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Assessment of groundwater quality and soil salinization risks in the central Tunisia aquifer systems: water resources management and public health implications

Valutazione della qualità delle acque sotterranee e dei rischi di salinizzazione del suolo nei sistemi acquiferi della Tunisia centrale: gestione delle risorse idriche e implicazioni per la salute pubblica

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Parole chiave: acquifero profondo di Upper Zebbag, sodificazione, contaminazione da nitrati, vulnerabilità della salute dei bambini, rischio sanitario non cancerogeno.

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Riassunto

Nelle zone desertiche e semi-aride, le risorse idriche sotterranee sono limitate e spesso di scarsa qualità, influenzando la salute umana e la fertilità del suolo. Nella regione di Maknassy, nella Tunisia centrale, l'agricoltura intensiva ha aumentato l'estrazione d'acqua dall'acquifero profondo di Upper Zebbag (UZ), provocando un abbassamento del livello delle acque sotterranee e mettendo a rischio questa risorsa. Questo studio mira a calcolare degli indici per valutare l'idoneità delle acque sotterranee all'uso domestico e agricolo, considerando fattori come la salinizzazione del suolo e le pratiche di irrigazione. L'analisi di questi indici fornisce informazioni sullo stato attuale della qualità dell'acqua sotterranea, che potrebbero servire come base per la gestione e la salvaguardia delle risorse idriche e del suolo nell'area di studio. Per raggiungere questo obiettivo, è stato adottato un approccio multidisciplinare che incorpora indici quali il Drinking Water Quality Index (DWQI), l'Irrigation Water Quality Index (IWQI), il Nitrate Pollution Index (NPI) e la Human Health Risk Assessment (HHRA), insieme a simulazioni statistiche multivariate. L'indice di qualità dell'acqua (WQI) mostra che il 53% dell'area ha acqua di buona qualità per il consumo umano, mentre il 47% presenta una qualità scarsa. Per quanto riguarda l'irrigazione, il 92% dell'area di studio mostra una buona qualità dell'acqua. Lo studio utilizza anche la Classificazione Gerarchica Ascendente (AHC) per identificare tre gruppi idrici, evidenziando i rischi legati alla salinizzazione e alla sodicizzazione del suolo. Il NPI rivela livelli medi di contaminazione da nitrati nel 26,67% dei campioni e mostra che i bambini sono più a rischio di problemi di salute non cancerogeni rispetto agli adulti. Questi risultati potrebbero costituire una base per la gestione e la protezione delle risorse idriche e del suolo nell'area di ricerca.

Abstract

In deserts and semi-arid areas, groundwater is limited and often of varying quality, affecting human health and soil fertility. In Central Tunisia's Maknassy region, intensive agriculture has increased the extraction of water from the Upper Zebbag deep aquifer (UZ), causing a decline in groundwater levels and posing a threat to this resource. This study aims to calculate indexes for assessing the suitability of groundwater for domestic and agricultural use, considering factors such as soil salinization and irrigation practices. The analysis of these indexes provides insights into the current state of groundwater quality, which could eventually serve as a foundation for managing and safeguarding the research area's soil and water resources. To achieve this, a multidisciplinary approach was used, incorporating indexes such as the Drinking Water Quality Index (DWQI), Irrigation Water Quality Index (IWQI), Nitrate Pollution Index (NPI), and Human Health Risk Assessment (HHRA), along with multivariate statistical simulations.The water quality index (WQI) shows that 53% of the area has good water for human consumption, while 47% is of poor quality. For irrigation, 92% of the study area show good quality. The study also uses the Ascending Hierarchical Classification (AHC) to identify three water groups, highlighting risks related to soil salinisation and sodisation. The NPI reveals medium levels of nitrate contamination in 26.67% of samples, and children are found to be more at risk of non-carcinogenic health issues compared to adults. These various findings could serve as a foundation for managing and safeguarding the research area's soil and water resources.

Introduction

Water is a critical resource for sustainable development, with increasing demand due to population growth leading to conflicts worldwide. Often termed "Blue Gold," groundwater serves as a vital alternative to surface water, which is becoming increasingly fragile. Over the past decade, human interactions have deteriorated water quality and quantity, necessitating a comprehensive response, especially in the Middle East and North Africa (MENA) region. In Tunisia, water scarcity impedes community development. Excessive water consumption has led to a significant drop in groundwater levels (Gaaloul et al., 2012). The country's limited water supply and groundwater quality render its water resources among the most vulnerable. Approximately 25% of water resources derive from aquifers that are poorly renewable and finite, with climate change further threatening these resources (Boughariou et al., 2018). Currently, agriculture accounts for 77% of water use, with 74% of irrigation relying on groundwater, which is often over-exploited through illicit boreholes. Globally, water issues can be classified into quantitative and qualitative challenges. The imbalance between supply and demand leads to quantitative issues, while qualitative concerns arise from local conditions and human activities. In Tunisia, agricultural and domestic sectors are the largest water consumers (Adimalla and Wu, 2019). The pressure on water supplies, especially in dry regions, is exacerbated by climatic conditions, leading to groundwater issues, including declining piezometric levels and deteriorating water quality (Mhamdi et al., 2006; Ahmadi and Sedghamiz, 2008; Fekkoul et al., 2013; Makni et al., 2013; Adimalla et al., 2019). In central Tunisia, where arid conditions prevail, water usage has surged to meet agricultural and domestic demands. The Maknassy basin, in particular, faces increased water consumption, primarily from subsurface sources. With 95% of available groundwater exploited, urgent measures are necessary to prevent over-exploitation and meet rising water needs. Nitrate contamination is a widespread issue affecting groundwater quality in many shallow aquifers in Tunisia. This research focuses on studying nitrate levels in the Maknassy Basin, where fertilizers like animal manure and commercial composites have been extensively used. Studies worldwide indicate that high nitrate concentrations often exceed permissible drinking water limits (Wagh et al., 2019; Zhang et al., 2020). The overuse of synthetic fertilizers is primarily blamed for this contamination, with denitrification processes from both fertilizers and anthropogenic organic matter further exacerbating the issue. The quality of agricultural water directly impacts soil health and crop growth (Wilcox, 1948; Ayers, 1977; Ayers & Westcot, 1985). Overconsumption of groundwater containing chemical contaminants such as nitrates (NO_3^-), might pose significant health hazards (Ahada and Suthar, 2018; Rizeei et al., 2018; Adimalla, 2019). Prolonged exposure to high nitrate levels can lead to methemoglobinemia (blue baby syndrome, especially in infants under six months), various cancers, heart disease, miscarriages, and thyroid disorders (Spalding & Exner, 1993; Gangolli et al., 1994). These health effects are of particular concern, as they directly affect vulnerable populations, including infants and pregnant women. Therefore, addressing nitrate contamination is essential to ensure the protection of human health, with a focus on preventing these non-carcinogenic risks (Adimalla, 2019; Panneerselvam et al., 2020).

Researchers have employed various models to assess groundwater quality and the health risks associated with chemical pollutants (Adimalla & Qian, 2019; Adimalla et al., 2019; Sadler et al., 2016).

For instance, multidimensional statistical techniques, like hierarchical cluster analysis (HCA) and principal component analysis (PCA), have improved understanding of hydrochemical mechanisms and their geographical distribution. The HCA categorizes physico-chemical and biological factors into two or more categories based on their similarities in terms of particular attributes. The data could be easier to interpret in a hydrochemical or geological context. Nevertheless, PCA reduces the number of variables as well as the structure of the relationship between them while explaining the covariance relationships between them (Nsiri et al., 2021; Ben Brahim et al., 2023).

The Water Quality Index (WQI) model, defined by Horton (1965), is an excellent tool for evaluating the extent of chemical contamination and the appropriateness of water for various applications, particularly human consumption and irrigation. This technique simplifies complex datasets into a single, often dimensionless value using multiple parameters, making water quality assessment easy to interpret and replicate (Adimalla, 2019). The Health Quotient (HQ) model, initially introduced by the U.S. Environmental Protection Agency (USEPA) in the 1980s, has since been widely used to evaluate non-carcinogenic health risks associated with groundwater contamination (USEPA, 1989; Zhai et al., 2017; Adimalla, 2019; Akber et al., 2020). In modern agricultural practices, the excessive use of nitrogen-rich fertilizers significantly contributes to elevated nitrate concentrations in subsurface water (Panneerselvam et al., 2020; Wagh et al., 2019).

Our study aims to: (1) determine the hydrochemical properties of groundwater in the Upper Zebbag (UZ) deep aquifer in the Maknassy Basin; (2) assess the adequacy of subsurface water for irrigation and consumption; and (3) estimate the non-carcinogenic risk associated with nitrate contamination in groundwater for exposed groups (children, adults, women, and men).

Materials and Methods

Study area

Maknessy basin, located in central Tunisia within the Sidi Bouzid governorate, spans approximately 1200 km² (Fig.1). It is bordered by Cretaceous anticlines, with the Meloussi and Majoura Jebels to the north (626 m and 874 m), the Bouhedma Jebel to the south (821 m), the Zebbeus and Dribika El Hamra Jebels to the east (461 m and 369 m), and the El Goussa Jebel to the west (609 m). The climatic conditions in Maknessy significantly impact daily life and the

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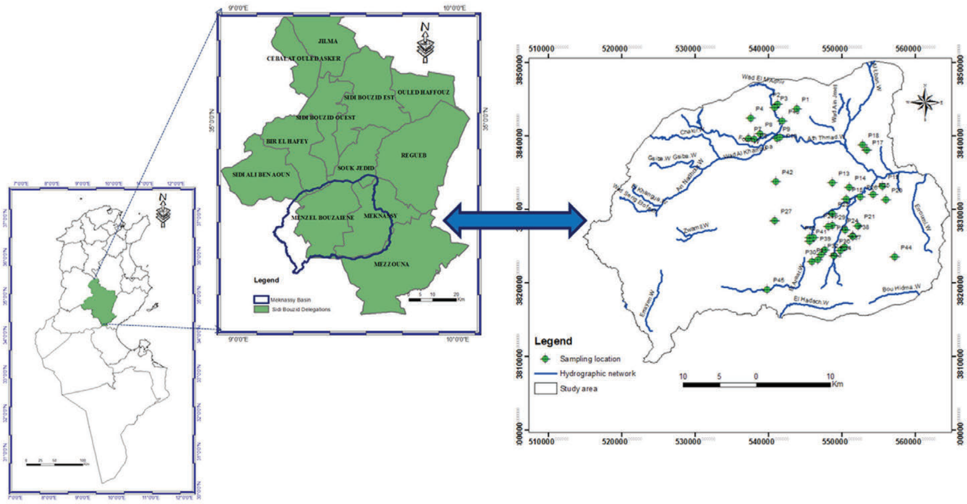

Fig. 1 - Geographical location of the Meknassy Basin and sampling sites in the Sidi Bouzid region, central Tunisia.

Fig. 1 - Carta dell'area di studio di Meknassy Basin e dei siti di campionamento nella regione di Sidi Bouzid, Tunisia centrale.

local ecosystem. Average temperatures range from 11.1°C in January to 26.9°C in August, indicating a cooler winter and warmer summer (Moussaoui et al., 2023).

Rainfall plays a crucial role in groundwater recharge. A significant decrease in average annual precipitation was recorded at Meknassy station, dropping from 738.1 mm in 1990 to 98.01 mm in 2021. This decline highlights considerable variability in rainfall patterns over the years, suggesting a likely influence of cyclical weather phenomena or long-term regional climate change. This observation aligns with projections indicating a decrease in precipitation across Tunisia, which could exacerbate water scarcity issues in the region (World Bank, 2022).

Geological and Hydrogeological Patterns

The Maknessy basin features a synclinal structure bordered by Djebels Melloussi and Majoura to the north and Djebels Orbata and Bouhedma to the south. Tectonic studies, including a seismic reflection section, reveal several large faults that shape the basin. The main El Mech fault, a dextral shear fault, truncates the ends of Djebels Orbata and Bouhedma (Ouda, 2000, Moussaoui et al., 2023). The Jebel Meloussi fault marks the northern limit of the syncline, while minor faults contribute to the step-like morphology of Cretaceous outcrops (Ouda, 2000) (Fig.2). A system of N-S guiding faults influences the eastern end of the basin, facilitating communication between water reservoir levels after uplift movements exposed Triassic formations (Zouaghi et al., 2011). The Maknessy hydrogeological basin comprises four reservoir levels:

1. Water Table: Found in Mio-Plio-Quaternary sandstone and sand layers, it is exploited via surface wells, despite its high salt content (2-3.5 g/L), yielding 10-23 L/s.
2. 1st Deep Aquifer: Located in dolomitic limestones of the Upper Zebbag formation (Lower Turonian), it is the most exploited aquifer in the region, averaging 400 m in thickness and offering specific flow rates of up to 21 L/s due to its karstified carbonate facies (Gasmi et al., 2009)

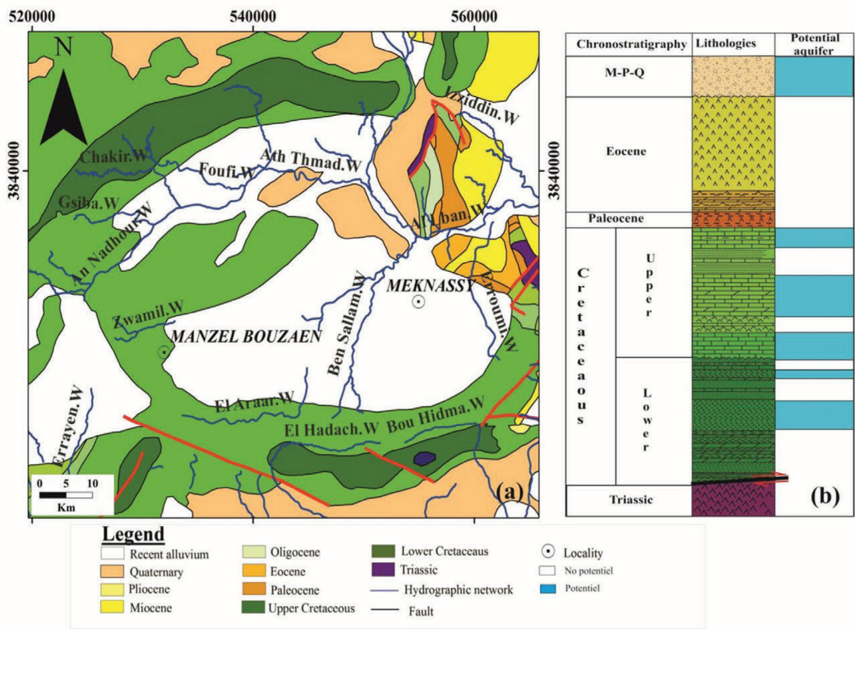

Fig. 2 - a) Geological map of the Meknassy Basin (extract from the geological map of Tunisia at a scale of 1:500,000) showing the basin's main geological features, and (b) Simplified regional lithostratigraphic column.

Fig. 2 - Carta geologica di Meknassy Basin (derivata dalla Carta Geologica della Tunisia a scal 1:500,000) che mostra le principali caratteristiche del bacino, e (b) Colonna litostratigrafica semplificata del bacino.

3. 2nd Deep Aquifer: Found in the Lower Zebbag formation (Lower Albian to Lower Cenomanian), it is partially exploited due to its depth.
4. 3rd Deep Aquifer: Located in the Boudinar formation (Lower Cretaceous), characterized by sandy sandstone facies, it exhibits excellent hydrogeological properties.

Sampling campaign and laboratory analysis

In 2023, two sampling campaigns were conducted in October and November, during which 45 groundwater samples were collected from difstinct locations within the Upper Zebbag Deep Aquifer (UZDA). Samples were taken in 1.5 L plastic bottles, thoroughly cleaned and rinsed with the sampled water to prevent contamination. Key physical parameters like electrical conductivity (EC) and pH were measured insitu using a calibrated HI 9828 multiparameter meter, following the manufacturer's instructions. The samples were then filtered (0.45 µm), stored at 4°C, and transported to the laboratory of the Regional Commissariat for Agricultural Development (CRDA) in Sidi Bouzid Gouvernorate. In the laboratory, bicarbonate (HCO_3^-) concentrations were determined by titration with HCl. Major ions such as K^+, Mg^{2+}, Cl^-, Na^+, Ca^{2+}, SO_4^{2-}, and NO_3^-, were analyzed using Metrohm 850 Professional IC ion chromatography.

Hydrochemical data processing

Data were analyzed through whisker diagrams created using IBM SPSS Statistics 26. Obtained plots provide a visual summary of data distribution by displaying the median, quartiles, and potential outliers.

This method helps compare dispersion between data series and is widely used in research for quick statistical summaries (Ben Brahim et al., 2022a).

Multivariate techniques like Hierarchical Cluster Analysis (HCA) and Principal Component Analysis (PCA) were employed to classify groundwater samples based on their geochemical characteristics and explore geochemical changes occurring across different groundwater sources and aquifers. The Shapiro–Wilk test confirmed data normality before HCA use. HCA clusters samples based on chemical similarities, while PCA reduces the number of variables, helping to identify groundwater mineralization processes. Both methods require normality checks, with Bartlett's sphericity and Kaiser-Meyer-Olkin (KMO) tests ensuring PCA validity (Ayed et al., 2017)

Water quality index (WQI)

Irrigation water quality index (IWQI)

The Irrigation Water Quality Index (IWQI), developed by Meireles et al. (2010), was applied to the UZ aquifer using various parameters (Table 1 and Equations 1-9) to assess its suitability for irrigation. This index evaluates the water quality based on factors that affect crop yields and soil fertility. The IWQI has been used in several studies to evaluate groundwater suitability for irrigation purposes (Yidana et al., 2010; Ayed et al., 2017; Nsiri et al., 2021).

-Total Hardness

$$TH\left(CaCO_3\right)mg/L = 2.497\left[Ca^{2+}\right] + 4.115\left[Mg^{2+}\right] \quad (1)$$

- Sodium Adsorption Ratio (SAR)

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

- Sodium percent (%Na)

$$\%Na = \frac{\left(Na^+ + K^+\right)}{\left(Ca^{2+}+Mg^{2+}+Na^+ + K^+\right)} \cdot 100 \quad (3)$$

- Soluble Sodium Percentage (SSP)

$$SSP = \left[\left(\frac{Na}{Ca^{2+}+Mg^{2+}+Na^+}\right)\right] \cdot 100 \quad (4)$$

- Permeability index (PI)

$$PI = \frac{\left(Na^+ + \sqrt{HCO_3^-}\right)}{\left(Ca^{2+}+Mg^{2+}+Na^+\right)} \cdot 100 \quad (5)$$

- Magnesium percent (% Mg)

$$\%Mg = \frac{Mg^{2+}}{\left(Ca^{2+}+Mg^{2+}\right)} \cdot 100 \quad (6)$$

- Kelly's Ratio (KR)

$$KR = \frac{Na^+}{\left(Ca^{2+}+Mg^{2+}\right)} \quad (7)$$

Where meq/L is used to express all ion concentrations.

The IWQI spatial distribution map was developed in three stages:

- The first step is to calculate the quality rating scale (qi) derived from each parameter, as provided by equation 8:

$$q_1 = q_{i\max} - \left[\left(\left(x_{ij} - x_{\inf}\right) \cdot q_{iamp} / x_{amp}\right)\right] \quad (8)$$

where :

– qimax: the maximum Qi value for the class, which is pre-determined based on commonly used reference values in water quality classification studies, such as Meireles et al. (2010) and Yidana et al. (2010).
– xij: observed value of the parameter
– xinf : value that corresponds to the lower limit of the class in which the parameter belongs.
– - qiamp: amplitude of the class
– - xamp: amplitude of the class in which the parameter belongs

To evaluate xamp, the upper limit of the last class of each parameter was taken as the highest value determined during the physio-chemical examination of the water samples.

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- In the second phase, the assignment of weights to each parameter was based on its significance in determining groundwater suitability for irrigation. Higher weights were given to parameters with greater influence on crop yield and soil fertility, following the classification systems of Meireles et al. (2010), Yidana et al. (2010), and Ayed et al. (2017). The weight values (Table 1) reflect expert judgment and are aligned with established guidelines (Wilcox, 1955; Richards, 1954; Szabolcs and Darab, 1964).
- The third step is to calculate the IWQI by by means of the following equation:

$$IWQI = \sum_{i=1}^{n} q_i w_i \qquad (9)$$

Where q_i: the quality of the ith parameter, w_i is its normalized weight, and n is the number of parameters.

Drinking water quality index (DWQI)

Groundwater safety and pollution levels were assessed using parameters like pH, TDS, Mg^{2+}, Ca^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, HCO_3^-, and NO_3^-. The Drinking Water Quality Index (DWQI) was calculated in three steps (Vasanthavigar et al., 2010; Yidana and Yidana, 2010; Egbueri et al., 2020).

Firstly, each of the ten indicators was assigned a weighting factor (wi) based on their relevance and concentration, with weights ranging from 1 to 5. The assignment of weights was determined by evaluating the potential health impact of each parameter on drinking water quality. Parameters such as NO_3^- and TDS, having a significant effect on water potability and are critical for human health, were assigned the highest weight of 5. In contrast, parameters like K^+ and HCO_3^-, having a lower direct impact on health, received lower weights. The relative weight (Wi) for each parameter was then calculated using Equation 10 (Karakuş and Yıldız, 2019) (Table 2).

Tab. 2 - WHO standards, weights and relative weights for water quality parameters for human consumption.

Tab. 2 - Standard WHO, pesi e pesi relativi per i parametri della qualità dell'acqua per consumo umano

Parameters	WHO Standard (2011)	Weight (wi)	Relative weight (Wi)
PH	6.5- 8.5	3	0.103
TDS (mg/L)	1000	5	0.172
Cl (mg/L)	250	3	0.103
SO^2_4 (mg/L)	250	3	0.103
NO_3 (mg/L)	50	5	0.172
HCO_3 (mg/L)	120	2	0.07
Na^+ (mg/L)	200	3	0.103
Ca^{2+} (mg/L)	75	2	0.07
Mg^{2+} (mg/L)	50	2	0.07
K^+ (mg/L)	12	1	0.034
Total		Σ wi= 29	Σ Wi= 1

Tab. 1 - Suitability of groundwater for irrigation based on irrigation water quality index (IWQI).

Tab. 1 - Idoneità delle acque sotterranee all'irrigazione in base all'indice di qualità delle acque irrigue (IWQI).

Parameters	Range	Class	Weight	Score	No. of samples	Percentage
EC (µS/cm) (Wilcox, 1955)	< 250	Excellent	4	5	-	-
	250-750	Good		4	-	-
	750-2250	Permissible		3	11	24.44%
	2250-5000	Doubtful		2	8	17.77%
	> 5000	Unsuitable		1	26	57.77%
SAR (Richards, 1954)	<3	Acceptable	3	3	18	40%
	3-9	Moderate		2	27	60%
	>9	Unsuitable		1	-	-
%Na (Wilcox, 1955)	< 20	Excellent	2	5	1	2.22%
	20-40	Good		4	40	88.88%
	40-60	Permissible		3	4	8.88%
	60-80	Doubtful		2	-	-
	> 80	Unsuitable		1	-	-
%Mg (Szabolcs and Darab,1964)	<50	Suitable	1	2	6	13.33%
	>50	Unsuitable		1	39	86.66%
ESP (Kshetrtmayum et Bajpai, 2012)	<50	Suitable	1	2	45	100%
	>50	Unsuitable		1	-	-
KR (Kelly, 1951)	< 1	Good	1	2	45	100%
	>1	Intolerate		1	-	-
PI (Doneen, 1964)	<25	Inadequate	1	1	1	2.22%
	25-75	Acceptable		2	44	97.77%
	>75	Excellent		3	-	-

$$W_i = w_i / \sum_{i=1}^{n} w_i \qquad (10)$$

Where:
W_i: Relative weight
w_i: represents the weight of each chemical parameter. n denotes the number of the employed chemical parameters.

The second step is to estimate the quality assessment scale (qi) for each parameter via Equation 11 (Wu et al., 2020; Ben Brahim et al., 2021):

$$q_i = \frac{C_i}{S_i} \cdot 100 \qquad (11)$$

Where:
q_i represents the quality assessment scale;
C_i is the concentration in mg/L of the physio-chemical parameters in each water sample
S_i is defined as the drinking water standard for each chemical parameter, in mg/L (WHO, 2017).

The third step is estimating the sub-index of the ith parameter (SI_i), as given by equation 12

$$SI_i = W_i \cdot q_i \qquad (12)$$

Ultimately, equation 13 was utilized to determine the DWQI value for every sample

$$DWQI = \sum_{i=1}^{n} SI_i \qquad (13)$$

Where n is the number of parameters and SI_i is the ith parameter's sub-index.

Nitrate Pollution Index (NPI)

In dry and semi-arid regions, groundwater is the primary source of drinking and irrigation water, making quality assessment essential to minimize health risks. Studies have shown that elevated nitrate levels in groundwater pose significant health risks (Gupta et al., 2000; Chen et al., 2017; Wu & Sun, 2016; Ahada and Suthar, 2018). Nitrate contamination is a major concern, contributing to the decline of groundwater quality globally (Adimalla et al., 2018; Adimalla and Venkatayogi, 2018). Continuous exposure to high nitrate levels can harm residents relying on groundwater for drinking, especially in rural areas, where 80% of diseases are linked to low-quality drinking water (Narsimha and Sudarshan, 2016). This study aims to map nitrate distribution and assess health risks in the Maknessy Basin (Table 3). The nitrate pollution intensity can be computed using equation 14 (Pannerselvam et al., 2020).

$$NPI = \frac{C - AHV}{AHV} \qquad (14)$$

HAV stands for the human acceptable level of nitrate which is 20 mg/L (Panneerselvam et al., 2020), and C is the sample's determined nitrate concentration.

Tab. 3 - Groundwater classification based on nitrate concentration.

Tab. 3 - Classificazione delle acque sotterranee sulla base della concentrazione del nitrato.

NO_3 concentration	Classification of health risk	N samples	Percentages
< 45	Low risk	34	75.56%
46–100	High risk	11	24.44%
>100	Very high risk	-	-

Human health risk assessment

Consuming contaminated groundwater can negatively impact human health through various pathways, including ingestion and skin contact (USEPA, 2001). The US Environmental Protection Agency (USEPA) developed a Human Health Risk Assessment (HHRA) approach to evaluate exposure and hazards based on pollutant concentrations and duration of exposure. Specifically, nitrate (NO_3^-) concentration in water, combined with daily water intake per kilogram of body weight, determines the amount of nitrate ingested. The USEPA model for estimating health risks from high nitrate levels in drinking water has been widely adopted for adults and children (Chen et al., 2017; Adimalla et al., 2018; 2019; Wagh et al., 2019; Akber et al., 2020; Wu et al., 2020; Yu et al., 2020). This model involves four key steps: hazard identification, dose-response assessment, exposure assessment, and risk characterization (Li et al., 2016). Research indicates that the main exposure pathways for nitrates in humans are ingestion and skin contact, with ingestion presenting a higher risk (Li et al., 2016; Wu and Sun, 2016; Chen et al., 2017). The USEPA model was used to calculate the chronic daily intake of nitrate, reflecting the associated non-carcinogenic risk (Eq. 15). Table 4 outlines the formula parameters for the relevant groups.

$$CDI = \frac{C \cdot IR \cdot ED \cdot EF}{ABW \cdot AET} \qquad (15)$$

where C represents the concentration of a specific contaminant in groundwater (mg/L), ABW refers to the average body weight (kg), ED is the exposure duration (years), AET is the average exposure time (days), IR is the human ingestion rate (L/day), and EF is the exposure frequency (days/years: 365 days).

Equation 16 (USEPA 1991) is utilized to calculate the hazard quotient index.

$$HQ\ nitrate = \frac{CDI}{RfD} \qquad (16)$$

where CDI denotes the chronic daily intake (mg/kg day), RfD refers to the reference dose of the pollutant, and HQ nitrate is the nitrate hazard quotient. The USEPA (1989) and the Integrated Risk Information System (IRIS, 2012) both fixed the oral reference dose of nitrogen at 1.6 mg/kg/day.

Tab. 4 - Parameters used to calculate hazard quotients (HQ) for health risk assessment.

Tab. 4 - Parametri utilizzati per calcolare i quozienti di rischio (HQ) per la valutazione del rischio per la salute.

Parameters	Description	Unit	Children	Adults	Women	Men	References
IR	Ingestion rate	L/day	1.5	3	2.5	2.5	Vetrimurugan et al. (2017), Adimalla (2019)
EF	Exposure frequency	days/years	365	365	365	365	USEPA (1989, 1991)
ED	Exposure duration	-	6	30	67	64	Zhang (2008), Adimalla (2019)
ABW	Average body weight	Kg	18.7	57.5	55	65	ICMR Expert Group (1990), Adimalla (2019)
AET	Average exposure time	Days	2190	10,950	24.455	23.360	Zhang (2008), Adimalla (2019), (Wagh et al., 2019)

Results and discussion

Groundwater chemical characteristics

The groundwater analyses conducted in the study reveal significant variability in the chemical composition, with notable implications for public health and the sustainability of water resources (Table 5). In fact, the pH values show that the groundwater is moderately alkaline, ranging from 7.1 to 8.53 (average 7.96), which is within the World Health Organization (WHO) standards for potable water. However, the Total Dissolved Solids (TDS) concentration is well above the WHO limit of 1000 mg/L, with an average of 2.11 g/L, suggesting high salinization, essentially due to excessive irrigation. This salinization concerns public health as it can affect the accessibility and potability of water resources. Sodium (Na^+, 226.37 mg/L) and chloride (Cl^-, 470.97 mg/L) are the most abundant ions in the analyzed samples, reaching high levels (Fig.3), which increase the risk of soil salinization and degrade the water quality (Ben Brahim et al.,2022a, 2022b, 2023). These results indicate that excessive irrigation

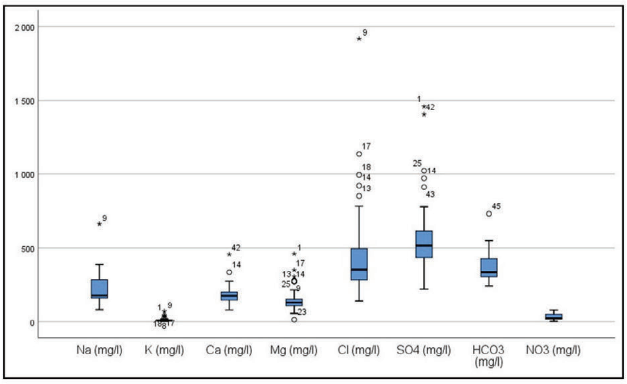

Fig. 3 - Box and Whisker plots showing ionic concentration variations in the UZDA within the Meknassy Basin.

Fig. 3 - Diagrammi Box and Whisker che mostrano le variazioni di concentrazione degli ioni maggiori nell'UZDA all'interno del bacino di Meknassy.

Tab. 5 - Statistical description of the variables and soil salinization-sodization risk indices determined in 45 samples from the deep aquifer of the Upper Zebbag-Maknessy Basin.

Tab. 5 - Descrizione statistica delle variabili e degli indici di rischio di salinizzazione-sodicizzazione del suolo determinati in 45 campioni dell'acquifero profondo del bacino superiore Zebbag-Maknessy.

	Minimum	Maximum	Average	STD	Standard WHO (2017)	NT 09.14 (SONEDE, 2012)
EC	1270	8700	3063.11	1514.714	2500	1500
TDS	0.880	6.090	2.112	1.053	1000	2500
Ph	7.10	8.530	7.963	0.471	6.5-8.5	6.5-8.5
Na (mg/L)	81.4	662.2	226.371	102.074	200	200
K (mg/L)	1.0	69.9	14.289	12.169	30	50
Ca (mg/L)	80.0	456.0	180.618	67.965	200	200
Mg (mg/L)	14.4	460.8	152.640	81.634	150	150
Cl (mg/L)	142.0	1917.0	470.967	309.611	250	600
NO_3 (mg/L)	1.800	79.000	32.128	19.7299	50	45
SO_4 (mg/L)	219.936	1457.118	564.987	257.710	400	600
HCO_3 (mg/L)	244.0	732.0	366.667	95.462	300	300
TH	476.736	2175.856	1079.116	415.366		
SAR	1.4176	6.693	2.955	0.933		
Na%	16.841	62.351	32.479	7.706		
ESP	0.824	7.929	2.989	1.269		
%Mg	10.909	87.272	56.679	11.982		
KR	0.195	0.857	0.462	0.139		
PI	20.591	53.686	38.386	6.675		

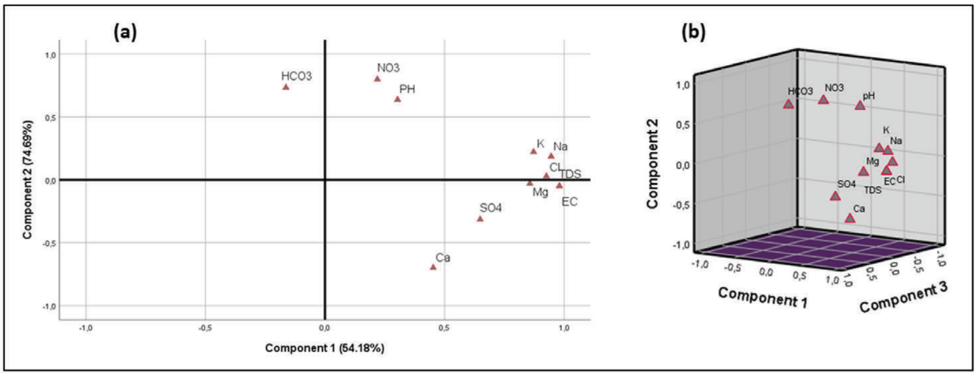

Fig. 4 - (a) Distrubition of variables based on two factors (2D PCA); (b) Rotation plot of hydrochemical parameters derived from R-mode factor analysis to assess water quality patterns.

Fig. 4 - (a) Distribuzione delle variabili in base a due fattori (PCA 2D); (b) Diagramma di rotazione dei parametri idrochimici derivati dall'analisi fattoriale R-mode per valutare i modelli di qualità dell'acqua.

and water use for agricultural activities can have harmful effects on water quality, with implications for the health of local populations. High sodium and chloride concentrations can lead to health issues such as hypertension and electrolyte imbalances, especially for individuals with pre-existing heart conditions. While 71% of Cl^- and 82% of SO_4^{2-} samples meet Tunisian standards, 27% of calcium (Ca^{2+}) and 31% of magnesium (Mg^{2+}) samples exceed limits. Overall, significant variability in groundwater quality exists, with many samples surpassing safe limits.

Application of Principal Component Analysis (PCA)

PCA was conducted using 45 water samples, revealing strong correlations between TDS, Na^+, Cl^-, and Mg^{2+} (Table. 1S). The first two axes explained 74.69% of the variance, with Factor 1 (F1) primarily representing mineralization driven by major ion dissolution (Tables. 2S and 3S). Nitrate concentrations (1.8 to 79 mg/L) indicate agricultural contamination, with excess fertilizers linked to high nitrate levels (Fig. 4a-b).

Application of Ascending Hierarchical Classification (AHC)

Using SPSS.26 software, hierarchical classification was applied to the sampled waters in the study area, based on 11 variables and 45 individuals, applying the Ward's aggregation criterion and the Euclidean distance. The obtained results are shown in dendrograms (Figs. 5 and 6).

The dendrogram of variables (Fig. 5) shows two groupings of variables, the first essentially grouping Na^+, Cl^-, K^+, Ca^{2+}, SO_4^{2-}, Mg^{2+} and TDS, showing strong to medium mineralisation. The second group consists of NO_3^-, HCO_3^-, and pH, reflecting a different geochemical behavior.

The dendrogram of the individual classifications (Fig. 6), reveals three main water clusters organised according to their predominant chemical compositions. Some clusters highlight the contribution of natural processes, namely water-rock interaction (dissolution), while others highlight contamination from backflow and excessive irrigation. These clusters correspond to wells with high mineralization, possibly influenced by agricultural activities. The results from HCA align with the PCA findings, confirming the mineralization and contamination trends.

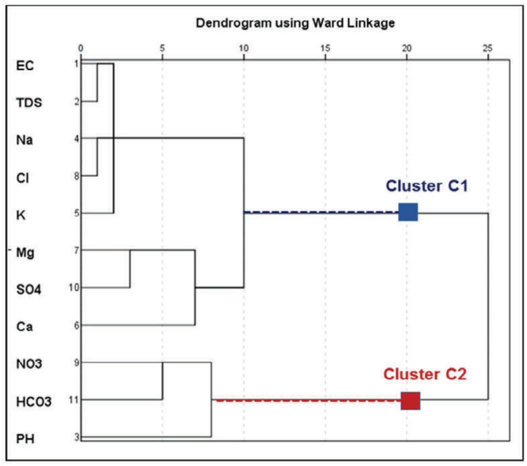

Fig. 5 - Dendrogram representing the hierarchical clustering of physico-chemical parameters in the Meknassy Basin.

Fig. 5 - Dendrogramma che rappresenta il clustering gerarchico dei parametri fisico-chimici nel bacino di Meknassy.

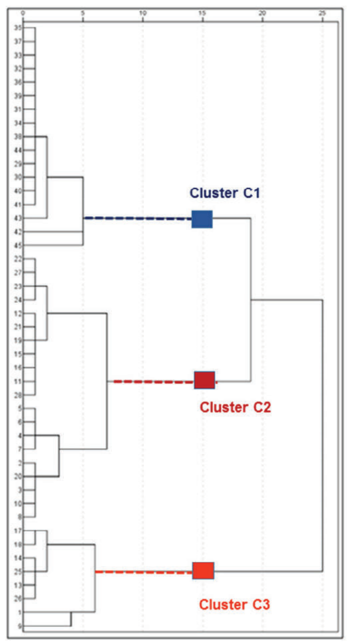

Fig. 6 - Individual HCA (Hierarchical Cluster Analysis) dendrogram showing the grouping of samples based on physico-chemical characteristics.

Fig. 6 - Dendrogramma HCA (Hierarchical Cluster Analysis) degli individui che mostra il raggruppamento dei campioni in base alle caratteristiche fisico-chimiche.

Multivariate statistical methods and soil salinization risk

The trustworthiness of the obtained results and the impact of the calculated ratios (ionic indices) are corroborated by the mean correlation between electrical conductivity (EC) and soil salinisation and sodisation risk indices such as total hardness (TH), exchangeable sodium index (ESP) and adsorbed sodium index (IP), as revealed by Pearson's correlation matrix (Table 4S). The application of PCA method revealed two factors accounting for 84.54% of the cumulative variability (Table. 5S). The factor F1 shows a significant positive charge with most of the ionic ratios such as ESP (0.954), SAR (0.952), KR (0.917), Na% (0.772), and IP (0.731), suggesting potential risks of water degradation and soil salinisation. Wheras, the factor F2, more strongly correlated, suggests the influence of sodic conditions, particularly in the Maknessy basin soils, with parameters such as EC, TH, and %Mg, playing a significant role in the classification (Table. 6S, Fig. 7a-b).

Furthermore, the HCA identified two distinct clusters based on the salinization and sodization risk indices (Fig. 8):

- Cluster 1: consisted of highly mineralised water samples (e.g., P1, P2, P3, P8, P9, P10, P14 , P19, P25, P17, P18, P43, P20, P24, P22, P7, P15, P6, P5 and P23), which indicate the highest risk of soil salinisation under the influence of TH, EC and Mg parameters;
- Cluster 2: comprised of samples from boreholes P42, P26, P21, P12, P44, P34, P35, P11, P4, P27 and P45, which illustrate the influence of the other indices and their medium to low risk of soil salinisation.

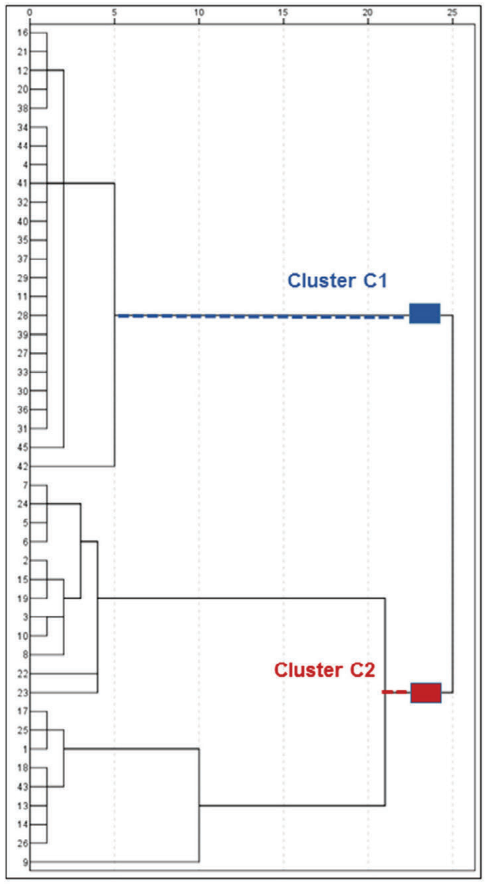

Fig. 8 - Dendrogram of individuals based on soil salinization and sodization indices, highlighting salinity and sodicity risk zones.

Fig. 8 - Dendrogramma degli individui basato sugli indici di salinizzazione e sodicizzazione del suolo, evidenziando le zone a rischio di salinità e sodicità.

.Water quality index (WQI)

Evaluation of water quality for irrigation uses

A statistical analysis of the parameters applied in this study is presented in Table 5. To visualize groundwater quality across the Maknassy Basin, digital maps were generated using ArcGIS 10.8. The spatial interpolation was carried out using the Inverse Distance Weighting (IDW) method, a geostatistical technique that estimates values at unmeasured locations based on the weighted influence of nearby data points. To ensure the accuracy of the interpolated maps, a cross-validation process was performed, comparing the predicted values with observed field data from independent monitoring locations. This validation ensured the reliability of the generated maps.The spatial distribution of electrical conductivity (EC) ranged from 1270 µS/cm to 8700 µS/cm, with most irrigation water classified as doubtful quality (2250 < EC < 5000). High salinity with low SAR does not impede infiltration, whereas low salinity with high SAR poses risks (Simsek and Gunduz, 2007; Ben Brahim et al., 2012). SAR values ranged from 1.42 to 6.69, indicating most samples fall into the acceptable to moderate class (Fig. 9b). The %Na varied from 16.84% to 62.35%, with most groundwater deemed suitable for irrigation (20 < %Na < 40), except for

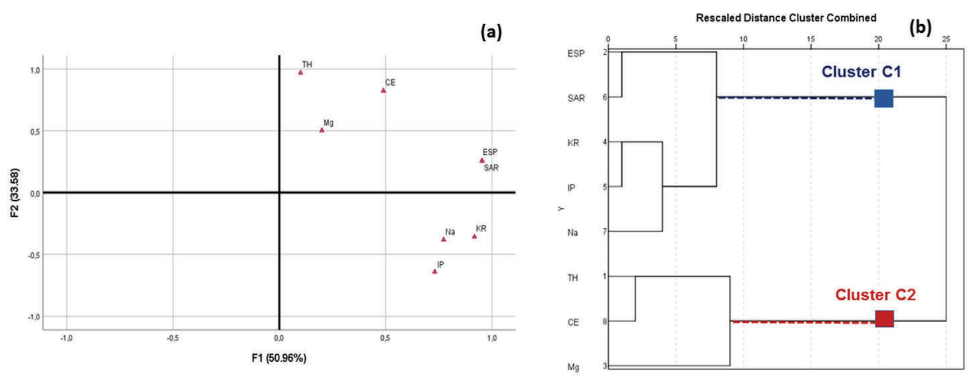

Fig. 7 - Multivariate statistical analysis of soil salinization and sodization risk indices: (a) Principal Component Analysis (PCA) and (b) Cluster Hierarchical Analysis (CHA)dendrogram identifying key risk patterns.

Fig. 7 - Analisi statistica multivariata degli indici di rischio di salinizzazione e sodicizzazione del suolo: (a) Analisi delle componenti principali (PCA) e (b) Analisi gerarchica dei cluster (CHA) dendrogramma che identifica i principali pattern di rischio.

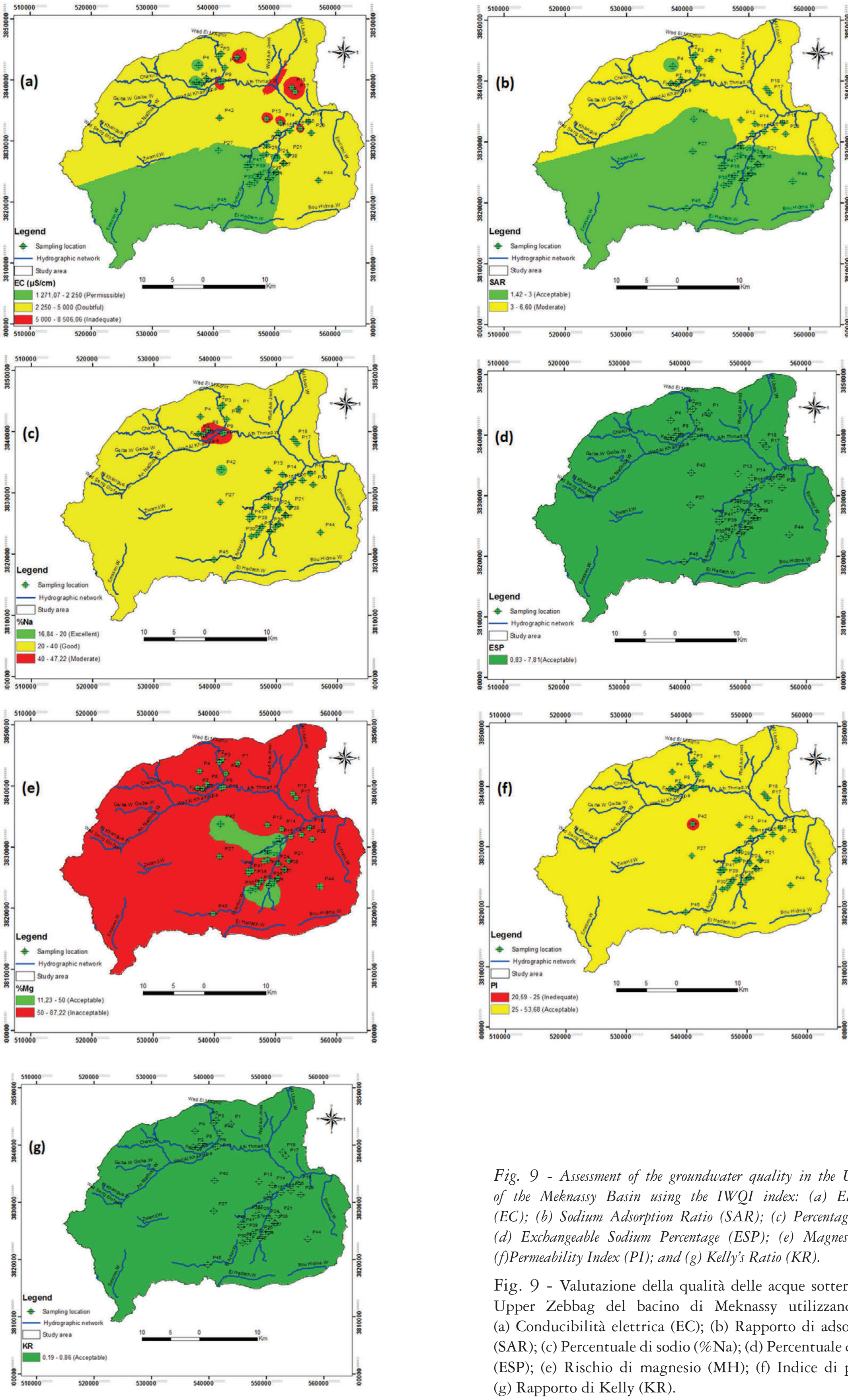

Fig. 9 - Assessment of the groundwater quality in the Upper Zebbag aquifer of the Meknassy Basin using the IWQI index: (a) Electrical Conductivity (EC); (b) Sodium Adsorption Ratio (SAR); (c) Percentage of Sodium (%Na); (d) Exchangeable Sodium Percentage (ESP); (e) Magnesium Hazard (MH); (f)Permeability Index (PI); and (g) Kelly's Ratio (KR).

Fig. 9 - Valutazione della qualità delle acque sotterranee nell'acquifero Upper Zebbag del bacino di Meknassy utilizzando l'indice IWQI: (a) Conducibilità elettrica (EC); (b) Rapporto di adsorbimento del sodio (SAR); (c) Percentuale di sodio (%Na); (d) Percentuale di sodio scambiabile (ESP); (e) Rischio di magnesio (MH); (f) Indice di permeabilità (PI); e (g) Rapporto di Kelly (KR).

boreholes P7, P8, P9, and P10 (Fig. 9c). ESP values ranged from 0.82% to 7.93%, with 100% of the area classified as suitable for irrigation (Fig. 9d). %Mg varied between 10.90% and 87.27%, averaging 56.67%, (Table 5) with 6 samples showing low risk for irrigation (Fig. 9e) . PI values ranged from 20.59% to 53.68%, indicating variable groundwater quality (Fig. 9f). All samples had KR values below 1, indicating suitability for irrigation (Fig. 9g). The IWQI calculation revealed that approximately 92% of groundwater samples were classified as good quality for irrigation, while 8% fell into the medium- quality category (Fig. 10a). Areas with unsuitable water quality, identified based on EC and %Na, align with those classified as poor according to the IWQI, highlighting elevated Na+ levels compared to Mg^{2+} and Ca2+.

This mapping serves as a decision-making tool for assessing groundwater quality in the Maknessy Basin. Regional water agencies and agricultural management bodies rely on these assessments to guide water quality management strategies and promote sustainable water use in the study area.

Index of groundwater quality for drinking (DWQI)

The DWQI assessment of the Maknessy UZ aquifer categorizes the water into two groups: good and unsuitable for human consumption. DWQI values range from 70 to 179, with approximately 53% of the study area identified as having good quality water, while around 47% are considered poor for human consumption (Fig. 10b).

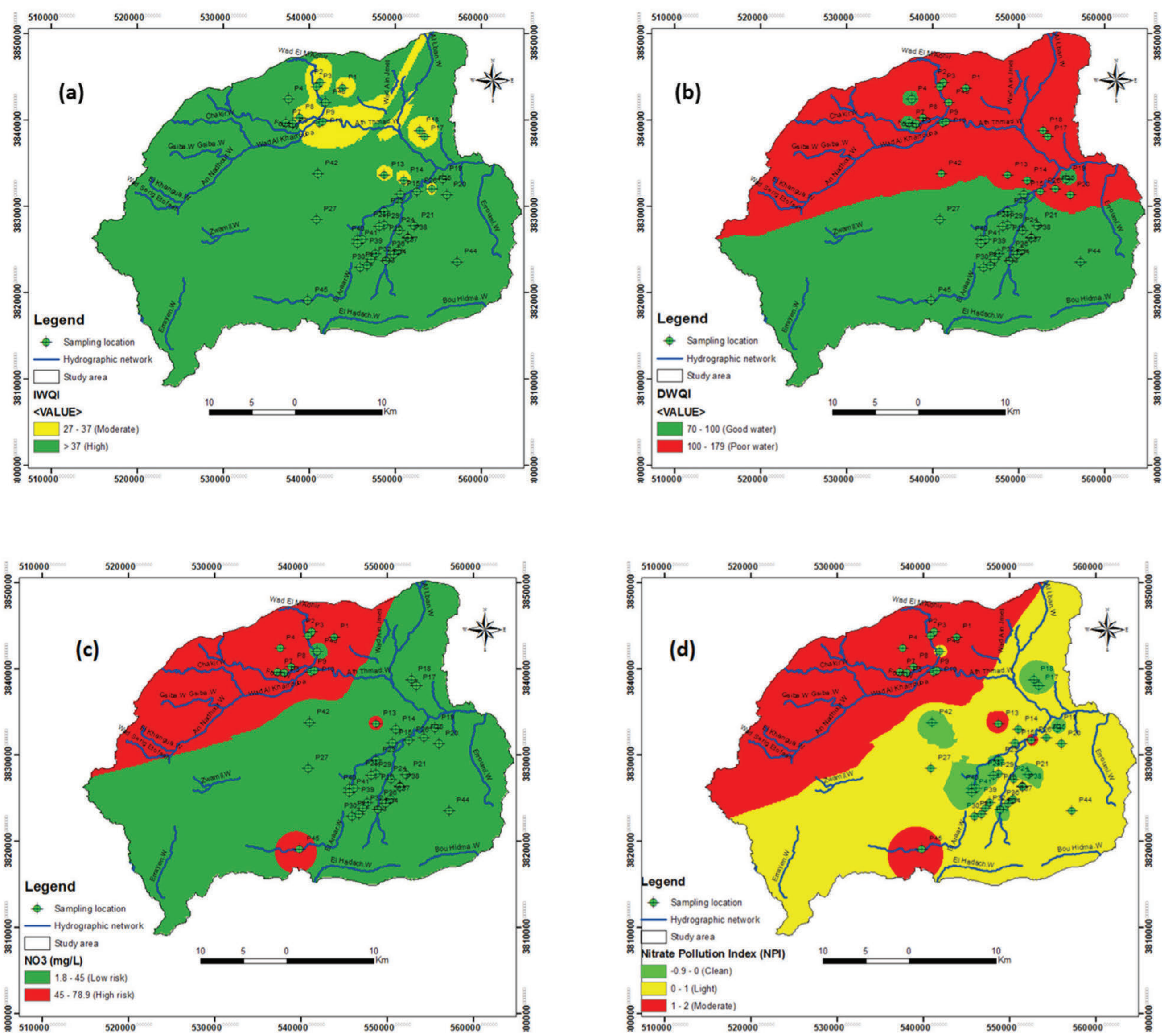

Fig. 10 - Spatial distribution maps of groundwater quality indices in the Meknassy Basin: (a) IWQI, (b) DWQI, (c) Nitrate concentration (NO_3), and (d) NPI classification for groundwater.

Fig. 10 - Carte di distribuzione spaziale degli indici di qualità delle acque sotterranee nel bacino di Meknassy: (a) IWQI, (b) DWQI, (c) concentrazione di nitrati (NO_3) e (d) classificazione NPI per le acque sotterranee.

Nitrate contamination in groundwater

In the present study, NO_3 levels in groundwater ranged from 1.8 to 79 mg/L, averaging 35.76 mg/L (Fig. 10c). Only 27% of samples exceeded the WHO-recommended limit of 50 mg/L (WHO, 2017).

Nitrate Pollution Index (NPI)

The NPI evaluates nitrate pollution in groundwater, with values ranging from -0.909 to 2.945 and an average of 0.787 (Table 6). The northwestern part shows moderate nitrate pollution, covering 38% of the area (Fig. 10d). Approximately 22.22% of samples are classified as clean, 51.11% with light pollution, and 26.67% as moderately polluted due to high nitrate levels (Table 6).

Tab. 6 - The NPI classification of groundwater.

Tab. 6 - Classificazione NPI delle acque sotterranee.

NPI	Type of pollution	N samples	Percentages
< 0	Clean	10	22.22%
0 – 1	Light	23	51.11%
1 – 2	Moderate	12	26.67%
2 – 3	Signficant	-	-
> 3	Very significant	-	-

Risk assessment for human health

High NO_3 concentrations can convert to nitrite in the body, posing serious health risks, especially for children (Adimalla, 2019). As was mentioned in the preceding NPI discussion, roughly 27% of the samples were polluted due to high nitrate contents in the groundwater. Therefore, assessing the noncarcinogenic health risk assessment in the research domain is crucial. Infact, the Hazard Quotient (HQ) serve as a key tool for assessing potential dangers associated with nitrate in various age groups and demographics (children, adults, women, and men) (Table 7). In terms of HQ oral values, the averages recorded for children, adults, women, and men were of 1.79, 1.165, 1.015 and 0.859, respectively. While ‘adults’ represent an overall estimate for the population, separate calculations were conducted for men and women to account for physiological differences (e.g., body weight, different exposure levels) that may influence nitrate metabolism and risk assessment. One (1) should be the maximum permissible figure for noncarcinogenic risk. In fact, HQnitrate < 1 denotes a level of noncarcinogenicity that is acceptable, while HQnitrate > 1 denotes a possible risk to health. With reference to Table 7, the proportions of sample sites with HQ values surpassing this permissible value for children, adults, women, and men, are 75.6%, 35.6%, 33.3%, and 24.4%, respectively.

Based on spatial analysis, the percentages (95%, 41%, 45%, and 34%) refer to the proportion of groundwater sampling locations where HQ values exceed the threshold, rather than the proportion of the total population affected (Fig. 11). A more precise assessment of the exposed population would require detailed demographic data, which is beyond the scope of this study. However, the spatial distribution of high HQ values suggests that a considerable number of individuals relying on groundwater may be at risk.

Tab. 7 - The hazard quotient assessment per children, adults, women and men.

Tab. 7 - Valutazione del quoziente di rischio per bambini, adulti, donne e uomini.

	HQ < 1	HQ > 1
HQ_Children	24.4%	75.6%
HQ_Adults	64.4%	35.6%
HQ_Women	66.7%	33.3%
HQ_Men	75.6%	24.4%

Given these findings, a significant portion of the studied groundwater is deemed hazardous for consumption, particularly for young children, whose lower body weight makes them more vulnerable to non-carcinogenic health risks than adults.

Discussion

The obtained results indicate that the suitability of groundwater for domestic and agricultural uses is significantly influenced by soil salinization and the impacts of excessive irrigation. Soil salinization, observed in several studied areas, can compromise both water quality and agricultural productivity, a phenomenon well-documented in the scientific literature (Kumar et al., 2019; Kim et al., 2019; Qadir et al., 2021; Stavi et al., 2021). In comparison with previous studies, our findings reveal similar trends in soil salinity, while highlighting specific nuances related to the study area. These elements confirm that water resources management in Tunisia, and more generally in Mediterranean regions, requires more targeted strategies face to intensive irrigation (Mzid et al., 2024).

The implications of salinization for public health and the sustainability of agricultural systems are concerning, as saline water affects the quality of drinking water and can pose health risks to local populations (Miller & Hutchins, 2017). Comparing with previous research, although several management solutions have been proposed, it is crucial to integrate strategies that focus on the rational use of water resources, particularly in areas vulnerable to excessive irrigation (Amanullah et al., 2020).

Obtained results suggest that current water management approaches could be strengthened by a better understanding of the factors contributing to salinization, particularly by considering local climatic conditions and agricultural practices (Mheni et al., 2024). However, it is important to note that our study has some limitations, particularly the geographical scope of the collected data and the lack of certain critical climatic variables. These limitations lead to developp future research, which should focus on expanding the geographical scope of the study and integrating new parameters, such as seasonal variations in groundwater levels and the long-term impacts of climate change (Agbasi et al., 2023).

In conclusion, this study highlights the importance of integrated water resource management adapted to local

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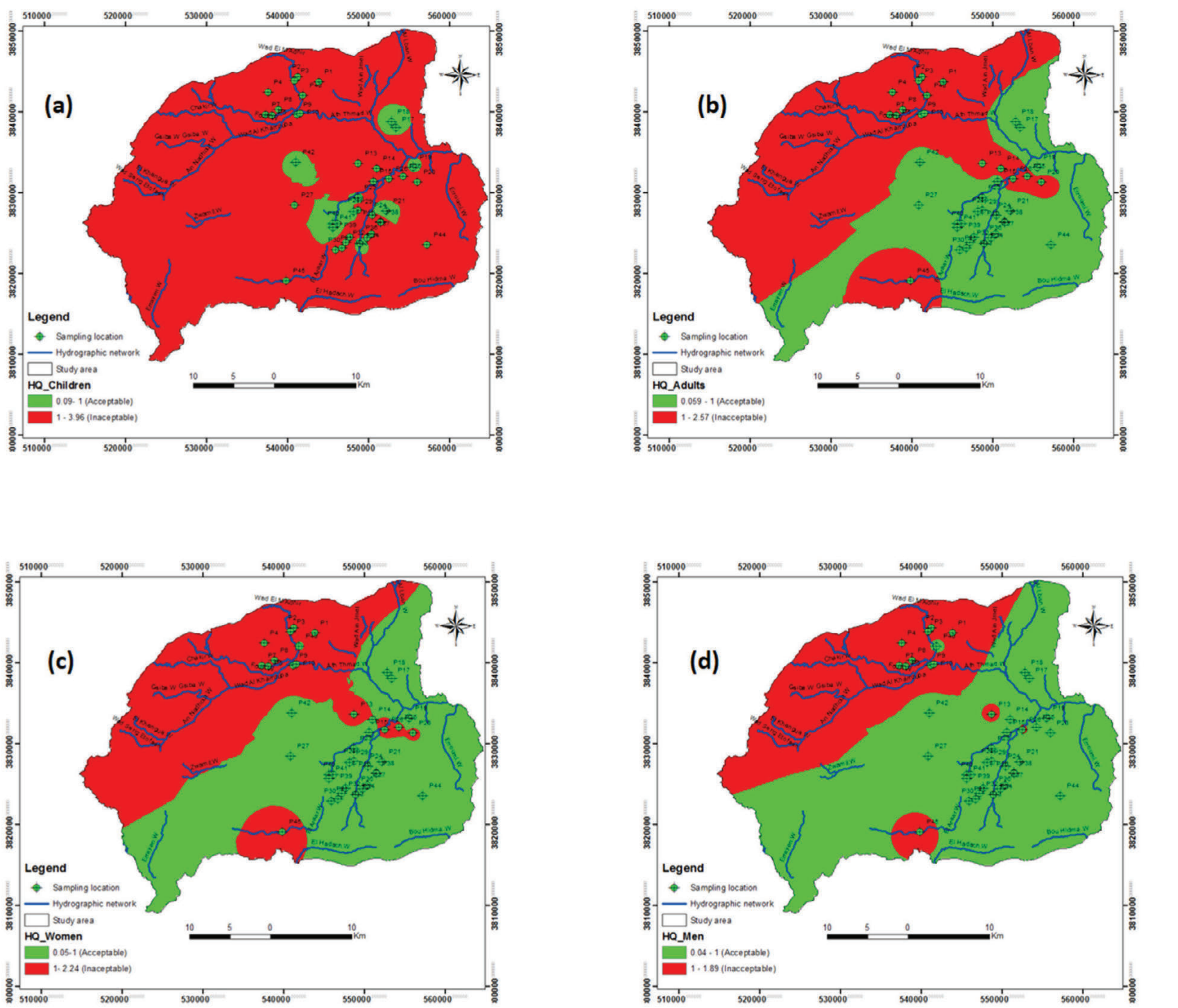

Fig. 11 - MenHazard quotient (HQ) assessment for different population groups in the study area: (a) HQ for Children; (b) HQ for Adults; (c) HQ for Women; and (d) HQ for Men.

Fig. 11 - Valutazione del quoziente di rischio (HQ) per diversi gruppi di popolazione nell'area di studio: (a) HQ per bambini; (b) HQ per adulti; (c) HQ per donne; e (d) HQ per uomini.

specifics in order to prevent risks related to water degradation and ensure the long-term sustainability of water resources.

Conclusions

Groundwater quality is crucial for health and development in Central Tunisia, serving as a key resource for domestic and agricultural use. This study assessed groundwater quality and its contamination from human activities. Physicochemical analyses indicate that the water is moderately alkaline and brackish, with total dissolved solids (TDS) ranging from 880 mg/L to 6090 mg/L (average: 2110 mg/L). Geochemical modeling shows a predominant sulfate-chloride-mixed water type with Mg^{2+} enrichment. Analysis identified three clusters of water boreholes based on chemical composition, reflecting both natural processes and contamination from agricultural practices. PCA revealed that two key factors explain over 84.54% of groundwater quality variability, indicating risks of water degradation and sodic conditions.

The computed IWQI indicated that approximately 92% of the area falls into the high-quality category for agricultural use, while the remaining 8% is of medium quality. Similarly, the DWQI classification identified two categories for drinking water: good and poor. About 53% of the area has water suitable for human consumption, whereas 47% falls into the poor-quality category. This apparent discrepancy arises from the different parameters prioritized in each index: the IWQI focuses on salinity and other factors affecting crop production, while the DWQI is concerned with parameters directly linked to human health.

The Nitrate Pollution Index (NPI) indicates that 38% of the area needs regular monitoring due to risks from waste disposal and fertilizer use. Hazard Quotient (HQ) analysis reveals that 75.6% of samples exceed safe limits for children, with significant contamination also noted for adults, women, and men. These findings highlight both the positive and negative aspects of groundwater quality and its vulnerability to contamination, especially for vulnerable populations like children.

These results offer a comprehensive assessment of groundwater quality and its associated risks. The IWQI and DWQI maps, along with the NPI and HQ analysis, can help in land-use planning, groundwater management, and quality monitoring in the Maknessy Basin.

The findings of this study emphasize the importance of continuous monitoring, informed decision-making, and the implementation of effective water management practices to safeguard both groundwater quality and public health in the Maknessy Basin.

Author contributions

Conceptualization: Zouhour MOUSSAOUI and Fatma BEN BRAHIM; Methodology: Zouhour MOUSSAOUI and Fatma BEN BRAHIM; Formal analysis and investigation: Naima HIDOURI and Mongi HAMDI; Writing original draft preparation: Zouhour MOUSSAOUI and Fatma BEN BRAHIM; Funding acquisition: Not applicable; Resources: Not applicable; Supervision: Salem Bouri and Hamed YOUNES. All authors read and approved the final manuscript.

Data Availability Statement

All datasets generated or analyzed during this study are included in this article and its supplementary information files.

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The authors declare that the funders had no role in the design of the study, in the collection, analyses, or interpretation of the data, in the writing of the manuscript; or in the decision to publish the results. This study was conducted without funding.

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary material

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Additional information

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REFERENCES

Adimalla, N. (2019). Spatial distribution, exposure, and potential health risk assessment from nitrate in drinking water from semi-arid region of South India. Human and Ecological Risk Assessment: An International Journal. https:// doi.org/10.1080/10807039.2018.1 508329.

Adimalla, N., & Qian, H. (2019). Groundwater quality evaluation using water quality index (WQI) for drinking purposes and human health risk (HHR) assessment in an agricultural region of Nanganur, south India. Ecotoxicology and Environmental Safety, 176, 153–161. https://doi.org/10. 1016/j.ecoenv.2019.03.066.

Adimalla, N., Qian, H., & Li, P. (2019). Entropy water quality index and probabilistic health risk assessment from geochemistry of groundwaters in hard rock terrain of Nanganur County, South India. Geochemistry. https://doi.org/10. 1016/j.chemer.2019.125544.

Adimalla, N., & Venkatayogi, S. (2018). Geochemical characterization and evaluation of groundwater suitability for domestic and agricultural utility in semi-arid region of Basara, Telangana State, South India. Applied Water Science. https://doi.org/10.1007/s13201-018-0682-1.

Adimalla, N., & Wu, J. (2019). Groundwater quality and associated health risks in a semi-arid region of south India: Implication to sustainable groundwater management. Human and Ecological Risk Assessment: An International Journal. https://doi.org/10.1080/10807039.2018.154655.

Agbasi, J. C., Egbueri, J. C., Ayejoto, D. A., Unigwe, C. O., Omeka, M. E., Nwazelibe, V. E., Ighalo, J.O., Januraga, P.P., Fakoya, A. A. (2023). The impact of seasonal changes on the trends of physicochemical, heavy metal and microbial loads in water resources of Southeastern Nigeria: a critical review. Climate change impacts on Nigeria: environment and sustainable development, 505-539. DOI: 10.1007/978-3-031-21007-5_25

Agoubi, B., Kharroubi, A., Bouri, S., & Abida, H. (2010). Contribution of geostatistical modelling to mapping groundwater level and aquifer geometry: Case study of Sfax's deep aquifer, Tunisia. Middle East Journal of Scientific Research, 6(3), 305–316.

Amanullah, Khalid, S., Imran, Khan, H. A., Arif, M., Altawaha, A. R., ... & Parmar, B. (2020). Effects of climate change on irrigation water quality. Environment, climate, plant and vegetation growth, 123-132.

Ahada, C. P. S., & Suthar, S. (2018). Groundwater nitrate contamination and associated human health risk assessment in southern districts of Punjab, India. Environmental Science and Pollution Research. https://doi.org/10.1007/s11356- 018-2581-2.

Ahmadi, S.H. and Sedghamiz, A. (2008) Application and Evaluation of Kriging and Cokriging Methods on Groundwater Depth Mapping. Environmental Monitoring and Assessment, 138, 357-368.
https://doi.org/10.1007/s10661-007-9803-2

Akber, M. A., Islam, M. A., Dutta, M., Billah, S. M., & Islam, M. A. (2020). Nitrate contamination of water in dug wells and associated health risks of rural communities in southwest Bangladesh. Environmental Monitoring and Assessment. https://doi.org/10.1007/s10661-020-8128-2.

Ayed, B., Jmal, I., Sahal, S., Mokadem, N., Saidi, S., Boughariou, E., & Bouri, S. (2017). Hydrochemical characterization of groundwater using multivariate statistical analysis: the Maritime Djeffara shallow aquifer (Southeastern Tunisia). Environmental Earth Sciences. https:// doi.org/10.1007/s12665-017-7168-6.

Ayers, R. S. (1977). Quality of water for irrigation. Journal of Irrigation and Drainage Div. ASCE, 103(IR2), 135–154.

Ayers, R. S., & Westcot, D. W. (1985). Water quality for agriculture (Vol. 29). Rome: Food and Agriculture Organization of the United Nations. http://www.fao.org/3/ T0234E/T0234E00.htm#TOC.

Ben Brahim, F., Khanfir, H., & Bouri, S. (2012). Groundwater vulnerability and risk mapping of the Northern Sfax Aquifer, Tunisia. Arabian Journal for Science and Engineering, 37(5), 1405-1421. DOI 10.1007/s13369-012-0261-y.

Ben Brahim F., Boughariou E., Bouri S. (2021) Multicriteria-analysis of deep groundwater quality using WQI and fuzzy logic tool in GIS: A case study of Kebilli region, SW Tunisia. Journal of African Earth Sciences, 180, 104224.https://doi.org/10.1016/j.jafrearsci.2021.104224

Ben Brahim F., Msaddki H., Bouri S. (2022a) Groundwater quality index mapping for irrigation purposes in the "El Hezma-El Hmila" (Medenine, Tunisia). CLEAN-Soil, Air, Water Journa. lhttps://doi.wiley.com/10.1002/clen.202100203

Ben Brahim F., Boughariou E, Hajji S., Bouri S. (2022b). Assessment of groundwater quality with Analytic Hierarchy Process, Boolean Logic and Clustering Analysis using GIS platform in the Kebilli's Complex Terminal groundwater, SW Tunisia Environmental Earth Sciences Journal.https://doi.org/10.1007/s12665-022-10541-3

Ben Brahim, F., Rhayma Z., Bouri, S. (2023). Application of Geospatial Multicriteria-Decision Analysis in the Evaluation of Groundwater Quality for Irrigation in the Northern sector of Gabes region (SE-Tunisia) Chapter in Groundwater Book of Arid and Semi-Arid Regions pp 131-157: Contaminants, Management and Options of Safe Water Supply. https://link.springer.com/book/9783031433474

Boughariou, E., Allouche, N., Jmal, I., Mokadem, N., Ayed, B., Hajji, S., Khanfir, H. & Bouri, S. (2018). Modeling aquifer behaviour under climate change and high consumption: Case study of the Sfax region, southeast Tunisia. Journal of African Earth Sciences, 141, 118-129.

Chen, J., Wu, H., Qian, H., & Gao, Y. (2017). Assessing nitrate and fluoride contaminants in drinking water and their health risk of rural residents living in a semiarid region of Northwest China. Expo Health, 9, 183–195. https://doi.org/ 10.1007/s12403-016-0231-9.

Doneen, L. D. (1964). Notes on water quality in agriculture (p. 48). University of California, Davis.

Egbueri, J. C., Ezugwu, C. K., Ameh, P. D., Unigwe, C. O., & Ayejoto, D. A. (2020). Appraising drinking water quality in Ikem rural area (Nigeria) based on chemometrics and multiple indexical methods. Environmental Monitoring and Assessment, 192, 308. https://doi.org/10.1007/s10661- 020-08277-3.

Egbueri, J. C., Mgbenu, C. N., & Chukwu, C. N. (2019). Investigating the hydrogeochemical processes and quality of water resources in Ojoto and environs using integrated classical methods. Modeling Earth Systems and Environment. https://doi.org/10.1007/s40808-019-00613-y.

Exner, M. E., A. J. Hirsh, and R. F. Spalding (2014). Nebraska's groundwater legacy: Nitrate contamination beneath irrigated cropland, WaterResour.Res., 50,4474–4489, doi:10.1002/2013WR015073.

Fekkoul, A., Zarhloule, Y., Boughriba, M., Barkaoui, A. E., Jilali, A., & Bouri, S. (2013). Impact of anthropogenic activities on the groundwater resources of the unconfined aquifer of Triffa plain (Eastern Morocco). Arabian Journal of Geosciences, 6, 4917-4924.

Gaaloul, N., Pliakas, F., Kallioras, A., Schuth, C., & Marinos, P. (2012). Simulation of seawater intrusion in coastal aquifers: Forty five-years exploitation in an eastern coast aquifer in NE Tunisia. The Open Hydrology Journal, 6(1). DOI: 10.2174/1874378101206010031

Gangolli, S. D., Van den Brandt, P. A., Feron, V. J., Janzowsky, C., Koeman, J. H., Speijers, G. J., Spiegelhalder, B., Walker, R., & Wishnok, J. S. (1994). Nitrate, nitrite and N-nitroso compounds. European Journal of Pharmacology: Environmental Toxicology and Pharmacology, 292(1), 1–38. https://doi.org/10.1016/0926-6917(94)90022-1.

Mzid, Nada, and Olfa Boussadia (2024). Challenges for Sustainable Water Resource Management: Irrigation and Salinity. The Olive Landscapes of the Mediterranean. Springer, Cham, 2024. 405-412.

Gupta, S. K., Gupta, R. C., Gupta, A. B., Seth, A. K., Bassin, J. K., & Gupta, A. (2000). Recurrent acute respiratory tract infections in areas with high nitrate concentrations in drinking water. Environmental Health Perspectives, 108(4), 363–366. https://doi.org/10.1289/ehp.00108363.

Horton, R. (1965). An index number system for rating water quality. J Water Pollut Control Fed 37:300–306

ICMR (Indian Council of Medical Research) Expert Group. (1990). Nutrient Requirements and Recommended Dietary Allowances for Indians: A Report of the Expert Group of the Indian Council of Medical Research.

IRIS (Integrated Risk Information System, US EPA). (2012). Nitrate (CASRN 14797–55–8). http://www.epa.gov/iris/ subst/0076.htm.

Karakus¸, C. B., & Yıldız, S. (2019). Evaluation for irrigation water purposes of groundwater quality in the vicinity of Sivas City centre (Turkey) by using Gis and an irrigation water quality index. Irrigation and Drainage. https://doi. org/10.1002/ird.2386.

Kelly, W. P. (1951). Alkali Soils: Their Formation, Properties and Reclamation. New York, Reinhold, 176. Science, 114(2969), 558. https://doi.org/10.1126/science.114.2969. 558.

Kim, H., Yu, S., Oh, J., Kim, K., Lee, J., Moniruzzaman, M., Kim, H. K., & Yun, S. (2019). Nitrate contamination and subsequent hydrogeochemical processes of shallow groundwater in agro-livestock farming districts in South Korea. Agriculture, Ecosystems & Environment, 273, 50–61. https://doi.org/10.1016/j.agee.2018.12.010

Kumar, D., Singh, A., Jha, R. K., Sahoo, B. B., Sahoo, S. K., & Jha, V. (2019). Source characterization and human health risk assessment of nitrate in groundwater of middle Gangetic Plain India. Arabian Journal of Geosciences, 12(11), 339. https://doi.org/10.1007/s12517-019-4519-5.

Li, P., Li, X., Meng, X., Li, M., & Zhang, Y. (2016). Appraising groundwater quality and health risks from contamination in a semiarid region of Northwest China. Exposure and Health, 8(3), 361–379. https://doi.org/10.1007/s12403- 016-0205-y.

Makni, J., Bouri, S., & Ben Dhia, H. (2013). Hydrochemistry and geothermometry of thermal groundwater of southeastern Tunisia (Gabes region). Arabian Journal of Geosciences, 6, 2673-2683. https://doi.org/10.1007/s12517-011-0510-5

Mhamdi, A., Gouasmia, M., Gasmi, M., Bouri, S., & Dhia, H. B. (2006). Évaluation de la qualité de l'eau par application de la méthode géoélectrique: exemple de la plaine d'El Mida–Gabes nord (Sud tunisien). Comptes rendus. Géoscience, 338(16), 1228-1239. https://doi.org/10.1016/j.crte.2006.09.005.

Meireles, A. C. M., Andrade, E. M., Chaves, L. C. G., Frischkorn, H., & Crisostomo, L. A. (2010). A new proposal of the classification of irrigation water. Revista Ciencia Agronomica, 41(3), 349–357. https://doi.org/10.1590/ S1806669020100003000005.

Miller, J. D., & Hutchins, M. (2017). The impacts of urbanization and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom. Journal of Hydrology: Regional Studies, 12, 345-362. https://doi.org/10.1016/j.ejrh.2017.06.006

Moussaoui, Z., Gentilucci, M., Wederni, K.; Hidouri, N., Hamdi, M., Dhaoui, Z., Hamed, Y. (2023). Hydrogeochemical and Stable Isotope Data of the Groundwater of a Multi-Aquifer System in the Maknessy Basin (Mediterranean Area, Central Tunisia). Hydrology 2023, 10, 32. https://doi.org/10.3390/ hydrology10020032

Mheni, N. T., Kilasi, N., Quiloy, F. A., Heredia, M. C., Bilaro, A., Meliyo, J., Dixit, S., Nchimbi Msolla, S. (2024). Breeding rice for salinity tolerance and salt-affected soils in Africa: a review. Cogent Food & Agriculture. https://doi.org/10.1080/23311932.2024.2327666

Narsimha, A., & Sudarshan, V. (2016). Contamination of fluoride in groundwater and its effect on human health: A case study in hard rock aquifers of Siddipet, Telangana State India. Applied Water Science, 7(5), 2501–2512. https://doi. org/10.1007/s13201-016-0441-0.

NT: Norme tunisienne NT 09–14, relative a` la qualite des eaux de boisson (2013).

Nsiri, M., Ben Brahim, F., Khlifi, M., Bouri S. (2021). Assessment of the effects of anthropogenic activities on the El Arich groundwater using hydrogeochemistry, GIS and multivariate statistical techniques: a case study of the semi-arid Kasserine region, Tunisia. Environmental Quality Management Journal. http://dx.doi.org/10.1002/tqem.21810

Ouda B., (2000). Paléohydrologie isotopique du bassin de Maknassy (Tunisie centrale) pendant le Quaternaire récent. Thèse de Doctorat, Faculté des Sciences de Tunis, 234p.

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). Human and Ecological Risk Assessment: An International Journal. https://doi.org/10.1080/10807039.2020.1833300.

Qadir, M., Sposito, G., Smith, C. J., & Oster, J. D. (2021). Reassessing irrigation water quality guidelines for sodicity hazard. Agricultural Water Management, 255, 107054. https://doi.org/10.1016/j.agwat.2021.107054

Richards, L. A. (1954). (US Salinity Laboratory) Diagnosis and improvement of saline and alkaline soils, US Department of Agriculture hand book.

Sadler, R., Maetam, B., Edokpolo, B., Connell, D., Yu, J., Stewart, D., Park, M. J., Gray, D., & Laksono, B. (2016). Health risk assessment for exposure to nitrate in drinking water from village wells in Semarang Indonesia. Environmental Pollution, 216(738), 745. https://doi.org/10. 1016/j.envpol.2016.06.041.

Sahu, P., & Sikdar, P. K. (2007). Hydrochemical framework of the aquifer in and around East Kolkata Wetlands, West Bengal India. Environmental Geology, 55(4), 823–835. https://doi.org/10.1007/s00254-007-1034-x.

Simsek, C., & Gunduz, O. (2007). IWQ index: A GIS-integrated technique to assess irrigation water quality. Environmental Monitoring and Assessment, 128(1–3), 277–300. https:// doi.org/10.1007/s10661-006-9312-8.

Spalding, R. F., & Exner, M. E. (1993). Occurrence of nitrate in groundwater. Environment Quality., 22(3), 392. https://doi.org/10.2134/jeq1993.00472425002200030002x.

Stavi, I., Thevs, N., & Priori, S. (2021). Soil salinity and sodicity in drylands: A review of causes, effects, monitoring, and restoration measures. Frontiers in Environmental Science, 9, 712831.

Szabolcs, I., Darab, C. (1964). The influence of irrigation water of high sodium carbonate content of soils. In Proceedings of 8th international congress of ISSS, Trans, 803–812.

US Environmental Protection Agency (USEPA). (2001). Baseline Human Health Risk Assessment Vasquez Boulevard and I-70 Superfund Site. Denver CO.

USEPA (United States Environmental Protection Agency). (1989). Superfund Public Health Evaluation Manual. Washington, DC.

USEPA (US Environmental Protection Agency). (1991). Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual (Part B, Development of RiskBased Preliminary Remediation Goals). http://epa-prgs. ornl.gov/radionuclides/HHEMB.

Vasanthavigar, M., Srinivasamoorthy, K., Vijayaragavan, K., Rajiv Ganthi, R., Chidambaram, S., Anandhan, P., Manivannan, R., & Vasudevan, S. (2010). Application of water quality index for groundwater quality assessment: Thirumanimuttar sub-basin, Tamilnadu India. Environmental Monitoring and Assessment, 171, 595–609. https://doi.org/ 10.1007/s10661-009-1302-1.

Vetrimurugan, E., Brindha, K., Elango, L., & Ndwandwe, O. M. (2017). Human exposure risk to heavy metals through groundwater used for drinking in an intensively irrigated river delta. Applied Water Science, 7(6), 3267–3280.

Wagh, V. M., Panaskar, D. B., Mukate, S. V., Aamalawar, M. L., & Laxman Sahu, U. (2019). Nitrate associated health risks from groundwater of Kadava River Basin Nashik, Maharashtra, India. Human and Ecological Risk Assessment: An International Journal. https://doi.org/10.1080/ 10807039.2018.1528861.

WHO. (2017). Guidelines for drinking-water quality. In Incorporating the first addendum (4th., pp. 38). WHO chronicle.

Wilcox, L. V. (1955). Classification and use of irrigation waters. USDA Circular No. 969. Washington, DC, 19.

World Bank (2022). Tunisia Country Climate and Development Report. Available at: https://www.banquemondiale.org/fr/country/tunisia/publication/tunisia-country-climate-and-development-report.

Wu, J., & Sun, Z. (2016). Evaluation of shallow groundwater contamination and associated human health risk in an alluvial plain impacted by agricultural and industrial activities, mid-west China. Expo Health, 8(3), 311–329. https://doi.org/10.1007/s12403-015-0170-x.

Wu, J., Zhang, Y., & Zhou, H. (2020). Groundwater chemistry and groundwater quality index incorporating health risk weighting in Dingbian County, Ordos basin of northwest China. Geochemistry. https://doi.org/10.1016/j.chemer. 2020.125607.

Yidana, S.M., Yakubo, B.B. and Akabzaa, T.M. (2010). Analysis of Groundwater Quality Using Multivariate and Spatial Analyses in the Keta Basin, Ghana. Journal of African Earth Sciences, 58, 220-234.

https://doi.org/10.1016/j.jafrearsci.2010.03.003

Yidana, S. M., & Yidana, A. (2010). Assessing water quality using water quality index and multivariate analysis. Environmental Earth Science, 59, 1461–1473. https://doi.org/10.1007/s12665-009-0132-3

Yu, G., Wang, J., Liu, L., Li, Y., Zhang, Y., & Wang, S. (2020). The analysis of groundwater nitrate pollution and health risk assessment in rural areas of Yantai China. BMC Public Health, 20, 437. https://doi.org/10.1186/s12889-020- 08583-y.

Zhang, H. (2008). Nitrate Contamination of Groundwater in Southern Hebei Plain and its Health Risk Assessment. Institute of Geographical Sciences and Natural Resources Research, Hebei.

Zhang, Q., Xu, P., & Qian, H. (2020). Groundwater quality assessment using improved water quality index (WQI) and human health risk (HHR) evaluation in a semi-arid region of Northwest China. Exposure and Health. https://doi.org/ 10.1007/s12403-020-00345-w.

Zouaghi, T., Bédir, M., Melki, F., Gabtni, H., Gharsalli, R., Bessioud, A., & Zargouni, F. (2011). Neogene sediment deformations and tectonic features of northeastern Tunisia: evidence for paleoseismicity. Arabian Journal of Geosciences, 4(7), 1301.