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Assessment of the Quality of Surface Water from El-Outaya Dam (Fountain of gazelles) for Irrigation at the Bioresource Station of the CRSTRA, El-Outaya Plain, Biskra, Algeria

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Abstract: This work was carried out in an arid zone, plain of El-Outaya (North of Biskra,). A part of this plain is irrigated by the dam Manbaâ El Ghozelan, marked interannual variations in electrical conductivity (EC), mainly influenced by climatic conditions. During the monitoring period, the EC at 25 °C ranged from 1.52 to 4.65 dS m⁻¹, indicating a high to very high salinity hazard for irrigation (C3S1–C4S1) associated with a low sodicity hazard. The increase in salinity is primarily related to elevated concentrations of sodium (Na⁺) and other dissolved salts. The hydrochemical facies evolved from calcium–magnesium chloride to sodium chloride and sodium–calcium sulfate types, reflecting temporal variations in the ionic composition of water. In this study, water supplied from the Fountain of Gazelles Dam to El Outaya Plain, was sampled and analyzed to evaluate its suitability for irrigation. Although the dam represents an important source of surface water for agricultural activities, its quantity remains insufficient to meet irrigation demands because of the irregular rainfall. Consequently, efficient management of the available water resources is essential to ensure the sustainability of irrigated agriculture. Geochemical analysis is carried out to know the type of minerals in water solution by studding the saturation Index SI, the negative SI values confirm that the geochemical environment is actively favoring mineral dissolution, which is the primary driver of the observed increasing salinity. We can use this water, absolutely with caution, for irrigation's El-Outaya plain but it was always insufficient guiding the decision maker to explore the groundwater using boreholes as an alternative solution.

Keywords: Water Quality; geochemical facies; Bioresource El- Outaya station; arid zone

1. Introduction

Deserts, in the broad sense, cover approximately one-third of the Earth's land surface. Arid and semi-arid regions are characterized by a persistent water deficit, where rainfall is scarce, irregular, and poorly distributed in both time and space. This chronic water

shortage, combined with high potential evapotranspiration (ETP), makes irrigation indispensable for agricultural production. However, irrigation in these regions is frequently based on the use of brackish or moderately saline water because of limited freshwater resources. Consequently, irrigated lands are increasingly exposed to the risk of secondary soil salinization, which threatens soil productivity and agricultural sustainability. Despite these constraints, irrigation remains essential for maintaining crop production and contributes significantly to food security in arid environments.

We know that the high concentration of the soil solution in soluble salts induces an increase in its osmotic pressure which limits the absorption of water by plants. [1]. This phenomenon of soil salinization affects more than a hundred countries where man and salt have survived together since ancient civilizations, especially in arid and poor regions. [2]. Therefore the study of water quality used in irrigation is necessary to avoid all obstacles because, today, the Global food security ask the farmer to produce more and better. The importance of dam water in arid area and their quality is different from source to another one. During the rainy season, water coming From upstream can be stored inside dams, than we can used it to irrigated the soils in question.

The Outaya region is located in the arid bioclimatic zone and receives an average annual rainfall of approximately 108 mm [3]. Irrigation water is supplied from two main sources : groundwater and surface water. Part of the agricultural land is irrigated with water from the Manbaâ El Ghazelan (Fountain of Gazelles) dam, which has a storage capacity of 55 hm³ and regulates an annual volume of approximately 14 hm³ for irrigation purposes. The dam supplies irrigation water to the El Hazima irrigation scheme (800 ha) and to several adjacent irrigated areas covering an additional 280 ha [4]. Given the importance of this water resource for agricultural production in the region, regular assessment of its quality is essential to ensure its suitability for irrigation and to prevent soil degradation.

The large alluvial plain of El Outaya is one of the regions where saline soils are widely distributed and where the use of saline water for irrigation is frequent [5,6, 7,8]. Recent studies have shown that the primary origin of salinity is likely related to evaporitic deposits formed in the Mediterranean Basin during the Messinian Salinity Crisis [9]. Indeed, Triassic and Miocene evaporitic formations are widely represented in the El-Outaya sedimentary basin and constitute a potential source of dissolved salts that may influence the quality of surface and groundwater resources, as well as soil salinization processes [6].

To evaluate the suitability of dam water for irrigation, this study investigates the physicochemical quality of water supplied from the “Fountain of Gazelles” Dam over the monitoring period. The main objective is to characterize the hydrogeochemical properties of the irrigation water used in the El Outaya Plain, an arid agricultural region of southeastern Algeria. The central research question is whether the quality of this surface water is suitable for sustainable irrigation and what potential risks it may pose to soils and agricultural production. The hydrogeochemical characterization of water resources in arid regions is a key component of sustainable water and land management. It provides essential information for assessing the suitability of water for irrigation, preventing soil salinization and sodification, and supporting informed decision-making for agricultural

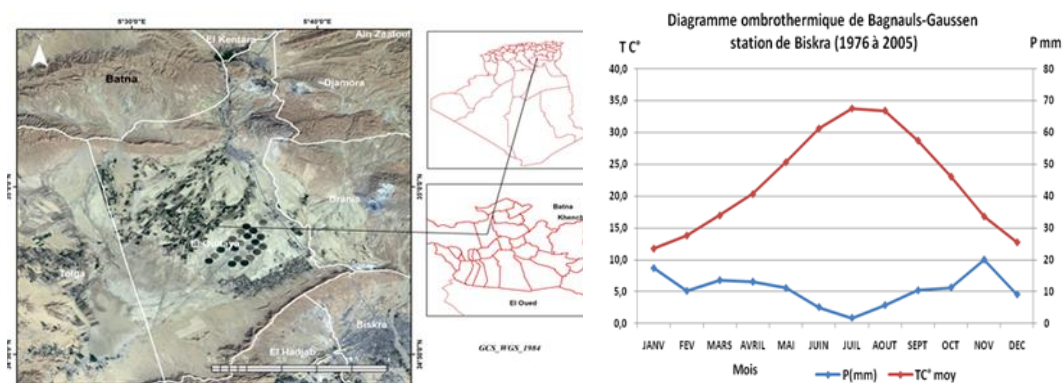
development. In regions where water scarcity is a major constraint, such assessments contribute to the sustainable use of available water resources and promote agricultural productivity while strengthening food security. Their importance is underscored by the global expansion of soil salinization, which is estimated to cause the loss of at least 3 hectares of arable land every minute [10]. This alarming trend highlights the need for regular monitoring of irrigation water quality and the implementation of appropriate management practices to preserve soil fertility and ensure the long-term sustainability of irrigated agriculture.

This work forms part of a sustainable management strategy for irrigated agroecosystems. By assessing the hydrogeochemical quality of irrigation water, it provides a basis for monitoring the long-term evolution of soil properties and evaluating the impact of irrigation on soil quality. Such an approach is essential for preventing land degradation, maintaining soil productivity, and promoting sustainable agricultural development in arid regions.

2. Materials and Methods

2.1. Study area

The El- Outaya area is located approximately 28 km north of the city of Biskra. It represents a transitional zone between the folded Atlas ranges to the north and the desert environments of the Saharan Platform to the south. The municipality of El Outaya covers an area of 406.10 km² and is bounded to the north by the municipalities of El Kantara and Bitam, to the east by Branis and Djemmorrah, to the west by Tolga, and to the south by the city of Biskra. The El-Outaya Plain covers a total area of approximately 33,000 ha, with a Utilized Agricultural Area (UAA/SAU) of 9,884 ha, of which 5,491 ha are irrigated. It forms a distinct geographical unit, consisting of an almost enclosed basin. The plain is bounded to the east by Oued Branis and Jebel Mohar, to the west by Jebel Rebaa, Ed Deba, and Ksoum, to the north by Jebel Mellah, Meddiane, and Magraoua, and to the south by



Jebel Oum Djenib, Gouara, and Amrousine [3,11, 12].

Figure 1. Geographical and Climatic Map of the El- Outaya Plain (Biskra, "Southeastern Algeria")

Indeed, the plain of El Outaya constitutes by very specific geographical position and by its great immensity, a great hydro-agricultural potential in the region. These natural resources offer great prospects for agricultural development in the wilaya of Biskra. However, these important resources obey natural laws, which it is important to know to ensure their rational and sustainable exploitation. According to climatic data from the

Biskra weather station, including the plain of El-Outaya is subject to a hot and dry climate, the region is characterized by scarce and irregular rainfall, with marked variability at both monthly and annual scales. The average annual precipitation was estimated at 145 mm for the period (1976–2005) and 157.07 mm for the period (1967–2012). The autumn and winter rains most often fall in the form of violent and short thunderstorms. Annual maximum and minimum temperatures are around 40 °C recorded in July and 6 °C in January. Evapotranspiration reaches 1898 mm / year according to Blaney-Criddle, with a very high water deficit of 1753 mm, which spreads practically throughout the year. Winds are generally moderate to strong, averaging 4.05 m/s. Cold winter winds are northeast and south, and southeast for warm summer winds. However, precipitation is always lower than potential or actual evapotranspiration (ETP or ETR) which leads to a deficit covering the whole year. This imbalance induces the need for significant irrigation for agriculture in these regions with the use of groundwater. However, we cannot ignore the presence of dam water of El-Outaya plain in which it irrigates the Mkinet perimeter. [3,12,11, [8].

The soils of the El Outaya Plain are predominantly associated with steppe rangelands characterized by degraded natural vegetation. According to the French soil classification system (CPSS, 1967), they are classified as raw mineral soils (2.7%), weakly developed soils (20%), and hydromorphic soils (64%) [5]. Cereal cultivation is widely practiced throughout the plain and constitutes one of the principal agricultural land uses.

More broadly, the Biskra region belongs to the Saharan bioclimatic zone, of which the El Outaya Plain forms part. According to the World Reference Base for Soil Resources (WRB) classification (IUSS Working Group WRB, 2014), the dominant soil groups in Biskra Province are Fluvisols (50.0%), followed by Calcisols and Gypsisols (37.8%), and Solonchaks (13.1%) [13,14]. These soil types reflect the combined influence of alluvial sedimentation, carbonate and gypsum accumulation, and salinization processes that are typical of arid environments.

2.2. Geological and Hydrogeological Context

The El Outaya Plain is a gently sloping glaciais located at the southern foothills of the Aurès Mountains, with elevations ranging from 180 to 250 m. This plain has functioned as a sedimentary basin throughout the Neogene period. In the lower parts of the basin, alluvial deposits become increasingly clayey and are frequently affected by salinity, ranging from saline to hypersaline conditions. The El Outaya basin is a well-developed Neogene basin, initially characterized by lagoonal-marine Miocene deposits (Bled Zemla, Branis, and El Outaya), followed by fluvial sandstones of Messinian–Pontian age and subsequently by Pliocene conglomerates (Ras Chicha). The upper stratigraphic formations, particularly those of the Pliocene, dip strongly toward the center of the basin, where they disappear beneath a considerable thickness of Quaternary sediments. Their uplift along the basin margins indicates that the area was affected by the most recent tectonic movements during the early Quaternary. The basin is characterized by its relatively small dimensions (approximately 30×70 km), its lozenge-shaped geometry bounded by faults with E–W, NW–SE, and NE–SW orientations, and its location within the Atlas domain. It forms a subsiding plain with a general ENE–WSW orientation, situated between two anticlines. The basin lies north of the Djebel Boughzel anticline (Biskra) and south of the

Djebel El Mellah dome, where Triassic formations outcrop at El- Outaya. Beneath this structure, the folded units of the Aurès Mountains are partially submerged [6].

The hydrographic network of the region is poorly developed and consists mainly of a principal watercourse, Oued Biskra, which belongs to the endorheic basin of Chott Melghir. This wadi receives several tributaries on its left bank, originating mainly from the Aurès Mountains and Djebel Mellah. Most of the hydrographic network remains dry throughout the year and is activated only during exceptional rainfall events [6, 23, 3, 15, 8]. The Mio-Pliocene aquifer system is the most exploited groundwater resource in the region. It is composed of several aquifer horizons with heterogeneous lithological characteristics, including detrital deposits, gravels, and sands embedded within a clayey matrix. With increasing depth, these formations become predominantly clayey and overlie an impermeable substratum composed of gypsum-bearing marls and Middle Eocene anhydrite. This aquifer extends over a large area, and numerous boreholes in the El Outaya Plain tap into this groundwater resource. Its thickness is limited in the foothill zones but gradually increases toward the central part of the plain. Groundwater recharge occurs mainly through exceptional rainfall events in the outcrop areas.

A major characteristic of the geological formations in the region is the abundance of evaporitic minerals, including limestone, gypsum, and soluble salts, which strongly influence the chemical composition of both surface water and groundwater [16].

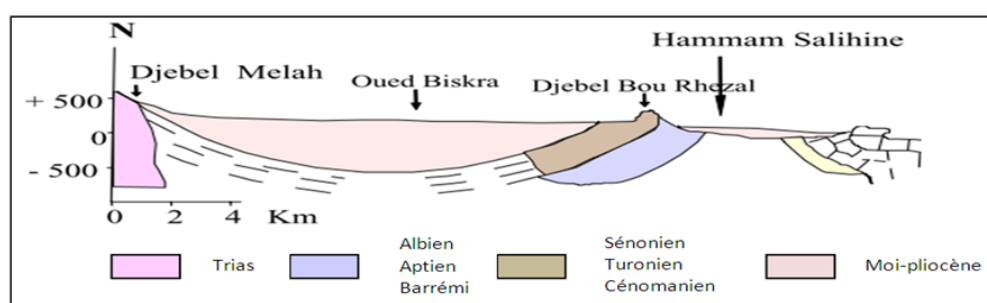


Figure 2. El- Outaya Salt diapir (Source [11]. based on ANRH hydrogeological maps, 1980).

2.3. Description of the CRSTRA Bioresource Experimental Station of El-Outaya

The Bioresource station covers an area of 20.4 ha. According to the salinity classification based on the electrical conductivity of the saturated paste extract (EC_e) at 25 °C (USSL, 1954), the soils range from saline to highly saline. They are characterized by several fine-textured horizons, predominantly silty-clay horizons, and are very to extremely calcareous, with a total limestone content of approximately 45%. The soils contain low levels of organic matter (2.3–2.4%), exhibit a slightly to moderately alkaline pH (7.2–8.6), and contain little or no gypsum. The dominant salinity facies is calcium–magnesium chloride–sulfate. The station is supplied with irrigation water from two sources: surface water from the Manbaâ El Ghozlan (Fountain of Gazelles) Dam and groundwater from the Mio-Pliocene aquifer. The main crops cultivated at the station include date palm (*Phoenix dactylifera* L.), olive (*Olea europaea* L.), fig (*Ficus carica* L.), greenhouse vegetable crops, as well as fruit tree and ornamental plant nurseries [12,17].

2.4. The irrigation

The advisability of the plain of El-Outaya is fed by a two source: The plain has a dam (Fountain of Gazelles), built in 2000 with a capacity of 55 Hm³. The water from the dam is

intended for the irrigation of the El Hazima perimeter (800 ha) and some taps totaling 280 ha, [4,18], and that of underground water represented by the Mio-Pliocene aquifer. Given the vastness of the 33,000 ha plain, the dam remains insufficient, which forces farmers to exploit the groundwater.

Surface water from Outaya Dam was collected from the storage basin supplying irrigation water to the Bioresource station of El- Outaya (CRSTRA Research Center). The available analytical data, obtained through random monitoring campaigns conducted over an 18-year period (2008–2025), were used to evaluate temporal variations in irrigation water quality.

As background information, a previous study by [19] evaluate the quality of water from Outaya Dam for irrigating barley and compared its performance with that of groundwater obtained from boreholes. The present study extends this work by providing a long-term assessment of the physicochemical quality of the dam water used for irrigation at the Bioresource Station.

The physicochemical parameters analyzed are the electrical conductivity CE at 25 °C and the hydrogen potential pH. A conductimeter and a pH meter (model multi 3430 SET K) determined them. The calcium (Ca^{2+}) and magnesium (Mg^{2+}) cations were determined by volumetry in the presence of ethylenediamine tetraacetic acid (EDTA) and the sodium (Na^+), potassium (K^+) cations by flame spectrophotometer SHERWOD. Chlorides (Cl^-) by the Mohr method (precipitation by silver nitrate in the presence of chromates), sulfates (SO_4^{2-}) by spectrophotometry UV-VIS DR 5000 precipitation with barium chloride and carbonates / bicarbonates $\text{CO}_3^{2-} / \text{HCO}_3^-$ by titrimetry at sulfuric acid. [20]. All physicochemical analyses were carried out at the Central Laboratory of the Scientific and Technical Research Center on Arid Regions (CRSTRA). Geochemical calculations, including mineral saturation index (SI) determinations, was performed using the PHREEQC geochemical modeling software (Interactive version 3.1.4-8929 [21]. Hydrochemical diagrams, including the US Salinity Laboratory (Riverside) diagram and the Piper diagram, were generated using DIAGRAMMES software [22].

3. Results

3.1. Assessment of surface water: dam "Manbaâ El Ghozlan/ Fountain of Gazelles"

This study focuses on assessing the quality of dam water in order to provide relevant information to the local population and decision-makers for the sustainable management of the agroecosystem. The "Fountain of Gazelles" Dam (Manbaâ El Ghozlan), located Northwest of the El-Outaya Plain, was constructed on Oued El Hai. Its watershed extends along a northeast–southwest axis and is surrounded by low mountain ranges. The hydrographic network supplying the dam is mainly composed of Oued Biskra to the east, which is fed by occasional heavy rainfall events, particularly during autumn and spring in the form of thunderstorms, as well as tributaries originating from the Aurès Mountains. To the west, Oued Selsou contributes a flow of endorheic character [23]. The dam has a storage capacity of 55 hm³ and became technically operational in May 2000. Its use for irrigating the El Outaya Plain began after 2004 following the completion of water transfer infrastructure to the plain. According to ONID (National Office of Irrigation and Drainage of Biskra, 2014), the dam regulates an annual volume of approximately 14 hm³, initially intended to irrigate 842 ha within the Mkinet perimeter, where the Bioresource station is

located, in the southern part of the plain at the foot of Jebel Boughezel. The regulated water volume is also used to irrigate other agricultural areas, including the Maghraoua area (58 ha), the Driss Amor farm (5 ha), and the Smala palm grove (7 ha).

According to the data collected during the period 2008–2025 (Table 1), the electrical conductivity (EC) of the dam water exhibits interannual variations influenced by climatic conditions. The irrigation water presents low to very high salinity hazards and low to high sodicity hazards, corresponding to the C3S1, C4S1, and C4S3 classes. These variations are mainly associated with changes in the concentration of sodium (Na^+) ions, which contribute to the alkalinity hazard of irrigation water (Fig. 3).

The electrical conductivity (EC) of the dam water at 25 °C ranges from 1.00 to 4.65 dS m^{-1} , indicating highly saline water with respect to soil salinity classification, while its effect on plants varies from slight to moderate salinity hazard. The highest EC values exceeded the threshold of 3 dS m^{-1} , recommended by [24] during two years of monitoring 2010 and 2015. During this two date, electrical conductivity and the concentrations of Ca^{2+} , Na^+ , and SO_4^{2-} increased markedly. The simultaneous increase of these ions suggests that evaporation acted in combination with the continuous dissolution of carbonate minerals (calcite and dolomite) and evaporite minerals (gypsum and halite), as demonstrated by the PHREEQC geochemical simulations (Table 3). The negative saturation index values ($\text{SI} < 0$) indicate that the reservoir water remained undersaturated with respect to these mineral phases, thereby favoring their continuous dissolution and contributing to the progressive enrichment of dissolved salts.

The pH value, an important indicator of the chemical evolution of water, remained alkaline throughout the study period, ranging from 7.56 to 8.08. Similar alkaline characteristics have been reported in other studies conducted by the same authors in arid environments, including the Sidi Okba oasis [25], the Oumache oasis [26], and the Bordj Ben Azouz oasis [27]. However, despite its importance as an irrigation resource, the quantity of water supplied by the dam remains insufficient to fully meet agricultural water requirements.

Table 1 : Temporal evolution of the ionic composition and balance of irrigation water from the “Fountain of Gazelles” (Manbaâ Ghozlane) Dam, El- Outaya, Biskra, southeastern Algeria.

année	CE dS/m à 25°C	pH	Cations (meq/l)				Anions (meq/l)			SAR	Classe USSL
			Ca^{++}	Mg^{++}	Na^+	K^+	Cl^-	SO_4^{--}	HCO_3^-		
2008	2.5	7.6	10.3	24.5	9.78	0.26	20.3	12.3	6.7	2.34	C4S1
2010	3.5	7.65	7.62	4.05	8	0.13	20	10.6	11	3.32	C4S1
2015	4.65	7.92	15.23	7.49	21.89	0.22	7.5	17.14	3.52	7.89	C4S1
2019	1.52	8.08	7.34	4.72	5.1	0.24	8.4	3.68	2.8	4.50	C3S1
2020	1.55	7.83	7.2	6.4	9.94	0.28	5.2	5.56	2.52	3.92	C3S1
2024	1.003	7,56	4.8	2.4	3.35	0.18	4.4	5.36	1.84	1.86	C3S1
2025	1,36	7,9	7	3	6,94	0,36	5,6	4,46	2,32	3,26	C3S1

The anionic distribution of the dam water varies over time. Chloride (Cl^-) is the dominant anion, followed by sulfate (SO_4^{2-}) and bicarbonate (HCO_3^-), during the years 2008, 2010, and 2019 ($\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$). In contrast, sulfate becomes the dominant anion during 2015, 2020, 2024, and 2025 ($\text{SO}_4^{2-} > \text{Cl}^- > \text{HCO}_3^-$). The cationic composition is generally dominated by sodium (Na^+), followed by magnesium (Mg^{2+}) and calcium (Ca^{2+}) ($\text{Na}^+ > \text{Mg}^{2+} > \text{Ca}^{2+}$), although some variations occur between Na^+ and Ca^{2+} dominance depending on the sampling period. This hydrochemical evolution reflects the influence of evaporitic formations, particularly Triassic deposits of Djebel El Mellah, which occupy an important position in the geological structure of the El Outaya Plain. The dissolution of evaporitic minerals contributes significantly to the enrichment of irrigation water in chloride, sulfate, sodium, and calcium ions.

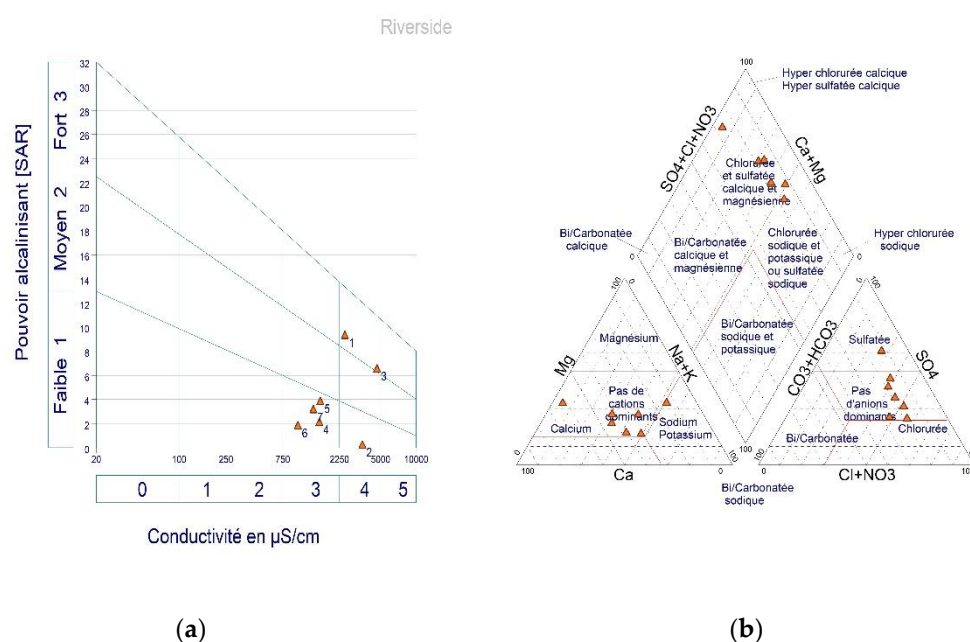


Figure 3. a) Riverside diagram of the irrigation water, **b)** Piper diagram of the evolution of the chemical facies of the dam water “Fountain of Gazelles” according to the Diagram Manual [22] .

The temporal variability of the chemical facies of the “Fountain of Gazelles” Dam water, as shown in Table 2 and the Piper diagram, reflects a transition between chloride–sulfate and sulfate–chloride facies, mainly resulting from changes in the relative dominance of chloride (Cl^-) and sulfate (SO_4^{2-}) anions. The presence of sulfate is mainly attributed to the dissolution of evaporitic formations of Neogene age within the watershed. Overall, these waters belong to the oligohaline chloride class, with rCl^- values ranging approximately between 15 and 40 meq L^{-1} (corresponding to chloride concentrations between 7 and 20 meq L^{-1} according to the adopted classification). [28, 8].

The surface waters stored in this dam appear to be less mineralized than the groundwater of the Neogene aquifer and show salinity levels close to the lowest values recorded for the regional groundwater system [7, 8].

Table 2. Evolution of the $\text{Cl}^-/\text{SO}_4^{2-}$ ratio and the type of salinization during the monitoring period (2008–2025) of El- Outaya Dam “Fountain of Gazelles” (Manbaâ Ghozlane) Dam, El- Outaya, Biskra, southeastern Algeria.

Dam water/year	Cl ⁻ /SO ₄ ²⁻ ratio	Type of salinization
2008	1,65	Chloride–sulfate salinization
2010	1,89	Chloride–sulfate salinization
2015	0,43	Sulfate–chloride salinization
2019	1,1	Chloride–sulfate salinization
2020	0,94	Sulfate–chloride salinization
2024	0,82	Sulfate–chloride salinization
2025	1,25	Chloride–sulfate salinization

3.2. Geochemistry and Mineral Saturation Index (SI) of the Water from the Fountain of Gazelles Dam

Table 3. Temporal evolution of mineral saturation indices (SI) in irrigation water from the “Fountain of Gazelles” (Manbaâ Ghozlane) Dam, El Outaya (Biskra, southeastern Algeria), during the 2008–2025 monitoring period.

Variables	2008	2010	2015	2019	2020	2024
IS halite	-7,66	-9,55	-8,32	-8,89	-8,81	-9,95
IS gypsum	-3,21	-3,27	-2,82	-3,73	-3,57	-3,72
IS anhydrite	-3,43	-3,49	-3,04	-3,95	-3,79	-3,94
IS aragonite	-2,10	-1,91	-1,87	-2,09	-2,40	-2,95
IS calcite	-1,96	-1,76	-1,73	-1,95	-2,25	-2,81
IS dolomite	-3,19	-3,45	-3,41	-3,74	-4,21	-5,57

Thermodynamic models, such as PHREEQC, are widely used to simulate mineral–water interactions, aqueous speciation, and geochemical processes in natural aquatic systems. These models allow the evaluation of mineral stability and the prediction of dissolution and precipitation processes through the calculation of the saturation index (SI). The saturation index is defined as the logarithm of the ratio between the ion activity product (IAP) of a mineral and its thermodynamic solubility product (K_{sp}): $SI = \log(IAP/K_{sp})$. Thus, $SI < 0$ indicates undersaturation, meaning that the aqueous solution is capable of dissolving the mineral phase ; $SI = 0$ indicates thermodynamic equilibrium between the mineral and the aqueous solution ; and $SI > 0$ indicates supersaturation, suggesting that mineral precipitation may occur [29,21, 30].

The PHREEQC simulation of the natural evaporation of water from the El -Outaya Dam (Fountain of Gazelles) indicates that the calculated saturation indices (SI) of the investigated mineral phases remain negative throughout the monitoring period (2008–2025). This persistent undersaturation demonstrates that the dam water has not reached thermodynamic equilibrium with respect to the major evaporite (gypsum and halite) and carbonate (calcite and dolomite) minerals. Consequently, mineral dissolution rather than

precipitation represents the dominant geochemical process controlling the chemical composition of the reservoir water.

This behavior is consistent with the geological framework of the El Outaya basin, which is strongly influenced by Triassic evaporitic formations cropping out in the Djebel El Mellah area. These formations contain abundant gypsum and halite that are readily dissolved during water–rock interactions, providing significant inputs of calcium, sulfate, sodium, and chloride ions to the surface water. Carbonate formations surrounding the basin also contribute calcium, magnesium, and bicarbonate through the dissolution of calcite and dolomite. The continuous supply of these dissolved constituents explains the progressive increase in water mineralization observed during the monitoring period.

Although the study area is characterized by an arid climate with intense evaporation and limited rainfall, the geochemical simulations indicate that evaporation alone was insufficient to produce supersaturation and subsequent precipitation of the investigated minerals. This suggests that the concentration of dissolved ions resulting from evaporation is continuously counterbalanced by the availability of undersaturated water capable of dissolving additional minerals from the surrounding geological formations. Therefore, the hydrochemical evolution of the dam water is controlled by the combined effects of evaporation and ongoing water–rock interactions rather than by evaporite precipitation.

The persistence of undersaturation also reflects the hydrological functioning of the reservoir. Seasonal inflows from upstream catchments introduce relatively dilute water that mixes with the stored water, maintaining the solution below equilibrium despite strong evaporative concentration. In addition, fluctuations in water level associated with wet and dry seasons continuously modify the physicochemical conditions of the reservoir, preventing the establishment of stable equilibrium with the surrounding mineral assemblages.

The predominance of mineral dissolution has important implications for water quality. The continuous release of Ca^{2+} , Mg^{2+} , Na^+ , Cl^- , SO_4^{2-} , and HCO_3^- increases electrical conductivity (EC), total dissolved solids (TDS), and total hardness, thereby reducing the suitability of the water for irrigation under prolonged use. Elevated salinity may promote secondary soil salinization in irrigated areas downstream of the reservoir, particularly under conditions of poor drainage and high evaporative demand, which are characteristic of the Biskra region.

From a hydrogeochemical perspective, the results suggest that the El- Outaya Dam represents an open geochemical system in which continuous water renewal and active water–rock interactions maintain undersaturated conditions. This interpretation is consistent with previous studies conducted in arid environments, which have shown that groundwater and surface water interacting with Triassic evaporitic formations generally evolve through progressive dissolution of gypsum, halite, calcite, and dolomite before reaching mineral saturation [31, 32, 29, 21]. Similar hydrochemical evolution has also been reported for aquifers and reservoirs in southeastern Algeria, where evaporite dissolution constitutes the principal source of dissolved salts [8, 28, 15, 12, 26].

Overall, the PHREEQC simulations demonstrate that mineral dissolution is the principal geochemical mechanism controlling the hydrochemical evolution of the El

Outaya Dam water. The combined effects of intense evaporation, continuous interaction with Triassic evaporitic formations, and seasonal hydrological renewal explain the persistence of undersaturated conditions and the progressive increase in salinity observed during the study period. These findings highlight the need for continuous hydrochemical monitoring of the reservoir to better assess the long-term impacts of salinity on irrigation water quality and the sustainability of agricultural production in the El Outaya–Biskra region.

4. Conclusions

The Fountain of Gazelles Dam represents a major hydraulic infrastructure in the arid region of El Outaya, southeastern Algeria. It was constructed to meet the increasing demand for irrigation water and plays a crucial role in sustaining agricultural production in this water-scarce environment. Assessing the quality of its irrigation water is therefore essential for preventing soil degradation and ensuring the sustainable management of irrigated agroecosystems.

The hydrogeochemical characterization of the dam water over the monitoring period (2008–2025) revealed temporal variations in its chemical composition, with hydrochemical facies evolving between chloride–sulfate and sulfate–chloride types. According to the US Salinity Laboratory classification, the irrigation water belongs mainly to the C3S1, C4S1, and occasionally C4S3 classes, indicating high to very high salinity hazards associated with low to moderate sodicity hazards. Electrical conductivity varied considerably according to climatic conditions, reflecting the influence of evaporation and the dissolution of evaporitic geological formations within the watershed.

Geochemical modeling using PHREEQC showed that the water remained undersaturated with respect to the principal evaporitic and carbonate minerals, indicating a continued tendency for mineral dissolution. This behavior is consistent with the geological setting of the El Outaya basin, where Triassic and Miocene evaporitic formations constitute an important source of dissolved salts that contribute to the mineralization of both surface water and groundwater.

Although the dam provides an essential source of irrigation water, its relatively high salinity represents a potential threat to soil quality. Under the arid climatic conditions of the El -Outaya Plain, characterized by high evapotranspiration, limited rainfall, endorheic drainage, and predominantly fine-textured soils, the long-term use of saline irrigation water may promote secondary soil salinization and, in some cases, sodification if appropriate management practices are not implemented.

Consequently, continuous monitoring of irrigation water quality, together with regular assessment of soil salinity and the implementation of appropriate drainage and irrigation management strategies, is essential to preserve soil fertility, maintain agricultural productivity, and ensure the long-term sustainability of irrigated agriculture in the El Outaya Plain.

Such an integrated approach is particularly important in the context of climate change, increasing water scarcity, and the growing need to optimize the use of non-conventional water resources in arid and semi-arid regions.

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