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Original article

Application of the Irrigation Water Quality Index Model to Assess the Suitability of Groundwater for Irrigation in Wadi Al-Ain, East of Tobruk, Libya

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Abstract
Water quality is a fundamental factor in agricultural production, particularly in arid and semi-arid regions, where salinity can adversely affect soil fertility and plant growth. This study aimed to evaluate the quality and irrigation suitability of groundwater from seven wells in Wadi Al-Ain, east of Tobruk, Libya, using physicochemical analyses, irrigation water quality indices, and the Irrigation Water Quality Index (IWQI) model. The analyzed parameters included pH, electrical conductivity (EC), calcium, magnesium, sodium, potassium, chloride, and bicarbonate. In addition, the sodium adsorption ratio (SAR), residual sodium carbonate (RSC), and permeability index (PI) were calculated. The results showed that the groundwater samples were generally suitable for agricultural use under appropriate management conditions. The pH values ranged from 6.9 to 7.6, Na% from 37.3 to 44.4%, SAR from 1.6 to 2.8, and RSC values were less than 1.5 meq/L, while PI values ranged from 55.6 to 66.3%. The IWQI values ranged from 58 to 81, with 71% of the samples classified as moderately suitable for irrigation, 14.5% as low suitability, and 14.5% Suitable for irrigation. These findings indicate that groundwater from the studied wells can be used for irrigation, provided that salt-tolerant crops are selected and water quality is monitored periodically to maintain sustainable agricultural production and soil fertility.
Keywords. Groundwater quality, Irrigation suitability, Irrigation Water Quality Index, Salinity, Wadi Al-Ain, Tobruk, Libya.

Introduction

Water is an essential natural resource that is indispensable for life, as it supports various life processes and ecological systems on Earth. Water resources and their management are therefore of critical importance, particularly in arid and semi-arid regions, owing to their scarcity and broad implications for several vital sectors, including agriculture, industry, domestic use, and the environment [1]. Libya suffers from severe water scarcity due to its location within arid and semi-arid zones, where rainfall is limited, and evaporation rates are high as a result of elevated temperatures and low humidity, particularly during summer. Population growth and the absence of effective water management policies further exacerbate this problem, along with the excessive exploitation of groundwater resources. The crisis is further intensified by the pollution of water sources caused by wastewater discharge, the lack of adequate treatment plants, and the excessive use of fertilizers and pesticides [2]. Several studies indicate that Libya relies heavily on groundwater, which accounts for approximately 98% of the country's water resources, whereas surface water represents about 2.30%, desalinated water about 4.0%, and treated wastewater about 0.66%. Despite this substantial dependence on groundwater reserves, the annual recharge of aquifers does not exceed approximately 250 million m^3, while total water consumption is estimated at 3 billion m^3. This reflects a significant imbalance in the water budget of most aquifers and a clear depletion of groundwater reserves, resulting in a sharp decline in groundwater levels, deterioration of aquifer quality, seawater intrusion, particularly in coastal areas, and continuous contamination of these resources [3].

The assessment of irrigation water quality is a crucial component of water resource management in arid and semi-arid regions. Continuous use of water with high salinity or elevated sodium content can deteriorate soil structure, increase salinization and alkalinity, reduce soil permeability, and consequently impair plant growth and productivity [4]. Furthermore, this type of assessment contributes to determining the suitability of groundwater for agricultural purposes and guides farmers regarding its optimal use. This can help reduce the risks of soil salinization and fertility degradation, while supporting the sustainability of agricultural productivity. It also contributes to protecting the agricultural ecosystem from the adverse effects associated with the irrational or inappropriate use of groundwater. Given that the study area is rural and depends directly on groundwater for irrigation, this study aimed to evaluate the quality of selected groundwater wells in Wadi Al-Ain, east of Tobruk, Libya, and to determine their suitability for irrigation. This was achieved through the application of the Irrigation Water Quality Index (IWQI) model, in addition to selected irrigation indices, including the sodium adsorption ratio (SAR), soluble sodium percentage (SSP%), residual sodium carbonate (RSC), and permeability index (PI).

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Materials and Methods

Study Area

The study area is located in northeastern Libya. It is bordered by the Rabie area to the east, the Marsalak area to the west, and the Mediterranean Sea coast to the north, as shown in (Figure 1). The climate of the study area is characterized as semi-desert; however, it is originally a desert climate influenced by the adjacent Mediterranean climatic conditions. Geographically, the area lies between longitudes 24°45′–24°48′ E and latitudes 31°57′–32°00′ N.

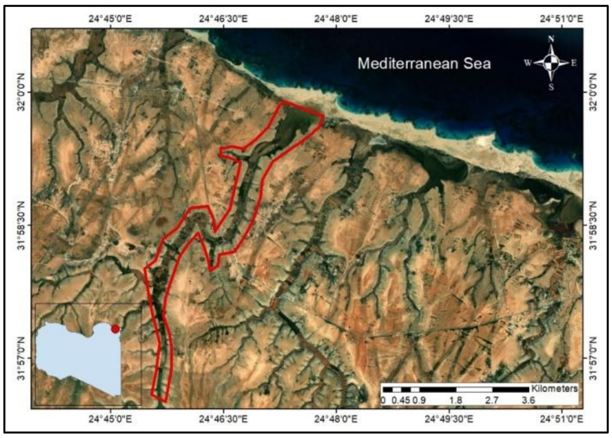

Figure 1. Location of the study area

Sample Collection

Water samples were collected from seven groundwater wells randomly distributed across the study area during April 2026. Three replicate samples were collected from each selected well. Sterilized plastic bottles were used for sample collection and were rinsed several times with water from the same well prior to sampling. The geographical coordinates of the studied wells were then recorded using a Global Positioning System (GPS) device, as shown in (Figure 2).

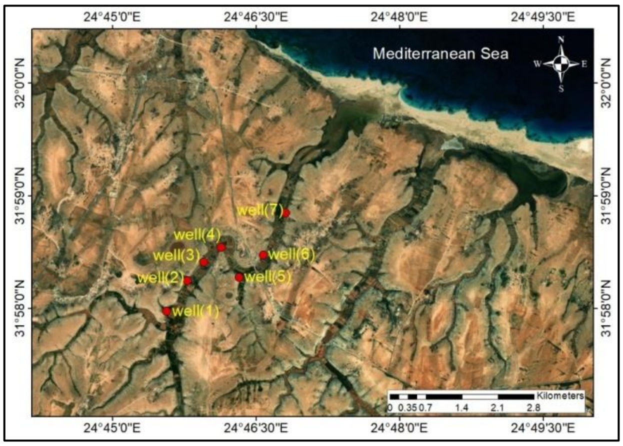

Figure 2. Locations of the studied wells in the study area

Physicochemical Analysis Methods

Hydrogen Ion Concentration (pH)

The pH of the water samples was measured immediately after collection using a pH meter, Model AR-50-HACH.

Electrical Conductivity (EC)

Electrical conductivity (EC) of the samples was measured using a conductivity meter according to the method described in [5].

Calcium and Magnesium (Ca^{2+} and Mg^{2+})

Calcium and magnesium ions in the water samples were determined using the titrimetric method through titration with EDTA. Eriochrome Black T (EBT) and murexide indicators were used, according to the procedure reported in [6].

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Chloride (Cl^-)
Chloride concentration was determined by titration using Mohr's method with silver nitrate solution and potassium chromate as an indicator, according to the method described in [7].

Sodium and Potassium (Na^+ and K^+)
Sodium and potassium concentrations were measured using a flame photometer, Models PFP7 and PFP7/C, JENWAY, according to the procedure reported in [6].

Bicarbonate (HCO_3^-)
Bicarbonate concentration was determined by titration with 0.01 N sulfuric acid using methyl orange indicator, according to the method described in [7].

Calculated Indices of Irrigation Water Quality
Sodium Percentage (%Na)
The sodium percentage (%Na) was calculated as the ratio of sodium ion concentration to the total concentration of major cations, expressed in milliequivalents per liter (meq/L), according to the following equation [8]:

$$Na\% = \frac{Na}{Ca + Mg + Na + K} \times 100$$

Sodium Adsorption Ratio (SAR)
The sodium adsorption ratio (SAR) was calculated based on the concentrations of sodium, calcium, and magnesium, expressed in milliequivalents per liter (meq/L), using the following equation [5]

$$\text{SAR} = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

Residual Sodium Carbonate (RSC)
Residual sodium carbonate (RSC) was calculated in milliequivalents per liter (meq/L) according to the equation proposed by [9]:

$$RSC = (CO_3^{-2} + HCO_3^{-}) - (Ca^{+2} + Mg^{+2})$$

Permeability Index (PI)
The permeability index (PI) was calculated using ion concentrations expressed in milliequivalents per liter (meq/L), according to the following equation [10]

$$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{(Ca^{2+} + Mg^{2+} + Na)} \times 100$$

Irrigation Water Quality Index Model (IWQI)
The Irrigation Water Quality Index (IWQI) is one of the models commonly used in agricultural water quality assessment [11]. Irrigation water quality and its associated risks directly affect soil properties and crop productivity. The IWQI is a mathematical model developed by [12]. In the first step, the selected parameters were considered the most relevant to agricultural use. In the second step, quality rating values (q_i) and aggregation weights (w_i) were determined. The quality rating values (q_i) were estimated based on the value of each parameter according to the irrigation water quality standards proposed by the University of California Committee of Consultants (UCCC). To assess irrigation water quality in the study area, variations among selected parameters were considered, including electrical conductivity (EC), sodium adsorption ratio (SAR), sodium ion concentration (Na^+), chloride ion concentration (Cl^-), and bicarbonate ion concentration (HCO_3^-). The proposed threshold values for these variables were determined according to irrigation requirements and tolerance levels. The contribution of each parameter to the IWQI calculation was determined separately. This contribution included both the estimated water quality rating value (q_i) and the relative weight (w_i), using the following mathematical model [12]:

$$qi = q_{\max} - \left(\frac{(xij - xinf) \times qimap}{ximap}\right)$$

where q_i represents the quality rating value for each parameter; qmax is the upper quality rating value of the corresponding class; xij is the observed value of the parameter in each sample; xinf is the lower limit of the corresponding class; qiamp is the amplitude of the quality rating class; and xamp is the amplitude of the parameter class.
The index range for each class was determined according to water type. (Table 1) presents the values representing different water quality classes for the selected parameters. The assigned weight (w_i), which

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reflects the relative importance of each parameter based on its water quality significance, was used as shown in (Table 2). These parameters were then integrated into a standard index to interpret the results for each water type and to derive the Irrigation Water Quality Index, as reported by [12]:

$$IWQI = \sum_{i=1}^{n} \text{qi wi}$$

Table 1. Estimated water quality rating values (q_i) according to the ranges of different parameters

q_i	EC (µS/cm)	SAR	Na^+ (meq/L)	Cl^- (meq/L)	HCO_3^- (meq/L)
85–100	200–750	2–3	2–3	< 4	≤ 1.5
60–85	750–1500	3–6	3–6	4–7	1.5–4.5
35–60	1500–3000	6–12	6–9	7–10	4.5–8.5
< 35	< 200 or > 3000	< 2 or ≥ 12	< 2 or ≥ 9	≥ 10	< 1 or ≥ 8.5

Source: [12]

Table 2. Relative weights (w_i) assigned to the different irrigation water quality parameters

Parameter	Weight (w_i)
Electrical conductivity, EC (µS/cm)	0.211
Sodium, Na^+	0.204
Bicarbonate, HCO_3^-	0.202
Chloride, Cl^-	0.194
Sodium adsorption ratio, SAR	0.189
Total	1.000

Source: [12]

Results and Discussion

Hydrogen Ion Concentration (pH)

pH is one of the most important chemical properties of irrigation water, as it indicates the acidity or alkalinity of water. The pH scale generally ranges from 0 to 14, where values below 7 indicate acidic conditions, values above 7 indicate alkaline conditions, and a value of 7 represents neutrality [13]. The results showed that pH values ranged from 6.9 to 7.6, with an overall mean of 7.2, as presented in (Table 3). This slight variation in pH values may be attributed to groundwater movement and its interaction with the different geological formations through which it flows. Accordingly, the groundwater samples from all studied wells fall within the acceptable range for irrigation use and are unlikely to cause alkalinity-related problems that could adversely affect plant growth or soil properties, as reported by [14].

Sodium Percentage (Na%)

Sodium concentration is an important factor in classifying water for irrigation purposes and is commonly used to evaluate water quality for agricultural use. An increase in the proportion of sodium relative to other major cations, such as calcium, magnesium, and potassium, in irrigation water increases the potential risk of alkalinity hazards to both soil and plants. It has been reported that when the sodium percentage exceeds 60%, irrigation water may become harmful to soil and plants and may reduce overall irrigation water quality [15]. Based on the results presented in (Table 3 and Figure 3), the sodium percentage values ranged from 37.3% to 44.4%, with an overall mean of 41.8%. When compared with the previously mentioned classification limits, all groundwater samples were below the critical threshold of 60%. Therefore, their use for irrigation is not expected to pose sodium-related hazards according to [15]. Accordingly, the studied groundwater can be used for agricultural purposes without significant risk of sodium-induced damage to soil under normal irrigation management conditions.

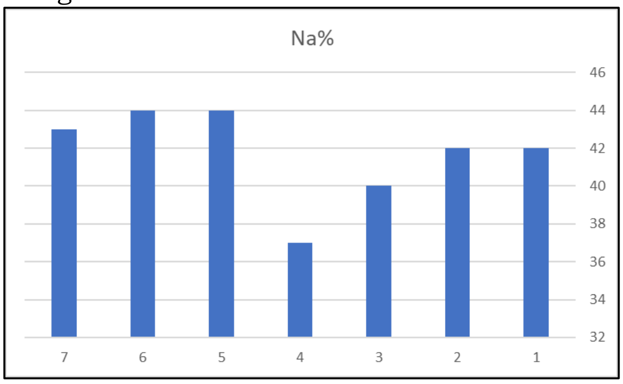

Figure 3. Distribution of sodium percentage (Na%) values across the studied groundwater wells

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Sodium Adsorption Ratio (SAR)

The sodium adsorption ratio (SAR) is one of the most important irrigation water quality criteria, as it reflects the potential sodium hazard that may affect soil structure and permeability. SAR expresses the relationship between sodium ions and the divalent cations calcium and magnesium, and indicates the tendency of irrigation water to participate in cation-exchange reactions in the soil. Elevated SAR values may lead to sodium accumulation, which can adversely affect soil physical properties and may cause toxicity symptoms in plants, thereby reducing plant growth and productivity [16]. The results presented in (Table 3 and Figure 4) showed that SAR values ranged from 1.6 to 2.8, with an overall mean of 2.1. This variation in SAR values may be attributed to differences in calcium and magnesium ion concentrations relative to sodium concentration. According to the classification of the U.S. Salinity Laboratory [5], the SAR values of all studied groundwater samples fall within the low sodium hazard class, indicating that the water from all studied wells is suitable for agricultural use, as also reported by [17].

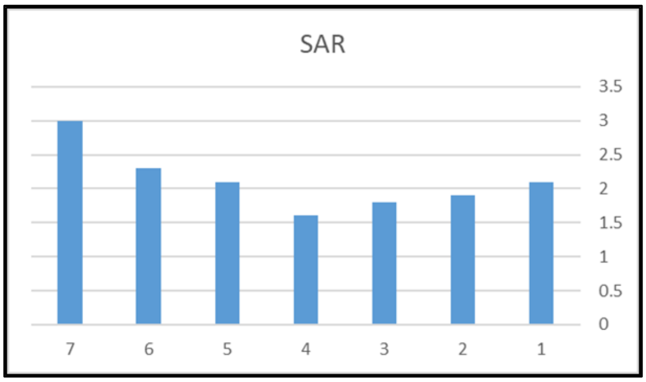

Figure 4. Sodium adsorption ratio (SAR) values in the studied groundwater wells

Residual Sodium Carbonate (RSC)

Residual sodium carbonate (RSC) is an important parameter for evaluating the suitability of water for irrigation purposes, as it reflects the effect of carbonate and bicarbonate concentrations in relation to calcium and magnesium. High RSC values in irrigation water may increase soil alkalinity and promote the precipitation of calcium and magnesium, thereby increasing the relative sodium hazard in the soil solution. Irrigation water is commonly classified based on RSC concentration, expressed in milliequivalents per liter (meq/L). Water is considered suitable for irrigation when RSC is less than 1.5 meq/L, marginally suitable when RSC ranges from 1.5 to 2.5 meq/L, and unsuitable when RSC exceeds 2.5 meq/L [18]. The results shown in (Table 3 and Figure 5) indicate that the RSC values of the studied groundwater wells were negative, ranging from −6.0 to −1.3 meq/L, with an overall mean of −2.7 meq/L. All values were below the critical limit of 1.5 meq/L. According to the adopted classification, these waters are considered suitable for irrigation. The negative RSC values indicate that calcium and magnesium concentrations exceed carbonate and bicarbonate concentrations, suggesting a low risk of sodium carbonate and bicarbonate accumulation in the soil, as reported by [19].

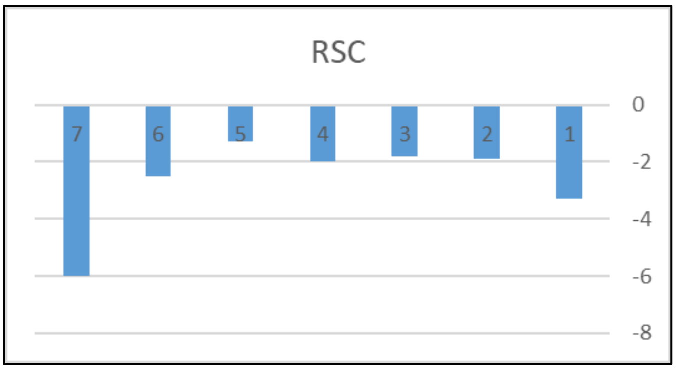

Figure 5. Residual sodium carbonate (RSC) values in the studied groundwater wells

Permeability Index (PI)

Soil permeability can be affected by the long-term use of irrigation water due to the influence of water constituents such as sodium, potassium, calcium, and bicarbonate [20]. A classification criterion for assessing irrigation water suitability based on the permeability index (PI%) was proposed by [21], in which irrigation water is divided into three classes. The first class represents good and suitable water for irrigation, where PI values are 75% or higher. The second class includes water with PI values ranging from 25% to 75%, which is considered suitable for irrigation. The third class represents water that is unsuitable for

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irrigation, where PI values are less than 25%. The results presented in (Table 3 and Figure 6) showed that the PI values of all studied groundwater wells ranged from 55.6% to 66.3%, with an overall mean of 60.6%. Accordingly, the groundwater of the studied wells can be classified as suitable for agricultural use and falls within the second class according to the classification proposed by [21].

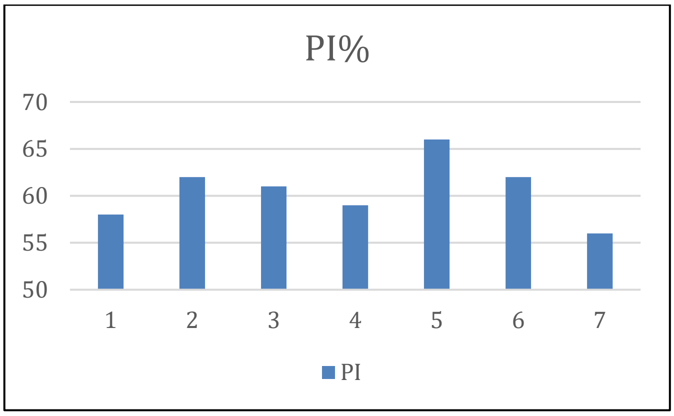

Figure 6. Permeability index (PI%) values in the studied groundwater wells

Table 3. Results of chemical analyses and calculated irrigation water quality indices for the studied groundwater wells

Well No	Ph	Mg meq/L	Ca meq/L	K meq/L	Na meq/L	HCO_3 meq/L	Na%	SAR	RSC	PI%
1	7.2	1.4	5.9	0.3	5.4	4.0	42	2.1	-3.3	58
2	6.9	1.3	4.4	0.2	4.2	3.8	42	1.9	-1.9	62
3	7.4	1.3	4.6	0.3	4.1	4.0	40	1.8	-1.8	61
4	7.1	1.3	4.9	0.3	3.9	4.2	37	1.6	-2.0	59
5	7	1.2	4.1	0.3	4.5	3.9	44	2.1	-1.3	66
6	7.6	1.3	5.5	0.4	5.7	4.4	44	2.3	-2.5	62
7	7.2	1.7	9.4	0.5	8.8	5.1	43	3.0	-6.0	56
MIN	6.9	1.2	4.1	0.2	3.9	3.8	37.3	1.6	-6.0	55.6
MAX	7.6	1.7	9.4	0.5	8.8	5.1	44.4	2.8	-1.3	66.3
AVE	7.2	1.4	5.5	0.3	5.2	4.2	41.8	2.1	-2.7	60.6

Irrigation Water Quality Index Model (IWQI)

The Irrigation Water Quality Index (IWQI) is a numerical expression used to convert a large set of water quality data into a single value that represents the overall water quality status. It summarizes water quality information either as a numerical score or as a descriptive class reflecting the suitability of water for irrigation. This approach can facilitate decision-making in water resource management by simplifying complex hydrochemical data into an interpretable index. The IWQI is based on the integration of several parameters related to water treatment requirements, soil properties, and crop tolerance. The IWQI model classifies irrigation water into five suitability classes, each representing a specific level of restriction for irrigation use [22], as shown in (Table 4).

The results presented in (Table 5) showed that the IWQI values of the studied wells ranged from 58 to 81. Based on the adopted classification, 71% of the studied samples were classified as moderately suitable for irrigation, while 14.5% were classified as suitable for irrigation. In contrast, 14.5% of the samples were classified as having low suitability for irrigation. The spatial distribution of IWQI values in the study area, as illustrated in (Figure 7), showed that the lowest IWQI value was recorded in the northern part of the study area, near the Mediterranean coast. This area may be more vulnerable to seawater intrusion, which could explain the increased salt concentration and the effects of sodium and chloride on irrigation water quality. Therefore, irrigation using this water requires appropriate management practices, such as selecting salt-tolerant crops, using soils with good permeability, and applying soil leaching practices to reduce salt accumulation.

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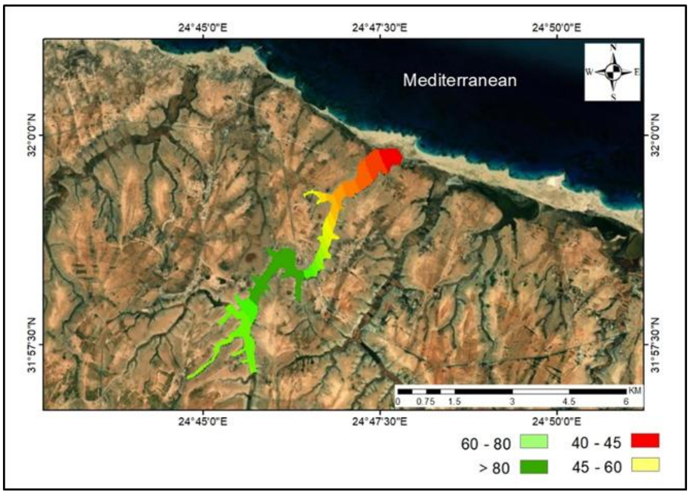

Figure 7. Spatial distribution of IWQI values in the study area

Table 4. Proposed classification of irrigation water suitability according to IWQI values

IWQI value	Irrigation water suitability class
> 80	Suitable for irrigation
60-80	Moderately suitable for irrigation
45-60	Low suitability for irrigation
30-45	Mostly unsuitable for irrigation
< 30	Unsuitable for irrigation

Source: [22]

Table 5. Irrigation Water Quality Index (IWQI) values and suitability classes for the studied groundwater wells

Well No	EC µs/cm	SAR	Na^+ meq/L	Cl^- meq/L	HCO_3^- meq/L	IWQI
1	1256	2.1	5.4	4.1	4.0	76
2	1115	1.9	4.2	2.9	3.8	81
3	1420	1.8	4.1	2.7	4.0	79
4	1317	1.6	3.9	2.5	4.2	80
5	1235	2.1	4.5	2.7	3.9	79
6	1443	2.3	5.7	3.3	4.4	73
7	2186	3.0	8.8	6.0	5.1	58

Conclusion

The results of this study showed that groundwater from the studied wells in Wadi Al-Ain, east of Tobruk, has physicochemical characteristics that make it generally suitable for agricultural use. The values of pH, Na%, SAR, RSC, and PI were within the acceptable limits for irrigation. In addition, the Irrigation Water Quality Index (IWQI) indicated that most of the samples were classified as moderately to highly suitable for irrigation. However, appropriate irrigation management practices are recommended, particularly in coastal areas where the risk of salinity increase and seawater intrusion may be higher. These practices include selecting salt-tolerant crops and applying suitable soil management techniques to reduce the potential accumulation of salts. The findings highlight the importance of continuous monitoring of groundwater quality to ensure the sustainability of water resources and to protect agricultural productivity from deterioration caused by declining water quality. The study also recommends conducting further seasonal comparative studies to assess the effect of rainfall and seasonal variation on groundwater quality in the study area.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

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