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Application of an integrated GIS-AHP water quality index to evaluate the groundwater suitability for irrigation in a coastal aquifer in northeastern Algeria

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Abstract

Groundwater in coastal regions worldwide is an essential resource for irrigation, but its quality is increasingly compromised by natural salinization and human activities. In the Collo Plain (northeastern Algeria), existing studies are scattered and lack a comprehensive spatial assessment framework. This study is the first to integrate hydrochemical analysis, Geographic Information Systems (GIS), remote sensing, and the Analytical Hierarchy Process (AHP) to compute a weighted Irrigation Water Quality Index (IWQI) and evaluate groundwater suitability for irrigation. Thirty groundwater samples were analyzed for major physicochemical parameters, and geostatistical interpolation mapped the spatial distribution of irrigation water quality. Groundwater pH ranged from 6.90 to 7.90, while electrical conductivity varied between 1356 and 3388 µS/cm. IWQI values ranged from 35.5 to 87.9, with a mean of 56.8 ± 14.7. Approximately 30% of the Collo Plain exhibited good irrigation water quality, 56.7% was classified as poor, and 13.3% as very poor. The northeastern sector, particularly near Ouled Mazzouz, showed the greatest degradation, driven by paleomarine transgressions, geogenic factors, agricultural practices, and untreated domestic effluents. This study advances irrigation water quality assessment by demonstrating the robustness of a GIS–AHP–IWQI framework. The resulting maps provide practical decision-support tools for farmers and water managers, enabling improved irrigation planning, targeted monitoring, and sustainable groundwater management in coastal agricultural plains.

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1. Introduction

Globally, over 1.2 billion people rely on groundwater increasingly threatened by salinization, nitrate enrichment, and heavy metals [1,2]. These pressures, driven by geogenic processes and anthropogenic activities, compromise irrigation suitability and food security [3,4]. Traditional assessments based on single parameters such as EC or SAR fail to capture cumulative effects, prompting the development of Water Quality Indices (WQIs) [5]. The Irrigation Water Quality Index (IWQI), enhanced through multi-criteria decision-making frameworks like the Analytical Hierarchy Process (AHP), allows parameter weighting based on agronomic relevance [6]. When integrated with Geographic Information Systems (GIS), IWQI provides spatially explicit insights into groundwater quality [7,8]. Despite successful applications in coastal aquifers worldwide, Algeria lacks such integrated assessments. This study addresses that gap by applying a GIS–AHP weighted IWQI to the Collo Plain, northeastern Algeria, aiming to (i) characterize groundwater physicochemistry, (ii) determine parameter importance via AHP, and (iii) map irrigation suitability. By linking hydrogeochemical data with spatial analysis, the study contributes to regional water management and global groundwater sustainability.

The United Nations' Sustainable Development Goals (SDGs) emphasize sustainable management of natural resources, with SDG 6 specifically aiming to ensure the availability and quality of water resources. Groundwater, as a critical source for irrigation, plays a central role in achieving SDG 2 (Zero Hunger) and SDG 15 (Life on Land) [9]. Globally, over 1.2 billion people rely on groundwater that is increasingly threatened by chemical contamination, including salinization, nitrate enrichment, and heavy metal intrusion [1,2,10]. These pressures, which result from both natural geogenic processes and anthropogenic activities such as agricultural drainage, untreated wastewater, and industrial effluents, compromise the suitability of groundwater for agriculture and human consumption [3,4,11–13]. The use of poor-quality irrigation water can degrade soils, alter plant physiological processes and ultimately reduce crop productivity [14–16].

Assessing irrigation water quality is traditionally based on individual physicochemical parameters such as electrical conductivity (EC), sodium adsorption ratio (SAR), and %Na, which may not fully capture the combined effects of multiple contaminants [17,18]. To address these limitations, Water Quality Indices (WQIs) have been developed, integrating multiple parameters into a single, dimensionless score that enables standardized evaluation of water suitability for specific uses [5,14]. Specifically, the Irrigation Water Quality Index (IWQI) accounts for the synergistic or antagonistic interactions among various chemical constituents and their potential impacts on soil health and crop productivity [19–21].

Recent advancements have enhanced the diagnostic precision of IWQIs through multi-criteria decision-making (MCDM) frameworks, notably the Analytical Hierarchy Process (AHP), which assigns parameter-specific weights reflecting their relative influence on irrigation suitability [6,22,23]. This weighted approach ensures a more accurate and nuanced assessment than traditional, unweighted indices parameters [24–26]. When combined with Geographic Information Systems (GIS), these approaches enable the spatial mapping of water quality, facilitating the identification of critical zones and guiding sustainable management strategies [36,55,65,76]. Recent GIS-based IWQI applications across Asia and Africa [7,8] demonstrate the method's robustness, yet Algerian contexts remain underexplored. Applications of AHP-GIS weighted IWQI frameworks have proven effective in diverse hydrogeological contexts, including coastal and semi-arid regions, yet remain underexplored in Algeria [22,43]. AHP was selected for its ability to incorporate expert judgment into parameter weighting, while GIS enables spatial visualization, together providing a more robust assessment than conventional unweighted indices.

The Collo Plain in Northeast Algeria is heavily reliant on groundwater for irrigated agriculture, making it particularly vulnerable to water quality degradation [21,27,39]. While hydrogeochemical investigations and conventional WQI assessments have been conducted in this region [28,58], no integrated spatial analysis using an AHP-weighted IWQI exists, leaving a critical gap in the assessment of irrigation suitability. By synthesizing physicochemical data, weighted IWQI computation, and GIS-based mapping, the present study provides a novel, spatially explicit evaluation of groundwater quality for agriculture in the Collo Plain, offering a model applicable to other similar semi-arid coastal regions. Therefore, the present study aims: (i) to characterize the physicochemical properties of groundwater in the Collo Plain; (ii) to determine the relative importance of key irrigation quality parameters using the AHP framework; and (iii) to compute the IWQI for each sampling site and generate its spatial distribution via GIS to delineate areas of varying irrigation suitability.

By integrating hydrogeochemical assessment with spatially weighted assessment, this study addresses regional water management needs while contributing to global groundwater sustainability, thereby providing a transferable methodology for regions facing comparable environmental challenges.

2. Materials and methods

2.1. Description of the study area

The study area is located in the western region of Skikda province, northeastern Algeria, encompassing the downstream part of the Wadi Guebli watershed. The Collo Plain, which forms the focus of this investigation, exhibits an elongated quadrilateral morphology, approximately 8 km long and 5 km wide along the Mediterranean coast (Fig 1). The climate of the area is classified as humid Mediterranean (Csa) according to the Köppen-Geiger system, characterized by hot, dry summers and mild, wet winters. Meteorological records indicate an average annual precipitation of 813 mm and temperature fluctuations ranging from 6°C in winter to 38°C in summer, with a potential evapotranspiration of about 933 mm/year. Seasonal rainfall variability strongly influences surface water flow, groundwater recharge, and the transport of dissolved solutes and contaminants.

This hydrological system, mainly drained by the Guebli wadi and its tributaries, consists of intermittent watercourses that reflect the Mediterranean rainfall regime. These watercourses play a key role in aquifer recharge and strongly influence the spatial distribution of salinity and other hydrogeochemical characteristics in the plain.

In the Collo Plain, the vegetation consists mainly of Mediterranean scrub, scattered shrubs, and crops, which interact with irrigation practices and affect local soil and water dynamics. Human activities in the region are mainly agricultural, including cereal cultivation, citrus orchards, and vegetable farming, supplemented by small-scale livestock farming and rural settlements. Environmental sanitation infrastructure is limited and, in some areas, the discharge of untreated domestic wastewater poses localized risks of groundwater contamination.

Geologically, the plain is formed by sequences of late-Oligocene and early-Miocene deep marine flysch, including turbiditic shales, hemipelagic mudstones, massive sandstones, and conglomerates overlying Miopliocene dark-grey marls and quartzolite (flint) chunks, part of the Teleza coastal nappe [28–30]. The alluvial plain results from the filling of an ancient valley incised into rigid rock massifs (granite, gneiss, schist) and exhibits heterogeneous Mio-Pliocene marine sediments and Quaternary alluvium, with thicknesses ranging from 5 to 25 m. Surrounding lithologies include: (i) western intrusions of igneous rocks such as pegmatitic and porphyritic granites, microgranodiorites, and microdiorites, (ii) eastern

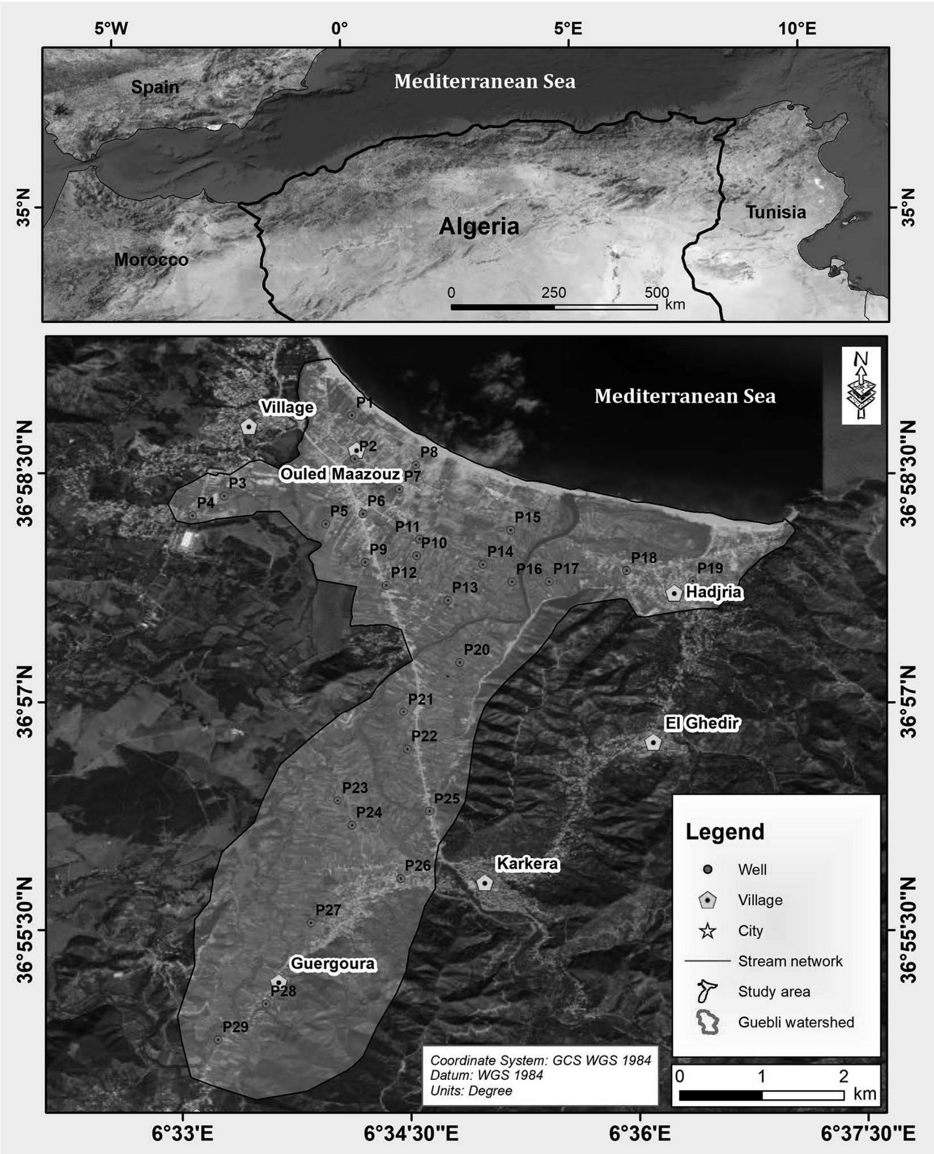

Fig 1. Geospatial distribution of goundwater sampling locations within the Collo plain.

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metamorphic formations (micaschists, banded gneisses, quartzites) in discordant contact with Oligo-Miocene Kabyle littoral sediments, (iii) localized central metamorphic outcrops, (iv) southern Oligocene molassic formations with algae-rich limestones, yellow clays, and dark grey marls, and (v) northern Quaternary sands and gravels with recent coastal dunes. The plain is underlain by Oligo-Miocene flysch and Mio-Pliocene marine sediments, with Quaternary alluvium up to 25 m thick. Surrounding lithologies include igneous intrusions, metamorphic formations, and molassic deposits, which influence aquifer heterogeneity.

Hydrogeologically, the aquifer system exhibits hydraulic conductivity values ranging from $2.6 \times 10^{+3}$ to 1.9×10^{-3} m/s, with lower values ($<10^{-5}$ m/s) in the southern plain. Groundwater flow generally moves from north to south in the western plain (hydraulic gradient ~6×10^{-3}) and from south to north in the eastern plain (hydraulic gradient ~1.8×10^{-3}) [31,69]. These hydrogeological characteristics strongly influence solute transport, salinization processes, and the suitability of groundwater for irrigation. These hydrogeological and climatic conditions are typical of Mediterranean coastal aquifers, where seasonal recharge variability and complex lithologies often exacerbate salinization and contamination risks.

2.2 Sampling protocol and analytical methodologies

A comprehensive hydrogeochemical survey was conducted in September 2022, encompassing 30 strategically distributed groundwater sampling sites across the Collo plain (Fig 1). Prior to sample acquisition, each well underwent a standardized purging protocol for 10–15 minutes to eliminate stagnant water and ensure the collection of representative aquifer sampling. Duplicate samples were collected in 100 mL polypropylene containers (Tarsons), with one aliquot acidified with HNO_3 to preserve cations. All samples were microfiltered (0.45 µm membrane) to remove suspended particulates and stored at 4°C until analysis.

In situ physicochemical parameters, including pH and electrical conductivity (EC), were measured immediately after sampling using a calibrated portable multiparameter probe (Oakton). The hydrogeochemical characterization involved the determination of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}, CO_3^{2-}) to assess water quality and classify groundwater types. Carbonate and bicarbonate concentrations were determined by potentiometric titration, while sulfate (SO_4^{2-}) was quantified spectrophotometrically using the barium sulfate turbidimetric method [32]. Major cations were analyzed by atomic absorption spectrometry (AA-6300 system) at the Algerian Water Laboratory (ADE).

Analytical quality assurance was performed through the calculation of ionic charge balance errors (% CBE) for all samples using Diagram Software (v6.72). The computed errors ranged from 2.26% to 4.1%, within the acceptable ±5% limit [33], confirming the reliability of the hydrogeochemical data. Groundwater sampling was conducted with the knowledge and approval of the National Water Resources Agency and the Collo Water Resources Subdivision. No specific permits were required, and no protected sites or private lands were accessed. Hydrochemical facies were determined using Piper diagrams, and stoichiometric equations describing key reactions are discussed in Section 4. All abbreviations (e.g., EC, SAR, CBE) are defined at first mention to ensure clarity.

2.3. Assessment of hydrochemical parameters for irrigation water suitability

Irrigation water quality significantly impacts crop productivity (e.g., cereals, vegetables) and soil salinity/alkalinity characteristics. Ensuring the utilization of water that provides essential nutrients (Ca^{2+}, Mg^{2+}, K^{+}) while being devoid of pathogenic and deleterious contaminants (Na^{+}, Cl^{-}, heavy metals) is imperative for achieving optimal crop yields and maintaining soil health. The evaluation of irrigation water suitability is critical, as excessive dissolved salts can impair soil permeability and crop yield [34]. To comprehensively assess and monitor irrigation water quality, a suite of parameters were utilized as indicators, encompassing: electrical conductivity (EC), sodium percentage (%Na) [35], sodium adsorption ratio (SAR) [36], Kelley's ratio (KR) [37], permeability index (PI) [38], magnesium adsorption ratio (MAR) [39], and total hardness (TH) [40]. Each parameter was normalized against standard reference values (FAO guidelines for irrigation water quality), ensuring that higher values were interpreted consistently as beneficial or detrimental depending on the parameter. For example, higher TH values were not penalized, while higher EC and %Na values were considered detrimental. These parameters were calculated using Equations 1–6 (Table 1) and provided a robust assessment of water quality for irrigation purposes. The ionic concentrations utilized in the computation of these parameters are expressed in milliequivalents per liter (meq/L). The analytical results of various water quality parameters are subsequently transformed into dimensionless numerical values according to the respective formulas and summarized in Table 1. These parameters formed the basis of the Irrigation Water Quality Index (IWQI). Each parameter was normalized against FAO irrigation water quality standards to ensure consistent interpretation of beneficial versus detrimental values. For example, higher EC and %Na values were penalized due to their adverse effects on soil permeability, while higher TH values were not

Table 1. Index classes used to calculate IWQI.

Indices		Values	Water quality	References
EC (µS/cm)	/	< 250	Excellent	[36]
		250–750	Good	
		750–2000	Permissible	
		2000–3000	Doubtful	
		> 3000	Unsuitable	
$\% Na^{+} = \frac{Na^{+}+K^{+}}{Ca^{2+}+Mg^{2+}+Na^{+}+K^{+}} \cdot 100$	(Eq 1)	0 – 20	Excellent	[35]
		20 – 40	Good	
		40 – 60	Suitable	
		60 – 80	Doubtful	
		80 – 100	Unsuitable	
$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}}$	(Eq 2)	<10	Excellent	[36]
		10 - 18	Good	
		19 - 26	Poor	
		> 26	Unsuitable	
$KR = \frac{Na^{+}}{Ca^{2+}+Mg^{2+}}$	(Eq 3)	< 1	Suitable	[37]
		> 1	Unsuitable	
$PI = \frac{Na^{+}+\sqrt{HCO_3^{-}}}{Na^{+}+Ca^{2+}+Mg^{2+}} \cdot 100$	(Eq 4)	> 75	Adequate	[38]
		25 – 75	Moderate	
		> 25	Unsuitable	
$MAR = \frac{Mg^{2+}}{Ca^{2+}+Mg^{2+}} \cdot 100$	(Eq 5)	< 50	Suitable	[39]
		> 50	Unsuitable	
$TH = 2.5.\ Ca^{2+} + 4.1.\ Mg^{2+}$ (in meq/L)	(Eq 6)	< 75	Soft	[40]
		75–150	Moderately hard	
		150–300	Hard	
		> 300	Very hard	

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considered detrimental. These indices, supported by both classical [35,36] and recent studies [22,23], formed the basis of the Irrigation Water Quality Index (IWQI). Their relative importance was subsequently determined using the Analytical Hierarchy Process (AHP), as detailed in Section 2.4.

2.4. Irrigation water quality index (IWQI) development

To integrate the physicochemical groundwater data and assess irrigation suitability, an Irrigation Water Quality Index (IWQI) was developed using a multivariate statistical approach. Key parameters influencing salinity and sodicity hazards; EC, TDS, major ions (Na^{+}, Ca^{2+}, Mg^{2+}, Cl^{-}, HCO_3^{-}, SO_4^{2-}), and irrigation indices (SAR, KR, %Na), were selected based on their relevance to irrigation water quality.

A Pearson correlation matrix was applied to standardized data to examine interrelationships among variables, identify dominant controlling factors, and reduce redundancy. This analysis supported the selection and weighting of parameters incorporated into the IWQI formulation. The weighted parameters were then aggregated to compute IWQI values for each sample. Finally, IWQI scores were classified into irrigation suitability categories and integrated into a Geographic Information System (ArcGIS-ArcMap v.10.3) to perform geospatial analysis and thematic cartography, enabling a comprehensive spatial interpretation of groundwater quality for irrigation management. Fig 2 illustrates the approach and methodology adopted to achieve the objective of this study. Weights for each parameter were determined through expert

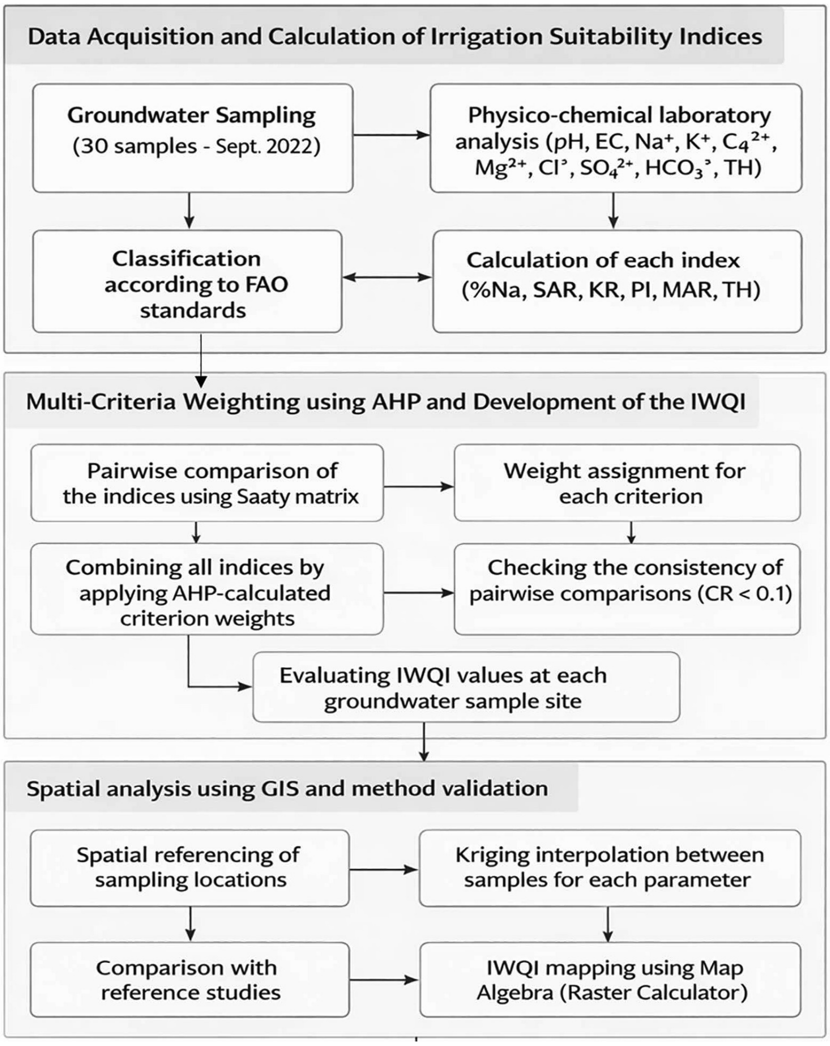

Fig 2. Flow chart of the methodology applied to this study.

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elicitation involving five specialists in irrigation agronomy and hydrogeology, using a structured questionnaire and Delphi consensus method. The IWQI was computed as: $IWQI = \Sigma (wj \times Oj/ Sj) \times 100$, where wj is the parameter weight, Oj the observed value, and Sj the FAO reference standard. Normalization ensured appropriate treatment of parameters where higher values are beneficial versus detrimental. Electrical Conductivity (EC) received the highest weight due to its strong influence on salinity hazards. Spatial interpolation was performed using IDW (power = 2, radius = 5 km, 12 neighbors), with cross-validation confirming accuracy. IWQI scores were classified into five categories (Excellent, Good, Poor, Very Poor, Unsuitable) and mapped in ArcGIS to delineate irrigation suitability zones.

2.4.1. Estimation of the weight assigned using AHP process. The Analytic Hierarchy Process (AHP), a widely recognized multi-criteria decision-making technique, was employed to determine the proportional weighting of thematic parameter layers and their associated attributes for the calculation of the IWQI. AHP was selected because it allows systematic incorporation of expert judgment and reduces subjectivity compared to equal weighting. This method, which utilizes a hierarchical framework to systematically evaluate multiple criteria [41,42], involves decomposing the problem into a hierarchical structure. Pairwise comparisons within a judgment matrix are performed to evaluate the relative significance of the criteria and sub-criteria [43]. Saaty [88] introduced the fundamental scale, while Yeh et al. [112] demonstrated its application in water resource studies. This hierarchical framework enables the independent evaluation of each parameter while accounting for the complex interplay of multiple parameters specific to the Collo Plain region. The implementation of the AHP method in this research involved four key sequential steps:

(i) Selection of Factors Influencing the IWQI. The initial stage of the AHP implementation involved the selection of factors influencing the IWQI and the determination of their relative importance. A pairwise comparison process was conducted, wherein each parameter was assigned a score ranging from 1 to 9 (Table 2). This scoring system adheres to the fundamental scale proposed by Saaty [44], where a score of 1 denotes an equal influence of the two parameters being compared, while a score of 9 signifies an extreme influence of one parameter over the other in terms of its contribution to the irrigation groundwater quality index (IWQI). The pairwise comparison matrix facilitated the quantification of relative priorities among the various parameters by eliciting judgments from subject matter experts or decision-makers. These judgments were based on the relative importance of each pair of factors in determining the appropriateness of groundwater for irrigation purposes. The subjective assessments were then translated into numerical scores using the 1–9 scale, where intermediate values represented varying degrees of importance (e.g., 3 for moderate importance, 5 for strong importance, 7 for very strong importance). This approach enabled the systematic integration of expert knowledge and stakeholder preferences into the decision-making process, ensuring that the IWQI accurately reflected the relative contributions of each parameter to the overall groundwater quality assessment.

(ii) Pairwise Comparison Matrix. The AHP methodology excels in transforming multifaceted spatial data into actionable numerical outputs. This process entails the systematic conversion of qualitative assessments from various thematic layers and their components into quantifiable metrics, adhering to Saaty's established scale. The formulation of a Pairwise Comparison Matrix (PCM) is a crucial step (Eq 7), as described Singh et al. [45], Abrams et al. [5], and Lentswe and Molwalefhe [60]. In this matrix, parameters are arranged in descending order of their influence on the primary objective (evaluation of water suitability for irrigation). In the constructed matrix, all elements along the principal diagonal are consistently set to one, indicating that each parameter is considered equivalent when compared to itself (Table 3). Non-diagonal

Table 2. Score assignment through the pairwise comparison process [44].

Less Important			Equally Important			More Important		
Extremely	**Very Strongly**	**Strongly**	**Moderately**	**Equally**	**Moderately**	**Strongly**	**Very Strongly**	**Extremely**
1/9	**1/7**	**1/5**	**1/3**	**1**	**3**	**5**	**7**	**9**

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Table 3. PCM for evaluated parameters.

Parameter	EC	SAR	%Na	KR	PI	MAR	TH
EC	1	3	3	5	5	5	7
SAR	0.33	1	3	3	5	5	5
% Na	0.33	0.33	1	1	3	3	5
KR	0.2	0.33	1	1	1	2	3
PI	0.2	0.2	0.33	1	1	1	3
MAR	0.2	0.2	0.33	0.5	1	1	1
TH	0.14	0.2	0.2	0.33	0.33	1	1
Totals	**2.4**	**5.26**	**8.86**	**11.83**	**16.33**	**18**	**25**

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entries are populated based on the relative significance of parameters, determined through pairwise comparisons, utilizing the appropriate Saaty score or its reciprocal, contingent upon the directionality of the comparison. This methodical approach to matrix population enables the quantification of each parameter's relative importance within the broader hydrogeological context. The resultant PCM serves as the foundation for subsequent mathematical operations, facilitating the derivation of priority vectors and parameter weightings. This process culminates in a comprehensive, quantitative evaluation of irrigation water quality suitability, integrating multiple spatial and qualitative variables into a singular, objective metric. The PCM structure ensures that the inherent trade-offs and interdependencies among the different parameters are accounted for in a consistent and logical manner, aligning with the principle of hierarchical composition intrinsic to the AHP methodology.

$$A = \begin{vmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{vmatrix} \quad (7)$$

The pairwise comparison matrix (PCM), denoted by A, is mathematically defined as follows (Eq 8):

$$A = [Xij].nxn \quad (8)$$

Where Xij indicates the relative significance of parameter *i* compared to parameter *j*, with *n* representing the total number of criteria evaluated. The PCM for the parameters assessed in this study is presented in Table 3. Electrical conductivity emerged as the primary parameter, exerting the most significant influence on IWQI, and was thus assigned the highest Saaty score of 7. The SAR and %Na were identified as the next most impactful parameters and were subsequently placed in the hierarchy. Following these, KR, PI, MAR, and TH were ranked in descending order of their influence.

To populate the PCM, each parameter was assigned a Saaty score relative to EC, quantifying its relative significance for the IWQI estimation. For instance, a Saaty score of 1/3 was attributed to SAR in relation to EC, indicating a moderate influence of EC over SAR concerning irrigation water quality. Conversely, when EC was compared to %Na, a score of 3 was assigned, reflecting a stronger influence of EC over %Na. The systematic construction of the PCM ensures that the relative priorities and inherent trade-offs among the various physicochemical parameters are explicitly considered and quantified based on their perceived impact on the IWQI. The resulting PCM forms the basis for subsequent mathematical operations within the AHP framework, enabling the determination of the final parameter weights for IWQI calculation.

(s. The relative weights for physicochemical parameters integral to the IWQI were derived through a systematic incorporation of expert judgments using the AHP process. This methodology, grounded in multi-criteria decision-making principles, quantifies the comparative significance and relative influence of each parameter on the IWQI [46]. The weights assigned to the thematic parameter layers were obtained through normalization of the pairwise comparison matrix (NPCM) [43,47]. This normalization procedure is expressed mathematically by Eq 9:

$$X_{ij} = \frac{C_{ij}}{\Sigma_j C_{ij}} \quad (9)$$

Where:

X_ij = Normalized value of the matrix element in row i and column j

C_ij = Value assigned to the criterion in row i and column j of the original matrix

∑_j C_ij = Sum of all elements in column j

To calculate the standardized weight (W_i) for each parameter i, we computed the arithmetic average of the normalized values in the respective row of the NPCM. This calculation can be expressed mathematically Equation (10) [48,49]:

$$W_i = \frac{\sum_j X_{ij}}{N} \tag{10}$$

Where:

W_i = Standardized weight for parameter i

X_{ij} = Normalized matrix element in row i and column j

N = Total number of criteria or parameters under consideration

This normalization process ensures that the sum of all derived weights equals unity ($\sum W_i = 1$), facilitating their direct interpretation as relative importance factors in the IWQI estimation. The standardized weights quantify the complex interrelationships and differential influences of the parameters on irrigation water quality, as captured through the pairwise comparisons and expert evaluations. The resultant weights (Table 4) provide a mathematically robust and objective foundation for IWQI calculation. This approach accounts for the multifaceted nature of water quality assessment in agricultural contexts, offering a comprehensive basis for parameter prioritization and subsequent index computation.

Following the determination of standardized weights through the normalization of the pairwise comparison matrix (NPCM), eigenvector and eigenvalue calculations were performed to assess the influence of thematic parameter layers and any potential constraints on the classification outcome (Table 5). The eigenvector was obtained by normalizing the column elements of the NPCM, dividing each element by its corresponding column sum (Table 4). The principal eigenvector, representing the relative weights of each parameter, was then obtained by averaging the elements across the rows of the normalized

Table 4. NPCM and Parameter Weights for IWQI Determination.

Parameter	EC	SAR	%Na	KR	PI	MAR	TH	Eigen Vector	Influence (%)	AHP Weight
EC	0.42	0.57	0.34	0.42	0.31	0.28	0.28	0.41	41.0	0.37
SAR	0.14	0.19	0.34	0.25	0.31	0.28	0.20	0.20	20.0	0.24
%Na	0.14	0.06	0.11	0.08	0.18	0.17	0.20	0.13	13.0	0.14
KR	0.08	0.06	0.11	0.08	0.06	0.11	0.12	0.08	8.0	0.09
PI	0.08	0.04	0.04	0.08	0.06	0.06	0.12	0.07	7.0	0.07
MAR	0.08	0.04	0.04	0.04	0.06	0.06	0.04	0.07	7.0	0.05
TH	0.06	0.04	0.02	0.03	0.02	0.06	0.04	0.04	4.0	0.04
Total effect	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**100**	**1.00**

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Table 5. Determining principal eigenvalues to quantify relative parameter importance.

Parameter	(1) Total Relative Weight (from Table 3)	(2) Eigenvector Value (from Table 4)	Eigenvalues (1) x (2)
EC	2.4	0.41	0.984
SAR	5.26	0.2	1.052
% Na	8.86	0.13	1.1518
KR	11.83	0.08	0.9464
PI	16.33	0.07	1.1431
MAR	18	0.07	1.26
TH	25	0.04	1.00
λ max			7.53

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matrix [41,107,112]. Furthermore, a consistency vector was calculated by multiplying the corresponding elements from the original pairwise comparison matrix with those in the NPCM, as defined by the following equation (Eq 11) [74,75]:

$$\lambda = \Sigma \left(C_{\_ij}.X_{\_ij}\right) \tag{11}$$

Where λ represents the ith element of the consistency vector, C_ij denotes the element in the ith row and jth column of the original pairwise comparison matrix, and X_ij is the corresponding element in the NPCM.

The consistency vector plays a pivotal role in evaluating the coherence and reliability of the pairwise comparisons and the derived weights. By quantifying the degree of inconsistency within the judgment matrix, the consistency vector enables the calculation of a consistency ratio, which serves as a diagnostic metric to validate the reliability of the AHP results.

The principal eigenvalue (λmax), which is the sum of the eigenvalues, quantifies the matrix's deviation from perfect consistency [50,51]. According to Saaty [87], a pairwise comparison matrix is considered fully consistent if its principal eigenvalue (λmax) is equal to or greater than the number of parameters (n) being evaluated. In this study, a principal eigenvalue of 7.53 was obtained for the 7 x 7 pairwise comparison matrix (Table 6). This value was subsequently used to calculate the consistency index.

(iv) Matrix Coherence Assessment. The coherence of the pairwise comparison matrix was assessed utilizing the consistency index (CI) and consistency ratio (CR) [52,53], as outlined in the following equations (Eqs 12–13):

$$CI = \frac{\lambda max - n}{\mathrm{n} - 1} \tag{12}$$

$$CR = \frac{CI}{\mathrm{RI}} \tag{13}$$

The consistency index (CI) quantifies the degree of inconsistency inherent in the pairwise comparison matrix (PCM), while the consistency ratio (CR) serves as a diagnostic metric to assess the acceptability of the derived priority weights. The CR incorporates a random index (RI) value corresponding to the number of variables (n) considered for a comprehensive assessment of the consistency of the pairwise comparisons. In an idealized scenario of perfect consistency, a decision-maker's judgments would yield a consistency index (CI) value of 0. However, minor deviations from perfect consistency are tolerable when the CI is less than 0.1. This study yielded an acceptable CI value of 0.08. It is important to note that a consistency ratio (CR) exceeding a predetermined threshold of 0.1 indicates unacceptable inconsistencies within the pairwise comparison judgments, requiring a reevaluation of the decision-making process. For a pairwise comparison matrix involving seven criteria, the corresponding random index (RI) value is 1.32 (Table 6). The weighting procedure employed in this research resulted in a consistency ratio (CR) of 0.06, indicating acceptable consistency with the principles of the AHP [44]. The weights attributed to the thematic layers of the GIS parameters (Table 5) demonstrate consistency with the AHP method. This rigorous assessment of matrix coherence through the CI and CR calculations ensures the reliability and coherence of the derived weights, thereby enhancing the robustness and validity of the subsequent IWQI estimation and classification based on the integrated GIS and remote sensing data.

Table 6. AHP consistency validation using random index values [44].

Number of variables (n)	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Random Index (RI)	0	0.58	0.9	1.12	1.24	1.32	1.41	1.49

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Expert judgments were elicited from five specialists (two irrigation agronomists, two hydrogeologists, one water resource manager) using a structured questionnaire and Delphi consensus method. The pairwise comparison matrix was constructed following Saaty's scale, and the consistency ratio (CR) was calculated (<0.1), confirming acceptable consistency. Electrical Conductivity (EC) received the highest weight due to its strong influence on salinity hazards and soil permeability, consistent with FAO irrigation guidelines. Parameter weights were derived from the normalized principal eigenvector of the PCM, ensuring a robust and transparent weighting process. The weighting procedure employed in this research resulted in a consistency ratio (CR) of 0.06, indicating acceptable consistency with the principles of the AHP. Electrical Conductivity (EC) received the highest weight due to its strong influence on salinity hazards and soil permeability, consistent with FAO irrigation guidelines. The derived weights were subsequently applied to compute IWQI values for each sampling site, which were then spatially interpolated and mapped to delineate irrigation suitability zones.

2.4.2. Estimation of the irrigation water quality index (IWQI). Following the determination of relative weights for all parameters through the application of the Analytical Hierarchy Process (AHP) method, the Irrigation Water Quality Index (IWQI) for each groundwater sample was calculated using a weighted linear combination formula, as defined in Eq 14:

$$IWQI = \Sigma\_j \left(\frac{wj\ .Oj}{Sj} \right) .100 \tag{14}$$

Where; wj denotes the weight assigned to the j^{th} parameter,

Oj epresents the observed value of the j^{th} parameter in the groundwater sample, and;

Sj is the corresponding standard reference value for the j^{th} parameter.

The standard reference values Sj were established based on internationally recognized guidelines for irrigation water quality [54]. These values correspond to the maximum permissible concentration for each parameter beyond which adverse effects on soil or crops may occur.

The resulting IWQI values were then used to classify groundwater suitability for irrigation into five classes: Excellent ($0 < IWQI < 25$), Good ($26 < IWQI < 50$), Poor ($51 < IWQI < 75$), Very Poor ($76 < IWQI < 100$), and Unsuitable ($IWQI > 100$). To visualize the spatial distribution of water quality, geostatistical interpolation was employed to generate continuous data surfaces from discrete sampling locations. Specifically, the Inverse Distance Weighting (IDW) algorithm was applied, which estimates values at unsampled points based on the principle of spatial autocorrelation, the influence of a known data point decreases with distance. Given the sparse and irregular sampling distribution in this study, IDW was deemed more suitable than distance threshold methods.

The resulting interpolated raster layers, representing both individual physicochemical parameters and calculated IWQI values, allowed the delineation of zones with varying groundwater suitability for irrigation. These spatial representations facilitate integration with other geographic data layers, supporting informed decision-making for groundwater management and sustainable agricultural practices. Normalization ensured that parameters where higher values are beneficial (e.g., Ca^{2+}, Mg^{2+}) were treated differently from those where higher values are detrimental (e.g., EC, Na^{+}), preventing misclassification. IDW interpolation was applied with a power parameter of 2, a search radius of 5 km, and 12 nearest neighbors. Cross-validation confirmed interpolation accuracy (RMSE < acceptable threshold). IWQI scores were consistently classified into five categories (Excellent, Good, Poor, Very Poor, Unsuitable), ensuring methodological transparency and reproducibility.

3. Results

To assess the hydrogeochemical parameters of the Collo plain aquifer, a comprehensive statistical analysis was carried out (Table 7). It includes descriptive statistics, notably central tendency (arithmetic mean) and dispersion (standard deviation) measurements, as well as ranging statistics (maximum and minimum values). These quantitative measures were employed to elucidate the groundwater's physicochemical characteristics and compositional variability.

The evaluation of chemical and physical properties revealed that water samples from the Collo plain exhibited pH levels between 6.90 and 7.90, with a mean value of 7.50. This falls within the acceptable limits for irrigation water quality (6.5 < pH < 9), as defined by the Food and Agriculture Organization of the United Nations [54]. Deviation from this range can negatively impact soil properties and nutrient availability, consequently affecting crop productivity. Additionally, the Electrical Conductivity (EC) is a critical parameter that indicates the concentration of dissolved ions, thereby serving as a measure of water mineralization. It is influenced by various geochemical processes, including the dissolution of geological formations, ion exchange, excessive groundwater exploitation, silicate weathering, sulfate reduction, oxidation reactions, and marine intrusion in coastal aquifers [55]. In this study, EC values ranged from 1356 to 3388 μS/cm, with an average of 2212.83 μS/cm (Table 7). The highest EC values were observed in wells located in the Ouled Maazouz area, likely due to the large urban agglomeration and the potential for seawater intrusion, particularly in wells P1 and P2. Additionally, wells situated to the northeast along the wadi Guebli also exhibited relatively high EC values, which can be attributed to the influence of groundwater flow from the upstream wadi Guebli inferoflow aquifer [27].

The abundance order of dissolved salts is $Cl^- > HCO_3^- > SO_4^{2-}$ for anions and $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ for cations. The high concentrations of evaporated elements (Na^+, K^+, and Cl^-) in the groundwater of the Teleza aquifer, with mean values of 262.06 mg/L, 11.70 mg/L and 355.86 mg/L respectively, are mainly attributed to interactions between the aquifer and the wadi for wells located to the northeast along the wadi Guebli, as well as to the saltwater intrusion, particularly to the northwest of the study area (P1 and P2). Bicarbonate (HCO_3^-) concentrations in the aquifer ranged from 145 to 605 mg/L, with a mean of 260.70 mg/L. Spatial analysis revealed peak concentrations in the southern study area, specifically at sampling points P28 and P27. This region's proximity to schistose basement formations bordering the plain's southern extent suggests a potential correlation between local geological structures and groundwater geochemistry. Dissolved calcium, primarily derived from the dissolution of evaporitic and carbonate lithologies, significantly influences the groundwater's total hardness. Chemical analyses (Table 7) indicated a minimum calcium concentration of approximately 88 mg/L in the northern discharge zone, contrasting with a maximum of 325 mg/L in the southern region. This elevated concentration may be attributed to the presence of shale formations and possible aquifer-wadi interactions. Magnesium concentrations in the groundwater samples exhibited a mean value of 83 mg/L, with 73.33% exceeding the FAO (1985) irrigation water standard. The lowest concentration (45 mg/L) was observed in the northern zone (sampling points P11 and P14), while the highest (122 mg/L) was recorded in the southern portion of the study area.

Table 7. Quantitative assessment of various groundwater characteristics.

Chemical Parameters	Unit	Max	Min	Median	Average	Standard Deviation
pH	/	7.90	6.90	7.50	7.5	0.25
EC	(μS/cm)	3388	1356	2187.50	2212.83	497.12
Ca^{2+}	mg/L	325	88	184	176.43	58.74
Mg^{2+}	mg/L	122	45	88	83.46	22.82
Na^+	mg/L	488	80	245.50	262.06	123.54
K^+	mg/L	19	5	12	11.70	2.90
SO_4^{2-}	mg/L	362	99.90	207.50	220.89	61.14
HCO_3^-	mg/L	605	145	216	260.70	104.04
Cl^-	mg/L	745	124	355.50	355.86	157.43
NO_3^-	mg/L	98	18	43	47.37	23.51
NO_2^-	mg/L	0.42	0.1	0.21	0.23	0.08
NH_4^+	mg/L	0.96	0.22	0.56	0.56	0.19
PO_4^{3-}	mg/L	0.98	0.19	0.42	0.49	0.22

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The concentrations of nitrogen and phosphorus compounds in the groundwater of the Collo plain, considered to be sensitive indicators of anthropogenic pollution, reveal nitrate (NO_3^-) levels ranging from 18 to 98 mg/L, with an average value of 47.37 mg/L. Nitrite (NO_2^-) concentrations vary between 0.10 and 0.42 mg/L, with an average of 0.23 mg/L. Ammonium (NH_4^+) concentrations ranged from 0.22 to 0.96 mg/L, with an average value of 0.56 mg/L, while phosphate (PO_4^{3-}) levels ranged from 0.19 to 0.98 mg/L, with an average concentration of 0.49 mg/L.

The relatively high nitrate concentrations recorded in wells located near agricultural areas close to the wadi (P1-P5, P13, and P16) indicate that chemical fertilizer leaching is a major source of NO_3^- contamination. Similarly, the presence of NH_4^+ and PO_4^{3-}, although at relatively lower concentrations, corresponds to inputs from both domestic wastewater discharges and manure spreading in agricultural areas. Nitrite (NO_2^-), which is generally unstable in groundwater systems, is detected at low concentrations, reflecting the microbial nitrification processes occurring in the aquifer. Correlation analysis (Fig 7) confirmed strong positive relationships between EC, Na^+, and IWQI, consistent with salinity hazards, while nitrate showed moderate positive correlation with IWQI, reflecting anthropogenic inputs. The observed EC and nitrate levels are comparable to those reported in Tunisian and Indian coastal aquifers, underscoring the severity of groundwater degradation in the Collo Plain. IWQI classifications were consistently applied as Excellent, Good, Poor, Very Poor, and Unsuitable, ensuring methodological clarity.

3.1 Hydrochemical typology and geochemical processes controlling groundwater quality

The analytical data are crucial for determining the origin, distribution, and hydrochemical facies types, thereby highlighting variations in groundwater quality within the aquifer. The Piper trilinear plot of chemical analysis results provides comprehensive information on hydrogeochemical facies [56,57]. In the cation triangle, most samples are plotted towards the sodium pole, except for wells P16, P27, and P28, which show a slight dominance of calcium, and wells P6, P23, and P24, which show a slight dominance of magnesium. This variation may be attributed to cation exchange phenomena. In the anion triangle, most samples are plotted towards the chloride pole, indicating the dominance of this anion. The Piper diagram reveals a diversity of chemical facies with three distinct groups (Fig 3); (i) Cl-Na facies, accounting for 63.33% of groundwater samples, observed throughout the plain, indicating contributions richer in Na+ than in Cl^-. (ii) Cl-Ca-Mg and HCO_3-Ca facies, representing 13.33% and 6.67% of samples respectively, linked to the dissolution of evaporite minerals in the recharge zone in the upstream part of the plain and to the influence of carbonate passages such as marls. (iii) SO_4^{2-} Na+ facies, constituting 16.67% of samples, observed in wells P4, P10, P14, P18, and P19, resulting from water circulating in the Oligo-Miocene Kabyle littoral sedimentary formation at the northeastern and northwestern extremities of the plain.

The hydrochemical characteristics of groundwater samples from the Collo plain were analyzed using Chadha's diagram [58] and the hydrochemical evolution facies (HEF) diagram, revealing complex geochemical processes and potential anthropogenic influences.

Chadha's diagram analysis (Fig 4a) demonstrated that the samples were distributed across fields 2 and 3. Approximately 70% of the samples clustered in subfield (2), indicative of an inverted ion exchange process. These samples exhibited Ca^{2+}-Mg^{2+}-Cl^- type hydrochemical facies, characterized by either Ca^{2+}-Mg^{2+} dominance with Cl^- as the primary anion or Cl^- dominance with Ca^{2+}-Mg^{2+} as the principal cations. The remaining 30% of samples were grouped in subfield (3), suggesting mixing with saline water. This phenomenon was particularly evident in the northern region of the plain, specifically in Ouled Maazouz and Hadjria, where Na^+-Cl^- and SO_4^{2-}-Na^+ type hydrochemical facies were observed, characterized by Na^+-dominant-Cl^- or Cl^--dominant-Na^+ compositions. The observed ionic composition suggests the occurrence of a cation exchange mechanism within the aquifer system. This process involves the substitution of divalent cations, specifically Ca^{2+} and Mg^{2+}, present in the groundwater, with monovalent cations, predominantly Na^+ and K^+, derived from the aquifer matrix. Consequently, this geochemical interaction manifests as a reduction in calcium and magnesium concentrations concurrent with an augmentation of sodium and potassium levels in the groundwater.

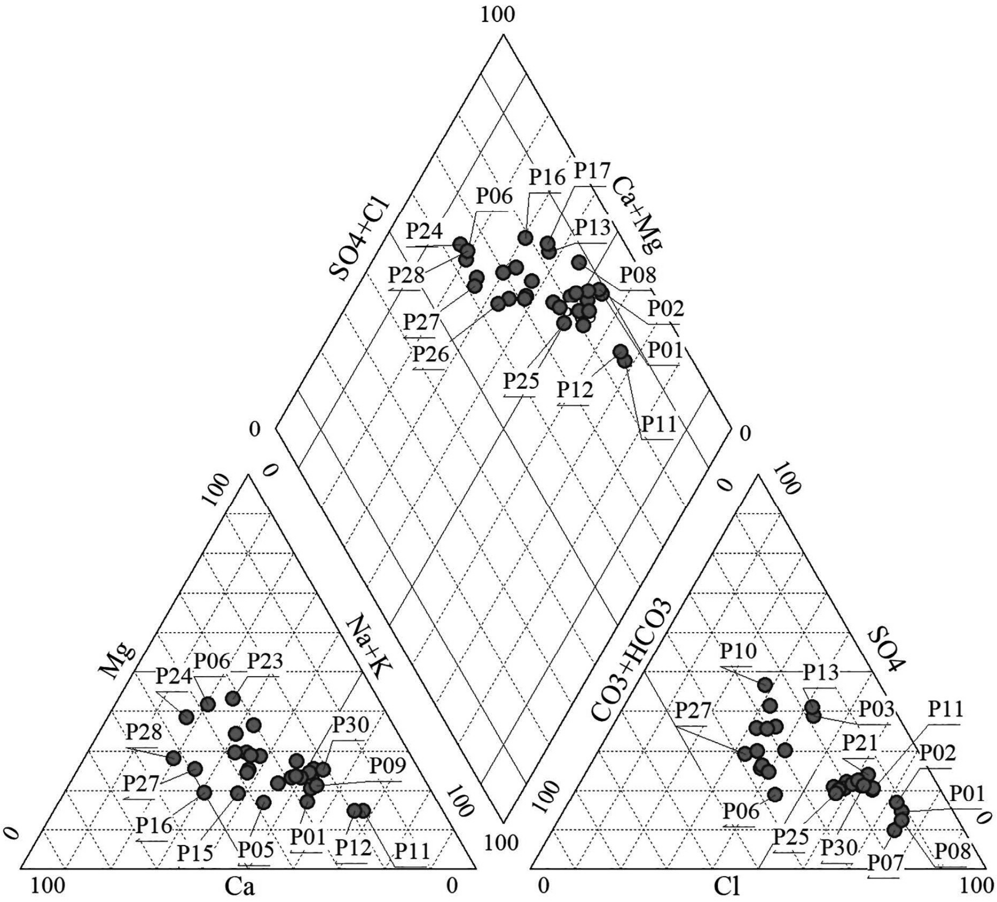

Fig 3. Identification of groudwater hydrogeochemical facies using Piper diagram.

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The HEF diagram analysis (Fig 4b) of all 30 groundwater samples revealed three distinct categories influenced by various hydrogeochemical and anthropogenic processes: (i) Samples situated above the mixing line (P4, P10, P14, P18, and P19) corresponded to unaffected groundwater characterized by an SO_4^{2-}-Na^+ facies. (ii) Samples located below the mixing line in its upper segment (P23, P24, P27, and P28) exhibited HCO_3^--Ca^{2+} and Cl^--Ca^{2+}/Mg^{2+} facies. These facies are associated with brines originating from the dissolution of evaporite minerals in the recharge area upstream of the plain, contributing to a progressive increase in groundwater salinity. (iii) Samples positioned below the mixing line in its lower segment (P1, P2, P7, P8, P16, and P17) represented affected groundwater characterized by a Cl^--Na^+ facies. Their distribution throughout the coastal zone suggests that saltwater intrusion is a significant contributor to dissolved solutes in these groundwater samples. This process is likely influenced by the Cherka and Guebli wadis, which maintain a direct connection to the Mediterranean Sea [59]. As illustrated in the piezometric maps produced by Chabour [24] and Boumaiza et al. [21], there is a discernible disruption in the groundwater piezometry, with observed flow directions towards the sea and towards the bordering wadis (Wadis Guebli and Cherka). This suggests the probable occurrence of a reverse flow of groundwater from the wadis towards the aquifer, potentially facilitated by the upstream migration of seawater through the wadi estuaries.

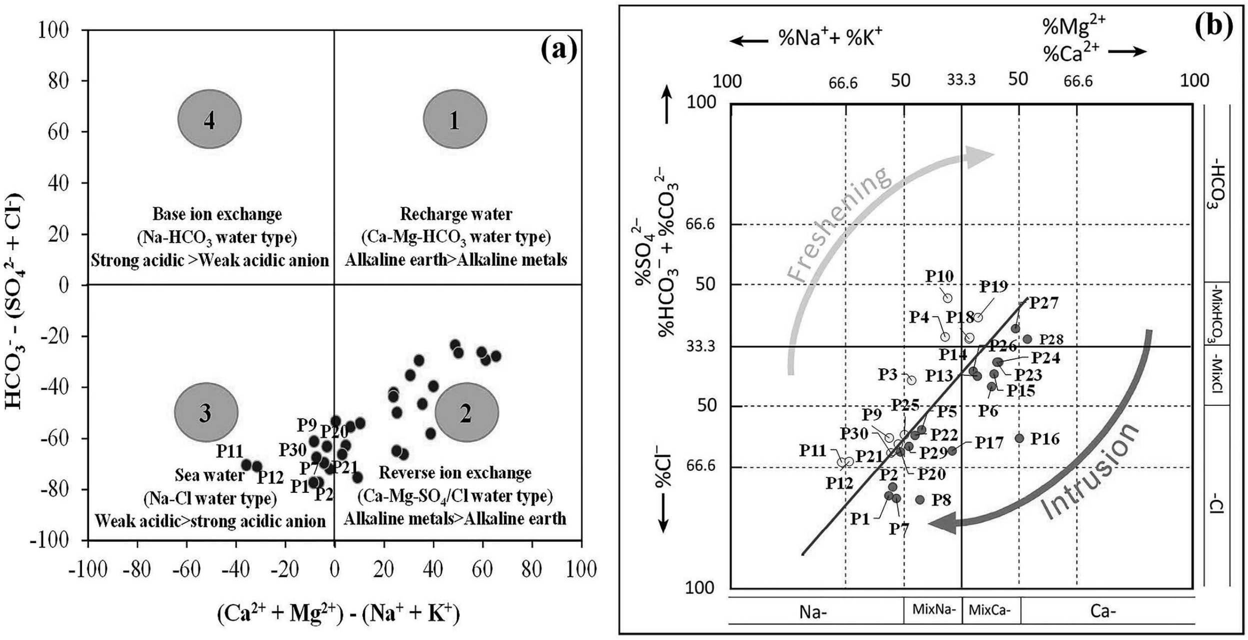

Fig 4. Geochemical processes affecting on groundwater quality. (a) Chadha diagram and (b) hydrochemical evolution facies diagram (HEF).

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The dominance of Cl-Na facies in the Collo Plain is consistent with findings from other Mediterranean coastal aquifers [6,60], highlighting the global relevance of seawater intrusion processes. The observed cation exchange can be represented by the reaction $Ca^{2+} + 2Na\text{-}X \leftrightarrow 2Na^{+} + Ca\text{-}X$, where X denotes exchange sites on clay minerals. This mechanistic understanding reinforces the role of both geogenic processes and anthropogenic pressures in shaping groundwater quality.

3.2 Spatial assessment of irrigation water quality indices

The spatial assessment of irrigation water quality in the Collo plain was performed using a GIS-based interpolation of the calculated irrigation indices (Table 8), followed by their classification according to widely accepted threshold criteria. To enhance the spatial interpretation of these indices, a Geographic Information System (GIS) approach was employed for interpolation and visualization. This methodology facilitates the transformation of point-based experimental data into continuous spatial distribution maps and thematic layers. The utilization of GIS-based spatial interpolation techniques serves to mitigate uncertainty factors inherent in the analyzed parameters. Furthermore, this approach enables the implementation of a robust, geostatistical methodology for synthesizing groundwater suitability assessments [61]. The results are presented and discussed exclusively on the basis of the classified water quality ratings (Fig 5), which provide a more synthetic and decision-oriented interpretation of groundwater suitability for irrigation.

Electrical Conductivity (EC), a key indicator of groundwater mineralization reflecting dissolved ionic content [62], shows that most of the Collo plain is characterized by moderate to high salinity levels. According to the EC-based classification (Fig 5a), approximately 56% of groundwater samples fall within the high salinity class (2000–3000 µS/cm), mainly distributed in the northeastern and southeastern sectors of the plain. Marginal-quality waters (1000–2000 µS/cm) account for about 36.66% of samples and are predominantly observed in the central and northwestern areas, particularly around

Table 8. Quantitative assessment of various indices of irrigation water quality.

Wells	SAR	KR	TH	PI	EC	MAR	%Na	IWQI
	/	/	meq/L	(%)	µS/cm	(%)	(%)	/
P1	11.43	1.20	54.71	57.87	3215	37.59	54.50	75.47
P2	11.06	1.15	60.76	56.77	3388	44.23	53.40	77.47
P3	9.40	0.92	59.92	52.28	2236	44.45	47.97	58.93
P4	6.90	0.62	53.31	43.63	1753	46.43	38.32	46.82
P5	8.58	0.82	48.63	49.80	2395	30.54	45.00	57.57
P6	3.24	0.26	63.50	26.48	2412	52.36	20.41	46.04
P7	10.73	1.10	47.54	56.26	2598	48.64	52.35	67.11
P8	8.73	0.84	52.08	49.07	2540	39.98	45.56	60.62
P9	11.39	1.19	34.75	58.82	2044	46.46	54.41	61.49
P10	6.72	0.60	58.13	42.57	1846	40.39	37.57	46.94
P11	17.04	2.13	26.38	71.93	2298	45.74	68.08	77.72
P12	15.97	1.93	29.40	69.72	2438	43.21	65.91	76.77
P13	6.74	0.60	58.19	41.83	1938	39.20	37.64	47.94
P14	6.12	0.54	26.63	40.58	1356	45.19	34.89	39.65
P15	6.88	0.62	40.93	43.62	1867	30.90	38.24	46.67
P16	5.22	0.44	43.83	35.31	1999	27.81	30.73	43.64
P17	6.42	0.57	62.13	40.36	2388	45.19	36.25	53.42
P18	5.12	0.43	54.48	35.71	1874	49.02	30.22	43.96
P19	5.58	0.48	53.57	37.59	1918	43.56	32.42	45.17
P20	10.55	1.07	36.33	56.10	2114	52.73	51.80	60.98
P21	10.37	1.05	54.67	54.97	2653	50.13	51.22	67.09
P22	9.14	0.89	41.31	51.74	2139	51.41	47.02	57.77
P23	4.11	0.34	48.83	31.20	1514	57.63	25.14	37.57
P24	2.72	0.21	57.33	23.48	1663	46.47	17.47	34.45
P25	10.01	1.00	30.14	54.87	1829	46.41	50.04	55.47
P26	5.73	0.50	45.32	39.08	1732	54.32	33.14	44.36
P27	4.23	0.35	75.48	31.94	2541	34.10	25.75	48.61
P28	3.08	0.24	71.83	25.49	2267	34.93	19.55	42.00
P29	9.62	0.95	64.80	52.83	2697	45.98	48.71	65.44
P30	11.24	1.17	62.31	57.99	2733	54.94	53.95	65.22
Max	**17.04**	**2.13**	**75.48**	**71.93**	**3388**	**57.63**	**68.08**	**77.72**
Min	**2.72**	**0.21**	**26.38**	**23.48**	**1356**	**27.81**	**17.47**	**34.45**
Avg.	**8.14**	**0.81**	**50.57**	**46.33**	**2213**	**44.33**	**41.59**	**55.08**

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Hajria. A limited proportion of samples (6.66%) exceeds the threshold of 3000 µS/cm defined by Richards [85], indicating highly mineralized groundwater concentrated in the northeastern part of the plain near Ouled Mazzouz.

The Sodium Adsorption Ratio (SAR), which evaluates the potential sodicity hazard relative to calcium and magnesium concentrations [63], indicates a generally favorable irrigation suitability across the study area. The SAR classification map (Fig 5b) shows that all groundwater samples fall within the excellent to good quality classes, with values remaining well below the critical limit of 26. This suggests a low risk of soil permeability degradation and structural deterioration associated with sodium accumulation [64,65].

The sodium percentage (%Na), an indicator of sodium dominance in irrigation water, serving for evaluating the potential risks associated with sodium accumulation in irrigation practices. Indeed, irrigation water with a high salt content can have

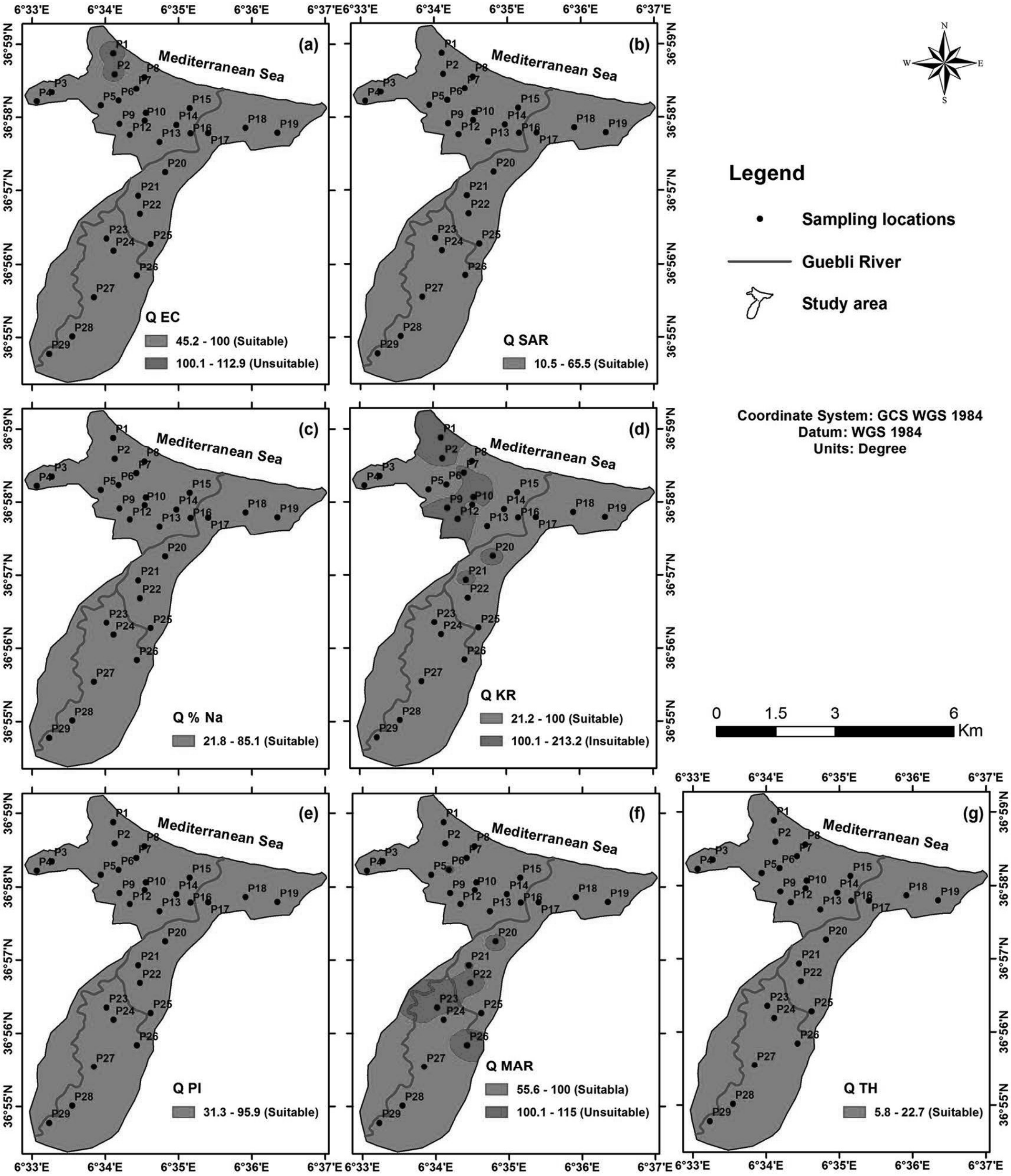

Fig 5. Spatial distribution of water rating quality. (a) Electrical Conductivity (EC), (b) Sodium Adsorption Ratio (SAR), (c) Sodium percentage (%Na), (d) Kelly's Ratio (KR), (e) Permeability Index (PI), (f) Magnesium Adsorption Ratio (MAR), and (g) Total Hardness (TH).

https://doi.org/10.1371/journal.pwat.0000511.g005

a profound impact on soil structure, potentially reducing its permeability and aeration capacity. This, in turn, can indirectly influence plant growth and development [66]. As shown in Fig 5c, the majority of samples are classified as excellent to permissible for irrigation, with %Na values not exceeding the recommended upper limit of 80%. Doubtful-quality waters are spatially limited and mainly occur in restricted central zones, while acceptable to good quality waters dominate the southern and northeastern sectors.

Kelly's Ratio (KR), which assesses the balance between sodium and divalent cations [37,102]. When it is less than 1, it indicates the water's suitability for irrigation, while when it is greater than 1, it indicates that the water is unsuitable. If sodium content exceeds that of calcium and magnesium, this may affect soil salinity and impede irrigation practices. The presence of excess magnesium in the soil matrix can also raise soil alkalinity, resulting in reduced crop yields. The KR classification map (Fig 5d) indicates that about 66.66% of groundwater samples are suitable for irrigation (KR $<$ 1), mainly distributed in the southern, central, and northeastern parts of the plain. In contrast, unsuitable waters (KR $>$ 1) are concentrated in the northwestern area, particularly around Ouled Mazzouz, reflecting localized sodium enrichment.

The Permeability Index (PI) reflects the potential impact of irrigation water on soil permeability. The soil matrix is pivotal in sustaining crop productivity and facilitating the intricate water circulation processes that characterize agricultural landscapes. However, soil permeability can be detrimentally impacted by prolonged exposure to excessive sodium, calcium, magnesium, and bicarbonate ions in groundwater resources [58,67]. These ionic constituents can induce deleterious effects on the soil structure, potentially compromising its ability to maintain adequate water infiltration and drainage, thereby hampering crop growth and yield potential. The spatial distribution of permeability index (PI) values shows that all samples remain below the critical threshold value of PI = 75, indicating overall suitability for irrigation (Fig 5e). Although most samples fall within the poor-to-moderate PI class, the classified map highlights that none of the groundwater sources exceed the limit associated with severe permeability hazards, emphasizing the importance of considering PI in conjunction with other indices and local soil management practices.

Magnesium Adsorption Ratio (MAR) values indicate that groundwater suitability is spatially heterogeneous. As illustrated in Fig 5f, approximately 76.66% of samples are classified as suitable for irrigation (MAR $<$ 50%), while unsuitable waters (MAR $>$ 50%) are mainly confined to the central part of the plain (23.33% of groundwater samples). Elevated MAR values may adversely affect soil structure under saline conditions [68,94].

Total Hardness (TH), which is largely controlled by water–rock interaction processes, indicates uniformly favorable conditions across the study area. The TH classification map (Fig 5g) shows that all groundwater samples fall within the soft water category (TH $<$ 75 mg/L), well below the acceptable limit for irrigation (300 mg/L), confirming the absence of hardness-related constraints.

Correlation analysis (Fig 7) confirmed strong positive relationships between EC, Na^+, and IWQI, consistent with salinity hazards, while nitrate showed moderate positive correlation with IWQI, reflecting anthropogenic inputs. The observed EC exceedances (6.7% of samples) are comparable to Tunisian coastal aquifers [60] but higher than those reported in Indian semi-arid aquifers [6], underscoring the severity of groundwater degradation in the Collo Plain. IWQI classifications were consistently applied as Excellent, Good, Poor, Very Poor, and Unsuitable, ensuring methodological clarity.

3.3. Correlation matrix

The correlation matrix provides quantitative evidence for the complex interplay of hydrogeochemical processes governing groundwater quality in the Collo Plain (Fig 6). A dominant feature of the matrix is the strong positive covariance among parameters indicative of salinity and sodicity. Electrical conductivity (EC) and total dissolved solids (TDS) exhibit robust positive correlations with major ions such as Na^+ and Cl^-, as well as with key sodicity indices including SAR, KR, and %Na. Crucially, IWQI is strongly and positively correlated with this entire suite of parameters (R $>$ 0.9). This validates the IWQI as a comprehensive proxy, effectively integrating the synergistic effects of multiple degradation pathways into a single, robust metric.

Sodium emerges as the principal driver of water quality deterioration for agricultural use [69], evidenced by its high correlation coefficients with IWQI (r = 0.92), SAR (r = 0.81), and %Na (r = 0.84). The hydrogeochemical mechanism underlying this relationship is well-documented: elevated sodium concentrations in irrigation water, particularly relative to calcium and magnesium, promote the substitution of divalent cations on the soil's cation exchange complex [70,71]. This process weakens the electrostatic forces that bind clay particles, leading to aggregate destabilization and clay dispersion [72]. The

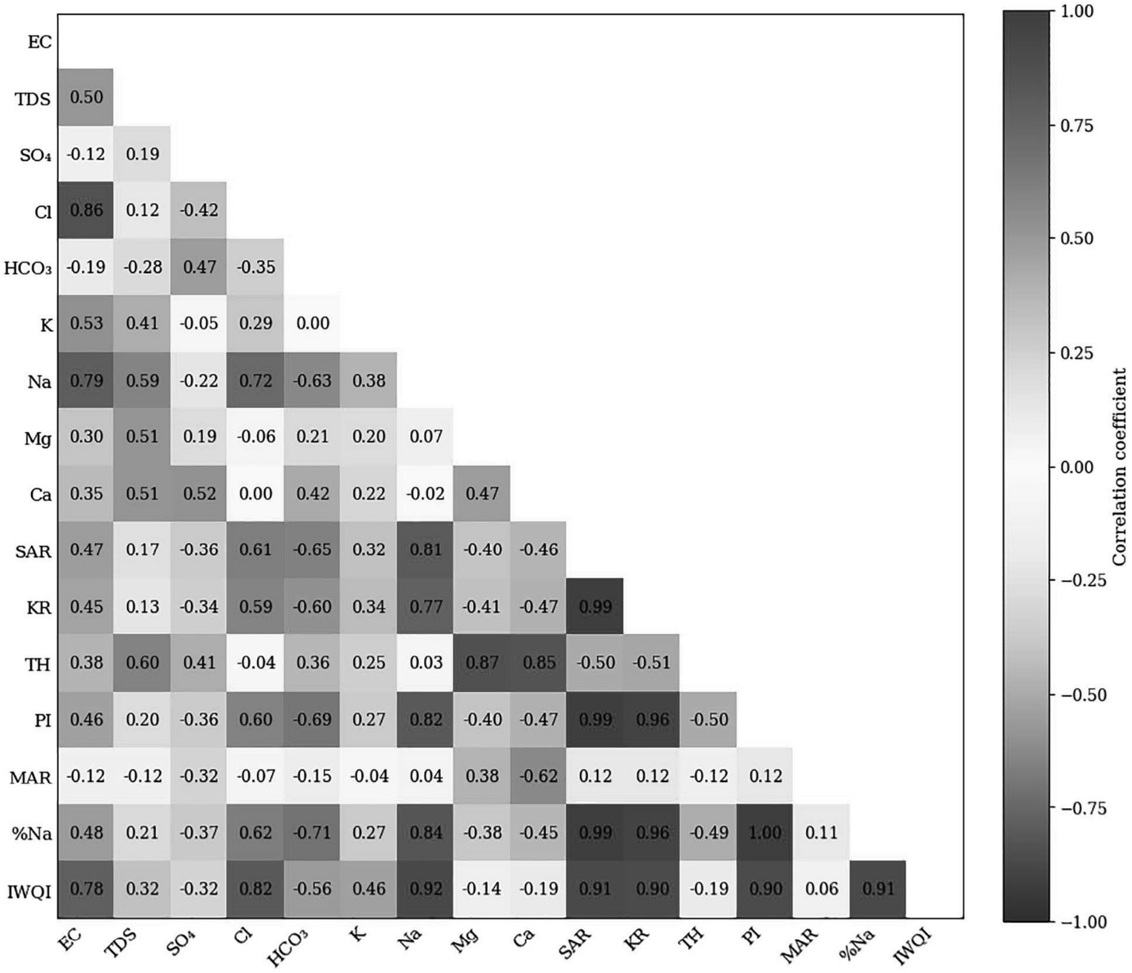

Fig 6. Correlations between IWQI, physicochemical parameters and different index.

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physical consequences are severe, including the clogging of soil pores, a significant reduction in hydraulic conductivity and water infiltration, and the creation of anaerobic conditions due to waterlogging [73]. These conditions directly impair root function, inhibit nutrient uptake, and ultimately suppress crop productivity [74]. Furthermore, the long-term accumulation of sodium can foster the formation of sodium carbonate and bicarbonate, driving soil pH upwards and exacerbating soil alkalization and degradation [45,116].

In contrast to the salinity-driven relationships, the matrix also reveals a distinct geogenic signature. The strong positive correlation between TH, Ca^{2}+, and Mg^{2}+ is indicative of water-rock interactions, primarily the dissolution of carbonate minerals (e.g., calcite and dolomite) within the aquifer matrix. Significantly, the negative correlation observed between bicarbonate (HCO_3^-) and the primary marine-sourced ions (Na^+ and Cl^-) suggests a competitive relationship between two dominant water types. This may reflect a simple dilution effect where bicarbonate-rich freshwaters mix with saline, chloride-dominated waters, or it may signify the presence of distinct hydrogeochemical facies within the aquifer system. This dichotomy confirms that the overall groundwater chemistry is governed by a dual influence: the natural weathering of carbonate geology and the superimposed effects of saline intrusion.

In conclusion, the correlation analysis substantiates that the fitness of groundwater for irrigation in the Collo Plain is primarily controlled by the balance between these geogenic and marine influences. The strong associations highlight the critical importance of monitoring not just bulk salinity (EC) but, more specifically, the ionic ratios that define sodicity hazards (i.e., SAR). Mitigating the risks of long-term soil degradation and ensuring agricultural sustainability necessitates proactive management [75]. The implementation of tailored strategies, including the blending of water sources, the application of chemical amendments like gypsum to counteract high sodium, and the adoption of advanced irrigation techniques to manage soil moisture and leaching, is imperative for preserving soil health and optimizing agricultural productivity in this vulnerable coastal environment [18].

Correlation analysis (Fig 6) confirmed strong positive relationships between EC, Na^+, Cl^-, and IWQI ($r > 0.9$), validating IWQI as a robust integrative metric. These findings are consistent with global reports from Tunisian and Indian coastal aquifers, highlighting the widespread impact of salinity-sodicity interactions on irrigation water quality. The consistency between matrix values and mechanistic interpretations underscores the dual geogenic and marine controls on groundwater chemistry in the Collo Plain.

3.4. Analytical hierarchy-based irrigation water quality index

The IWQI represents an invaluable diagnostic metric for governmental entities, environmental organizations, and communities to effectively monitor and and improve sustainable water resource management practices [76]. In this context, IWQI mapping is essential for assessing groundwater suitability for irrigation in the Collo plain, providing an essential resource for designing forward-looking agricultural management strategies. The calculated IWQI values within the study area fluctuate from 35.5 to 87.9 (avg. 56.8) (Table 7). These results were visually represented in the IWQI map (Fig 7), which delineated three distinct water quality classes across the surveyed region. Notably, 30% of groundwater samples fell into the good quality' category ($26 < IWQI < 50$), predominantly located north of the Guergoura locality and at the Hadjria locality in the northeast. This class is characterized by waters with low concentrations of alkaline elements and higher concentrations of alkaline-earth elements, indicative of 'hard waters'. These waters are generally more favorable for irrigation due to their lower propensity to cause soil salinization, an important consideration for sustainable agricultural practices in the region.

Furthermore, 56.66% of groundwater samples were categorized as poor quality ($51 < IWQI < 75$), representing the largest area within the study region. This class is divided in the same way as the poor class for electrical conductivity (Fig 5a), the permissible class for sodium percentage (Fig 5c), and the moderate class for permeability index (Fig 5e). Poor water quality within this class is associated with moderately high EC values, ascribed to pronounced sodium and chloride accretions, which engenders a perceptible decline in groundwater quality. This, in turn, poses formidable impediments to agricultural sustainability within the affected regions. In situ observation highlights the necessity for implementing integrated water quality management strategies to alleviate the detrimental effects of salinization and ion toxicity on soil fertility and agronomic yields.

A 13.3% prevalence of groundwater samples exhibited a very poor quality classification ($76 < IWQI < 100$), with a significant concentration observed in the northeastern part of the Collo plain, proximal to the Ouled Mazzouz region. This class demonstrates a concordance with the unsuitable class delineated by the Kelly's ratio index (Fig 5d). The latter represents a diagnostic index of the predominance of sodium ions compared with calcium and magnesium ions. Water quality degradation is symptomatic of the deterioration of groundwater resources, which can be attributed to a multitude of factors.

Firstly, groundwater contamination by fossilized water from ancient marine transgressions over geological timescales [27] represents a significant contributor. Additionally, geogenic sources, such as the dissolution of mineral phases and rock-water interactions, can further augment the concentrations of harmful ions. Furthermore, the adverse impacts of excessive anthropogenic activities must be considered. Such activities can introduce a multitude of contaminants,

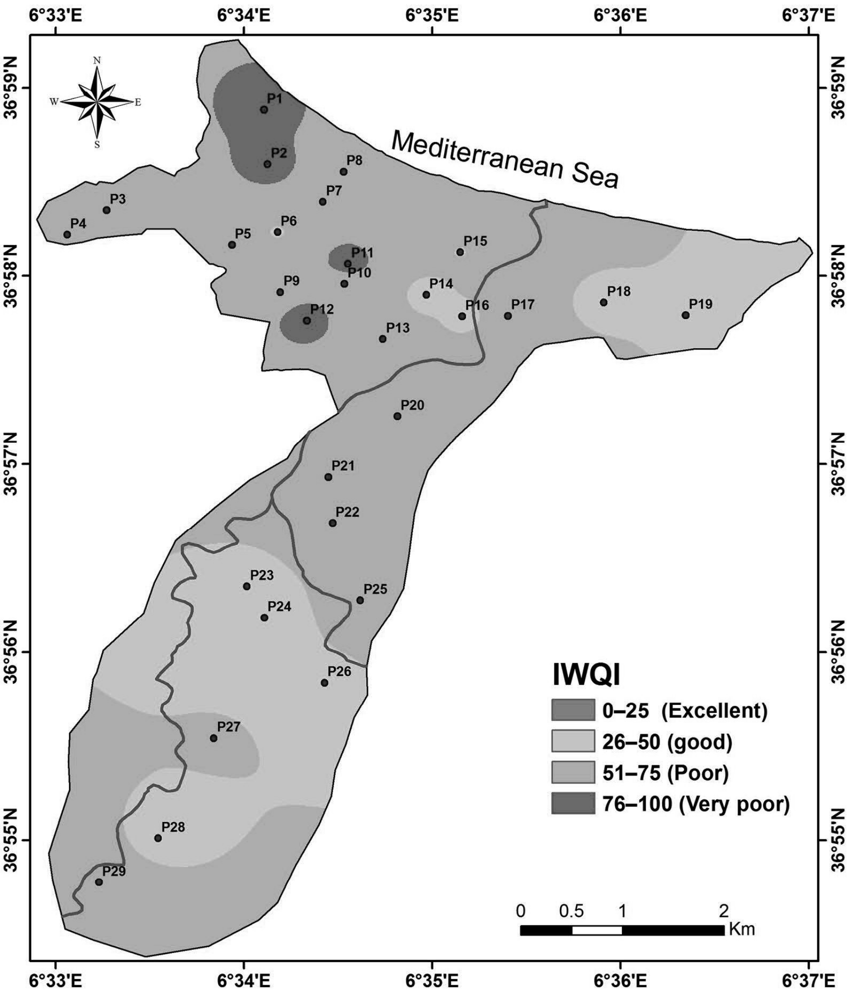

Fig 7. Spatial distribution of the IWQI scores.

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including organic pollutants, heavy metals, and excess nutrients, thereby posing significant risks to water quality and ecosystem health. In addition, unsupervised drainage of domestic waste aggravates the degradation of the groundwater.

Overall, IWQI classifications revealed that 30% of samples were Good, 56.7% Poor, and 13.3% Very Poor, with no samples falling into the Excellent or Unsuitable categories. The dominance of Poor and Very Poor classes highlights the severity of salinization and sodium hazards in the Collo Plain. These results are consistent with findings from Tunisian and Indian coastal aquifers, underscoring the global relevance of IWQI as a diagnostic tool for irrigation water management. The IWQI map (Fig 7) provides a practical decision-support resource for farmers and water managers, enabling targeted interventions to mitigate salinity and sodicity risks.

4. Discussion

The spatial variability of groundwater quality in the Collo Plain reflects the combined influence of natural hydrogeochemical processes and anthropogenic pressures. The calculated IWQI classes indicate a progressive deterioration of water quality from the upstream recharge areas toward the coastal zone, which is characterised by intensive agricultural activity.

This spatial trend reflects increasing mineralisation and gradual water quality degradation along the general flow direction of groundwater.

These patterns are consistent with water–rock interaction processes, including carbonate dissolution, silicate weathering, and cation exchange (Eqs 15–17), which drive gradual increases in electrical conductivity (2000–3000 μS/cm) and major ion concentrations as groundwater residence time increases.

$$CaCO_3\ (\text{Calcite})\ + H_2O\ +\ CO_2\ =\ Ca_2Ca2+\ +\ 2H\,CO_3^- \tag{15}$$

$$CaMg(CO_3)_2(\text{dolomite}) + 2H^+ =\ Ca^{2+} + Mg^{2+} +\ 2H\,CO_3^- \tag{16}$$

$$Na - clay\ + ½\,Ca^{2+}\ =\ Na^+\ +\ ½\,Ca - clay_2. \tag{17}$$

Comparable trends have been reported in coastal and semi-arid aquifers worldwide, where extended flow paths promote geochemical maturation [77,78]. In addition to natural processes, anthropogenic activities further modulate these spatial patterns, locally exacerbating the degradation of groundwater quality.

High concentrations of NO_3^-, NO_2^-, and NH_4^+ (18–98 mg/L, 0.10 to 0.42 mg/L, and 0.22 to 0.96 mg/L, respectively) provide clear hydrogeochemical evidence of anthropogenic influence, mainly related to agricultural practices and urban activities. These enrichments are mainly attributed to the excessive use of nitrogen fertilizers and the discharge of untreated wastewater.

Nitrate, a well-established tracer of anthropogenic pollution in shallow, unconfined aquifers, exhibits a spatial distribution that overlaps with areas of high population density and irrigated agriculture, indicating inputs from both domestic effluents and agrochemical sources. The concomitant presence of NO_2^- and NH_4^+ further suggests recent nitrogen inputs and active biogeochemical processes, including nitrification and mineralization of organic matter. Similar patterns of nitrate enrichment linked to wastewater infiltration and irrigation return flows have been reported in coastal aquifers in Saudi Arabia [78] and in other semi-urban and agricultural environments worldwide [79–90].

Over-exploitation of the aquifer is a major factor in the deterioration of groundwater quality in the Collo plain. Intensive pumping, mainly for irrigation purposes, causes a drop in piezometric levels, promotes vertical flows, and accelerates the transfer of contaminants from the surface to the aquifer. In coastal areas, these withdrawals also increase vulnerability to salinization processes, although direct marine intrusion is not yet predominant [59,91–93].

Similar degradation of groundwater quality linked to overexploitation has been widely documented in arid and semi-arid regions, particularly within the Saharan aquifer system [94–96].

The IWQI values calculated for the Collo plain indicate that groundwater quality is mostly poor to very poor for irrigation, with 56.66% of samples classified as poor and 13.33% as very poor. Only limited areas (30%) have water that is considered good quality and suitable for unrestricted use.

Comparison with similar studies highlights the relative severity of the deterioration observed in the Collo Plain. In the Al-Jawf basin in Yemen, IWQI-based assessments reported by Al-Mashreki et al. [97] show that most samples fall into the good to acceptable categories, reflecting lower anthropogenic pressure despite comparable climatic conditions. Similarly, studies conducted in the Souf Valley and Doucen Plain in Algeria [98,99] show slightly more favorable IWQI distributions, attributed to the presence of deeper aquifers and reduced exposure to surface contamination sources.

Conversely, assessments of irrigation water quality conducted in Ghana [100] and in certain regions of South Asia [101] show that IWQI values similar to those in the Collo Plain are generally associated with intensive agriculture, shallow aquifers, and limited wastewater treatment infrastructure. These comparisons place the Collo Plain among the moderately to severely stressed coastal aquifers worldwide, highlighting the urgent need to implement sustainable groundwater resource management strategies.

Conventional diagrams and multivariate statistical analysis confirm that groundwater chemistry in the Collo Plain is controlled by the combined effect of geogenic and anthropogenic sources. Carbonate dissolution is the main natural contribution to Ca^{2+} and HCO_3^- ions, while the relative enrichment of Na^+ relative to Cl^- observed in some samples reflects the influence of cation exchange processes. These mechanisms are consistent with classical models of hydrogeochemical evolution reported in different geographical contexts, notably in India and the Middle East [102–106]. Anthropogenic signatures, particularly nitrate enrichment, indicate diffuse pollution linked to agricultural practices and inputs from urban wastewater. Recent studies combining source attribution, quality indices, and advanced modeling approaches have shown that these integrated frameworks are essential for identifying complex contamination pathways [107–111]. The present study follows this approach by demonstrating that water quality indices, when interpreted in conjunction with hydrogeochemical signatures, constitute a robust diagnostic tool rather than a mere descriptive indicator [60,112].

Compared to previous regional and international studies, the originality of this work lies in its integrated spatial interpretation of IWQI results within a vulnerable Mediterranean coastal plain, explicitly linking index-based classifications with underlying hydrogeochemical processes and identifiable anthropogenic pressures. Moving beyond the conventional use of IWQI as a standalone indicator, this study advances irrigation water quality assessment by integrating AHP-derived parameter weighting, IWQI computation, and GIS-based spatial analysis. Limitations of this study include the restricted number of sampling points (30), seasonal coverage limited to September 2022, and reliance on IDW interpolation, which may smooth local variability. Future work should incorporate multi-seasonal sampling, larger datasets, and advanced geostatistical methods (e.g., kriging) to refine spatial predictions. This framework enhances robustness, enables mechanistic interpretation of IWQI patterns, and supports regional comparisons. The resulting IWQI maps therefore constitute an effective decision-support tool for farmers, water managers, and local authorities by identifying priority areas for intervention and supporting optimized irrigation planning, targeted monitoring, and mitigation measures such as controlled pumping, water blending, and soil amendment strategies [94,113–116].

The findings have direct implications for groundwater management in the Collo Plain and comparable coastal agricultural basins worldwide. Quantitative comparisons with Mediterranean, African, and Asian aquifers indicate that current groundwater exploitation practices in the Collo Plain are approaching thresholds observed in more severely degraded systems. Consequently, rationalizing groundwater withdrawals, strengthening wastewater treatment, and optimizing fertilizer application are essential to prevent further deterioration of groundwater quality. In this context, the study contributes not only to the local assessment of water resources but also to the broader scientific debate on the sustainable management of irrigation water in highly stressed coastal aquifers.

No samples in the Collo Plain fell into the Excellent or Unsuitable IWQI categories, with the majority classified as Poor to Very Poor. Limitations of this study include the restricted number of sampling points, single-season sampling, and reliance on IDW interpolation, which may smooth local variability. Future research should expand temporal coverage, increase sampling density, and apply advanced geostatistical techniques to refine predictions. Despite these limitations, the integrated GIS-AHP-IWQI framework provides a robust diagnostic tool for irrigation water quality assessment. Comparisons with aquifers in Yemen, Algeria, Ghana, and South Asia highlight that the Collo Plain is among the moderately to severely stressed coastal aquifers worldwide, underscoring the urgent need for sustainable groundwater management strategies.

5. Conclusion

This study presents an integrated and spatially explicit assessment of groundwater suitability for irrigation in the Collo Plain (northeastern Algeria) through the combined application of hydrogeochemical analysis, an AHP-weighted Irrigation Water Quality Index (IWQI), and Geographic Information Systems (GIS). By incorporating multi-criteria decision-making into the IWQI framework, the proposed methodology overcomes the limitations of conventional single-parameter or unweighted index approaches and provides a more realistic evaluation of irrigation water quality in complex coastal aquifer systems.

The results reveal pronounced spatial variability in groundwater quality across the study area. IWQI values ranged from 35.5 to 87.9, indicating that about 30% of the aquifer is suitable for irrigation, 56.7% is classified as poor, and 13.3% as very poor, with the latter mainly concentrated in the northeastern coastal sector near Ouled Mazzouz. This degradation is mainly driven by elevated salinity and sodium hazards, associated with marine intrusion, paleomarine deposits, geogenic water–rock interactions, and intensified anthropogenic pressures, including agricultural practices and untreated domestic effluents. The strong correlations observed between IWQI, electrical conductivity, sodium-related indices, and major ions confirm that salinity and sodicity are the dominant constraints on irrigation suitability in the Collo Plain.

This study has certain limitations, including the use of a single sampling campaign and the absence of analyses of trace elements, which may influence the suitability of groundwater for irrigation. Future research should incorporate multi-seasonal monitoring, isotopic and geochemical tracers, and soil and crop sensitivity analysis, while taking into account climate change and groundwater withdrawal trends. Despite these limitations, the proposed GIS-AHP-IWQI framework is transferable to other semi-arid and coastal agricultural regions and is a relevant tool for improving sustainable water resource management and supporting water and agricultural security.

Supporting information

S1 Checklist. Inclusivity in global research.
(DOCX)

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References

1. FAO. The State of the World's Land and Water Resources for Food and Agriculture – Systems at Breaking Point. Rome: FAO. 2022. https://doi.org/10.4060/cb9910en
2. World Health Organization. Guidelines for drinking-water quality: incorporating the first and second addenda. World Health Organization. 2022. https://www.who.int/publications/i/item/9789240045064

3. Maghrebi M, Noori R, Bhattarai R, Mundher Yaseen Z, Tang Q, Al-Ansari N, et al. Iran's Agriculture in the Anthropocene. Earth's Future. 2020;8(9). https://doi.org/10.1029/2020ef001547
4. Singh G, Singh J, Wani OA, Egbueri JC, Agbasi JC. Assessment of groundwater suitability for sustainable irrigation: A comprehensive study using indexical, statistical, and machine learning approaches. Groundwater for Sustainable Development. 2024;24:101059. https://doi.org/10.1016/j.gsd.2023.101059
5. Kim HI, Kim D, Mahdian M, Salamattalab MM, Bateni SM, Noori R. Incorporation of water quality index models with machine learning-based techniques for real-time assessment of aquatic ecosystems. Environ Pollut. 2024;355:124242. https://doi.org/10.1016/j.envpol.2024.124242 PMID: 38810684
6. Çelik MÖ, Kuşak L, Yakar M. Assessment of groundwater potential zones utilizing geographic information system-based analytical hierarchy process, Vlse Kriterijumska Optimizacija Kompromisno Resenje, and technique for order preference by similarity to ideal solution methods: a case study in Mersin, Türkiye. Sustainability. 2024;16(5):2202. https://doi.org/10.3390/su16052202
7. Mamun M, Kim JY, An K-G. Multivariate Statistical Analysis of Water Quality and Trophic State in an Artificial Dam Reservoir. Water. 2021;13(2):186. https://doi.org/10.3390/w13020186
8. Njuguna SM, Onyango JA, Githaiga KB, Gituru RW, Yan X. Application of multivariate statistical analysis and water quality index in health risk assessment by domestic use of river water. Case study of Tana River in Kenya. Process Safety and Environmental Protection. 2020;133:149–58. https://doi.org/10.1016/j.psep.2019.11.006
9. Alcamo J. Water quality and its interlinkages with the Sustainable Development Goals. Current Opinion in Environmental Sustainability. 2019;36:126–40. https://doi.org/10.1016/j.cosust.2018.11.005
10. Noori R, Maghrebi M, Mirchi A, Tang Q, Bhattarai R, Sadegh M, et al. Anthropogenic depletion of Iran's aquifers. Proc Natl Acad Sci U S A. 2021;118(25):e2024221118. https://doi.org/10.1073/pnas.2024221118 PMID: 34161268
11. Chakravarty T, Gupta S. Assessment of water quality of a hilly river of south Assam, north east India using water quality index and multivariate statistical analysis. Environmental Challenges. 2021;5:100392. https://doi.org/10.1016/j.envc.2021.100392
12. Kouadri S, Pande CB, Panneerselvam B, Moharir KN, Elbeltagi A. Prediction of irrigation groundwater quality parameters using ANN, LSTM, and MLR models. Environ Sci Pollut Res Int. 2022;29(14):21067–91. https://doi.org/10.1007/s11356-021-17084-3 PMID: 34748181
13. Alizadeh M, Noori R, Omidvar B, Nohegar A, Pistre S. Human health risk of nitrate in groundwater of Tehran-Karaj plain, Iran. Sci Rep. 2024;14(1):7830. https://doi.org/10.1038/s41598-024-58290-6 PMID: 38570538
14. Al-Shammary SHE, Al-Mayyahi SOM. Groundwater quality assessment for drinking purposes using water quality index in Ali Al-Gharbi District, Iraq. Journal of Water and Land Development. 2021;:274–80. https://doi.org/10.24425/jwld.2021.138183
15. Ben Moussa A, Guerchi A, Bel Haj Salem S. Assessment of the suitability of groundwater quality for drinking and irrigation purposes using water quality indices: a case study of the Ghardimaou shallow aquifer, North-western Tunisia. Arab J Geosci. 2021;14:2584. https://doi.org/10.1007/s12517-021-08712-w
16. Gautam VK, Pande CB, Moharir KN, Varade AM, Rane NL, Egbueri JC, et al. Prediction of Sodium Hazard of Irrigation Purpose using Artificial Neural Network Modelling. Sustainability. 2023;15(9):7593. https://doi.org/10.3390/su15097593
17. Hussein HA, Ricka A, Kuchovsky T, El Osta MM. Groundwater hydrochemistry and origin in the south-eastern part of Wadi El Natrun, Egypt. Arab J Geosci. 2017;10:170–84. https://doi.org/10.1007/s12517-017-2960-x
18. Singh G, Rishi MS, Arora NK. Integrated GIS-based modelling approach for irrigation water quality suitability zonation in parts of Satluj River Basin, Bist Doab region, North India. SN Appl Sci. 2019;1(11). https://doi.org/10.1007/s42452-019-1405-4
19. Regmi RK, Mishra BK, Masago Y, Luo P, Toyozumi-Kojima A, Jalilov S-M. Applying a water quality index model to assess the water quality of the major rivers in the Kathmandu Valley, Nepal. Environ Monit Assess. 2017;189(8):382. https://doi.org/10.1007/s10661-017-6090-4 PMID: 28685372
20. Şener Ş, Şener E, Davraz A. Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey). Sci Total Environ. 2017;584–585:131–44. https://doi.org/10.1016/j.scitotenv.2017.01.102 PMID: 28147293
21. Unigwe CO, Egbueri JC, Omeka ME. Geospatial and statistical approaches to nitrate health risk and groundwater quality assessment of an alluvial aquifer in SE Nigeria for drinking and irrigation purposes. Journal of the Indian Chemical Society. 2022;99(6):100479. https://doi.org/10.1016/j.jics.2022.100479
22. Alvando PV, Rohmat D, Rohmat FIW, Irawan DE. Integrating GIS-Based AHP and groundwater quality assessment to delineate groundwater potential zones in the Rontu Watershed, West Nusa Tenggara, Indonesia. Results in Earth Sciences.:100110. https://doi.org/10.1016/j.rines.2025.100110
23. Salem S, Gaagai A, Ben Slimene I, Moussa A, Zouari K, Yadav K, et al. Applying Multivariate Analysis and Machine Learning Approaches to Evaluating Groundwater Quality on the Kairouan Plain, Tunisia. Water. 2023;15(19):3495. https://doi.org/10.3390/w15193495
24. Derdour A, Jodar-Abellan A, Pardo MÁ, Ghoneim SSM, Hussein EE. Designing Efficient and Sustainable Predictions of Water Quality Indexes at the Regional Scale Using Machine Learning Algorithms. Water. 2022;14(18):2801. https://doi.org/10.3390/w14182801
25. Azzeddine R, Abdelmalek D, Ewuzie U, Faouzi Z, Taha-Hocine D. Compositional data analysis (CoDA) and geochemical signatures of the terminal complex aquifer in an arid zone (northeastern Algeria). Journal of African Earth Sciences. 2024;210:105162. https://doi.org/10.1016/j.jafrearsci.2023.105162

26. Hussein EE, Jat Baloch MY, Nigar A, Abualkhair HF, Aldawood FK, Tageldin E. Machine Learning Algorithms for Predicting the Water Quality Index. Water. 2023;15(20):3540. https://doi.org/10.3390/w15203540
27. Chabour N. La surexploitation des eaux souterraines dans les plaines littorales: la nappe de Télezza dans la plaine de Collo (nord-est algérien). Sciences & Technologie. 2004;22:127–32.
28. Bouillin JP. Géologie alpine de la petite Kabylie dans les régions de Collo et El Milia. France: Univ de Paris. 1979.
29. Raoult JF. Nouvelles donnees sur les flyschs au nord du Kef Sidi Dris et dans la zone du col des Oliviers (nord du Constantinois, Algerie). Bull Soc Geol de France. 1969;S7-Xi(4):516–22. https://doi.org/10.2113/gssgfbull.s7-xi.4.516
30. Vila JM. La chaîne alpine d'Algérie orientale et des confins algero-tunisiens. Paris VI: Université Pierre et Marie Curie. 1980.
31. Mecibah I. Les ressources en eau et gestion intégrée du bassin versant d'Oued Guebli (Nord-Est Algérien). Univ Annaba. 2017.
32. Massoumi A, Cornfield AH. A rapid method for determining sulphate in water extracts of soils. Analyst. 1963;88(1045):321. https://doi.org/10.1039/an9638800321
33. Deutsch WJ. Groundwater Geochemistry: Fundamentals and Applications to Contamination. Boca Raton, FL, USA: Lewis Publishers. 1997.
34. Shil S, Singh UK, Mehta P. Water quality assessment of a tropical river using water quality index (WQI), multivariate statistical techniques and GIS. Appl Water Sci. 2019;9(7). https://doi.org/10.1007/s13201-019-1045-2
35. Wilcox LV. Classification and use of irrigation waters. Washington, DC: USDA. 1955.
36. Richards LA. Diagnosis and improvement of saline and alkali soils. New Delhi: USDA and IBH Pub. Coy Ltd. 1954.
37. Kelly WP. Alkali soils-their formation, properties and reclamation. New York: Reinhold Publ. 1951.
38. Doneen LD. Notes on water quality in agriculture. 4001. California: Department of Water Sciences and Engineering, University of California. 1964.
39. Raghunath, HM, 1987. Groundwater. Wiley Eastern Ltd, New Delhi, p 563.
40. Todd D. Groundwater hydrogeology. 2nd ed. New York: Willey. 1980.
41. Saaty TL. Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World. Pittsburgh, PA, USA: RWS Publications. 1990.
42. Yeh HF, Lee CH, Hsu KC, Chang PH. GIS for the assessment of the groundwater recharge potential zone. Environ Earth Sci. 2008;58:185–95. https://doi.org/10.1007/s00254-008-1504-9
43. Saaty TL. Decision making with the analytic hierarchy process. Int J Serv Sci. 2008;1:83–98.
44. Saaty TL. The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. New York, NY, USA: McGraw. 1980.
45. Singh LK, Jha MK, Chowdary VM. Multi-criteria analysis and GIS modeling for identifying prospective water harvesting and artificial recharge sites for sustainable water supply. Journal of Cleaner Production. 2017;142:1436–56. https://doi.org/10.1016/j.jclepro.2016.11.163
46. Lentswe GB, Molwalefhe L. Delineation of potential groundwater recharge zones using analytic hierarchy process-guided GIS in the semi-arid Motloutse watershed, eastern Botswana. J Hydrol Reg Stud. 2020;28:100674. https://doi.org/10.1016/j.ejrh.2020.100674
47. Rezaei-Moghaddam K, Karami E. A multiple criteria evaluation of sustainable agricultural development models using AHP. Environ Dev Sustain. 2007;10:407–26. https://doi.org/10.1007/s10668-006-9072-1
48. Jahan CS, Rahaman MdF, Arefin R, Ali MdS, Mazumder QH. Delineation of groundwater potential zones of Atrai–Sib river basin in north-west Bangladesh using remote sensing and GIS techniques. Sustain Water Resour Manag. 2018;5(2):689–702. https://doi.org/10.1007/s40899-018-0240-x
49. Sahoo S, Dhar A, Kar A, Ram P. Grey analytic hierarchy process applied to effectiveness evaluation for groundwater potential zone delineation. Geocarto International. 2016;32(11):1188–205. https://doi.org/10.1080/10106049.2016.1195888
50. Bojer AK, Bekalo DJ, Debelee TG, Nadarajah S, Al-Quraishi AMF. Rainwater Harvesting Site Selection for Drought-Prone Areas in Somali and Borena Zones, Oromia Regional State, Ethiopia: A Geospatial and Multi-Criteria Decision Analysis. Water. 2024;16(13):1789. https://doi.org/10.3390/w16131789
51. Bonilla Valverde J, Blank C, Roidt M, Schneider L, Stefan C. Application of a GIS Multi-Criteria Decision Analysis for the Identification of Intrinsic Suitable Sites in Costa Rica for the Application of Managed Aquifer Recharge (MAR) through Spreading Methods. Water. 2016;8(9):391. https://doi.org/10.3390/w8090391
52. Mageshkumar P, Subbaiyan A, Lakshmanan E, Thirumoorthy P. Application of geospatial techniques in delineating groundwater potential zones: A case study from South India. Arab J Geosci. 2019;12:151. https://doi.org/10.1007/s12517-019-4289-0
53. Rahmati O, Samani AAN, Mahdavi M, Pourghasemi HR, Zeinivand H. Groundwater potential mapping at Kurdistan region of Iran using analytic hierarchy process and GIS. Arab J Geosci. 2014;8:7059–71. https://doi.org/10.1007/s12517-014-1668-4
54. FAO. World agriculture towards 2030/2050. Prospects for food, nutrition, agriculture, and major commodity groups. Interim report. Rome: Food and Agriculture Organization of the United Nations. 2006.
55. Zahi F, Medjani F, Djidel M, Drouiche A. Groundwater quality and its suitability for different uses in lower Djendjen Watershed, Northest Algeria. AJRC. 2021;:179–85. https://doi.org/10.52711/0974-4150.2021.00033
56. Drouiche A, Zahi F, Debieche TH, Lekoui A, Mahdid S. Assessment of surface water quality: a case of Jijel region, North-East Algeria. Arab J Geosci. 2022;15:252. https://doi.org/10.1007/s12517-022-09458-9

57. Liu J, Wang H, Jin D, Xu F, Zhao C. Hydrochemical characteristics and evolution processes of karst groundwater in Carboniferous Taiyuan formation in the Pingdingshan coalfield. Environ Earth Sci. 2020;79(6). https://doi.org/10.1007/s12665-020-8898-4

58. Chadha DK. A proposed new diagram for geochemical classification of natural waters and interpretation of chemical data. Hydrogeol J. 1999;7:431–9. https://doi.org/10.1007/s100400050216

59. Boumaiza L, Chesnaux R, Drias T, Walter J, Huneau F, Garel E, et al. Identifying groundwater degradation sources in a Mediterranean coastal area experiencing significant multi-origin stresses. Sci Total Environ. 2020;746:141203. https://doi.org/10.1016/j.scitotenv.2020.141203 PMID: 32795761

60. Hfaiedh E, Gaagai A, Moussa AB, Petitta M, Mlayah A, Elsayed S, et al. An Innovative ML and GIS-Integrated Approach for Predicting Irrigation Water Quality in Coastal Aquifers. Earth Syst Environ. 2025. https://doi.org/10.1007/s41748-025-00851-4

61. Vaiphei SP, Kurakalva RM, Sahadevan DK. Water quality index and GIS-based technique for assessment of groundwater quality in Wanaparthy watershed, Telangana, India. Environ Sci Pollut Res Int. 2020;27(36):45041–62. https://doi.org/10.1007/s11356-020-10345-7 PMID: 32779065

62. Zahi F, Drouiche A, Medjani F, Azzeddine R, Djidel M. Hydrogeochemical processes controlling surface water quality for irrigation in a Mediterranean wetland ecosystem, Northeast Algeria. Environ Monit Assess. 2024;196(10):881. https://doi.org/10.1007/s10661-024-13019-w PMID: 39223287

63. Sappa G, Ergul S, Ferranti F. Water quality assessment of carbonate aquifers in southern Latium region, Central Italy: a case study for irrigation and drinking purposes. Appl Water Sci. 2013;4(2):115–28. https://doi.org/10.1007/s13201-013-0135-9

64. Hadef S, Zahi F, Debieche TH, Drouiche A, Lekoui A. Assessment of the surface water suitability for irrigation purposes: Case of the Guenitra dam watershed (Skikda, NE Algeria). Jordan J Earth and Environ Sci. 2021;12(4):344–52.

65. Jain CK, Vaid U. Assessment of groundwater quality for drinking and irrigation purposes using hydrochemical studies in Nalbari district of Assam, India. Environ Earth Sci. 2018;77(6). https://doi.org/10.1007/s12665-018-7422-6

66. Bouderbala A. Assessment of Water Quality Index for the Groundwater in the Upper Cheliff Plain, Algeria. Journal of the Geological Society of India. 2017;90(3):347–56. https://doi.org/10.1007/s12594-017-0723-7

67. Barik R, Pattanayak SK. Assessment of groundwater quality for irrigation of green spaces in the Rourkela city of Odisha, India. Groundwater for Sustainable Development. 2019;8:428–38. https://doi.org/10.1016/j.gsd.2019.01.005

68. Chidambaram S, Bala Krishna Prasad M, Manivannan R, Karmegam U, Singaraja C, Anandhan P, et al. Environmental hydrogeochemistry and genesis of fluoride in groundwaters of Dindigul district, Tamilnadu (India). Environ Earth Sci. 2012;68(2):333–42. https://doi.org/10.1007/s12665-012-1741-9

69. Maghrebi M, Noori R, Partani S, Araghi A, Barati R, Farnoush H, et al. Iran's Groundwater Hydrochemistry. Earth and Space Science. 2021;8(8). https://doi.org/10.1029/2021ea001793

70. Zahi F, Drouiche A, Medjani F, Lekoui A, Djidel M. Evaluation of soil salinity of the Fetzara Lake Region (North-East Algeria). FENS. 2022;21(2). https://doi.org/10.4316/fens.2022.016

71. Tolossa HH. Assessment of salinity status of soils and irrigation water quality in dry season wheat production in selected districts of west hararghe zone, ethiopia. Haramaya University. 2023.

72. Hu F, Li S, Xu C, Gao X, Miao S, Ding W, et al. Effect of soil particle interaction forces in a clay-rich soil on aggregate breakdown and particle aggregation. European J Soil Science. 2018;70(2):268–77. https://doi.org/10.1111/ejss.12740

73. Zhu W, Gu S, Jiang R, Zhang X, Hatano R. Saline–Alkali Soil Reclamation Contributes to Soil Health Improvement in China. Agriculture. 2024;14(8):1210. https://doi.org/10.3390/agriculture14081210

74. Xing Y, Wang X, Mustafa A. Exploring the link between soil health and crop productivity. Ecotoxicol Environ Saf. 2025;289:117703. https://doi.org/10.1016/j.ecoenv.2025.117703 PMID: 39808880

75. Mishra H. Environmental degradation and impacts on agricultural production: A challenge to urban sustainability. In Sustainable urban environment and waste management: Theory and practice (pp. 53–92). Singapore: Springer Nature Singapore. 2025.

76. khezami F, Khiari N, Drouiche A, Chkirbene A, Zahi F, Debieche T-H, et al. Hydrogeochemical assessment and modeling of groundwater processes and pollution: a case study of the Grombalia aquifer in Northeast Tunisia. Model Earth Syst Environ. 2024;10(3):3573–92. https://doi.org/10.1007/s40808-024-01968-7

77. Masoud M, El Osta M, Alqarawy A, Elsayed S, Gad M. Evaluation of groundwater quality for agricultural under different conditions using water quality indices, partial least squares regression models, and GIS approaches. Applied Water Science. 2022;12(10):244. https://doi.org/10.1007/s13201-022-01770-9

78. Abba SI, Egbueri JC, Benaafi M, Usman J, Usman AG, Aljundi IH. Fluoride and nitrate enrichment in coastal aquifers of the Eastern Province, Saudi Arabia: The influencing factors, toxicity, and human health risks. Chemosphere. 2023;336:139083. https://doi.org/10.1016/j.chemosphere.2023.139083 PMID: 37331666

79. Abagissa WY, Geremew GB, Ayana MT, Ayele EG, Tilahun AK. GIS-based surface irrigation potential assessment of Gololcha River Watershed, Awash Basin, Ethiopia. World Water Policy. 2025;11(1):326–52.

80. Boukich O, Ben-tahar R, Brahmi M, Alzain MN, Noman O, Shahat AA, et al. Assessment of groundwater quality for irrigation using a new customized irrigation water quality index. Journal of Hydrology: Regional Studies. 2025;59:102346. https://doi.org/10.1016/j.ejrh.2025.102346

81. Egbueri JC, Agbasi JC, Ikwuka CF, Chiaghanam OI, Khan MI, Khan MYA, et al. Nitrate health risk and geochemical characteristics of water in a semi-urban: implications from graphical plots and statistical computing. International Journal of Environmental Analytical Chemistry. 2023;104(19):8491–511. https://doi.org/10.1080/03067319.2023.2206022

82. Boulabeiz M, Klebingat S, Belgacem H, Bousnoubra H. GIS-based GALDIT method for vulnerability assessment to seawater intrusion of the Quaternary coastal Collo aquifer (NE-Algeria). Arab J Geosci. 2018;11:1–14. https://doi.org/10.1007/s12517-018-3400-2

83. Saaidia B, Mahia M, Chaab S. Identification of marine intrusion in the plain of Collo, northeastern Algeria. Journal of Water and Land Development. 2017;35(1):211–9. https://doi.org/10.1515/jwld-2017-0086

84. Mecibah I, Medjani F, Zahi F, Djidel M. Groundwater quality assessment using Water Quality Indices and GIS within the Oued Guebli Downstream Subbasin (Collo plain, Northeastern Algeria). Environ Eng Manag J. 2024;23(4):755–70. https://doi.org/10.30638/eemj.2024.059

85. Abdelkarim B, Telahigue F, Abaab N, Boudabra B, Agoubi B. AHP and GIS for assessment of groundwater suitability for irrigation purpose in coastal-arid zone: Gabes region, southeastern Tunisia. Environ Sci Pollut Res Int. 2023;30(6):15422–37. https://doi.org/10.1007/s11356-022-23193-4 PMID: 36169841

86. Eid MH, Elbagory M, Tamma AA, Gad M, Elsayed S, Hussein H, et al. Evaluation of groundwater quality for irrigation in deep aquifers using multiple graphical and indexing approaches supported with machine learning models and GIS techniques, Souf Valley, Algeria. Water. 2023;15(1):182. https://doi.org/10.3390/w15010182

87. Gaagai A, Aouissi HA, Bencedira S, Hinge G, Athamena A, Heddam S, et al. Application of water quality indices, machine learning approaches, and GIS to identify groundwater quality for irrigation purposes: A case study of Sahara Aquifer, Doucen Plain, Algeria. Water. 2023;15(2):289. https://doi.org/10.3390/w15020289

88. Al-Mashreki MH, Eid MH, Saeed O, Székács A, Szűcs P, Gad M, et al. Integration of Geochemical Modeling, Multivariate Analysis, and Irrigation Indices for Assessing Groundwater Quality in the Al-Jawf Basin, Yemen. Water. 2023;15(8):1496. https://doi.org/10.3390/w15081496

89. Abu M, Egbueri JC, Agbasi JC. Groundwater quality assessment for drinking and irrigation uses within the vicinities of Volta Lake and Akosombo Dam in Ghana: a multi-methodological approach. Environ Earth Sci. 2025;84(7). https://doi.org/10.1007/s12665-025-12174-8

90. Ibrahim H, Yaseen ZM, Scholz M, Ali M, Gad M, Elsayed S, et al. Evaluation and Prediction of Groundwater Quality for Irrigation Using an Integrated Water Quality Indices, Machine Learning Models and GIS Approaches: A Representative Case Study. Water. 2023;15(4):694. https://doi.org/10.3390/w15040694

91. Karmakar B, Singh MK, Choudhary BK, Singh SK, Egbueri JC, Gautam SK, et al. Investigation of the hydrogeochemistry, groundwater quality, and associated health risks in industrialized regions of Tripura, northeast India. Environmental Forensics. 2021;24(5–6):285–306. https://doi.org/10.1080/15275922.2021.2006363

92. Shahmirnoori A, Hasani Zonoozi M, Samadi M. Evaluating groundwater quality using health risk assessment and irrigation indexes: Saveh Aquifer, Iran. Water Practice & Technology. 2023;18(12):3333–46. https://doi.org/10.2166/wpt.2023.216

93. Jodhani KH, Gupta N, Dadia S, Patel H, Patel D, Jamjareegulgarn P, et al. Sustainable groundwater management through water quality index and geochemical insights in Valsad India. Sci Rep. 2025;15(1):8769. https://doi.org/10.1038/s41598-025-92053-1 PMID: 40082503

94. Raheja H, Goel A, Pal M. Groundwater quality appraisal using IWQI and PCA for irrigation uses. ISH Journal of Hydraulic Engineering. 2023;29(sup1):264–73. https://doi.org/10.1080/09715010.2023.2218829

95. Eid MH, Saeed O, Szűcs P, Kovács A, Székács A, Mörtl M, et al. Impacts and sources of potential toxic elements on water quality and optimizing machine learning models for sustainable management. Model Earth Syst Environ. 2025;11(5). https://doi.org/10.1007/s40808-025-02548-z

96. Egbueri JC, Agbasi JC, Khan MYA, Abba SI, Turki AF, ElKashouty M. Assessing the Environmental, Health, and Food Security Implications of Heavy Metals in Irrigation Water: A Multi-Index Analytical Framework. Analytical Letters. 2025;59(3):373–408. https://doi.org/10.1080/00032719.2025.2484451

97. Hussein EE, Derdour A, Zerouali B, Almaliki A, Wong YJ, Ballesta-de los Santos M, et al. Groundwater Quality Assessment and Irrigation Water Quality Index Prediction Using Machine Learning Algorithms. Water. 2024;16(2):264. https://doi.org/10.3390/w16020264

98. Lakhdari AS, Bouselsal B, Saibi H, Ouarekh M. Assessment of groundwater quality and hydrogeochemical properties in the adrar continental intercalaire aquifer of the Algerian Sahara. Appl Water Sci. 2025;15(7). https://doi.org/10.1007/s13201-025-02552-9

99. Anyango GW, Bhowmick GD, Sahoo Bhattacharya N. A critical review of irrigation water quality index and water quality management practices in micro-irrigation for efficient policy making. Desalination and Water Treatment. 2024;318:100304. https://doi.org/10.1016/j.dwt.2024.100304

100. AbdelRahman MAE, Farg E, Saleh AM, Sayed M, Abutaleb K, Arafat SM, et al. Mapping of soils and land-related environmental attributes in modern agriculture systems using geomatics. Sustain Water Resour Manag. 2022;8(4). https://doi.org/10.1007/s40899-022-00704-2

101. Megahed HA, GabAllah HM, AbdelRahman MAE, D'Antonio P, Scopa A, Darwish MH. Geomatics-Based Modeling and Hydrochemical Analysis for Groundwater Quality Mapping in the Egyptian Western Desert: A Case Study of El-Dakhla Oasis. Water. 2022;14(24):4018. https://doi.org/10.3390/w14244018

102. Megahed HA, GabAllah HM, Ramadan RH, AbdelRahman MAE, D'Antonio P, Scopa A, et al. Groundwater Quality Assessment Using Multi-Criteria GIS Modeling in Drylands: A Case Study at El-Farafra Oasis, Egyptian Western Desert. Water. 2023;15(7):1376. https://doi.org/10.3390/w15071376

103. Saraswat A, Nath T, Omeka ME, Unigwe CO, Anyanwu IE, Ugar SI, et al. Irrigation suitability and health risk assessment of groundwater resources in the Firozabad industrial area of north-central India: An integrated indexical, statistical, and geospatial approach. Front Environ Sci. 2023;11:1116220. https://doi.org/10.3389/fenvs.2023.1116220

104. Abrams W, Ghoneim E, Shew R, LaMaskin T, Al-Bloushi K, Hussein S, et al. Delineation of groundwater potential (GWP) in the northern United Arab Emirates and Oman using geospatial technologies in conjunction with Simple Additive Weight (SAW), Analytical Hierarchy Process (AHP), and Probabilistic Frequency Ratio (PFR) techniques. Journal of Arid Environments. 2018;157:77–96. https://doi.org/10.1016/j.jaridenv.2018.05.005

105. Bouselsal B, Satouh A, Egbueri JC, Hashim MA, Arafat AA, Paramasivam P, et al. Groundwater for drinking and sustainable agriculture and public health hazards of nitrate: Developmental and sustainability implications for an arid aquifer system. Results in Engineering. 2025;25:104160. https://doi.org/10.1016/j.rineng.2025.104160

106. Etuk MN, Igwe O, Egbueri JC. An integrated geoinformatics and hydrogeological approach to delineating groundwater potential zones in the complex geological terrain of Abuja, Nigeria. Model Earth Syst Environ. 2022;9(1):285–311. https://doi.org/10.1007/s40808-022-01502-7

107. Foufou A. The development of mountain agriculture in the wilaya of Skikda (eastern Algeria) facing new legal framework, program evaluation in action and future prospects. Int J Adv Res. 2015;3(5):824–34.

108. Hussain G, Al-Saati AJ, Al-Wardy MB. Groundwater quality and its effects on soil and plant health in Al-Rustaq area. J Mater Environ Sci. 2019;10:543–55.

109. Khan MYA, ElKashouty M, Zaidi FK, Egbueri JC. Mapping Aquifer Recharge Potential Zones (ARPZ) Using Integrated Geospatial and Analytic Hierarchy Process (AHP) in an Arid Region of Saudi Arabia. Remote Sensing. 2023;15(10):2567. https://doi.org/10.3390/rs15102567

110. Megahed HA, Farrag AE-HA, Mohamed AA, Darwish MH, AbdelRahman MAE, El-Bagoury H, et al. GIS-based modeling and analytical approaches for groundwater quality suitability for different purposes in the Egyptian Nile Valley, a case study in Wadi Qena. Front Water. 2025;7. https://doi.org/10.3389/frwa.2025.1502169

111. Murmu P, Kumar M, Lal D, Sonker I, Singh SK. Delineation of groundwater potential zones using geospatial techniques and analytical hierarchy process in Dumka district, Jharkhand, India. Groundw Sustain Dev. 2019;9:100239. https://doi.org/10.1016/j.gsd.2019.100239

112. Nithya CN, Srinivas Y, Magesh NS, Kaliraj S. Assessment of groundwater potential zones in Chittar basin, Southern India using GIS based AHP technique. Remote Sensing Applications: Society and Environment. 2019;15:100248. https://doi.org/10.1016/j.rsase.2019.100248

113. Pande CB, Tolche AD, Egbueri JC, Mohd Sidek L, Singh R, Mishra AP, et al. Implications of seasonal variations of hydrogeochemical analysis using GIS, WQI, and statistical analysis method for the semi-arid region. Appl Water Sci. 2025;15(4). https://doi.org/10.1007/s13201-025-02387-4

114. Selvakumar S, Chandrasekar N, Kumar G. Hydrogeochemical characteristics and groundwater contamination in the rapid urban development areas of Coimbatore, India. Water Resources and Industry. 2017;17:26–33. https://doi.org/10.1016/j.wri.2017.02.002

115. Singh S, Ghosh NC, Gurjar S, Krishan G, Kumar S, Berwal P. Index-based assessment of suitability of water quality for irrigation purpose under Indian conditions. Environ Monit Assess. 2017;190(1):29. https://doi.org/10.1007/s10661-017-6407-3 PMID: 29260421

116. Snousy MG, Wu J, Su F, Abdelhalim A, Ismail E. Groundwater Quality and Its Regulating Geochemical Processes in Assiut Province, Egypt. Expo Health. 2021;14(2):305–23. https://doi.org/10.1007/s12403-021-00445-1