JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(9), 324–343
https://doi.org/10.12911/22998993/222197
ISSN 2299–8993, License CC-BY 4.0

Received: 2026.03.16
Accepted: 2026.07.15
Published: 2026.08.01

Impact of hydrological variability on the quality of irrigation water from the Beni Bahdel dam (western Algeria)

Hadjila Othman[1*], Baghli-Merabet Naoual[2], Kazi Tani Hicham Abdeslam[1], Mahdi Ziane[3], Benaissa Radouane[1]

[1] Laboratory No. 25, Department of Hydraulics, Institute of Science and Technology, University Centre of Maghnia, 13300 Tlemcen, Algeria
[2] EOLE Laboratory, Department of Agronomy, Faculty of Natural and Life Sciences, Earth and Universe Sciences, University of Tlemcen, 13300 Tlemcen, Algeria
[3] EOLE Laboratory, Department of Hydraulics, Faculty of Technology, University of Tlemcen, 13300 Tlemcen, Algeria
* Corresponding author's e-mail: o.hadjila@cu-maghnia.dz

ABSTRACT

In semi-arid regions, climate fluctuations and recurrent drought episodes strongly affect both the quantity and quality of surface water stored in reservoirs. In this context, the Beni Bahdel Dam, located in western Algeria, constituting an important source of irrigation water, is increasingly experiencing the effects of current climate change. This research investigated how wet and dry hydrological periods influence the hydrochemical properties of the dam water and its appropriateness for agricultural use. The study relied on the assessment of major hydrochemical variables together with several irrigation water quality indices, namely sodium adsorption ratio (SAR), Kelly's ratio (KR), sodium percentage (Na%), magnesium adsorption ratio (MAR), cation ratio of structural stability (CROSS), and irrigation water quality index (IWQI). The results highlight a significant impact of hydrological variability on water quality. In particular, they reveal a doubling of the average electrical conductivity (EC), increasing from 402.46 (μS/cm) during the wet period to 810.25 (μS/cm) during the dry period. Furthermore, the IWQI showed a decrease in its median value, from 71.19 to 65.73, indicating a shift toward a "moderate restriction" class. The CROSS index also proved to be a particularly sensitive indicator of aridification conditions, with an increase of 32.93% (from 1.64 to 2.18). Finally, the Magnesium Adsorption Ratio (MAR) exceeded the critical threshold of 50 during the dry period, reaching an average value of 53.60. Descriptive statistical methods and Pearson correlation analysis were applied to explore the relationships between ionic composition and irrigation suitability indicators. The findings contribute to a better understanding of the effects of climate variability on water quality and provide useful evidence for improving sustainable reservoir management in semi-arid environments.

Keywords: Surface water, Beni Bahdel dam, irrigation water quality, hydrochemical facies.

INTRODUCTION

Due to the irregular and restricted availability of water resources, together with rising water demand, achieving sustainable water resource management has become a major challenge in semi-arid regions (Nadhir et al., 2024; Kinzelbach et al., 2010). This situation is further intensified by climate change, which manifests as declining precipitation and the increasing frequency and severity of drought events (Chiang et al., 2021; Sumi et al., 2022). Consequently, the water stored in reservoirs is increasingly exposed to stress caused by lower storage volumes and high evaporation rates, both of which contribute to water quality degradation (Mozzi et al., 2021). Furthermore, surface water quality is shaped by a combination of natural processes and human-induced pressures, including metal pollution, which can disturb the ecological equilibrium of aquatic ecosystems (Khatri and Tyagi, 2015). The Beni Bahdel dam is fully in line with this issue. Located in western Algeria, on a catchment area of approximately 1016 km² and with an initial storage capacity of 63 million m³, it is one of the main hydraulic structures in the region. It provides both water supply and irrigation for vast agricultural areas, while facing increasing pressure from climate variability and continuously rising water demand. This situation makes it essential to control the quality of its waters in order to ensure sustainable and secure management for agricultural uses. The present study focused on evaluating the Beni Bahdel dam water by examining both its physico-chemical composition and the main indicators used to determine irrigation water quality across two distinct hydrological conditions: wet and dry. These periods were identified using the standardised precipitation index (SPI), which allows for a better understanding of the influence of climate variability on irrigation suitability. Such an approach also reveals seasonal changes in water chemistry and the extent to which the measured parameters meet irrigation requirements, an important consideration for ensuring agricultural sustainability (Barik et al., 2026; Sayel et al., 2026; Marif and Esmail, 2025). Prior research in Algeria has evaluated the physico-chemical quality of dam water and its appropriateness for irrigation, particularly at the Koudiet M'douar, Tagharist (Nadhir et al., 2024) and Grouz (Allia et al., 2022) dams. These studies have highlighted the importance of rigorous monitoring of such parameters as electrical conductivity, pH, nitrate and phosphorus content, which are key indicators of the degradation of surface water resources (Nadhir et al., 2024; Allia et al., 2022).

This research is essential for understanding the mechanisms of water quality deterioration and for implementing effective management strategies. The physico-chemical characterisation of dam waters is a fundamental step in determining their suitability for agricultural use, in particular by assessing parameters such as conductivity, chlorides, calcium and sulphates, the high concentrations of which may indicate significant mineralisation (Nadhir et al., 2024; Allia et al., 2022). It is in this context of increased climate variability that the present study aimed to assess the hydrochemical quality of the waters of the Beni Bahdel dam and their suitability for agricultural irrigation. The approach adopted is based on a comparison of two contrasting hydrological periods (September 2008-August 2012 and September 2018-August 2021), with the distinction between wet and dry periods established using the Standardised Precipitation Index on a monthly scale (SPI-1), which makes it possible to characterise the influence of climatic fluctuations on water resources. The analysis is based on 84 monthly analyses of raw water from the dam, provided by Algerian Water Company (ADE) and validated by the ionic balance, supplemented by the rainfall data from the dam station provided by National Hydraulic Resources Agency (ANRH).

The main physical and chemical parameters studied included pH, electrical conductivity, total dissolved salts, and major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-} and NO_3^-). To determine whether the dam water is appropriate for irrigation, the assessment was based on a set of widely accepted hydrochemical indicators (Mussa et al., 2025), including the irrigation water quality index, the sodium adsorption ratio, the sodium percentage, the permeability index, magnesium adsorption ratio and Kelly's ratio (Abadi et al., 2025; Meireles et al., 2010; Doneen, 1975; Kelley, 1963; Wilcox, 1955). Adopting such a comprehensive framework allows a clearer understanding of how hydrological fluctuations affect reservoir water quality, while also supporting more sustainable agricultural water management in western Algeria.

This study adopted a three-pronged approach aimed at gaining a better understanding of the interactions between climate variability and agricultural sustainability. Firstly, it sought to gain a better understanding of the hydrochemical quality of the water in the Beni Bahdel reservoir by identifying the impact of climatic fluctuations. To this end, the Standardised Precipitation Index (SPI-1) is used to characterise contrasting wet and dry episodes during two ten-year periods (2008–2012 and 2018–2020). Secondly, the study sought to characterise changes in the main physico-chemical parameters of the water samples (pH, electrical conductivity, total dissolved salts and major ions), as well as numerous indicators of water quality for irrigation purposes. Drawing on indicators such as the irrigation water quality index (IWQI), the sodium adsorption ratio (SAR), the percentage of sodium (Na%), the permeability index (PI), the magnesium adsorption ratio (MAR), the Kelly's ratio (KR) and the cationic structural stability ratio (CROSS), this study aimed to investigate how hydrological fluctuations influence the risks of salinisation and structural degradation of soils. Finally, this research examined the consequences of these changes on the suitability of the water for irrigation and proposed a set of evidence-based management recommendations. This integrated approach is thus intended to provide a decision-making framework for the sustainable management of water resources and the adaptation of irrigation practices to the challenging conditions of the semi-arid regions of western Algeria.

MATERIALS AND METHODS

Study area

The Beni Bahdel dam, located in western Algeria, is both an important storage facility and vulnerable to the vagaries of climate change. With a capacity of 63 Mm^3 fed by a 1016 km^2 basin (Bouanani et al., 2011), it provides drinking water and irrigation for several thousand hectares of arable land. In addition, it regulates water in this region, which is characterised by a semi-arid climate and increasing climate variability (Figure 1).

Methodology

The methodology adopted in this study is based on a two-step approach. First, the wet and dry periods were identified using the Standardised Precipitation Index (SPI-1) (Abu Arra et al., 2025). Second, the water quality of the Beni Bahdel dam was assessed by analysing several physicochemical parameters and indices (Abadi et al., 2025; Zhou et al., 2020; Smith et al., 2015; Meireles et al., 2010), namely: hydrogen potential (pH), electrical conductivity (EC), total dissolved salts (TDS), total hardness (TH), sodium adsorption ratio (SAR), sodium percentage (Na%), Magnesium adsorption ratio (MAR), permeability index (PI), residual sodium bicarbonate (RSBC), Kelly's ratio (KR), salinity potential (PS), the cation ratio of structural stability (CROSS) and irrigation water quality index (IWQI). In total, 84 water samples from the dam were analysed and provided by the Algerian Water Company (ADE) of Tlemcen, while the rainfall data came from the dam's meteorological station (National Hydraulic Resources Agency (ANRH)).

Standardised precipitation index (SPI)

The standardised precipitation index (SPI) is widely used for monitoring meteorological drought and identifying wet and dry climatic conditions over multiple temporal scales. The index was originally proposed by (McKee et al., 1993) and is based exclusively on precipitation records. By transforming precipitation series into a normalised probability distribution, SPI enables the comparison of rainfall anomalies across different climatic regions and time scales, such as 1, 3, 6 or 12 months (McKee et al., 1993; World Meteorological Organization, 2012).

The computation of SPI involves fitting the precipitation data to a gamma probability

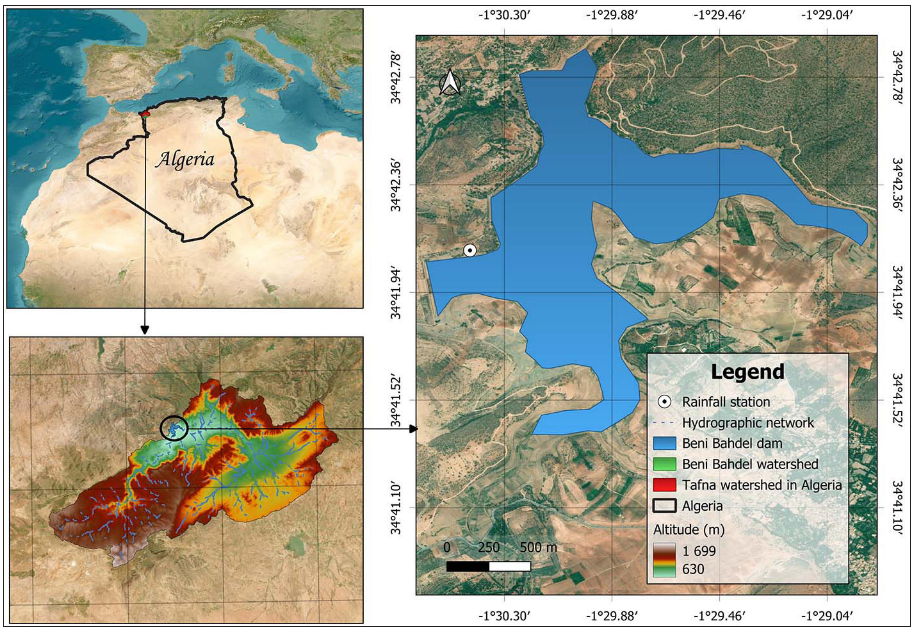

Figure 1. Location of the Beni Bahdel dam

distribution, which has been shown to effectively represent the positively skewed nature of rainfall series in most climatic regions (Wu et al., 2017; Guttman, 1999). This distribution converts observed precipitation values into a standardised form with a mean of zero and a variance of one, allowing the identification of both drought and excessively wet conditions. The gamma probability density function is defined as:

$$g(x) = \frac{1}{\Gamma(\alpha)\beta^{\alpha}} x^{\alpha-1} e^{-\frac{x}{\beta}} \quad (1)$$

where: α is the shape parameter, β is the scale parameter, x represents the amount of monthly precipitation and $\Gamma(\alpha)$ denotes the Gamma function.

The Gamma function itself is expressed as:

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1} e^{-y} dy \quad (2)$$

The parameters of the gamma distribution α and β are estimated using the maximum likelihood estimation method, which is applied independently for each station and each selected time scale (World Meteorological Organization, 2012; Guttman, 1999). The parameters are calculated using the following relationships:

$$\begin{cases} \alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \\ \beta = \frac{\bar{X}}{\alpha} \\ A = ln(\bar{X}) - \frac{\sum_{i=1}^{n} ln(x_i)}{n} \end{cases} \quad (3)$$

where: $\bar{X}$ denotes the mean precipitation, n represents the total number of observations, and x_i corresponds to precipitation recorded at time i.

Once the parameters are determined, the cumulative probability distribution describing precipitation occurrence can be written as:

$$G(x) = \int_0^{x} g(x)dx = $$

$$= \frac{1}{\Gamma(\alpha)\beta^{\alpha}} \int_0^{x} x^{\alpha-1} e^{-x/\beta} dx \quad (4)$$

Because the gamma distribution is undefined when precipitation equals zero, the cumulative probability must be corrected to account for the probability of zero rainfall events. This adjustment is expressed as:

$$H(x) = q + (1-q)G(x)\, dx \quad (5)$$

where: q represents the probability of zero precipitation.

The cumulative probability $H(x)$ is subsequently transformed into a standard normal distribution, allowing the derivation of SPI values. According (Fettam et al., 2025; Wu et al., 2017), the SPI is SPI can be approximated using the following equations:

$$\begin{cases} SPI = -\left(t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \\ for\ 0 < H(x) \leq 0.5 \\ SPI = +\left(t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \\ for\ 0.5 < H(x) < 1.0 \end{cases} \quad (6)$$

The parameter t is given by:

$$\begin{cases} t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)}\ for\ 0 < H(x) \leq 0.5 \\ t = \sqrt{\ln\left(\frac{1}{(1-H(x))^2}\right)}\ for\ 0.5 < H(x) < 1.0 \end{cases} \quad (7)$$

The empirical constants used in this approximation are:

$C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$.

Drought conditions were classified into eight categories based on SPI values, ranging from extremely wet to extremely dry conditions Table 1 (Pandhumas et al., 2020).

Frequency analysis

Using the drought classification scheme, a frequency analysis was carried out to describe the temporal distribution of each category over the study period. This procedure quantifies how often each drought class occurs and is expressed by:

Table 1. Classification of drought or wetness categories according to SPI values

SPI value	Categories
2.00 or more	Extremely wet
1.50 to 2.00	Very wet
1.00 to 1.49	Moderately wet
0.00 to 0.99	Mild wet
-0.99 to 0.00	Mild dry
-1.00 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
-2.00 or less	Extremely dry

$$Frequency\,\% = = \frac{Number\ of\ months\ in\ each\ class}{Total\ number\ of\ months} \times 100\% \quad (8)$$

By expressing drought occurrence as a percentage, the frequency analysis offers a clear picture of the intensity and persistence of different drought conditions. This approach is essential for characterising drought regimes, evaluating their severity, and interpreting the temporal pattern of drought episodes (Abu Arra et al., 2025).

Assessment of water quality for agricultural irrigation

To determine the suitability of Beni Bahdel dam water for agricultural irrigation, a broad set of physical and chemical variables was analysed in accordance with the methodological framework, and multiple irrigation-related indices were computed. These included pH, EC, TDS, TH, SAR, Na%, MAR, PI, RSBC, KR, PS, CROSS, and IWQI. The interpretation of the results was based on the threshold values reported in Table 2, with the evaluation carried out separately for two distinct hydrological periods. For all calculations, ionic concentrations were reported in meq/L (Abadi et al., 2025).

Cation ratio of structural stability (CROSS)

This ratio, referred to as CROSS, was employed as a key indicator for evaluating the risk of sodicity associated with irrigation water in this study. Its main advantage is that it explicitly accounts for the influence of potassium and magnesium on soil structural stability. CROSS was computed from the concentrations of the main cations in solution using the equation proposed by (Smith et al., 2015), which extends the SAR concept by incorporating the higher dispersive effect of $K^+$and the lower flocculating efficiency of Mg^{2+} relative to Ca^{2+}:

$$CROSS = \frac{Na^{+}+0.335\,K^{+}}{\sqrt{0.5(Ca^{2+}+0.0758\,Mg^{2+})}} \quad (9)$$

The formula was established through optimisation using experimental measurements of electrical conductivity and key electrolyte concentrations. It shows that K^+ has a harmful effect on soil permeability that is about three times lower than that of Na^+, whereas Mg^{2+} needs to be present at substantially higher levels than Ca^{2+} to produce an equivalent flocculating action. In addition, recent studies have suggested a threshold value for CROSS interpretation, considering that a CROSS of 10 defines the limit above which exchangeable sodium becomes problematic, calcium and magnesium are reduced, and serious effects on soil permeability as well as crop productivity and quality may occur. Consequently, this threshold has been proposed as an operational reference for the assessment of recycled irrigation water (Isaya Kisekka et al., 2024; Oster et al., 2016; Smith et al., 2015).

Irrigation water quality index (IWQI)

In accordance with the procedure described by (Meireles et al., 2010), IWQI evaluates irrigation suitability by integrating five key chemical indicators:EC, SAR, Na^+, Cl^- and HCO_3^-. The procedure first assigns a dimensionless sub index Q_i to each parameter; higher Q_i values reflect better quality. The sub index is computed using the class based framework described by (Ayers and Westcot, 1985) **:**

$$Q_i = q_{max} - \left(\frac{(X_{ij} - X_{inf}) \times q_{imap}}{X_{amp}}\right) \quad (10)$$

where: q_{max} is the maximum possible value of Q_i for each class, X_{ij} is the measured value of the parameter, X_{inf} is the lower limit of the class in which this value falls, q_{imap} is the class amplitude expressed in terms of quality, and X_{amp} is the range of the class expressed in terms of concentration, determined from the highest value obtained during sample analysis.

The threshold concentrations used to assign a Q_i value to each parameter, together with the corresponding weights W_i, are reported in Table 3. These weights, which sum to unity ($\sum Wi = 1$), represent the relative contribution of each parameter to the overall IWQI, following (Meireles et al., 2010).

The final IWQI is a dimensionless value that varies between 0 and 100 and is calculated as:

$$IWQI = \sum_{i=0}^{n} Q_i W_i \quad (11)$$

The IWQI classification provides a practical framework for assessing the suitability of irrigation water and supporting agricultural water management (Meireles et al., 2010). According to this index, water quality is categorised into five classes based on the degree of restriction for irrigation use. IWQI values between 85 and 100 correspond to “no restriction”, indicating low salinity and sodicity levels and therefore suitability for most soils

Table 2. Criteria and indices for assessing water quality for agricultural irrigation

Index	Equation	Intervalle	Classification	References
pH	-	[6.5, 8.4]	Acceptable	(Ayers and Westcot, 1985)
EC (µs/cm)	-	<250	Excellent	(Vasanthavigar et al., 2013)
		[250, 750]	Good	
		[750, 2000]	Permissible	
		[2000, 3000]	Doubtful	
		>3000	Unsuitable	
TDS (mg/L)	-	<450	Preferred for irrigation	(Amwele et al., 2021)
		[450, 2000]	Slightly to moderate	
		>2000	Unsuitable	
TH (°F)	$TH = 2.5Ca^{2+} + 4.1Mg^{2+}$	<7.5	Soft	(Abadi et al., 2025)
		[7.5, 15]	Moderately hard	
		[15, 30]	Hard	
		>30	Very hard	
SAR	$SAR = \left(\frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}\right)$	<10	Excellent	(Abadi et al., 2025)
		[10, 18]	Good	
		[18, 26]	Doubtful	
		>26	Unsuitable	
Na%	$Na\,\% = \frac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} \times 100$	< 20	Excellent	(Wilcox, 1955)
		[20, 40]	Good	
		[40, 60]	Permissible	
		[60, 80]	Doubtful	
		>80	Unsafe	
MAR	$MH = \frac{Mg^{2+}}{(Ca^{2+} + Mg^{2+})} \times 100$	<50	Suitable	(Paliwal, 1972)
		>50	Unsuitable	
PI	$PI = \frac{Na^{+} + \sqrt{HCO_3^{-}}}{(Ca^{2+} + Mg^{2+} + Na^{+})} \times 100$	>75	Excellent	(Gad et al., 2025; Doneen, 1975)
		[25, 75]	Good	
		<25	Unsuitable	
RSBC	$RSBC = HCO_3^{-} - Ca^{2+}$	<5	Safe	(Siraj et al., 2023; Zhou et al., 2020; Eaton, 1950)
		[5, 10]	Marginal	
		>10	Unsatisfactory	
KR	$KR = \frac{Na^{+}}{Ca^{2+} + Mg^{2+}}$	<1	Suitable	(Kelley, 1963)
		[1, 2]	Marginal suitable	
		>2	Unsuitable	
PS	$PS = Cl^{-} + \frac{SO_4^{2-}}{2}$	<5	Excellent to good	(Falalu et al., 2022; Doneen, 1975)
		[5, 10]	Good to Injurious	
		>10	Injurious to unsatisfactory	

and crops without significant toxicity risks. Values ranging from 70 to 85 indicate "low restriction" (Abadi et al., 2025), where water can generally be used for irrigation but may require caution for salt-sensitive crops (Abadi et al., 2025). When IWQI values fall between 55 and 70 (Meireles et al., 2010), the water is classified as having "moderate restriction", meaning its use is more appropriate for soils with adequate permeability and for crops with moderate salinity tolerance (Vemana and Kurakalva, 2025). Lower values, between 40 and 55, represent "high restriction"(Meireles et al., 2010), suggesting that irrigation should preferably be limited to permeable soils and to crops

Table 3. Limit values for quality parameters (Q_i) and weights (W_i) used in the IWQI calculation, according to (Meireles et al., 2010)

Q_i	EC	SAR	Na^+	Cl^-	HCO_3^-
	(μS/cm)		(meq /L)		
85–100	[200, 750]	[2, 3]	[2, 3]	[1, 4]	[1, 1.5]
60–85	[750, 1500]	[3, 6]	[3, 6]	[4, 7]	[1.5, 4.5]
35–60	[1500, 3000]	[6, 12]	[6, 9]	[7, 10]	[4.5, 8.5]
0–35	less 200	less 2	less 2	less 1	less 1
	Or more 3000	Or more 12	Or more 9	Or more 10	Or more 8.5
W_i	0.211	0.189	0.204	0.194	0.202

with moderate to high salt tolerance (Vemana and Kurakalva, 2025). Finally, IWQI values between 0 and 40 indicate "severe restriction" (Meireles et al., 2010), where irrigation should be restricted to highly salt-tolerant crops and requires careful management to minimise soil salinisation and productivity loss (Diaz et al., 2025). This classification system is widely used to interpret irrigation water quality and to guide appropriate agricultural practices (Abadi et al., 2025; Abbasnia et al., 2019; Meireles et al., 2010).

RESULTS AND DISCUSSION

The computations of the different parameters outlined in the technique have resulted in the following evaluations:

Drought at the Beni Bahdel dam weather station

The results of calculations of monthly SPI variations (SPI-1) at the Beni Bahdel dam weather station over the period 1980–2020 (Figure 2) indicate an overall water balance in the region, with a slight predominance of wet months (52%) over dry months (48%). The period between 1990 and 2010, particularly the decade of 2010 (average SPI-1 = +0.229), is characterised by slightly wet climatic conditions. In contrast, the 1980s and early 2020s were relatively dry, marked by a critical extreme episode in 1999 (SPI-1 = -2.83 in April). In addition, eleven months were classified as extremely wet, mainly in 1996, 2002 and 2008. July appears to be the most frequently wet month (SPI-1 = +0.408). Although drought episodes are generally short-lived (averaging two months), the 118 dry events over 41 years highlight the need for adaptive management. Finally, the recent trend towards increased drought during the period 2020-2021 calls for forward-looking and adaptive management of the Beni Bahdel dam and agricultural irrigation.

Wet and dry periods based on SPI-1 analysis

Based on a comparative analysis of SPI-1 distribution frequencies between the two periods (September 2008-August 2012) and (September 2018-August 2021), the results presented in Table 4 show a gradual shift towards drier conditions at the Beni Bahdel dam. The proportion of wet categories (SPI-1 > 0) decreased from 58.33% to 47.22%, while that of dry categories (SPI-1 < 0) increased from 41.67% to 52.78%, a variation of 11.11%. Extremely wet events disappeared completely, falling from 4.17% to 0%, and very wet conditions declined sharply (from 6.25% to 2.78%). At the same time, the frequency of moderate droughts doubled (from 2.08% to 5.56%), while severe drought episodes appeared for the first time (2.78%) (Table 4).

The transition to drier conditions points to a continuing decline in regional hydroclimatic stability, marked by more frequent and more severe water shortages (Benhizia et al., 2026). The observed pattern underscores the effects of climate change, together with greater variability in precipitation, on the availability and condition of water resources in the region (Spinoni et al., 2015; Trenberth, 2011). This increasing aridification constitutes a major constraint on sustainable water resource governance and threatens the persistence of dam-dependent agricultural activities.

Variability of salinity and hydrochemical parameters through boxplot analysis

Analysis of the box plots (Figure 3) highlights pronounced salinisation during the dry season,

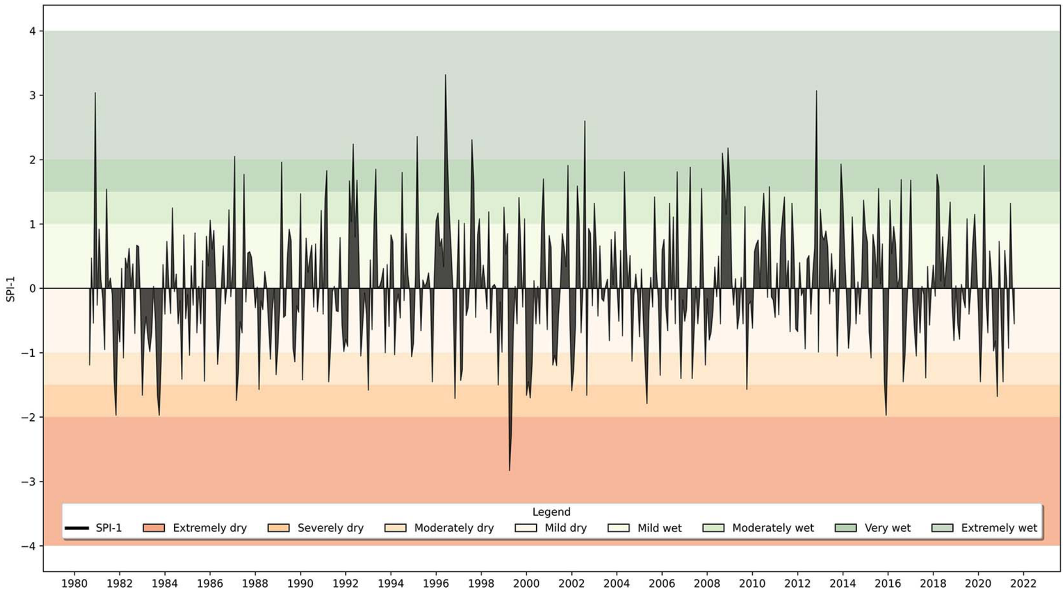

Figure 2. Monthly SPI-1 variability and classification of drought conditions at the Beni Bahdel dam weather station (1980–2020)

illustrated by a doubling of the mean electrical conductivity from 402.46 ± 75.18 (µS/cm) in the wet period to 810.25 ± 93.66 (µS/cm) in the dry period. This concentration effect also influences the major ions (Na^+, Cl^-, HCO_3^-), with the exception of Ca, which shows a marked decrease between the two periods (69.07 vs 55.95 (mg/L)). Furthermore, nitrate (NO_3^-) concentrations indicate a degradation of water quality during the arid period: although the mean value increases only

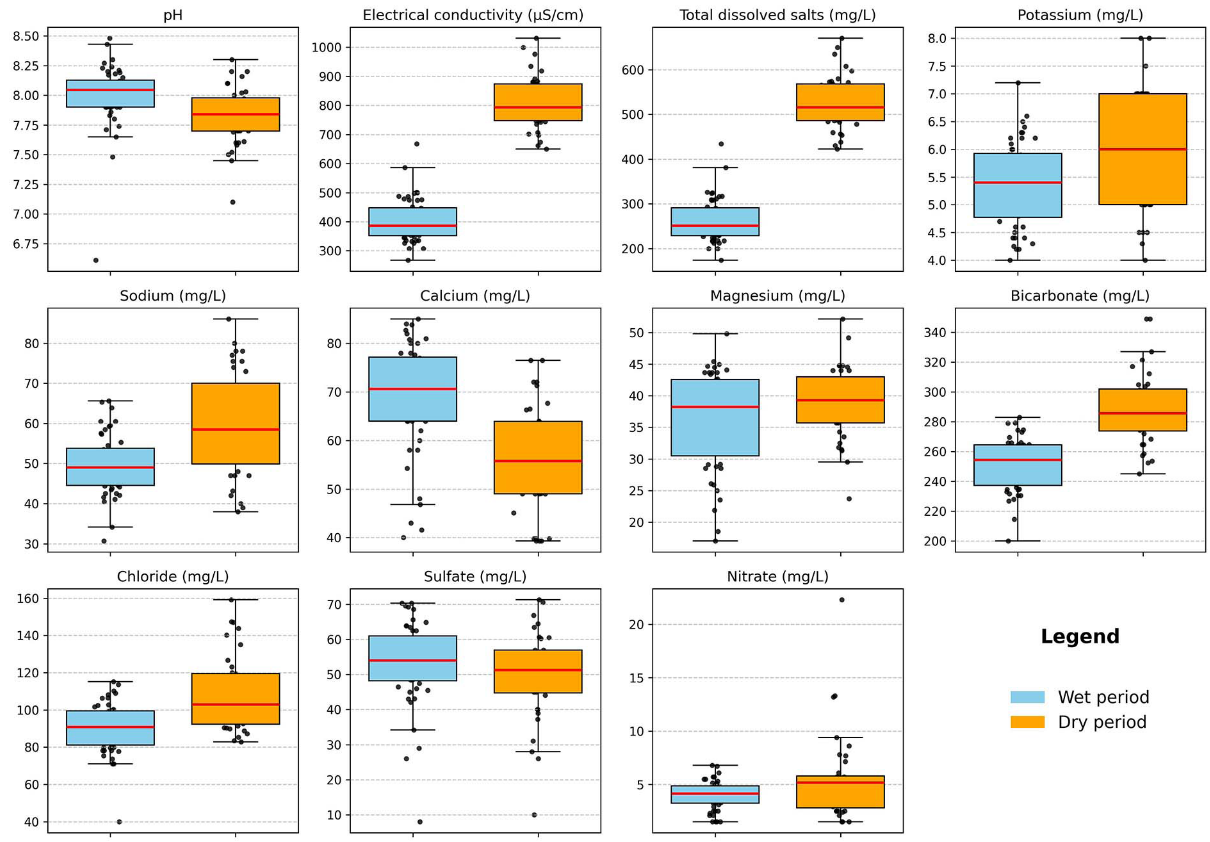

Figure 3. Variability of salinity and hydrochemical parameters

Table 4. Comparison of SPI-1 distribution frequencies between two periods (September 2008-August 2012) and (September 2018-August 2021)

SPI value	Categories	Frequency % SPI-1 (Sep 2008–Aug 2012)	Frequency % SPI-1 (Sep 2018–Aug 2021)
2.00 or more	Extremely wet	4.17	0
1.50 to 2.00	Very wet	6.25	2.78
1.00 to 1.49	Moderately wet	12.50	11.11
0.00 to 0.99	Mild wet	35.42	33.33
-0.99 to 0.00	Mild dry	39.58	44.44
-1.00 to -1.49	Moderately dry	2.08	5.56
-1.50 to -1.99	Severely dry	0.00	2.78
-2.00 or less	Extremely dry	0.00	0.00

moderately, variability becomes much higher, with peaks of 22.3 (mg/L), compared with a maximum of 6.8 (mg/L) during the wet period. This pattern reflects the concentration of pollutants caused by limited dilution.

Water quality of the Beni Bahdel dam for agricultural purposes

Figure 4 presents, in percentage terms, the results of the analyses of the hydrochemical

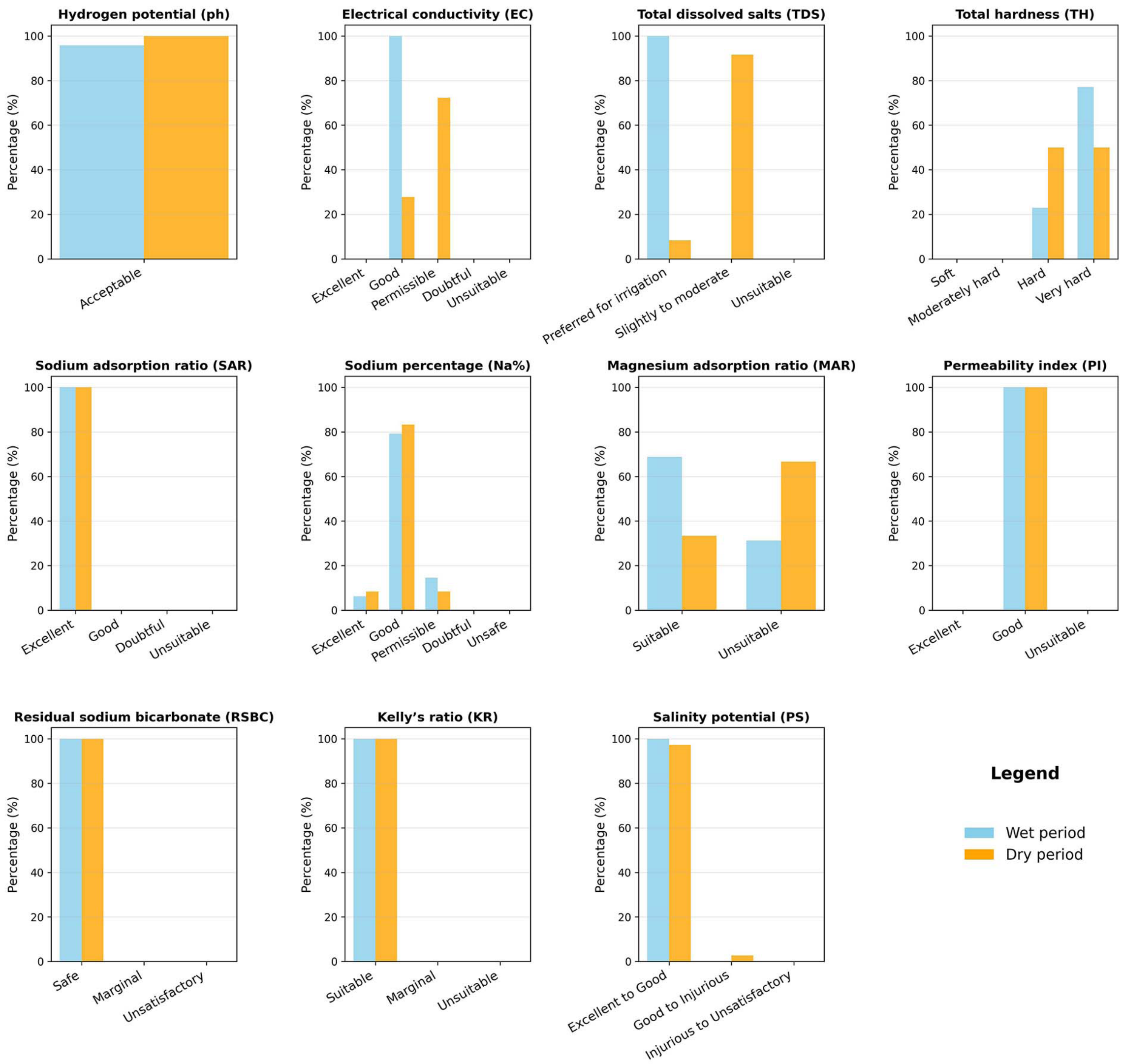

Figure 4. Water quality indices for the Beni Bahdel dam during wet and dry periods for irrigation purposes

parameters of the Beni Bahdel dam water, based on 84 samples collected to evaluate its quality and suitability for irrigation. Figure 4 reveals a marked deterioration between the wet and dry periods. This degradation is directly associated with the combined effects of climate change and anthropogenic pressures in the study area (Rocha et al., 2020).

The interpretation of the results presented in Figure 4, in line with agricultural irrigation requirements, allows for a successive analysis of the main parameters and indices characterising the quality of the dam water.

Hydrogen potential (pH)

In the wet period, 95.83% of samples have pH values between 6.5 and 8.4, while in the dry period this proportion reaches 100%. These results indicate that, in almost all of the samples analysed, the pH remains within the recommended range for irrigation. This stability reflects the maintenance of a good acid–base balance in the waters of the Beni Bahdel dam, even during periods of water stress. Overall, these waters are characterised by a neutral to slightly alkaline pH, making them perfectly suited for agricultural use (Al-Khashman and Alnawafleh, 2020).

Electrical conductivity (EC) and total dissolved salts (TDS)

The results show a marked variation in EC and TDS between the two study periods. During the wet period, all samples (100%) had EC values classified as "good", ranging from 250 to 750 (μS/cm). During the dry period, only 27.78% of samples remained in the "good" class, while 72.22% fell into the "permissible" category, with values between 750 and 2000 (μS/cm). A similar trend is observed for TDS: during the wet season, 100% of samples belong to the "Preferred for irrigation" class, with concentrations below 450 (mg/L). However, during the dry period, this proportion decreased to 8.33%, while 91.67% of samples had concentrations between 450 and 2000 (mg/L), corresponding to the "Slightly to moderate restrictive" class. The observed increase in salinity during the dry period can be attributed to the combined effects of reduced inflow, enhanced evaporation, and the progressive concentration of dissolved ions in the reservoir (Jalali et al., 2019). Such processes are typical in semi-arid reservoirs where limited hydrological renewal promotes the accumulation of mineral salts (Mosley, 2015). In the context of climate change, this phenomenon is gradually compromising long-term irrigation capacity (Jalali et al., 2019; Mosley, 2015).

Total hardness (TH)

Hardness is a major issue. During the wet period, 77.08% of samples were classified as "very hard" (TH>30), while during the dry period this proportion stabilised at 50%. Conversely, 22.92% were " Hard" during the wet period, compared to 50% during the dry period. The total absence of "soft and Moderately hard" water (TH<7.5 and 7.5<TH<15) in both periods indicates a continuous and high presence of calcium and magnesium. Although the concentration decreases slightly during dry periods, the water remains hard to very hard. For irrigation, this hardness presents a risk of clogging irrigation systems (Jalali et al., 2019).

Sodium adsorption ratio (SAR)

The SAR values remain below the threshold of 10 for all samples in both hydrological periods, indicating an excellent irrigation water quality with respect to sodicity hazard (Gharaibeh et al., 2021).

Sodium percentage (Na%)

The results for Na% reveal a slight variation between the two studied periods. In the wet period, 6.25% of samples were classified as "excellent" (Na% <20), compared to 8.33% in the dry period. However, the majority of samples fell into the "good" category (20–40%), with proportions of 79.17% in the wet period and 83.33% in the dry period. Additionally, a small proportion of samples was placed in the "Permissible" class (40–60%) during the dry period (8.33%), while no samples reached the "poor" (60–80%) or "unsuitable" (>80%) categories, regardless of the period considered. These findings indicate a generally stable distribution of soluble sodium, characterised by moderate levels in the waters of the Beni Bahdel dam.

The predominance of calcium and magnesium ions, as illustrated in (Figure 5), aligns with this distribution. Consequently, the risks of soil degradation due to alkalinisation are limited.

The Piper diagram (Figure 5) clearly indicates the persistent dominance of calcium and magnesium ions in the waters of the Beni Bahdel dam during both the wet period (a) and the dry period (b). The majority of samples plot within the "Calcium-Magnesium" field of the cation triangle,

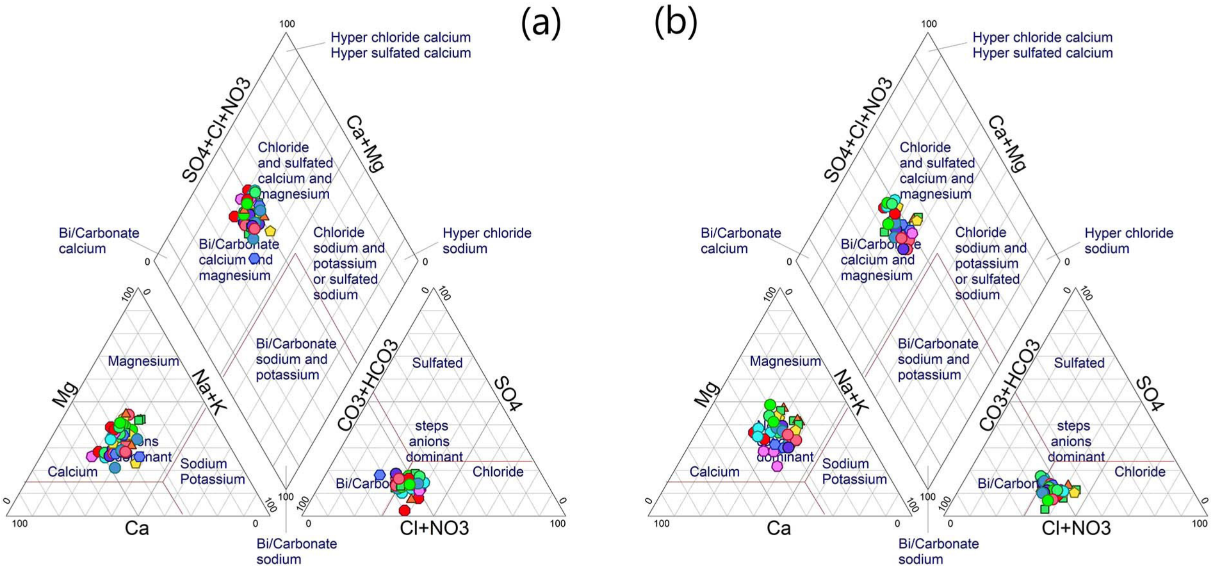

Figure 5. Piper diagram of water samples from the Beni Bahdel dam: (a) wet period and (b) dry period

confirming that alkaline earth metals constitute the predominant cationic fraction, irrespective of the hydrological regime. Within the central diamond field of the diagram, samples from both wet and dry periods are primarily located in the "calcium–magnesium bicarbonate" domain. This homogeneous distribution is characteristic of a Ca-Mg-HCO_3 hydrochemical facies, typical of a system governed by the natural weathering of carbonate and silicate minerals. The hydrolysis and dissolution of calcite, dolomite, and feldspar minerals from the geological substratum therefore represent the principal mechanisms controlling the ionic composition of the water (Amadi et al., 2014; Tay, 2021). The nearly identical spatial distribution of points between the two periods (a and b) demonstrates a remarkable geochemical stability of the system. In contrast to the conditions associated with significant ion exchange processes or saline contamination, the samples do not shift toward the Na-Cl field of the diagram. This stability explains why, despite variations in SAR and Na%, the water chemistry remains controlled by the dominance of alkaline earth cations ($Ca^{2+} + Mg^{2+} > Na^{+} + K^{+}$).

Overall, the Piper diagram provides clear evidence that the dam's hydrochemistry is intrinsically controlled by the weathering of calcium and magnesium carbonates. This geochemical control accounts for the observed high water hardness and supports the relative suitability of these waters for irrigation, even during the dry season when evaporative concentration increases (Tay, 2021).

Magnesium adsorption ratio (MAR)

In line with the hydrochemical stability dominated by alkaline earth cations, dissolved magnesium shows a significant increase between wet and dry periods. During wet period, 68.75% of samples fall into the "suitable" class (MAR <50), while only 31.25% belong to the "unsuitable" class (MAR >50). In contrast, during dry period, just 33.33% of samples remain "suitable" (MAR <50), whereas 66.67% shift to the "unsuitable" class (MAR >50). According to irrigation water quality standards, when MAR >50, irrigation is typically discouraged due to potential adverse effects on sensitive crops and possible degradation of soil structure and infiltration capacity (Ahmed et al., 2023; Ben Ayed et al., 2022; Zhang et al., 2020).

Permeability index (PI)

The PI is good in both periods, with 100% of samples falling into the "good" category (25-75%) in both wet and dry periods. This index, which measures the ability of water to infiltrate into the soil, suggests that infiltration rates should remain acceptable, despite the significant presence of other factors such as hardness and salinity (Bounab et al., 2022; Tejashvini et al., 2024).

Residual sodium bicarbonate (RSBC)

All samples (100%) are classified as "safe" with an RSBC<5 in both wet and dry periods. This means that the accumulation of sodium and bicarbonate at soil, water interfaces remains limited, thus reducing the risk of secondary alkalinity induced by irrigation (Abou El-Defan et al., 2016).

Kelly's ratio (KR)

The KR is in the "Suitable" category, assessed by all samples (100%) at a KR<1 in wet and dry periods. This means that the sodium load remains under control in relation to alkaline earth cations, making it favourable for long-term soil structural stability (Nedjar et al., 2022).

Potential salinity (PS)

With a PS value <5 for 100% of samples in wet periods and 97.22% in dry periods, this PS is classified as "excellent to good". Nevertheless, only 2.78% of samples in the dry periods fall into the "Good to Injurious" category ([5,10]). This suggests persistent good overall infiltrability (Mokhtar et al., 2022).

Cation ratio of structural stability (CROSS)

The CROSS values increased by 32.93%, rising from 1.64 ± 0.28 in the wet period to 2.18 ± 0.51 in the dry period, while still remaining well below the critical threshold of 10 (Isaya Kisekka et al., 2024). The temporal trajectory of these results reveals deterioration in water quality.

Irrigation water quality index (IWQI)

A comparison of IWQI between the wet and dry periods highlights a gradual change in the quality of the water in the Beni Bahdel dam. A combined analysis of statistical indicators and the distribution of quality classes makes it possible to track changes in water quality between the two hydrological periods (Figure 6).

During the wet period, IWQI shows a mean value of 66.37 and a median of 71.19, indicating overall water quality generally suitable for irrigation purposes. The majority of samples (58.33%) fall within the "low restriction class ([70–85]), reflecting predominantly non-limiting conditions for agricultural use. The median exceeding the mean suggests that the most frequent values remain relatively high, pointing to hydrochemical stability typical of a period characterised by sufficient hydrological inputs. Under these conditions, irrigation can be practiced using conventional management approaches without the need for specific mitigation measures. In contrast, the dry period is marked by a progressive deterioration in irrigation water quality. The mean IWQI decreases to 64.53 and the median to 65.73, indicating a general shift of values toward lower quality classes. This trend is reflected in a significant increase in the proportion of samples classified under "moderate restriction" (69.44% ;[55–70]), while favourable conditions become less frequent. The median decline of 5.46 points (-7.67%) clearly illustrates this shift toward a quality level requiring enhanced precautionary measures in agricultural water use. This categorical transition demonstrates that the observed degradation is not limited to changes in average values, but corresponds to a modification of the risk profile for agricultural users. The sensitivity of IWQI to hydroclimatic variability is well

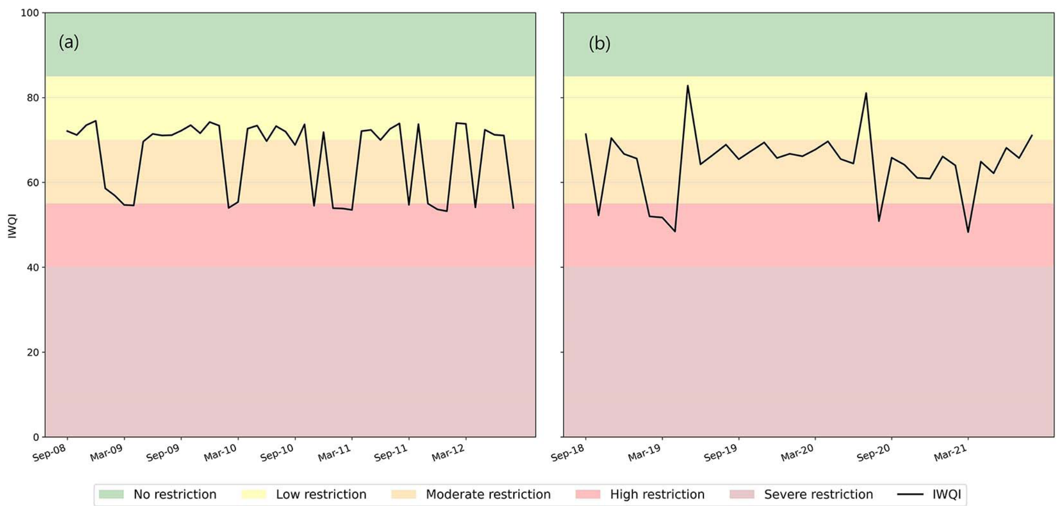

Figure 6. Temporal variation in the irrigation water quality index (IWQI) of the Beni Bahdel dam: comparative analysis between the wet period (a) and the dry period (b)

documented in semi-arid environments. Several studies report that prolonged drought periods lead to IWQI deterioration due to the combined effects of increased concentrations of dissolved salts (EC, Na^+, Cl^-), elevated SAR, reduced water inputs, and intensified evaporation (Davoodi Memar Otagvar et al., 2025; Laoufi et al., 2025; Meireles et al., 2010; M'nassri et al., 2022).

Figure 7 provides descriptive statistics for the hydrochemical parameters and various indices across wet and dry periods.

These statistical variations are reflected, first and foremost, in a marked increase in water mineralisation between the two periods. The average electrical conductivity (EC) more than doubled, rising from 402.46 (µS/cm) in the wet period to 810.25 (µS/cm) in the dry period, directly correlated with the simultaneous increase in total dissolved salts (TDS), which rose from 261 to 526 (mg/L).

The comparative analysis of the salinity diagram of the U.S. Salinity Laboratory (USSL) (Figure 8) for the waters of the Beni Bahdel Dam indicates a clear deterioration in irrigation water quality between the two hydrological periods. This shift is quantified using the Cx-Sy classification system (Table 5), which assesses salinity hazard (based on EC) and sodicity hazard (based on SAR).

During the wet period, almost all samples fall within the C2-S1 class, characterised by moderate salinity (EC between 250 and 750 (µS/cm)) and a low sodicity hazard (SAR<10), thus confirming good-quality water under a dilution-dominated regime (Fadl et al., 2024; Alsubih et al., 2022). In contrast, during the dry period, a significant shift toward the C3-S1 class is observed, where salinity becomes high (EC between 750 and 2250 (µS/cm)),while the sodicity hazard remains low. This transition from "permissible" to "doubtful" irrigation water, according to the criteria proposed by (Vasanthavigar et al., 2013), is now required and results directly from evaporative concentration processes (Subramani et al., 2005). Consequently, agricultural management precautions, including effective drainage systems and the selection of salt-tolerant crops, in order to prevent soil salinisation (Machado and Serralheiro, 2017).

This phenomenon is primarily explained by a concentration process driven by evaporation, as conceptualised by (Gibbs, 1970). In a semi-arid setting, the reduction in reservoir storage volume, combined with intense evaporative conditions,

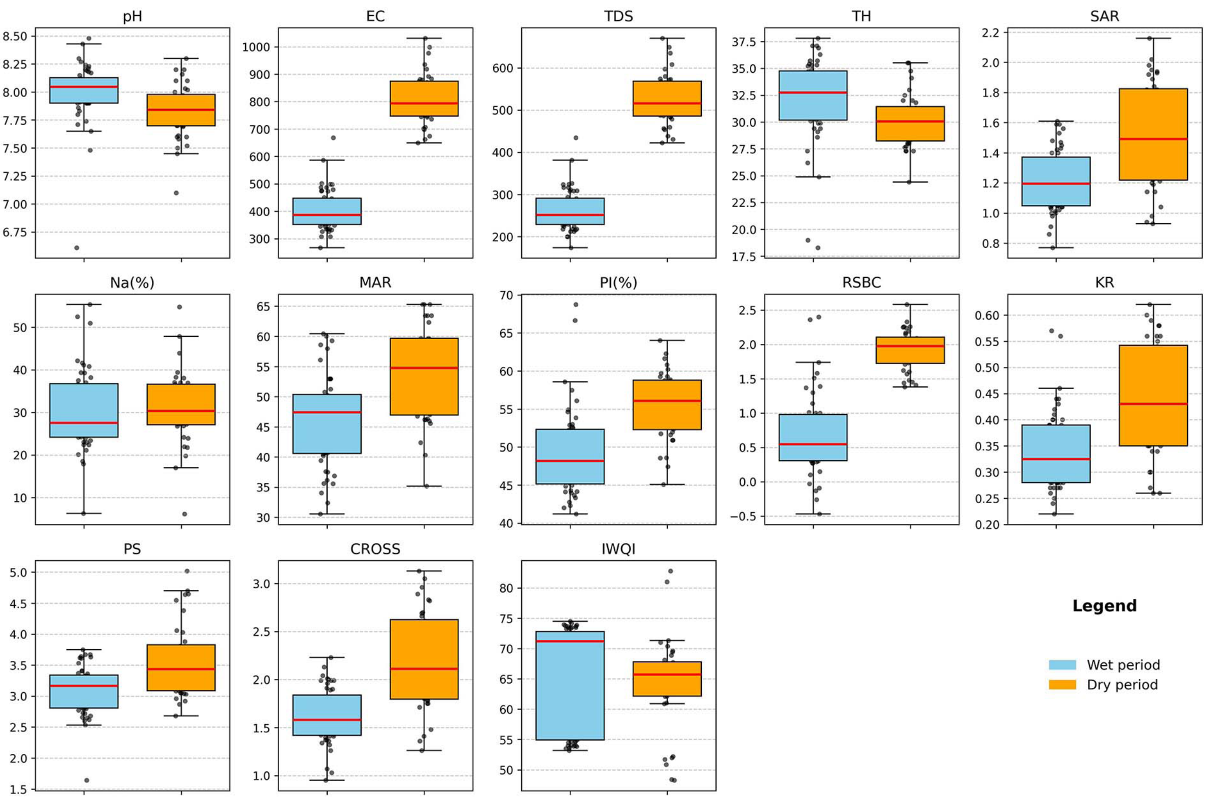

Figure 7. Descriptive statistics of hydrochemical parameters and irrigation water quality indices across wet and dry periods

Table 5. Classification of irrigation water quality according to the USSL Diagram (Cx-Sy Classes)

Salinity hazard			Sodicity hazard		
Class	EC (µs/cm)	Remark on quality	Class	SAR	Remark on quality
C1	100-250	Low-salinity water	S1	<10	Low-sodium water
C2	250-750	Moderate-salinity water	S2	10-18	Medium-sodium water
C3	750-2250	High-salinity water	S3	18-26	High-sodium water
C4	>2250	Very high-salinity water	S4	>26	Very high-sodium water

results in passive enrichment of the aqueous phase in dissolved solutes. Consequently, the system progressively shifts from a dilution-controlled regime to an evaporation-dominated regime, as reported for numerous reservoirs located in arid and semi-arid environments (Adimalla and Qian, 2019). Despite the increase in salinity, total hardness (TH) remains stable or slightly decreases during the wet period (mean = 32.07) compared to the dry period (mean = 30.18), suggesting that calcite saturation has been reached and that calcium precipitation is occurring, thereby limiting any further increase in hardness (Appelo and Postma, 2004).

The MAR index exceeds 50 during the dry period (Mean = 53.60), indicating a relative enrichment in magnesium attributable to the preferential precipitation of calcium. This condition increases the risk of clay dispersion in irrigated soils (Xiao et al., 2018; Wrence et al., 1970).

Finally, Pearson correlation matrices (Figure 9) reveal a reorganisation of hydrochemical processes influencing water quality and its suitability for irrigation.

The Pearson correlation matrices (Figure 9) for the wet and dry hydrological periods reveal distinct relationships between ionic parameters and irrigation suitability indices. The evolution of these relationships reflects a fundamental shift in the dominant hydrochemical processes, transitioning from a dilution-controlled regime during the wet period to an evaporation-driven concentration regime during the dry period. During the wet period, total hardness (TH) emerges as the structuring hydrochemical parameter, exhibiting strong negative correlations with PI% (r = -0.91) and the Kelly's ratio (r = -0.74). This pattern highlights the stabilising role of divalent cations (Ca^{2+} and Mg^{2+}) in mitigating sodicity risk. These cations, present at relatively high concentrations, directly limit sodium adsorption onto clay particles, thereby reducing the risk of soil structural degradation (Saadi et al., 2025; Islam and Mostafa, 2022; Bhat et al., 2018). This interaction illustrates the classical ion-exchange process: sodium ions tend to replace divalent cations within the adsorption complex; however, the abundance of Ca^{2+} and Mg^{2+} counterbalances sodicity effects, maintaining adequate soil infiltrability. CROSS exhibits a strong correlation with SAR (r = 0.88), independently of overall salinity (EC, r = 0.05), indicating that sodicity risk and bulk mineralisation represent two distinct processes during the wet period.

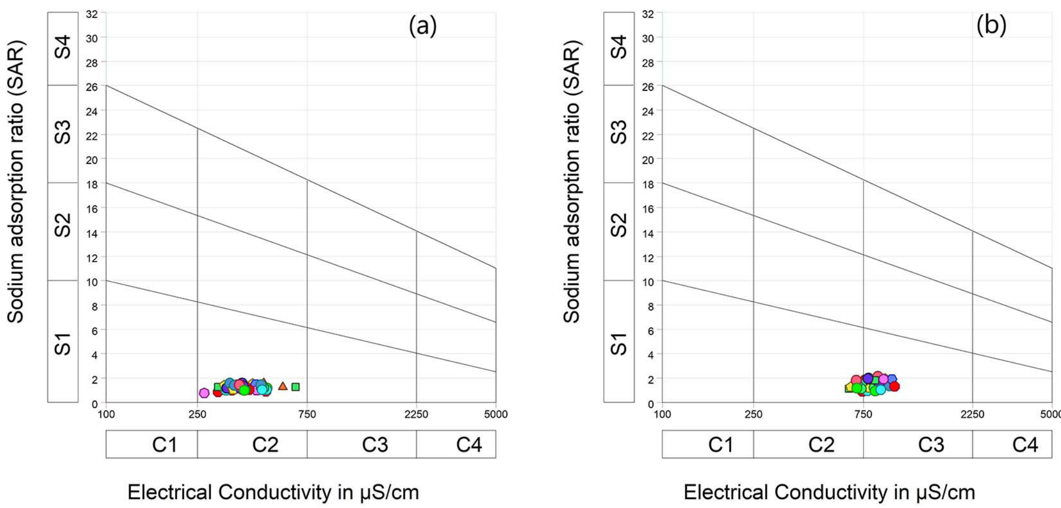

Figure 8. US salinity diagram for of water samples from the Beni Bahdel dam: (a) wet period and (b) dry period

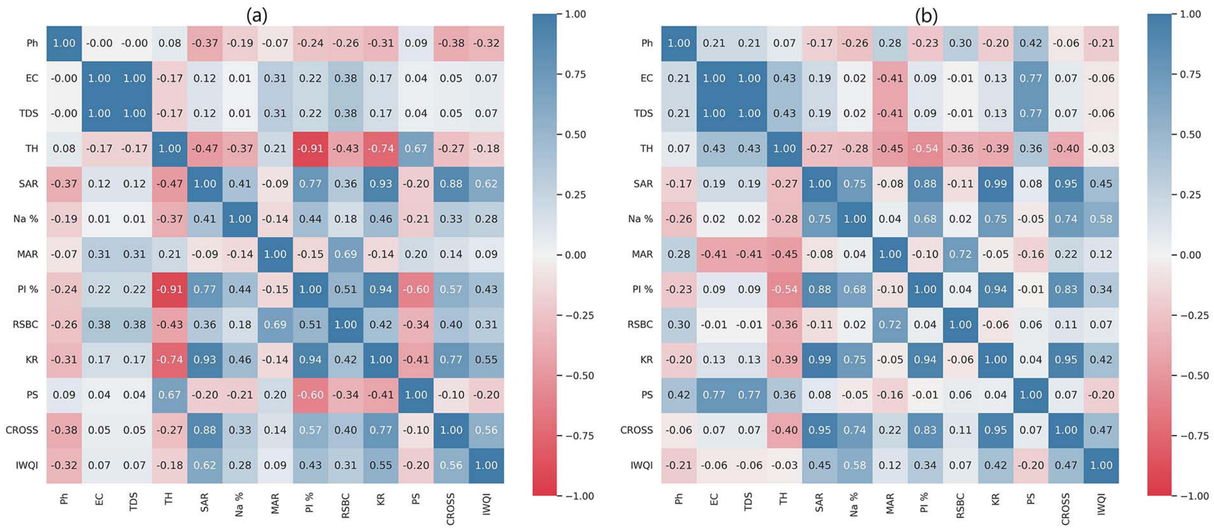

Figure 9. Pearson correlation matrix of irrigation suitability parameters for the Béni Bahdel Dam during the (a) wet period and (b) dry period

In contrast, during the dry period, evaporation-induced concentration progressively governs water chemistry. The marked intensification of the CROSS-Na% relationship (r= 0.33 wet period to r=0.74 dry period ; +124%) demonstrates the concurrent accumulation of sodium and potassium, exceeding the increase observed for SAR-Na% (+83%). The strengthening of CROSS-SAR and CROSS-KR correlations (r = 0.95 in dry period) confirms that CROSS becomes the most relevant indicator for monitoring sodicity. This evolution reflects a cyclical hydrochemical dynamic: dilution and relative stability during the wet period, versus concentration and enhanced sodicity risk during the dry period, directly affecting irrigation suitability and soil management. Simultaneously, the influence of SAR on IWQI increases (r = 0.62), suggesting active watershed leaching processes, whereby runoff inputs introduce additional sodium into the reservoir. Strong correlations between SAR-KR and KR-PI% (r = 0.93, r = 0.94) indicate that rock dissolution and water mixing processes, typical of recharge periods, remain operative (Pandurang et al., 2025; Bhat et al., 2018). The relationship between CROSS and KR reaches r = 0.77, confirming the synchronisation between sodicity indices and soil permeability. Collectively, these coherent relationships characterise a relatively stable hydrochemical system during the wet period.

Conversely, during the dry period, evaporation-driven concentration dominates the hydrochemical regime. Very strong correlations between SAR-KR and KR-PI% (r = 0.99, r = 0.94) reflect intensified synchronisation of sodicity risk. The increase in CROSS-Na% from r = 0.33 in wet period to r = 0.74 in dry period (+124%) indicates joint sodium and potassium accumulation, exceeding the SAR-Na% increase (+83%), thereby revealing a geochemical reality not fully captured by conventional SAR. Both CROSS-SAR and CROSS-KR reach r = 0.95, confirming the diagnostic efficiency of CROSS as a sodicity indicator. When water levels decline, a more pronounced concentration of dissolved salts is observed, particularly those belonging to the sodium group. This phenomenon, already well documented in Mediterranean aquatic environments (Pandurang et al., 2025; Saadi et al., 2025), results in stronger associations among these elements. IWQI remains primarily driven by sodium content (correlation coefficient r = 0.58). However, its relationship with the sodium adsorption ratio (SAR) weakens markedly (IWQI-SAR: r = 0.45, representing a 27% decrease), indicating a shift in the controlling factors, with sodium assuming greater relative importance. In contrast, the CROSS index maintains a stable correlation with IWQI (r = 0.47). This suggests that, under water-scarce conditions, CROSS constitutes a reliable indicator for assessing irrigation water quality. When water levels decline, a more pronounced concentration of dissolved salts is observed, particularly those belonging to the sodium group. This phenomenon, already well documented in Mediterranean aquatic

environments (Pandurang et al., 2025; Saadi et al., 2025), results in stronger associations among these elements. The irrigation water quality index (IWQI) remains primarily driven by sodium percentage (Na%; r = 0.58). However, its relationship with the SAR weakens markedly (IWQI-SAR: r = 0.45, representing a 27% decrease), indicating a shift in the controlling factors, with sodium assuming greater relative importance. In contrast, the CROSS index maintains a stable correlation with IWQI (r = 0.47). This suggests that, under water scarcity conditions, CROSS constitutes a reliable indicator for assessing irrigation water quality.

The analysis highlights a pronounced cyclical variation in hydrochemical parameters and irrigation suitability in the Beni Bahdel dam reservoir. The wet period is characterised by progressive solute dilution resulting from increased fluvial inputs and precipitation. This process significantly improves global salinity indicators (EC; TDS) as well as irrigation suitability indices (Saadi et al., 2025; Islam & Mostafa, 2022; Tlili-Zrelli et al., 2018). The dry period exhibits the opposite hydrochemical regime, dominated by intensified evaporation and markedly reduced discharge. These conditions induce selective and progressive concentration of major ions, leading to substantial degradation of irrigation water quality. This deterioration is primarily driven by disproportionate accumulation of sodium (Na^+) and chloride (Cl^-), resulting in significant increases in sodicity risk indices (SAR +24.79 %; CROSS +32.93 %) and a marked decline in IWQI. The inversion of the TH-MAR relationship (from r = +0.21in wet period to r = -0.45 in dry period) indicates geochemical fractionation under evaporative conditions, characterised by calcium precipitation and relative magnesium enrichment in solution. In this context, CROSS, being independent of total salinity (correlation with EC, r = 0.05 in wet period and r = 0.07 in dry period), proves to be a more robust diagnostic tool than conventional SAR for evaluating sodicity risk in semi-arid regions subjected to increasing hydric stress (Kisekka et al., 2024; Qadir et al., 2021). The extreme low-water conditions observed necessitate the implementation of adaptive management strategies, including controlled soil leaching, to mitigate salt accumulation and prevent long-term agricultural soil degradation (Islam and Mostafa, 2022; Saadi et al., 2025).

CONCLUSIONS

This research highlights the importance of identifying drought and wet periods, as well as assessing the hydrochemical indices of reservoir water quality, in order to analyse their interrelationships and temporal dynamics. In the Tlemcen region, a semi-arid area in western Algeria particularly exposed to climatic variability, the Beni Bahdel Dam, which supplies both drinking water and irrigation water, is subjected to a dual pressure resulting from climate variability and the progressive deterioration of water quality. The objective of this study was to provide decision-support tools for the integrated and sustainable management of the dam, enabling the anticipation of risks related to water resource degradation and the optimisation of agricultural water use under regional climate change scenarios.

The methodological approach was based on the analysis of the SPI-1 over the period 1980–2020, which revealed a marked trend toward aridification, characterised by a significant increase in the frequency and intensity of drought episodes between September 2018 and August 2021. At the same time, the quality of the dam water was evaluated using several hydrochemical parameters and indices (pH, EC, TDS, TH, SAR, Na, MAR, PI, RSBC, KR, and PS), together with the IWQI and the CROSS. The results showed that the CROSS index exhibits superior performance compared with the conventional SAR in assessing the risk of soil structure degradation under water stress conditions. Indeed, this index increased by 32.93%, rising from 1.64 ± 0.28 during the wet period to 2.18 ± 0.51 during the dry period. This sensitivity is explained by its independence from total salinity and its ability to account for the combined accumulation of sodium and potassium, making it a particularly relevant predictive indicator for semi-arid environments.

The results indicate that climatic evolution directly affects the dam's water quality. During wet periods, dilution processes maintain moderate mineralisation and generally suitable irrigation quality, as evidenced by low electrical conductivity (mean EC: 402.46 (μS/cm)) and total dissolved salts (mean TDS: 261.60 (mg/L)). Conversely, the dry period induced a concentration regime driven by evaporation, leading to increased salinity (mean EC: 810.25 (μS/cm)). Selective accumulation of sodium and chloride ions resulted in a significant rise in sodicity risk, with SAR increasing by 24.79% and CROSS by 32.93%. The correlated deterioration of IWQI, the median of which decreased from 71.19 to 65.73, reflects a shift toward a moderate restriction class. This degradation, combined with increased MAR and persistently high total hardness, underscores the need for adaptive management strategies. However, the Piper diagram indicates a remarkable stability of the Ca-Mg-HCO_3 hydrochemical facies, suggesting that salinisation results from evaporative concentration rather than external contamination. The selective concentration process reveals a major decoupling phenomenon: although EC nearly doubled, total hardness remained quasi-stationary, indicating endogenous calcite precipitation of calcium. Magnesium, being more soluble, accumulated proportionally, leading to increased MAR values and heightened clay dispersion risk. This confirms intensified evaporative processes. Exceeding the MAR = 50 threshold implies the necessity of enhanced leaching fractions.

In conclusion, water resources of the Beni Bahdel Dam are experiencing increasing hydroclimatic pressure, threatening their sustainability and irrigation suitability. Proactive management integrating priority monitoring of CROSS and IWQI indices is imperative. Such management should incorporate adaptive measures, including adjustment of irrigation scheduling, adoption of water-efficient irrigation systems, selection of salt-tolerant crops, and implementation of controlled soil leaching protocols to mitigate salt accumulation. These findings are transferable to Mediterranean semi-arid reservoirs and highlight the urgent need to revise dam management strategies in accordance with regional climate projections.

REFERENCES

1. Abadi, H. T., Alemayehu, T., Berhe, B. A. (2025). Assessing the suitability of water for irrigation purposes using irrigation water quality indices in the Irob catchment, Tigray, Northern Ethiopia. *Water Quality Research Journal*, *60*(1), 177–195. https://doi.org/10.2166/wqrj.2024.055
2. Abbasnia, A., Yousefi, N., Mahvi, A. H., Nabizadeh, R., Radfard, M., Yousefi, M., Alimohammadi, M. (2019). Evaluation of groundwater quality using water quality index and its suitability for assessing water for drinking and irrigation purposes: Case study of Sistan and Baluchistan province (Iran). *Human and Ecological Risk Assessment: An International Journal*, *25*(4), 988–1005. https://doi.org/10.1080/10807039.2018.1458596
3. Abou El-Defan, T., El-Raies, S., El-Kholy, H., Osman, A. (2016). A summary of water suitability criteria for irrigation. *Journal of Soil Sciences and Agricultural Engineering*, *7*(12), 981–989. https://doi.org/10.21608/jssae.2016.40540
4. Abu Arra, A., Alashan, S., Şişman, E. (2025). Advancing innovative trend analysis for drought trends : Incorporating drought classification frequencies for comprehensive insights. *Natural Hazards*, *121*(8), 9195–9219. https://doi.org/10.1007/s11069-025-07119-0
5. Adimalla, N., Qian, H. (2019). Groundwater quality evaluation using water quality index (WQI) for drinking purposes and human health risk (HHR) assessment in an agricultural region of Nanganur, south India. *Ecotoxicology and Environmental Safety*, *176*, 153–161. https://doi.org/10.1016/j.ecoenv.2019.03.066
6. Ahmed, N., Zhang, B., Bozdar, B., Chachar, S., Rai, M., Li, J., Li, Y., Hayat, F., Chachar, Z., Tu, P. (2023). The power of magnesium : Unlocking the potential for increased yield, quality, and stress tolerance of horticultural crops. *Frontiers in Plant Science*, *14*, 1285512. https://doi.org/10.3389/fpls.2023.1285512
7. Al-Khashman, O. A., Alnawafleh, H. M. (2020). Hydrochemistry and quality assessment of water in Tannur Dam, Southern Jordan. *Open Journal of Modern Hydrology*, *10*(01), 1–19. https://doi.org/10.4236/ojmh.2020.101001
8. Allia, Z., Lalaoui, M., Chebbah, M. (2022). Hydrochemical assessment for the suitability of drinking and irrigation use of surface water in Grouz Dam Basin, Northeast Algeria. *Sustainable Water Resources Management*, *8*(3), 88.
9. Alsubih, M., Mallick, J., Islam, A. R. Md. T., Almesfer, M. K., Kahla, N. B., Talukdar, S., Ahmed, Mohd. (2022). Assessing surface water quality for irrigation purposes in Some Dams of Asir Region, Saudi Arabia using multi-statistical modeling approaches. *Water*, *14*(9), 1439. https://doi.org/10.3390/w14091439
10. Amadi, A., Olasehinde, P., Dan-Hassan, M., Okoye, N., Ezeagu, G. (2014). *Hydrochemical facies classification and groundwater quality studies in Eastern Niger Delta, Nigeria*.
11. Amwele, H. R., Kgabi, N. A., Kandjibi, L. I. (2021). Sustainability of groundwater for irrigation purposes in semi-arid parts of Namibia. *Frontiers in Water*, *3*, 767496. https://doi.org/10.3389/frwa.2021.767496
12. Appelo, C. A. J., Postma, D. (2004). *Geochemistry, Groundwater and Pollution* (C. A. J. Appelo & D. Postma, Éds.; 0 éd.). CRC Press. https://doi.org/10.1201/9781439833544

13. Ayers, R. S., Westcot, D. W. (1985). *Water quality for agriculture* (Vol. 29). Food and agriculture organization of the United Nations Rome.
14. Barik, Y., Dalai, A., Mohanty, S., Tripathi, V. K., Chand, S. (2026). Seasonal groundwater quality assessment and irrigation suitability in coastal aquifers of Puri District, Odisha, India. *Scientific Reports*, *16*(1), 7895. https://doi.org/10.1038/s41598-026-39145-8
15. Ben Ayed, L., Horry, M., Sabbahi, S., Nouiri, I., Karanis, P. (2022). Physico-chemical quality of the Medjerda River in Tunisia and suitability for irrigation during the moist and the dry seasons. *Bulletin de la Société Royale des Sciences de Liège*. https://doi.org/10.25518/0037-9565.10857
16. Benhizia, R., Abdelkebir, B., Ata, B., Vele, S. M., Phinzi, K., Szabó, G. (2026). *Bi-decadal drought assessment in Northwestern Algeria : Integrating meteorological and remote-sensing indices.* In Review. https://doi.org/10.21203/rs.3.rs-8711142/v1
17. Bhat, M. A., Wani, S. A., Singh, V. K., Sahoo, J., Tomar, D., Sanswal, R. (2018). An overview of the assessment of groundwater quality for irrigation. *Journal of Agricultural Science and Food Research.*
18. Bouanani, A., Baba-hamed, K., Bouanani, R. (2011). Use of a global model for rainfall-runoff modeling: case of the upper Tafna basin (NW Algeria). *Le Journal de l'Eau et de l'Environnement*, *10*(18), 47–58.
19. Bounab, S., Khemmoudj, K., Sedrati, N. (2022). Assessment and physicochemical characterization of groundwater quality for irrigation and drinking purposes in Bazer Sakhra (Eastern Area of Algeria). *Journal of Ecological Engineering*, *23*(8), 118-131. https://doi.org/10.12911/22998993/150696
20. Chiang, F., Mazdiyasni, O., AghaKouchak, A. (2021). Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. *Nature Communications*, *12*(1), 2754. https://doi.org/10.1038/s41467-021-22314-w
21. Davoodi Memar Otagvar, L., Fataei, E., Naeimi, B., Tajiabadi, M. (2025). Evaluation of temporal and spatial changes of irrigation water quality classes in Qazvin Plain, Iran, using machine learning models. *Anthropogenic Pollution*, *9*(1). https://doi.org/10.57647/J.JAP.2025.0901.01
22. Diaz, B. G., Acuña, A. J., Almonacid, L. R., Gaspari, M. F., Bertinat, M., Bertoni, O., Peri, P. L. (2025). Water quality assessment of streams and rivers for irrigation in Southern Continental Patagonia. *Revista de la Facultad de Ciencias Agrarias UNCuyo*, *57*(1), 28–40. https://doi.org/10.48162/rev.39.149
23. Doneen, L. (1975). Water quality for irrigated agriculture. In *Plants in saline environments* (p. 56–76). Springer.
24. Eaton, F. (1950). *Significance of carbonate in irrigation water, soil sciences*.
25. Fadl, M. E., ElFadl, D. M. A., Hussien, E. A. A., Zekari, M., Shams, E. M., Drosos, M., Scopa, A., Megahed, H. A. (2024). Irrigation water quality assessment in Egyptian Arid Lands, utilizing irrigation water quality index and geo-spatial techniques. *Sustainability*, *16*(14), 6259. https://doi.org/10.3390/su16146259
26. Falalu, B., Hamidu, H., Kana, A., Abdullahi, S., Bala, A., Rose, A., Dayabu, M. (2022). Multivariate statistical and geochemical assessment of groundwater quality within challawa and sharada industrial areas, Kano Metropolis, Northwestern Nigeria. *IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)*.
27. Fettam, D., Gherissi, R., Belarbi, H. (2025). Comparison of meteorological indices for drought assessment and monitoring : A case study from the Tafna watershed, Northwestern Algeria. *Atmósfera*, *39*. https://doi.org/10.20937/ATM.53453
28. Gad, M., El Hamed, R. A., El Fadaly, E. A., Mousa, I. E., Gaagai, A., Aouissi, H. A., Eid, M. H., Abukhadra, M. R., Alqhtani, H. A., Allam, A. A., Elsayed, S. (2025). New approach to predict wastewater quality for irrigation utilizing integrated indexical approaches and hyperspectral reflectance measurements supported with multivariate analysis. *Scientific Reports*, *15*(1), 16395. https://doi.org/10.1038/s41598-025-01181-1
29. Gharaibeh, M. A., Albalasmeh, A. A., Pratt, C., El Hanandeh, A. (2021). Estimation of exchangeable sodium percentage from sodium adsorption ratio of salt-affected soils using traditional and dilution extracts, saturation percentage, electrical conductivity, and generalized regression neural networks. *CATENA*, *205*, 105466. https://doi.org/10.1016/j.catena.2021.105466
30. Gibbs, R. J. (1970). Mechanisms controlling world water chemistry. *Science*, *170*(3962), 1088-1090.
31. Guttman, N. B. (1999). Accepting the standardized precipitation index: A calculation algorithm 1. *JAWRA Journal of the American Water Resources Association*, *35*(2), 311–322.
32. Isaya Kisekka, Al-Dughaishi, U., Platts, B., Cahn, M., Pedrero, F., Grattan, S. R. (avec Isaya Kisekka). (2024). *Developing a New Foundational Understanding of SAR-Soil Structure Interactions for Improved Management of Agricultural Recycled Water Use* (p. 8.15 MB) [PDF]. The Water Research Foundation. https://doi.org/10.34951/E2159H
33. Islam, Md. S., Mostafa, Md. G. (2022). Comparison of classical and developed indexing methods for assessing the groundwater suitability for irrigation. *Journal of Sustainable Agriculture and Environment*, *1*(3), 226–239. https://doi.org/10.1002/sae2.12027

34. Jalali, L., Zarei, M., Gutiérrez, F. (2019). Salinization of reservoirs in regions with exposed evaporites. The unique case of Upper Gotvand Dam, Iran. *Water Research*, *157*, 587–599. https://doi.org/10.1016/j.watres.2019.04.015
35. Kelley, W. P. (1963). Use of saline irrigation water: *Soil Science*, *95*(6), 385–391. https://doi.org/10.1097/00010694-196306000-00003
36. Khatri, N., Tyagi, S. (2015). Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Frontiers in Life Science*, *8*(1), 23–39. https://doi.org/10.1080/21553769.2014.933716
37. Kinzelbach, W., Brunner, P., Von Boetticher, A., Kgotlhang, L., Milzow, C. (2010). Sustainable water management in arid and semi-arid regions. *International Hydrology Series Groundwater Modelling in Arid and Semi-Arid Areas; Wheater, H., Mathias, S., Li, X., Eds*, 119–130.
38. Laoufi, A., Guettaia, S., Boudjema, A., Derdour, A., Almalki, A. S., Bojer, A. K., El-Nagdy, K. A., Ali, E. (2025). Seasonal groundwater quality analysis in a drought prone agricultural region using GIS and IWQI for nitrate contamination insights. *Scientific Reports*, *15*(1), 22948. https://doi.org/10.1038/s41598-025-06884-z
39. Machado, R., Serralheiro, R. (2017). Soil salinity: Effect on vegetable crop growth. Management practices to prevent and mitigate soil salinization. *Horticulturae*, *3*(2), 30. https://doi.org/10.3390/horticulturae3020030
40. Marif, A. A., Esmail, A. O. (2025). Assessing the impact of seasonal variability on irrigation water quality and suitability for agricultural use in wet and dry conditions. *Acta agriculturae Slovenica*, *121*(4). https://doi.org/10.14720/aas.2025.121.4.21860
41. McKee, T. B., Doesken, N. J., Kleist, J. (1993). *The relationship of drought frequency and duration to time scales*. *17*(22), 179–183.
42. Meireles, A. C. M., Andrade, E. M. D., Chaves, L. C. G., Frischkorn, H., Crisostomo, L. A. (2010). A new proposal of the classification of irrigation water. *Revista Ciência Agronômica*, *41*(3), 349–357. https://doi.org/10.1590/S1806-66902010000300005
43. M'nassri, S., El Amri, A., Nasri, N., Majdoub, R. (2022). Estimation of irrigation water quality index in a semi-arid environment using data-driven approach. *Water Supply*, *22*(5), 5161–5175. https://doi.org/10.2166/ws.2022.157
44. Mokhtar, A., Elbeltagi, A., Gyasi-Agyei, Y., Al-Ansari, N., Abdel-Fattah, M. K. (2022). Prediction of irrigation water quality indices based on machine learning and regression models. *Applied Water Science*, *12*(4), 76. https://doi.org/10.1007/s13201-022-01590-x
45. Mosley, L. M. (2015). Drought impacts on the water quality of freshwater systems; review and integration. *Earth-Science Reviews*, *140*, 203–214. https://doi.org/10.1016/j.earscirev.2014.11.010
46. Mozzi, G., Pavelic, P., Alam, M. F., Stefan, C., Villholth, K. G. (2021). Hydrologic assessment of check dam performances in Semi-Arid Areas: A case study from Gujarat, India. *Frontiers in Water*, *3*, 628955. https://doi.org/10.3389/frwa.2021.628955
47. Mussa, M. M., Lohani, T. K., Eshete, A. A. (2025). Evaluation of groundwater quality for drinking and irrigation purposes in the Gidabo watershed, Ethiopia. *Heliyon*, *11*(15), e44063. https://doi.org/10.1016/j.heliyon.2025.e44063
48. Nadhir, B., Hicham, K., Saci, N., Belkacem, T., Zouhir, Z. (2024). Assessment of surface water quality for drinking and irrigation purposes in two dams in the semi-arid region of Northeast Algeria. *Global NEST Journal 26*(8), 5912.
49. Nedjar Et Al., Y. (2022). Water quality assessment for irrigation purposes in a semi-arid region: Wadi Baghai (North East of Algeria). *Egyptian Journal of Aquatic Biology and Fisheries*, *26*(5), 1289-1302. https://doi.org/10.21608/ejabf.2022.268496
50. Oster, J. D., Sposito, G., Smith, C. J. (2016). Accounting for potassium and magnesium in irrigation water quality assessment. *California Agriculture*, *70*(2), 71–76. https://doi.org/10.3733/ca.v070n02p71
51. Paliwal, K. (1972). Irrigation with saline water, Monogram no. 2 (New series). *New Delhi, IARI*, *198*.
52. Pandhumas, T., Kuntiyawichai, K., Jothityangkoon, C., Suryadi, F. X. (2020). Assessment of climate change impacts on drought severity using SPI and SDI over the Lower Nam Phong River Basin, Thailand. *Engineering and Applied Science Research*, *47*(3), 326–338.
53. Pandurang, A., Basanagouda, R., Nayaka, M. (2025). Evaluation of seasonal variation of groundwater quality by using the correlation matrices method in Koppal Taluk Karnataka India. *Advances in Environmental Technology*, (Online First). https://doi.org/10.22104/aet.2025.6973.1913
54. Qadir, M., Sposito, G., Smith, C. J., Oster, J. D. (2021). Reassessing irrigation water quality guidelines for sodicity hazard. *Agricultural Water Management*, *255*, 107054. https://doi.org/10.1016/j.agwat.2021.107054
55. Rocha, J., Carvalho-Santos, C., Diogo, P., Beça, P., Keizer, J. J., Nunes, J. P. (2020). Impacts of climate change on reservoir water availability, quality and irrigation needs in a water scarce Mediterranean region (southern Portugal). *Science of The Total Environment*, *736*, 139477. https://doi.org/10.1016/j.scitotenv.2020.139477

56. Saadi, H., Diongue, D. M. L., Ogilvie, A., Martin, D., Tall, O., Bellanger, J., Ndiaye, A., Faye, S. (2025). Seasonal variations and drivers of water quality in semi-arid freshwater lakes: Multivariate spatial analysis in Lake Guiers, Senegal. *Journal of Hydrology: Regional Studies*, *61*, 102695. https://doi.org/10.1016/j.ejrh.2025.102695
57. Sayel, J. J., Khalaf, A. M., Najm, A. B. A. (2026). Multivariate analysis of seasonal variability in surface water quality for irrigation in Western Iraq. *European Journal of Sustainable Development Research*, *10*(1), em0353. https://doi.org/10.29333/ejosdr/17444
58. Siraj, G., Khan, H. H., Khan, A. (2023). Dynamics of surface water and groundwater quality using water quality indices and GIS in river Tamsa (Tons), Jalalpur, India. *HydroResearch*, *6*, 89–107. https://doi.org/10.1016/j.hydres.2023.02.002
59. Smith, C. J., Oster, J. D., Sposito, G. (2015). Potassium and magnesium in irrigation water quality assessment. *Agricultural Water Management*, *157*, 59–64. https://doi.org/10.1016/j.agwat.2014.09.003
60. Spinoni, J., Naumann, G., Vogt, J. V., Barbosa, P. (2015). The biggest drought events in Europe from 1950 to 2012. *Journal of Hydrology: Regional Studies*, *3*, 509–524. https://doi.org/10.1016/j.ejrh.2015.01.001
61. Subramani, T., Elango, L., Damodarasamy, S. R. (2005). Groundwater quality and its suitability for drinking and agricultural use in Chithar River Basin, Tamil Nadu, India. *Environmental Geology*, *47*(8), 1099-1110. https://doi.org/10.1007/s00254-005-1243-0
62. Sumi, T., Kantoush, S. A., Saber, M. (2022). *Wadi flash floods: Challenges and advanced approaches for disaster risk reduction*. Springer.
63. Tay, C. K. (2021). Hydrogeochemical framework of groundwater within the Asutifi-North District of the Brong-Ahafo Region, Ghana. *Applied Water Science*, *11*(4), 72. https://doi.org/10.1007/s13201-021-01398-1
64. Tejashvini, A., Subbarayappa, C. T., -, M., Chowdappa, H. D., Ramamurthy, V. (2024). Assessment of irrigation water quality for groundwater in Semi-Arid Region, Bangalore, Karnataka. *Water Science*, *38*(1), 548–568. https://doi.org/10.1080/23570008.2024.2414131
65. Tlili-Zrelli, B., Gueddari, M., Bouhlila, R. (2018). Spatial and temporal variations of water quality of mateur aquifer (Northeastern Tunisia): Suitability for irrigation and drinking purposes. *Journal of Chemistry*, *2018*, 1–15. https://doi.org/10.1155/2018/2408632
66. Trenberth, K. (2011). Changes in precipitation with climate change. *Climate Research*, *47*(1), 123-138. https://doi.org/10.3354/cr00953
67. Vasanthavigar, M., Srinivasamoorthy, K., Prasanna, M. V. (2013). Identification of groundwater contamination zones and its sources by using multivariate statistical approach in Thirumanimuthar sub-basin, Tamil Nadu, India. *Environmental Earth Sciences*, *68*(6), 1783–1795. https://doi.org/10.1007/s12665-012-1868-8
68. Vemana, E. V. R. K., Kurakalva, R. M. (2025). Hydrogeochemical process, multivariate statistical, geospatial and index approach for evaluation of groundwater quality for irrigation purposes at Visakhapatnam region, Southern India. *Environmental Geochemistry and Health*, *47*(5), 150. https://doi.org/10.1007/s10653-025-02457-1
69. Wilcox, Lv. (1955). *Classification and use of irrigation waters* (Numéro 969). US Department of Agriculture.
70. World Meteorological Organization. (2012). Standardized precipitation index user guide. *J. Appl. Bacteriol.*, *63*(3), 197–200.
71. Wrence, L., Hardie, A., Eugster, H. (1970). The evolution of closed-basin brines. *Mineral. Soc. Amer. Spec. Pap*, *3*, 273-290.
72. Wu, Z., Zhang, D., Cai, Y., Wang, X., Zhang, L., Chen, Y. (2017). Water quality assessment based on the water quality index method in Lake Poyang: The largest freshwater lake in China. *Scientific Reports*, *7*(1), 17999. https://doi.org/10.1038/s41598-017-18285-y
73. Xiao, Y., Shao, J., Frape, S. K., Cui, Y., Dang, X., Wang, S., Ji, Y. (2018). Groundwater origin, flow regime and geochemical evolution in arid endorheic watersheds: A case study from the Qaidam Basin, northwestern China. *Hydrology and Earth System Sciences*, *22*(8), 4381–4400. https://doi.org/10.5194/hess-22-4381-2018
74. Zhang, R., Sun, Z., Li, G., Wang, H., Cheng, J., Hao, M. (2020). Influences of water chemical property on infiltration into mixed soil consisting of feldspathic sandstone and aeolian sandy soil. *Scientific Reports*, *10*(1), 19497. https://doi.org/10.1038/s41598-020-76548-7
75. Zhou, Y., Li, P., Xue, L., Dong, Z., Li, D. (2020). Solute geochemistry and groundwater quality for drinking and irrigation purposes : A case study in Xinle City, North China. *Geochemistry*, *80*(4), 125609. https://doi.org/10.1016/j.chemer.2020.125609