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Integrated assessment of groundwater quality in the Mitidja Plain (Algeria) using Moran's I Spatial Analysis, Groundwater Pollution Index (GPI), and Entropy-Weighted Water Quality Index (EWQI) in support of artificial recharge planning

Valutazione integrata della qualità delle acque sotterranee nella pianura di Mitidja (Algeria) utilizzando l'analisi spaziale di Moran I, l'indice di inquinamento delle acque sotterranee (GPI) e l'indice di qualità dell'acqua ponderato per entropia (EWQI) a supporto della pianificazione della ricarica artificiale

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Abstract

Monitoring the quality of groundwater intended for the drinking water supply in the Mitidja aquifer is a key element of the preliminary feasibility study into recharging the aquifer with treated wastewater. The degradation of the aquifer is due to infiltration water from irrigation and industrial discharges, as well as marine intrusion. As part of the study, 49 water points were monitored throughout 2019. Sampling campaigns covered 26 points during the high-water period and 23 points during the low-water period. The chemical analysis of the collected samples focused on major ions and physical parameters. For this article, two quality indices were used: the Groundwater Pollution Index (GPI) and the Entropy Water Quality Index (EWQI), which were applied to the two seasons studied (high and low water). The spatial extent of pollution was assessed using ordinary kriging (OK) and an interpolation technique based on the Moran's I index. The results revealed strong autocorrelation for the hydrochemical parameters Cl^-, SO_4^{2-}, EC, and TDS using Moran's I index during the wet season and for Cl^-, SO_4^{2-}, TH, and TDS during the dry season. This indicates strong spatial dependence with a confidence level ranging from 99% to 90% ($P < 0.01$ and $P < 0.1$). Groundwater quality estimated from the GPI shows 3.8% and 17.4% as "high pollution" and 38.4% and 43.4% as "moderate pollution" in the wet and dry seasons respectively. The cumulative percentages of waters classified as having "insignificant pollution" or "low pollution" were found to be 57.6% and 49.1% for the wet and dry seasons, respectively. Similarly, 76.9% and 65.1% of groundwater falls into the 'excellent' to 'good' quality classes for consumption according to the entropy index (EWQI), while 23% and 30.4% belong to the 'medium' quality class for the wet and dry seasons, respectively. An increase in GPI and EWQI concentration levels was observed during the dry season. This increase was observed in the far western area, characterised by agricultural land use, and in the far eastern area, which is highly urbanised and densely populated and corresponds to the Rouiba industrial zone. It is imperative that actions are urgently implemented to detect and control pollution sources before the aquifer is artificially recharged, in order to prevent any additional risk of contamination.

Riassunto

Il monitoraggio della qualità delle acque sotterranee destinate all'approvvigionamento idrico potabile nella falda acquifera di Mitidja è un elemento chiave dello studio preliminare di fattibilità sul ricaricamento della falda con acque reflue trattate. Il degrado della falda acquifera è dovuto all'infiltrazione di acque provenienti dall'irrigazione e dagli scarichi industriali, nonché all'intrusione marina. Nell'ambito dello studio, nel corso del 2019 sono stati monitorati 49 punti idrici. Le campagne di campionamento hanno riguardato 26 punti durante il periodo di piena e 23 punti durante il periodo di magra. L'analisi chimica dei campioni raccolti si è concentrata sugli ioni principali e sui parametri fisici. Per questo articolo sono stati utilizzati due indici di qualità: l'indice di inquinamento delle acque sotterranee (GPI) e l'indice di qualità dell'acqua entropico (EWQI), che sono stati applicati alle due stagioni studiate (alta e bassa marea). L'estensione spaziale dell'inquinamento è stata valutata utilizzando il kriging ordinario (OK) e una tecnica di interpolazione basata sull'indice di Moran I. I risultati hanno rivelato una forte autocorrelazione per i parametri idrochimici Cl^-, SO_4^{2-}, EC e TDS utilizzando l'indice di Moran I durante la stagione umida e per Cl^-, SO_4^{2-}, TH e TDS durante la stagione secca. Ciò indica una forte dipendenza spaziale con un livello di confidenza compreso tra il 99% e il 90% ($P < 0,01$ e $P < 0,1$). La qualità delle acque sotterranee stimata dal GPI mostra il 3,8% e il 17,4% come "alto inquinamento" e il 38,4% e il 43,4% come "inquinamento moderato" rispettivamente nella stagione umida e in quella secca. Le percentuali cumulative delle acque classificate come "inquinamento insignificante" o "basso inquinamento" sono risultate pari al 57,6% e al 49,1% rispettivamente per la stagione umida e quella secca. Analogamente, il 76,9% e il 65,1% delle acque sotterranee rientrano nelle classi di qualità da "eccellente" a 'buona' per il consumo secondo l'indice di entropia (EWQI), mentre il 23% e il 30,4% appartengono alla classe di qualità "media" rispettivamente per la stagione umida e quella secca. Durante la stagione secca è stato osservato un aumento dei livelli di concentrazione di GPI ed EWQI. Tale aumento è stato osservato nella zona occidentale, caratterizzata da un uso agricolo del suolo, e nella zona orientale, altamente urbanizzata e densamente popolata, che corrisponde alla zona industriale di Rouiba. È indispensabile attuare con urgenza misure volte a individuare e controllare le fonti di inquinamento prima che la falda acquifera venga ricaricata artificialmente, al fine di prevenire qualsiasi ulteriore rischio di contaminazione.

Parole chiave:
Qualità delle acque sotterranee, indice di Moran I, indice di inquinamento delle acque sotterranee (GPI), indice di entropia della qualità dell'acqua (EWQI), falda acquifera di Mitidja (Algeria), valutazione del rischio di inquinamento.

Introduction

An increasing demand for drinking water, driven by climate change, drought, pollution and population growth, is putting greater pressure on groundwater resources (Adimalla et al., 2019a; Belkendil et al., 2025). More than one-quarter of the global population relies on groundwater as a source of drinking water (El Mountassir et al., 2020; He et al., 2015; UN Report, 2022; Wagh et al., 2020; Xing et al., 2013; Yousefi et al., 2018). However, rapid population growth poses a serious threat to groundwater quality (Ahmed et al., 2019; El Morabet et al., 2021; Siddiqi et al., 2021; Y. Wang et al., 2023, Quevauviller et al., 2024). The difficulty of stopping or reversing groundwater pollution once it has begun poses a significant challenge (Amiri et al., 2014). Therefore, it is imperative to regularly monitor groundwater quality, implement protective strategies and measures (Vasanthavigar et al., 2010), assess its suitability for human consumption and maintain ecological balance (Radfard et al., (2019); (Bahir et al., 2019); (Gad et al., 2024); (Zhang, Jia et al., 2021a); (Uddin et al., 2023); (Adimalla & Qian, 2019). This will also require improving the tools used for evaluation (Trabelsi & Ali, 2022; Wang et al., 2022a). Temporal variations continuously influence changes in groundwater quality through recharge from atmospheric precipitation and irrigation. Upon contact with the soil, the quality of these inputs changes and is further affected by the leaching of soil horizons (Amiri et al., 2014; Broers & van der Grift, 2004; Reza & Singh, 2010, Moussaoui et al., 2025). Several pollution indices, along with statistical methods based on geostatistics, have been developed to monitor groundwater pollution (Adimalla et al., 2019a, Abaidia et al.,2025) and assess the spatial clustering or dispersion of these values. Among these, Subba Rao (2012) proposed the Groundwater Pollution Index (GPI) to quantify the contamination of groundwater intended for consumption. The Groundwater Pollution Index (GPI) is a widely adopted, useful and effective numerical indicator (Wang et al., 2022b; Trabelsi & Ali, 2022; Al-Aizari et al., 2023; Rao et al., 2018; Nourani et al., 2022; Wang et al., 2020; Adimalla, 2020; Sanad et al., 2024; Kerboub et al., 2023). It is based on a subjective weighting method, whereby weights are calculated using expert judgement and prior experience (Egbueri et al., 2020; Wang et al., 2022a), and has been used by many other researchers (Pei-Yue et al., 2010; Prasanna et al., 2011; Sunitha & Reddy, 2022; Varol & Davraz, 2015; Verma et al., 2018, Agidi et al., 2024). The entropy-weighted water quality index (EWQI), developed by Shannon (1948), is widely used to evaluate the suitability of groundwater for consumption in different regions (Adimalla et al., 2018, 2020; Adimalla & Qian, 2019; Subba Rao et al., 2020; Su et al., 2018; Wang et al., 2023). In this method, a weight is assigned to each selected parameter based on its degree of pollution; the higher the weight, the greater the parameter's impact on the result of the groundwater quality assessment (Wang et al., 2022b). The measurement of spatial autocorrelation includes both global and local indicators. Global indicators, such as the Moran's I index (Moran, 1950), reveal the spatial structure of the entire region and reflect its overall characteristics (Zhang et al., 2021a; Zhang et al., 2021b). Geostatistics and spatial analyses using Moran's spatial autocorrelation index can identify statistically significant spatial pattern structures within the study area (Islam et al., 2017, 2021; Brella et al., 2023; Meng et al., 2021; Zhang et al., 2014).

The Mitidja aquifer is located in the Algiers coastal basin (02a) in northern Algeria. It is heavily exploited for the supply of drinking water, which continuously lowers its piezometric level (Leulmi et al., 2021; Bouderbala, 2018; Hallouz et al., 2023). Consequently, the government and researchers are closely monitoring the quantity and quality of these waters using various methods and models. These include geophysical techniques (Nemer et al., 2023); the Water Quality Index (WQI) (Aziez et al., 2018); the DRASTIC, GOD, SI and GALDIT methods (Djoudar/Hallal et al., 2018; Boufekane et al., 2022); and isotopic assessment (Dalale Khous et al., 2019; Yahiaoui et al., 2023). This work forms part of a research project investigating the artificial recharge of the Mitidja aquifer using treated wastewater. The project's primary objective was to evaluate the status of the groundwater quality prior to recharge by comparing two pollution indices and applying Moran's statistical index to measure spatial autocorrelation on a global scale. The Groundwater Pollution Index (GPI) is calculated from parameters that are weighted according to their relative importance (using limit values established by the WHO), whereas the Entropy Water Quality Index (EWQI) uses a more complex approach to quantify the uncertainty relating to water quality based on the variability of these parameters. Moran's spatial autocorrelation index quantifies the spatial similarity of GPI and EWQI data, i.e. the tendency for similar values to cluster or disperse spatially, using spatial distribution in a GIS framework (Ordinary Kriging (OK) in this case). This comparison is also carried out over time, across two seasons: the wet and dry seasons. The results will contribute to the study of the project, providing significant data to assist managers with decision-making and recharge management.

Materials and methods

Study area

The Mitidja coastal aquifer is a major water resource in the Mitidja Plain in north-central Algeria. The groundwater body opens into the Mediterranean Sea in the east and extends from east to west across four wilayas: Boumerdes, Algiers, Blida and Tipaza. It is 100 km long, 10–18 km wide and covers an area of 1,450 km². It is situated within the latitudinal range of 36°22'30" to 36°48'58" N and the longitudinal range of 2°32'07" to 3°28'14" E (see Fig. 1). The plain has an average

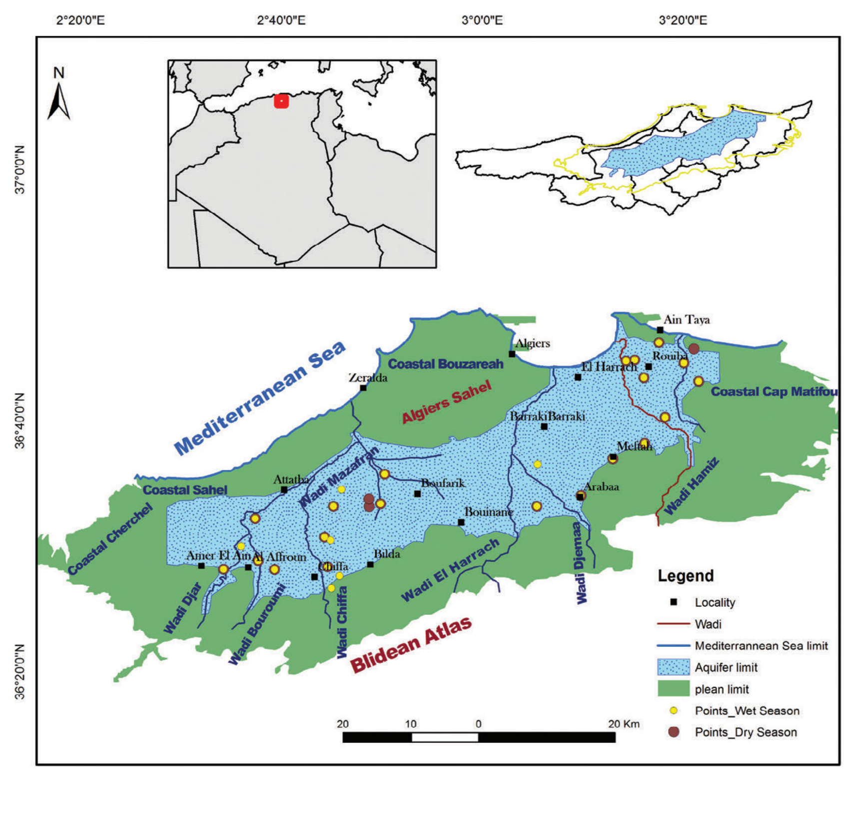

Fig. 1 - Localization map of study area with sampling sites in the Mitidja plain.

Fig. 1 - Carta di localizzazione dell'area di studio con i siti di campionamento nella pianura di Mitidja.

elevation of 50 metres, gradually increasing from sea level in the north towards the foothills of the Blidean Atlas in the south and the Sahel in the north. The topography is relatively flat. The climate is Mediterranean, with mild, rainy winters and hot, dry summers. The mean annual temperature is 18 °C. Precipitation ranges from 500 mm to 780 mm, with July being the driest month (0 mm). January is the coldest month, with an average temperature of 12 °C, and evapotranspiration values range from 970 mm to 1,250 mm. The Mitidja alluvial aquifer drains towards the Mediterranean Sea to the north via four main rivers flowing from east to west: The Réghaia, the Hamiz, the El Harrach and the Mazafran (see Fig. 1). These rivers originate from a dense hydrographic network in the high peaks of the Blidean Atlas Mountains, south of the area.

The Mitidja plain's geology was formed by a subsidence basin filled with Pleistocene deposits, which favoured the formation of two main aquifers: the deeper Astian aquifer and the surface Mitidja aquifer. The clays of the El Harrach Formation separate these two superimposed aquifers (see Fig. 2a, Fig. 2b). Coarse alluvial materials (gravel, pebbles, silt and clay) form the unconfined aquifer of the Mitidja plain. In the western part of the study area (Mazafran), the alluvial aquifer is confined by a layer of grey silt extending south of the gorge (Fig. 2a). The marly-sandy facies is the most dominant in the Astian Formation. The clayey El Harrach Formation (Villafranchian) separates the two aquifers. The plain is characterised by its agricultural vocation, favoured by its strategic geographical location at the northern tip of the African continent and its almost flat topography. Almost all types of crop are cultivated there, including market gardening, arboriculture, cereal crops and industrial crops. Large agricultural areas are located in the central and western parts of the plain, while the agri-food industry is mainly established in the central and eastern parts of Mitidja.

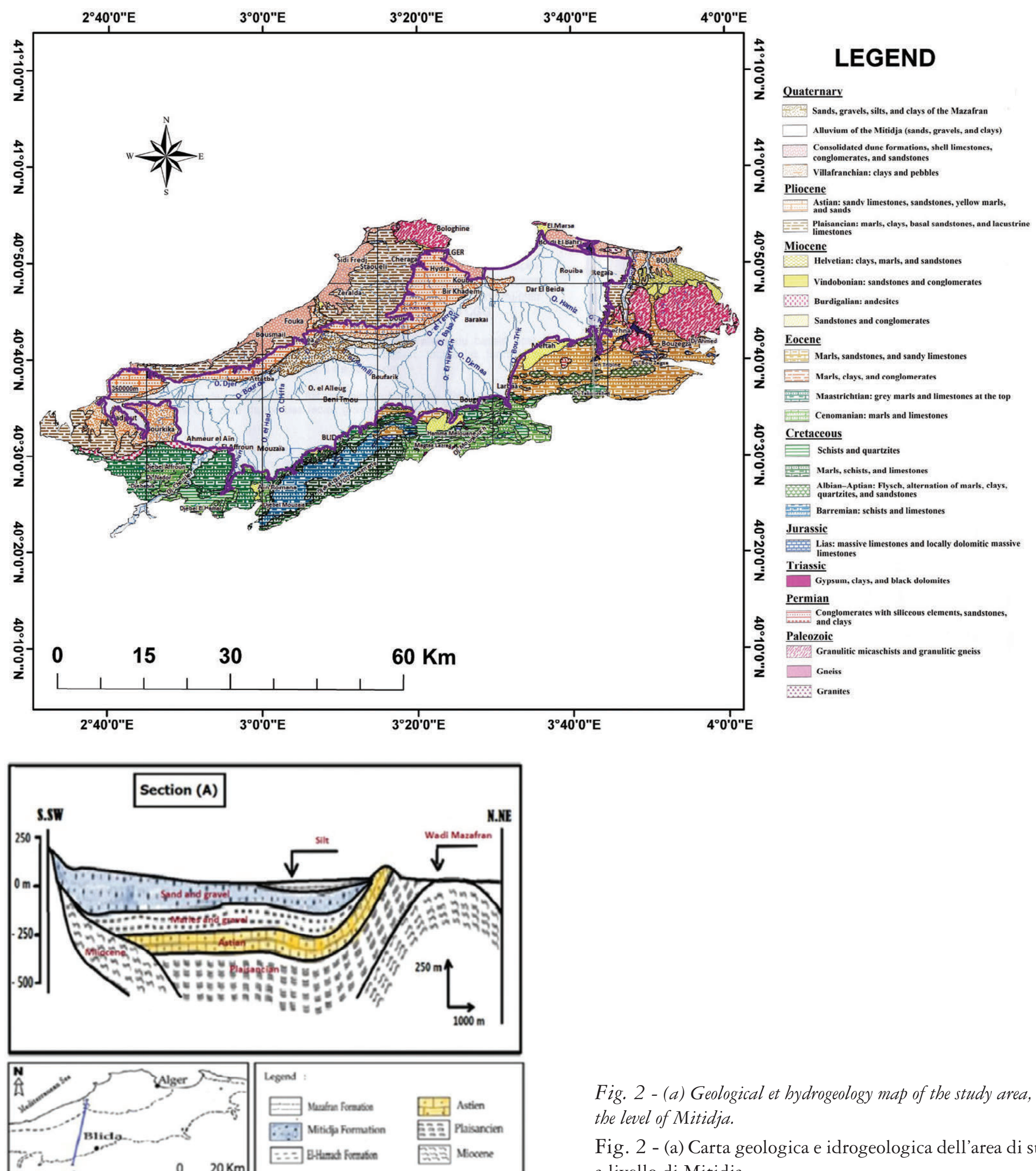

Fig. 2 - (a) Geological et hydrogeology map of the study area, (b) Geological cross-section AA' at the level of Mitidja.

Fig. 2 - (a) Carta geologica e idrogeologica dell'area di studio (b) Sezione geologica AA' a livello di Mitidja.

Data and Analysis

As part of the present study, Figure 1 shows the locations of the groundwater samples collected by the National Agency of Water Resources (ANRH) in Blida and Algiers in 2019. The samples were collected from 26 monitoring wells during the high-water (wet) period and 23 monitoring wells during the low-water (dry) period. A total of 49 water points were sampled.

The ANRH manages the national network for monitoring the physicochemical parameters and major ions of groundwater quality. Samples are collected in cleaned acidified plastic bottles that are rinsed with distilled water before use. The sampling point is purged to obtain a representative sample of the borehole or well. Parameters measured immediately on site include pH, temperature and electrical conductivity. Laboratory analyses include: total hardness (TH) by complexometric titration with EDTA and an Eriochrome Black T indicator; calcium (Ca^{2+}) and magnesium (Mg^{2+}) by EDTA titration with a Murexide indicator (complexometric titration); chlorides (Cl^-) by titration with the Mohr method (argentometric titration); Sulfates (SO_4^{2-}) are measured nephelometrically via spectrophotometry at 420 nm after the formation of a barium sulfate precipitate. Finally, sodium (Na^+) and potassium (K^+) are determined using flame emission photometry with a Jenway flame photometer.

The study of groundwater quality expressed in milliequivalents per liter (meq/L) for each sample focused on 12 parameters as major anions (HCO_3^-, Cl^-, NO_3^-, SO_4^{2-}), major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), dissolved solids (TDS), electrical conductivity (EC), total hardness (TH), and pH (Tab. 1). This study highlights the critical parameters essential for understanding groundwater quality (Belkindil et al., 2025, Abaidia et al., 2025). The calculation of the percent charge balance error (%CBE) (Eq. 1) allowed us to observe that all samples had a result ≤ ± 5%, except one, which had a %CBE value equal to 8.66 and which remains acceptable (< ± 10%).

$$\%CBE = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} \cdot 100 \quad (1)$$

Spatial Autocorrelation Analysis (Moran's I Index)

This statistical method is used to assess the correlation of a single hydrochemical variable collected at several adjacent locations within a two-dimensional area (Moran, 1948, 1950; Cliff and Ord, 1973, 1981; Yeh et al., 2022; Brella et al., 2023; Meng et al., 2021).

The global Moran's I index (Moran, 1950) determines whether a variable tends to cluster or disperse within its spatial distribution. Values range from –1 to 1, and spatial aggregation of the variable is considered significant and positively correlated when the value is close to 1. Conversely, spatial correlation is negative (spatial difference) when the value is close to –1; the smaller the value, the greater the spatial difference. When the Moran's I index equals 0, the variable is randomly distributed in space. The formula is as follows:

$$\mu(x) \doteq \frac{N}{W} \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} w_{iJ}\left(x_i - \bar{x}\right)\left(x_j - \bar{x}\right)}{\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2} \ldots \quad (2)$$

where N is the number of spatial units indexed by *i* and *j*, *x* is the variable of interest, $\bar{x}$ is the mean of x_i, w_{ij} are the elements of a spatial weights matrix with zeros on the diagonal (i.e.: w_{ii}=0), and W is the sum of all w_{ij} given by:

$$W \doteq \sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij} \ldots. \quad (3)$$

In this study, the global Moran's I statistic was calculated using the Global Moran's I tool in the Spatial Statistics Tools package in ArcGIS 10.6 software. This computes the Moran's I index value, as well as the z-score and p-value, which provide further validation of the statistic. The z-score represents the number of standard deviations and a small p-value indicates that the observed spatial pattern is unlikely to have been generated by random processes (Meng et al., 2021; Nori-Sarma et al., 2020).

Pollution Index of Groundwater (GPI)

According to Subba Rao (2012, 2017, 2018), Al-Aizari (2023a, b), Akakuru (2022) and Subba Rao & Chaudhary (2019), the Groundwater Pollution Index (GPI) method proposed by Subba Rao (2012) is used to evaluate the overall potability of groundwater by assessing the condition of its chemical constituents. Subba Rao (2012) described the five main steps involved in calculating this index:

Step 1: Assign a relative weight (RW) ranging from 1 to 5 to each chemical parameter selected for analysis, based on its degree of pollution and its impact on human health. The highest RW value of "5" is assigned to chemical parameters with significant health impacts (e.g. NO_3^-, Cl^-, SO_4^{2-}), while the lowest RW value of "1" is assigned to parameters with a low impact (e.g. K^+, HCO_3^-). Similarly, RW values of "2", "3" and "4" are assigned according to their respective levels of impact (Tab. 4).

Step 2: Calculate the weight parameter (WP), representing the ratio of the relative weight (RW) of each chemical parameter to the sum of all relative weights (Eq. 4).

$$WP = RW / \sum RW \quad (4)$$

Step 3: Calculate the status of concentration (SC) by dividing the concentration of each chemical parameter (Cin) by the standard water quality limit (WQS) established by specialised agencies. In this study, WQS values were taken from the World Health Organization (WHO, 2011) (Eq. 5).

$$SC = C_i^n / WQS \quad (5)$$

Step 4: Multiply the weight parameter (WP) of each chemical parameter by its concentration status (SC) to obtain the partial groundwater pollution index (PPIG) value (Eq. 6).

$$PPIG = \sum WP * SC \quad (6)$$

Step 5: The Groundwater Pollution Index (GPI) is finally obtained by summing the PPIG values for all parameters (Eq. 7) (Tab 4).

$$GPI = \sum PPIG \qquad (7)$$

The GPI values of each collected water sample are classified according to the five categories given by Subba Rao (2012): GPI < 1: insignificant pollution; 1 < GPI < 1.5: low pollution; 1.5 < GPI < 2: moderate pollution; 2 < GPI < 2.5: high pollution; and GPI > 2.5: very high pollution (Tab. 5).

Entropy Water Quality Index

Claude Shannon (1948) introduced the theory of information entropy, in which he proposed that entropy could be used to measure information or uncertainty. According to Shannon entropy, the degree of uncertainty influences the prediction of an event's outcome (Shyn et al., 2011). Smaller entropy values indicate a greater amount of effective information, resulting in a larger corresponding weight (Gao, 2020). Indeed, this technique mathematically quantifies the randomness of an event (Shyu et al., 2011). Several authors have applied the EWQI in various hydrological and water quality fields, including Gao (2020), Özkul et al. (2000), Kawachi et al. (2001), Li et al. (2011 and 2021), Amiri et al. (2014) and Gorgij et al. (2017), as well as Kumar and Augustine (2022).

The steps for calculating entropy are as follows:

The first step is the calculation of the eigenvalue matrix, X, which is associated with m groundwater samples and n hydrochemical parameters of each in Eq. 8.

$$X = \begin{vmatrix} x_{11} & x_{12} \ldots x_{1n} \\ x_{21} & x_{22} \ldots x_{2n} \\ x_{m1} & x_{m2} \ldots x_{mn} \end{vmatrix} \qquad (8)$$

where, "m" (i=1, 2, 3, 4, …, m) represents the groundwater samples; n (j=1, 2, 3, 4, ……., n) represents the number of hydrochemical parameters of each sample.

In the second step, the eigenvalue matrix, X, is then converted into a standard-grade matrix, Y, to remove the effect of different units and quantity grades of groundwater quality parameters. The standard-grade matrix is defined in Eq. 9

Then, the ratio of parameter index value, j, and the i sample is calculated by Eq. 10

$$Y_{iJ} = \frac{x_{ij} - \left(x_{ij}\right)_{\min}}{\left(x_{ij}\right)_{\max} - \left(x_{ij}\right)_{\min}} \qquad (9)$$

$$Y = \begin{vmatrix} y_{11} & y_{12} \ldots y_{1n} \\ y_{21} & y_{22} \ldots y_{2n} \\ y_{m1} & y_{m2} \ldots y_{mn} \end{vmatrix} \qquad (10)$$

where, x_{ij} is the initial matrix; (x_{ij})min and (x_{ij})max are the minimum and maximum values of the hydrochemical parameters of the samples, respectively.

The third step is to compute the entropy "e_j" and entropy weight "w_j " by the following equations (11);(12);(13) :

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} P_{ij} \ln\left(P_{ij}\right) \qquad (11$$

$$P_{ij} = \frac{\left(1 + y_{ij}\right)}{\sum_{i=1}^{m} \left(1 + y_{ij}\right)} \qquad (12)$$

$$W_j = \frac{\left(1 - e_j\right)}{\sum_{i=1}^{m} \left(1 - e_j\right)} \qquad (13)$$

The fourth step is to compute the quality rating scale "q_j " of the "j" parameter by the following equations (14) :

$$q_j = \begin{cases} \frac{c_j}{s_j} x100 \\ \hline \frac{c_{pH^{-7}}}{s_{pH^{-7}}} \end{cases} \qquad (14)$$

where, "C_j" is the concentration of chemical parameters "j" (mg/L); "S_j " is the permissible limit of World Health Organizations (WHO) standards of parameter "j" (mg/L); "C_{pH}" represents the value of pH; "S_{pH}" is the permissible limit of pH (6.5 to 8.5), if the measured pH is larger than 7, "S_{pH}" is to be taken 8.5, while the pH is smaller than 7, "S_{pH}" is equal to 6.5 to confirm the value of "q_j" is positive. (Amiri et al., 2014; Gorgij et al., 2017; Kumar et Augustine, 2022)

In the fifth and last step EWQI is calculated by using the Eq. (15):

$$EWQI = \sum_{j=1}^{m} w_j q_j \qquad (15)$$

The EWQI has been classified as excellent quality if <50, good quality from 50 to 100, medium quality from 100 to 150, poor quality from 150 to 200, and extremely poor quality if >200 (Tab. 5).

Results and Discussion

General characteristics of hydrochemical parameters

Statistical analysis of hydrochemical parameters in groundwater provides insight into its chemical composition, as well as the spatial variation of elements across the entire area and over both seasons. It indicates the presence or absence of extreme and/or outlier values, and enables the evaluation of potential relationships between elements (Agrouche et al., 2024). This analysis provides an overview of aquifer water quality, facilitating the creation of spatial maps for improved water management and assessment of its impact on human health. It also supports informed decision-making for sustainable use (Agrouche et al., 2024; Nemer et al., 2023; Wang et al., 2023). Multivariate analysis and Pearson's correlation were performed using the 2013 version of the XLSTAT software. The results of the elemental concentrations in the Mitidja aquifer groundwater are presented in Table 1. Specific geological conditions can lead to significant disparities in hydrochemical conditions (Xie et al., 2025). The standard deviation of all elements is lower than the mean, indicating that the values of the variables are not widely dispersed (Table 1), which reflects a certain hydrochemical homogeneity of the sampled waters in the study area (Madene et al., 2023). However, the recorded means for electrical conductivity (EC), Ca^{2+}, Mg^{2+}, HCO^{3-}, TH and TDS are high, exceeding WHO standards for both seasons. 92.3% and 95.6% of the total groundwater samples in our study area had Ca^{2+} concentrations above the WHO limits, and approximately 95% of HCO^{3-} samples exceeded the standard limits in the wet and dry seasons, respectively (Tab 1). For Mg^{2+}, 61.5% and 60.8% of samples were above the limit in the wet and dry seasons, respectively. These high values are due to the dissolution of carbonate formations in the Blidean Atlas. Mg^{2+} ions may originate from the dissolution of magnesium-rich carbonate formations (e.g. dolomite). The leaching of Pliocene (Villafranchian) clay formations further increases their presence (Djoudar Halla et al., 2014, 2018).

The dissolution of carbonate rocks rich in limestone and magnesium in the Blida Atlas, which is considered the recharge zone of the aquifer, is the main factor responsible for the hardness of Mitidja groundwater. The mean total hardness (TH) value was found to range from 495.9 to 560.9 mg/L in the wet and dry seasons, exceeding the standard by 92.3% and 95.6%, respectively. According to Sawyer and McCarthy's (1967) classification, the water is considered very hard for drinking purposes, with categories ranging from soft (TH < 75), moderately hard (75–150), hard (150–300), to very hard (> 300). Only 3.8% and 4.3% of samples fall into the moderately hard category in the wet and dry seasons, respectively. High electrical conductivity (EC) values are mainly found in the eastern part of the Mitidja aquifer due to marine intrusion in the Bay of Algiers (Djoudar and Toubal, 2014; Morsli et al., 2017; Nemer et al. 2023). High EC values are also found in the southwest of the aquifer due to the presence of halite, which increases salt weathering and dissolution. This is further exacerbated by rapid recharge of shallow aquifers and anthropogenic contributions (Chaudhari et al., 2025; Xie et al., 2025). The pH values indicate that the groundwater varies from neutral to slightly alkaline due to the calcareous nature of the aquifer (see Tab 1). The mean concentrations recorded in mg/L for other elements in the wet and dry seasons, such as Na^+ (86.5 and 95.6), K^+ (0.69 and 1.34), Cl^- (143.8 and 152.6), NO_3^- (50.1 and 50.5) and SO_4^{2-} (185.7 and 180.6), were below 43% of World Health Organization standard levels. Nevertheless, maximum values were recorded in the Bay of Algiers area and the Ahmer El Ain zone. The order of cation abundance was $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ and the order of anion abundance was $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$ for both the wet and dry seasons (see Tables 1 and 2). Based on these results, Mitidja aquifer water can be classified as a freshwater, characterised by a high concentration of HCO_3^-.

An initial assessment of the studied parameters was followed by a Pearson correlation analysis of twelve parameters, to determine their influence on groundwater quality. Tab 2 shows the degree of correlation between the physicochemical parameters of the groundwater samples. The most significant positive correlations during the dry and wet seasons, respectively, were: EC–TDS (r = 0.980 and r = 0.975), EC–TH (r = 0.904 and r = 0.920), Ca^{2+}–TDS (r = 0.900 and r = 0.795), Ca^{2+}–TH (r = 0.911 and r = 0.792), and EC–Na^+ (r = 0.864 and r = 0.765).730, r = 0.634), Na^+–Cl^- (r = 0.896, r = 0.790), Ca^{2+}–HCO_3^- (r = 0.712, r = 0.602) and Mg^{2+}–SO_4^{2-} (r = 0.582, r = 0.603) at a 99% confidence level. Significant positive correlations may indicate similar natural

Tab. 1 - Statistics of hydrochemical parameters of groundwater (Wet and Dry season 2019).

Tab. 1 - Statistiche dei parametri idrochimici delle acque sotterranee (stagione umida e secca 2019).

Variables	Wet season					Dry season				
(mg/L)	Min	Max	Mean	SD	CV %	Min	Max	Mean	SD	CV %
Ca^{2+}	20	224	126,38	49,53	39,19	19,61	278,43	159,22	54,69	34,35
Mg^{2+}	9,6	109,71	43,2	25,59	59,24	11,76	82,35	39,1	18,25	46,68
Na^+	26	224	86,5	49,03	56,68	25	209	95,65	59,81	62,53
K^+	0	4,5	0,69	1,21	175,96	0	12	1,34	2,58	192,68
Cl^-	38	394	143,88	102,71	71,38	38	360	152,61	97,88	64,14
SO_4^{2-}	10	338	185,77	83,35	44,87	0	370	180,65	96,73	53,54
HCO_3^-	61	533,75	295,38	98,17	33,23	137,25	732	405,78	134,82	33,22
NO_3^-	1	115	50,12	35,5	70,83	0	125	50,57	30,45	60,22
pH	7,6	8,7	7,95	0,23	2,86	7,5	8,3	7,79	0,18	2,31
CE*	437	2 350	1 346,6	506,68	37,63	445	2 490	1 459,4	555,69	38,08
TH	90	850	495,94	173,16	34,92	98,04	882,35	560,98	175,83	31,34
TDS	218,34	1 677,5	939,48	330,53	35,18	329,13	1 787,9	1 093,7	388,71	35,54

Tab. 2 - Results of the Pearson correlation coefficients of physicochemical parameters in the study area (Dry season and Wet season 2019).

Tab. 2 - Risultati dei coefficienti di correlazione di Pearson dei parametri fisico-chimici nell'area di studio (stagione secca e stagione umida 2019).

Dry Season 2019												
	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	NO_3^{-}	pH	CE	TH	TDS
Ca^{2+}	1											
Mg^{2+}	0.309	1										
Na^{+}	0.649	0.241	1									
K^{+}	0.275	0.464	0.598	1								
Cl^{-}	0.582	0.278	0.896	0.462	1							
SO_4^{2-}	0.823	0.582	0.495	0.284	0.407	1						
HCO_3^{-}	0.712	0.504	0.615	0.625	0.412	0.580	1					
NO_3^{-}	0.481	0.067	0.192	-0.259	0.253	0.340	0.081	1				
pH	-0.381	-0.029	-0.161	0.068	-0.219	-0.260	-0.220	-0.028	1			
CE	0.876	0.516	0.864	0.524	0.847	0.779	0.730	0.359	-0.294	1		
TH	0.911	0.673	0.609	0.415	0.573	0.892	0.772	0.403	-0.309	0.904	1	
TDS	0.900	0.531	0.844	0.547	0.757	0.807	0.831	0.356	-0.280	0.980	0.929	1

Wet Season 2019												
	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	NO_3^{-}	pH	CE	TH	TDS
Ca^{2+}	1											
Mg^{2+}	0,124	1										
Na^{+}	0,552	0,192	1									
K^{+}	0,197	0,121	0,383	1								
Cl^{-}	0,544	0,483	0,79	0,21	1							
SO_4^{2-}	0,623	0,603	0,444	0,375	0,409	1						
HCO_3^{-}	0,602	0,434	0,457	0,291	0,428	0,434	1					
NO_3^{-}	0,394	0,278	0,21	-0,274	0,232	0,414	0,092	1				
pH	-0,377	-0,531	-0,209	0,073	-0,377	-0,397	-0,509	-0,282	1			
CE	0,738	0,637	0,765	0,303	0,886	0,733	0,634	0,417	-0,517	1		
TH	0,792	0,705	0,513	0,215	0,686	0,817	0,698	0,453	-0,597	0,92	1	
TDS	0,795	0,591	0,766	0,319	0,809	0,766	0,748	0,425	-0,532	0,975	0,933	1

or anthropogenic sources (Agrouche et al., 2025; Khelfi et al., 2025; Mdene et al., 2023; Islam et al., 2017). Nitrate (NO_3^-) showed weak correlations with some elements and a slight negative correlation with pH during both periods. Overall, correlation rates were higher in the dry season than in the wet season. This can be explained by groundwater flowing from relatively elevated zones of the Blida Atlas in the south towards the Bay of Algiers in the northeast of the plain (Fig. 1). This reduces the residence time of rock–water interactions, consequently decreasing ion concentrations in groundwater (Islam et al., 2017, Zhang et al., 2014).

Spatial distribution model of hydrochemical parameters: Moran's I index

Moran's I index is a statistically significant spatial measure used to determine the presence or absence of spatial autocorrelation (Chaudhari et al., 2025). In this study, the spatial distribution pattern of hydrochemical parameters in the Mitidja groundwater was analysed using Moran's I index for both the wet and dry seasons. The results of the spatial autocorrelation analysis based on the Moran I-index values for each hydrochemical parameter are presented in Table 2. The SO_4^{2-} content in groundwater exhibited strong autocorrelation at the 99% confidence level for the two seasons ($p < 0.0004$ and $p < 0.0002$, respectively, with z-values of 3.54 and 3.78), with Moran's I index values of 0.63 and 0.73. The Cl^- content exhibited strong spatial autocorrelation at the 97% and 99% confidence levels ($p < 0.03$ and $p < 0.00015$, respectively; $z > 2.16$ and $z > 2.99$, respectively), with Moran's I index values of 0.37 and 0.57 for the wet and dry seasons, respectively. These results indicate significant positive spatial correlations between these two variables in both seasons. In the wet season, strong autocorrelation was recorded at the 95% confidence level for electrical conductivity (EC) ($p < 0.03$, $z > 2.19$) with a Moran's I index of 0.37. In the dry season, strong autocorrelation was recorded at the 95% confidence level for total dissolved solids (TDS) ($p = 0.035$, $z > 2.10$) with a Moran's I index of 0.38. TDS content showed autocorrelation at the 90% confidence level in both seasons ($p < 0.085$, $z > 1.71$ and $p < 0.066$, $z > 1.83$) with Moran's I index values of

Tab. 3 - Statistical significance level of Moran's I index.
Tab. 3 - Livello di significatività statistica dell'indice I di Moran.

Variables	Wet season					Dry season				
(mg/L)	Pattern	Moran's I	Expected I	z score	P Value	Pattern	Moran's I	Expected I	z score	P Value
Ca^{2+}	Random	0,1945	-0,04	1,2407	0,2147	Random	0,2187	-0,0455	1,3513	0,1766
Mg^{2+}	Random	0,1906	-0,04	1,2114	0,2257	Random	0,0234	-0,0455	0,3423	0,7321
Na^{+}	Random	0,1809	-0,04	1,1879	0,2349	Random	0,1811	-0,0476	1,0825	0,2791
K^{+}	Random	0,1111	-0,04	0,888	0,3745	Random	-0,2148	-0,0476	-1,2085	0,2269
Cl^{-}	Clustered	0,3708	-0,04	2,1699	0,03	Clustered	0,5771	-0,0476	2,9927	0,0028
SO_4^{2-}	Clustered	0,6355	-0,04	3,5481	0,0004	Clustered	0,7385	-0,0476	3,7892	0,0002
HCO_3^{-}	Random	-0,133	-0,04	-0,5027	0,6151	Random	-0,287	-0,0476	-1,1544	0,2483
NO_3^{-}	Random	0,1671	-0,04	1,0734	0,2831	Random	0,0626	-0,0476	0,5314	0,5951
pH	Random	0,1012	-0,04	0,8012	0,423	Random	-0,1655	-0,0476	-0,5931	0,5531
CE*	Clustered	0,3745	-0,04	2,1947	0,0282	Random	0,2122	-0,0455	1,2938	0,1957
TH	Random	0,2598	-0,04	1,5911	0,1116	Clustered	0,3835	-0,0476	2,1056	0,0352
TDS	Clustered	0,2854	-0,04	1,7174	0,0859	Clustered	0,3395	-0,0476	1,8333	0,0668

0.28 and 0.33 respectively. However, Moran's I index values for Mg^{2+} and NO_3^- in the dry season are 0.023 and 0.062 respectively, indicating that these variables are distributed completely randomly in space.

In this model, z-scores below -1.65 indicate a dispersed emission pattern; z-scores between -1.65 and 1.65 represent a random emission pattern; and z-scores above 1.65 indicate a clustered emission pattern (Chaudhari et al., 2025; Mohammadi et al., 2020; Brella et al., 2023). Table 2 shows that, in the wet season, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, NO_3^-, pH and TH exhibited a random distribution (z-scores ranging from –0.50 to 1.59). The same is true of the dry season for the elements Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, NO_3^-, pH and EC, with z-scores ranging from -1.15 to 1.35. This random pattern can be explained by the fact that these elements can be released from various potential sources (Chaudhari et al., 2025; Mohammadi et al., 2020).

Furthermore, it can be seen that the hydrochemical parameters Cl^- and SO_4^{2-}, EC and TDS in the wet season, and Cl^- and SO_4^{2-}, TH and TDS in the dry season, show strong spatial autocorrelation in the Mitidja Plain. Each of these parameters has a score greater than 1.65 (ranging from 1.71 to 3.54 in the dry season and from 1.83 to 3.79 in the wet season) and low p-values. This indicates that high and/or low values of each parameter are clustered in space (Chaudhari et al., 2025; Mohammadi et al., 2020). A spatial autocorrelation analysis was also carried out on the water quality indicators (GPI and EWQI) to assess differences in their spatial patterns (see Tab. 2 and Tab. 3).

However, during the dry season, non-significant positive Moran's I values ($p > 0.10$) were detected within the study area for the EWQI, which can be attributed to spatial heterogeneity in contaminant loads and lowered groundwater levels during this period (Aziez et al., 2021). The difference in spatial autocorrelation between the global water quality indices may be due to the regulation of groundwater flow and the effect of rainfall (Islam et al., 2017; Siddique et al., 2022)

Pollution Index of Groundwater (GPI)

The GPI model is used to assess the quality of groundwater for consumption purposes. It provides an overall measure of the collective impact of all chemical variables on groundwater quality. The output value is a single figure that indicates the overall pollution rate of the groundwater (Subba Rao, 2012, 2017, 2018, 2019). Table 4 shows the analysed parameters and their respective values for the dry (RW) and wet (WP) seasons, compared to WHO standards. It shows that the parameter with the greatest impact on groundwater pollution is '5', which concerns the elements Cl^-, SO_4^{2-} and NO_3^-.

Tab. 4 - Parameters and analyses of the respective values (RW), (WP), and WHO.
Tab. 4 - Parametri e analisi dei rispettivi valori (RW), (WP) e OMS.

Parameter	Units	RW	WP	WHO Standard (2011)
pH		4	0,0976	6.5--8.5
TH	(mg/L)	4	0,0976	300
EC	(µS/cm)	4	0,0976	500
TDS	(mg/L)	4	0,0976	500
K^+	(mg/L)	1	0,0244	12
HCO_3^-	(mg/L)	1	0,0244	150
Ca^{2+}	(mg/L)	2	0,0488	75
Mg^{2+}	(mg/L)	2	0,0488	30
Na^+	(mg/L)	4	0,0976	200
SO_4^{2-}	(mg/L)	5	0,122	200
Cl^-	(mg/L)	5	0,122	250
NO_3^-	(mg/L)	5	0,122	50
Sum.		41	1	

The highest percentages of the GPI index for the wet and dry seasons are 38.4% and 43.4% respectively, both of which are recorded for moderate pollution ($1.5 \leq GPI < 2.0$), i.e. ten water points in each season. No 'very high' pollution ($GPI \geq 2.5$) was recorded in either season. A total of 15 water points (57.6%) represent 'insignificant' pollution ($GPI < 1.0$), and

Tab. 5 - GPI and EWQI value and quality rank of samples based on WHO standards for Wet season and dry season (2019).

Tab. 5 - Valore GPI ed EWQI e classificazione qualitativa dei campioni secondo gli standard OMS per la stagione umida e la stagione secca (2019).

Index method	Rank	Water quality	Number of locations		GPI% of simple	
GPI Value			Wet season	Dry season	Wet season	Dry season
< 1.0	1	Insignificant pollu-tion	5	3	19,23	13,04
1.0 to 1.5	2	Low pollution	10	6	38,46	26,08
1.5 to 2.0	3	Moderate pollution	10	10	38,46	43,48
2.0 to 2.5	4	High pollution	1	4	3,85	17,4
> 2.5	5	Very high pollution	0	0	0	0
Index method	Rank	Water quality	Number of locations		EWQI% of simple	
EWQI val-ue			Wet season	Dry season	Wet season	Dry season
<50	1	Excellent quality	4	3	15,4	13,04
50-100	2	Good	16	12	61,53	52,17
100-150	3	Medium	6	7	23,07	30,44
150-200	4	Poor	0	1	0	4,35
>200	5	Extremely Poor	0	0	0	0

9 water points (49.1%) represent ‘low’ pollution (1.0 ≤GPI <1.5) in the wet and dry seasons, respectively (Tab. 5). ‘High’ pollution (2.0 ≤ GPI < 2.5) ranged from 3.8% (one water point) in the wet season to 17.4% (four water points) in the dry season. To minimise pollution and prevent the deterioration of aquifers, it is necessary to avoid recharging them with only secondary-treated water (Clemens et al., 2020). Where recharge is necessary, this water must undergo advanced treatment and the recharge zone must be carefully selected.

Overall, the GPI index indicates that around half of the well samples in the study area are suitable for consumption, corresponding to the ‘insignificant’ and ‘low’ pollution classes, during both the wet and dry seasons.

The spatial distribution of the GPI index shows that well samples with ‘high’ contamination levels (Fig. 3a, Fig. 3b) are located at the southwestern edge of the aquifer. This is mainly due to anthropogenic contamination linked to the agricultural use of this part of the area, as well as geological pollution associated with the presence of halite.

The same applies to ‘moderate’ pollution, which is located at both the eastern and western ends of the aquifer. To the east, industrial zones and a population density of around one million inhabitants are found (Rouïba, Réghaïa, Hamiz, Dar El Beïda, El Harrach, etc.) (ONS, 2020). In contrast, the western part is mainly occupied by large agricultural areas.

The Management Plan report for the Réghaïa Lake Nature Reserve highlights a significant increase in wastewater volumes generated by the Héraoua population (Thibault et al., 2006).

Entropy weighted water quality (EWQI)

To evaluate the quality of the drinking water in the study area, twelve chemical elements that were previously considered in the Moran’s I and GPI indices were used. This approach provides a comprehensive and explicit overview of the results

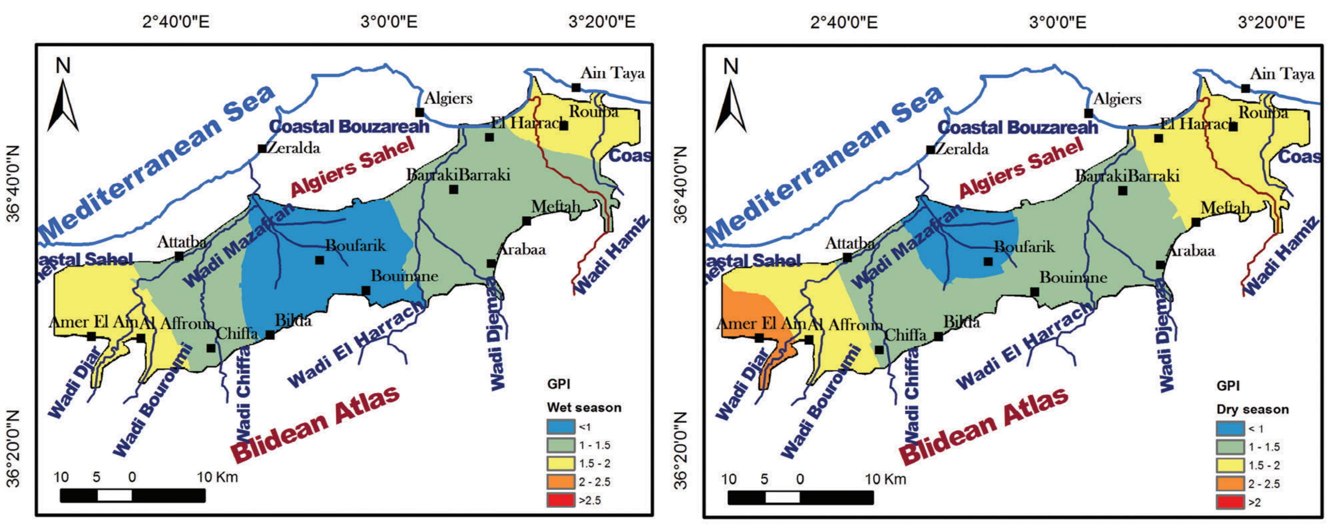

Fig. 3 - Spatial variation maps with OK of GPI index : (a) variation of GPI in Wet season, (b) variation of GPI in Dry season (2019).

Fig. 3 - Mappe delle variazioni spaziali con OK dell’indice GPI: (a) variazione del GPI nella stagione umida, (b) variazione del GPI nella stagione secca (2019).

obtained from the different indices. The EWQI index results are presented in Tab. 5 and illustrated in Figure 4.

The findings indicate that 61.5% and 52.1% of Mitidja groundwater samples are of good quality (50 ≤ EWQI < 100), corresponding to 16 and 12 water points, respectively, in the wet and dry seasons.

Water of excellent quality (EWQI <50) accounts for 15.4% (4 water points) in the wet season and 13% (3 water points) in the dry season. Overall, 76.9% and 65.1% of the groundwater samples fall within the good or excellent categories (ranks 1 and 2) in the wet and dry seasons, respectively, indicating that they can be consumed without significant health risks.

Notably, no sample exhibited extremely poor quality (EWQI ≥ 200) during either season. Poor quality water (150 ≤ EWQI < 200) was recorded at one water point only during the dry season, accounting for 4.3% of samples. This could be due to an unusually high concentration of a specific element in that sample, or a potential analytical anomaly.

The remaining water points (six in the wet season and seven in the dry season) fall within the medium quality category (100 ≤ EWQI < 150). These represent 23% and 30.4% of the samples, respectively. This classification indicates the presence of a certain level of contamination or pollutants in the groundwater, though not sufficient to categorise it as poor or very poor quality (Brella et al., 2023).

The graphical visualisation of the spatial distribution of the EWQI index was carried out using OK interpolation (see Fig. 5), showing that quality classes 1 and 2 dominate almost the entire surface of the Mitidja aquifer. During the wet season, a class 3 'medium' quality zone emerges in the south-west (the Amer El Ain area), which is an agricultural zone where pollution may result from runoff and deep leaching of irrigation or rainwater carrying excess fertilisers and/or pesticides used on agricultural land. This affects both aquatic life and human health (Brella et al., 2023; Wang et al., 2023; Kumar and Augustine, 2022). During the dry season, this pollution zone in the southwest extends as far as Affroun, covering a larger area than before due to the concentration of chemical elements at this time of year (Tab. 1). Another Class 3 (medium quality) zone appears in the extreme eastern part of the Mitidja aquifer, specifically in the Bay of Algiers area and slightly further inland (Bordj El Kiffan, Bordj El Bahri, Rouiba, Réghaïa, Hamiz and Dar El Beïda). This area is affected by marine intrusion and is characterised by industrial zones. Continuous and excessive industrial discharges can exacerbate pollution levels, posing a serious threat to human health (Wang et al., 2023).

Nevertheless, particular attention should be paid to the relatively high concentrations of Ca^{2+}, HCO_3^-, EC, TDS and TH, as these contribute to the increase in EWQI values. Attention should also be paid to the presence of spatial autocorrelation in Moran's I index for the parameters Cl^-, SO_4^{2-}, EC, TDS and TH (Tab. 3). Recharging the aquifer with only secondary-treated water could exacerbate pollution levels and promote their spread. Therefore, recharge should be carried out using water that has undergone more thorough treatment, accompanied by regular monitoring of aquifer quality after each operation, to ensure optimal resource management.

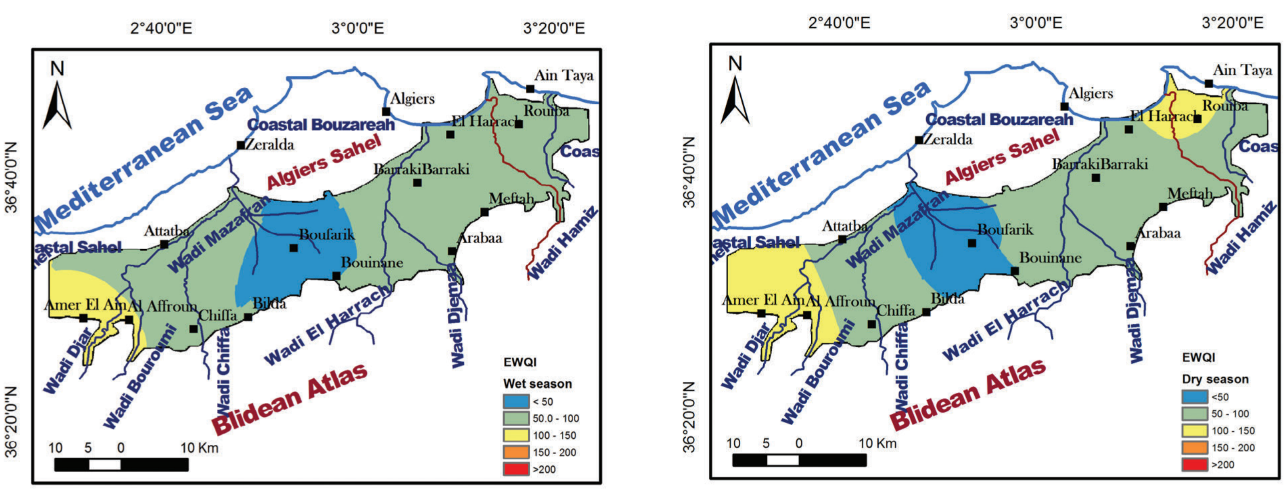

Fig. 4 - Spatial variation maps with OK of EWQI index: (a) variation of EWQI in Wet season, (b) variation of EWQI in Dry season (2019).

Fig. 4 - Carte delle variazioni spaziali con OK dell'indice EWQI: (a) variazione dell'EWQI nella stagione umida, (b) variazione dell'EWQI nella stagione secca (2019).

Tab. 6 - Spatial autocorrelation analysis between GPI and EWQI in Wet and Dry season.

Tab. 6 - Analisi di autocorrelazione spaziale tra GPI ed EWQI nella stagione umida e nella stagione secca.

Index	Wet season					Dry season				
	Pattern	Moran's I	Expected I	z score	P Value	Pattern	Moran's I	Expected I	z score	P Value
GPI	Clustered	0.3380	0,0359	1,9943	0,0461	Clustered	0,4088	0,0442	2,1702	0,0299
EWQI	Clustered	0,4316	0,0367	2,4617	0,0138	Random	0,1887	0,0405	1,1625	0,245

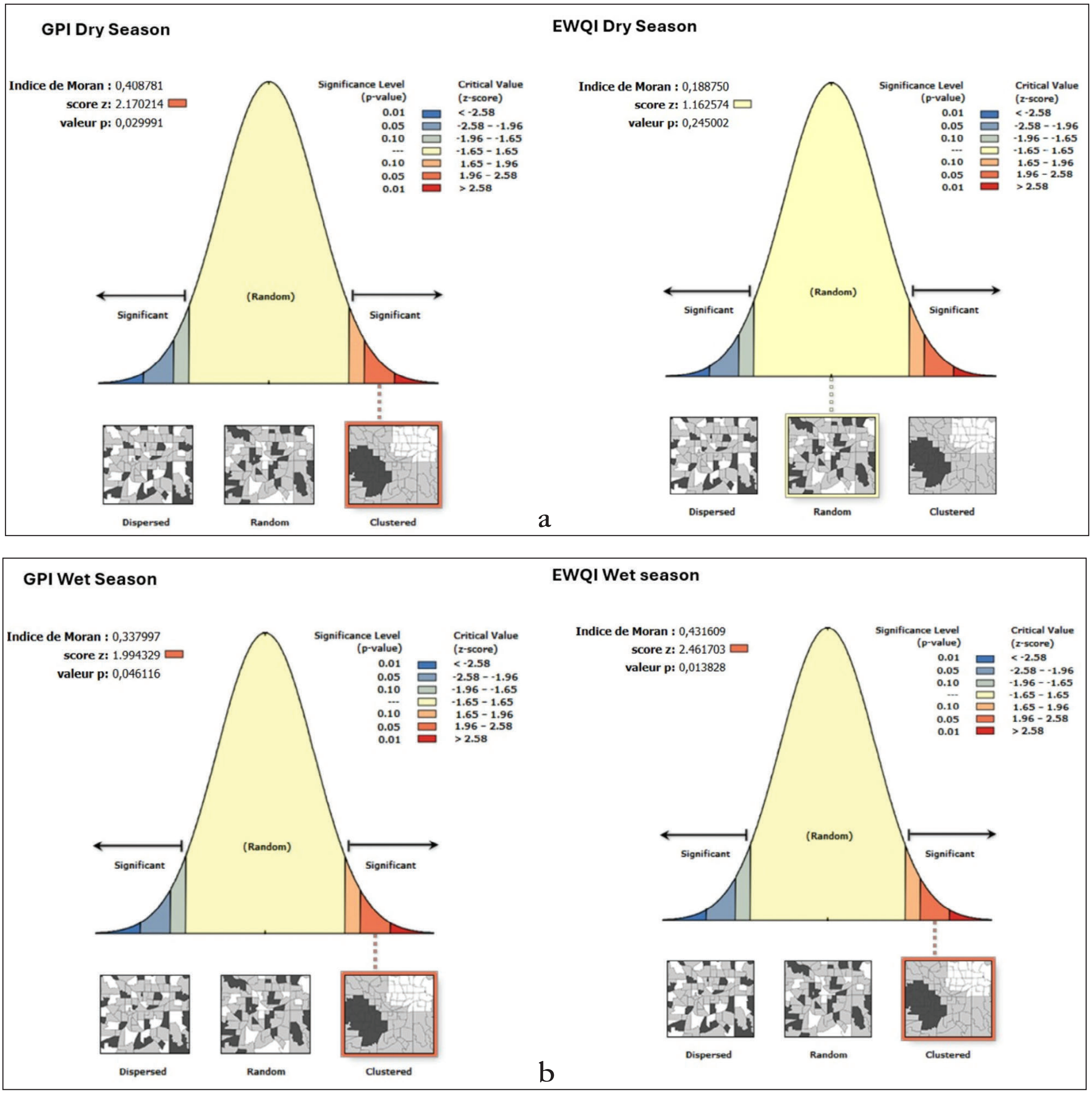

Fig. 5 - Spatial autocorrelation model (Moran's I) for GPI and EWQ indices for the two periods: (a) dry period and (b) wet period (2019).

Fig. 5 - Modello di autocorrelazione spaziale (Moran's I) per gli indici GPI ed EWQ per i due periodi: (a) periodo secco e (b) periodo umido (2019).

Spatial autocorrelation analysis, using the global Moran's I index and applied to both pollution indicators (GPI and EWQI), revealed a random distribution pattern for the EWQI during the dry season (Moran's I = 0.1887; z = 1.62; non-significance interval: −1.65 < z < 1.65; (Tab. 6 and Fig. 5). This indicates that pollution dispersion is random and that EWQI values among nearby water points do not exhibit significant similarities. This pattern can be explained by the fact that, of the 23 water points analysed in the dry season, 12 displayed good quality and three displayed very good quality, as previously mentioned.

In contrast, the EWQI in the wet season, as well as the GPI in both the wet and dry seasons, exhibited significant positive spatial autocorrelation, with z-scores exceeding 1.65 (I = 0.4316; z = 2.4617; I = 0.3380; z = 1.9943; and I = 0.4088; z = 2.1702, respectively) (Tab. 6 and Fig. 5). These results suggest that points in close proximity tend to have similar values, indicating pollution dispersion in areas contaminated by agricultural activities in the south-western and central Mitidja plains and/or industrial or wastewater discharges in the central and eastern parts of the plains.

To further this analysis, a complementary study using the local Moran's I index (LISA) would be beneficial. This approach would highlight the influence of neighbouring points and provide a better explanation for the observed differences in correlation, thus constituting a logical extension of the present work.

Conclusion

This study forms part of a preliminary research project which aims to assess the quality of the groundwater in the Mitidja aquifer. This groundwater is intended for use in supplying drinking water to the population and for irrigating the region, prior to the potential implementation of an artificial recharge operation using treated wastewater.

The quality assessment was carried out using two indices: the Groundwater Pollution Index (GPI) and the Entropic Water Quality Index (EWQI).

To clearly represent the spatial distribution of these indices, we applied spatial analysis, combining the global Moran's I index with ordinary kriging (OK), to the hydrochemical parameters of the groundwater over two periods: the wet and dry seasons.

The results revealed strong autocorrelation for Cl^-, SO_4^{2-}, EC, and TDS during the wet season and for Cl^-, SO_4^{2-}, TH, and TDS during the dry season, with a confidence level ranging from 90% to 99% ($p < 0.1$ and $p < 0.01$). This highlights the spatial dependence and geographical clustering of these parameters in Mitidja's groundwater.

The GPI indicates that 57.6% (wet season) and 49.1% (dry season) of samples have water quality classified as 'insignificant' or 'low' pollution. In contrast, 'moderate pollution' classes accounted for 38.4% in the wet season and 43.4% in the dry season, requiring particular attention from water managers. Seasonal or even annual monitoring, combined with investigations into pollution sources, is recommended.

The Entropic Water Quality Index (EWQI) shows that 76.9% (wet season) and 65.1% (dry season) of the groundwater is of "excellent" to "good" quality for consumption. 'Medium' quality classes represent 23% and 30.4% respectively, with values progressively increasing from southwest to northwest, in line with the direction of groundwater flow. Values also increase from the coast towards the eastern interior, likely due to seawater intrusion and/or effluent discharge towards the Oued Hamiz outlet.

In light of the results obtained in this study, further investigation into the quality of treated wastewater and precise characterisation of potential recharge zones is strongly recommended, in order to ensure informed decision-making.

Using water treated only at the secondary level could expand the existing pollution zone, contaminate previously unaffected areas and prolong the time it takes for pollutants to disperse in the aquifer. Furthermore, recharge carried out in an area with a shallow vadose zone could exacerbate the spread of pollution.

Therefore, any decision to implement artificial recharge of the Mitidja aquifer should only be taken after a comprehensive assessment of the quality of the water intended for recharge has been carried out.

- a comprehensive assessment of the quality of the water intended for recharge;
- a detailed lithological study of the recharge zone.
- hydrogeological simulations to model the transfer and fate of dissolved elements present in the recharge water.

These steps are essential to ensure the sustainable and safe management of this strategic resource.

Competing interest
The authors declare no competing interest.

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Author contributions
The work and design were initiated by Ouahiba Aziez, Dahbia djoudar Hallal, Sonia Leulmi. Material preparation, sampling and data collection were carried out by Fairouz Aouar, Ounissa Saoudi, Taher Mahlab, Dallal Khous, Dahbia djoudar Hallal and Ouahiba Aziez. Data analysis was carried out by Ouahiba Aziez, Dahbia djoudar and Mohamed EL Amine Khelfi. The manuscript was written and revised by Ouahiba Aziez, Dahbia djoudar Hallal and Sonia Leulmi... All the authors have read and approved the final manuscript. Correction and review by Aziez Ouahiba, Djoudar Hellal Dahbia, Khelfi Mohamed Amine, Remini Boualem and Habi Mohamed.

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REFERENCES

Abaidia, S., Remini, B., & Ezziane, K. (2025). Integrated groundwater suitability analysis for irrigation purposes: A case study from the Middle Cheliff plain, Algeria. Glasnik Srpskog geografskog drustva, 105(1), 235-254. https://doi.org/10.2298/GSGD2501235A

Adimalla, N. (2020). Controlling factors and mechanism of groundwater quality variation in semiarid region of South India: an approach of water quality index (WQI) and health risk assessment (HRA). Environmental Geochemistry and Health, 42(6): 1725–1752. Springer. https://doi.org/10.1007/S10653-019-00374-8/METRICS

Adimalla, N., Li, P., and Venkatayogi, S. (2018). Hydrogeochemical Evaluation of Groundwater Quality for Drinking and Irrigation Purposes and Integrated Interpretation with Water Quality Index Studies. Environmental Processes, 5(2): 363–383. Springer Basel. https://doi.org/10.1007/S40710-018-0297-4/METRICS

Adimalla, N., and Qian, H. (2019). Groundwater quality evaluation using water quality index (WQI) for drinking purposes and human health risk (HHR) assessment in an agricultural region of Nanganur, south India. Ecotoxicology and Environmental Safety, 176: 153–161. Academic Press. https://doi.org/10.1016/J.ECOENV.2019.03.066

Adimalla N., Qian H.& Li P. (2019 a). Entropy water quality index and probabilistic health risk assessment from geochemistry of groundwaters in hard rock terrain of Nanganur County, South India, Geochemistry (2019). https://doi.org/10.1016/j.chemer.2019.125544

Agidi, B.M., Akakuru, O.C., Aigbadon, G.O., Schoeneich, K., Isreal, H., Ofoh, I., Njoku, J., and Esomonu, I. (2024). Water quality index, hydrogeochemical facies and pollution index of groundwater around Middle Benue Trough, Nigeria. International Journal of Energy and Water Resources, 8(1): 35–54. Springer. https://doi.org/10.1007/S42108-022-00187-Z

Ahmed, I., Tariq, N., and Al Muhery, A. (2019). Hydrochemical characterization of groundwater to align with sustainable development goals in the Emirate of Dubai, UAE. Environmental Earth Sciences, 78(1): 1–17. Springer Verlag. https://doi.org/10.1007/S12665-018-8030-1/METRICS

Akakuru, O.C., Eze, C.U., Okeke, O.C., Opara, A.I., Usman, A.O., Iheme, O., Ibeneme, S.I., and Iwuoha, P.O. (2022). Hydrogeochemical evolution, water quality indices, irrigation suitability and pollution index of groundwater (PIG) around eastern Niger Delta, Nigeria. International Journal of Energy and Water Resources, 6(3): 389–411. Published by International Journal of Energy and Water Resources. https://doi.org/10.1007/S42108-021-00162-0

Agrouche S. Mansouri Z. Reghais A. Kardache R. Dinar H. Abdelkader L. 2024. Assessment of Groundwater Quality for Irrigation and Drinking Using Water Quality Indexes in the Upper Sebaou Valley (Tizi Ouzou-eastern Algeria) Jordan Journal of Earth & Environmental Sciences, 2025, vol. 16, no 1.

Al-Aizari, H.S., Aslaou, F., Al-Aizari, A.R., Al-Odayni, A.B., and Al-Aizari, A.J.M. (2023a). Evaluation of Groundwater Quality and Contamination Using the Groundwater Pollution Index (GPI), Nitrate Pollution Index (NPI), and GIS. Water 2023, Vol. 15, Page 3701, 15(20): 3701. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/W15203701

Al-Aizari HS, Ghfar AA, Al-Aizari AR, Al-Aizari A-JM, Moshab MS, Sillanpää M. (2023b). Assessing Groundwater Quality and Diagnosing Nitrate Pollution in the Sidi Allal Region: A GIS-Based Approach Utilizing the Groundwater Pollution Index. Hydrology. 10(12):227. https://doi.org/10.3390/hydrology10120227

Amiri, V., Rezaei, M., and Sohrabi, N. (2014). Groundwater quality assessment using entropy weighted water quality index (EWQI) in Lenjanat, Iran. Environmental Earth Sciences, 72(9): 3479–3490. Springer Verlag. https://doi.org/10.1007/S12665-014-3255-0/METRICS

Aziez, O., Remini, B., Habi, M., Ammari.A. (2018). Assessment of groundwater contamination by different interpolation methods for water resource management in the Mitidja plain aquifer (North-Central Algeria). Desalination and Water Treatment 132(1s):167-178. https://doi.org/10.5004/dwt.2018.22921

Bahir, M., Ouhamdouch, S., Carreira, P.M., and Zouari, K. (2019). Relationship Between Hydrochemical Variation and the Seawater Intrusion Within Coastal Alluvial Aquifer of Essaouira Basin (Morocco) Using HFE-Diagram. Advances in Science, Technology and Innovation,: 195–197. Springer, Cham. https://doi.org/10.1007/978-3-030-01572-5_47

Belkendil A., Habi M., Yakhlefoune M., Sarra A., Mekkaoui A., Tariq A., Zineb M. (2025). Integrated GIS-Based approach for groundwater potential mapping in Arid Regions: A case study of Kenadsa-Bechar using AHP and frequency ratio methods. Groundw Sustain Dev 101461. https://doi.org/10.1016/j.gsd.2025.101461

Bouderbala, A. (2018). Effects of Climate Variability on Groundwater Resources in Coastal Aquifers (Case of Mitidja Plain in the North Algeria). 43–51. Springer, Cham. https://doi.org/10.1007/978-3-319-69356-9_6

Boufekane, A., Yahiaoui, S., Meddi, H., Meddi, M., and Busico, G. (2022). Modified DRASTIC index model for groundwater vulnerability mapping using geostatistic methods and GIS in the Mitidja plain area (Algeria). Environmental Forensics, 23(5–6): 539–556. Taylor & Francis. https://doi.org/10.1080/15275922.2021.1913674

Brella, D., Belkhiri, L., Tiri, A., Salhi, H., Lakouas, F.E., Nouibet, R., Amrane, A., Merdoud, R., and Mouni, L. (2023). Identification of the Groundwater Quality and Potential Noncarcinogenic Health Risk Assessment of Nitrate in the Groundwater of El Milia Plain, Kebir Rhumel Basin, Algeria. Hydrology 2023, Vol. 10, Page 171, 10(8): 171. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/HYDROLOGY10080171

Broers, H.P., and Van Der Grift, B. (2004). Regional monitoring of temporal changes in groundwater quality. Journal of Hydrology, 296(1-4): 192–220. Elsevier. https://doi.org/10.1016/J.JHYDROL.2004.03.022

Chaudhari, U., Kumari, D., Mittal, S., Sahoo, P.K. (2025). GIS-Based Spatial Autocorrelation and Multivariate Statistics for Understanding Groundwater Uranium Contamination and Associated Health Risk in Semiarid Region of Punjab, India. Water 2025, 17, 2064. https://doi.org/10.3390/ w17142064

Clemens, M., Khurelbaatar, G., Merz, R., Siebert, C., van Afferden, M., and Rodiger, T. (2020). Groundwater protection under water scarcity; from regional risk assessment to local wastewater treatment solutions in Jordan. Sci. Total Environ. 706, 136066. https://doi.org/10.1016/j.scitotenv.2019.136066

Cliff, A. D., & Ord, K. (1970). Spatial autocorrelation: a review of existing and new measures with applications. Economic Geography, 46(sup1), 269-292.

Dalale Khous, Ait-amar, H., Belaid, M., and Chorfi, H. (2019). Geochemical and Isotopic Assessment of Groundwater Quality in the Alluvial Aquifer of the Eastern Mitidja Plain. Water Resources, 46(3): 443–453. Pleiades Publishing. https://doi.org/10.1134/S0097807819030060

Djoudar/hallal, D., Zahouani, S., and Khaldi, A. (2018). Application of the GALDIT Method to the Study of Groundwater Vulnerability of the East Mitidja Alluvial Waters. Advances in Science, Technology and Innovation, 677–680. Springer, Cham. https://doi.org/10.1007/978-3-319-70548-4_200

Djoudar D, Toubal A. (2014). Etat actuel de l'invasion marine dans la baie d'Alger *"Current state of marine invasion in the Bay of Algiers"* Production scientifique-Communications, 1. https:// www. iwra. org/ congr ess/ 2008/ resou rce/ autho rs/ abs142_ artic le. pdf

Egbueri, J.C., Ameh, P.D., and Unigwe, C.O. (2020). Integrating entropy-weighted water quality index and multiple pollution indices towards a better understanding of drinking water quality in Ojoto area, SE Nigeria. Scientific African, 10: e00644. Elsevier. https://doi.org/10.1016/J.SCIAF.2020.E00644

El Morabet, R., Barhazi, L., Khan, R.A., Hejjaj, A., Harrara, R., Bouhafa, S., Khan, A.R., Khan, N.A., and Yeremenko, S. (2021). Study of seasonal variation and index based assessment of water quality and pollution in semi-arid region of morocco. Ecological Questions, 32(4). Nicolaus Copernicus University. doi:10.12775/EQ.2021.037.

El Mountassir, O., Bahir, M., Ouazar, D., Ouhamdouch, S., Chehbouni, A., and Ouarani, M. (2020). The use of GIS and water quality index to assess groundwater quality of krimat aquifer (Essaouira; Morocco). SN Applied Sciences, 2(5). Springer Nature. https://doi.org/10.1007/s42452-020-2653-z

Gad, M., Gaagai, A., Agrama, A.A., El-Fiqy, W.F.M., Eid, M.H., Szűcs, P., Elsayed, S., Elsherbiny, O., Khadr, M., Abukhadra, M.R., Alfassam, H.E., Bellucci, S., and Ibrahim, H. (2024). Comprehensive evaluation and prediction of groundwater quality and risk indices using quantitative approaches, multivariate analysis, and machine learning models: An exploratory study. Heliyon, 10(17): e36606. https://doi.org/10.1016/j.heliyon.2024.e36606

Gao, Y., Qian, H., Ren, W., Wang, H., Liu, F., and Yang, F. (2020). Hydrogeochemical characterization and quality assessment of groundwater based on integrated-weight water quality index in a concentrated urban area. Journal of Cleaner Production, 260: 121006. Elsevier. https://doi.org/10.1016/J.JCLEPRO.2020.121006

Gorgij, A.D., Kisi, O., Moghaddam, A.A., and Taghipour, A. (2017). Groundwater quality ranking for drinking purposes, using the entropy method and the spatial autocorrelation index. Environmental Earth Sciences, 76(7). Springer Verlag. https://doi.org/10.1007/s12665-017-6589-6

Hallouz, F., Meddi, M., Mahe, G., Ali Rahmani, S.E., and Zettam, A. (2023). Hybrid Analysis of Rainfall Erosivity in Northern Algeria: Integrating Empirical and Modeling Approaches. Pure and Applied Geophysics, 180(11): 3995–4023. Birkhauser. https://doi.org/10.1007/S00024-023-03360-5/METRICS

He, W., Qian, F., Lam, J., Chen, G., Han, Q.L., and Kurths, J. (2015). Quasi-synchronization of heterogeneous dynamic networks via distributed impulsive control: Error estimation, optimization and design. Automatica, 62: 249–262. Pergamon. https://doi.org/10.1016/J.AUTOMATICA.2015.09.028

Islam, A.R.M.T., Ahmed, N., Bodrud-Doza, M., and Chu, R. (2017). Characterizing groundwater quality ranks for drinking purposes in Sylhet district, Bangladesh, using entropy method, spatial autocorrelation index, and geostatistics. Environmental Science and Pollution Research, 24(34): 26350–26374. Springer Verlag. https://doi.org/10.1007/s11356-017-0254-1

Islam, A.R.M.T., Kabir, M.M., Faruk, S., Al Jahin, J., Bodrud-Doza, M., Didar-ul-Alam, M., Bahadur, N.M., Mohinuzzaman, M., Fatema, K.J., Safiur Rahman, M., and Choudhury, T.R. (2021). Sustainable groundwater quality in southeast coastal Bangladesh: co-dispersions, sources, and probabilistic health risk assessment. Environment, Development and Sustainability, 23(12): 18394–18423. Springer Science and Business Media B.V. http://doi:10.1007/S10668-021-01447-4/METRICS.

Khelfi, M. E. A., Hallal, D. D., Guastaldi, E., Alili, M., & Nadri, M. (2025). Assessment of the vulnerability and sensitivity of groundwater for drinking water supply and irrigation: The case of the Mitidja alluvial aquifer (Northern Algeria). Geomatics, Landmanagement and Landscape, 119-145. https://doi.org/10.15576/GLL/200413

Kawachi, T., Maruyama, T., and Singh, V.P. 2001. Rainfall entropy for delineation of water resources zones in Japan. Journal of Hydrology, 246(1–4): 36–44. Elsevier. https://doi.org/10.1016/S0022-1694(01)00355-9

Kerboub, D., Fehdi, C., El hmaidi, A., Ousmana, H., Azzi, Y., and Khemissi, C. (2023). Pig based water quality assessment in El-Hai River Basin, Elkantara Plain, Algeria. Journal of Fundamental and Applied Sciences, 14(1): 26–59. African Journals Online (AJOL). https://doi.org/10.4314/jfas.v14i1.2

Kumar, P.J.S., Augustine, C.M. (2022). Entropy-weighted water quality index (EWQI) modeling of groundwater quality and spatial mapping in Uppar Odai Sub-Basin, South India. Model. Earth Syst. Environ. 8, 911–924 https://doi.org/10.1007/s40808-021-01132-5

Leulmi, S.M., Aidaoui, A., Hallal, D.D., Khelfi, M.A., Ferraira, J.P.L., Ammari, A., and Aziez, O. (2021). Spatio-temporal analysis of nitrates and piezometric levels in groundwater using geostatistical approach: case study of the Eastern Mitidja Plain, North of Algeria. Arabian Journal of Geosciences, 14(5): 1–15. Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/S12517-021-06642-1/METRICS

Li, C., Gao, Z., Chen, H., Wang, J., Liu, J., Li, C., Teng, Y., Liu, C., and Xu, C. (2021). Hydrochemical analysis and quality assessment of groundwater in southeast North China Plain using hydrochemical, entropy-weight water quality index, and GIS techniques. Environmental Earth Sciences, 80(16): 1–15. Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/S12665-021-09823-Z/METRIC .

Li, X., Wang, K., Liuz, L., Xin, J., Yang, H., and Gao, C. (2011). Application of the Entropy Weight and TOPSIS Method in Safety Evaluation of Coal Mines. Procedia Engineering, 26: 2085–2091. No longer published by Elsevier. https://doi.org/10.1016/J.PROENG.2011.11.2410

Madene, E., Boufekane, A., Derardja B., Busico, G., Meddi, M. (2023). The influence of lithology and climatic conditions on the groundwater quality in the semi-arid-regions: case study of the Eastern Middle Cheliff alluvial aquifer (north-western Algeria) Acque Sotterranee - Italian Journal of Groundwater, 12(4) https://doi.org/10.7343/as-2023-671

Meng, F., Liang, X., Xiao, C., and Wang, G. (2021). Integration of GIS, improved entropy and improved catastrophe methods for evaluating suitable locations for well drilling in arid and semi-arid plains. Ecological Indicators, 131. Elsevier B.V. http:// https://doi.org/10.1016/j.ecolind.2021.108124

Mohammadi, A., Mansour, S. N., Faraji, M., Abdolahnejad, A., Toolabi, A., & Miri, M. (2020). A protocol for pollution index, source identification, and spatial analysis of heavy metals in top soil. Journal of Environmental Health and Sustainable Development. 5 (4) https://doi.org/10.18502/jehsd.v5i4.4965

Moran, P. A. P. (1948). The Interpretation of Statistical Maps." Journal of the Royal Statistical Society. Series B (Methodological), vol. 10, no. 2, pp. 243–51. JSTOR, http://www.jstor.org/stable/2983777.

Moran, P.A.P. (1950). Some Theorems on Time Series: II The Significance of the Serial Correlation Coefficient. Biometrika, 35(3/4): 255. JSTOR. https://doi.org/10.2307/2332344

Morsli, B., Habi, M., & Bouchekara, B. (2017). Study of marine intrusion in coastal aquifers and its repercussions on the land degradation by the use of a multidisciplinary approach. LARHYSS Journal P-ISSN 1112-3680/E-ISSN 2521-9782, (30), 225-237.

Moussaoui, Z., Ben Brahim, F., Hamdi, M., Hidouri, N., Younes, H., Bouri, S. (2025). Assessment of groundwater quality and soil salinization risks in the central Tunisia aquifer systems: water resources management and public health implicationsAcque Sotterranee - Italian Journal of Groundwater, 14(1), 47 - 62 https://doi.org/10.7343/as-2025-825

National Office of Statistics ONS (2020). Statistical Directory of the wilaya of Algiers 2020. https://www.ons.dz/.

Nemer, Z., Khaldaoui, F., Benaissa, Z., Belaroui, A., Tebbouche, M.Y., and Ydri, A. (2023). Hydrogeophysical investigation of aquifer parameters and seawater intrusion: a case study from Eastern Mitidja plain, Algeria. Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 9(1): 1–19. Springer Science and Business Media Deutschland GmbH. http://10.1007/S40948-023-00610-7/FIGURES/11

Nori-Sarma, A., Thimmulappa, R.K., Venkataramana, G. V., Fauzie, A.K., Dey, S.K., Venkareddy, L.K., Berman, J.D., Lane, K.J., Fong, K.C., Warren, J.L., and Bell, M.L. (2020). Low-cost NO_2 monitoring and predictions of urban exposure using universal kriging and land-use regression modelling in Mysore, India. Atmospheric Environment, 226. Elsevier Ltd. https://doi.org/10.1016/j.atmosenv.2020.117395

Nourani, V., Ghaneei, P., and Kantoush, S.A. (2022). Robust clustering for assessing the spatiotemporal variability of groundwater quantity and quality. Journal of Hydrology, 604: 127272. Elsevier. https://doi.org/10.1016/J.JHYDROL.2021.127272

Ozkul, S., Harmancioglu, N.B., and Singh, V.P. (2000). Entropy-Based Assessment of Water Quality Monitoring Networks. Journal of Hydrologic Engineering, 5(1): 90–100. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)1084-0699(2000)5:1(90)

Pei-Yue, L., Hui, Q., and Jian-Hua, W. (2010). Groundwater Quality Assessment Based on Improved Water Quality Index in Pengyang County, Ningxia, Northwest China. Journal of Chemistry, 7(SUPPL. 1): S209–S216. John Wiley & Sons, Ltd. https://doi.org/10.1155/2010/451304

Prasanna, M. V., Chidambaram, S., Gireesh, T. V., and Ali, T.V.J. (2011). A study on hydrochemical characteristics of surface and sub-surface water in and around Perumal Lake, Cuddalore district, Tamil Nadu, South India. Environmental Earth Sciences, 63(1): 31–47. Springer Verlag. https://doi.org/10.1007/S12665-010-0664-6/METRICS

Quevauviller, P., Hinsby, K., Karlsson Seidenfaden, I., Pulido Velázquez, D., Sapiano, M., Coelho, R., Gattinesi, P., Hohenblum, P., Jirovsky, V., Marinheiro, F., Simas, L., Teixeira, R., Ugarelli, R., Cardarilli, M., Paraskevopoulos, S., Vrachimis, S., Medema, G., Eliades, D., La Vigna, F. (2024). Review: The Urban Water Security and Safety ParadoxAcque Sotterranee – Italian Journal of Groundwater, 13(3), 11 - 24 https://doi.org/10.7343/as-2024-775

Radfard, M., Gholizadeh, A., Azhdarpoor, A., Badeenezhad, A., Mohammadi, A.A., and Yousefi, M. (2019). Health risk assessment to fluoride and nitrate in drinking water of rural residents living in the Bardaskan city, arid region, southeastern Iran. Desalination and Water Treatment, 145: 249–256. Elsevier. https://doi.org/10.5004/DWT.2019.23651

Rao, N.S., Sunitha, B., Rambabu, R., Rao, P.V.N., Rao, P.S., Spandana, B.D., Sravanthi, M., and Marghade, D. (2018). Quality and degree of pollution of groundwater, using PIG from a rural part of Telangana State, India. Applied Water Science, 8(8): 1–13. Springer Verlag. https://doi.org/10.1007/S13201-018-0864-X/TABLES/7

Reza, R., and Singh, G. (2010). Assessment of Ground Water Quality Status by Using Water Quality Index Method in Orissa, India. World Applied Sciences Journal, 9(12): 1392–1397.

Sanad, H., Mouhir, L., Zouahri, A., Moussadek, R., El Azhari, H., Yachou, H., Ghanimi, A., Oueld Lhaj, M., and Dakak, H. (2024). Assessment of Groundwater Quality Using the Pollution Index of Groundwater (PIG), Nitrate Pollution Index (NPI), Water Quality Index (WQI), Multivariate Statistical Analysis (MSA), and GIS Approaches: A Case Study of the Mnasra Region, Gharb Plain, Morocco. Water 2024, Vol. 16, Page 1263, 16(9): 1263. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/W16091263

Sawyer, C.N., & McCarty, P. L. (1967). Chemistry for Sanitary Engineers. McGraw-Hill, New York. Shang, Y., You, B., & Shang, L. (2016). China's environmental strategy towards reducing deep groundwater exploitation. https://doi.org/10.1007/s12665-016-6110-7

Shannon, C.E. (1948). A Mathematical Theory of Communication. Bell System Technical Journal, 27(3): 379–423. John Wiley & Sons, Ltd. https://doi.org/10.1002/J.1538-7305.1948.TB01338.X

Shyu, G.S., Cheng, B.Y., Chiang, C.T., Yao, P.H., and Chang, T.K. (2011). Applying factor analysis combined with kriging and information entropy theory for mapping and evaluating the stability of groundwater quality variation in Taiwan. International Journal of Environmental Research and Public Health, 8(4): 1084–1109. MDPI. https://doi.org/10.3390/ijerph8041084

Siddiqi, S.A., Al-Mamun, A., Baawain, M.S., and Sana, A. (2021). Groundwater contamination in the Gulf Cooperation Council (GCC) countries: a review. Environmental Science and Pollution Research, 28(17): 21023–21044. Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/S11356-021-13111-5/METRICS

Siddique, M. A. B., Islam, A. R. M. T., Hossain, M. S., Khan, R., Akbor, M. A., Hasanuzzaman, M. & Bodrud-Doza, M. (2022). Multivariate statistics and entropy theory for irrigation water quality and entropy-weighted index development in a subtropical urban river, Bangladesh. Environmental Science and Pollution Research, 29(6), 8577-8596. https://doi.org/10.1007/s11356-021-16343-7

Subba Rao, N. (2012). PIG: a numerical index for dissemination of groundwater contamination zones. Hydrological Processes, 26(22): 3344–3350. John Wiley & Sons, Ltd. https://doi.org/10.1002/HYP.8456

SUBBA RAO (2017). Hydrogeology: problems with solutions. PHI Learning Private Limited.

Subba Rao, N. (2018). Groundwater quality from a part of Prakasam District, Andhra Pradesh, India. Appl Water Sci 8, 30. https://doi.org/10.1007/s13201-018-0665-2

Subba Rao, N., and Chaudhary, M. (2019). Hydrogeochemical processes regulating the spatial distribution of groundwater contamination, using pollution index of groundwater (PIG) and hierarchical cluster analysis (HCA): A case study. Groundwater for Sustainable Development, 9. Elsevier B.V. https://doi.org/10.1016/j.gsd.2019.100238

Subba Rao, N., Sunitha, B., Adimalla, N., and Chaudhary, M. (2020). Quality criteria for groundwater use from a rural part of Wanaparthy District, Telangana State, India, through ionic spatial distribution (ISD), entropy water quality index (EWQI) and principal component analysis (PCA). Environmental Geochemistry and Health, 42(2): 579–599. Springer. https://doi.org/10.1007/S10653-019-00393-5/METRICS

Su, H., Kang, W., Xu, Y., and Wang, J. (2018). Assessing Groundwater Quality and Health Risks of Nitrogen Pollution in the Shenfu Mining Area of Shaanxi Province, Northwest China. Exposure and Health, 10(2): 77–97. Springer. https://doi.org/10.1007/S12403-017-0247-9/METRICS

Sunitha, V., and Reddy, B.M. (2022). Geochemical characterization, deciphering groundwater quality using pollution index of groundwater (PIG), water quality index (WQI) and geographical information system (GIS) in hard rock aquifer, South India. Applied Water Science, 12(3): 1–20. Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/S13201-021-01527-W/FIGURES/4

Trabelsi, F., and Ali, S.B.H. (2022). Exploring Machine Learning Models in Predicting Irrigation Groundwater Quality Indices for Effective Decision Making in Medjerda River Basin, Tunisia. Sustainability (Switzerland), 14(4). MDPI. https://doi.org/10.3390/su14042341

Uddin, M.G., Nash, S., Rahman, A., and Olbert, A.I. (2023). A sophisticated model for rating water quality. Science of the Total Environment, 868. Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2023.161614

UN W.W.D. Rapport. (2022). UN World Water Development Report 2022 UN-Water. Available from https://www.unwater.org/publications/un-world-water-development-report-2022. [accessed 26 August 2024]

Varol, S., and Davraz, A. (2015). Evaluation of the groundwater quality with WQI (Water Quality Index) and multivariate analysis: a case study of the Tefenni plain (Burdur/Turkey). Environmental Earth Sciences, 73(4): 1725–1744. Springer Verlag. https://doi.org/10.1007/S12665-014-3531-Z/METRICS

Vasanthavigar, M., Srinivasamoorthy, K., Vijayaragavan, K., Rajiv Ganthi, R., Chidambaram, S., Anandhan, P., Manivannan, R., and Vasudevan, S. (2010). Application of water quality index for groundwater quality assessment: Thirumanimuttar sub-basin, Tamilnadu, India. Environmental Monitoring and Assessment, 171(1–4): 595–609. Springer. https://doi.org/10.1007/S10661-009-1302-1/METRICS

Verma, D.K., Bhunia, G.S., Shit, P.K., and Tiwari, A.K. (2018). Assessment of Groundwater Quality of the Central Gangetic Plain Area of India Using Geospatial and WQI Techniques. Journal of the Geological Society of India, 92(6): 743–752. Geological Society of India. https://doi.org/10.1007/S12594-018-1097-1/METRICS

Wagh, V., Mukate, S., Muley, A., Kadam, A., Panaskar, D., and Varade, A. (2020). Study of groundwater contamination and drinking suitability in basaltic terrain of Maharashtra, India through PIG and multivariate statistical techniques. Journal of Water Supply: Research and Technology-Aqua, 69(4): 398–414. IWA Publishing. https://doi.org/10.2166/AQUA.2020.108

Wang, D., Wu, J., Wang, Y., and Ji, Y. (2020). Finding High-Quality Groundwater Resources to Reduce the Hydatidosis Incidence in the Shiqu County of Sichuan Province, China: Analysis, Assessment, and Management. Exposure and Health, 12(2): 307–322. Springer. https://doi.org/10.1007/S12403-019-00314-Y/METRICS

Wang, X., Xu, Y.J., & Zhang, L. (2022a). Watershed scale spatiotemporal nitrogen transport and source tracing using dual isotopes among surface water, sediments and groundwater in the Yiluo River Watershed, Middle of China. Science of the Total Environment, 833, 155180. https://doi.org/10.1016/j.scitotenv.2022.155180

Wang, X., Xiao, C., Liang, X., and Li, M. (2022b). Groundwater Quality Assessment in the Northern Part of Changchun City, Northeast China, Using PIG and Two Improved PIG Methods. International Journal of Environmental Research and Public Health, 19(15). MDPI. https://doi.org/10.3390/ijerph19159603

Wang, Y., Li, R., Wu, X., Yan, Y., Wei, C., Luo, M., Xiao, Y., and Zhang, Y. (2023). Evaluation of Groundwater Quality for Drinking and Irrigation Purposes Using GIS-Based IWQI, EWQI and HHR Model. Water (Switzerland), 15(12). MDPI. https://doi.org/10.3390/w15122233

World Health Organization (WHO). (2011). Evaluating Household Water Treatment Options. Guidelines for drinking water, 4th edn. Geneva, pp 564.

Xie Z., Liu W., Chen S., Yao R., Yang C., Zhang X., Li J., Wang Y., Zhang Y., (2025). Machine learning approaches to identify hydrochemical processes and predict drinking water quality for groundwater environment in a metropolis. Journal of Hydrology: Regional Studies. Volume 58. https://doi.org/10.1016/j.ejrh.2025.102227

Xing, L., Guo, H., and Zhan, Y. (2013). Groundwater hydrochemical characteristics and processes along flow paths in the North China Plain. Journal of Asian Earth Sciences, 70–71: 250–264. Pergamon. https://doi.org/10.1016/J.JSEAES.2013.03.017

Yahiaoui, S., Meddi, M., Razack, M., Boufekane, A., and Bekkoussa, B.S. (2023). Hydrogeochemical and isotopic assessment for characterizing groundwater quality in the Mitidja plain (northern Algeria). Environmental Science and Pollution Research, 30(33): 80029–80054. Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/S11356-023-27952-9/METRICS

Yeh, H.F., Chang, J.C., Huang, C.C., and Chen, H.Y. (2022). Spatial correlation of groundwater level with natural factors using geographically weighted regression model in the Choushui River Alluvial Fan, Taiwan. Frontiers in Earth Science, 10. Frontiers Media S.A. https://doi.org/10.3389/feart.2022.977611

Yousefi, M., Ghoochani, M., and Hossein Mahvi, A. (2018). Health risk assessment to fluoride in drinking water of rural residents living in the Poldasht city, Northwest of Iran. Ecotoxicology and Environmental Safety, 148: 426–430. Academic Press. https://doi.org/10.1016/J.ECOENV.2017.10.057

Zhang, Y., Jia, R., Wu, J., Wang, H., & Luo, Z. (2021a). Evaluation of Groundwater Using an Integrated Approach of Entropy Weight and Stochastic Simulation: A Case Study in East Region of Beijing. International Journal of Environmental Research and Public Health, 18(14), 7703. https://doi.org/10.3390/ijerph18147703

Zhang, Y., Li, F., Zhang, Q., Li, J., and Liu, Q. (2014). Tracing nitrate pollution sources and transformation in surface- and groundwaters using environmental isotopes. Science of The Total Environment, 490: 213–222. Elsevier. https://doi.org/10.1016/J.SCITOTENV.2014.05.004

Zhang, Y., Li, X., Luo, M., Wei, C., Huang, X., Xiao, Y., Qin, L., and Pei, Q. (2021b). Hydrochemistry and Entropy-Based Groundwater Quality Assessment in the Suining Area, Southwestern China. Journal of Chemistry, 2021(1): 5591892. John Wiley & Sons, Ltd. https://doi.org/10.1155/2021/5591892