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Hydro chemical Characteristics and Portability of Consumer Water Sources in Arid Regions: A Case Study of Biskra (South-East of Algeria).

الخصائص الهيدروكيميائية وصلاحية مصادر مياه المستهلك للشرب في المناطق الجافة: دراسة حالة لولاية بسكرة (جنوب شرق الجزائر) .

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Abstract:

This study evaluates the hydro chemical properties of eleven water samples in Biskra region. The sources studied included six tap water samples from different urban neighborhoods, three groundwater samples distributed by tanker trucks, and two samples (raw and treated water) from the Bouchegroun desalination plant. The physicochemical properties were systematically analyzed. Statistical evaluation was performed using SPSS software, applying one-way ANOVA to identify statistically significant differences ($p<0.05$) in the mean physicochemical values between the water sources and different areas, followed by Tukey's HSD test to identify homogeneous subgroups. All experimental results were rigorously compared with national standards and WHO guidelines. Nitrate concentrations in all samples were found to be acceptable, being less than 50 mg/L. The water quality index classification results showed that the tap water was of poor quality, containing high levels of salinity, electrical conductivity, chloride, and sulfate, significantly exceeding the limits permitted in Algeria and by the WHO. This indicates the need for water treatment before use for human consumption. In contrast, groundwater samples transported by tankers showed mineralization that met standards and were classified as potable. Furthermore, the reverse osmosis membrane technology used at the Bouchegroun desalination plant demonstrated outstanding performance, achieving an overall ion rejection and treatment

ISSN: 3078 – 2767 Online

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efficiency of 90%. This underscores the high reliability of reverse osmosis technology in reducing salinity and successfully converting brackish groundwater into high-quality freshwater suitable for drinking under arid climatic constraints. This study will assist decision-makers in the region to make informed decisions regarding tap water treatment for human consumption.

Keywords: Groundwater quality, Potability, Reverse Osmosis, One-way ANOVA, Algerian standards, WHO guidelines.

المستخلص:

تقيّم هذه الدراسة الخصائص الهيدروكيميائية لإحدى عشرة عينة مياه في منطقة بسكرة. تشمل المصادر المدروسة ست عينات من مياه الصنبور من أحياء حضرية مختلفة، وثلاث عينات من المياه الجوفية وُزعت بواسطة شاحنات صهريجيه، وعينتين (مياه خام ومياه معالجة) من محطة بوشغرون لتحلية المياه. وتم تحليل الخصائص الفيزيائية والكيميائية بشكل منهجي. أُجري التقييم الإحصائي باستخدام برنامج SPSS، بتطبيق تحليل التباين أحادي الاتجاه لتحديد الفروق ذات الدلالة الإحصائية ($p < 0.05$) في متوسط القيم الفيزيائية والكيميائية بين مصادر المياه والمناطق المختلفة، متبوعًا باختبار Tukey HSD لتحديد المجموعات الفرعية المتجانسة. تمت مقارنة جميع نتائج التجارب بدقة مع المعايير الوطنية وإرشادات منظمة الصحة العالمية. وتبين أن تركيزات النترات في جميع العينات كانت مقبولة، حيث كانت أقل من 50 مغ/لتر. وأظهرت نتائج تصنيف مؤشر جودة المياه أن مياه الصنبور كانت ذات جودة رديئة، إذ احتوت على مستويات عالية من الملوحة والتوصيل الكهربائي والكلوريد والكبريتات، متجاوزة بشكل ملحوظ الحدود المسموح بها في الجزائر ومن قِبل منظمة الصحة العالمية. في المقابل، أظهرت عينات المياه الجوفية المنقولة بواسطة صهاريج، تمعدنًا متوافقًا مع المعايير، وصُنفت على أنها صالحة للشرب. علاوة على ذلك، أظهرت تقنية أغشية التناضح

ISSN: 3078 – 2767 Online

العكسـي المسـتخدمة في محطة بوشـغرون لتحلية المياه أداءً متميزًا، حيـث حققـت كفـاءة إجمـاليـة في رفض الأيونـات ومعالجتها وصلت الى 90%. يؤكد هذا على الموثوقية العالية لتقنية التناضـــح العكســـي في تخفيف الملوحة وتحويل المياه الجوفية قليلة الملوحة بنجاح إلى مياه عذبة عالية الجودة صالحة للشرب في ظل قيود مناخية قاحلة، وبالتالي، ستساعد هذه الدراســـة صـــنـاع القرار في المنطقة على اتخاذ قرارات مستنيرة بشأن معالجة مياه الصنبور للاستهلاك البشري.

الكلمات المفتاحية: جودة المياه الجوفية، صـــلاحية الشـــرب، التناضـــح العكســـي، تحليل التباين أحادي الاتجاه، المعايير الجزائرية، إرشادات منظمة الصحة العالمية.

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1. Introduction

Water resources and their quality are crucial for urban and environmental development, particularly in areas suffering from severe water scarcity (Xiao *et al.,* 2019), where they play a pivotal role in various vital and structural activities (Fraktia *et al.,* 2021). In arid and semi-arid regions, groundwater and surface water are vital resources, providing essential supplies for agricultural irrigation and drinking water, thus supporting food and water security. In Algeria, freshwater is extremely scarce, especially in terms of quality, necessitating careful management to maintain the delicate natural balance. In sub-Saharan Africa, the use of groundwater for irrigation plays a key role in improving rural livelihoods by reducing poverty, enhancing food security, increasing agricultural productivity in terms of land and labor, creating rural employment opportunities, and supporting inclusive economic growth (Lekhares *et al.,* 2017). In southern Algeria, groundwater is heavily relied upon to meet the growing demand for human consumption, industry, and agriculture (Bouchmal and Achour, 2015). Population growth and ongoing development projects have increased water demand, leading to the depletion of groundwater reserves (Adimala *et al.,* 2019). In regions like Biskra, groundwater remains a vital resource for drinking water and irrigation. Consequently, groundwater quantity and quality have become critical considerations in recent years.

In Biskra, residents rely heavily on groundwater, which is stored in household cisterns due to the irregularity of municipal water supplies. However, this practice exposes the water to pollution and increased salinity, a problem exacerbated in recent years by drought, climate change, and overexploitation of groundwater (Hecini *et al.,* 2023). To address these challenges, households often resort to alternative sources such as commercially bottled water or water delivered by tankers. While bottled water is relatively expensive, tanker water is available at affordable prices but requires continuous daily monitoring of each tanker by the responsible authorities to prevent potential health risks to residents. Although numerous studies have addressed water quality in Algeria, a comprehensive comparative analysis of tap water, tank water, and treated water in the context of urban consumption in Biskra is lacking. Water resources and their quality are crucial for urban and environmental development, particularly

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

in areas suffering from severe water scarcity (Xiao *et al.,* 2019), where they play a pivotal role in various vital and structural activities (Fractia *et al.,* 2021). In arid and semi-arid regions, groundwater and surface water are vital resources, providing essential supplies for agricultural irrigation and drinking water, thus supporting food and water security. In Algeria, freshwater is extremely scarce, especially in terms of quality, necessitating careful management to maintain the delicate natural balance. In sub-Saharan Africa, the use of groundwater for irrigation plays a key role in improving rural livelihoods by reducing poverty, enhancing food security, increasing agricultural productivity in terms of land and labor, creating rural employment opportunities, and supporting inclusive economic growth (Lechares *et al.,* 2017). In southern Algeria, groundwater is heavily relied upon to meet the growing demand for human consumption, industry, and agriculture (Bouchmal and Achour, 2015). Population growth and ongoing development projects have increased water demand, leading to the depletion of groundwater reserves (Ademala *et al.,* 2019). In regions like Biskra, groundwater remains a vital resource for drinking water and irrigation. Consequently, groundwater quantity and quality have become critical considerations in recent years.

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2. Materials and Methods:

1.2. Study Area:

The study was conducted in the Biskra province, located in the northeastern part of the Algerian Sahara. Biskra lies approximately 480 km southeast of Algiers, covers an area of 127.55 km², and has a population of about 266,763 inhabitants. The region is characterized by an arid climate and significant agricultural activity, particularly date palm cultivation. Biskra serves as the administrative capital of the municipality, district, and province and is surrounded by the municipalities of El Hadjeb, Oumache, Sidi Okba, Chetma, Branis, and El Outaya (Figure 1).

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
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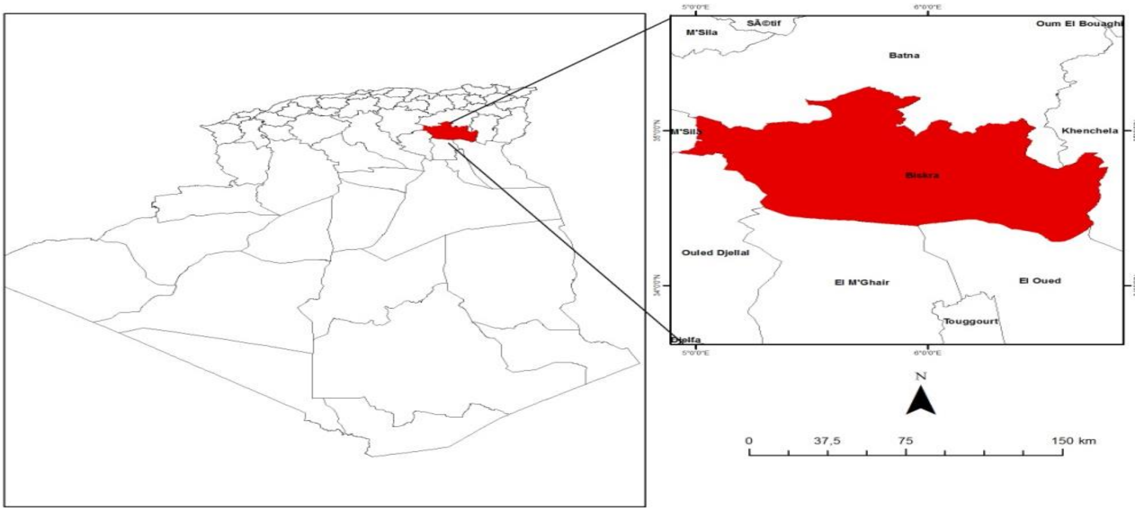

Figure 1: Study area location map

2.2. Hydrogeological and Hydrochemistry Framework:

The regional hydrogeological system in Biskra comprises three primary aquifer horizons as shown in the figure 2 (Kessasra *et al.,* 2023):

1. The Quaternary Alluvial Aquifer: A shallow, unconfined system associated with wadi beds and superficial alluvial deposits.
2. The Complex Terminal (CT) Aquifer System: A multi-layered, highly productive aquifer subdivided into a shallow Mio-Pliocene sandy-conglomeratic horizon and a deeper, highly productive Maastrichtian-Eocene carbonate reservoir.
3. The Continental Intercalary (CI) Aquifer: A deep, confined, and highly geothermal sandstone reservoir of regional scale.

Driven by aggressive agricultural expansion and rising municipal demands, these aquifers have undergone severe anthropogenic stress. Overexploitation is characterized by a high extraction rate, resulting in a cumulative hydraulic head decline of nearly 300% over the last four decades (Mebrek *et al.,* 2025). This intense draft has triggered rapid water-level drawdown, the expansion of localized piezometric depressions, and a progressive deterioration of water quality. From a hydrochemical perspective, the groundwater is heavily mineralized, dominated by Ca-SO4 and mixed Ca-Mg-Cl-SO4 hydrochemical facies (Kherifi *et al.,* 2026). The hydrochemical signature of the system is primarily driven by intense evaporation rates characteristic of the arid climate (Kessasra *et al.,* 2023), Water-rock interactions, specifically the dissolution of evaporitic minerals such as gypsum ($CaSO_4 . 2H_2O$) and halite (NaCl) hosted within the gypsiferous clay formations (Masmoudi *et al.,* 2024).

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

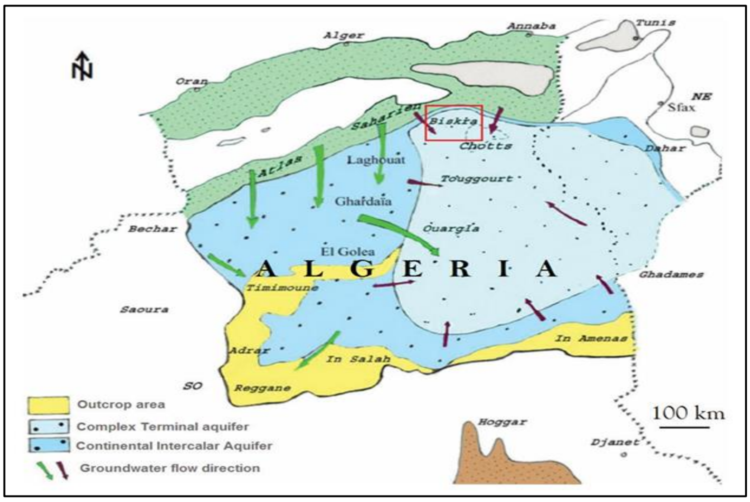

Figure (2): Hydrogeological map of the Complex Terminal and Continental Intercalary (UNESCO, 1972)

3.2. Sampling and Sample Collection:

A total of 11 water samples were collected during March 2023. These samples included six tap water samples collected from households in different neighborhoods (Ben Yakoub Lemssala, Sidi Berkate, Haret El Melh, Lebchacha, and Ben Taleb), three samples from mobile tanker trucks (Sidi Okba, Feiesh and Sidi Khelil), and two samples from the Bouchakroun drinking water desalination plant, taken before and after treatment.

Samples were collected in 0.5 L plastic bottles, previously rinsed three times with tap water, and filled without the addition of preservatives. All samples were transported to the laboratory for physicochemical analysis. All analyses were performed at the Water Quality Laboratory of the Scientific and Technical Research Center for Arid Regions (CRSTRA), Biskra, under controlled laboratory conditions.

4.2. Desalination Plant Description:

Water samples from the Bouchakroun drinking water desalination plant were collected to evaluate the efficiency of the treatment process. The plant operates using reverse osmosis technology and produces drinking water distributed via tanker trucks and packaged in 10 L and 15 L containers.

5.2. Analytical Methods:

Physicochemical analyses were carried out using standard methods for water quality assessment as described by Rodier (2016).

- Temperature, pH, electrical conductivity (EC), and salynity were measured using a multiparameter analyzer (Multi 3430 SET K).
- Total hardness (TH), corresponding to the sum of Ca^{2+} and Mg^{2+}, was determined by EDTA titration. A buffer solution (pH = 10) and Eriochrome Black T indicator were used, and the endpoint was indicated by a color change from wine red to green.
- Total alkalinity (TAC) which represents concentration of bicarbonates (HCO_3^-) was determined by titration of 10 mL of the water sample with 0.02 N sulfuric acid, using methyl orange as an indicator, until a brick-red endpoint was reached.

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

- Chloride ions (Cl^-) were quantified by titration with silver nitrate ($AgNO_3$) using potassium chromate (K_2CrO_4) as an indicator, following the Mohr method.
- Sulfate ions (SO_4^{2-}) were measured using the nephelometric method with a HACH DR 5000 spectrophotometer at a wavelength of 600 nm, based on the formation of barium sulfate.
- Nitrate ions (NO_3^-) were determined using UV spectrophotometry with a HACH DR 5000 spectrophotometer at a wavelength of 220 nm, according to the nephelometric method.

3. Results and Discussion:

1.3. Physicochemical Characteristics of Tap Water:

1.1.3. In situ Parameters:

The physical parameters of tap water samples collected from different neighborhoods in Biskra are presented in Table 1 and Figure 3.

Table (1): Results of in situ parameters analyses of the studied samples and their comparison with the Algerian standards (2011) and the World Health Organization (WHO, 2011)

Area / Parameters	Mean±SD			
	T°C	pH	EC(µS/cm)	Salinity (mg/L)
Ben Yakoub	22,5±0,50	7,55±0,40	4860±5,77	2394,09±2,84
M'esalah	22,9±0,00	7,2±0,09	6030±5,77	2970,44±2,84
Sidi Barket	22,8±0,1	7,09±0,02	6210±10,00	3064,04±4,93
El Maleh	22,8±0,06	7,33±0,05	7000±5,77	3448,28±2,84
Lebchache	22,3±0,15	7,78±0,02	6810±1,88	3354,68±0,92
Hai Ben Taleb	22,2±0,1	7,4±0,1	6590±2,89	3246,31±1,42
JORADP (2011)	25	6,5 - 8,5	2800	2000
WHO Standards (2011)	25	6,5 - 8,5	/	300-1500

EC: Electrical conductivity

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

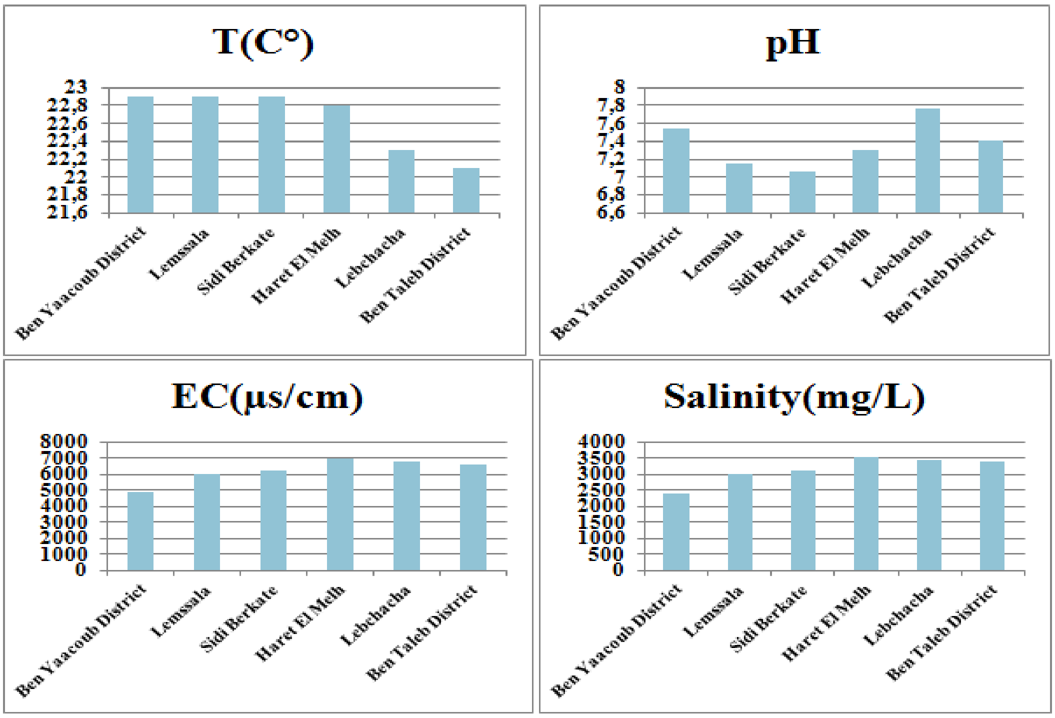

Figure (3): Evaluation of in situ parameters of the analyzed tap water samples

Water temperature ranged from 22.2 to 22.9 °C during March 2023. These values are consistent with groundwater temperatures in arid regions and are mainly controlled by aquifer depth and climatic conditions. Similar trends were reported in previous studies conducted in southern Algeria.

The pH values of almost all samples ranged from 7.09 to 7.78, indicating a predominantly low-alkaline groundwater type that is suitable for both drinking and irrigation uses.

Electrical conductivity (EC) values were exceptionally high, ranging from 4860 µS/cm in Ben Yaoub to 7000 µS/cm in Harret El Melh, largely exceeding national and international guidelines. The significant variation in EC reflects the influence of regional geochemical processes.

All water samples analyzed exceeded drinking water standards WHO. (2011), likely due to cumulative contamination from agricultural activities, sewage systems, and irrigation networks, resulting in increased groundwater salinity (Gabr *et al.*, 2021).

Total dissolved solids concentrations confirmed the excessive salinity of tap water, with values exceeding 3.5 g/L in some neighborhoods. These concentrations are approximately 2-3 times higher than the permissible limits for drinking water. The spatial variation in salinity indicates heterogeneous mineral dissolution within the aquifer system.

2.1.3. Physic-chemical Parameters:

1.2.1.3. Total Hardness, Calcium, Magnesium, and Bicarbonates:

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

Total hardness values in all tap water samples exceeded the Algerian standard range (10-50 °F), with a maximum of 133°F recorded in M'esalah. These results classify the waters as very hard, mainly due to elevated calcium and magnesium concentrations. Groundwater samples frequently exceed permissible limits for various contaminants, including salinity, hardness, and microbial agents, posing health risks (Aldroujee et al., 2025). Calcium concentrations slightly exceeded permissible limits in most neighborhoods, while magnesium concentrations remained within acceptable limits, except in M'esalah (184.8 mg/L). Cations analysis results are summarized in Table 2 and Figure 4**.**

Table (2): Results of the cations analyses of the studied samples and their comparison with the Algerian standards (2011) and the World Health Organization (WHO, 2011).

Area / Parameters	Mean±SD			
	TH(°F)	Ca^{+2}(mg/L)	Mg^{+2}(mg/L)	HCO_3^-(mg/L)
Ben Yakoub	73±3	184±10,07	60±11,84	369,66±33,11
M'esalah	133±2,52	228±6,11	184,80±6,35	366±0,00
Sidi Barket	125±1,53	252±10,07	146±9,09	256,2±25,40
El Maleh	115±4,36	252±4,00	124,80±12,70	305±14,09
Lebchache	110±5	220±8,00	132±16,8	305±24,40
Hai Ben Taleb	117±1,53	264±2,31	122,4±5,00	305±24,40
JORADP (2011)	10-50	75-200	150	/
WHO Standards (2011)	/	100 - 200	30-50	/

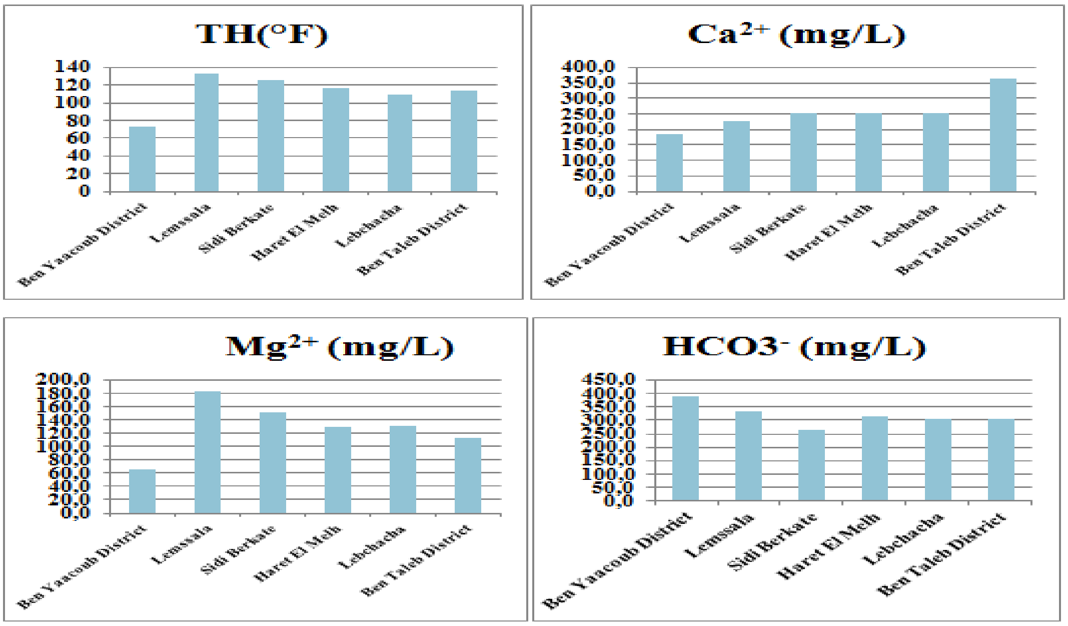

Figure (4): Evaluation of the chemical parameters (Cations) of the analyzed tap water samples

Calcium concentrations in all samples surpassed the maximum allowable limit for drinking water (75 mg/L) set by WHO. (2011). This excess is primarily governed by ion-exchange mechanisms and the dissolution of calcium-bearing minerals, such as calcite,

ISSN: 3078 – 2767 Online

dolomite, gypsum, and anhydrite. Soil water evaporation may further intensify mineral accumulation, increasing the potential for groundwater contamination (Earle, 2019).

Results indicate bicarbonate (HCO_3^-) concentration between (256 – 370 mg/L). The enrichment of bicarbonate in groundwater is mainly governed by geochemical processes such as atmospheric CO_2 dissolution, silicate mineral weathering, and the dissolution of carbonate rocks, particularly limestone and dolomite, which enhance HCO_3^- concentrations in the aquifer system (Roy et al., 2020). It is worth noting that the World Health Organization (WHO) does not establish a specific health-based guideline value for bicarbonate (HCO_3^-) in drinking water, as it is not considered harmful to human health at concentrations typically found in natural waters. Instead, WHO addresses bicarbonate indirectly through Total Alkalinity and pH parameters, which influence water taste and infrastructure scaling rather than health.

2.2.1.3.Nitrates, Chlorides, and Sulfates:

Nitrate concentrations ranged between 3.7 and 6.47 mg/L. Notably, none of the analyzed samples exceeded the maximum permissible nitrate concentration for drinking water (50 mg/L). All nitrate values remained within the acceptable limits established by the Algerian guidelines (2011). The presence of nitrate in groundwater is primarily attributed to agricultural activities, particularly the extensive use of both synthetic and organic fertilizers. Inappropriate farming practices, such as leaving manure exposed on the soil surface, can enhance nitrate transport through surface runoff and infiltration. Additional nitrate enrichment may also result from sewage discharge, including leakage from septic systems. These inputs mainly originate from non-point sources associated with agricultural and residential areas. Furthermore, the decomposition of organic matter contributes to nitrate accumulation, influenced by various local factors related to both point and diffuse pollution sources (Ustaoğlu et al., 2020). Anions analysis results are summarized in Table 3 and Figure 5.

Table (3): Results of the anions analyses of the studied samples and their comparison with the Algerian standards (2011) and the World Health Organization (WHO, 2011)

Area / Parameters	Mean±SD		
	Cl^-(mg/l)	SO_4^{-2}(mg/l)	NO_3^-(mg/l)
Ben Yakoub	1240±70,9	2321,98±10,9	3,7±0,002
M'esalah	1276,2±54,15	1285,45±2,14	6,64±0,002
Sidi Barket	1347,1±73,80	1382,04±2,14	6,47±0,00
El Maleh	1488,9±54,15	1144,27±2,15	6,44±0,002
Lebchache	1559,8±54,15	1066,25±3,72	4,59±0,00
Hai Ben Taleb	1311,65±35,45	724,46±18,58	4,6±0,00
JORADP (2011)	200-500	200-400	50
WHO Standards (2011)	25 - 200	25 - 250	50

ISSN: 3078 – 2767 Online

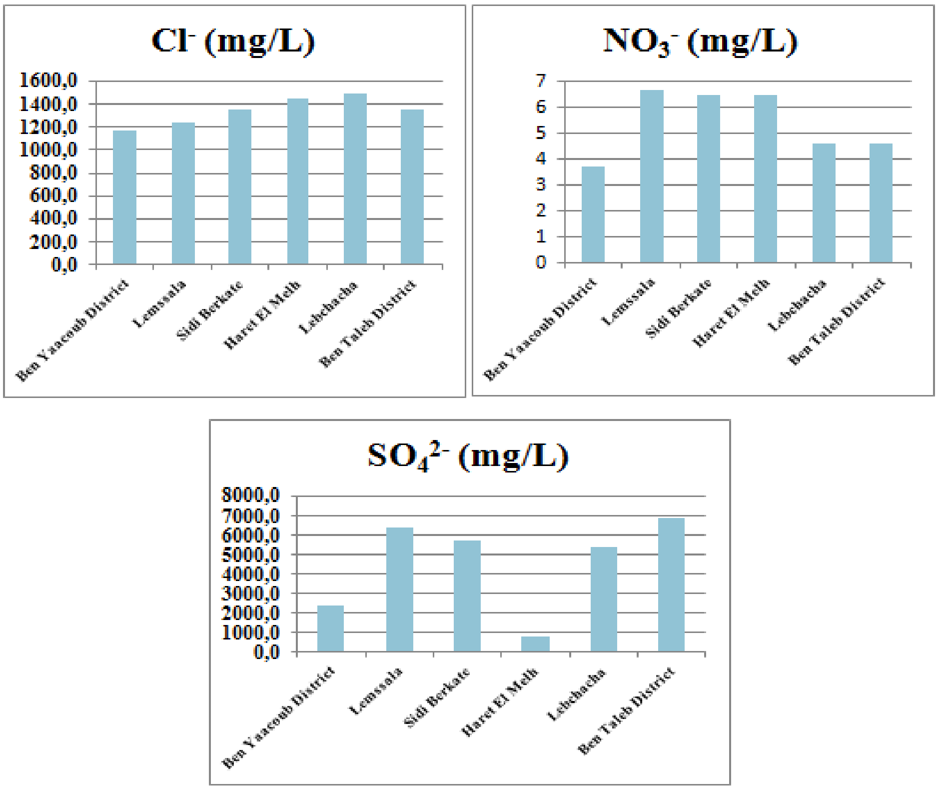

Figure (5): Evaluation of the anions parameters of the analyzed tap water samples

In contrast, Cl^- concentrations values ranging from 1240 to 1488.9 mg/L in all tap water samples. SO_4^{2-} concentrations values 724,46 mg/L in Ben Table**.**

Based on the standards outlined in WHO. (2011), the maximum allowable concentration for Cl^- and SO_4^{2-} in drinking water is 250 mg/L. Such elevated concentrations of chloride and sulfate are attributed to the dissolution of evaporate minerals present in the geological formations of the study area (Bencer *et al.,* 2016).

3.1.3. Physicochemical Characteristics of Water from Tanker Trucks:

The physicochemical properties of water supplied by mobile tanker trucks are presented in Table 4 and Figures (6, 7, and 8). All measured parameters, including EC, salinity, pH, hardness, major ions, and nitrates, complied with Algerian and WHO drinking water standards. These results indicate that tanker water, originating from the Feliesh, Sidi Okba, and Sidi Khelil boreholes, is chemically suitable for human consumption. The similarity in physicochemical characteristics among the three sources suggests that they tap into the same groundwater aquifer. However, the absence of microbiological analyses represents a limitation of the present study and should be addressed in future investigations.

2.3. Performance of the Bouchakroun Desalination Plant:

The physicochemical characteristics of water samples collected before and after treatment at the Bouchakroun desalination plant are shown in Table 5 and Figures (9 and 10). Untreated

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

groundwater, extracted from a depth of approximately 150 m, exhibited very high salinity and ion concentrations, exceeding drinking water standards for most parameters, except nitrates (<3 mg/L).

Table (4): Results of the physicochemical analyses of the studied samples and their comparison with the approved Algerian standards (2011) and the World Health Organization (WHO, 2011).

	Mean±SD				
Parameters	**Sidi Okba**	**Feliesh**	**Sidi Khelil**	**JORADP (2011)**	**WHO Standards (2011)**
T°	22,6±0,1	23,7±0,06	22,4±0,1	25	25
pH	7,2±0,08	7,85±0,02	7,7±0,14	≥ 6,5 ≤ 8,5	≥ 6,5 ≤ 8,5
CE (µS/cm)	203±1,15	203±1,15	196±1,15	2800	/
Salinity⁺(mg/L)	100±0,57	100±0,57	96,55±0,57	2000	300-1500
TH(°F)	5±0,58	5±0,00	5±0,00	10-50	/
Ca^{2+}(mg/L)	16±2,31	12±0,00	12±0,00	75-200	100 - 200
Mg^{2+} (mg/L)	2,40±1,39	4,8±0,00	4,8±0,00	150	30 -50
HCO_3^- (mg/L)	61±0,00	61±0,00	61±0,00	/	/
Cl^- (mg/L)	283,6±70,15	248,15±40,93	319,05±54,15	500	25 - 200
SO_4^{2-} (mg/L)	222,91±10,72	260,06±21,45	222,91±10,72	400	25 - 250
NO_3^- (mg/L)	2,64±0,00	2,76±0,00	2,56±0,00	50	50

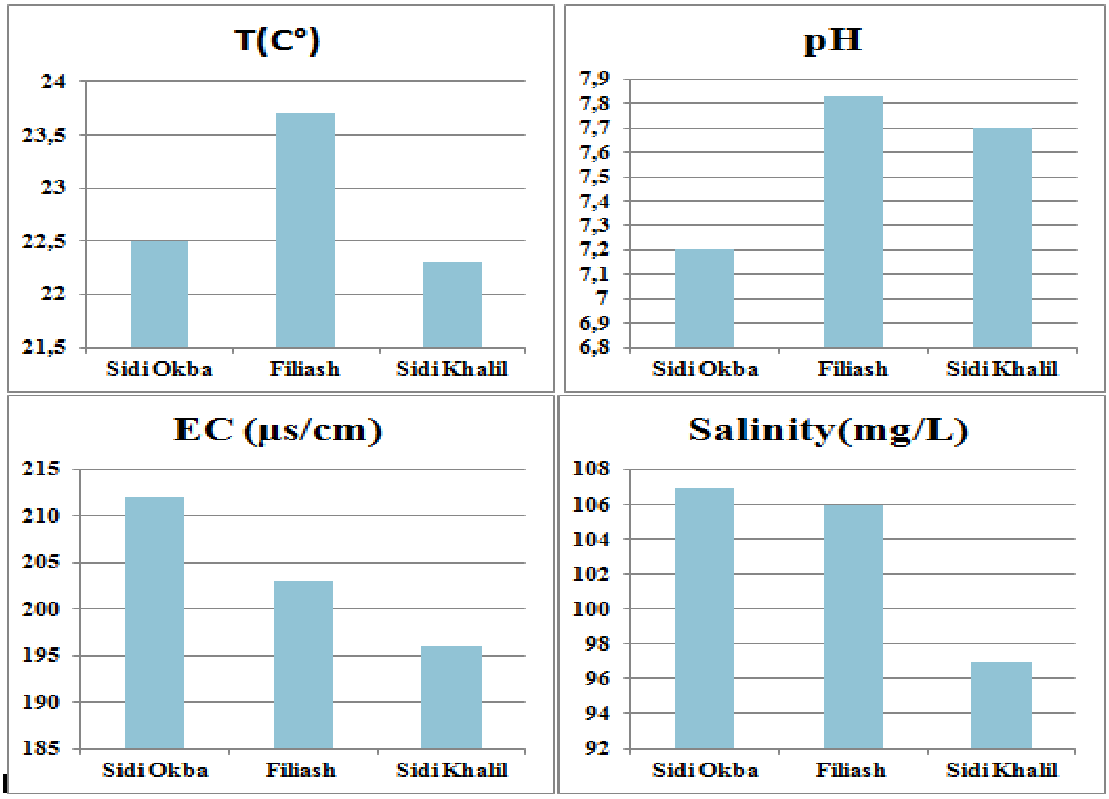

Figure (6): Evaluation of the physical parameters of the analyzed tanker water samples

ISSN: 3078 – 2767 Online

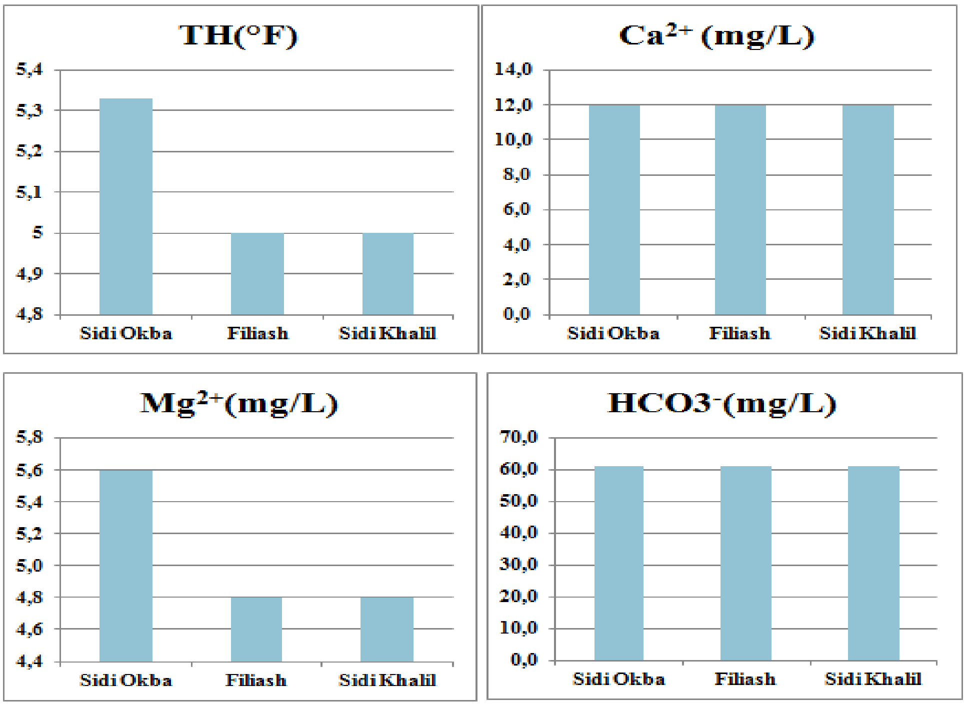

Figure (7): Evaluation of the chemical parameters (Cations) of the analyzed tanker water samples

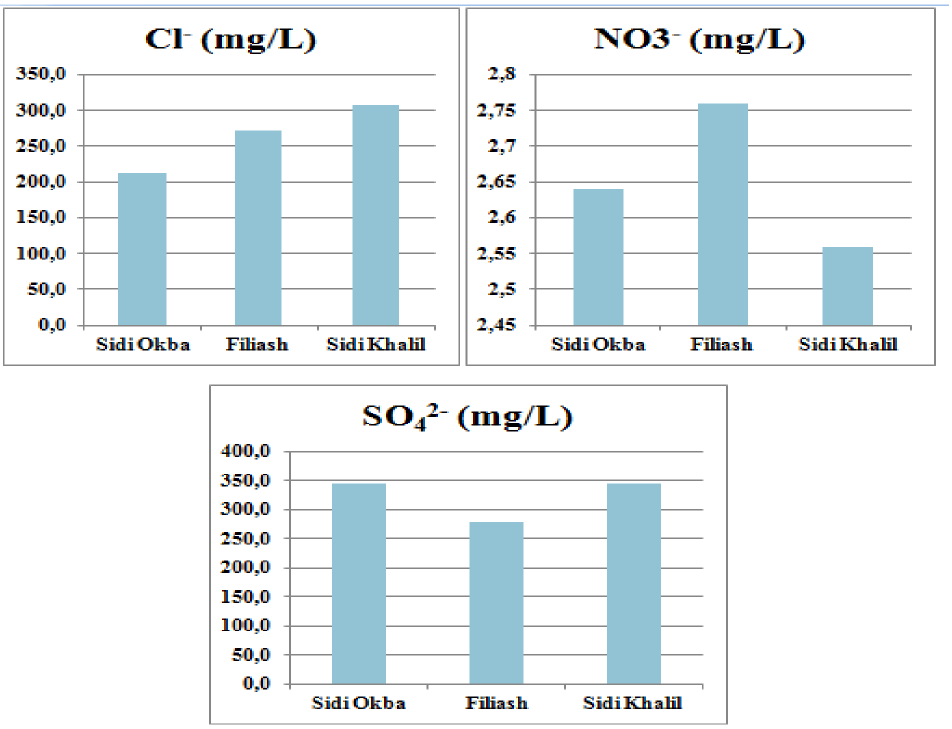

Figure (8): Evaluation of the chemical parameters (Anions) of the analyzed tanker water samples

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026

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ISSN: 3078 – 2767 Online

Table (5): Physicochemical properties of Bouchagroun desalination plant samples (B.T vs. A.T), treatment efficiency, and compliance with national and international standards.

Mean±SD					
Parameters	**Bouchagroun Plant (B.T)**	**Bouchagroun Plant (A.T)**	**JORADP (2011)**	**WHO Standards (2011)**	**Treatment efficiency (%)**
T°	28,3±0,17	27,8±0,21	25	25	/
pH	7,48±0,03	6,8±0,09	≥ 6,5 ≤ 9	≥ 6,5≤ 8,5	/
CE (µS/cm)	3360±5,77	226±0,58	2800	/	93,27
Salinity (mg/l)	1655,17±2,84	111,33±0,28	2000	300-1500	93,29
TH (°F)	100±0,00	10±0,00	10-50	/	90,00
Ca^{2+} (mg/l)	352±11,55	32±0,00	75-200	100 - 200	90,91
Mg^{2+} (mg/l)	28,80±6,93	4,8±0,00	150	30 -50	83,33
HCO_3^- (mg/l)	244±0,00	61±0,00	/	/	75,00
Cl^- (mg/l)	425,40±54,15	106,35±35,45	200-500	25 - 200	75,00
SO_4^{2-} (mg/l)	393,81±2,14	282,35±2,14	200-400	25 - 250	28,30
NO_3^- (mg/l)	1,66±0,00	0,68±0,00	50	50	59,04

B.T: Before treatment; A.T: After treatment

After reverse osmosis treatment, a substantial reduction in EC, Salinity, hardness, chlorides, and calcium and magnesium concentrations was observed. Removal efficiencies ranged between 75 and 93% for most ions, confirming the effectiveness of reverse osmosis in desalinating highly mineralized groundwater.

The pH slightly decreased from 7.48 to 6.8 after treatment but remained within acceptable limits. This decrease may be attributed to temperature effects and chlorination during post-treatment processes.

Sulfate removal efficiency was notably lower (<30%), suggesting partial membrane selectivity or operational limitations. Despite this, all post-treatment values confirmed with Algerian and WHO standards.

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

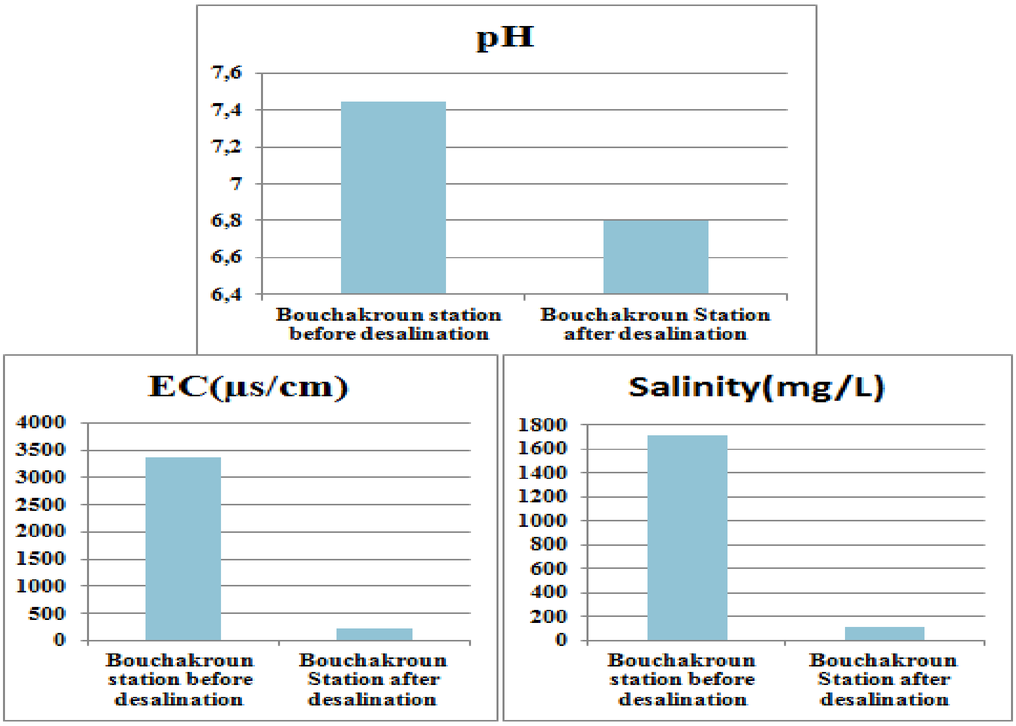

Figure (9): Evaluation of the physical parameters of the analyzed Bouchagroun desalination plant samples (Before treatment vs. after treatment).

4. Statistical analysis:

To evaluate the spatial and geographical influence on water quality across the studied regions, a One-way Analysis of Variance (ANOVA) followed by Tukey's Honestly Significant Difference (HSD) post-hoc test was executed using SPSS software (version 15). This framework was deployed to delineate the spatial behavior of physical and chemical parameters within centralized tap networks and decentralized tanker water systems at a significance threshold of $p < 0.05$. Characterizing this spatial heterogeneity is critical for assessing the structural stability of water quality across different supply modes, thereby providing a robust empirical foundation for public health risk assessments and strategic resource management.

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

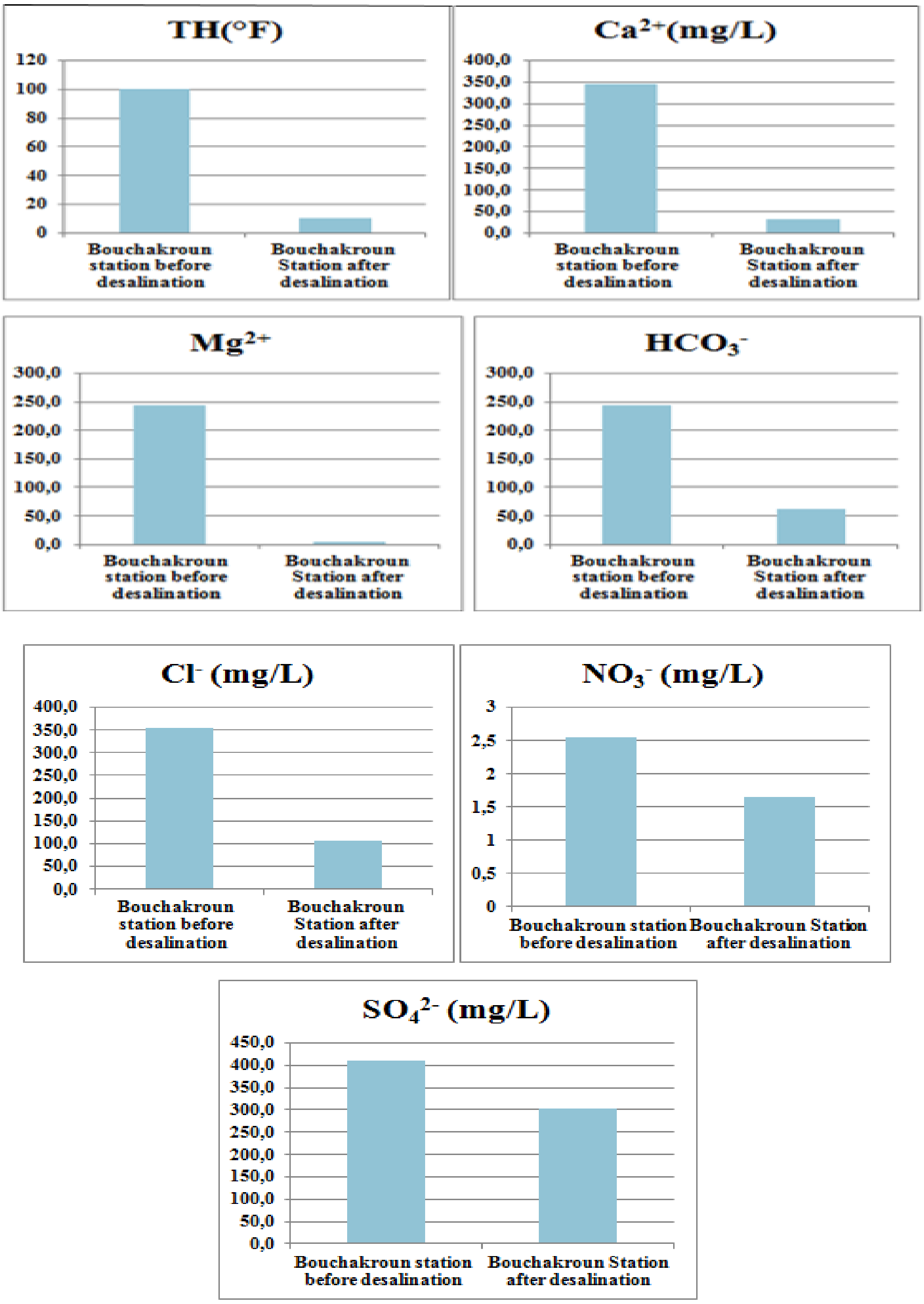

Figure (10): Evaluation of the physico-chimical parameters of the analyzed Bouchagroun desalination plant samples (Before treatment vs. after treatment).

1.4. Statistical Evaluation of Tap and Tanker Water Quality:

The Descriptive statistics for the regional variations of tap water and tanker water are compiled in Table 7. Notably, because the desalination plant operates as a singular centralized treatment

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

unit, it was represented by a single baseline sample profile and was therefore excluded from the spatial variance analysis.

Table (7): Descriptive statistics (Minimum, Maximum, and Mean±SD) of the physicochemical parameters of tap water and tanker-hauled water across the studied regions

	Tap water			Tanker Water		
Parameters	**Max**	**Min**	**Mean±SD**	**Max**	**Min**	**Mean±SD**
T°C	22,90	22,20	22,65±0,29	23,70	22,40	22,60±0,70
pH	7,78	7,09	7,37±0,25	7,85	7,20	7,70±0,34
CE µSm/cm	7000	4860	6405	203	196	203±4,04
TH°F	133	73	116±20,83	5,00	5,00	5±0,00
Sal (mg/l)	3448,28	2394,09	3155,17±379,86	100,00	96,55	100±1,99
HCO_3^-(mg/l)	369,66	36,60	305±116,59	61,00	61,00	61±0,00
Ca^{2+}(mg/l)	264,00	184,00	240±29,25	16,00	12,00	12±2,31
Mg^{2+}(mg/l)	184,80	60,00	128,4±40,61	4,80	2,40	4,8±1,39
Cl^-(mg/l)	1559,80	1240,75	1329,38±126,17	319,05	248,15	283,60±35,45
SO_4^{2-}(mg/l)	2321,98	724,46	1214,86±540,17	260,06	222,91	222,91±21,45
NO_3^-(mg/l)	6,64	3,70	5,52±1,26	2,76	2,56	2,64±0,10

The comparative spatial assessment via One-way ANOVA revealed diverging hydrochemical dynamics between the two water supply modes (Table 6). For tap water, highly statistically significant spatial heterogeneity ($p < 0.001$) spanned all evaluated physicochemical parameters (EC, Sal, TH, and major ions), except for temperature ($p=0.006$). This pronounced variance is dictated by the distinct hydrogeological signatures of the feeding groundwater aquifers combined with in-conduit interactions (e.g., corrosion and precipitation), corroborating the lithogenic frameworks of Al-Omran *et al.* (2015) and Akoachere et al. (2018).

Conversely, truck-hauled water exhibited a shifting pattern; while most parameters varied significantly ($p<0.001$), water temperature ($p=0.208$) and chloride concentrations ($p = 0.376$) remained statistically uniform across regions. As noted by Berkani et al. (2023), this chloride and thermal homogeneity signals abstraction from a shared, hydrochemically uniform or saline source near demand centers. However, the localized spatial fluctuations observed in tanker pH, SO_4^{2-}, and NO_3^- highlight secondary, post-abstraction vulnerabilities. Driven by non-uniform tank maintenance, disparate sanitization protocols, and solar-exposed storage durations, these findings align with Abou Abbass *et al.* (2023) and Constantine *et al.* (2017), illustrating how decentralized distribution introduces localized variations despite a homogenous water source.

5. Water Quality Index (WQI):

A number of biological, physical, and chemical factors are evaluated in order to determine the Water Quality Index (WQI). The parameters are indications of the various ways that water resources are used in human consumptive contexts, including recreational activities, potable water supply, industrial applications, irrigation, and residential use. The steps involved in the WQI computation are as follows:

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

Weights (wi) ranging from 1 to 5 were assigned to each of the ten chemical features in the first phase, indicating their respective importance in affecting the overall quality of irrigation water. The weights assigned to these criteria range from one to five. Due to their frequent and significant effects on groundwater quality, nitrate (NO_3^-), chloride (Cl^-), and sulfate (SO_4^{2-}) were each indicated as the maximum weight of five (Sahu and Sikdar, 2008). The minimal weight of 1 was given to bicarbonate (HCO_3^-), a fact that rarely has a significant impact on groundwater quality. Conversely, the weights of calcium (Ca^{+2}), magnesium (Mg^{+2}), conductivity (EC) varied from 1 to 5 (Hamlat and Guidoum, 2018). Equation (1) was then used to calculate the relative weight (Wi) of these parameters.

$$\boldsymbol{wi} = \frac{wi}{\sum_{i=1}^{n} wi} \qquad (1)$$

Table 8. Standard limits, weights (wi), and calculated relative weights (Wi) for the water quality parameters based on WHO guidelines.

Measured parameter	Permissible limit (Si)	Weight (wi)	Relative weight (Wi)
pH	8.5	4	0.1333
Electrical Conductivity µS/cm	1500	4	0.1333
Calcium mg/L	75	3	0.1000
Magnesium mg/L	50	3	0.1000
Chloride mg/L	250	5	0.1667
Sulfate mg/L	250	5	0.1667
Nitrate mg/L	50	5	0.1667

Where the total number of water quality parameters is represented as n and the weight allocated to the i-th water quality parameter is referred to as wi. Each parameter a side from pH was given a quality rating (qi) in the third stage. The content in each water sample was divided by the limit values set by the Algerian Standards (2014) and WHO (2011) to get this rating. The following equation (2) was used to perform this calculation:

$$\boldsymbol{qi} = \frac{Ci}{Si} \times 100 \qquad (2)$$

The quality rating is represented as qi where Si is the corresponding drinking water standard for each chemical parameter in accordance with the WHO and Algerian standards guidelines, and Ci is the concentration of each chemical parameter in each water sample, expressed in mg/L. Equation (3) is then used to generate the water quality sub-indices (SIi) for each chemical parameter. SIi denotes the sub-index assigned to the ith parameter.

$$\boldsymbol{SIi} = Wi \times qi \qquad (3)$$

Lastly, the following equation (4) was used to calculate the overarching water quality i ndex (WQI), which is used to assess the overall water quality for each sample.

$$\boldsymbol{WQI} = \sum_{n=1}^{n} SIi \qquad (4)$$

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

The computed WQI values were then divided into five different groups to determine the water quality status, ranging from "excellent water" to "water unsuitable for drinking," as shown in Table 8.

Table (9): WQI ranges and water quality status of the water sample (Masmoudi et al., 2024).

WQI ranges	Water quality status
<50	Excellent
50.1-100	Good
100.1-200	Poor

1.5. Water Quality Index for Tap water:

The Water Quality Index (WQI) serves as an effective tool to synthesize complex physicochemical data into a single indicator reflecting drinking water suitability. In this study, the calculated WQI values (table 9) across the six investigated regions ranged from 214.10 to 249.20, uniformly classifying all sources as "Poor to Very Poor Quality" (WQI > 100) and rendering them unfit for direct human consumption without intensive treatment. Spatial analysis revealed that Haret Elmelh exhibited the highest degradation (WQI = 249.20), whereas Ben Taleb City was the relatively least degraded (WQI = 214.10). This severe qualitative decline is primarily driven by critical elevations in electrical conductivity (EC), chloride (Cl^-), and sulfate (SO_4^{2-}), which strongly corroborates the highly significant spatial variations identified by the one-way ANOVA. This hydrochemical profile is attributed to mineral dissolution and water-rock interactions within the aquifer (Ramakrishnaiah et al., 2009), posing long-term health risks that demand advanced technological interventions, such as reverse osmosis, to restore water quality to permissible international standards (Vasanthavigar et al., 2010).

Table 4. Drinking Water Quality Index (WQI) values and spatial quality classification for the studied locations.

Water Source	Location	(WQI)Value	WQI Status
Tap Water	**Ben Yakoub**	238.45	**Poor / Very Poor**
	El'MSalah	226.70	Poor
	Sidi Barket	218.15	Poor
	Haret Elmelh	249.20	Poor
	L'ebchech	246.30	Poor
	Ben Taleb	214.10	Poor
Tanker Water	**Sidi Okba**	38.65	Excellent
	Feliesh	41.20	Excellent
	Sidi Khelil	43.85	Excellent
Bouchegroun plant	**Befor treatment**	148.40	Poor
	After treatment	35.15	Excellent

2.5. Water Quality Index for tanker water and desalination plant:

The calculated Drinking Water Quality Index (WQI) scores revealed a radical contrast between alternative water supplies and tap network. Tanker water distributed across Sidi Okba, Feliesh, and Sidi Khelil exhibited excellent quality ($38.65 \leq$ WQI ≤ 43.85), falling safely below the ideal threshold (WQI} < 50) due to balanced salinity and low electrical conductivity.

مجلة سوزوسا العلمية المحكمة
Sozusa Peer-Reviewed Scientific Journal 5 (2): 140-162, 2026
ISSN: 3078 – 2767 Online

Similarly, the Bouchegroun desalination plant demonstrated outstanding treatment efficiency, yielding a 76\% reduction in the index score from a poor pre-treatment baseline of 148.40 down to an excellent post-treatment value of 35.15. These findings support the assertion by Canstantine et al. (2017) that mobile tankers serve as a critical temporary alternative to highly saline municipal networks in arid zones. Furthermore, the profound qualitative improvement achieved at Bouchegroun plant underscores the indispensable role of desalination technologies in reclaiming highly mineralized groundwater to satisfy strict international drinking standards (WHO, 2011).

6. Conclusion:

In conclusion, this comprehensive hydrochemical evaluation highlights the significant impact of local geological formations and arid climatic conditions on water quality across the studied sectors. The integration of spatial variance modeling provided definitive evidence regarding water safety, infrastructure performance and its supplies when compared to national and international legislative frameworks:

- Tap Water: One-Way ANOVA confirmed highly significant regional variations across all major physical and chemical parameters ($p = 0.001$), with the exception of water temperature ($p = 0.006$). This quality disparity was further validated by the Drinking Water Quality Index (WQI), where values uniformly ranged from 214.10 up to 249.20, exceeding the maximum limits allowed in the Algerian Executive Decree (JORADP, 2011) and the guidelines of the World Health Organization (WHO, 2011). According to standard thresholds (WQI > 100), the direct tap supply across all six urban sectors is classified as "Poor to Very Poor Quality" establishing its absolute unsustainability for direct human consumption without advanced purification.
- Tanker Water: Conversely, mobile tanker distributions offered a temporary alternative, exhibiting relative spatial homogeneity for key parameters such as chloride levels ($p = 0.376$) and establishing highly favorable, recording excellent values and conforming to national and international standards with a water quality index ranging between 38.65 and 43.85. This characterizes the tanker supply within the targeted sectors as "Excellent Quality" for drinking purposes .
- Bouchakroun Plant: The investigation proved the critical necessity of advanced engineered interventions. Raw groundwater feeding the Bouchakroun facility presented highly restrictive baseline salinity metrics and a non-compliant pre-treatment WQI of 148.40.
- Following the deployment of reverse osmosis, treatment efficiencies effectively engineered a radical 75% reduction in contaminant loads, lowering the post-treatment index score to an exceptional 35.15. This achieves full and perfect compliance with nationally and internationally approved drinking standards.

Consequently, future strategic directions focus on three pillars: expanding solar-powered brackish water desalination plants, enforcing strict sanitary regulation and testing for mobile tankers, and deploying advanced hydrogeological and isotope mapping to ensure long-term aquifer sustainability.

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