurements, laboratory analyses, and statistical outputs. To achieve a comprehensive groundwater geochemical characterization of the Gabès aquifer systems, this study integrated various findings. Box-and-whisker plots were utilized to interpret variations in physicochemical parameters of groundwater, while Piper's hydrogeochemical categorization approach was employed to classify the dominant groundwater facies type. Isotope analyses ($\delta^{18}O$, $\delta^{2}H$) for the year 2020 were conducted at the Gabès High Institute of Water Research and Technology using a mass spectrometer. Environmental stable-isotope samples ($\delta^{18}O$, $\delta^{2}H$) were collected following the approach described by. The analytical errors for $\delta^{18}O$ and $\delta^{2}H$ were determined as 0.1 and 1, respectively, expressed in accordance with the. The stable isotope data were reported in Sfax Standard Mean Ocean Water (S-SMOW) using the appropriate conversion equation (Eq. 2) (Elmeknassi et al. 2022): By employing these methods and integrating the obtained data, this study aimed to provide a detailed understanding of the groundwater geochemistry in the Gabès region. This research approach, which combines statistical analysis, hydrogeochemical categorization, and stable isotope analysis, will contribute to a comprehensive assessment of the groundwater system and assist in making informed decisions regarding its management and sustainability.

$$\delta(‰) = \left[\left(^{\text{R sample}}/_{\text{Rstandard}}\right) - 1\right] \times 1000, \tag{2}$$

where "Rsample" and "Rstandard" to the measured isotopic ratio of ($^{18}O/^{16}O$) and ($^{2}H/^{1}H$) from the analyzed groundwater sample and standard material, respectively.

In order to differentiate the origin of the water body and measure the conversion between groundwater and rainwater, two- and three-component isotope hydrograph separations were utilized. Isotope mass conservation was the fundamental premise. The approach is described by the equations below:

$$Q_{\mathrm{t}} = \sum_{m=1}^{n} Q_m \tag{3}$$

$$Q_{\mathrm{t}} * C_{\mathrm{t}}^{j} = \sum_{m=1}^{n} Q_m * C_m^{j}, j = 1, \ldots, k, \tag{4}$$

where Q_{t} is the total discharge, Q_m is the discharge of component m, and C_m^j is the tracer j integrated into component m.

The methodology outlined in research papers by Wang et al. (2017) and was utilized to determine the origin of the aquifer recharge and the corresponding mechanism. This involved assessing whether the recharge originated from the surface as a natural process or through upward drainage between different layers of aquifers in the region. To understand the geochemical mechanisms responsible for the evolution of groundwater or variations in its quality, inverse geochemical modeling processes (described in were employed. Estimations of both aqueous species and saturation indices were conducted to identify the geochemical reactions that contribute to variations in the chemical composition of groundwater along the flow pathway. When selecting the flow pathways, careful consideration was given to the hydrogeology, hydraulic variations within the flow system, and the potential spatial locations of recharge areas. The inverse geochemical modeling focused exclusively on the minerals present in the study area, enabling a targeted analysis. The research methodology employed a combination of groundwater environmental stable isotopes and the hydrogeochemistry of different aquifer systems to investigate groundwater recharge mechanisms in the study area. The resulting data and information were subsequently processed and integrated, as depicted in Fig. 3.

Results and discussion

Groundwater hydrochemistry

Elementary descriptive statistics of groundwater composition in the Gabès aquifer system are presented in Table 1.

The temperatures of the analyzed samples from the CI and the Djeffara aquifers in the research region ranged from 21.6 to 70 °C. The results presented no statistical relation between groundwater temperature and well depth. Thermal groundwater ascending from deep reservoirs via the region's porous fault structure could explain the temperature increase. Groundwater pH values ranged from 6.8 to 8.2, with an average value of 7.4 (Table 1). The neutral to basic pH values are associated with water–rock interaction processes.

Groundwater EC values ranged from 1.1 to 11 ms/cm (Table 1). The majority of these waters are classified as ranging from moderate to impermissible resources for drinking and irrigation (Abdelkarim et al. 2022b). Areas characterized by very bad water quality are said to have the highest EC values. As a result, the salinity has a wide range of values, and they have the same lateral variation as those for the TDS (Fig. 4), which ranged from 1.6 to 7 g/L.

The lower salty area is ascribed to the surrounding mountains and adjacent lands (Fig. 1a), implying a considerable contribution from recent water recharge (Fig. 5). Higher-quality groundwater resources are located in the mountainous areas such as Matmata and in the south part of the Gabès region, where natural recharge is in process (Abdelkarim et al. 2022a, b). Furthermore, the TDS values and distribution give a general idea of the basin's discharge zones.

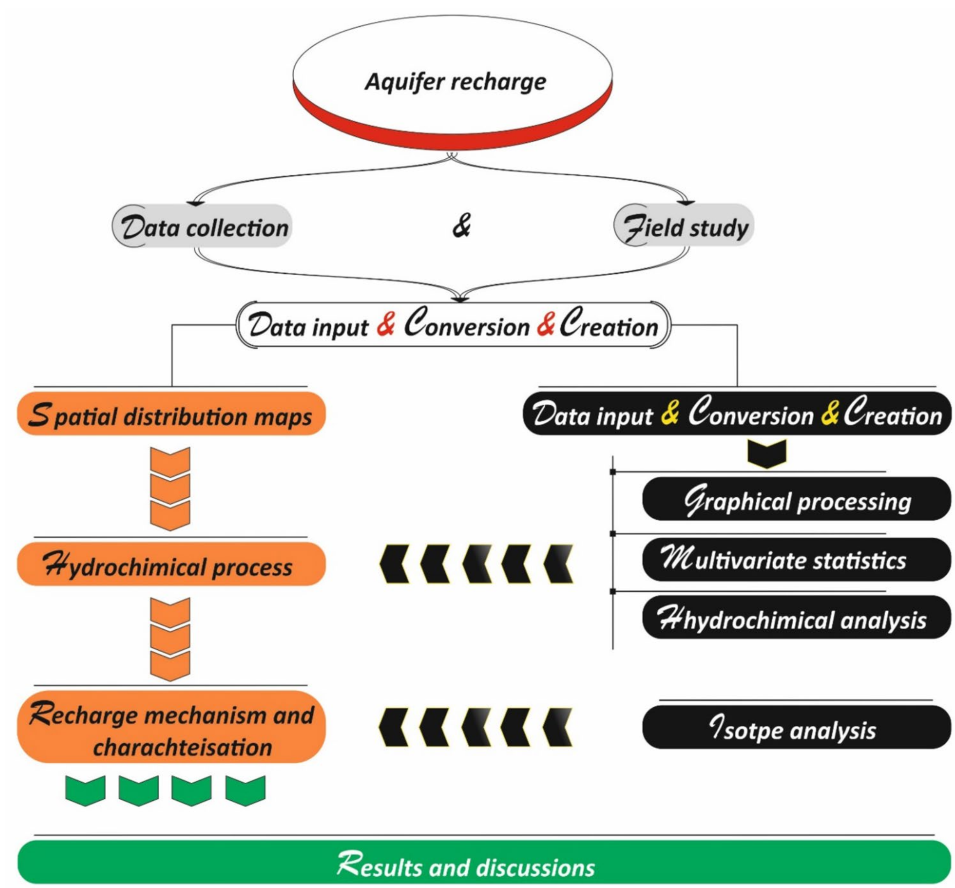


Fig. 3 Flowchart illustrating the methodology applied in the study area

Table 1 Descriptive statistics of the groundwater composition in the Gabès aquifer system

Parameter	Maximum	Minimum	Average standard deviation
Ca^{2+} (mg/L)	261	91	168
Mg^{2+} (mg/L)	131	42	70
Na^{+} (mg/L)	1443	201	340
K^{+} (mg/L)	78	6	24
SO_4^{2-} (mg/L)	1456	454	646
Cl^{-} (mg/L)	1902	244	450
HCO_3 (mg/L)	186	133	164
F^{-} (mg/L)	2	0	1
PO_4^{3-} (mg/L)	6	0	2
pH	8	7	7
TDS (g/L)	7	0	2
EC (ms/cm)	11	1	5
T (°C)	70	22	35

On the other hand, the groundwater flow directions, lengthy residence times, and heightened water–rock interaction processes confirm the variation in groundwater quality. The salinity maps (shown in Fig. 5) give a general idea of the interconnection between the CI and the Djeffara aquifers.

Hydrochemical facies

The groundwater samples from Gabès region were plotted in a Piper diagram, which indicates the occurrence of different water types (Fig. 5a). The first type is characterized by chlorinated calcium/magnesium, whereas the second is classified as chlorinated sodium.

There are some points which show the mixing of waters in the Piper diagram. The hydrochemical zonation of the groundwater aquifer systems in the Gabès region coincides with the path flow of the groundwater, and it distinguishes between the thermal deep aquifer of CI in the western part of the study area and the other aquifer systems, such as the Djeffara aquifer and the shallow Neogene aquifer. Furthermore, according to the Langelier–Ludwig diagram, the sampled waters present the mixing of waters between the different aquifer system. Also, the Djeffara aquifer recharge is controlled by the groundwater of the CI thermal aquifer due to the vertical interconnection within the fault ramification in the study area, especially in the El Hamma region.

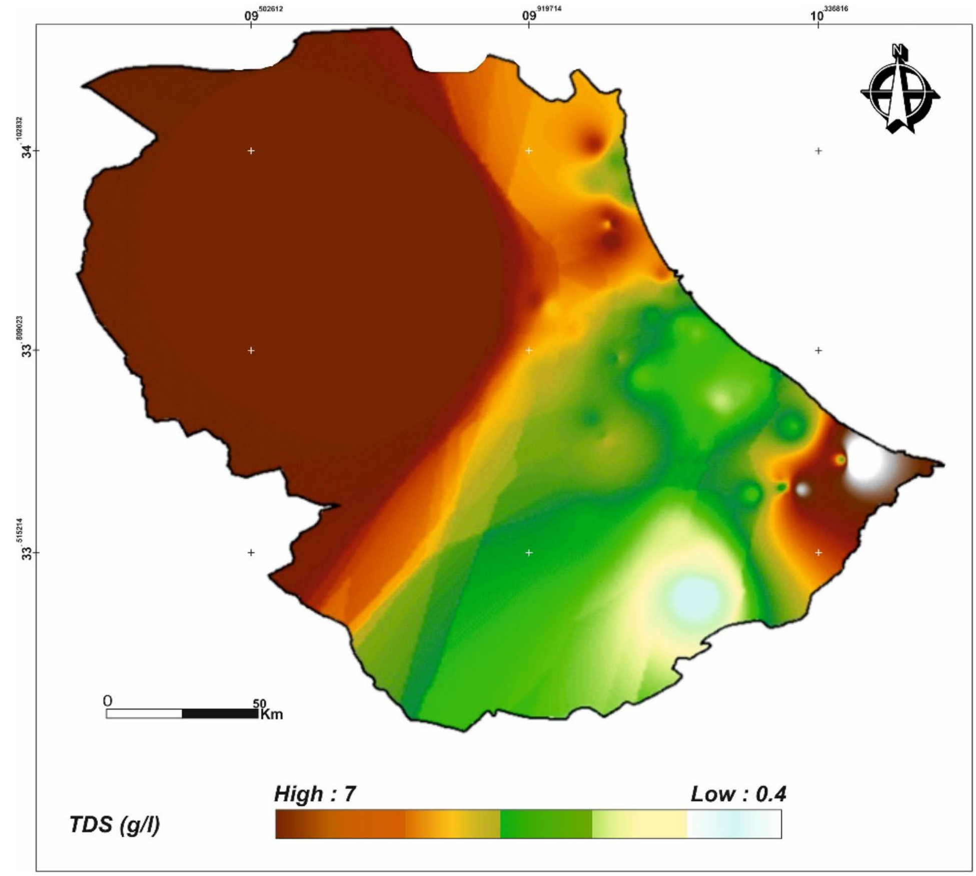


Fig. 4 Spatial distribution map of salinity in the Gabès region

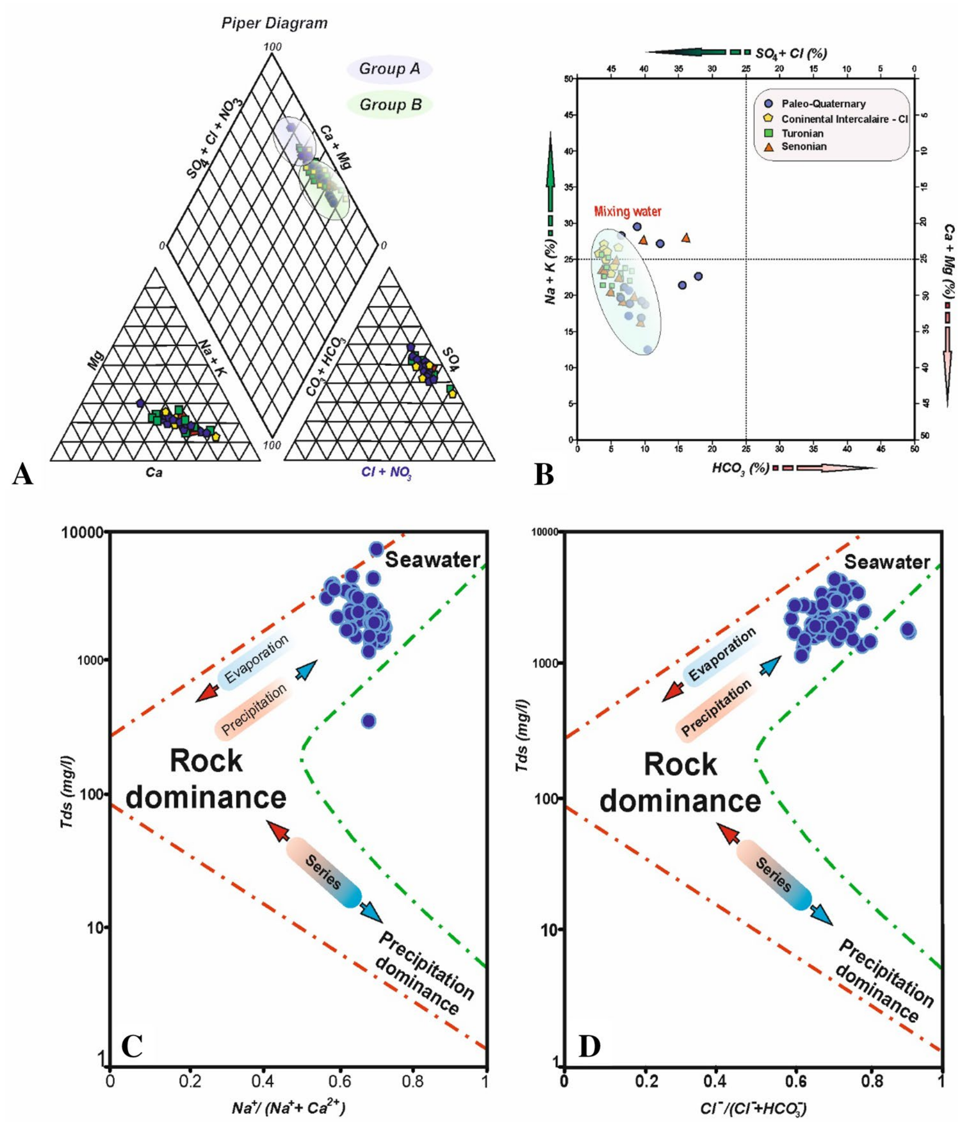
The Gibbs diagram, which was initially drawn by Gibbs in 1970, was applied to the study area. Evaporation and rock weathering processes are the main influences on the groundwater aquifers (Fig. 5c, d). Evaporation effects suggest that the groundwater temperature variation will accelerate mineral dissolving processes and rapidly increase the salinity of the water.

Groundwater isotopes ($\delta^{18}O$ and $\delta^{2}H$)

The isotopic compositions of groundwater samples from the two most important aquifer systems in the Gabès region (CI and Djeffara) were examined. These analyses provide relevant information about the aquifers' recharge mechanisms. Due to the lack of isotopic data for rainfall in the research region, the regional meteoric water line of Sfax (RMWLS) was used to calculate precipitation isotope values.

The variation diagrams for ^{18}O and ^{2}H groundwater isotopes were plotted on a standard diagram (Fig. 6a). The CI thermal water displays ^{18}O values ranging between 8 and 6, while ^{2}H varies from 70 to 51. The groundwater aquifer becomes lighter westward towards the Gabès region, which coincides with the main wind direction and the geographical distribution of the precipitation that influences the natural recharge, especially in the mountains of Dahar and near the coastal plain, where the Neogene aquifer is exposed not far from the surface. Different mineralization processes can be explained by the relationship between the ^{18}O and chloride concentrations in the groundwater, and there are two distinct groups (Fig. 6c). The first groundwater group, with ^{18}O values ranging from − 7.84 to − 3.42 and chloride concentrations between 6 and 13 meq/L, indicates the dominance of the evaporation process (Fig. 6c). This group corresponds to the western part of the Gabès region, which is associated with the CI aquifer system. The second groundwater group is primarily associated with the dissolution process, with 18 values ranging from 7.5 to 4.6, chloride concentrations largely above 15 meq/L, and deuterium excess values varying from 58 to 40. This groundwater group is represented by CI and the Djeffara aquifer systems (Figs. 6a, c). Furthermore, the diagrams of Cl and TDS versus ^{18}O (Figs. 6c, d) confirm the presence of different groups of groundwater and the influence of dissolution and mixing processes. Additionally, a scatter plot of ^{2}H versus EC shows various groundwater groups with increasing mineralization below the recharge reference point. According to this research, the main causes of the dispersed isotopic data appear to be the disintegration of the hosted rocks and the mixing of different water sources.

Fig. 5 Projection of the groundwater samples from the Gabès region **a** according to the Piper classification, **b** onto a Langelier–Ludwig diagram, and **c**, **d** onto Gibbs charts



Discussion

The mechanical attributions described in the study have important implications for understanding the complex groundwater dynamics in the research region. The presence of fault systems, permeable formations, and tectonic events plays a crucial role in shaping groundwater recharge mechanisms and the overall hydrogeological functioning of the aquifer systems (Ben Alaya et al. 2013). Coastal recharge, as indicated by isotopic composition analysis, is influenced by the proximity of the piezometric level to the surface. The intensive agricultural activities in the northeastern part of the region contribute to this recharge mechanism (Abdelkarim et al. 2022b, c). However, it is important to note that the recharge in this area is limited to non-permanent flows, highlighting potential challenges in maintaining sustainable water resources (Abdelkarim et al. 2022b, c). In the western part of the region, a different mechanism of recharge from deep CI aquifers to the Djeffara aquifer systems through fault systems was identified (Fig. 7). This phenomenon is particularly intriguing, as it demonstrates the complex interplay between different aquifer layers and highlights the potential for connectivity between these systems. Furthermore, the structure of the region, combined with tectonic events, significantly influences the hydrodynamic functioning of the aquifer systems.

The lateral discontinuity of water-bearing strata and the presence of fault systems create interference issues, particularly with the continuous decline in groundwater pressure due to overexploitation of the CI aquifer. This can result in a decreased recharge and limited renewable flows in the system aquifer south saharien (SASS) system, posing significant challenges to groundwater availability and sustainability. The presence of a permeable fault structure running

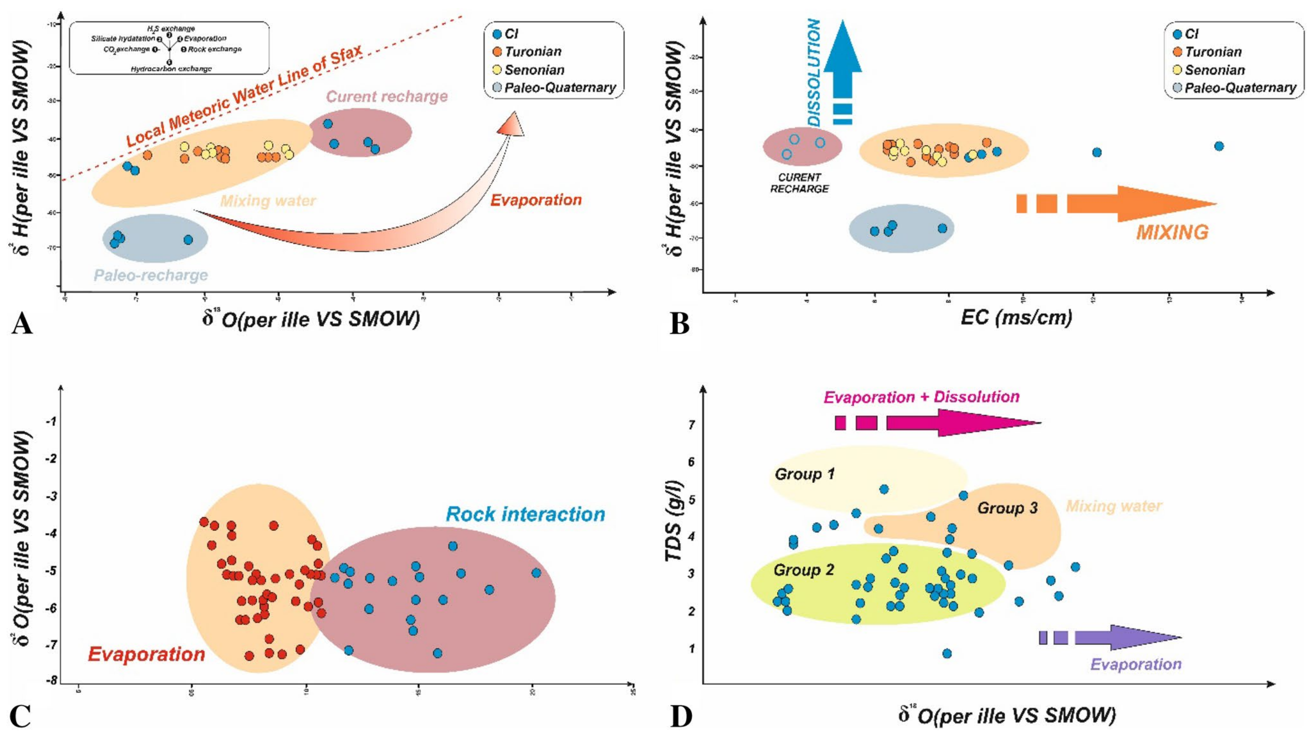


Fig. 6 Isotopic scatter plots of **a**^{2}H versus δ^{18}O, **b**^{2}H versus EC, **c** δ^{18}O versus Cl, and **d** TDS versus δ^{18}O

through the CI aquifer is another critical factor influencing the recharge mechanisms (Ben Alaya et al. 2013). This fault structure provides a preferential pathway for vertical up-recharging, enabling water movement between different aquifer layers. Such vertical preferential routes have important implications for groundwater management and can significantly impact the overall hydrogeological dynamics of the region.

These mechanical attributions, supported by various studies (Ben Alaya et al. 2013), shed light on the complexities of groundwater recharge and movement in the research region. Understanding these processes is essential for effective water resource management, as overexploitation, insufficient recharge, and human demands pose significant threats to the sustainability of groundwater systems. Therefore, it is imperative to develop sustainable management practices that consider these mechanical attributions and aim to protect and preserve the available water resources in the region for both present and future generations.

Recent studies (Ibrahimi et al. 2022; Khan et al. 2021; Jubeen et al. 2020; Beig et al. 2022) have explored innovative agricultural systems and technologies to enhance productivity while minimizing negative environmental impacts. Sustainable practices such as precision agriculture, vertical farming, hydroponics, and aquaponics have shown promising results in optimizing resource use and reducing pollution. Efficient irrigation methods like drip irrigation and micro-sprinklers have been studied to minimize water wastage, while rainwater harvesting and wastewater reuse have been investigated to alleviate water stress. The use of nanofertilizers has gained attention as a means of improving nutrient uptake efficiency and reducing losses. These technologies have shown positive effects on production, soil properties, and resource optimization. However, further research is needed to understand their long-term environmental impacts and ensure safe implementation. Efforts to mitigate potential pollution risks through best management practices and environmentally friendly inputs are underway. Continued research is essential to assess the sustainability and effectiveness of these approaches in agriculture.

Conclusion

This study provides valuable insights into the recharge mechanisms of groundwater in the Gabès-region aquifer, which were gained through the integration of data on chemical parameters, a stable environmental isotope of oxygen, and deuterium. The research focused on a large area encompassing recently exploited aquifers in the Gabès region in southwestern Tunisia. Hydrogeochemical analysis reveals the presence of two distinct recharge mechanisms. The groundwater in the Quaternary aquifer is primarily influenced by processes such as rock weathering and carbonate

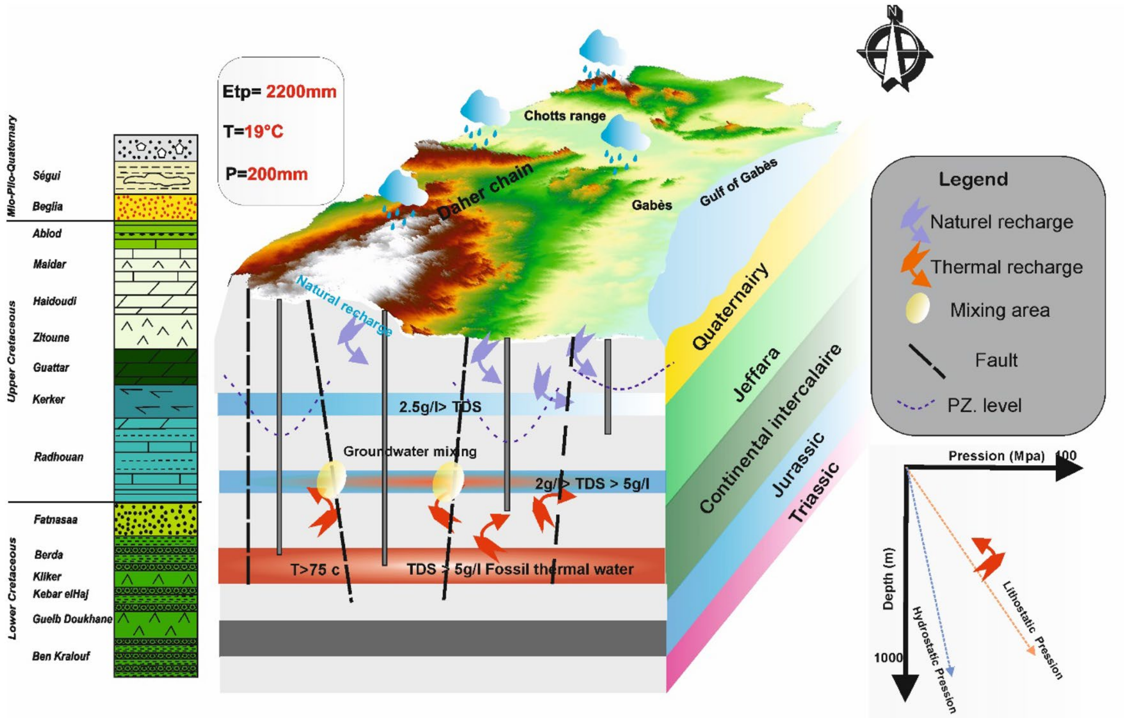


Fig. 7 Conceptual model of the different recharge mechanisms in the Gabès region

and evaporite dissolution. The validity of the mixing process between paleowater and modern water is confirmed by the grouping of distinct water types based on chemical data, which aligns well with the isotopic results. This water mixing is further supported by the interconnection with the carbonate aquifer through deep-seated faults and fractures. Isotopic analysis demonstrates the mixing of shallow aquifer water with paleowater, which varies based on the distance, depth to groundwater, and structural characteristics within the carbonate aquifer. Additionally, as we move towards deeper wells, the contribution of paleowater to the mixing process increases. To better understand the positions and attributes of the structural features facilitating the recharge of the Eocene carbonate aquifer, a combination of remote sensing and geophysical technologies should be employed. This approach would enable the identification of these structural features and enhance our understanding of their role in promoting groundwater recharge of the aquifer.

Acknowledgements The authors are grateful to the staff of the Applied Hydrosciences Laboratory for their effort and support during laboratory analysis. This research was developed under the program FCT–Fundação para a Ciência e a Tecnologia, I.P., through the project's references UIDB/04683/2020 and UIDP/04683/2020.

Author contributions The authors significantly contributed to the preparation, writing, and revision of the manuscript. B. Abdelkarim: the idea for the original draft, water sampling, data collection and analysis, conceptualization, writing the original draft, and formal analysis. I. M. H. R. Antunes: revising the original draft. N. Abaab: construction of the methodology section in the paper. B. Agoubi: resources, writing—review, and editing.

Funding The authors declare that this work had no foundation support.

Data availability The datasets used and analyzed during the current study are available from the authors on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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