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Overexploitation and quality assessment of groundwater in arid areas: Adrar province, Southwest Algeria

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Abstract: The study evaluated the water quality of the Adrar municipality over a decade, using physical and chemical analyses of 12 groundwater wells. Results showed a decrease in sulphate (SO_4^{2-}), bicarbonate (HCO_3^-) and sodium (Na^+) concentrations, accompanied by an increase in total hardness (*TH*), potassium (K^+) and nitrate (NO_3^-) levels. The analysis of the Piper diagram confirmed these changes, revealing a transition from the dominance of the sodium sulphate facies to the calcium, magnesium, and chloride sulphate facies. The drinking water quality index (*DWQI*) showed that all water samples during this period can be classified as suitable to drink, except for well 11, which was classified as poor quality. The analysis of water quality indicators, such as residual sodium carbonate (*RSC*), sodium adsorption ratio (*SAR*), and permeability index (*PI*), revealed that this water was suitable for irrigation during this period, with some indicators showing improvement, especially Kelly index (*KI*) and sodium percentage (NA%). The Wilcox diagram showed a clear improvement in the quality of water used for irrigation, as all samples in 2024 were classified as good for irrigation. According to Richards' diagram and the irrigation water quality index (*IWQI*), this water is classified as suitable for irrigating salt-tolerant crops in well-drained soils. Therefore, local authorities and farmers in the Adrar region should implement sustainable management practices, such as planting salt-tolerant crops, adopting irrigation techniques that reduce salt accumulation and water waste, and regularly monitoring water quality.

Keywords: Algerian Sahara, drinking water, groundwater, irrigation, overexploitation

INTRODUCTION

Arid and semi-arid areas represent nearly 41% of the Earth's land surface (Prăvălie, 2016). These regions are characterised by low and irregular precipitation, as well as high evapotranspiration (Kendouci *et al*., 2016; Smith *et al*., 2019). These conditions make them extremely challenging environments, necessitating heavy reliance on groundwater supply (Travi, 2021; Derdour *et al*., 2023). Algeria is considered one of the countries heavily affected by a dry climate, with vast regions within the country experiencing significantly arid conditions. Geographic factors such as high plateaus and deserts contribute to the prevalence of this dry climate (Hirche *et al*., 2011). The dry climate in Algeria presents numerous challenges, including water scarcity and desertification, which impact agriculture and wildlife (Touitou and Al-Amin, 2018; Medjani *et al*., 2023). Adrar, located in the Algerian part of Sahara Desert, is one of the arid regions profoundly affected by its harsh desert climate. It receives less than 15 mm of annual rainfall, making surface water an extremely scarce resource (Benhamida, 2020). This severe lack of precipitation directly affects agriculture and creates significant challenges in accessing sufficient water resources for both farming and daily needs (Mebarki, Kendouci, and Bendida, 2024). The region experiences extreme temperatures throughout the year. In summer, temperatures can soar up to 45°C, making it one of the hottest regions in Algeria. These extreme temperatures further exacerbate life challenges in Adrar (Sekkoum *et al*., 2012). The harsh climatic conditions diminish biodiversity and accelerate desertification, leading to the deterioration of agricultural lands (Bonnet *et al*., 2024). The Adrar region is considered part of the Grand Erg Occidental basin, which includes the continental intercalary aquifer, one of the largest groundwater reservoirs in the world (Kendouci *et al*., 2016; Bendida, Kendouci and Tidjani, 2021). Firstly, the quality of groundwater is affected by natural factors. The natural component arises from interactions between groundwater and aquifer minerals, where hydrochemical processes modify groundwater composition across both spatial and temporal scales (Subramani, Rajmohan and Elango, 2010). Secondly, the human factor has also contributed to the gradual deterioration of groundwater quality through overexploitation as the primary source of water for drinking and irrigation (Chang *et al*., 2017; Bouderbala and Merouchi, 2023; Ferchichi *et al*., 2024). In addition, the unregulated use of fertilisers and pesticides (Kachi, Kachi and Bousnoubra, 2016; Megahed *et al*., 2023) further contributes to the deterioration of water quality.

This situation raises many concerns regarding the quantity and quality of groundwater, highlighting the urgent need to study and analyse spatial and temporal variations in groundwater quality, involving the assessment of physical and chemical parameters to determine its suitability for various applications. Multiple methodologies, including traditional graphical representations and groundwater quality indices, are employed to analyse water quality. This study aims to provide a comprehensive overview of groundwater quality changes in the Adrar area, identifying factors that contribute to its deterioration. It underscores the importance of effective management of water distribution networks and usage patterns necessary to maintain groundwater quality.

MATERIALS AND METHODS

STUDY AREA

The commune of Adrar, the capital of the wilaya, is located in southwestern Algeria within a desert region, approximately 1,500 km from Algiers (Fig. 1). It is bordered by the Saba municipality to the north, Timmi municipality to the south, Timentit municipality to the east, and Bouda to the west. Adrar has an area of about 633 km^2 and population of roughly 85,650, according to statistics from the Ministry of Interior, Communities, and Regional Planning of Algeria (Fr.: Le ministre de l'Intérieur, des Collectivités locales et de l'Aménagement du territoire) (Bendida, Kendouci and Tidjani, 2021). The municipality's economy is mainly based on agriculture, including palm trees, vegetables, cereals, and livestock farming in oases.

HYDROGEOLOGY

The Continental Intercalary (CI) is the only water aquifer present within the study area. Geologically, it dates back to the Lower Cretaceous period (Edmunds *et al*., 2003; Fabre, 2005). The CI formations have an average thickness of 325 m and are located

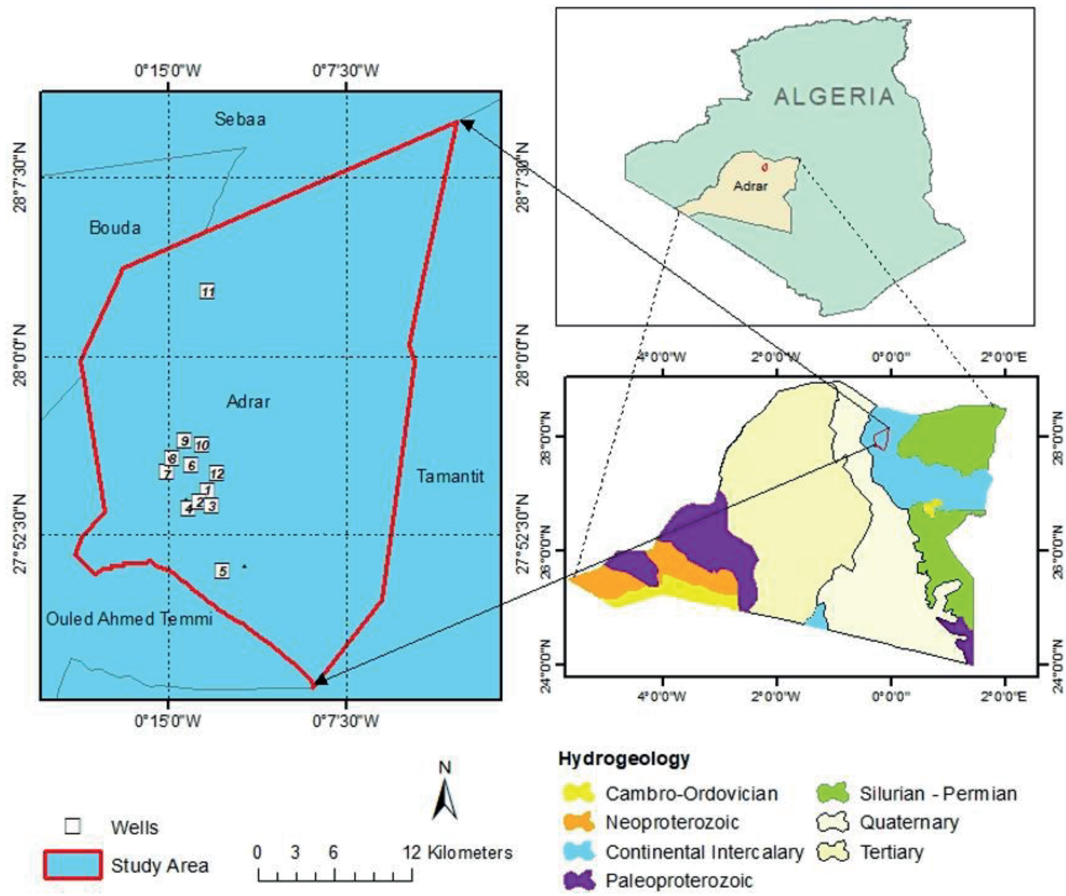

Fig. 1. Geographical location and hydrogeology of the study area; source: own elaboration

beneath the Albian series of the Tademaït region. These formations are eroded on this plateau and they terminate in a bevel on the Paleozoic rocks outcropping in the peripheries by a chain of Sebkhas, which serve as the outlets for groundwater. From a hydrogeological perspective, the CI aquifer is a major freshwater reservoir, shared between three Maghreb countries: Algeria, Tunisia, and Libya. The Algerian part of the continental intercalary aquifer covers 600,000 km^2. It stores a considerable volume of water, estimated at approximately 50,000 bln m^3. Most of the water in this resource was replenished during the rainy periods of the Quaternary. The recharge zones of this aquifer system are mainly located in Algeria at the level of the Saharan Atlas chain, the Tinrhet plateau, and the Grand Erg Oriental (OSS, 2003). In the study area, groundwater from the continental intercalary aquifer is mainly used for drinking and irrigation. Groundwater can be found at shallow depths ranging from 10 to 30 m, but it can exceed 100 m beneath the Tadimait Plateau, where it is accessed through wells and foggaras (Conrad, 1969). According to Benhamza (2013), piezometric analyses conducted over the past 40 years have indicated a decline in groundwater levels exceeding eight metres in the Adrar region. The same research also indicated that due to over-exploitation, the decline could reach 15–20 m over the next 20 years.

ASSESSMENT GROUNDWATER QUALITY

To assess groundwater quality and the change in its characteristics over time, the years 2014 and 2024 were selected as basic reference points for comparative analysis. This temporal approach is based on the climate changes that the region witnessed during this period, most notably, the significant decrease in rainfall and droughts, which may directly affect the recharge of aquifers and water quality. An overview of the methodology used to assess groundwater quality is illustrated in Figure 2.

SAMPLING

The present study assesses groundwater quality in this area through comprehensive physicochemical analyses conducted in 2014 and 2024. The methods described by Rodier (1996) were rigorously applied, both in the field and in laboratory analyses. However, due to the possibility of errors that could affect the accuracy of measurements, the measurement and laboratory analyses were repeated. This methodological rigour ensured the validity and quality of data by ensuring that the samples were representative in terms of groundwater properties in their original

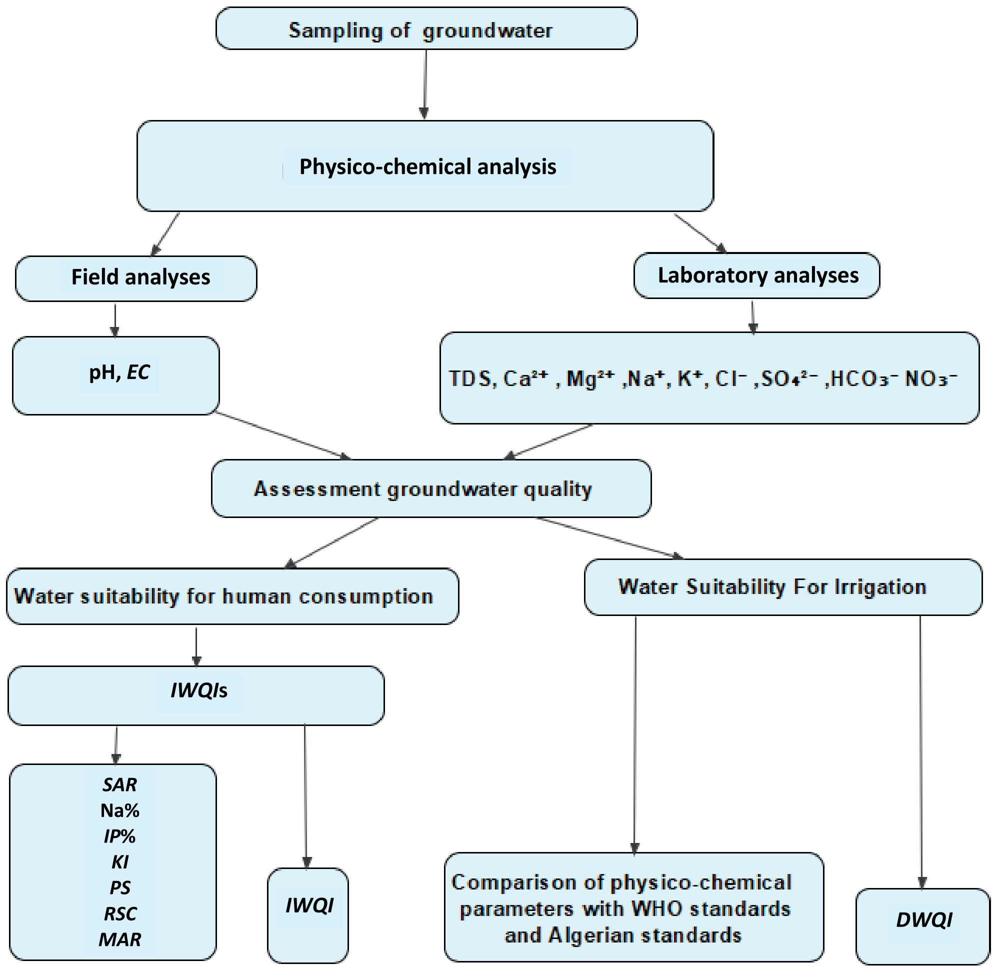

Fig. 2. Methodological flowchart for this study; *EC* = electrical conductivity, TDS = total dissolved solids, *IWQI* = irrigation water quality index, *SAR* = sodium absorption ratio, *PI%* = permeability index, *KI* = Kelly index, *PS* = potential salinity, *RSC* = residual sodium carbonate, *MAR* = magnesium absorption ratio, *DWQI* = drinking water quality index; source: own elaboration

environment. To ensure temporal comparability and take seasonal changes in water quality into account, calculations included the average value of all samples for each well throughout the year, including rainy and dry seasons. This enhances the reliability of the longitudinal comparison. Samples were taken from 12 wells in various locations in the Adrar region. With the assistance of the Algerian Water Company based in Adrar, we prepared Table 1 which details the locations of wells, along with their geographic coordinates and technical characteristics.

$$TW = \sum_{i=1}^{n} w_i \tag{2}$$

$$Rw_i = \frac{w_i}{TW} \tag{3}$$

where: Rw_i = relative weight, w_i = weight of each parameter, n = number of parameters; calculated values of Rw_i are given in the Table 2.

Table 1. Geographic coordinates and technical characteristics of wells

Well name	Coordinates			Depth (m)	Mobilised flow	Exploited flow	Static level	Dynamic level
	X	*Y*	*Z*		$dm^3 \cdot s^{-1}$		m	
W1	00°13'20.04" W	27°54'19.8" N	275	150	30	22.22	6.93	20.00
W2	00°13'40.8" W	27°53'54.5" N	273	150	45	27	4.67	13.83
W3	00°13'10.9" W	27°53'43.5" N	274	150	50	33	7.80	20.00
W4	00°14'13.8" W	27°53'59.1" N	277	150	55	18	12.50	20.55
W5	00°12'43" W	27°50'59" N	276	150	35	17	11.20	16.14
W6	00°14'02.3" W	27°55'24.5" N	272	272	40	22	12.00	52.2
W7	00°15'01.9" W	27°55'09.4" N	275	150	50	24	11.66	33.23
W8	00°14'49.7" W	27°55'42.7" N	269	150	48	25	11.85	19.00
W9	00°14'18.4 » W	27°56'26.7" N	265	150	45	38	11.55	19.00
W10	00°13'32.7" W	27°56'16.5" N	274	150	45	23	10.47	34.55
W11	00°16'50.8" W	27°59'26.67" N	249	100	50	30	11.50	24.00
W12	00°12'54.9" W	27°55'4.9" N	272	150	45	30	12.90	31.50

Source: own elaboration.

WATER SUITABILITY FOR HUMAN CONSUMPTION

The chemical quality of drinking water in the Adrar area was assessed in two stages. First, the results were compared with the World Health Organization and Algerian drinking water standards. Additionally, the percentage change (R_i) in the concentrations of physical and chemical parameters of well water between the two years was analysed using graphic representations. The percentage was calculated as follows:

$$R_i = \frac{C_{i2024} - C_{i2014}}{C_{i2024}} 100 \tag{1}$$

where: C_{i2014} = concentration of each parameter in each water sample in 2014, C_{i2024} = concentration of each parameter in each water sample in 2024.

Second, the drinking water quality index (*DWQI*) method was used to assess water quality by classifying it (excellent: <50, good: 50–100, poor: 100–200) using physical and chemical parameters of water according to the guidelines of the World Health Organization (WHO, 2011).

Three steps are followed to calculate the *DWQI*. In the first step, each parameter is assigned a weight (w_i) according to its relative importance in the overall water quality.

In the second step, the relative weight (Rw_i) is estimated from the following formula:

Table 2. Weight and relative weight of physiochemical parameters

Parameter	WHO (2011)	Weight (w_i)	Relative weight (Rw_i)
pH	6.5–8.5	4	0.114
EC ($\mu S \cdot cm^{-1}$)	1500	4	0.114
TDS ($mg \cdot dm^{-3}$)	300	5	0.142
Ca^{2+} ($mg \cdot dm^{-3}$)	75	2	0.057
Mg^{2+} ($mg \cdot dm^{-3}$)	50	1	0.028
Na^{+} ($mg \cdot dm^{-3}$)	200	2	0.057
K^{+} ($mg \cdot dm^{-3}$)	12	2	0.057
Cl^{-} ($mg \cdot dm^{-3}$)	250	3	0,086
SO_4^{2-} ($mg \cdot dm^{-3}$)	120	3	0.086
HCO_3^{-} ($mg \cdot dm^{-3}$)	250	4	0.114
NO_3^{-} ($mg \cdot dm^{-3}$)	50	5	0.142
Total		**35**	**1.000**

Explanations: pH = potential hydrogen, *EC* = electrical conductivity, TDS = total dissolved solids.
Source: WHO (2011).

Third, the quality rating scale (Q_i) is assigned for each parameter by dividing its concentration by its standard concentration (WHO). The result is multiplied by 100:

$$Q_i = \frac{C_i}{S_i} 100 \tag{4}$$

where: C_i = concentration of each parameter in each water sample ($mg \cdot dm^{-3}$), S_i = WHO drinking water standard for each parameter ($mg \cdot dm^{-3}$) according to the guidelines of WHO (2011).

For the calculation of the water quality index (*WQI*), the Sl_i is the first index to determine for each parameter. The sum of the Sl_i values gives the water quality index for each sample.

$$Sl_i = Q_i \, R\mathrm{w_i} \tag{5}$$

$$WQI = \sum_{i=1}^{n} Sl_i \tag{6}$$

WATER SUITABILITY FOR IRRIGATION PURPOSES

Irrigation in the Adrar area relies primarily on groundwater extracted from wells and the traditional foggara system. A chemical assessment of these waters was undertaken to avoid potential risks to agriculture and to determine the appropriate type of crops for achieving optimal yields. The suitability of water for irrigation was evaluated using parameters such as electrical conductivity (*EC*), permeability index (*PI*), magnesium hazard (*MH*), sodium adsorption ratio (*SAR*), sodium percentage (Na%), Kelly ratio (*RK*), and residual sodium carbonate (*RSC*). These parameters were calculated using specific formulas (Tab. 3).

IRRIGATION WATER QUALITY INDEX (*IWQI*)

The *IWQI* is used to classify water according to its suitability for irrigation. Its calculation is based on five key parameters: electrical conductivity (*EC*), sodium absorption ratio (*SAR*), chloride concentration (Cl^-), sodium concentration (Na^+), and bicarbonate concentration (HCO_3^-) according to the guidelines of the World Health Organization (Abbasnia *et al.*, 2018). The *IQWI* was calculated based on different water quality parameters (q_i) and corresponding weight data (w_i); q_i values are determined as follows:

$$q_i = q_{i\max} - \frac{\left(x_{ij} - x_{\inf}\right) q_{i\mathrm{amp}}}{x_{\mathrm{amp}}} \tag{7}$$

where: $q_{i\max}$ = maximum value of q_i for the class, x_{ij} = observed value of the parameter, $x_{\inf}$ = lower limit value of the parameter class, $q_{i\mathrm{amp}}$ = class amplitude for q_i classes; x_{amp} = amplitude of the parameter class.

The variables in Equation (7) are obtained from the data presented in Table 4 (Meireles *et al.*, 2010; Abbasnia *et al.*, 2018; Batarseh *et al.*, 2021).

Finally, the irrigation water quality index (*IWQI*) was calculated using the Equation (8):

$$IWQI = \sum_{i=1}^{n} (q_i \, w_i) \tag{8}$$

According to Meireles *et al.* (2010), the assigned weights (w_i) for the *IWQI* parameters are: *EC* = 0.211, Cl^- = 0.194, HCO_3^- = 0.202,

Table 3. The key indices used to assess irrigation water quality

Irrigation water quality index	Formula	Source
Sodium percentage (Na%)	$\mathrm{Na\%} = \frac{\mathrm{Na^+}}{\mathrm{Ca^{2+} + Mg^{2+} + Na^+ + K^+}} 100$	Wilcox (1955)
Sodium absorption ratio (*SAR)*	$SAR = \frac{\mathrm{Na^{2+}}}{\sqrt{(\mathrm{Ca^{2+} + Mg^{2+}})/2}}$	Richards (ed.) (1954)
Permeability index (*PI*%)	$PI\% = \frac{\mathrm{Na^+} + \sqrt{\mathrm{HCO_3}}}{\mathrm{Ca^{2+} + Mg^{2+} + Na^+}} 100$	Doneen (1962)
Kelly index (*KI)*	$KI = \frac{\mathrm{Na^+}}{\mathrm{Ca^{2+} + Mg^{2+}}}$	Kelly (1940)
Residual sodium carbonate (*RSC)*	$RSC = (\mathrm{HCO_3^-} + \mathrm{CO_3^-}) - \left(\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}}\right)$	Eaton (1950)
Potential salinity (*PS*)	$PS = \mathrm{Cl^-} + \frac{1}{2}\,\mathrm{SO_4^{2-}}$	Alaya *et al.* (2014)
Magnesium absorption ratio (*MAR*)	$MAR = \frac{\mathrm{Mg^{2+}}}{\mathrm{Ca^{2+} + Mg^{2+}}} 100$	Paliwal (1972)
Total hardness (*TH*)	$TH = 2.5\mathrm{Ca^{2+}} + 4.1\mathrm{Mg^{2+}}$	Todd (1980)

Source: own elaboration based on literature.

Table 4. Proposed limiting values irrigation for water quality parameters

Parameter	Limiting values at q_i			
	85–100	60–85	35–60	0–35
EC (μS·cm^{-1})	200 ≤ *EC* < 750	750 ≤ *EC* < 1500	1500 ≤ *EC* < 3000	*EC* < 200 or *EC* >3000
Na^+ (meq·dm^{-3})	2 ≤ Na < 3	3 ≤ Na < 6	6 ≤ Na < 9	Na < 2 or Na ≥ 9
SAR (meq·dm^{-3})$^{1/2}$	2 ≤ *SAR* < 3	3 ≤ *SAR* < 6	6 ≤ *SAR* <12	*SAR* >12
Cl^- (meq·dm^{-3})	1 ≤ Cl < 4	4 ≤ Cl < 7	7 ≤ Cl <10	Cl < 1 or Cl ≥10
HCO^{3-} (meq·dm^{-3})	1 ≤ HCO_3 < 1.5	1.5 ≤ HCO_3 < 4.5	4.5 ≤ HCO_3 < 8.5	HCO_3 < 1 or HCO_3 ≥ 8.5

Explanations: q^i = water quality parameters; *EC* = electrical conductivity, *SAR* = sodium absorption ratio.
Source: Batarseh *et al.* (2021), modified.

Na^+ = 0.204, and *SAR* = 0.189, with the total weight normalised to 1.

After calculating the *IWQI*, water use restrictions are determined according to range as shown in Table 5.

RESULTS AND DISCUSSION

GENERAL INFORMATION

This research aims to evaluate the quality of groundwater in Adrar Province (Algeria), focusing on its suitability for human consumption and agricultural use. This water originates primarily from the continental aquifer, and its characteristics have been studied through physical and chemical analyses.

Descriptive statistics of physical and chemical parameters for the groundwater samples are presented in Table 6. The data was used to assess water quality and its evolution over time (2014–2024).

HYDROGEOCHEMICAL FACIES

Among the most widely used graphical methods is the Piper diagram, which is employed to interpret analytical results, identify chemical facies, and compare groundwater characteristics spatially and temporally within the Adrar region.

Table 5. Classification of groundwater suitability for irrigation using irrigation water quality index (*IWQI)*

IWQI range	Restriction level	Suitability of water and recommendation
85–100	no restriction (NR)	Suitable for most soil types and does not pose a toxicity risk to most plants. Leaching is recommended, except for soils with very low permeability.
70–85	low restriction (LR)	Suitable for light-textured or moderately permeable soils. Leaching is recommended, and the use of this water should be avoided in heavy clay soils and salt-sensitive plants.
55–70	moderate restriction (MR)	Suitable for soils with moderate to high permeability; moderate leaching is recommended, along with the cultivation of moderately salt-tolerant plants.
40–55	high restriction (HR)	Suitable for highly permeable soils without compact layers; high-frequency irrigation needed for water with high *EC* >2,000 μS·cm^{-1} and *SAR* >7.0. Suitable for plants with moderate to high salt tolerance.
0–40	severe restriction (SR)	Generally unsuitable. Only for salt-tolerant plants.

Source: own elaboration based on Meireles *et al.* (2010).

Table 6. Descriptive statistics for physical and chemical parameters

Parameter	Algerian standard (Dècret, 2011)	WHO standard (2011)	Min.	Max.	Mean	*SD*	Percent of samples in	
							Algerian standard	WHO standard
Values for 2014								
pH	6.5–8.5	6.5–8.5	7.45	7.80	7.57	0.09	100.00	100.00
EC (μS·cm^{-1})	2800	1500	1078	1738.00	1231.17	171.97	100.00	91.16
TH (mg·dm^{-3})	500	300	275.46	415.42	319.15	37.72	100.00	33.33
TDS (mg·dm^{-3})	1500	500	700.70	1129.70	800.26	111.78	100.00	0
Ca^{2+} (mg·dm^{-3})	200	75	48.10	104.21	69.22	17.08	100.00	25.00

cont. Tab. 6

Parameter	Algerian standard (Dècret, 2011)	WHO standard (2011)	Min.	Max.	Mean	*SD*	Percent of samples in	
							Algerian standard	WHO standard
Mg^{2+} ($mg \cdot dm^{-3}$)	150	50	30.13	58.32	36.33	7.83	100.00	91.16
Na^{+} ($mg \cdot dm^{-3}$)	200	200	124.00	225.00	164.25	26.80	91.16	91.16
K^{+} ($mg \cdot dm^{-3}$)	20	12	4.00	10.00	6.58	1.50	100.00	100.00
Cl^{-} ($mg \cdot dm^{-3}$)	500	250	138.00	178.00	151.50	11.06	100.00	100.00
SO_4^{2-} ($mg \cdot dm^{-3}$)	400	250	226.83	412.45	281.21	50.17	100.00	41.60
HCO_3^{-} ($mg \cdot dm^{-3}$)	250	120	136.64	176.90	152.14	13.44	100.00	100.00
NO_3^{-} ($mg \cdot dm^{-3}$)	50	50	2.44	14.00	6.85	4.15	100.00	100.00
Values for 2024								
pH	6.5–8.5	6.5–8.5	7.39	7.95	7.68	0.13	100.00	100.00
EC ($\mu S \cdot cm^{-1}$)	2800	1500	1058.00	1821.00	1195.33	198.70	100.00	91.16
TH ($mg \cdot dm^{-3}$)	500	300	291.52	464.56	324.06	45.58	100.00	25.00
TDS ($mg \cdot dm^{-3}$)	1500	500	686.33	1117.53	776.19	112.66	100.00	0
Ca^{2+} ($mg \cdot dm^{-3}$)	200	75	56.11	84.96	70.41	8.06	100.00	66.66
Mg^{2+} ($mg \cdot dm^{-3}$)	150	50	23.32	66.58	36.81	10.04	100.00	91.16
Na^{+} ($mg \cdot dm^{-3}$)	200	200	97.90	168.00	111.36	21.81	100.00	100.00
K^{+} ($mg \cdot dm^{-3}$)	20	12	4.60	21.40	16.63	4..68	100.00	16.66
Cl^{-} ($mg \cdot dm^{-3}$)	500	250	112.68	245.88	158.85	39.58	100.00	100.00
SO_4^{2-} ($mg \cdot dm^{-3}$)	400	250	214.66	375.00	241.20	44.16	100.00	83.33
HCO_3^{-} ($mg \cdot dm^{-3}$)	250	120	90.16	177.00	111.64	27.42	100.00	91.16
NO_3^{-} ($mg \cdot dm^{-3}$)	50	50	6.68	29.20	21.36	6.87	100.00	100.00

Explanations: pH = potential hydrogen, *EC* = electrical conductivity, *TH* = total hardness, TDS = total dissolved solids.

In 2014, the Piper diagram indicates the dominance of a sulphated-sodium facies, while in 2024, most samples exhibit chloride-sulphated-calcium-magnesium facies (Fig. 3). The Piper diagram analysis showed clear changes in this period, with the majority of well water showing a transition from the dominance of the sodium sulphated facies to the calcium, magnesium, and chloride sulphated facies.

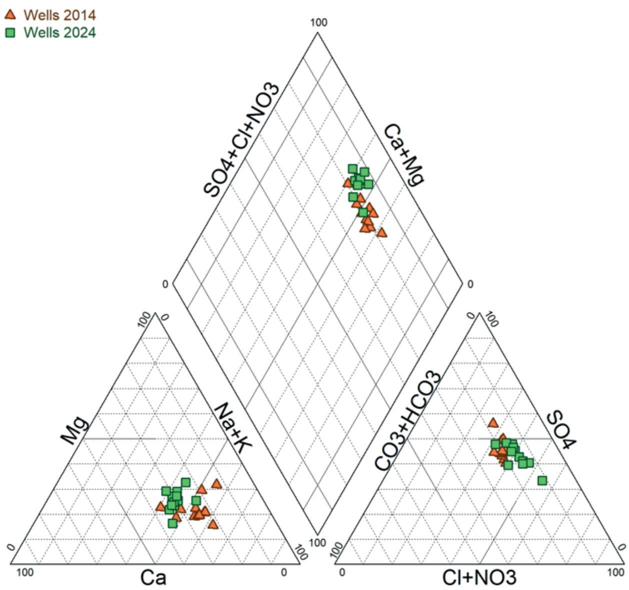

Fig. 3. Graphical representation of groundwater on the Piper diagram in 2014 and 2024; source: own study

WATER SUITABILITY FOR HUMAN CONSUMPTION

Physical parameters

The geological composition of the environment in which water is found directly affects the degree of acidity or alkalinity, which is expressed using the pH (Rodier, 2009). According to data in Table 6, the pH values recorded for 2014 are between 7.45 and 7.80, while for 2024 they vary between 7.39 and 7.95. These pH values comply with both WHO (2008) recommendations and the Algerian standards, ranging from 6.5 to 8.5. As shown in Figure 4, most of the well samples exhibited slight increase in pH over the past decade, with the maximum pH increase of 4.11% in well W11. In contrast, the greatest decrease occurred in well W7 (3.5%).

According to Table 6, the values of *EC* range between 1,078 and 1,738 $\mu S \cdot cm^{-1}$, with an average of 1,231.17 ±171.97 in 2014, and between 1,058 and 1,821 $\mu S \cdot cm^{-1}$, with an average of 1,195.33 ±198.70 in 2024. These measurements indicate a significant presence of dissolved salts and minerals in groundwater in the Adrar Region. This applies in particular to W11, which recorded the maximum value. During this period, one well (W11) exceeded

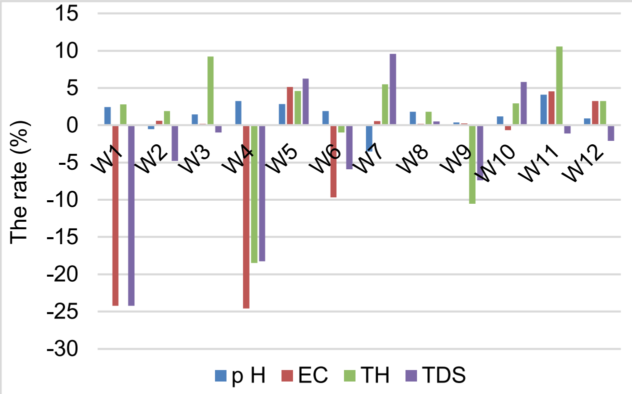

Fig. 4. Variation rate of potential of hydrogen (pH), electrical conductivity (*EC*) and total dissolved solids (TDS) between 2014 and 2024; source: own study

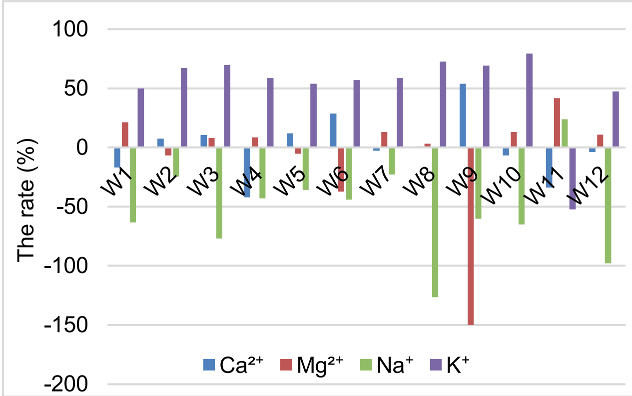

Fig. 5. Temporal variation of major cations in 2014 vs 2024; source: own study

the World Health Organization standards but not the Algerian standards. According to maximum values in *EC* (Fig. 4), it is observed that well W11 shows an increase of 4.56% compared to the previous period. In contrast, well W4 shows a significant decrease of 24.57% in *EC*.

Total dissolved solids (TDS) represent the total concentration of organic and inorganic substances dissolved in water, where inorganic substances can include minerals and salts. The values of TDS range between 700.70 and 1129.70 mg·dm^{-3}, with an average of 800.26 ±111.78 in 2014, and between 686.33 and 1117.53 mg·dm^{-3}, with an average of 776.19 ±112.66 in 2024 (Tab. 6). This means that in both years, all well samples exceeded the limits recommended by the World Health Organization (500 mg·dm^{-3}) (WHO, 2008) but did not exceed the Algerian standards. According to Figure 4, the maximum increase in TDS was recorded in W5 (6.24%) compared with the previous period, while the maximum decrease occurred in well W4 (18.27%).

Major elements

The presence of calcium ions (Ca^{2+}) in groundwater is due to water interactions with geological formations such as carbonate ($CaCO_3$) and gypsum formations ($CaSO_4$) (Chéry, 2006). Calcium concentrations in 2014 ranged from 48.10 to 104.21 mg·dm^{-3}, with an average of 69.22 ±17.08, while in 2024 its concentrations ranged from 56.11 to 84.96 mg·dm^{-3}, with an average of 70.41 ±8.06 (Tab. 6). Based on the results of the analysis, it was observed that during this period some samples exceeded the World Health Organization recommended limit of 75 mg·dm^{-3} (WHO, 2008) but complied with Algerian standards. The maximum rate of increase was recorded in well W9 (53.76%) and a strong decrease in well W4 (42.17%) – Figure 5.

Magnesium (Mg^{+2}). Their presence is generally associated with the interaction of water with calcareous-dolomitic rocks in the aquifer (Bendida, Kendouci and Tidjani, 2021). The magnesium content in the groundwater of the study area ranged from 30.13 to 58.32 mg·dm^{-3} in 2014, and from 23.32 to 66.58 mg·dm^{-3} in 2024 (Tab. 6). The majority of well water in this area remained within the World Health Organization (WHO) standards. According to Figure 5, there was a significant increase (41.60%) in magnesium levels in well 11 during this period, while well 9 showed a strong decrease of the parameter (150%).

Sodium (Na^+). The presence of sodium in groundwater is often attributed to the leaching of halite (NaCl) from evaporative deposits (Bouselsal, 2016). This process releases sodium ions (Na^+) and chloride (Cl^-) into water, affecting water quality, especially in areas with extensive evaporate formations (Abd El-Aziz, 2018). High levels of sodium in drinking water can alter its taste and may be associated with health concerns, including high blood pressure and cardiovascular disease (Haritash *et al.*, 2008). The Na^+ values recorded in 2014 range between 124 and 225 mg·dm^{-3}, with an average of 164.25 ±26.80, while in 2024, they vary between 97.90 and 168.00 mg·dm^{-3}, with an average of 111.36 ±21.81 (Tab. 6) .All samples, except for well 11 in this period, were below the WHO limit of 200 mg·dm^{-3} for the maximum sodium concentration. In 2024, the water from wells in the studied area witnessed a significant decrease in sodium concentration compared to 2014, except for well W11, indicating an improvement in groundwater quality in terms of sodium content. Well W8 recorded the largest decrease of 126.35%, while well W11 recorded an increase of 23% (Fig. 5).

Potassium (K^+). Some evaporate deposits, such as potassium salts (sylvite, sylvinite), can dissolve when they come into contact with groundwater, releasing K^+ into solution (Alaya *et al.*, 2014). The K^+ concentrations in the water samples analysed in 2014 range from 4.00 to 10.00 mg·dm^{-3} with an average of 6.58 ±1.50, while in 2024, they range from 4.60 to 21.40 mg·dm^{-3} with an average of 16.63 ±4.68 (Tab. 6). K^+ concentrations in all groundwater samples in 2014 were within the WHO standards, but in 2024 most of them exceeded the WHO standards; however, they complied with Algerian standards (Tab. 6). This reflected the degradation of this water over time with regard to potassium content. According to Figure 5, well W11recorded a decrease of 52.17%, while the rest of the wells recorded an increase, the maximum of which was in W10 (79.27%).

Chloride (Cl^-). Chloride is naturally found in both groundwater and surface water and can originate from salts such as halite (NaCl) and sylvine (KCl) (Bendida, Kendouci and Tidjani, 2021). Elevated Cl^- levels can result from geological formations it passes through or from inadequate sewage treatment (Dey *et al.*, 2024). The Cl^- concentrations in the analysed waters in 2014 range between 138.00 and 178.00 mg·dm^{-3}. In 2024, the chloride values range between 112.68 and 245.88 mg·dm^{-3} (Tab. 6). The chloride values comply with both WHO recommendations and the Algerian standards in this period. The Cl^- increased rate reached 43.87% in well W10 and a decrease of 35.31% in well W1 (Fig. 6).

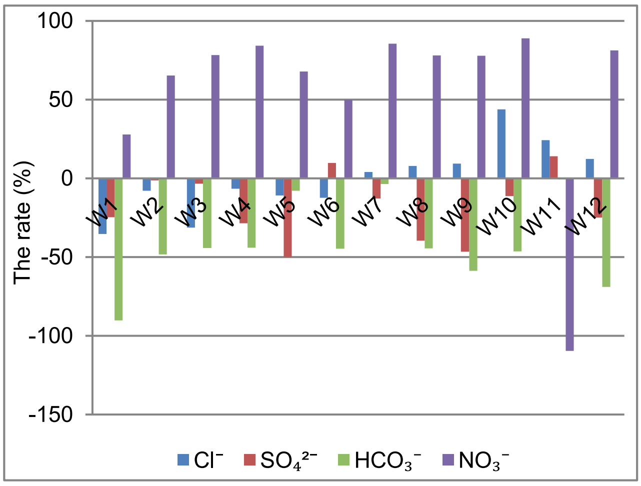

Fig. 6. Temporal variation of major ions in 2014 vs 2024; source: own study

Sulphate (SO_4^{2-}). The high SO_4^{2-} concentrations in the water are mainly due to the leaching of evaporitic geological formations in the region. These formations are composed of sulphate-rich minerals like gypsum ($CaSO_4$·$2H_2O$) and anhydrite ($CaSO_4$) (Abd El-Aziz, 2018). The SO_4^{2-} concentrations in the water samples analysed in 2014 range from 226.83 to 412.45 mg·dm^{-3}, with an average of 281.21 ±50.17 while in 2024, they range from 214.66 to 375.00 mg·dm^{-3}, with an average of 241.20 ±44.16 (Tab. 6). A decrease in SO_4^{2-} values was observed in most wells, indicating an improvement in water quality. In 2014, SO_4^{2-} values were 41% within the limits of the World Health Organization standards (WHO, 2008), and in 2024 they became 66%. Referring to Figure 6, a maximum decrease of 49.98% in SO_4^{2-} concentrations is observed in well W5. In contrast, well W11 recorded a 14.13% increase in sulphate concentrations.

Nitrates (NO_3^-). Nitrates are a major factor affecting the degradation of groundwater quality. Its presence in groundwater is primarily due to agricultural activity, including the use of nitrogen fertilisers and organic animal waste. Additionally, domestic wastewater discharge is also an additional factor contributing to increased nitrate concentrations in groundwater sources (Chen, Wu and Qian, 2016; Touafek, Tidjani and Bendida, 2025). The NO_3^- levels in the groundwater of the study area in 2014 range from 2.44 to 14.00 mg·dm^{-3}, In 2024, the NO_3^- levels ranged from 6.68 to 29.20 mg·dm^{-3} exceeding the WHO standard set at 50 mg·dm^{-3} (Tab. 6). These values indicated that the NO_3^- concentrations in the water samples from these wells did not exceed the limits recommended by the World Health Organization. According to Figure 6, a significant increase in nitrate concentrations in well water samples was observed, especially in W10 (88.89%), and a decrease recorded in W11 (109.58%).

Bicarbonates (HCO_3^-). Bicarbonates are found in water as a result of the dissolution of carbonate formations (limestone, dolomite) (Varliero *et al.*, 2024). The simplified chemical equation for this process is as follows: $CaCO_3$ (solid) + CO_2 (gas) + H_2O ⇌ Ca_2^+ + 2 HCO_3^-. The HCO_3^- levels in the groundwater in 2014 range from 136.64 to 176.90 mg·dm^{-3}, exceeding the WHO standard set at 120 mg·dm^{-3}. In 2024, the HCO_3^- levels range from 90.16 to 177.00 mg·dm^{-3}, with three well water samples exceeding the limit recommended by the WHO (Tab. 6). However, it is noted that these levels do not exceed the Algerian standards of 250 mg·dm^{-3} for this period. According to Figure 6, HCO_3^- concentration levels in 2024 decreased in the water of all wells compared to 2014, noting that well W1 recorded the maximum decrease (90.11%) in HCO_3^- levels during this period.

Drinking water quality index (*DWQI*)

Researchers have developed a comprehensive and simplified method for assessing drinking water quality by calculating the drinking water quality index (*DWQI*). Based on physical and chemical criteria, this indicator allows water quality to be classified as excellent, good or poor (Tab. 7).

Table 7. Groundwater classification based on drinking water quality index (*DWQI*)

Well code	*DWQI* 2014	Water class	*DWQI* 2024	Water class
W1	89.34	good	78.43	good
W2	76.79	good	82.21	good
W3	75.82	good	81.50	good
W4	84.19	good	81.00	good
W5	85.75	good	84.42	good
W6	79.86	good	83.85	good
W7	74.80	good	84.53	good
W8	78.84	good	80.42	good
W9	82.01	good	85.12	good
W10	76.95	good	89.61	good
W11	101.26	poor	103.38	poor
W12	76.50	good	75.76	good

Source: own study.

The *DWQI* values in 11 wells fall within the second class [50–100] during the period (2014–2024), indicating that groundwater is of good quality and suitable for drinking (Fig. 7). In contrast, there is only one well whose values fall within the third class [100–200], which indicates that the quality of water is poor and unsuitable for drinking.

According to Figure 8, the maximum percentage increase during this period was in well W10 (14.12%), while the maximum percentage decrease was in well W1 (13.90%).

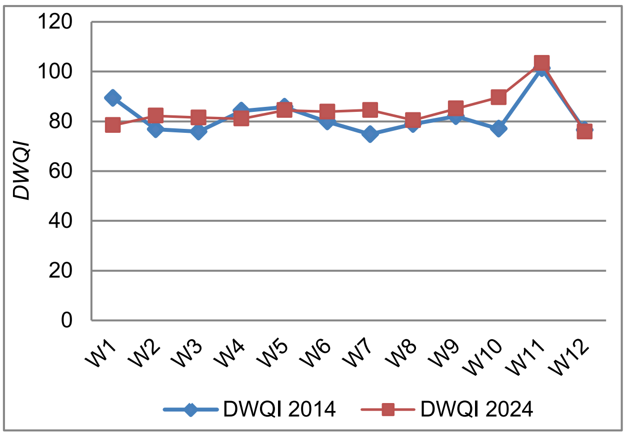

Fig. 7. Groundwater classification based on drinking water quality index (*DWQI*); source: own study

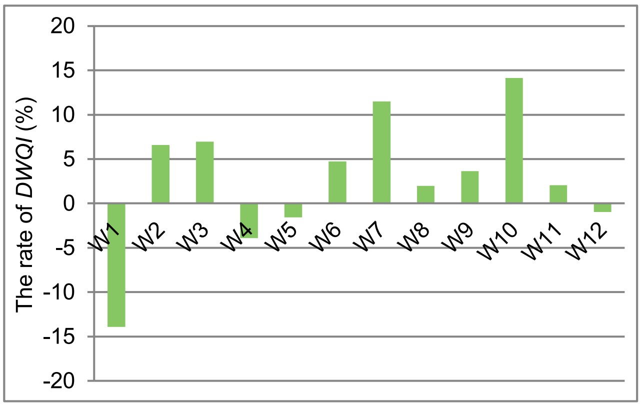

Fig. 8. Temporal variation of drinking water quality index (*DWQI*) in 2014 vs 2024; source: own study

WATER SUITABILITY FOR IRRIGATION PURPOSES

The physico-chemical analyses of groundwater in the study area have covered several parameters commonly used for assessing the quality of irrigation water. These parameters are shown in Table 8.

The residual sodium carbonate (*RSC*) index of irrigation water is used to indicate the alkalinity hazard for soil. High *RSC* values indicate a potential hazard to soil structure and fertility, as they can lead to increased soil sodicity and reduced soil permeability (Elsayed *et al.*, 2020; Dimple *et al.*, 2022). In 2014, *RSC* values ranged from −5.53 to −2.99. In 2024, *RSC* values varied from −6.54 to −3.58 (Tab. 8). According to Figure 9, the majority of well water samples during this period showed an increase, with the maximum recorded in well W1 (30.97%). However, all measured *RSC* values in the samples were below 1.25, indicating that the water is considered suitable for irrigation (Tab. 9).

The *SAR* value is very important in assessing how likely soil is to disperse when irrigated with sodium-rich water (Zaman, Shahid and Heng, 2018). Furthermore, elevated sodium concentrations, as indicated by the *SAR*, can lead to the formation of alkaline soil conditions (Saghebian *et al.*, 2014; Bendida *et al.*, 2024). Based on Table 8, it was observed that the maximum *SAR* value during this period did not exceed 10. Thus, groundwater in the study area is classified as excellent irrigation quality (Tab. 9). With regard to differences between the two years (2014–2024), a decrease in *SAR* was observed in eleven wells. The maximum decrease was observed in well W8 (128.45%) compared to the previous year (2014). In contrast, well W11 showed the opposite trend, with the *SAR* increasing by 19.49% (Fig. 9).

Richards introduced a diagram that classifies irrigation water by plotting electrical conductivity (*EC*) against the sodium adsorption ratio (*SAR*). This classification aids in assessing the potential risks of soil salinisation and sodicity due to irrigation practices. Richards' diagram (Fig. 10) indicated an improvement in the quality of irrigation water during this period, especially in well W11, which shifted from class C3S2 to class C3S1. According to the diagram, all well water samples in 2024 were classified as class C3S1, indicating water suitable for irrigating salt-tolerant crops in well-drained soils (Richards, ed., 1954).

The sodium percentage (NA%) is an important indicator in the assessment of irrigation water quality, as high levels indicate that the concentration of sodium exceeds that of calcium and magnesium. This may disrupt soil structure, contributing to the degradation of its physical properties such as permeability and ventilation, thereby negatively affecting crop productivity (Zaman, Shahid and Heng, 2018). In 2014, Na% values ranged from 39.20 to 61.31, with an average of 51.58 ±5.47. In 2024, Na% values varied from 36.02 to 48.12 with an average of 40.61 ±3.09 (Tab. 8). This period witnessed a significant improvement in Na%, as the majority of well water in 2014 (83.33%) fell within permissible levels (Tab. 9). In 2024, 58.33% of the wells had shifted to the good quality class, while 41.67% remained within

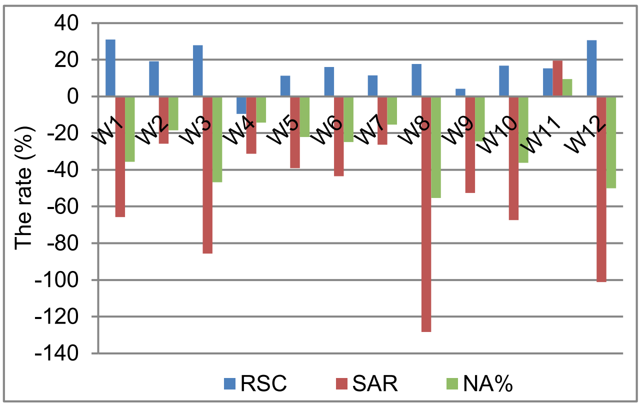

Fig. 9. Temporal variation of residual sodium carbonate (RSC), sodium adsorption ratio (*SAR*), and sodium percentage (Na%) between 2014 and 2024; source: own study

Table 8. Statistical description of water quality indices for irrigation

Parameter	Value 2014				Value 2024			
	min.	max.	mean	*SD*	min.	max.	mean	*SD*
SAR	2.71	5.63	3.99	0.73	2.04	3.39	2.66	0.39
Na%	39.20	61.31	51.58	5.47	36.02	48.12	40.61	3.09
RSC	−5.53	−2.99	−3.99	0.74	−6.54	−3.58	−4.76	0.68
KI	0.66	1.62	1.12	0.23	0.59	0.99	0.73	0.10
PI%	51.89	71.32	63.90	5.02	50.66	62.65	54.01	3.04
PS	6.38	8.37	7.20	0.66	5.64	10.53	6.99	1.35
MAR	35.76	71.22	46.90	9.50	31.39	58.80	46.07	6.70

Explanations: *SD* = standard deviation, *SAR* = sodium absorption ratio, Na% = sodium percentage, *RSC* = residual sodium carbonate, *KI* = Kelly index, *PI*% = permeability index, *PS* = potential salinity, *MAR* = magnesium absorption ratio.
Source: own study.

Table 9. Water quality classification for irrigation in 2014 and 2024

Parameter	Value range	Water class	Representing wells			
			2014		2024	
			No. of samples	% of samples	No. of samples	% of samples
pH	6.5–8.5	good	12	100.00	12	100.00
SAR	<10	excellent	12	100	12	100.00
	10–18	good	0	0	0	0
	18–26	doubtful	0	0	0	0
	>26	unsuitable	0	0	0	0
Na%	<20	excellent	1	8.33	0	0
	20–40	good	1	8.33	7	58.33
	40–60	permissible	10	83.33	5	41.67
	60–80	doubtful	1	8.33	0	0
	>80	unsuitable	0	0	0	0
RSC	<1.25	good	12	100.00	12	100.00
	1.25–2.5	doubtful	0	0	0	0
	>2.5	unsuitable	0	0	0	0
KI	<1	suitable	3	25	12	100.00
	>1	unsuitable	9	75	0	0
PI%	>75	excellent	0	0	0	0
	75–25	good	12	100.00	12	100.00
	<25	unsuitable	0	0	0	0
PS	<5	excellent to good	0	0	0	0
	5–10	good to injurious	12	100.00	11	91.67
	>10	injurious to unsatis-factory	0	0	1	8.33
MAR	<50	suitable	10	83.33	9	75.00
	>50	unsuitable	2	16.67	3	25.00

Explanations: pH = potential of hydrogen, the other as in Tab. 8.
Source: own study.

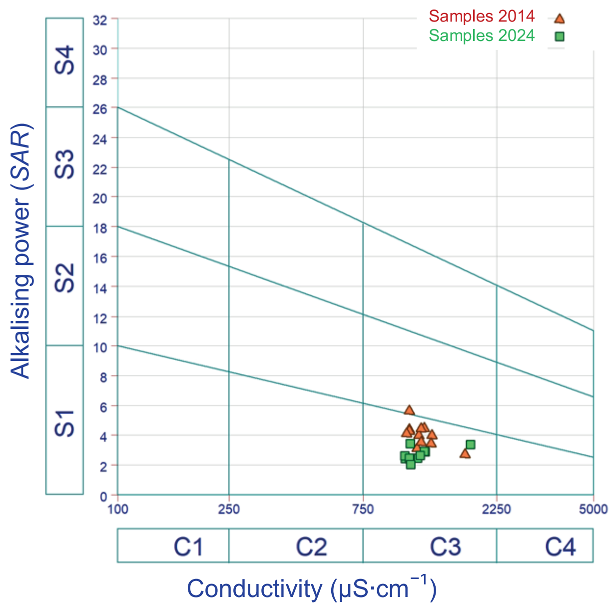

Fig. 10. Richards' diagram of the well water in the study area for two campaigns (2014, 2024); *SAR* = sodium adsorption ratio; source: own study

the permissible class. Figure 9 supports such improvement, showing a decrease in sodium levels in most wells. A maximum decrease of 55.28% in %Na is observed in well (W8), while a maximum increase of 9.51% in %Na is seen in well (W11) – Figure 9.

The Wilcox diagram is a graphical method used to evaluate water quality by the %Na against *EC*. It helps determine the salinity hazard of irrigation water, as increased Na^+ levels can negatively impact soil structure and hinder plant growth (Wilcox, 1955). The Wilcox diagram (Fig. 11) showed a clear improvement in the quality of irrigation water as all samples in 2024 fell into the good quality class.

High levels of sodium and potassium concentrations can lead to soil degradation and reduce its permeability. Conversely, an increase in magnesium and calcium can be beneficial for soil structure and permeability (Bendida, Kendouci and Tidjani, 2021). To evaluate this balance, a relationship has been established between these chemical elements, represented by the permeability index (*PI*) (Guo *et al.*, 2021). The *PI* values ranged from 51.89 to 71.32% in 2014, with an average of 63.90% ±5.02. For the year 2024, the values ranged from 50.66 to 62.65%, with an average of 54.01% ±3.04 (Tab. 8). The data related to the

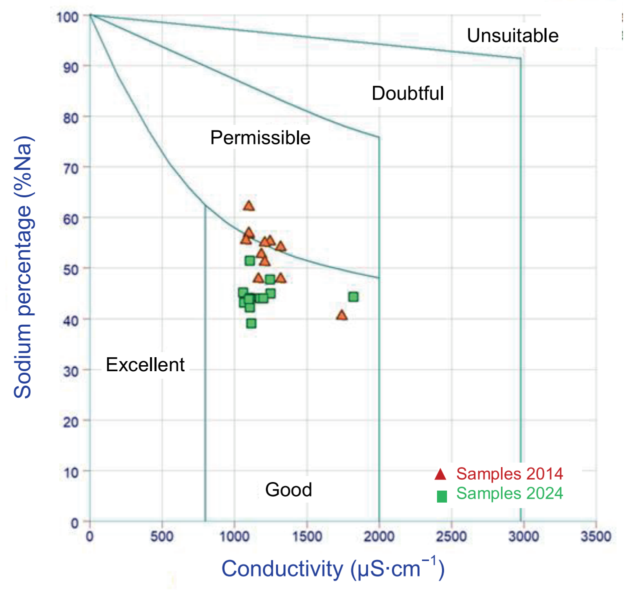

Fig. 11. Groundwater classification according to Wilcox; source: own study

PI ratio indicate that the groundwater quality in the study area remained within a good range during this period (Tab. 9). Additionally, according to Figure 12, the majority of well water recorded a decrease in permeability value, indicating an improvement in this index over time.

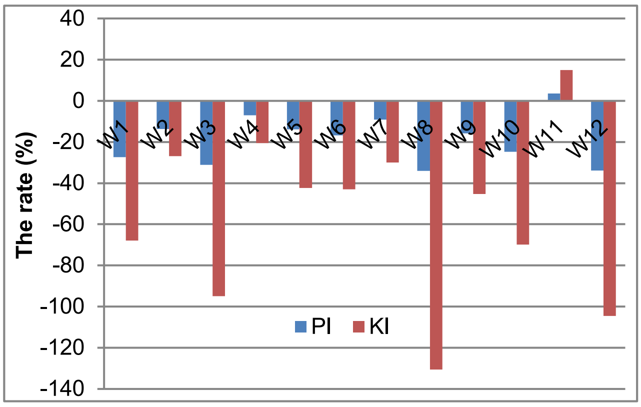

Fig. 12. Temporal variation of permeability index (*PI*) and Kelly index (*KI*) between 2014 and 2024; source: own study

Kelly index (*KI*) is a chemical indicator used to analyse the quality of irrigation water and to assess sodium concentration compared to calcium and magnesium concentrations. This index is used to assess the potential impact of irrigation water on soil structure, as well as on plant growth and productivity (Boussaada *et al.*, 2023).

The Kelly index (*KI*) in the study area ranged from 0.66 to 1.62 in 2014, with an average of 1.12 ±0.23. In 2024, the *KI* values ranged between 0.59 and 0.99, with an average of 0.73 ±0.10 (Tab. 8). Based on these results, it is evident that there is an improvement in the quality of irrigation water, as most of the samples in 2014 were unsuitable for irrigation, and in 2024, all 12 well water samples became suitable for irrigation due to the decrease in the value of *KI* (decrease in sodium concentrations) during this period (Tab. 9), as shown in Figure 12. The maximum decrease in the *KI* was in well W8 (130.56%), whereas well W11showed an increase of 14.92%.

Potential salinity (*PS*) is a measure of the impact of soluble salts in irrigation water on soil quality, as these salts may precipitate and accumulate in the soil over time (Subbarao and Reddy, 2018). The *PS* values ranged from 6.38 to 8.37 in 2014, with an average of 7.20 ±0.66. In 2024, the *PS* values ranged from 5.64 to 10.53, with an average of 6.99 ±1.35 (Tab. 8). During this period, all the *PS* values were found to be within acceptable limits for irrigation, except for one well in 2024 (Tab. 9). According to Figure 13, it is noted that W10 shows the maximum increase in *PS* value (30.40%) compared to the previous period, whereas well W1 shows the maximum decrease in *PS* value (30.94%).

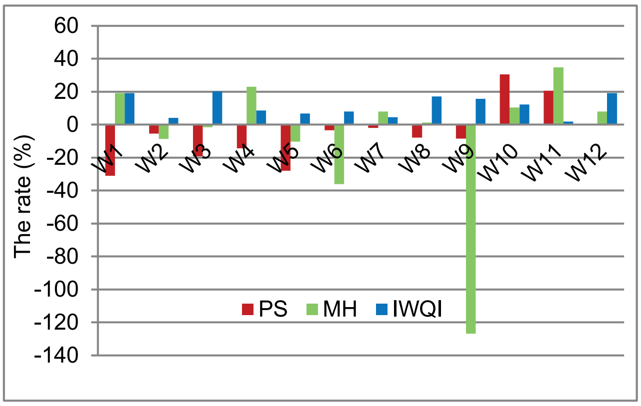

Fig. 13. Temporal variation of potential salinity (*PS*), magnesium hazard index (*MH*) and irrigation water quality index (*IWQI*) in 2014 and 2024; source: own study

The magnesium absorption ratio (*MAR*), also referred to as magnesium hazard, was introduced by Paliwal (1972) to assess water suitability for irrigation. When the *MAR* value exceeds 50%, it indicates a potential soil alkaline risk, which may adversely affect crop yields (Ravikumar, Somashekar and Angami, 2011). The percentage of the *MAR* in the study area ranged from 35.76 to 71.22% in 2014, with an average of 46.90 ±9.50. In 2024, the *MAR* values ranged from 31.39 to 58.80%, with an average of 46.07 ±6.70 (Tab. 8). The percentage of water suitable for irrigation based on *MAR* was 83% in 2014 but decreased to 75% in 2024 (Tab. 9). It was observed that this parameter showed a negative trend over time. Figure 13 shows the maximum increase in *MAR* during this period, which reached 34.79% in W11, and the maximum decrease, which reached 126.89% in W9.

The *IWQI* is an essential tool for evaluating and managing water resources, especially in arid regions such as Adrar, where groundwater is critical for irrigation. Regular analysis of the *WQI* ensures the sustainable use of these resources while minimising adverse effects on soils and crops. The Table 10 displays the partial index (*Wi·qi*) values for various physical and chemical parameters of well water, as well as the sum of these values, which represents the overall *IWQI* for each well, for the years 2014 and 2024.

Data presented in Table 10 shows a significant improvement in irrigation water quality over the past decade, with the number of wells classified under the low restriction [70–85] class increasing from five wells in 2014 to eleven wells in 2024. This water quality category indicates reduced limitations to its use for irrigation, making it suitable for light-textured or moderately

Table 10. Groundwater classification based on irrigation water quality index (*IWQI*) in 2014 and 2024

Well code	The partial index (*Wi qi*) of					*IWQI*	Water class
	EC	*SAR*	Na^+	Cl^-	HCO_3^-		
2014							
W1	13.91	9.62	10.61	15.39	17.21	66.74	moderate restriction
W2	15.00	15.94	13.27	16.16	17.00	77.38	low restriction
W3	15.46	7.69	9.65	16.21	16.85	65.86	moderate restriction
W4	13.94	15.44	11.35	15.75	16.96	73.44	low restriction
W5	14.87	14.54	10.10	16.39	15.56	71.45	low restriction
W6	14.69	15.24	11.94	15.89	16.85	74.60	low restriction
W7	15.49	14.04	10.24	16.39	15.75	71.91	low restriction
W8	15.47	11.93	5.81	16.30	17.05	66.56	moderate restriction
W9	14.47	7.33	8.47	15.98	17.32	63.57	moderate restriction
W10	14.70	7.41	8.54	16.67	17.09	64.41	moderate restriction
W11	11.82	13.93	9.09	9.21	14.81	58.86	moderate restriction
W12	14.14	8.98	10.61	16.62	16.94	67.29	moderate restriction
2024							
W1	15.73	17.05	15.20	17.36	17.21	82.55	low restriction
W2	14.95	16.93	15.08	16.66	17.00	80.63	low restriction
W3	15.45	17.23	15.21	17.82	16.85	82.55	low restriction
W4	15.77	16.71	14.68	16.20	16.96	80.31	low restriction
W5	14.42	16.29	13.35	17.03	15.56	76.64	low restriction
W6	15.44	16.92	15.16	16.66	16.85	81.03	low restriction
W7	15.45	15.45	12.51	16.12	15.75	75.27	low restriction
W8	15.46	16.91	15.09	15.73	17.05	80.24	low restriction
W9	14.45	14.57	13.72	15.27	17.32	75.32	low restriction
W10	14.76	15.84	14.01	11.75	17.09	73.45	low restriction
W11	10.40	12.46	10.02	12.24	14.81	59.94	moderate restriction
W12	15.37	18.73	16.47	15.73	16.94	83.24	low restriction

Explanations: *EC* = electrical conductivity, *SAR* = sodium adsorption ratio.
Source: own study.

permeable soils. However, it is advisable to avoid its use with salt-sensitive crops. Instead, it should be directed toward cultivating crops with moderate to high salt tolerance, such as tomatoes, onions, date palm, barley, and wheat. Despite its relative suitability, leaching is recommended to reduce salt concentrations, and it is also advised not to use this water in heavy clay soils to prevent salt accumulation and its detrimental effects on agricultural productivity. This improvement in the quality of irrigation water, as all well water samples recorded an increase in the value of the water quality index in 2024 compared to 2014, and the maximum percentage of increase was in W3 20.21%

CONCLUSIONS

This study aims to assess the evolution of groundwater quality in the Adrar region, located in the Algerian Sahara, over the past decade (2014–2024). The region relies on groundwater originating from the continental intercalary aquifer, which has significant salinity levels, as reflected in the values of the electrical conductivity (*EC*), total dissolved solids (TDS), and total hardness (*TH*). However, these values remain within the acceptable limits established by Algerian standards. Based on physical and chemical analyses, the Piper diagram results indicate a significant shift in the hydrochemical properties of groundwater during this period. Prevailing water facies of the sodium sulphate type have been transformed into new facies characterised by the predominance of calcium, magnesium, and chloride sulphate ions. The results of the study showed a clear improvement in the quality of drinking water in terms of certain chemical elements bicarbonate (HCO_3^-), sulphate (SO_4^{2-}), and sodium (Na^+) concentrations, as well as a deterioration due to increased concentration of potassium (K^+) concentrations and nitrate (NO_3^-) that did not exceed the limits of Algerian standards. As part of the comprehensive assessment of drinking water suitability, the drinking water quality index (*DWQI*) was used. The results showed that most of the groundwater samples during this period fell within the class of good-quality water, except for well W11, which maintained its classification under the category of poor-quality water. The water of this well shows a notable deterioration in the quality of groundwater compared to other wells, indicating a notable spatial heterogeneity in the chemical characteristics of the groundwater. This degradation is likely linked to the effects of repeated irrigation and uncontrolled fertiliser application on the adjacent agricultural land. It is also possible that the well water passes through layers rich in soluble salts, such as halite (NaCl) and gypsum ($CaSO_4 \cdot 2H_2O$).

Regarding irrigation water quality, several hydrochemical parameters were calculated to assess its quality during this period. It was observed that the permeability index (*PI*), residual sodium carbonate (*RSC*), and sodium adsorption ratio (*SAR*) were within suitable limits for irrigation. Kelly ratio (*KR*) values also recorded an improvement as the proportion of water suitable for irrigation increased from 25 in 2014 to 100 in 2024. Sodium percentage (Na %) has also improved significantly, from 18.33 to 58.33 in the category of good-quality water for irrigation. Additionally, Wilcox and Richards diagrams were used to illustrate the suitability for irrigation in the study area. The Wilcox diagram (Na–*EC*) shows the improvement in groundwater quality, with all well water samples in 2024 being classified as good for irrigation. Richard's diagram (*EC*–*SAR*) reveals an improvement in this period as all samples in 2024 fell into C3S1 zone, indicating high salinity and low sodium levels. These characteristics indicate that the water is suitable for irrigating salt-tolerant crops in well-drained soils. This assessment was also confirmed by the water quality index (*WQI*), which recommends avoiding its use for salt-sensitive crops.

Finally, it is essential that local authorities and farmers in semi-arid regions adopt sustainable management practices. These include growing salt-tolerant crops, adopting irrigation techniques that reduce salt accumulation and water waste, and conducting periodic monitoring of water quality, all of which are fundamental to ensure the continuity of agricultural activities in fragile environments. Ensuring the availability of safe drinking water also requires conducting periodic well water examinations and applying effective treatment techniques in accordance with public health standards. These integrated measures are crucial to ensuring water security and promoting sustainable development in arid regions.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

REFERENCES

Abbasnia, A. *et al.* (2018) "Assessment of groundwater quality and evaluation of scaling and corrosiveness potential of drinking water samples in villages of Chabahr city, Sistan and Baluchistan province in Iran," *Data in Brief*, 16, pp. 182–192. Available at: https://doi.org/10.1016/j.dib.2017.11.003.

Abd El-Aziz, S.H. (2018) "Application of traditional method and water quality index to assess suitability of groundwater quality for drinking and irrigation purposes in south-western region of Libya," *Water Conservation and Management*, 2(2), pp. 20–32. Available at: https://doi.org/10.26480/wcm.02.2018.20.32.

Alaya, M.B. *et al.* (2014) "Suitability assessment of deep groundwater for drinking and irrigation use in the Djeffara aquifers (Northern Gabes, south-eastern Tunisia)," *Environmental Earth Science*, 71(8), pp. 3387–3421. Available at: https://doi.org/10.1007/s12665-013-2729-9.

Batarseh, M. *et al.* (2021) "Assessment of groundwater quality for irrigation in the arid regions using irrigation water quality index (IWQI) and GIS-Zoning maps: Case study from Abu Dhabi Emirate, UAE," *Groundwater for Sustainable Development*, 14, 100611. Available at: https://doi.org/10.1016/j.gsd.2021.100611.

Bendida, A. *et al.* (2024) "Wastewater purification and recycling using plants in an arid environment for agricultural purposes: case of the Algerian Sahara," *Applied Water Science*, 14(6), 123. Available at: https://doi.org/10.1007/s13201-024-02148-9.

Bendida, A., Kendouci, M.A. and Tidjani, A.E.-B. (2021) "Characterization of Algerian Sahara groundwater for irrigation and water supply: Adrar region study case," *Journal of Water and Land Development*, 49, pp. 235–243. Available at: https://doi.org/10.24425/jwld.2021.137117.

Benhamza, M. (2013) *Aperçu hydrogéologique et hydrochimique sur le système de captage traditionnel des eaux souterraines «foggara» dans la région d'Adrar [Hydrogeological and hydrochemical overview of the traditional groundwater collection system «foggara» in the Adrar region]*. MSc Thesis. Annaba: Université Badji Mokhtar.

Benhamida, S.A. (2020) *Approche géochimique à l'étude du Système Aquifère du Sahara Septentrional SASS, application à la nappe du Continental Intercalaire de la région Ouest du Sahara: Touat – Gourara – Tidikelt [Geochemical approach to the study of the North Western Sahara Aquifer System (SASS), application to the continental intercalaire aquifer in the Western Sahara Region: Touat – Gourara – Tidikelt]*. PhD Thesis. Ouargla: University Kasdi Merbah.

Bonnet, B. *et al.* (2024) *Desertification and climate change: Are they part of the same fight?*. Versailles: Éditions Quae. Available at: https://doi.org/10.35690/978-2-7592-4030-2.

Bouderbala, A. and Merouchi, H. (2023) "Impact of climate change and human activities on groundwater resources in the alluvial aquifer of Upper Cheliff, Algeria," *Indian Journal of Ecology*, 50(3), pp. 575–583. Available at: https://doi.org/10.55362/IJE/2023/3937.

Bouselsal, B. (2016) *Étude hydrogéologique et hydrochimique de l'aquifère libre d'El Oued Souf (SE Algérie) [Hydrogeological and hydrochemical study of the unconfined aquifer of El Oued Souf (SE Algeria)]*. PhD Thesis. Annaba: Université Badji Mokhtar. Available at: https://biblio.univ-annaba.dz/wp-content/uploads/2019/07/These-Bouselsal-Boualem.pdf (Accessed: March 10, 2025).

Boussaada, N. *et al.* (2023) "Geochemistry and water quality assessment of continental intercalary aquifer in Ouargla Region (Sahara, Algeria)," *Journal of Ecological Engineering*, 24(2), pp. 279–294. Available at: https://doi.org/10.12911/22998993/156832.

Chang, F.J. *et al.* (2017) "Conservation of groundwater from over-exploitation – Scientific analyses for groundwater resources management," *Science of the Total Environment*, 598, pp. 828–838. Available at: https://doi.org/10.1016/j.scitotenv.2017.04.142.

Chen, J., Wu, H. and Qian, H. (2016) "Groundwater nitrate contamination and associated health risk for the rural communities in an agricultural area of Ningxia, Northwest China," *Exposure and Health*, 8(3), pp. 349–359. Available at: https://doi.org/10.1007/s12403-016-0208-8.

Chéry, L. (2006) *Guide technique : Qualité naturelle des eaux souterraines: Méthode de caractérisation des états de référence des aquifères français [Technical guide: Natural quality of groundwater: Method for characterizing reference states of French aquifers]*. Orléans : Bureau de Recherches Géologiques et Minières (BRGM). Available at: https://side.developpement-durable.gouv.fr/Default/doc/SYRACUSE/84538/guide-technique-qualite-naturelle-des-eaux-souterraines-methode-de-caracterisation-des-etats-de-refe?_lg=fr-FR (Accessed: March 10, 2025).

Conrad, G. (1969) *L'évolution continentale post-hercynienne du Sahara algérien (Saoura, Erg Chech-Tanezrouft, Ahnet-Mouydir) [Post-Hercynian continental evolution of the Algerian Sahara (Saoura, Erg Chech-Tanezrouft, Ahnet-Mouydir)]*. Paris: Éditions du Centre National de la Recherche Scientifique (CNRS).

Dècret (2011) "Dècret exècutif n° 11-125 du 17 Rabie Ethani 1432 correspondant au 22 mars 2011 relatif à la qualitè de l'eau de consommation humaine [*Executive Decree No. 11-125 of 17 Rabie Ethani 1432 corresponding to 22 March 2011 on the quality of water intended for human consumption*]," *Journal Officiel De La Republique Algerienne*, 18, pp. 6–24. Available at: https://cntpp.dz/wp-content/uploads/2023/11/decret-11-125.pdf (Accessed: March 10, 2025).

Derdour, A. *et al.* (2023) "Groundwater quality assessment for sustainable human consumption in arid areas based on GIS and water quality index in the watershed of Ain Sefra (SW of Algeria)," *Environmental Earth Sciences*, 82(21), 510. Available at: https://doi.org/10.1007/s12665-023-11183-9.

Dey, S. *et al.* (2024) "Removal of chlorides and hardness from contaminated water by using various biosorbents: A comprehensive review," *Water-Energy Nexus*, 7, pp. 39–76. Available at: https://doi.org/10.1016/j.wen.2024.01.003.

Dimple *et al.* (2022) "Groundwater quality parameters for irrigation utilization," *The Indian Journal of Agricultural Sciences*, 92(7), pp. 803–810. Available at: https://doi.org/10.56093/ijas.v92i7.114186.

Doneen, L.D. (1962) "*The influence of crop and soil on percolating water," Proceedings of the 1961 Biennial Conference on Groundwater Recharge*, pp. 156–163.

Durand, J.B. and Zimmer, B.J. (1982) *Pinelands surface water quality. Part I.* New Brunswick, New Jersey: Center for Coastal and Environmental Studies, Rutgers University.

Eaton, F.M. (1950) "Significance of carbonates in irrigation waters," *Soil Science*, 69, 2, pp. 123–134. Available at: https://journals.lww.com/soilsci/citation/1950/02000/significance_of_carbonates_in_irrigation_waters.4.aspx (Accessed: March 10, 2025).

Edmunds, W.M. *et al.* (2003) "Groundwater evolution in the Continental Intercalaire aquifer of Southern Algeria and Tunisia: Trace element and isotopic indicators," *Applied Geochemistry,* 18(6), pp. 805–822. Available at: https://doi.org/10.1016/S0883-2927(02)00189-0.

Elsayed, S. *et al.* (2020) "Application of irrigation water quality indices and multivariate statistical techniques for surface water quality assessments in the Northern Nile Delta, Egypt," *Water,* 12(12), 3300. Available at: https://doi.org/10.3390/w12123300.

Fabre, J. (2005) *Géologie du Sahara occidental et central [Geology of the Western and Central Sahara]*. Tervuren: Musée royal de l'Afrique centrale.

Ferchichi, I. *et al.* (2024) "La visualisation spatiale: un outil de dialogue sur la gestion des eaux souterraines dans les palmeraies de Kébili, Tunisie [Spatial visualization: A tool for dialogue on groundwater management in the oases of Kébili, Tunisia]," *Cahiers Agricultures*, 33, 24. Available at: https://doi.org/10.1051/cagri/2024021.

Guo, H. *et al.* (2021) "Evaluation of groundwater suitability for irrigation and drinking purposes in an agricultural region of the North China Plain," *Water*, 13(23), 3426. Available at: https://doi.org/10.3390/w13233426.

Haritash, A.K. *et al.* (2008) "Suitability assessment of groundwater for drinking, irrigation and industrial use in some North Indian villages," *Environmental Monitoring and Assessment*, 145, pp. 397–406. Available at: https://doi.org/10.1007/s10661-007-0048-x.

Hirche, A. *et al.* (2011) "Landscape changes of desertification in arid areas: The case of south-west Algeria," *Environmental Monitoring and Assessment*, 179, pp. 403–420. Available at: https://doi.org/10.1007/s10661-010-1744-5.

Kachi, N., Kachi, S. and Bousnoubra, H. (2016) "Effects of irrigated agriculture on water and soil quality (case perimeter Guelma, Algeria)," *Soil and Water Research*, 11(2), pp. 97–104. Available at: https://doi.org/10.17221/81/2015-SWR.

Kelly, W.P. (1940) "Permissible composition and concentration of irrigated waters," *Proceedings of the American Society of Civil Engineers*, 66, pp. 607–613. Available at: https://doi.org/10.1061/TACEAT.0005384.

Kendouci, M.A. *et al.* (2016) "Physicochemical quality of groundwater and pollution risk in arid areas: The case of Algerian Sahara," *Arabian Journal of Geosciences*, 9, 146. Available at: https://doi.org/10.1007/s12517-015-2221-9.

Mebarki, S., Kendouci, M.A. and Bendida, A. (2024) "Monitoring the spatial evolution of groundwater quality during its diversion in the drinking water supply network in arid areas, case of Bechar city (Algeria Sahara)," *Applied Water Science*, 14, 118. Available at: https://doi.org/10.1007/s13201-024-02157-8.

Medjani, F. *et al.* (2023) "Effect of a hyperarid climate on groundwater salinity: A case study of the Ouargla shallow aquifer (Northern Sahara, Algeria)," *Archives of Environmental Protection*, 29(4), pp. 70–79. Available at: https://doi.org/10.24425/aep.2023.148686.

Megahed, H.A. *et al.* (2023) "Groundwater quality assessment using multi-criteria GIS modeling in drylands: A case study at El-Farafra Oasis, Egyptian Western Desert," *Water*, 15(7), 1376. Available at: https://doi.org/10.3390/w15071376.

Meireles, A.C.M. *et al.* (2010) "A new proposal of the classification of irrigation water," *Revista Ciência Agronômica,* 41, pp. 349–357. Available at: https://doi.org/10.1590/S1806-66902010000300005.

OSS (2003) *The North-Western Sahara Aquifer System (Algeria, Tunisia, Libya): Joint management of a transboundary basin.* Tunis: Observatoire du Sahara et du Sahel. Available at: https://www.oss-online.org/en/releases/OSS-SASS-CSn1_En (Accessed: March 10, 2025).

Paliwal, K.V. (1972) *Irrigation with saline water*. New Delhi: Water Technology Centre, Indian Agricultural Research Institute.

Prăvălie, R. (2016) "Drylands extent and environmental issues. A global approach," *Earth-Science Reviews*, 161, pp. 259–278. Available at: https://doi.org/10.1016/j.earscirev.2016.08.003.

Ravikumar, P., Somashekar, R.K. and Angami, M. (2011) "Hydrochemistry and evaluation of groundwater suitability for irrigation and drinking purposes in the Markandeya River Basin, Belgaum District, Karnataka State, India," *Environmental Monitoring and Assessment*, 173, pp. 459–487. Available at: https://doi.org/10.1007/s10661-010-1399-2.

Richards, L.A. (ed.) (1954) *Diagnosis and improvement of saline and alkali soils*. Washington, D.C.: U.S. Government Printing Office. Available at: https://www.ars.usda.gov/ARSUserFiles/20360500/hb60_pdf/hb60complete.pdf (Accessed: March 10, 2025).

Rodier, J. (1996) *The analysis of water: natural water, wastewater, sea water*. 8th edn. Paris: Dunod.

Saghebian, S.M. *et al.* (2014) "Ground water quality classification by decision tree method in Ardebil Region, Iran," *Arabian Journal of Geosciences*, 7(11), pp. 4767–4777. Available at: https://doi.org/10.1007/s12517-013-1042-y.

Sekkoum, K. *et al.* (2012) "Water in Algerian Sahara: Environmental and health impact," in R.Y. Ning (ed.) *Advancing desalination*. IntechOpen, pp. 197–216. Available at: https://doi.org/10.5772/50319.

Smith, W.K. *et al.* (2019) "Remote sensing of dry land ecosystem structure and function: Progress, challenges, and opportunities," *Remote Sensing of Environment*, 233, 111401. Available at: https://doi.org/10.1016/j.rse.2019.111401.

Subbarao, M. and Reddy, M.R.B. (2018) "Groundwater quality assessment in Srikalahasthi Mandal, Chittoor District, Andhra Pradesh, South India," *IOSR Journal of Engineering*, 8, pp. 33–42. Available at: https://www.researchgate.net/publication/331247612.

Subramani, T., Rajmohan, N. and Elango, L. (2010) "Groundwater geochemistry and identification of hydrogeochemical processes in a hard rock region, Southern India," *Environmental Monitoring and Assessment*, 162, pp. 123–137. Available at: https://doi.org/10.1007/s10661-009-0781-4.

Todd, D.K. (1980) *Groundwater hydrology*. 2nd edn. New York: Wiley.

Touafek, A., Tidjani, A.E.B. and Bendida, A. (2025) "Improving the efficiency of aerobic biological treatment of domestic wastewater by using fixed culture media," *Ecological Engineering and Environmental Technology*, 26(9), pp. 23–35. Available at: https://doi.org/10.12912/27197050/208692.

Touitou, M. and Al-Amin, A.Q. (2018) "Climate change and water resources in Algeria: Vulnerability, impact and adaptation strategy," *Economic and Environmental Studies*, 18(1), pp. 415–429. Available at: https://doi.org/10.25167/ees.2018.45.23.

Travi, Y. (2021) "Les ressources en eau profonde du désert du Sahara et de ses confins arides et semi-arides [Deep groundwater resources of the Sahara Desert and its arid and semi-arid margins," *Les dossiers thématiques du CSFD*, 14. Available at: https://www.csf-desertification.org/dossier-csfd/ressources-en-eau-profonde-du-desert-du-sahara-et-de-ses-confins-arides-et-semi-arides/ (Accessed: March 10, 2025).

Varliero, S. *et al.* (2024) "Assessing the limit of CO_2 storage in seawater as bicarbonate-enriched solutions," *Molecules*, 29(17), 4069. Available at: https://doi.org/10.3390/molecules29174069.

WHO (2008) *Guidelines for drinking water quality. Vol. 1. Recommendations*. 3rd edn. incorporating the first and second addenda. Geneva: World Health Organization. Available at: https://iris.who.int/bitstream/handle/10665/204411/9789241547611_eng.pdf?sequence=1 (Accessed: March 10, 2025).

WHO (2011) *Guidelines for drinking water quality*. 4th edn. incorporating the first addendum. Geneva: World Health Organization. Available at: https://iris.who.int/bitstream/handle/10665/254637/9789241549950-eng.pdf?sequence=1 (Accessed: March 10, 2025).

Wilcox, L. (1955) "Classification and use of irrigation waters," *Circular*, 969. Washington, DC.: USDA. Available at: https://ia803201.us.archive.org/10/items/classificationus969wilc/classificationus969-wilc.pdf (Accessed: March 10, 2025).

Zaman, M., Shahid, S.A. and Heng, L. (2018) *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques*. Cham: Springer International Publishing. Available at: https://doi.org/10.1007/978-3-319-96190-3.