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Groundwater quality dynamics in Doukkala, Morocco – Exploring seasonal and temporal variations in physicochemical and bacteriological traits

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ABSTRACT

The groundwater resources in Morocco are critical for agricultural and domestic use, yet they face increasing pressures from environmental changes and human activities. This study investigated the seasonal and temporal dynamics of groundwater quality in Doukkala (western Morocco) by analyzing physicochemical and bacteriological parameters over a defined period. Water samples were collected from multiple wells across the region and analyzed for key indicators, including temperature, pH, electrical conductivity, ionic composition, alkalinity, and microbial contamination. The results reveal significant variations in water quality that correlate with seasonal changes, particularly during periods of intense agricultural activity. Nitrate levels exceeded 50 mg/l in six stations, and bacterial contamination levels surpassed 20,000 CFU/100 ml in stations S2, S7, and S8. On the basis of these discriminant traits, the majority of the analyzed experimental stations exhibited groundwater quality ranging between medium and poor. Elevated nitrate levels and microbial contamination observed during the irrigation season raise concerns about the sustainability of groundwater use in the region. The findings underscore the need for improved management practices to protect groundwater resources as well as ensure the health and well-being of local communities. This study provides a comprehensive assessment of groundwater quality dynamics in Doukkala, offering valuable insights for policymakers and stakeholders involved in water resource management.

Keywords: bacteriological contamination, Doukkala region, groundwater quality, seasonal variations.

INTRODUCTION

Water is an indispensable natural resource, fundamental to all forms of life on Earth, and its availability as well as quality are crucial for sustaining human health and well-being [Jhariya et al., 2022]. The access to potable drinking water is a basic human right and an essential need that underpins social and economic development [Grönwall and Danert, 2020]. Groundwater and surface water serve as the primary sources of drinking water, fulfilling the needs of millions of people in both urban and rural areas around the world [Adeloju et al., 2021]. Groundwater, often stored in aquifers beneath the Earth's surface, is particularly vital in the regions where surface water is scarce or unreliable, providing a consistent and often cleaner source of water that can be accessed through wells and boreholes [Ahmed and El-Rawy, 2024].

Groundwater is one of the most critical natural resources on the planet, playing an indispensable role in sustaining life, supporting ecosystems, and enabling economic development worldwide [Scanlon et al., 2023]. As a major source of freshwater, groundwater provides nearly half of the global population with drinking water and serves as a key resource for agricultural irrigation, which in turn supports food security for billions of people [Irfeey et al., 2023]. Groundwater not only supplies households and communities with clean, potable water but also supports industrial processes, energy production, and numerous other essential activities [Thomas et al., 2022]. Moreover, it acts as a buffer during the periods of drought, maintaining water availability when surface water sources are depleted [Marchionni et al., 2020]. Beyond its direct uses, groundwater plays a crucial ecological role by sustaining rivers, lakes, wetlands, and other surface water bodies, especially during dry periods, thereby maintaining the health of ecosystems that depend on consistent water availability [Gupta and Sharma, 2023].

However, this crucial resource is increasingly threatened by various sources of contamination impacting both human health and the environment [Karunanidhi et al., 2021]. Several studies have revealed that the contaminants sources with agricultural practices being a major contributor [Raimi et al., 2022; Rao et al., 2022]. Fertilizers and pesticides used in farming can leach harmful chemicals into the soil, contaminating groundwater with excess nutrients, like nitrates and toxic substances [Hossain et al., 2022]. Industrial activities, including improper waste disposal and leakage from storage tanks, introduce hazardous substances such as heavy metals, solvents, and chemicals into the groundwater, which can persist for long periods and disrupt ecosystems [Hasan et al., 2021]. Urbanization further exacerbates the problem, with pollutants from wastewater, sewage, and runoff infiltrating aquifers and degrading water quality [Kaur et al., 2023]. Additionally, the natural geological composition of the region can influence the movement and concentration of contaminants, complicating the efforts to predict and manage contamination [You et al., 2020].

Morocco, like other Mediterranean countries, has faced recurrent droughts, intensifying the strain on its already limited water resources [Adiba et al., 2021, 2022; Gaaloul et al., 2021; Hamdani et al., 2022]. The nation's total renewable water resources, encompassing both surface and groundwater, are estimated at 29 billion cubic meters annually, with only 20 billion cubic meters being utilizable, 16 billion cubic meters from surface water and 4 billion cubic meters from groundwater [Hssaisoune et al., 2020]. Currently, around 70% of this potential is exploited, primarily to support agriculture, drawing heavily from both surface and groundwater sources [El Mountassir et al., 2022]. This extensive use has led to the depletion of aquifers, with groundwater levels decreasing by 0.5 to 2 meters per year on average, largely due to inadequate recharge and the expansion of agricultural activities [Ait Kadi and Ziyad, 2018]. Moreover, pollution is emerging as a critical issue, with contaminants such as nitrates, heavy metals, and pathogens increasingly compromising groundwater quality [Hssaisoune et al., 2020].

The Doukkala region in western Morocco experiences significant seasonal fluctuations in climate, characterized by wet and dry periods, which can greatly influence groundwater quality [Adnani et al., 2020; Ouhakki et al., 2024b]. These variations, along with anthropogenic activities, such as the extensive use of fertilizers and pesticides, contribute to the degradation of water quality through the leaching of contaminants into the groundwater [Doubi et al., 2021]. Consequently, monitoring the physicochemical and bacteriological traits of groundwater is crucial to understanding the extent of these impacts and guiding the development of effective water management strategies [Ouhakki et al., 2024a]. In relation with this situation, the objective of this study was to analyze the seasonal and temporal variations in the physicochemical and bacteriological characteristics of groundwater in Doukkala, Morocco. By examining these variations, the research aimed to identify the key factors influencing groundwater quality dynamics in the region, with a particular focus on the impacts of agricultural practices, natural environmental changes, and potential contamination sources. The findings are intended to provide insights for improving groundwater management strategies and mitigating the risks associated with groundwater pollution.

MATERIALS AND METHODS

Study area and sampling locations

The Doukkala-Abda region of Morocco presents a highly fragile environment, influenced by both natural and anthropogenic factors. This area is characterized by a semi-arid climate, limited forested territory, and predominantly calcareous soils. Economic activities that are detrimental to the environment, such as phosphate extraction and processing, mining, overfishing, overgrazing, and uncontrolled urbanization, are heavily concentrated in this region.

The most significant environmental pressure in Doukkala-Abda arises from air pollution caused by emissions from the industrial sector. This includes the manufacture of nitrogenous products and fertilizers, phosphate extraction and calcination, as well as the industrial zone at Jorf Lasfar. These activities have profound impacts on the air quality of the region and contribute to the overall environmental degradation. Given these conditions, the study aimed to investigate the dynamics of groundwater quality in Doukkala, focusing on seasonal and temporal variations in physicochemical and bacteriological traits. Understanding these variations is crucial for managing water resources and mitigating the adverse effects of industrial activities on groundwater quality.

The groundwater samples were meticulously collected from nine experimental stations in the Doukkala region (Table 1 and Fig. 1). The sampling process adhered to strict protocols to

Table 1. Sampling wells and their coordinates in the Doukkala region

Sampling Well	Station code	X (m)	Y (m)
Fatna Ben Haddou	S1	183.550	265.400
Ouled Rbia	S2	167.869	250.164
Cooperative Bhayllat	S3	237.236	251.126
Sersif	S4	215.300	265.100
Laatatra	S5	217.165	230.490
Douar Ouled Chaikh	S6	189.592	239.822
Faiss Bouchaib	S7	231.857	281.083
Sfia	S8	234.400	265.250
Douar Slaoui	S9	191.800	275.250

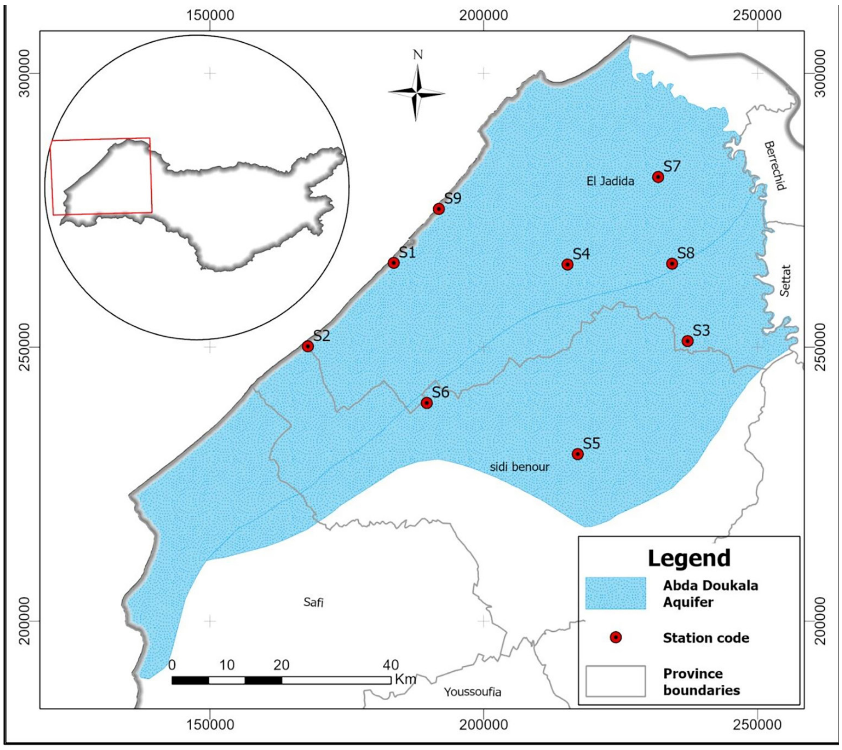

Figure 1. Geographical distribution of groundwater sampling points in the Doukkala region, Morocco; S1: Fatna Ben Haddou, S2: Ouled Rbia, S3: Cooperative Bhayllat, S4: Sersif, S5: Laatatra, S6: Douar Ouled Chaikh, S7: Faiss Bouchaib, S8: Sfia, S9: Douar Slaoui

preserve the integrity of the samples. Clean polypropylene bottles, pre-cleaned with a 10% nitric acid solution and rinsed with double-distilled water, were used to collect the samples. To capture potential seasonal variations in water quality, sampling was conducted six times: three times in winter and three times in summer. The water samples, each 125 mL in volume, were stored at a controlled temperature of 4 °C, ensuring sample stability in accordance with the APHA [2005] standards. A subset of each sample was vacuum-filtered using 0.45 – Millipore membrane filter paper to eliminate particulate matter, while an unfiltered portion (250 mL) was retained for raw sample analysis, allowing for a comprehensive comparison of hydrochemical and bacteriological properties.

Analyzed traits

Physicochemical traits analysis

The groundwater physicochemical quality of the nine experimental stations of the Doukkala region is assessed based on the measured of the air and water temperature, pH and electrical conductivity. Indeed, the air temperature at each sampling site was measured concurrently with water temperature using a digital thermometer. The thermometer was placed in the shade to avoid direct sunlight interference, and readings were recorded to the nearest 0.1 °C. Thus, the pH of the groundwater was measured using a portable, calibrated pH meter. Moreover, Electrical conductivity (EC) was measured using a calibrated portable conductivity meter.

Determination of groundwater anions and cations

The concentrations of the groundwater anions and cations were determined using a combination of standard analytical techniques. The Ca^{2+} and Mg^{2+} cations were measured by the complexometry method (EDTA). The Na^{+} and K^{+} contents were determined using flame photometry, ensuring accurate detection of these alkali metals. Bicarbonate (HCO_3^-) was determined by titration against standard H_2SO_4 solution (0.0392 N). Ammonium (NH_4^+) concentrations were measured using the Nesslerization method, where a colorimetric reaction provides a sensitive indicator of ammonium levels. Thus, the SO_4^{2-} anion contents were determined by the nephelometric method. However, chloride (Cl^-), sulfate (SO_4^{2-}), nitrite (NO_2^-), and nitrate (NO_3^-) ions were quantified using ion chromatography, providing precise identification and quantification of these anions. All measurements were performed in accordance with APHA [2005] standards to ensure accuracy and reproducibility of the results.

Bacteriological traits

The enumeration and analysis of total coliforms (CT), fecal coliforms (CF), and fecal staphylococcus (SF) in groundwater samples were conducted using standard microbiological techniques. For the detection and quantification of CT and CF, the membrane filtration method was employed. The presence of fecal staphylococcus (SF) was determined by inoculating samples onto Baird-Parker agar, followed by incubation at 37 °C for 48 hours. The ratio of CF to SF (CF/SF) was calculated to evaluate the relative prevalence of fecal coliforms compared to fecal staphylococci in the groundwater, providing insights into the potential sources and pathways of contamination. All bacteriological analyses were conducted in triplicate to ensure accuracy and reproducibility of the results.

Statistical analyses

Data analysis was performed using SPSS version 22. The differences among the experimental stations were evaluated using Analysis of Variance (ANOVA). This method enabled a thorough examination of the variations in physicochemical and bacteriological traits across the different stations. Additionally, a Student-Newman-Keuls (SNK) test was conducted to compare the means of the traits across all analyzed groups. The SNK test, a post-hoc analysis, was employed to identify specific differences between individual groups, thereby providing a detailed understanding of the distinctiveness of each experimental site concerning the studied parameters.

RESULTS AND DISCUSSION

Physicochemical traits

The results of Table 2 reported the variation of the air and water temperature, pH, conductivity and the permeability index of groundwater samples collected from nine experimental stations of the Doukkala region, Morocco. No significant variation of the air and water quality was observed between the analyzed stations. However, a clear

Table 2. Seasonal variation in groundwater physicochemical traits in the Doukkala region

Station	Season	Air temperature (°C)	Water temperature (°C)	pH	Electrical conductivity (µS/cm)	Permeability index
S1	Summer	25.67	23.47	7.33	3726.67 c	1.55 b
	Winter	15.75	20.4	7.52	3452.5 b	2.05 b
S2	Summer	26.00	23.60	7.40	3470.00 c	2.56 a
	Winter	17	19.8	7.53	2996.25 b	1.17 bc
S3	Summer	28.00	23.70	7.13	2670.00 cd	1.56 b
	Winter	17.75	20.33	7.22	3106.50	2.18 ab
S4	Summer	27.75	22.25	7.28	2475.00 cd	2.33 ab
	Winter	18.00	22.00	7.28	2470.00 bc	2.37 ab
S5	Summer	29.00	23.67	7.13	2773.33 cd	1.14 bc
	Winter	13.75	18.40	7.16	2735.00 bc	1.04 c
S6	Summer	27.83	23.80	7.34	5390.00 ab	2.68 a
	Winter	17.00	20.97	7.12	5813.33 a	2.47 ab
S7	Summer	28.33	24.50	7.58	1379.67 d	0.63 c
	Winter	16.25	17.03	7.56	1374.75 c	1.12 bc
S8	Summer	34	24.15	7.32	4055 b	1.78 b
	Winter	16.33	15.67	7.18	4142.00 ab	1.86 b
S9	Summer	25.67	21.83	7.27	6526.67 a	2.33 ab
	Winter	15.00	18.43	7.46	5725.50 a	3.26 a
ANOVA	-	ns	ns	ns	*	*

Note: Ns: non-significant difference; *: significant difference at $p < 0.05$.

seasonal variation was noted, with higher temperatures in summer and lower temperatures in winter. The highest recorded summer air temperature is 34 °C (S8), and the lowest winter air temperature is 13.75 °C (S5). Similarly, water temperatures are higher in summer and lower in winter. The highest summer water temperature is 24.50 °C (S7), while the lowest winter water temperature is 15.67 °C (S8). For the water pH, the data indicates that the groundwater in the Doukkala region is neutral to slightly alkaline and it is relatively stable across seasons and stations, ranging from 7.12 to 7.58. On the other hand, electrical conductivity, which measures the ability of water to conduct electricity, shows significant seasonal and spatial variation. In summer, the highest water conductivity (6526.67 µS/cm) was reported in S9, while the lowest value (1379.67 µS/cm) was detected in S7. However, in winter, the highest conductivity 5813.33 µS/cm was reported in the S6 and the lowest value 1374.75 µS/cm was observed in the S7. The permeability index, which indicates water suitability for irrigation based on ion composition, also varied significantly across stations. In summer, the permeability index ranged from 0.63 at S7 to 2.68 at S6. For the winter samples, the highest value was observed at S9 (3.26), while the lowest was at S5 (1.04).

These findings reveal important insights into the seasonal and spatial variations of key physicochemical traits in groundwater in the Doukkala region. The lack of significant variation in air and water temperatures across different stations suggests a degree of environmental homogeneity within the region. Similar results were reported in other Moroccan regions, such as Essaouira basin [El Mountassir et al., 2022], Western Haouz [Sefiani et al., 2019], plain of Triffa (northeast) [Fetouani et al., 2008] and Timahdite Almis Guigou area (Middle Atlas) [Amrani et al., 2022]. However, the observed seasonal differences, with higher temperatures in summer and lower temperatures in winter, align with expected climatic patterns in the semi-arid regions of Moroccan [Adiba et al., 2021, 2023 2024a, 2024b; El Fallah et al., 2024; Hamdani et al., 2021, 2024]. The stability of pH levels across seasons and stations, ranging from neutral to slightly alkaline, suggests that the groundwater in Doukkala maintains a consistent buffering capacity, likely influenced by the local geological composition, which may contain carbonate minerals that naturally buffer pH changes. This stability is particularly important for agricultural applications, as it helps maintain soil health and nutrient availability [Hajihashemi et al., 2018]. Additionally, consistent agricultural and irrigation practices in the region might contribute to this pH stability by introducing limited seasonal variability in water quality parameters. This pattern aligns with observations in other Mediterranean regions, where groundwater pH remains relatively stable across seasons, despite environmental shifts [Boujghad et al., 2019; Zouahri et al., 2015].

The significant seasonal and spatial variation in electrical conductivity, with higher values in summer, may be attributed to increased evapotranspiration and reduced recharge rates during the dry season, leading to the concentration of dissolved salts in the groundwater [Yuan et al., 2022]. Similar patterns have been reported in the studies conducted in arid and semi-arid regions of North Africa and the Middle East, where elevated conductivity levels during the dry season are linked to the concentration of salts due to limited water recharge [Adnani et al., 2020; Kurunc et al., 2016]. The variation in conductivity across stations may also reflect differences in local geology and land use, influencing the mineral content and ion concentration of the groundwater [Gupta and Roy, 2012].

The permeability index, which indicates the suitability of groundwater for irrigation, showed significant variability across stations and seasons, highlighting the influence of ion composition on water quality. Higher permeability index values observed in some stations during the summer suggest a greater concentration of sodium ions, which can affect soil structure and crop yield if used for irrigation without proper management [Rawat et al., 2018]. The observed values are consistent with studies conducted in other agricultural regions where seasonal changes in groundwater composition impact its suitability for irrigation [Kadam et al., 2021]. These findings underscore the importance of continuous monitoring and management of groundwater resources in the Doukkala region to ensure sustainable agricultural practices and water quality.

Ionic composition

The data in Table 3 illustrates the seasonal variation of groundwater ionic composition in the Doukkala region, capturing changes in ion concentrations between summer and winter across different sampling sites (S1 to S9). Significant differences were found between stations for all tested ions except Mn^{2+} and NO_2^-. Sodium (Na^+) concentration was especially high at the 'Ouled Chaikh' station, reaching 1010.00 mg/L

Table 3. Seasonal variation of groundwater ionic composition in the Doukkala region

Station		Na^+	Cl^-	K^+	Ca^{2+}	Mg^{2+}	Mn^{2+}	HCO_3^-	SO_4^{2-}	NH_4^+	NO_2^-	NO_3^-
S1	Summer	387.67 cd	940.33 bcd	8.86 b	302.33 ab	140.33 abc	0.05	203.67 c	612.67 ab	0.02	0.01 c	68.73 abc
	Winter	335 bc	790.5 c	8.4825 b	348 a	113.1 bc	0.05	188 cde	710.25 ab	0.02	0.01 b	51.75 cd
S2	Summer	575.33 c	1242.33 bc	12.59 ab	338.00 a	179.33 a	0.05	253.33 bc	761.33 a	0.02	0.05 ab	51.23 bcd
	Winter	247.5 c	557.25 cd	5.95 a	362.5 a	95.6 bcd	0.05	200.5 cde	757.5 a	0.023	0.012 b	48.85 cd
S3	Summer	383.00 cd	937.33 bcd	3.42 c	186.33 bc	110.37 cd	0.05	313.67 ab	132.67 de	0.02	0.015 c	33.27 d
	Winter	412.75 bc	891.50 bc	3.61 c	208.75 b	85.20 cd	0.07	302.00 bcd	126.75	0.16	0.03 b	29.38 de
S4	Summer	289.50 d	593.00 cd	4.15 c	144.10 c	101.90 d	0.05	250.00 bc	310.00 bcd	0.04	0.01 c	39.70 cd
	Winter	270.33 c	610.00 cd	3.97 c	222.33 b	63.40 d	0.07	245.00 cd	317.67 bc	0.08	0.02 ab	33.67 de
S5	Summer	301.00 d	679.67 cd	1.22 d	170.37 bc	121.90 bcd	0.06	326.67 ab	282.00 cd	0.02	0.02 c	70.67 abc
	Winter	281.50 c	630.50 cd	1.09 d	271.75 ab	57.43 d	0.07	325.25 bc	273.25 cd	0.02	0.01 b	63.38 bcd
S6	Summer	1010.00 a	1668.00 a	1.74 d	98.17 cd	139.33 abc	0.05	289.67 abc	286.67 cd	0.02	0.02 c	85.23 ab
	Winter	1038.33 a	1868.00 a	2.17 cd	151.00 c	120.00 abc	0.07	282.00 bcd	333.33 bc	0.02	0.01 b	71.80 bc
S7	Summer	270.67 e	226.33 d	1.99 d	43.43 d	23.57 e	0.05	392.67 a	61.43 f	0.02	0.03 bc	65.73 bc
	Winter	275.50 c	211.25 d	1.52 cd	46.35 d	17.90 e	0.06	429.50 a	62.23 e	0.02	0.03 a	65.55 bc
S8	Summer	467.5 c	1336.5 bc	3.98 c	227 abc	159 ab	0.05	251 bc	90.7 de	0.018	0.016 c	27.8 e
	Winter	446.00 bc	1320.33 bc	4.28 c	267.33 ab	136.33 ab	0.08	252.67 cd	97.70 de	0.02	0.01 b	24.07 e
S9	Summer	664.33 b	1335.33 bc	13.54 a	283.00 ab	143.67 abc	0.05	293.00 abc	524.00 bc	0.02	0.08 a	91.30 a
	Winter	855.50 ab	1695.50 ab	15.76 a	211.75 b	163.50 a	0.07	367.00 bc	260.50 cd	0.02	0.03 a	100.75 a
ANOVA	-	*	*	*	*	*	ns	*	-	ns	*	*

Note: Ns: non-significant difference; *: significant difference at $p < 0.05$.

in summer and 1038.33 mg/L in winter. Similarly, chloride (Cl^-) levels were elevated at this site, with 1668.00 mg/L in summer and 1868.00 mg/L in winter. Thus, the water potassium (K^+) content, exhibits considerable variation, particularly in site S9, where it reaches 13.54 mg/L in summer and 15.76 mg/L in winter. In contrast, much lower potassium levels were recorded at the 'Laatatra' site (S5), highlighting spatial heterogeneity in groundwater chemistry. For the calcium (Ca^{2+}) and magnesium (Mg^{2+}) content, the data revealed that 'Ouled Rbia' (S2), has the highest calcium and magnesium levels, particularly in summer (338.00 mg/L and 179.33 mg/L respectively); however, 'Faiss Bouchaib' (S7), displays the lowest calcium concentrations, with 43.43 mg/L and 23.57 mg/L in summer and 46.35 mg/L and 17.90 mg/L in winter.

Notably, the finding reported that the highest bicarbonate (HCO_3^-) concentration was observed in the 'Faiss Bouchaib' (S7) station peaking at 392.67 mg/L in summer and 429.50 mg/L in winter, which suggests significant carbonate weathering or organic matter decomposition. However, 'Fatna Ben Haddou' (S1) exhibits lower bicarbonate levels, with 203.67 mg/L in summer and 188 mg/L in winter. For the sulfate (SO_4^{2-}) concentration in the groundwater of the Doukkala region, the highest values were observed in the S2 experimental station (761.33 mg/L in summer, and 757.5 mg/L in winter), while the lowest values were detected in the S3 station, with 61.43 mg/L in summer and 62.23 mg/L in winter. On the other hand, for the nitrite (NO_2^-) content, the 'Slaoui' station (S9), records a slight increase in nitrite levels during summer (0.08 mg/L), while other sites show consistently low concentrations, indicating minimal impact from nitrite contamination. Similarly, for the nitrate (NO_2^-) concentration, the S9 simples exhibit the highest nitrate levels, with 91.30 mg/L in summer and 100.75 mg/L in winter; however, the S8 simples show the lowest nitrate concentrations, with 27.8 mg/L in summer and 24.07 mg/L in winter.

A comprehensive analysis of the variation in major ions, such as Na^+, Cl^-, K^+, NH_4^+, Ca^{2+}, Mg^{2+}, Mn^{2+}, NO_3^-, NO_2^-, HCO_3^-, and SO_4^{2-} within groundwater samples is imperative for a nuanced understanding of the groundwater composition and overall quality [Avci et al., 2018; Ravikumar et al., 2010]. In this sense, the high sodium and chloride concentrations at the 'Ouled Chaikh' station, with levels exceeding 1000 mg/L for Na^+ and 1600 mg/L for Cl^-, are indicative of significant salinization, which could be attributed to the intrusion of saline water or the dissolution of evaporite deposits [Jalali et al., 2019]. Similar findings were reported by Attar et al. [2022] who revealed elevated sodium and chloride levels in the Souss-Massa basin, Morocco, attributing them to over-extraction of groundwater leading to seawater intrusion and the dissolution of halite deposits. Thus, potassium levels, particularly at site S9, show considerable seasonal variation, which might be influenced by agricultural practices, such as the use of potassium-rich fertilizers, as suggested by Malki et al. [2017] in their study of groundwater in the Chtouka-Massa, Morocco. The spatial variability observed, especially the contrast between sites S9 and S5, underscores the influence of local factors, such as soil composition and land use. For the calcium and magnesium levels are highest in the 'Ouled Rbia' (S2) station, particularly during summer, which aligns with findings from other semi-arid regions where higher temperatures enhance the dissolution of carbonate minerals, leading to increased concentrations of these ions [Ouhakki et al., 2024b]. In contrast, the lower concentrations observed at the 'Faiss Bouchaib' (S7) station suggest limited mineral dissolution, possibly due to lower temperatures and different geological substrates [Ouhakki et al. 2024].

The high bicarbonate concentrations at some stations, such as the 'Faiss Bouchaib' (S7) station, could indicate significant carbonate weathering or the decomposition of organic matter, processes known to increase the bicarbonate levels in groundwater [Macpherson et al., 2008]. On the other hand, the lower bicarbonate levels were linked to the presence of less reactive carbonate rocks or reduced organic matter inputs [Seibert et al., 2016].

For the sulfate, the highest concentrations were notably a result of the oxidation of sulfide minerals or the dissolution of gypsum, as documented in similar contexts by Sharma and Kumar [2020]. However, the low sulfate concentration reported at the S3 station can be related to the minimal interaction with sulfate-bearing minerals or limited anthropogenic inputs [Han et al., 2016].

The nitrite and nitrate levels show distinct patterns in the Doukkala region, with the highest nitrate concentrations observed at the S9 station, particularly in winter. This could be indicative of agricultural runoff, as nitrates are common components of fertilizers. This pattern aligns with the findings by Craswell [2021], who observed elevated nitrate levels in agricultural areas due to fertilizer use. The relatively low nitrate levels at the S8 station could suggest less intensive agricultural activity or more effective nitrate attenuation mechanisms in the local aquifer. Overall, the findings from the Doukkala region highlight the complex interplay between geological, climatic, and anthropogenic factors in shaping groundwater chemistry.

Table 4 presents seasonal variations in groundwater hydrotimetric titre (HT), total alkalimetric titre (TAC), residual alkalinity (RAS), and total iron content (TI) across different experimental sites (S1 to S9) during summer and winter season. The finding reveals substantial site-specific disparities and seasonal fluctuations, particularly in RAS and TI. Indeed, samples of the experimental station 'Ouled Rbia' (S2) exhibit significantly elevated HT values during summer (158.03), indicating pronounced water hardness, whereas the samples of the site S7 consistently demonstrate the highest TAC values, reaching 35.20 in winter. Thus, the RAS measurements underscore notable seasonal variability, with sites S6 and S9 presenting peak values in winter (4218.33 and 4299.00, respectively). Conversely, the experimental station (S3) manifests lowest RAS values, particularly in winter, underscoring intraregional heterogeneity. The TI levels remain predominantly low across most analyzed stations, except for a notable increase at the S3 station, during winter (0.59), suggesting localized iron contamination.

The analysis of seasonal variations in groundwater hydrotimetric titre, total alkalimetric titre, residual alkalinity, and total iron content across the experimental sites in Doukkala reveals significant site-specific disparities and temporal fluctuations. Indeed, the pronounced increase in HT values during the summer at some regions, such as Ouled Rbia station highlights the susceptibility of the region to increased water hydrotimetric titre under elevated temperatures. These findings align with studies conducted in similar semi-arid regions, where seasonal temperature variations have been observed to influence water hydrotimetric, likely due to changes in the solubility of calcium and magnesium salts [Nassri et al., 2024].

Furthermore, the consistently high TAC values at the 'Faiss Bouchaib' suggest a possible influence of local geological formations rich in bicarbonates, which could contribute to higher alkalinity. This pattern is consistent with research

Table 4. Seasonal variation of groundwater hydrotimetric titre, total alkalimetric titre, residual alkalinity and total iron content in the Doukkala region

Station		HT	TAC	RAS	TI
S1	Summer	133.07 ab	16.67 c	2780.00 cd	0.11 ab
	Winter	133.25 a	15.425 c	2356 cd	0.13 ab
S2	Summer	158.03 a	20.77 b	3751.67 ab	0.09 b
	Winter	129.72 a	16.45 c	2199.5 cd	0.05 abc
S3	Summer	91.90 bc	25.70 ab	2346.00 d	0.14 ab
	Winter	87.15 bc	24.75 ab	2367.00 cd	0.59 abc
S4	Summer	77.90 cd	20.50 b	1960.50 e	0.15 ab
	Winter	81.57 cd	20.10 bc	1941.67 d	0.19 a
S5	Summer	92.70 bc	26.80 ab	2200.00 d	0.09 b
	Winter	91.43 bc	26.68 ab	2143.50 cd	0.10 ab
S6	Summer	81.70 bcd	23.73 ab	3984.00 a	0.16 ab
	Winter	87.05 bc	23.10 ab	4218.33 a	0.09 ab
S7	Summer	20.50 e	33.17 a	1026.00 e	0.07 b
	Winter	18.93 e	35.20 a	1020.25 e	0.07 ab
S8	Summer	122.2 abc	20.6 b	3185 bc	0.25 a
	Winter	122.67 ab	20.73 bc	3098.00 bc	0.09 ab
S9	Summer	129.67 ab	24.03 ab	4057.67 a	0.10 ab
	Winter	120.25 ab	30.08 a	4299.00 a	0.09 ab
ANOVA	-	*	*	*	*

Note: Ns: non-significant difference; *: significant difference at $p < 0.05$.

conducted in other regions, such as the Mediterranean basin, where groundwater alkalinity has been attributed to the dissolution of carbonate minerals under cooler temperatures [Farid et al., 2015].

The substantial seasonal variability observed in RAS in the experimental stations, with peak values recorded at sites S6 and S9 during winter, underscores the complex interplay between temperature, precipitation, and aquifer characteristics in influencing groundwater chemistry. These findings are in line with studies from other regions with similar climatic conditions, where seasonal shifts in residual alkalinity have been linked to fluctuations in recharge rates and the chemical weathering of silicate minerals [Kenoyer and Bowser, 1992]. The lower RAS values at the S3 station, particularly during winter, further emphasize the intraregional heterogeneity, which can be driven by localized differences in soil composition and groundwater flow dynamics [Ouhakki et al., 2024a].

The low TI levels across most stations, with the exception of the notable increase at S3 during winter (0.59), suggest that iron contamination is not widespread but rather localized, potentially linked to specific anthropogenic activities or the presence of iron-rich sediments in the vicinity [Kontny et al., 2021]. Similar localized increases in groundwater iron content have been documented in studies from other regions, where the mobilization of iron is often associated with reductive dissolution processes under anoxic conditions [Annaduzzaman et al., 2021; Xia et al., 2022]. Overall, these findings provide valuable insights into the spatial and temporal dynamics of groundwater quality in the Doukkala region, contributing to the broader understanding of how seasonal and site-specific factors influence hydrochemical characteristics.

Bacteriological traits

Table 5 presents the seasonal variation in groundwater contamination by total coliforms (CT), fecal coliforms (CF), fecal staphylococcus (SF), and the ratio of CF to SF (CF/SF) across nine experimental stations (S1 to S9) during summer and winter. Indeed, a significant variation between the experimental stations is observed in all analyzed bacterial compositions. Indeed, CT values range from 153 (S3) to 80307 CFU/100 ml (S9) in summer and from 49 (S5) to 26321 CFU/100 ml (S7) in winter. For the CF content, the data revealed the values ranged from 35 (S3) to 12371 CFU/100 ml (S9) in summer and from

Table 5. Seasonal variation of groundwater bacteriological traits in the Doukkala region

Station	Season	CT	CF	SF	CF/SF
S1	Summer	273 d	75 de	30 e	2.54 bc
	Winter	10803 abc	292 cd	167 cd	1.75bc
S2	Summer	33870 bcd	1177 bc	1382 ab	0.85 cd
	Winter	1973 bc	196 d	131 cd	1.50 bc
S3	Summer	153 e	35 e	130 d	0.27 e
	Winter	18113 ab	1370 bc	1278 ab	1.07 bc
S4	Summer	30800 bc	3500 b	550 c	6.36 ab
	Winter	17202 ab	2486 a	845 bc	2.94 ab
S5	Summer	251 d	55 de	31 e	1.76 bc
	Winter	49 d	16 f	14 f	1.14 bc
S6	Summer	11573 cd	687 d	1633 a	0.42 d
	Winter	92 d	60 de	44 de	1.37 bc
S7	Summer	20640 bcd	962 cd	539 c	1.78 bc
	Winter	26321 a	2118 ab	1423 a	1.49 bc
S8	Summer	21015 bcd	960 cd	320 cd	3.00 b
	Winter	574 cd	190 d	52 de	3.63 a
S9	Summer	80307 a	12371 a	1463 ab	8.45 a
	Winter	15028 ab	595 c	363 c	1.64 bc
ANOVA	-	*	*	*	*

Note: CT: Total coliforms; CF: Fecal coliforms, SF: Fecal staphylococcus, Ns: non-significant difference; *: significant difference at $p < 0.05$.

16 (S5) to 2486 CFU/100 ml (S4) in winter. The S1 station revealed the lowest SF values in summer, while in the S6 station the highest values were detected (1633 CFU/100 ml) in this season. However, during winter the SF values ranged from 14 in S5 to 1423 CFU/100 ml in S7 station. On the other hand, the CF/SF ratio ranges from 0.27 (S3) to 8.45 (S9) in summer and from 1.07 (S3) to 3.63 (S8) in winter.

The results indicate a marked fluctuation in bacterial contamination levels between summer and winter, suggesting the influence of environmental factors and human activities on groundwater quality [Wang et al., 2023]. During the summer, the CT values were notably higher at most stations, this seasonal increase in CT levels during the warmer months aligns with the findings from other studies in Mediterranean regions, where elevated temperatures and increased agricultural activity have been linked to higher bacterial contamination in groundwater [Jorge-Mardomingo et al., 2015; Mas-Pla and Menció, 2019]. Similarly, the CF content exhibited substantial seasonal variation, with a peak of 12.371 CFU/100 ml at S9 in summer, significantly higher than the winter values. This trend may be attributed to the increased survival and proliferation of fecal coliforms in warmer temperatures, as well as potential runoff from agricultural fields during irrigation [Pachepsky et al., 2011].

However, the SF values also demonstrated seasonal variability, with the highest levels observed at S6 in summer (1633 CFU/100 ml) and a noticeable decline in winter. The lower SF concentrations during the cooler season may reflect reduced bacterial growth rates and lower levels of contamination sources such as livestock or human waste, consistent with observations in similar studies conducted in semi-arid regions [Kim and Kim, 2012]. Furthermore, the CF/SF ratio, an indicator of the relative contribution of fecal coliforms and staphylococci to groundwater contamination, varied considerably between seasons and stations [Djatsa et al., 2022]. The highest CF/SF ratio was observed at S9 in summer, suggesting a predominance of fecal coliform contamination, potentially due to agricultural runoff or wastewater discharge [Mherzi et al., 2020]. In contrast, lower ratios in winter across various stations indicate a more balanced or reduced contamination level, likely influenced by seasonal changes in water usage and environmental conditions [Mherzi et al., 2020]. These results underscore the importance of considering seasonal factors in groundwater quality assessments, as they highlight the dynamic nature of bacterial contamination in response to environmental and anthropogenic influences. The observed patterns of variation in Doukkala are consistent with findings from other regions with similar climatic conditions in Morocco, emphasizing the need for targeted water management strategies to address seasonal contamination risks [Ouhakki et al., 2024b].

Correlation among analyzed traits

To gain deeper insights into the impact of seasonal and temporal dynamics on groundwater quality in Doukkala, a bivariate correlation analysis was conducted using the Pearson correlation coefficient. This analysis examined the relationships between all mean values of the analyzed traits. Statistically significant correlations at the 0.05 and 0.01 levels are highlighted and reported in Table 6. Indeed, the effect of the seasonal variation on the temperature and total alkalimetric titre were positively correlated at r = 0.615, suggesting that higher temperatures are associated with increased alkalinity in the groundwater. This could be attributed to the enhanced dissolution of carbonate minerals at higher temperatures, which contributes to alkalinity. Similar results were reported in the groundwater of other Moroccan regions [Ouhakki et al., 2024b]. The variation of the groundwater EC in the Doukkala region is highly correlated with potassium content with, hydrotimetric titre and total alkalimetric titre with a correlation coefficient of 0.983, 0.997 and 0.716 respectively, indicating that higher EC values, which reflect increased ionic concentration, are associated with greater levels of potassium and alkalimetric in the groundwater of this region. This relationship is consistent with the idea that EC is good indicators of overall mineral content in groundwater which conforms to the results of Sarker et al. [2020].

Thus, the seasonal variation of the groundwater NH_4^+ content was positively correlated with several ionic traits, including sodium (Na^+) (r = 0.682), calcium (Ca^{2+}) (r = 0.721), magnesium (Mg^{2+}) (r = 0.708), chloride (Cl^-) (r = 0.685) and sulfate (SO_4^{2-}) (r = 0.703). These correlations suggest that the areas with higher ammonium levels tend to have higher concentrations of these major cations and anions, potentially due to anthropogenic inputs or natural geochemical processes.

Table 6. Matrix of coefficients correlations between the analyzed traits involved in the study

	T	pH	EC	NH_4^+	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	NO_2^-	NO_3^-	HCO_3^-	TI	SO_4^{2-}	TH	TAC
T	1															
pH	-0.129	1														
EC	0.329	-0.431	1													
NH_4^+	0.243	-0.488	0.704*	1												
Na^+	0.132	-0.638*	0.400	0.682*	1											
K^+	0.268	-0.504	0.983**	0.715*	-0.682*	1										
Ca^{2+}	0.203	-0.403	-0.531	0.721*	-0.063	0.169	1									
Mg^{2+}	0.242	-0.496	0.228	0.708*	0.005	0.288	0.685*	1								
Cl^-	0.321	-0.444	-0.496	0.685*	0.024	-0.364	0.418	0.685*	1							
NO_2^-	0.112	0.519	-0.046	-0.142	-0.043	-0.063	-0.067	-0.067	-0.041	1						
NO_3^-	-0.434	-0.245	-0.311	0.240	-0.300	-0.237	-0.240	-0.274	-0.296	-0.100	1					
HCO_3^-	-0.755*	0.129	-0.679*	-0.300	-0.571	-0.551	-0.553	-0.683*	-0.673*	-0.148	0.657*	1				
TI	0.111	0.270	0.511	0.366	0.706*	0.634*	0.660*	0.665*	0.702*	0.359	-0.560	-0.701*	1			
SO_{42}^-	0.388	-0.502	-0.081	0.703*	0.708*	0.578	-0.673*	-0.297	-0.560	-0.090	-0.297	-0.712*	0.657	1		
TH	0.234	-0.505	0.997**	0.712*	0.366	-0.218	0.401	-0.101	-0.217	-0.069	-0.263	-0.677*	0.658*	0.998**	1	
TAC	0.615*	-0.546	0.078	0.720*	0.578	0.129	-0.683*	0.401	-0.148	-0.063	-0.217	-0.660*	0.620*	0.983**	0.997**	1

Note: ** Correlation is significant at the 0.01 level. * Correlation is significant at the 0.05 level.

In addition, the variation of the groundwater bicarbonate (HCO_3^-) under the environmental conditions of the Doukkala region has a significant negative correlation with temperature variation (r = -0.755), indicating that bicarbonate concentrations decrease as temperatures increase, possibly due to decreased solubility of carbonates at higher temperatures. In the same, the TI variation shows positive correlations with several traits, including sodium (Na^+), potassium (K^+), and sulfate (SO_4^{2-}), suggesting that iron content may be influenced by similar geochemical processes or sources as these ions. On the other hand, the seasonal effect of the environmental conditions of the groundwater TAC is strongly correlated with TH (r = 0.997) and sulfate (SO_4^{2-}) (r = 0.983), indicating that total alkalinity in the groundwater is closely tied to the presence of these ions.

CONCLUSIONS

This study provides valuable insights into groundwater resources in Doukkala, Morocco, but it is essential to acknowledge certain limitations, including the spatial coverage and sample size, which may affect the generalizability of the obtained findings. While the analysis of physicochemical and bacteriological parameters across multiple wells has highlighted significant seasonal and temporal variations in water quality, indicating that many stations exhibit groundwater quality ranging from medium to poor, further research is necessary. Future studies should focus on expanding the spatial coverage and increasing sample sizes to develop a more comprehensive understanding of groundwater dynamics in the region. Additionally, investigating the underlying factors contributing to elevated nitrate levels and microbial contamination will be crucial for informing effective groundwater management strategies. By addressing these limitations and pursuing these research directions, the understanding of groundwater sustainability and the impacts of agricultural activities in Doukkala can be enhanced.

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