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Assessing the impact of seasonal variability on irrigation water quality and suitability for agricultural use in wet and dry conditions

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Abstract: This study investigates the seasonal variation in water quality for irrigation from 57 wells in Sulaimani City, using two classification models: Ayers & Westcot (1985) and Maia & Rodrigues (2012). Key water parameters such as pH, electrical conductivity (EC), sodium adsorption ratio (SAR), bicarbonates (HCO_3^-), and (Cl^-) concentrations were analyzed. Results showed that during the wet season, 45 wells had no restrictions (NR), while 12 had slight to moderate restrictions (S-MR). In the dry season, 29 wells were classified as NR and 28 as S-MR. Water quality was generally favorable for irrigation in the wet season but required management strategies for wells with higher EC and SAR, particularly in the dry season when salinity and ion concentrations increased. The Ayers & Westcot classification reflected seasonal variations in EC, SAR, and bicarbonates, with water quality declining slightly in the dry season, leading to more wells classified as S-MR. Using the Irrigation Water Quality Index by Maia & Rodrigues, some wells shifted from "Good" to "Excellent" in the dry season due to changes in EC levels. These results highlight the need for continuous water quality monitoring and adaptive irrigation management to optimize water use and prevent soil salinization in regions with seasonal variability.

Key words: irrigation water quality, EC, pH, season variation

Ocenjevanje vpliva sezonske spremenljivosti na kakovost vode za namakanje in primernost za kmetijsko uporabo v vlažnih in sušnih razmerah

Izvleček: Študija je preučevala sezonske razlike v kakovosti vode za namakanje iz 57 vodnjakov v mestu Sulaimani z uporabo dveh klasifikacijskih modelov: Ayers & Westcot (1985) ter Maia & Rodrigues (2012). Analizirani so bili ključni parametri vode, kot so pH, električna prevodnost (EC), adsorpcijsko razmerje natrija (SAR), koncentracija bikarbonatov (HCO_3^-) in klorida (Cl^-). Rezultati so pokazali, da med deževno sezono 45 vodnjakov ni imelo omejitev (NR), 12 pa je imelo rahle do zmerne omejitve (S-MR). V sušnem obdobju je bilo 29 vodnjakov razvrščenih kot NR in 28 kot S-MR. Kakovost vode je bila na splošno ugodna za namakanje v deževnem obdobju, vendar so bile potrebne strategije upravljanja za vodnjake z večjima EC in SAR, zlasti v sušnem obdobju, ko sta se povečali slanost in koncentracija ionov. Klasifikacija Ayers & Westcot je odražala sezonska nihanja EC, SAR in bikarbonatov, pri čemer se je kakovost vode nekoliko zmanjšala v sušnem obdobju, zaradi česar je več vodnjakov razvrščenih kot S-MR. Z uporabo indeksa kakovosti vode za namakanje Maie & Rodriguesa so se nekateri vodnjaki v sušnem obdobju spremenili iz »dobrih« v »odlične« zaradi sprememb EC. Ti rezultati poudarjajo potrebo po stalnem spremljanju kakovosti vode in prilagodljivem upravljanju namakanja za optimizacijo rabe vode in preprečevanje zasoljevanja tal v regijah s sezonsko spremenljivostjo.

Ključne besede: kakovost vode za namakanje, EC, pH, sezonska nihanja

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1 INTRODUCTION

The quality of irrigation water plays a critical role in determining the success and sustainability of agricultural practices (Laoufi et al.,2025: Marif and Esmail, 2023). As global climate patterns fluctuate and regions experience more extreme weather conditions, understanding how seasonal variability affects irrigation water quality has become increasingly important. Seasonal changes, particularly between wet and dry conditions, can significantly alter the chemical composition and suitability of water for irrigation (Panday et al., 2025: Marif, 2023). In agricultural settings, the assessment of water quality is crucial for maintaining soil health, ensuring optimal crop growth, and minimizing the risks of salinization, nutrient imbalances, and toxicity (Sharma and Pillai, 2025; Surucu et al., 2020). The use of water classification systems allows farmers and policymakers to make informed decisions on water management and irrigation practices, ensuring long-term agricultural productivity. This article delves into the impact of seasonal variability on irrigation water quality and suitability, specifically examining how wet and dry seasons influence water chemistry and its classification according to two prominent models (Ayers and Westcot, 1985, Maia and Rodrigues, 2012).

The Maia and Rodrigues, 2012 model is one of the most widely applied approaches for evaluating irrigation water quality, as it provides a comprehensive framework that integrates a range of important parameters. These include salinity levels, pH balance, and the concentration of essential and potentially harmful ions, which together determine the degree of water suitability for agricultural use and crop productivity (Marif and Esmail, 2023). By considering multiple factors simultaneously, the model allows for a more accurate classification of water quality compared to traditional single-parameter methods. Seasonal variations also play a crucial role in shaping irrigation water quality, especially in regions with distinct wet and dry periods. During the wet season, rainfall contributes to the dilution of contaminants and lowers the salinity of surface and groundwater sources. This natural dilution effect can improve the chemical balance of irrigation water, reducing the risks of soil salinization and ion toxicity. As a result, water resources that may be marginal or unsuitable during dry periods can become more favorable for irrigation in the rainy season. In contrast, the dry season may exacerbate water quality issues, such as higher salinity, due to the lower availability of water and increased evaporation rates (Mohsen and Al-Mohammed, 2023). By analyzing the differences in water quality classifications during these two distinct periods, this model offers valuable insights into how agricultural irrigation practices should be adapted to seasonal conditions, ensuring the optimal use of water resources and minimizing negative environmental impacts (Rajab and Esmail, 2022).

On the other hand, the global classification system developed by (Ayers and Westcot, 1985) offers a more universally applicable and standardized framework for assessing irrigation water quality, making it highly valuable for agricultural management across diverse regions. This system evaluates water quality primarily through critical parameters such as electrical conductivity (EC), which reflects the salinity level of water; the sodium adsorption ratio (SAR), which indicates the potential for sodium-related soil structural problems; and the concentrations of specific ions that may affect plant growth or soil health (Yan et al., 2024). By incorporating these parameters, the model provides a clear basis for determining whether water is suitable for irrigation under different environmental and cropping conditions. Seasonal variability strongly influences the results derived from this system. In wet conditions, for instance, excess rainfall can contribute to the dilution of salts and ions in water bodies, resulting in lower EC values and, consequently, an improvement in water quality according to this classification. Conversely, in the dry season, high evaporation rates tend to concentrate salts and dissolved ions in irrigation sources, leading to increased EC values that can make the water less suitable for sustainable crop irrigation (Gupta and Kumar, 2024). Because of its adaptability and wide acceptance, this classification system has been extensively applied to guide irrigation practices globally, particularly in regions with diverse soils, climates, and agricultural needs. It not only supports farmers and decision-makers in identifying risks associated with poor-quality irrigation water but also assists in planning management strategies that minimize long-term soil degradation. Therefore, understanding how this system evaluates water quality under both wet and dry seasonal conditions is crucial, as it provides essential information for improving water use efficiency, protecting soil health, and ultimately optimizing agricultural productivity under varying climatic scenarios (Hanoon et al., 2021).The primary aim of this article is to assess and compare the seasonal impact on irrigation water quality by classifying water using both the (Maia and Rodrigues, 2012) model and the (Ayers and Westcot, 1985) classification system. By analyzing the changes in water quality between wet and dry seasons, the article seeks to provide a comprehensive evaluation of how different seasonal conditions influence the suitability of water for agricultural use. Through this comparison, the article aims to offer practical recommendations for water management strategies that can adapt to seasonal changes, ensuring sustainable agricultural practices across diverse climatic zones.

2 MATERIALS AND METHODS

2.1 STUDY AREA AND SAMPLING LOCATIONS

The present study was conducted across 57 deep wells strategically distributed within the Sulaimani Governorate, encompassing a wide range of geographic zones and hydrogeological formations. These wells were carefully selected to represent areas with varying land uses, agricultural practices, and irrigation demands, thereby providing a comprehensive and representative overview of groundwater quality in the region. The inclusion of wells from locations with different topographies, soil characteristics, and cultivation intensities was particularly important to capture both spatial variability and the combined influence of natural hydrogeological conditions and anthropogenic activities such as fertilizer application, intensive irrigation, and land management. To ensure temporal reliability and account for seasonal and short-term fluctuations in groundwater chemistry, water samples were systematically collected every two weeks from each well throughout the study period. This bi-weekly sampling approach allowed for continuous monitoring of changes in water quality, such as variations in salinity, pH, and ionic concentrations, which are often influenced by rainfall, irrigation intensity, and evaporation rates. In addition, the geographic coordinates and elevation details of all wells were carefully recorded and are presented in Figure 1 and Table 1, serving as a spatial reference for data interpretation and for facilitating future monitoring programs. As part of this disserta-

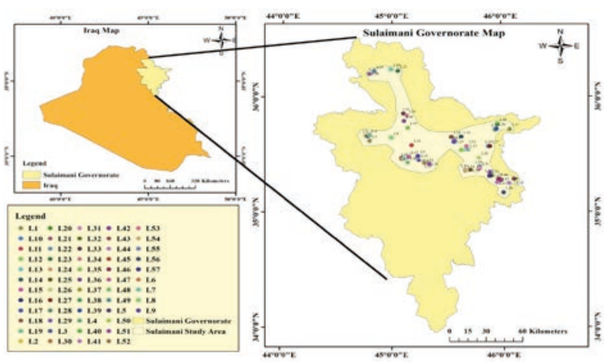

Figure 1. Study area of fifty-seven wells with their GPS readings in Utm system

Table 1: Study area of fifty-seven wells with their GPS readings in Utm system

Wells Number	Well Name	Elevation (Meter)	GPS points		Depth (m)
			N	E	
L1	Turka	744	518312	3942218	90
L2	Palka Rash	727	522025	3947156	180
L3	TakTak	726	519937	3946535	76
L4	Gazalan	646	518352	3947459	54
L5	Khan Ali /Goshqut	684	492339	3925659	94
L6	Ali Zangana	680	492565	3924852	75
L7	Sofi hassan	721	490323	3925264	100
L8	Kani Shaitan	914	500478	3945133	60
L9	Darikali	873	478610	3927687	100
L10	Bazian	793	485490	3936873	100
L11	Sharawany Allahi	882	483690	3937843	54
L12	Kazhzwa Village shar bazher	1116	442901	3933460	80
L13	Barzinja Village	1313	500000	3873043	95
L14	Kanisard S1	896	450996	3946263	102
L15	GorgadarS1	1083	448567	3942290	70
L16	GorgadarS2	972	448900	3941182	110
L17	GorgadarS3	969	449026	3941126	60
L18	kani sard S2	903	451016	3946170	80

L19	Twa soran	560	500699	4010969	120
L20	Girdjan S1	542	518366	4006752	100
L21	Girdjan S2	542	518366	4006752	286
L22	Chwarqurna	542	514571	4009056	120
L23	Dolabafra	559	495160	4009491	86
L24	Uch tapan	549	419334	3915725	150
L25	Qalijo Village	557	435322	3914364	60
L26	Qawella Village	778	428382	3926247	96
L27	Hajikadir no.17	515	420780	3937212	50
L28	Kanispika Parkhy	577	427844	3917653	60
L29	Hajiqadir well no.11	527	420556	3911950	100
L30	Kazhzwa Sharazwr Village	562	439646	3913727	70
L31	Mindol /Lano Nursery	553	427563	3915927	71
L32	Nawgrdan Village	510	418146	3909220	90
L33	Swrdash	1027	490620	3968490	30
L34	Homarqawm	1044	487683	3966574	48
L35	Piramagrwn	807	486883	3954699	150
L36	Kanimeran	790	489995	3961328	150
L37	Gokhlan	1259	404897	3954728	150
L38	Hangazhal	1277	415101	3953043	75
L39	Garmik	1259	414124	3954094	96
L40	Barrawa	1231	413262	3958718	165
L41	Basharaty KhwarwS1	528	413359	3902496	141
L42	Shashk	557	410009	3904340	150
L43	Sargat	1047	399304	3905726	50
L44	Golp	732	403559	3901782	30
L45	TapiSafay khwarwS1	546	411185	3905487	153
L46	TapiSafay khwarw S2	522	412231	3905443	107
L47	Baroy Shahid	941	473936	3926803	160
L48	Braimawa S1	951	470244	3921389	150
L49	Braimawa S2	951	470148	3921467	100
L50	Braimawa S3	958	470154	3921525	113
L51	Hargena	954	469135	3919985	80
L52	Tangisar Village	860	473726	3920645	110
L53	Wandarena Village	1338	500000	3651287	63
L54	Zerinjoy sarw	552	500000	3873043	57
L55	Sarzal	969	500000	3873043	75
L56	Bakhtiary	815	591253	3873500	100
L57	Berashka	504	419307	3908612	110

tion, this robust sampling framework forms the methodological foundation for assessing irrigation water quality, identifying potential risks to soil health and crop productivity, and supporting the development of scientifically informed, region-specific water management strategies that enhance agricultural sustainability in the governorate.

2.2 WATER SAMPLING

Water samples were systematically collected from 57 deep wells across the study area during the wet season (May to June), with the sampling depths corresponding to the specific hydrogeological characteristics of each well and each 2-week (14 days) samples were taken as outlined in Table 1. To ensure the reliability and representativeness of the samples, collection was performed using clean, sterilized polyethylene bottles, which effectively minimize the risk of contamination during handling and transport. Prior to sampling, each well was thoroughly purged by pumping 2–3 times its well volume, a standard practice designed to remove stagnant water from the borehole and ensure that only fresh groundwater was obtained for analysis. This step was particularly important for wells of varying depths, as indicated in Table 1, since deeper aquifers may show different chemical compositions compared to shallower sections. Once collected, the samples were subjected to a detailed physicochemical analysis focusing on parameters critical for evaluating irrigation water quality. This included pH, measured using a calibrated portable pH meter, and electrical conductivity (EC), determined in situ with a portable conductivity meter to assess salinity levels. Furthermore, the chemical composition of the water was analyzed for major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and major anions (HCO_3^-, SO_4^{2-}, Cl^-, NO_3^-), which were quantified in mmolc l^{-1} following standard analytical methods recommended for water quality assessment. This rigorous methodological framework not only ensured the accuracy and comparability of results but also provided a strong scientific basis for interpreting groundwater quality variations in relation to depth, hydrogeological setting, and agricultural suitability.

2.3 CALCULATION WATER QUALITY INDEX (IWQI) ACCORDING TO MAIA AND RODRIGUES, 2012

The main steps for determining IWQI was summarized as follow:

2.3.1 Calculating the deviation from the reference values for each variable, considering normal distribution of data, the Z-test was applied for data standardization as follow:

$$\bullet\ z_i = (x_i - \overline{x})\ /\ SD \ldots\ldots\ldots\ldots 1$$

Where: Zi = Standardized value of the studied parameter. Xi = Value of the property determined at the water source. = Mean value of the variable evaluated from the reference population. SD = Standard deviation of the parameter determined from the reference population.

2.3.2 Calculating the IWQI for the studied parameters such as (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^-, SO_4^{2-}, Cl^-, and NO_3^-) by using the following equations

$$\bullet\ \mathbf{WQI} = \sqrt[2]{(z_i)^2} \cdot \ldots\ldots\ldots\ldots 2$$

WQIi = The Index value for the characteristic of the studied water quality. Zi = The standardized variable value.

$$\bullet\ IWQI = \frac{1}{N}\sum_{i=1}^{n} WQIi \ldots\ldots\ldots\ldots 3$$

Where:

WQIi is the Water Quality Index for the characteristic, and IWQI stands for Irrigation Water Quality Index. Table 2

2.3.3 Ayers and Westcot, 1985 Model

The (Ayers and Westcot, 1985)model focuses on the salinity and sodicity of irrigation water. The key parameters for the calculation include EC, SAR, and Na %. The steps for calculating the IWQI according to this model are:

1. Electrical Conductivity (EC) Classification: Based on the EC, the water is classified into one of the following categories:
   - Low salinity (EC ≤ 0.7 dS m^{-1})
   - Medium salinity (0.7 < EC ≤ 2 dS m^{-1})
   - High salinity (EC > 2 dS m^{-1})
2. Sodium Absorption Ratio (SAR) Classification: Based on SAR, the water is classified as:
   - Low SAR (SAR ≤ 3)
   - Medium SAR (3 < SAR ≤ 6)

Table 2: Shows irrigation water classes depending on irrigation water quality index (IWQI) (Maia and Rodrigues, 2012)

IWQi or WQIi	Restriction
WQIi or IWQI ≤ 1.96	1- (Excellent)
1.96 < WQIi or IWQI ≤ 5.88	2- (Good)
5.88 < Wii or IWQI ≤ 9.80	3- (Average)
WQIi or IWQI > 9.80	4- (Poor)

– High SAR (SAR > 6)

3. Na % Classification: Sodium percentage is used to assess the water's potential to cause soil permeability problems. The classification is as follows:

– Low Na % (Na % ≤ 20)

– Medium Na % (20 < Na % ≤ 40)

– High Na % (Na % > 40)

4. Overall water quality: The final classification is determined by the intersection of the EC, SAR, and Na% classifications, using a salinity-sodicity diagram from (Ayers and Westcot, 1985)

5. Data Analysis

The results from both models were analyzed and compared for consistency. The IWQI values from both models were categorized into water quality classes for irrigation.

2.4 STATISTICAL ANALYSIS

The collected data were analyzed using the statistical software XLSTAT (version 2019.2.2.59614) to assess seasonal variations in water quality. Analysis of variance (ANOVA) was applied to detect significant differences in the measured parameters between seasons, ensuring a clear understanding of how water quality fluctuates over time. In addition, correlation analysis was performed to identify the strength and direction of relationships among the different water quality parameters, such as pH, electrical conductivity, dissolved salts, and nutrient concentrations. This approach not only revealed whether the seasonal changes were statistically significant but also provided insights into how certain variables are interrelated, thereby offering a more comprehensive evaluation of the overall water quality dynamics.

3 RESULTS AND DISCUSSIONS

3.1 IRRIGATION WATER CLASSIFICATION DEPENDING ON GLOBAL CLASSIFICATION (AYERS AND WESTCOT, 1985) IN WET AND DRY SEASON

The classification of wells based on key irrigation water quality parameters—such as pH, electrical conductivity (EC), sodium adsorption ratio (SAR), bicarbonate (HCO_3^-), and chloride (Cl^-) concentrations—revealed clear seasonal variations and corresponding restrictions on water use in the study area. During the wet season, the majority of wells (45 in total) were categorized as having no restriction (NR), while 12 wells fell into the slight to moderate restriction (S-MR) category. As shown in Table 3, the pH values for these wells ranged from 6.7 to 7.8, EC values were between 0.30 and 0.70 dS m^{-1}, and SAR levels varied from 0.02 to 1.01 (mmolec $l^{-1})^1/^2$. According to the classification framework outlined by Ayers and Westcot (1985), such low EC and SAR values correspond to unrestricted water quality that is generally favorable for irrigation, whereas slight to moderate restrictions indicate that careful management is necessary due to elevated parameter values. A similar trend was observed in the dry season, when 29 wells remained within the NR class and 28 shifted into the S-MR category, again demonstrating the seasonal sensitivity of groundwater quality. Although most wells displayed consistent parameter ranges across both seasons, certain wells (e.g., 45, 54, and 57) consistently maintained NR status, suggesting greater resilience to seasonal variability. By contrast, wells such as 12 and 55 recorded higher EC, SAR, and chloride levels, which contributed to S-MR classification and pose risks for soil structure and long-term crop performance. These findings are consistent with the results of Fadl et al. (2024) and Meena et al. (2024), who similarly reported that seasonal fluctuations in water quality directly affect irrigation suitability. The observed seasonal dynamics highlight the necessity of continuous monitoring and adaptive management, as emphasized by Kisekka (2024), to prevent adverse impacts on soil fertility and crop yields. Furthermore, the broader significance of this research aligns with the conclusions of Zhang et al. (2024), Marif (2023), and Marif and Esmail (2023), who underline that systematic water quality assessments are fundamental for sustaining irrigation practices in regions experiencing strong climatic seasonality.

3.2 CLASSIFICATION OF IRRIGATION WATER DEPENDING ON CATIONS AND ANIONS CONCENTRATION USING PRINCIPAL'S COMPONENT ANALYSIS (PCA) IN WET SEASON

In the dry season, the classification of irrigation water from various wells based on the guidelines from (Ayers and Westcot, 1985) reveals important insights into water quality for agricultural use. According to the data presented in Table 4, water from 29 wells showed no restrictions (NR) for irrigation, with electrical conductivity (EC) values ranging from 0.35 to 0.69 dS m^{-1} and a pH ranging from 6.6 to 7.9. Additionally, the sodium adsorption ratio (SAR) for these wells ranged from 0.014 to 0.317 mmole l^{-1}^1/2, indicating that they are generally safe for irrigation purposes with minimal adverse effects on soil properties. In contrast, water from 28 wells fell under the slight to moderate restriction (S-MR) category, with EC values between 0.76 and 1.76 dS m^{-1} , and SAR

Table 3: Classification of irrigation water according to international method Ayers & Westcote (1985) in wet season

Water clasess	Well Number	pH	EC dS m^{-1}	SAR $(mmol_{c1} l^{-1})^{1/2}$	No .of wells
No Restrictions (NR)	1, 2, 3, 4, 8, 9, 10, 12, 13, 14, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 53, 54, 55, 56, and 57	6.8 to 7.8	0.30 to 0.70	0.02 to 1.01	45
Slight to Moderate (SM)	5, 6, 7, 11, 15, 25, 47, 48, 49, 50, 51, and 52	6.7 to 7.6	0.76 to 1.76	0.06 to 0.56	12

values ranging from 0.034 to 0.757 mmole l^{-1}. While still usable for irrigation, the water from these wells may lead to some long-term soil salinity issues or mild changes in the water's sodium content. The classification system also accounts for additional factors such as bicarbonate (HCO3-) and chloride (Cl-) concentrations, which further influence water suitability (Hammoumi et al., 2024, Benaissa et al., 2024). For instance, the water from well 57, with a bicarbonate concentration exceeding 8.5 mmole l^{-1}, was classified as having severe restrictions (S), which is a significant concern for its agricultural use. The detailed water classifications provided in Table 4 highlight the variability in water quality across wells and provide a comprehensive view of how EC, SAR, and other factors interact to determine irrigation suitability. This data is crucial for managing water resources efficiently in regions dependent on irrigation, ensuring that water used for agricultural purposes does not negatively impact soil health or crop yields in the long term(Ali et al., 2024, Ishola, 2024a). This table summarizes the classification of water samples based on various parameters, providing a clear overview of how water quality varies and its suitability for agricultural use. The classification system, based on EC, SAR, pH, and ionic concentrations, is essential for understanding how water quality can impact irrigation practices and long-term soil health, as discussed in the 2024 context by(Ayers and Westcot, 1985).

Table 5 presents the seasonal variation in the classification of irrigation water quality based on the criteria provided by (Ayers and Westcot, 1985) comparing data between the wet and dry seasons for various water parameters, including Electrical Conductivity (EC), pH, sodium adsorption ratio (SAR), bicarbonates (HCO_3^-), and chloride (Cl^-). The table also includes the number of wells categorized under different classifications during the wet and dry seasons (Abugu et al., 2024; Hamed Al Maliki et al., 2024). In the wet season, most of the wells (45) fall under the "NR" (Normal) category, which indicates that the water quality is within acceptable limits for irrigation, as reflected by relatively balanced levels of EC, pH, SAR, HCO_3^-, and Cl^-. In contrast, during the dry season, the number of wells classified as "NR" decreases slightly to 29, suggesting that water quality deteriorates in terms of salinity (EC) and ion concentrations, possibly due to reduced water availability or concentration effects as water levels drop (Hailu et al., 2024). The "S-MR" (Slightly Marginally Restricted) classification is observed in 12 wells during the wet season, with a noticeable increase to 28 wells in the dry season, indicating that the water quality becomes marginally less suitable for irrigation due to an increase in certain factors like SAR or bicarbonates, which can affect soil structure and crop health (Muthu et al., 2024). The number of wells categorized as "Severe" remains at zero during the wet

Table 4: Classification of irrigation water according to international method (Ayers and Westcot, 1985) in dry season

Water clasess	Well number	pH	EC dS m^{-1}	SAR $(mmol_c l^{-1})^{1/2}$	No .of wells
No Restrictions (NR)	2, 9, 10, 11, 19, 22, 23, 27, 29, 30, 32, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 53, 54, 55, 56 and 57	6.6 to 7.9	0.35 to 0.69	0.014 to 0.317	29
Slight to Moderate (SM)	1, 3, 4, 5, 6, 7, 8, 12, 13, 14, 15, 16, 17, 18, 20, 21, 24, 25, 26, 28, 31, 33, 47, 48, 49, 50, 51 and 52	6.6 to 7.9	0.70 to 1.70	0.034 to 0.757	28

season but increases to one in the dry season, which may reflect worsening water conditions, such as high salinity or sodium levels that severely affect crop growth and soil permeability. This seasonal variation is significant in terms of irrigation management, as the increased salinity and ion concentration in the dry season may lead to more challenges in managing irrigation practices, with the need for monitoring water quality and potentially modifying irrigation techniques to avoid long-term soil degradation or crop yield reductions. Thus, the seasonal fluctuations in water quality, including the higher EC, pH, SAR, and bicarbonates in the dry season, point to a direct link between seasonal changes in water availability and irrigation water quality, highlighting the need for adaptive management strategies in areas that experience such variations(Ishola, 2024b, Semar et al., 2024).

3.3 IRRIGATION WATER CLASSIFICATION USING (MAIA AND RODRIGUES, 2012) MODEL IN WET SEASON

In the wet season, the water quality from the wells showed distinct classifications based on the Irrigation Water Quality Index (IWQI) values, with results falling into the "excellent," "good," "average," and "poor" categories, reflecting the variation in suitability for irrigation. Specifically, 16 wells exhibited an "excellent" water quality, with IWQI values ranging from 1.34 to 1.92, which is consistent with water having low electrical conductivity (EC) of 0.30 to 0.55 dS m^{-1}.(Martínez et al., 2024, Lal et al., 2024) These findings indicate that the water from these wells is ideal for irrigation, as it falls within the ideal range for nutrient delivery and minimal salinity. On the other hand, 32 wells were classified as "good" with IWQI values between 2.09 and 5.87, associated with EC levels ranging from 0.30 to 1.72 dS m^{-1}. Although still within acceptable limits for irrigation, this classification suggests that these waters may require more careful management to avoid long-term soil salinization. A further 7 wells showed "average" quality, with IWQI values spanning from 5.89 to 8.90 and EC between 0.35 to 1.22 dS m^{-1}, indicating that these waters can be used for irrigation, but may necessitate specific soil amendments or more intensive monitoring. Finally, two wells were classified as "poor," with IWQI values of 21.55 to 22.79 and EC values of 0.55 to 1.76 dS m^{-1}. Such water would be considered less suitable for irrigation without significant treatment or blending with higher quality sources, as the high IWQI reflects potential salinity risks to soil and crops. These results align with the findings of (Rodríguez-Aguilar et al., 2024) and (Scheibel et al., 2024) who also observed similar variations in water quality in different seasonal conditions. Table 6, as presented, outlines these classifications based on (Maia and Rodrigues, 2012, MARIF and ESMAIL, 2023) model in the wet season, demonstrating the range of EC and IWQI values that characterize each water class, underscoring the variability in irrigation water quality across the studied wells(Ferreira et al., 2024).

3.4 IRRIGATION WATER CLASSIFICATION USING MAIA & RODIREGUES (2012) MODEL IN DRY SEASON

In the dry season, the irrigation water from various wells was classified according to the model established by (Maia and Rodrigues, 2012) revealing a broad spectrum of water quality as reflected by the Irrigation Water Quality Index (IWQI) values. Specifically, the irrigation water from 37 wells was categorized as excellent, showing IWQI values ranging from 0.35 to 1.79 and electrical conductivity (EC) values between 0.39 and 0.85 dS m^{-1}, suggesting that these wells provide optimal water quality for irrigation. Seventeen wells were classified as good, with IWQI values ranging from 2.05 to 4.00 and EC values between 0.69 and 1.23 dS m^{-1}, indicating that while the water quality is still suitable for irrigation, it may require more management to avoid potential adverse effects on crops (Kisekka, 2024). One well was classified as average, with an IWQI of 5.98 and

Table 5: Sesonal varaiation of classification of irrigation water according to (Ayers and Westcot, 1985) compariosn in wet and dry season

Water Class	Wet season					Dry season				
	EC	pH	SAR	HCO_3^-	Cl^-	EC	pH	SAR	HCO_3^-	Cl^-
	No. of wells in wet season					No. of wells in dry season				
NR	45	57	57	2	54	29	57	57	0	57
S-MR	12	0	0	55	3	28	0	0	56	0
Severe	0	0	0	0	0	0	0	0	1	0

Table 6: Classification of irrigation water according to (Maia and Rodrigues, 2012)model in wet season

Water clasess	Well number	EC dS m-1	IWQI	No .of wells
Excellent	10, 19, 23, 27, 35, 36, 37, 38, 39, 40, 42, 43, 44, 54, 55 and 56	0.30 to 0.55	1.34 to 1.92	16
Good	1, 2, 3, 4, 5, 6, 8, 9, 11, 13, 16, 17, 20, 21, 22, 24, 25, 26, 28, 29, 30, 31, 32, 33, 34, 41, 45, 46, 47, 49, 53 and 57	0.30 to 1.72	2.09 to 5.87	32
Average	14, 15, 18, 48, 50, 51 and 52	0.35 to1.22	5.89 to 8.90	7
Poor	12 and 7	0.55 to 1.76	21.55 to 22.79	2

an EC of 1.29 dS m^{-1}, reflecting a less desirable quality for irrigation, where water management strategies become more crucial (Muthu et al., 2024). Finally, two wells were rated as poor, with a fixed IWQI of 10.72 and EC values ranging from 1.12 to 1.70 dS m^{-1}, making the water from these wells unsuitable for irrigation without treatment or careful management due to the higher risk of salinity affecting crop growth. The IWQI values for these classifications were consistent with the findings of (SHARMA, 2024) and (Sharma et al., 2024), who reported similar trends in water quality assessments(Saeed et al., 2024). This classification provides a clear understanding of water quality across the studied wells and is crucial for guiding sustainable irrigation practices. The following table summarizes the detailed classification of the irrigation water based on (Maia and Rodrigues, 2012). This classification underscores the variability in irrigation water quality within the region and its potential impact on crop production, highlighting the need for tailored water management strategies based on the IWQI and EC values in different wells (Shaw and Sharma, 2024).

The seasonal variations significantly influence the classification of water quality across different wells, as evidenced by the data from 15 and 6 wells during the dry season. Specifically, during the dry season, water from these wells, which initially fell under the "Good" and "Average" categories, shifted to the "Excellent" category. This suggests an improvement in water quality, likely driven by changes in key water parameters such as electrical conductivity (EC) and the chemical composition of the water, as discussed by (Haq and Muhammad, 2023). Conversely, during the wet season, water quality was predominantly categorized as "Good," with 32 wells in this category, while the number of wells classified as "Excellent" remained lower at 16. However, a notable shift occurred during the transition from the wet season to the dry season, where 21 wells, which had been classified as "Good" or "Average" in the wet season, were reclassified into the "Excellent" category. This transition reflects a decrease in the number of wells in the "Good" and "Average" categories, resulting in an overall increase in the number of wells classified as "Excellent" during the dry season. Such shifts in classification could be attributed to the changes in water chemistry, as noted in the seasonal variational classification provided by (Maia and Rodrigues, 2012) and the findings in Table 8, which highlight a clear increase in water quality classification during the dry season.

4 DISCUSSION

Table 7: Classification of irrigation water according to (Maia and Rodrigues, 2012) model in dry season

Water clasess	Well number	EC dS m-1	IWQI	No of wells
Excellent	2, 5, 10, 11, 13, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 53, 54, 55, 56 and 57	0.39 to 0.85	0.35 to 1.79	37
Good	1, 3, 4, 6, 8, 9, 14, 15, 16, 17, 18, 33, 47, 48, 49, 50 and 51	0.69 to 1.23	2.05 to 4.00	17
Average	52	1.29	5.98	1
Poor	7 to 12	1.12 to 1.70	10.72 to 10.72	2

Table 8: The Seasonal variational classification of irrigation water according to (Maia and Rodrigues, 2012)

	Water classification according to (Maia and Rodrigues, 2012)			
Seasons	Excellent	Good	Average	Poor
Wet season	16	32	7	2
Dry season	37	17	1	2
No. of wells	21	15	6	0
Variations	Increase	Decrease	Decrease	0

The study of water quality in Sulaimani City (2023), which classified irrigation water suitability across wet and dry seasons using the models of Maia and Rodrigues (2012) and Ayers and Westcot (1985), opens an important discussion about the broader implications for sustainable irrigation management in the region. The results clearly demonstrated that water quality parameters such as EC, SAR, pH, HCO_3^-, and Cl^- fluctuate seasonally, highlighting the need for long-term monitoring systems that can capture inter-annual trends and provide more reliable insights into how these fluctuations influence soil health and crop productivity over time. Establishing such monitoring networks across different wells would not only help track temporal shifts in water quality but also strengthen adaptive strategies for irrigation planning. Additionally, the study revealed significant spatial differences among wells, with certain wells showing higher resilience to seasonal changes, thereby emphasizing the importance of developing site-specific irrigation management strategies. Such localized approaches, supported by decision support tools that integrate water quality data with crop requirements, soil conditions, and seasonal forecasts, could enhance water-use efficiency and minimize risks of soil salinization. Another key issue raised by the findings is the lack of direct assessment of long-term impacts of irrigation water on soil properties. In areas classified as having slight to moderate restrictions, elevated levels of EC, SAR, and bicarbonates could gradually lead to soil salinity, poor structure, and reduced fertility, ultimately threatening crop yields. Therefore, future research should focus on linking irrigation water quality with soil health outcomes and testing mitigation practices such as soil amendments. Moreover, while this study employed established classification models, the discussion highlights the potential value of incorporating modern analytical tools like machine learning to improve the precision and predictive capacity of irrigation water assessments. By training models on historical datasets and integrating them into real-time decision-making platforms, researchers and practitioners could achieve more dynamic and accurate management outcomes. Finally, given that climate change is projected to alter rainfall regimes, evaporation rates, and overall water availability, its likely influence on irrigation water quality cannot be overlooked. Anticipating shifts in salinity, ion concentrations, and related parameters under future climatic conditions is critical to safeguard agricultural sustainability. Overall, these findings underline that sustainable irrigation management in Sulaimani requires a comprehensive and integrated approach that combines long-term monitoring, site-specific strategies, soil health assessments, advanced predictive modeling, and climate change considerations.

5 CONCLUSION

In conclusion, this study has highlighted the significant seasonal variations in water quality, as classified according to (Ayers and Westcot, 1985) for irrigation purposes. The analysis of wells during both the wet and dry seasons revealed notable shifts in water quality, particularly in terms of Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), and other ionic concentrations such as bicarbonates and chloride. During the wet season, most wells showed no restrictions, indicating favorable water conditions for irrigation. However, the dry season saw an increase in slight to moderate restrictions, suggesting that water quality may deteriorate with reduced water availability or concentration effects, especially concerning salinity and sodium levels. These findings underline the necessity for continuous monitoring and adaptive water management strategies to ensure sustainable irrigation practices and mitigate potential long-term impacts on soil health and crop productivity.

Furthermore, the use of the Irrigation Water Quality Index (IWQI) by (Maia and Rodrigues, 2012) provided additional insight into the variability of water quality across the studied wells. The classification of water quality into categories ranging from “Excellent” to “Poor” revealed how seasonal shifts in key parameters such as EC and pH can influence the suitability of water for irrigation. In the wet season, water from many wells was classified as good, while the dry season saw some improvements in water quality, with more wells categorized as "Excellent." These shifts emphasize the importance of understanding the dynamic nature of water quality and its impact on irrigation efficiency. By incorporating both seasonal and index-based classifications, this study contributes valuable knowledge to the management of irrigation water resources, providing guidance for farmers to adjust their irrigation strategies in response to changing environmental conditions and to optimize agricultural productivity throughout the year.

Recommendations

Incorporation of Advanced Analytical Techniques (Machine Learning) for Classification and Prediction

- **Rationale**: The classification of irrigation water quality is done using traditional models, which could be enhanced by incorporating modern data analysis methods. Advanced techniques like machine learning could provide more accurate, real-time assessments of water quality and predict future trends based on historical data.
- **Future Work**: Develop a machine learning-based model that can predict irrigation water quality based on various parameters (EC, SAR, pH, HCO_3^-, and Cl^-). This model could be trained using historical data from wells and incorporated into a web-based platform for real-time decision support in irrigation management.
- Evaluation of the Effects of Climate Change on Irrigation Water Quality
- **Rationale**: The study provides insights into seasonal variations in water quality but does not explore how climate change may affect future water quality. As climate change is likely to alter precipitation patterns, evaporation rates, and water availability, these changes could exacerbate salinity and ion concentration issues in irrigation water.
- **Future Work**: Conduct a study that integrates climate change projections with current water quality data to assess how future climatic conditions might influence irrigation water suitability. This could involve modeling the effects of temperature increases, altered rainfall patterns, and changing evaporation rates on the water quality parameters critical for irrigation.

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Data availability statement

All data are included in the manuscript.

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