JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2024, 25(9), 81–91
https://doi.org/10.12911/22998993/190684
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.06.12
Accepted: 2024.07.21
Published: 2024.08.01

Assessing Groundwater Quality and its Impact on Agricultural Productivity in Morocco

Hicham Ouhakki[1*], Kamal El Fallah[2], Atman Adiba[3], Taouil Hamid[1], Nouredine El Mejdoub[1]

[1] Laboratory Organic Chemistry, Catalysis and Environment, Department of Chemistry, Faculty of Science, University Ibn Toufail, BP 133-14000 Kenitra, Morocco

[2] Laboratory of Natural Resources and Sustainable Development, Department of Biology, Faculty of Science, University Ibn Toufail, BP 133-14000, Kenitra, Morocco

[3] Regional Agricultural Research Center of Tadla, National Institute of Agricultural Research, Avenue Ennasr, P.O. Box 415, Rabat 10090, Morocco

* Corresponding author's e-mail: ouhakki_hic@yahoo.fr

ABSTRACT

This study investigates the relationship between groundwater quality and agricultural productivity across six experimental stations in Morocco: Doukkala, Bahira, Tassaout, Beni Amir, Beni Moussa and Tadla. To assess groundwater suitability for irrigation, a comprehensive suite of indices was employed, including the permeability index (PI), Kelly index (KI), sodium strength percentage (SSP), sodium adsorption ratio (SAR), residual sodium carbonate (RSBC), magnesium hazard (MH), Langelier saturation index (LSI), Ryznar stability index (RSI), aggression index (AI), Larson and Skold index (LS), and Puckorious saturation index (PSI). Results indicated significant variations among the stations. Doukkala showed moderate permeability and low salinity risk but high sodium levels (SSP 50.14, SAR 6.87). Bahira had similar trends with slightly higher PI and KI values. Tassaout demonstrated lower values across all indices, suggesting better groundwater quality. Beni Amir and Beni Moussa exhibited decreasing trends in indices, with Beni Moussa having the lowest values overall. Notably, Beni Amir had the most negative RSBC value, indicating a high sodium hazard and potential soil structure issues, while Tadla had the least negative RSBC value, indicating favorable conditions. Water in Beni Amir and Beni Moussa, with MH values of 56.37 and 56.84 respectively, was deemed unsuitable for irrigation, whereas Doukkala, Bahira, Tassaout, and Tadla, with MH values below 50, were considered suitable. The study concludes that groundwater quality varies significantly across regions, impacting agricultural productivity, with some regions posing higher risks due to sodium and magnesium hazards.

Keywords: groundwater quality, agricultural productivity, irrigation suitability, water quality indices, sustainable water management.

INTRODUCTION

Agriculture is the largest consumer of water worldwide, with irrigation systems accounting for approximately 70% of global freshwater withdrawals [Hossain et al., 2020]. Groundwater plays a crucial role in providing irrigation water, particularly in semi-arid regions where surface water sources are limited [Gao et al., 2018]. In many agricultural regions, farmers predominantly rely on groundwater for their irrigation needs due to its reliability as a water source [Shil et al., 2019]. Consequently, the use of groundwater for irrigation has been increasing, often resulting in unsustainable levels of exploitation [Foster et al., 2018]. This trend raises significant concerns about the long-term viability of groundwater resources and highlights the need for sustainable management practices [Gleeson et al., 2012]. Furthermore, the quality of the groundwater used for irrigation is a crucial factor that directly affects the productivity of the irrigation process [Pulido-Bosch et al., 2018]. Furthermore, several studies have revealed that the water productivity and the efficiency of irrigated water are crucial for ensuring food security [Rickson et al., 2015; Issaka and Ashraf, 2017]. Indeed, the crop yields are significantly influenced by both water intake and the properties of soil and irrigation water [Choudhary et al., 2011]. The chemistry of irrigation water, including the concentration of dissolved salts and ions, is a key factor in determining its quality [Zaman et al., 2018]. This quality not only affects crop yields but also the nutritional value of the crops. Additionally, contaminants present in irrigation water can be absorbed by plants, potentially entering the human diet [Khalid et al., 2018]. Therefore, assessing the quality of irrigation water is essential for accurately predicting crop yields and ensuring sustainable agricultural practices.

The natural geochemical processes are the most important factors that influence groundwater chemistry [Ren et al., 2021]. These include the geological characteristics of the aquifers, the quality of recharging water, the chemical weathering of different rock types, the length of time water resides in aquifers, and a range of dissolution, precipitation, interactions with soil gases, and ion exchange reactions [Thockchom and Kshetrimayum, 2019; Hossain et al., 2020]. In addition to these natural processes, human activities such as the disposal of industrial waste, agricultural practices and sewage contribute significantly to the presence of undesirable elements in groundwater, leading to its deterioration [Akhtar et al., 2021]. Consequently, many countries are currently facing a shortage of suitable groundwater for irrigation purposes.

Several variables, including toxic metals such as total Cu^{2+}, Fe, Ni^{2+}, Zn^{2+}, Co^{2+}, Pb^{2+} and Cd^{2+}, along with excess concentrations of cations (Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}) and anions (HCO_3^-, SO_4^{2-}, Cl^-, NO_3^-, PO_4^{3-}), as well as organic salts, are recognized as significant water contaminants [Hossain et al., 2020]. To address these issues, various water quality indices have been developed and are extensively used to assess the suitability of water for irrigation. Among the most commonly applied indices are electrical conductivity [Lauer et al., 2023], magnesium hazard [Chebet et al., 2021], soluble sodium percentage [Aydin et al., 2021], residual sodium carbonate [Ahsan et al., 2021], permeability index [Batarseh et al., 2021], and sodium adsorption ratio [El Bilali and Taleb, 2020]. These indices provide critical qualitative assessments that are instrumental in the development of effective groundwater management strategies by public and regulatory authorities, ensuring sustainable agricultural practices and water resource management [Calliera et al., 2021].

The present study aims to assess groundwater quality and its impact on agricultural productivity across six experimental stations. A multi-index approach will be employed, utilizing a combination of key indices including the irrigation potential (IP), Kelly's index (KI), sodium adsorption ratio (SAR), residual sodium carbonate (RSBC), magnesium hazard (MH), irrigation suitability index (ISI), sodium percentage (SP) and others. This comprehensive approach offers a holistic perspective on groundwater quality and its implications for agricultural practices, enabling a nuanced understanding of the relationships between groundwater characteristics and their impact on crop yields and soil health. The significance of this study lies in its potential to guide sustainable groundwater management practices and optimize agricultural productivity in diverse agro-climatic regions. Understanding the intricate relationships between groundwater quality and agricultural productivity is essential for developing effective water resource management strategies. Furthermore, it is crucial for mitigating the negative impacts of declining water quality on crop yields, soil properties and ultimately human well-being.

MATERIAL AND METHODS

Study area

The study encompassed a geographically diverse expanse in Morocco, specifically targeting six distinct regions: Doukkala, Bahira, Tassaout, Beni Amir, Beni Moussa, and Tadla (Fig. 1). A central aspect of this investigation was the determination of fifty-six safeguarded dug wells distributed throughout these areas. This broad geographic distribution was meticulously chosen to encapsulate a wide array of hydrogeological variations, thereby providing a thorough understanding of water quality and the sustainability of dug wells in varied environmental settings. Each region was deliberately selected for its unique geological and hydrological traits, ensuring that the study could offer a comprehensive analysis of the factors affecting water quality in these protected dug wells. The strategic selection of these regions was designed to yield valuable insights

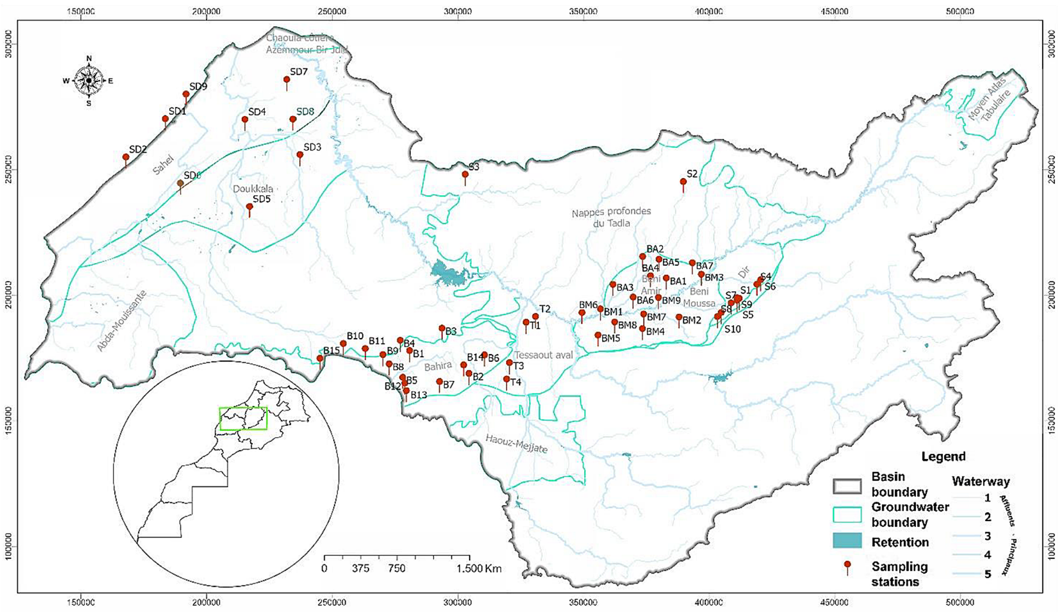

Figure 1. Location map of the study area

into water resource management and conservation strategies, addressing broader implications for the effective stewardship of water resources in the areas under study.

Sampling

Groundwater samples were meticulously collected from six experimental stations in Morocco, ensuring the preservation of their integrity through a carefully controlled process. Clean polypropylene bottles were employed for sample collection, having been pre-cleaned with a 10% nitric acid solution and thoroughly rinsed with double-distilled water to eliminate any potential contaminants. Each sample, precisely measured at 125 ml, was stored at a controlled temperature of 4 °C, adhering to the standards set forth by the APHA [2005]. This meticulous storage protocol is critical for maintaining the stability of the samples and preventing any alterations in their hydrochemical and bacteriological properties during storage. Additionally, a portion of each sample was vacuum-filtered through a 0.45 Millipore membrane filter paper to eliminate particulate matter, ensuring a clear distinction between filtered and unfiltered samples. For comprehensive analysis, an unfiltered portion of 250 ml was also retained, facilitating a direct comparison with the filtered samples and providing a more complete understanding of the groundwater's original composition.

Water analysis

Permeability index

The permeability index is determined using the approach proposed by [Joshi et al., 2009]. The formula for PI is:

$$PI = [(Na^+ + HCO_3^-)/ /(Ca^{2+} + Mg^{2+} + Na^+)] \times 100 \tag{1}$$

The PI serves as a measure to assess the sodium risks associated with irrigation water.

Kelly index (KI)

The appropriateness of water properties for irrigation is also assessed using Kelly's index, which evaluates the proportion of sodium relative to calcium and magnesium. The Kelly index is determined using the formula [Srinivasamoorthy et al., 2014].

$$KI = Na^+ / (Ca^{2+} + Mg^{2+}) \tag{2}$$

A KI value greater than one (KI > 1) suggests an abundance of sodium, whereas a KI value less than one (KI < 1) indicates that the water is fit for irrigation purposes.

Soluble sodium percentage index

The percentage of sodium is frequently used to evaluate the suitability of water for agricultural purposes. This measurement is also referred to as the soluble sodium percentage (SSP), a term first introduced by Wilcox in 1955. SSP is calculated using the following formula:

$$SSP = Na^{+} \times 100 / (Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}) \quad (3)$$

According to study of Ravikumar et al. [2011], water with a sodium percentage exceeding 60% is deemed unsafe, while water with a sodium percentage below 60% is classified as safe for agricultural activities.

Sodium adsorption ratio

The sodium adsorption ratio serves as an essential measure for assessing irrigation water quality and used to measure the proportion of sodium ions relative to calcium and magnesium ions in water [Srinivasamoorthy et al., 2014]. Increased salinity impedes osmotic processes, reducing the soil's capacity to deliver water and nutrients to plants. This interference affects water transport to the aerial organs and disrupts plant metabolism [Arumugam and Elangovan 2009]. Indeed, water quality is categorized into four classes based on SAR values. Water with SAR less than 10 is classified as excellent. SAR values between 10 and 18 indicate good quality. SAR values ranging from 19 to 26 are considered doubtful or fair to poor. When SAR exceeds 26, the water is deemed unsuitable (class S-IV).

Residual sodium carbonate index

The residual sodium carbonate (RSBC) index was used to evaluate water quality concerning alkalinity hazards. The carbonate ions are usually absent in natural waters and bicarbonate ions do not precipitate magnesium ions. Consequently, the RSBC index serves as a more accurate measure of alkalinity hazards. The RSBC is determined using the formula provided by Ravikumar et al. (2011).

$$RSBC = HCO^{-}_{3} - Ca^{2+} \quad (4)$$

The concentrations of different ions are represented in meq/L.

Magnesium hazard

Typically, Ca^{2+} and Mg^{2+} are balanced in most water sources. Nevertheless, an excess of Mg^{2+} can negatively impact crop productivity [Ali and Ali 2018]. Magnesium can degrade soil structure, particularly in sodium-dominated and highly saline water. Elevated Mg^{2+} levels are often the result of exchangeable Na^{+} in irrigated soils. In this research, the magnesium hazard was calculated using the following formula:

$$MH = (Mg^{2+}) / (Ca^{2+} + Mg^{2+}) \quad (5)$$

A magnesium concentration exceeding 50 me/L is deemed detrimental, rendering the water unsuitable for both drinking and irrigation. In this study, magnesium hardness (MH) was found to vary from 12.6 to 65.4 meq/L. specifically; the water samples from points S1, S2, and S5 exhibited MH values above 50 meq/L, making them unsuitable for agricultural use.

Langelier saturation index

Measuring the Langelier saturation index (LSI) in water involves assessing its potential for scaling or corrosion. The LSI is calculated using parameters such as pH, temperature, total dissolved solids (TDS), calcium concentration, and alkalinity. By combining these factors, the LSI indicates whether the water is likely to deposit calcium carbonate (positive LSI), maintain equilibrium (LSI of zero), or dissolve calcium carbonate (negative LSI). The LSI can be determined using the following formula:

$$LSI = pHa - pHs \quad (6)$$

where: pHa represents the measured pH of the water, while pHs denotes the equilibrium pH of water with specific calcium content and alkalinity.

Ryznar stability index

The Ryznar index serves as a practical tool to forecast the likelihood of scaling in water systems, derived from observations of water performance across different saturation levels. Introduced by John Ryznar in 1944, the stability index incorporates the Langelier index into a novel formula, enhancing its precision in anticipating water's propensity for scaling or corrosion. The RSI can be determined using the following formula:

$$RSI = 2\,(pHs) - pH = pHs - LSI \quad (7)$$

Aggressive index

The aggressive index serves as a tool for monitoring water flow within asbestos pipes, offering insights into water corrosiveness as an alternative to the Langelier index. The AI provides a simpler and more practical assessment compared to the Langelier index, which accounts for temperature effects [Langelier, 1936]. The AI can be determined using the following formula:

$$AI = pH_{actual} + C + D \quad (8)$$

where: the C and D values are determined using the method of Langelier [1936].

Larson and Skold index

Measuring the Larson and Skold index (LS) in water involves evaluating the corrosive potential of the water, particularly in terms of its impact on metallic structures. This index is determined by analyzing the concentrations of chloride, sulfate, and bicarbonate ions in the water. High levels of chlorides and sulfates can increase water's corrosivity, while bicarbonates can mitigate this effect. By calculating the ratio of the harmful ions to the protective bicarbonates, the Larson and Skold index provides a useful metric for assessing the risk of corrosion in water systems. The LS was determined using the following formula:

$$LS = (Cl^{-} + SO_4^{2-})/(HCO_3 + CO_3^{2-}) \quad (9)$$

where: the LS value falls below 0.08, it suggests that chloride and sulfate are improbable to disrupt the formation of a protective film. However, when the LS value ranges between 0.8 and 1.2, corrosion rates might surpass anticipated levels. Conversely, an LS value exceeding 1.2 indicates a likelihood of elevated rates of localized corrosion.

Puckorious saturation index

Determining the Puckorius saturation index (PSI) in water involves evaluating the scaling potential and corrosive tendencies of water. The PSI provides insights into whether water will precipitate calcium carbonate, leading to scale formation, or if it will remain under saturated, potentially causing corrosion. This index is particularly useful in managing water treatment processes to maintain system efficiency and longevity. The interpretation of the PSI is similar to the interpretations used for RSI.

Data analyses

To comprehensively assess the variation of water quality indices across six experimental stations, the dataset comprising measurements from each station was subjected to descriptive statistical analysis to characterize central tendency and dispersion measures for each quality index. Additionally, analysis of variance (ANOVA) was employed to evaluate the significance of differences among the experimental stations. Student-Newman and Keuls test (SNK) was utilized to identify specific pairwise differences between stations at $p \leq 0.05$. This robust statistical approach provided valuable insights into the spatial variability of water quality indices among the experimental stations, facilitating a deeper understanding of the factors influencing water quality in the study area.

RESULTS AND DISCUSSION

The Table 1 presents a comprehensive overview of the variation in groundwater quality across six regions in Morocco, as indicated by four key indices: permeability index, Kelly index, sodium ion (Na^+) strength percentage index and sodium adsorption ratio. Across the regions, notable differences are observed in these indices, reflecting diverse groundwater characteristics. In the Doukkala region, the permeability index stands at 56.54, indicating moderate permeability, while the Kelly index of 1.28 suggests a relatively low risk of water salinity. However, the Na^+ SSP and SAR index are notably high at 50.14 and 6.87, respectively, signifying elevated sodium levels and potential risks associated with sodium adsorption. In Bahira, a similar pattern is observed with slightly higher values for PI and KI at

Table 1. Variation of permeability index (PI), Kelly index (KI), sodium ion (Na+), strength percentage index (SSP) and sodium adsorption ratio (SAR)

Station	IP	KI	SSP	SAR
Doukkala	56.54 a	1.28 a	50.14 a	6.87
Bahira	59.77 a	0.95 ab	47.63 ab	4.37
Tassaout	48.21 ab	0.52 bc	33.73 cd	2.54
Beni amir	45.44 ab	0.83 abc	40.86 bc	5.95
Beni moussa	37.69 c	0.49 c	23.28 d	2.00
Tadla	43.61 b	0.15 d	12.59 e	0.63
	*	*	*	ns

Note: values with different letters indicate significant difference ($p < 0.05$, SNK test); ns: non-significant difference; *: significant difference at $p < 0.05$.

59.77 and 0.95, respectively, while SSP and SAR remain high but comparatively lower than Doukkala, suggesting a comparable level of groundwater salinity and sodium content. Contrastingly, the Tassaout region exhibits lower values across all indices, indicating potentially better groundwater quality with a PI of 48.21, KI of 0.52, SSP of 33.73, and SAR of 2.54, suggesting lower salinity and sodium levels. Similarly, Beni Amir and Beni Moussa regions show decreasing trends in all indices, with Beni Moussa registering the lowest values overall, suggesting relatively good groundwater quality compared to other regions in the dataset. Remarkably, Tadla station stands out with the lowest values across all indices, indicating excellent groundwater quality with a PI of 43.61, KI of 0.15, SSP of 12.59 and SAR of 0.63, suggesting minimal risks associated with salinity and sodium content, making it potentially suitable for various applications without significant treatment requirements.

The obtained results induced that each region exhibits unique characteristics, as evidenced by variations in these indices. Indeed, in the Doukkala region, moderate permeability is noted with an elevated PI value, coupled with a relatively low risk of water salinity indicated by a high KI value. However, elevated levels of sodium are highlighted by the high SSP and SAR values of 50.14 and 6.87, respectively, suggesting potential risks associated with sodium adsorption [Acharya et al., 2018; Adimalla et al., 2018]. Similarly, the Bahira region mirrors this trend with slightly higher PI and KI values, yet comparable levels of salinity and sodium content. In contrast, the Tassaout region showcases lower values across all indices, indicative of potentially better groundwater quality, with lower salinity and sodium levels. Similar results were reported by Abualhaija et al. [2020] in Jordan, and Güngör and Arslan, [2016] in Turkey. Moreover, the Beni Amir and Beni Moussa regions exhibit decreasing trends in all indices, with Beni Moussa displaying the lowest values overall, implying relatively good groundwater quality based on the water quality assessment of Kalaivanan et al. [2018] compared to other tested regions. Notably, the Tadla station emerges as an outlier, demonstrating the lowest values across all indices, signaling excellent groundwater quality with minimal risks associated with salinity and sodium content, thus making it potentially suitable for various applications without significant treatment requirements based on the investigation method of Adimalla, [2019]. These results enhance our comprehension of the nuanced differences in groundwater quality among various regions of Morocco, emphasizing the significance of conducting assessments tailored to specific regions in water resource management and planning. This study complements existing research endeavors aimed at evaluating water quality in Morocco [Kanga et al., 2020; Ait Said et al., 2023; Al-Aizari et al., 2023; Ouhakki et al., 2024].

The variation in groundwater quality across six regions in Morocco through the analysis of the residual sodium carbonate index, magnesium hazard index, Langelier saturation index, and Ryznar stability index was presented in the Table 2. The findings revealed distinct patterns among the regions, suggesting notable differences in water quality parameters. Across the six regions in Morocco, significant variations in key water quality parameters were observed, highlighting the diverse characteristics of groundwater quality. For the RSBC index, the results exhibited that the Beni Amir region exhibited the most negative variation at -23.11, indicating a substantially higher sodium hazard compared

Table 2. Variation of the residual sodium carbonate index (RSBC), magnesium hazard index (MH), Langelier saturation index (LSI) and ryznar stability index (RSI) in the experimental stations

Station	RSBC	MH	LSI	RSI
Doukkala	-15.10 ab	45.14 b	-2.07	11.48
Bahira	-5.86 c	46.06 b	-2.05	11.55
Tassaout	-6.99 c	44.45 b	-2.02	11.54
Beni amir	-23.11 a	56.37 a	-2.31	11.80
Beni moussa	-11.07 bc	56.84 a	-2.47	12.19
Tadla	-1.27 d	37.82 c	-2.19	11.8
	*	*	ns	ns

Note: values with different letters indicate significant difference ($p < 0.05$, SNK test); ns: non-significant difference; *: significant difference at $p < 0.05$.

to other regions such as Doukkala (-15.10) and Beni Moussa (-11.07). Conversely, the Tadla region displayed the least negative RSBC value at -1.27, suggesting a lower sodium hazard level relative to other regions. Secondly, focusing on the magnesium hazard index, both Beni Amir and Beni Moussa regions displayed relatively higher values (56.37 and 56.84, respectively) compared to other regions, indicating a greater magnesium hazard. Conversely, Doukkala, Bahira, and Tassaout regions demonstrated lower MH indices, suggesting a comparatively lower magnesium hazard. Thirdly, the Langelier saturation index varied across the regions but this variation was not significant, with Beni Moussa exhibiting the most negative value at -2.47, indicating a higher tendency towards scaling, followed by Beni Amir (-2.31). Conversely, Doukkala, Bahira, and Tadla regions displayed relatively less negative LSI values, suggesting a lower propensity towards scaling. Finally, the Ryznar stability index showed relatively consistent values across the regions, with slight a not significant variation.

The study of these indices provides insightful data on regional variations and potential impacts on water usability for agriculture and human consumption. These findings align with and contrast other regional studies, revealing unique and comparable trends in groundwater quality parameters. Indeed, the finding induced that the Beni Amir region exhibited the most negative RSBC value indicates a significantly higher sodium hazard, which can adversely affect soil structure and crop yield. This extreme negative variation suggests more intensive ion exchange and potential soil sodicity issues. In contrast, Tadla displayed the least negative RSBC value, indicating a lower sodium hazard and thus more favorable conditions for agricultural activities. In this sense, several results induced that the prolonged utilization of water with high residual sodium carbonate results in the accumulation of sodium in the soil, thereby modifying its physical and chemical characteristics [Murtaza et al., 2021]. The sodium adsorption ratio signifies the sodicity risk associated with irrigation water [Qadir et al., 2021]. Additionally, other studies have shown that water with elevated RSBC levels poses a greater threat than water with no RSBC but similar SAR [Gupta, 2015; Murtaza et al., 2021]. The achieving sustainable agriculture on such soils necessitates the implementation of specific management practices tailored to the site before employing these low-quality waters for economically viable crop production [Minhas and Bajwa, 2021]. On the other hand, magnesium hazard is a crucial qualitative criterion for assessing water quality for irrigation purposes. An elevated Mg^{2+} ratio in water can disrupt the balanced ratio of Ca^{2+} to Mg^{2+}. Moreover, excessive Mg^{2+} levels can increase water alkalinity, adversely impacting plant growth [Khanoranga and Khalid, 2019]. Water with MH values of 50 or higher is deemed unsuitable for irrigation. For instance, Beni amir and Beni moussa water, with an MH value of 56.37 and 56.84 respectively, are not fit for irrigation, whereas the Doukkala, Bahira, Tassaout and Tadla with MH values below 50 suggesting lesser magnesium-related risks and are considered suitable.

The LSI is an indicator of the scaling potential of water, with more negative values suggesting a higher tendency to form scale [Lodha et al., 2023]. In this study, the Beni Moussa region showed the most negative LSI value, indicating a higher scaling tendency. Although the variation in LSI values across the regions was not significant, the trend is noteworthy for its implications on water infrastructure and aligns with the general understanding that groundwater chemistry can vary subtly within relatively short distances, affecting the management of water distribution systems. Furthermore, the Ryznar stability index is similar to the LSI and provides insights into the corrosive potential of water. In the same way, Taghipour et al. [2012] reported RSI values of 8.16 for the drinking water resources in Tabriz, which are slightly lower than the values found in our study. Conversely, a study of Hasania1 et al. [2021] on the quality and stability of drinking water in Meshginshahr city, Iran, using RSI and LSI, found the water to be corrosive. Similarly, Shams et al. [2012] analyzed rural water supply networks and found that 90% of the water samples exhibited corrosion as indicated by the RSI. These phenomena of corrosion and scaling greatly influence the quality of drinking water, highlighting the importance of evaluating pertinent parameters and implementing appropriate measures.

The investigation of the groundwater quality of the six experimental stations based on the aggression index, Larson and Skold index and Puckorious saturation index was presented in the Table 3. No significant difference was detected between the six experimental stations based on the IA and PSI index. Indeed, in the Doukkala station, the AI is recorded at 9.63, ISLS at 7.87, PSI at 12.27 and

Table 3. Variation of the aggression index (AI), Larson and Skold index (LS) and Puckorious saturation index (PSI) in the experimental stations

Station	IA	LS	PSI
Doukkala	9.63	7.87 a	12.27
Bahira	9.59	2.94 b	12.37
Tassaout	9.64	2.74 b	12.48
Beni amir	9.38	8.35 a	12.77
Beni moussa	9.17	3.20 ab	12.67
Tadla	9.49	0.38 c	12.53
	ns	*	ns

Note: values with different letters indicate significant difference ($p < 0.05$, SNK test); ns: non-significant difference; *: significant difference at $p < 0.05$.

S3 at 1.48. Notably, the highest AI is observed in Beni amir (9.38), while the lowest is in Beni moussa (9.17). However, Beni amir station also exhibits the highest LS (8.35), suggesting potentially elevated levels of certain pollutants. Meanwhile, Tadla displays the lowest LS (0.38), indicating comparatively lower levels of contaminants. The highest PSI is noted in Beni amir (12.77), potentially indicating increased mineral saturation levels, whereas the lowest is in Tassaout (12.48).

The analyses of these traits provide a comprehensive picture of the groundwater characteristics in the study area, considering factors such as acidity, pollution levels, mineral saturation and salinity. For the aggression index, the results indicate that the groundwater across these stations is consistently aggressive, with only slight variations, which suggested that external factors influencing AI are relatively uniform across the stations. This index is generally used to assess the corrosive tendency of water and its potential impact on asbestos-cement pipes and was related to the water's pH, hardness and alkalinity [Bhuyan et al., 2021]. However, for the Larson and Skold index, which used to assess the presence of certain pollutants, primarily focusing on the corrosively related to chloride and sulfate ions [Kalyani et al., 2017]. The Beni Amir shows the highest LS which points to potentially elevated pollutant levels, particularly chloride and sulfate. In contrast, Tadla exhibits the lowest LS at 0.38, indicating much lower pollutant concentrations. These significant differences highlight varying degrees of industrial or agricultural runoff and natural mineral content influencing water quality [Boualem et al., 2024]. On the other hand, the results of the Puckorius Saturation Index in the six experimental stations suggests that all locations have a high tendency for scale formation, with minor differences likely due to local geological and hydrological conditions. For the S3 index which evaluates the water salinity, a crucial factor for agricultural suitability and potability.

The agricultural landscapes of the six experimental regions used in this study are characterized by a diverse array of crops and trees cultivated in varying agro-ecological zones. The predominant agricultural practices used in these areas include the cultivation of cereals such as wheat and barley, oilseed plants such as sesame alongside high-value cash crops like, pomegranate, olives, citrus fruits, and vegetables [Adiba et al., 2021; Kouighat et al., 2022]. Additionally, these regions are renowned for its extensive vineyards, contributing significantly to Morocco's viticulture sector. Given the reliance of these agricultural economies on irrigation, the quality of water used plays a pivotal role in determining crop productivity and sustainability [Bouasria et al., 2021]. The rigorous assessment of water quality indices for irrigation purposes in these regions is paramount, as it directly impacts soil health, crop yield, and overall agricultural viability [Laaraj et al., 2024]. By employing established water quality tests and indices can effectively manage irrigation practices, mitigate potential soil degradation and optimize agricultural production. Moreover, the integration of water quality assessment into agricultural management strategies enhances the resilience of farming communities against environmental stressors, thereby promoting long-term sustainability and food security in these regions of Morocco. In relation with this situation and by analyzing the variation in water quality indices in these regions, we have laid the foundation for identifying plant species that are best adapted to the specific environmental conditions of each region. This knowledge is invaluable for informing agricultural practices and guiding crop selection decisions, ultimately contributing to the sustainability and resilience of agricultural systems in these regions. Furthermore, by promoting the cultivation of plant types that are well-suited to local conditions, our findings have the potential to enhance agricultural productivity, mitigate risks associated with climate variability, and support the livelihoods of farmers in these regions.

CONCLUSIONS

The study on groundwater quality and its effect on agricultural productivity in Morocco reveal a significant variation among the experimental stations, with distinct implications for agricultural productivity. The Doukkala and Bahira regions, despite moderate permeability and low salinity risks, face challenges due to high sodium levels, which can affect soil and crop health. The Tassaout region, with lower values across all indices, indicates better groundwater quality and fewer risks for agriculture. In contrast, Beni Amir and Beni Moussa, particularly with high magnesium hazard values, are unsuitable for irrigation, with Beni Amir showing severe sodium hazards that could lead to soil structure problems. Tadla presents the most favorable conditions with the least sodium hazards. Overall, the findings underscore the need for tailored water management strategies in each region to mitigate risks and enhance agricultural productivity.

Acknowledgements

I am grateful to all those with whom I have enjoyed working during this research.

REFERENCES

1. Abualhaija M.M., Abu Hilal A.H., Shammout M.W., Mohammadd A.H. 2020. Assessment of reservoir water quality using water quality indices: A case study from Jordan. International Journal of Engineering Research and Technology, 13(3), 397–406.
2. Acharya S., Sharma S.K., Khandegar V. 2018. Assessment of groundwater quality by water quality indices for irrigation and drinking in South West Delhi, India.
3. Adiba A., Razouk R., Charafi J., Haddioui A., Hamdani A. 2021. Assessment of water stress tolerance in eleven pomegranate cultivars based on agronomic traits. Agricultural Water Management, 243, 106419.
4. Adimalla N. 2019. Groundwater quality for drinking and irrigation purposes and potential health risks assessment: a case study from semi-arid region of South India. Exposure and health, 11(2), 109–123.
5. Adimalla N., Li P., Venkatayogi S. 2018. Hydrogeochemical evaluation of groundwater quality for drinking and irrigation purposes and integrated interpretation with water quality index studies. Environmental Processes, 5, 363–383.
6. Ahsan W.A., Ahmad H.R., Farooqi Z.U.R., Sabir M., Ayub M.A., Rizwan M., Ilic P. 2021. Surface water quality assessment of Skardu springs using water quality index. Environmental Science and Pollution Research, 28, 20537–20548.
7. Ait Said B., Mili E.M., El Faleh E.M., Mehdaoui R., Mahboub A., Hamid F.E., El Fakir R. 2023. Hydrochemical evolution and groundwater quality assessment of the Tinejdad-Touroug quaternary aquifer, South-East Morocco. Frontiers in Ecology and Evolution, 11, 1201748.
8. Akhtar N., Syakir Ishak M.I., Bhawani S.A., Umar K. 2021. Various natural and anthropogenic factors responsible for water quality degradation: A review. Water, 13(19), 2660.
9. Al-Aizari H.S., Ghfar A.A., Al-Aizari A.R., Al-Aizari A.J.M., Moshab M.S., Sillanpää M. 2023. Assessing groundwater quality and diagnosing nitrate pollution in the Sidi Allal Region: A GIS-based approach utilizing the groundwater pollution index. Hydrology, 10(12), 227.
10. Ali S.A., Ali U. 2018. Hydrochemical characteristics and spatial analysis of groundwater quality in parts of Bundelkhand Massif, India. Applied water science, 8(1), 39.
11. APHA. 2017. Standard Methods for the Examination of Water and Wastewater. American Public Health Association.
12. Arumugam K., Elangovan K. 2009 Hydrochemical characteristics and groundwater quality assessment in Tirupur Region, Coimbatore District, Tamil Nadu, India. Environ Geol, 58, 1509–1520.
13. Aydin H., Ustaoğlu F., Tepe Y., Soylu E.N. 2021. Assessment of water quality of streams in northeast Turkey by water quality index and multiple statistical methods. Environmental forensics, 22(1–2), 270–287.
14. Batarseh M., Imreizeeq E., Tilev S., Al Alaween M., Suleiman W., Al Remeithi A.M., Al Alawneh, M. 2021. Assessment of groundwater quality for irrigation in the arid regions using irrigation water quality index (IWQI) and GIS-Zoning maps: Case study from Abu Dhabi Emirate, UAE. Groundwater

for Sustainable Development, 14, 100611.

15. Bhuyan S.C., Behera J., Kar J., Barik P.K. 2021. Seepage of water quality analysis of a concrete gravity dam using Langlier and aggressive index. In Advanced Modelling and Innovations in Water Resources Engineering: Select Proceeding, 409–418.
16. Boualem B., Egbueri J.C. 2024. Graphical, statistical and index-based techniques integrated for identifying the hydrochemical fingerprints and groundwater quality of In Salah, Algerian Sahara. Environmental Geochemistry and Health, 46(5), 158.
17. Bouasria A., Ibno Namr K., Rahimi A., & Ettachfini E.M. 2021. Geospatial assessment of soil organic matter variability at Sidi Bennour District in Doukkala Plain in Morocco. Journal of Ecological Engineering, 22(11), 120–130.
18. Calliera M., Capri E., Marsala R.Z., Russo E., Bisagni M., Colla R., Suciu N. 2021. Multi-actor approach and engagement strategy to promote the adoption of best management practices and a sustainable use of pesticides for groundwater quality improvement in hilly vineyards. Science of the Total Environment, 752, 142251.
19. Chebet E.B., Kibet J.K., Mbui D. 2020. The assessment of water quality in river Molo water basin, Kenya. Applied Water Science, 10, 1–10.
20. Choudhary O.P., Ghuman B.S., Thuy N., Buresh R.J. 2011. Effects of long-term use of sodic water irrigation, amendments and crop residues on soil properties and crop yields in rice–wheat cropping system in a calcareous soil. Field Crops Research, 121(3), 363–372.
21. Davil M.F., Mahvi A.H., Norouzi M., Mazloomi S., Amarluie A., Tardast A., Karamitabar Y., 2009. Survey of corrosion and scaling potential produced water from Ilam water treatment plant. World Applied Sciences Journal, 7, 01–06.
22. Eaton A.D., Clesceri L.S., Rice E.W., Greenberg A.E. 2005. Standard Methods for the Examination of Water and Wastewater. American Public Health Association.
23. El Bilali A., Taleb A. 2020. Prediction of irrigation water quality parameters using machine learning models in a semi-arid environment. Journal of the Saudi Society of Agricultural Sciences, 19(7), 439–451.
24. Foster S., Pulido-Bosch A., Vallejos Á., Molina L., Llop A., MacDonald A.M. 2018. Impact of irrigated agriculture on groundwater-recharge salinity: a major sustainability concern in semi-arid regions. Hydrogeology Journal, 26(8), 2781–2791.
25. Gao X., Huo Z., Xu X., Qu Z., Huang G., Tang P., Bai Y. 2018. Shallow groundwater plays an important role in enhancing irrigation water productivity in an arid area: The perspective from a regional agricultural hydrology simulation. Agricultural water management, 208, 43–58.
26. Gleeson T., Alley W.M., Allen D.M., Sophocleous M.A., Zhou Y., Taniguchi M., VanderSteen J. 2012. Towards sustainable groundwater use: Setting long-term goals, backcasting, and managing adaptively. Groundwater, 50(1), 19–26.
27. Güngör A., Arslan H. 2016. Assessment of water quality in drainage canals of Çarşamba plain, Turkey, through water quality indexes and graphical methods.
28. Hasani K., Sadeghi H., Dargahi A., Vosoughi M., Mokhtari A., Pirasteh M. 2021. Scaling and corrosion potential in drinking water distribution systems of Meshginshahr City, Iran using Langelier Saturation Index and Ryznar Stability Index. Journal of Advances in Environmental Health Research, 9(3), 201–208.
29. Hossain M., Patra P.K., Begum S.N., Rahaman C.H. 2020. Spatial and sensitivity analysis of integrated groundwater quality index towards irrigational suitability investigation. Applied geochemistry, 123, 104782.
30. Issaka S., Ashraf M.A. 2017. Impact of soil erosion and degradation on water quality: A review. Geology, Ecology, and Landscapes, 1(1), 1–11.
31. Joshi D.M., Kumar A., Agrawal N. 2009. Assessment of the irrigation water quality of river Ganga in Haridwar district. Rasayan Journal Chemestry, 2(2), 285–292.
32. Kalyani D.S., Rajesh V., Reddi E.U.B., Kumar K.C., Rao S.S. 2017. Correlation between corrosion indices and corrosiveness of groundwater: A study with reference to selected areas of Krishna District, Andhra Pradesh, India. Environmental Earth Sciences, 76, 1-13.
33. Kanga I.S., Naimi M., Chikhaoui M. 2020. Groundwater quality assessment using water quality index and geographic information system based in Sebou River Basin in the North-West region of Morocco. International Journal of Energy and Water Resources, 4(4), 347–355.
34. Khalid S., Shahid M., Natasha Bibi I., Sarwar T., Shah A.H., Niazi, N.K. 2018. A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries. International journal of environmental research and public health, 15(5), 895.
35. Kouighat M., Nabloussi A., Adiba A., Fechtali M.E., Hanine H. 2022. First study of improved nutritional properties and anti-oxidant activity in novel sesame mutant lines as compared to their wild-types. Plants, 11(9), 1099.
36. Langelier W.F. 1936. The analytical control of anti-corrosion water treatment. Journal American Water Works Association, 28, 1500–1521
37. Lodha R., Sharma Y., Surecha O.P., Trivedi A., Chaplot H., Chaudhary M., Choudhary S. 2023. Scaling potential and corrosion assessment through Langelier Saturation Index and Ryznar Stability Index of Under Ground Water in Udaipur, Rajasthan.

International Advanced Research Journal in Science, Engineering and Technology, 10(7), 254–260.

38. Minhas P.S., Bajwa M.S. 2021. Use and management of poor quality waters for the rice-wheat based production system. In The Rice-Wheat Cropping System of South Asia, 273–306.
39. Minhas P.S., Bajwa M.S. 2021. Use and management of poor quality waters for the rice-wheat based production system. In The Rice-Wheat Cropping System of South Asia, 273–306.
40. Murtaza G., Rehman M.Z., Qadir M., Shehzad M.T., Zeeshan N., Ahmad H.R., Naidu R. 2021. High residual sodium carbonate water in the Indian subcontinent: concerns, challenges and remediation. International Journal of Environmental Science and Technology, 18, 3257–3272.
41. Pulido-Bosch A., Rigol-Sanchez J.P., Vallejos A., Andreu J.M., Ceron J.C., Molina-Sanchez L., Sola F. 2018. Impacts of agricultural irrigation on groundwater salinity. Environmental earth sciences, 77, 1–14.
42. Qadir M., Sposito G., Smith C.J., Oster J.D. 2021. Reassessing irrigation water quality guidelines for sodicity hazard. Agricultural Water Management, 255, 107054.
43. Ravikumar. P, Somashekar R.K., Angami M. 2011. Hydrochemistry and evaluation of groundwater suitability for irrigation and drinking purposes in the Markandeya River basin, Belgaum District, Karnataka State, India. Environmental monitoring and assessment, 173, 459–487
44. Ren X., Li P., He X., Su F., Elumalai V. 2021. Hydrogeochemical processes affecting groundwater chemistry in the central part of the Guanzhong Basin, China. Archives of environmental contamination and toxicology, 80, 74–91.
45. Rickson R.J., Deeks L.K., Graves A., Harris J.A.H., Kibblewhite M.G., Sakrabani R. 2015. Input constraints to food production: The impact of soil degradation. Food security, 7, 351–364.
46. Ryznar J.W. 1944. A new index for determining amount of calcium carbonate scale formed by a water. Journal-American Water Works Association, 36(4), 472–483.
47. Shams M, Mohamadi A, Sajadi S.A. 2012. Evaluation of corrosion and scaling potential of water in rural water supply distribution networks of Tabas, Iran. World Applied Sciences Journal, 17(11), 1484–1489.
48. Shil S., Singh U.K., & Mehta P. 2019. Water quality assessment of a tropical river using water quality index (WQI), multivariate statistical techniques and GIS. Applied water science, 9, 1–21.
49. Srinivasamoorthy K., Gopinath M., Chidambaram S., Vasanthavigar M., Sarma V.S., 2014. Hydrochemical characterization and quality appraisal of groundwater from Pungar sub basin, Tamilnadu, India. Journal of King Saud University-Science, 26, 37–52
50. Taghipour H, Shakerkhatibi M, Pourakbar M, Belvasi M. 2012. Corrosion and scaling potential in drinking water distribution system of Tabriz, northwestern Iran. Health Promot Perspect, 2(1),103–111
51. Zaman M., Shahid S.A., Heng L., Zaman M., Shahid S.A., Heng, L. 2018. Irrigation water quality. Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques, 113–131.