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Ola Muayad Ali Altaie
 Department of Soil Science
 and Water, Faculty of
 Agriculture, University of
 Kufa, Najaf, Iraq

Hydrochemical assessment and irrigation suitability of groundwater in the Bahr Al-Najaf area, Najaf Governorate, Iraq

Ola Muayad Ali Altaie¹

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ABSTRACT

Groundwater is an important water resource for agricultural irrigation in the arid environment of Bahr Al-Najaf, Iraq, where increasing salinity and variations in groundwater chemistry may affect soil and crop productivity. The present study was aimed to assess the hydrochemical properties and irrigation suitability of groundwater by using Physico-chemical parameters, irrigation water quality indices and GIS techniques. Twenty groundwater wells (W1-W20) were studied in the agricultural areas of Bahr Al-Najaf. The analyzed parameters were pH, electrical conductivity (EC), total dissolved solids (TDS), Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , SO_4^{2-} , HCO_3^- and NO_3^- . The quality of irrigation water was evaluated through sodium adsorption ratio (SAR), sodium percentage (Na%), residual sodium carbonate (RSC), Kelley's ratio (KR), permeability index (PI), potential salinity (PS), magnesium hazard (MH) and Irrigation Water Quality Index (IWQI). The results showed that the groundwater was mostly neutral to slightly alkaline and the EC and TDS showed high spatial variations reflecting the differences in groundwater mineralization. The irrigation indices indicated salinity and sodium hazards as the main controlling factors for the suitability of groundwaters. The negative values of RSC indicated no significant residual carbonate hazard. The results of IWQI showed significant differences in the overall irrigation suitability of the studied wells, with better conditions in terms of low salinity and sodium concentrations. The combined application of hydrochemical indices and GIS provided an efficient method for identifying the spatial variations of ground water quality and irrigation suitability. The results emphasize the necessity of proper irrigation and soil-management practices to minimize the possible effects of groundwater salinity and to promote sustainable agricultural water use in the Bahr Al-Najaf area.

Keywords: Groundwater, Bahr Al-Najaf, Irrigation Water Quality, Hydrochemistry, IWQI, SAR, Salinity, GIS

Introduction

Groundwater is one of the main water sources for irrigation in arid and semi-arid areas with limited rainfall, high evaporation and limited surface water resources, and agriculture production is highly dependent on groundwater. However, the groundwater quality varies with geological conditions, groundwater-rock interactions, evaporation, recharge processes and human activities. Therefore, assessment of groundwater chemistry is necessary for evaluation of groundwater suitability for irrigation and its potential effects on soil properties, crop productivity and sustainable agricultural management (Awadh *et al.*, 2016; Al-Aboodi *et al.*, 2019) [1, 2]. Salinity is one of the major problems of groundwater irrigation. Continued use of water with high dissolved salt concentrations may increase the buildup of salts in the soil, particularly in areas with high evaporation and poor drainage. Electrical conductivity (EC) and total dissolved solids (TDS) are commonly used as key indicators of salinity risk. The effects of saline irrigation water depend on many factors such as soil properties, salt tolerance of crops, climatic conditions, irrigation practices and drainage efficiency (Awadh *et al.*, 2016; Abdulshaheed *et al.*, 2024) [1, 3]. Sodium is also an important consideration in evaluating irrigation water because high concentrations of sodium relative to calcium and magnesium can cause soil sodicity, clay dispersion, reduced infiltration and loss of the hydraulic properties of the soil. Hence, the sodium adsorption ratio (SAR) is commonly used for the assessment of sodium hazards. Other indices such as Sodium Percentage (Na%), Residual Sodium Carbonate (RSC), Kelley's Ratio (KR), Permeability Index (PI), Potential Salinity (PS) and Magnesium Hazard (MH) provide more information about the possible impacts of groundwater on agricultural soils (Awadh *et al.*, 2016; Al-Owaidi *et al.*, 2021) [1, 4]. Hydrochemical assessment of groundwater normally comprises estimation of major physicochemical parameters and dissolved ions as pH, EC, TDS, Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , SO_4^{2-} , HCO_3^- , CO_3^{2-} and NO_3^- . The inclusion of these parameters in the irrigation-water quality indices provides a more comprehensive picture than the use of a single indicator. The Irrigation Water Quality Index (IWQI) can be used to compile different water qual

Corresponding Author:
Ola Muayad Ali Altaie
 Department of Soil Science
 and Water, Faculty of
 Agriculture, University of
 Kufa, Najaf, Iraq

ity parameters and categorize groundwater based on its suitability for agricultural irrigation (Al-Owaidi *et al.*, 2021; APHA *et al.*, 2023) [4, 5]. Geographic Information Systems (GIS) are an efficient tool for assessing the spatial variability of groundwater quality. GIS can combine chemical measurements with geographic coordinates to map the spatial distribution of EC, TDS, SAR, major ions, and integrated water-quality indices. Such maps can identify areas with relatively suitable or unsuitable groundwater and give useful information for agricultural water-resource management (APHA *et al.*, 2023; Ayers *et al.*, 1994) [5, 6]. The Bahr Al-Najaf area is one of the important areas for studying groundwater and agricultural water due to the arid nature of the climate of the area and the dependence on groundwater resources in agricultural activities. Previously, studies have indicated spatial variability in the groundwater chemistry and irrigation suitability in the Bahr Al-Najaf and broader Najaf region, highlighting the need for continued assessment of groundwater resources (FAO, 1985; Wilcox, 1955) [7, 8]. As groundwater use, agricultural procedures, and evaporation and irrigation return flow change over time, water quality can be affected, so periodic monitoring is especially important. The present study is therefore undertaken to provide a complete hydrochemical assessment of groundwater used for agricultural irrigation in Bahr Al-Najaf area, Najaf Governorate, Iraq. The study evaluates the physicochemical characteristics and major dissolved ions of the groundwater, calculates the major irrigation-water quality indices, viz. EC, TDS, SAR, Na%, RSC, KR, PI, PS and MH and applies GIS-based spatial analysis to determine the distribution and irrigation suitability of groundwater. The results are expected to provide useful scientific information for sustainable use of groundwater, irrigation management and protection of agricultural soils in the region of Bahr Al-Najaf.

Study area

Study area The study was conducted in Bahr Al-Najaf region, south west of Najaf City, Najaf Governorate, Central Iraq. The area is a natural depression in an arid desert environment. The area is characterized by low precipitation, high temperatures and high evaporations rates. Such climatic conditions make groundwater a more important water resource for agricultural activities in the vicinity. The hydrogeological conditions of Bahr Al-Najaf are spatially variable and groundwater chemistry is influenced by geological formations, water-rock interactions, evaporation and other hydrochemical processes. Previous studies have highlighted the significance of groundwater resources in the area for irrigation and have reported substantial spatial variability in groundwater quality. Agricultural activity is dispersed around the Bahr Al-Najaf depression, and is partially dependent on groundwater drawn from wells. Recent studies of groundwater in the vicinity of the Bahr Al-Najaf depression have shown that pH, electrical conductivity, total dissolved solids and major dissolved ions vary between wells. This points to the need for systematic hydrochemical and spatial assessment of the groundwater used for irrigation. To represent the spatial variability of groundwater quality, the present study selected 20 groundwater wells (W1–W20) spread throughout the study area and surrounding agricultural lands. We recorded the geographic coordinates of each well on a GPS device and related them to the corresponding chemical measurements using a Geographic Information System (GIS). Thereafter, the spatial distribution of sampling wells was used to study the variability of important irrigation-water quality parameters including pH, EC, TDS, SAR, Na%, RSC and IWQI, and to determine areas with varying degrees of suitability for agricultural irrigation.

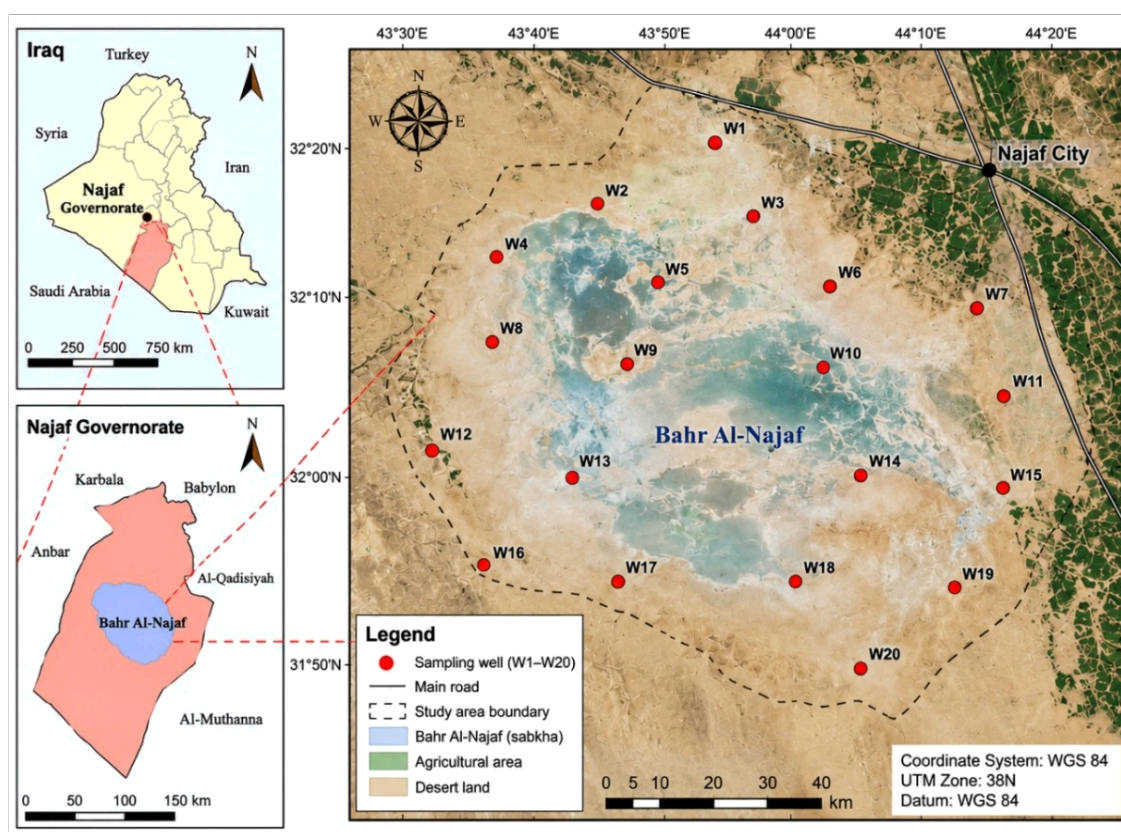


Figure 1. Location of the Bahr Al-Najaf study area and spatial distribution of the 20 groundwater sampling wells.

Materials and methods

Groundwater sampling and laboratory analysis

A total of 20 groundwater wells (W1–W20) were selected from the agricultural areas of Bahr Al-Najaf. Groundwater samples were collected in clean polyethylene bottles, properly labeled, and transported

to the laboratory for chemical analysis. Field measurements of pH, electrical conductivity (EC), and total dissolved solids (TDS) were performed using a portable Hanna HI98194 multiparameter water quality meter. The instrument is designed for field measurement of several water-quality parameters and provides automatic calibration for pH and EC. The major ions, including Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- ,

SO_4^{2-} , HCO_3^- , CO_3^{2-} , and NO_3^- , were determined using standard analytical procedures (FAO, 1985; Wilcox, 1955) [7, 8].



Figure 2. Hanna HI98194 multiparameter water quality meter used for field measurement of groundwater quality (pH, EC, and TDS).

Irrigation water quality assessment

Suitability of groundwater for agricultural irrigation was evaluated based on EC, TDS, sodium adsorption ratio (SAR), soluble sodium percentage (Na%), residual sodium carbonate (RSC), Kelley's ratio (KR), permeability index (PI), potential salinity (PS) and magnesium hazard (MH). These indices were used to evaluate salinity, sodium hazard, soil permeability and the effect of major dissolved ions on agricultural soils (Wilcox, 1955; Eaton, 1950) [8, 9].

The sodium adsorption ratio was computed as:

$$\text{SAR} = \text{Na}^+ / \sqrt{(\text{Ca}^{2+} + \text{Mg}^{2+}) / 2}$$

The soluble sodium percentage was calculated as:

$$\text{Na\%} = \left[\text{Na}^+ / (\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+) \right] \times 100$$

The residual sodium carbonate was calculated as:

$$\text{RSC} = (\text{CO}_3^{2-} + \text{HCO}_3^-) - (\text{Ca}^{2+} + \text{Mg}^{2+})$$

All ionic concentrations used in the equations were expressed in meq/L (Wilcox, 1955; Eaton, 1950) [8, 9].

Hydrochemical and GIS Analysis

The Piper and Gibbs diagrams were used to characterize the major cations and anions of the groundwater hydrochemistry. These methods were used to determine the dominant hydrochemical facies and the main processes controlling the groundwater composition (Tanji, 1990) [10]. The geographical coordinates of the 20 wells were related to the analytical results using GIS techniques and spatial distribution maps of groundwater-quality parameters and irrigation indices were prepared. The method was used to identify the spatial variations of groundwater quality and its suitability for irrigation (Richards, 1954) [11]. 2.4 Statistical Analysis Descriptive statistics (minimum, maximum, mean, standard deviation and coefficient of variation) were calculated for all parameters studied. The Pearson correlation analysis was applied to evaluate the relationship among the physicochemical parameters and major ions. The hydrochemical and GIS analysis was interpreted together with statistical results to identify the major factors controlling groundwater quality.

Results and discussion

Physicochemical characteristics and major ions

Table 1 presents the physicochemical characteristics and major dissolved ions of the groundwater samples collected from the 20 wells studied (W1–W20). These parameters are basic chemical characteristics of ground water and very important for evaluation of suitability of ground water for agricultural irrigation. Results included pH, electrical conductivity (EC), total dissolved solids (TDS), and major cations and anions. Differences between wells may reflect differences in mineral dissolution, evaporation, groundwater residence time and water–rock interaction. Such processes are especially important in dry environments such as Bahr Al-Najaf (Todd *et al.*, 2005; Rhodes *et al.*, 1992) [12, 13].

Table 1. Physicochemical characteristics and major ions of groundwater samples from Bahr Al-Najaf

Well	pH	EC (dS/m)	TDS (mg/L)	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	HCO_3^-	NO_3^-
W1	7.18	3.21	2080	210	92	310	8.2	410	620	185	1.2
W2	7.24	3.85	2490	245	105	365	9.4	480	710	201	1.4
W3	7.12	4.16	2710	268	118	410	10.1	535	795	214	1.1
W4	7.29	2.74	1780	185	80	275	6.8	350	510	172	0.9
W5	7.21	4.73	3070	295	132	455	12.4	610	890	226	1.6
W6	7.16	5.12	3330	320	145	495	13.1	675	960	239	1.8
W7	7.26	2.96	1920	198	87	292	7.5	385	560	178	1.0
W8	7.14	5.68	3690	350	158	540	14.8	735	1080	251	1.7
W9	7.19	6.21	4030	382	170	585	16.2	810	1170	265	1.9
W10	7.23	4.48	2910	275	124	430	11.6	570	835	220	1.3
W11	7.11	6.74	4380	410	185	640	18.5	880	1280	278	2.1
W12	7.27	3.52	2290	225	98	335	8.7	445	665	193	1.0
W13	7.20	7.18	4670	435	196	680	19.3	930	1360	291	2.2
W14	7.15	5.46	3550	338	151	520	14.0	710	1025	244	1.8
W15	7.28	2.58	1680	175	74	250	6.1	325	470	165	0.8
W16	7.13	6.52	4240	395	178	615	17.4	845	1230	272	2.0
W17	7.22	4.01	2610	252	110	385	9.8	505	750	207	1.3

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Well	pH	EC (dS/m)	TDS (mg/L)	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	NO ₃ ⁻
W18	7.17	7.64	4960	455	205	720	20.5	990	1450	305	2.4
W19	7.25	3.67	2380	232	101	350	8.9	460	690	198	1.1
W20	7.10	5.91	3840	365	164	560	15.6	760	1120	258	1.9
Mean ±	7.20±0.06	4.78	3105 ± 946	299 ± 79	135	461±137	12.5±4.2	619±194	917±282	232	1.5
SD		± 1.46		± 40					± 38	± 0.5	

The pH values ranged from 7.10 to 7.29 indicating neutral to slightly alkaline groundwater. Conversely, EC ranged from 2.58 to 7.64 dS/m and TDS ranged from 1680 to 4960 mg/L indicating a substantial variation in the salinity of the groundwater. W18 achieved maximum EC and TDS values while W15 exhibited minimum values. High EC and TDS were observed in several wells suggesting salinity is a major factor affecting suitability for irrigation. More mineralized wells may have relatively high concentrations of Na⁺, Cl⁻ and SO₄²⁻ due to evaporation and dissolution of soluble minerals. A similar variability in the groundwater chemistry was reported for the Bahr Al-Najaf region (Todd *et al.*, 2005) [12].

Irrigation water quality indices

Some water quality indices were computed from the major ion concentrations to have a better assessment of the irrigation suitability. Results are presented in Table 2. The SAR and Na% were used to assess the sodium hazard and RSC, KR, PI, PS and MH for the additional effects related to carbonate, permeability, salinity and magnesium. It is recommended to use these indices in combination because irrigation-water quality is controlled by several interacting chemical factors rather than a single parameter (Rhodes *et al.*, 1992; Oster, 1994) [13, 14].

Table 2. Irrigation-water quality indices of the investigated groundwater wells

Well	SAR	Na%	RSC (meq/L)	KR	PI (%)	PS	MH (%)
W1	3.18	55.4	-2.1	1.24	54.2	17.6	31.5
W2	3.65	57.2	-2.4	1.34	55.7	20.1	30.8
W3	4.02	58.6	-2.7	1.42	56.3	22.4	31.2
W4	2.91	53.8	-1.8	1.17	53.1	15.0	30.4
W5	4.37	59.1	-3.0	1.47	57.0	25.3	31.7
W6	4.72	60.3	-3.2	1.53	58.1	27.8	31.9
W7	3.04	54.6	-2.0	1.20	53.8	16.5	30.9
W8	5.01	61.4	-3.5	1.61	59.2	30.2	32.0
W9	5.38	62.7	-3.8	1.68	60.1	33.0	32.2
W10	4.19	58.9	-2.8	1.45	56.8	23.6	31.3
W11	5.82	64.1	-4.1	1.76	61.4	36.8	32.5
W12	3.36	56.2	-2.3	1.28	54.8	18.9	31.0
W13	6.11	65.3	-4.4	1.84	62.0	39.1	32.7
W14	4.86	60.8	-3.3	1.57	58.7	29.0	32.1
W15	2.72	52.4	-1.6	1.10	51.7	13.9	30.1
W16	5.61	63.5	-3.9	1.72	60.8	35.5	32.4
W17	3.82	57.9	-2.5	1.39	55.9	21.2	31.1
W18	6.48	66.2	-4.7	1.95	63.1	41.5	32.9
W19	3.47	56.8	-2.2	1.31	55.1	19.7	30.7
W20	5.22	61.9	-3.6	1.64	59.6	31.5	32.3

The SAR values was ranged from 2.72 to 6.48 and Na% from 52.4% to 66.2%. The highest values were obtained at W18 which also had the highest EC and TDS. This correspondence suggests that the more saline groundwater samples are also characterized by greater sodium-related constraints. However, RSC values were negative in all wells, ranging from -1.6 to -4.7 meq/L, suggesting no significant residual carbonate hazard. The variation of PI and MH values was relatively small indicating that their contribution to overall irrigation constraints was less than that of salinity and sodium.

Integrated irrigation water quality index

The Irrigation Water Quality Index (IWQI) was used to assess the overall suitability of the groundwater for irrigation. The calculated values and their classifications are given in Table 3. The IWQI considers the effects of some water quality parameters and offers a simple way of comparing the overall irrigation quality of the studied wells. This approach is especially useful when the groundwater quality varies spatially within an agricultural area (Oster *et al.*, 1996) [15].

Table 3. IWQI and overall irrigation suitability of groundwater wells

Well	IWQI	Quality Class
W1	61.4	Moderate
W2	57.8	Moderate
W3	54.6	Moderate
W4	68.2	Moderate
W5	49.7	Poor
W6	45.9	Poor
W7	64.8	Moderate
W8	42.5	Poor
W9	38.7	Poor
W10	52.1	Moderate
W11	34.6	Poor
W12	62.7	Moderate
W13	31.8	Poor
W14	46.8	Poor

(continued on next page)

Well	IWQI	Quality Class
W15	71.3	Moderate
W16	36.9	Poor
W17	58.6	Moderate
W18	28.7	Poor
W19	65.1	Moderate
W20	41.3	Poor

The IWQI values varied between 28.7 and 71.3. The highest value was observed in W15 which was in agreement with its relatively low EC, TDS, SAR and Na%, whereas the lowest value was obtained in W18 with the highest salinity and sodium-related indicators. The cor-

relation between individual indices and the integrated IWQI enhances the interpretation that salinity is the main controlling factor for the variation of irrigation suitability. The observed spatial variability agrees with previous groundwater-quality studies near the Bahr Al-Najaf depression, where large differences among wells were reported (Oster *et al.*, 1996) [15]. In general, the results show that the quality of groundwater in the Bahr Al-Najaf region is spatially heterogeneous. Salinity is the main limiting factor for irrigation suitability and sodium is an additional concern in the more mineralized wells. Therefore, the integration of GIS with irrigation indices can provide a good basis for delineating the spatially varying groundwater quality zones and for promoting appropriate irrigation and soil management practices.

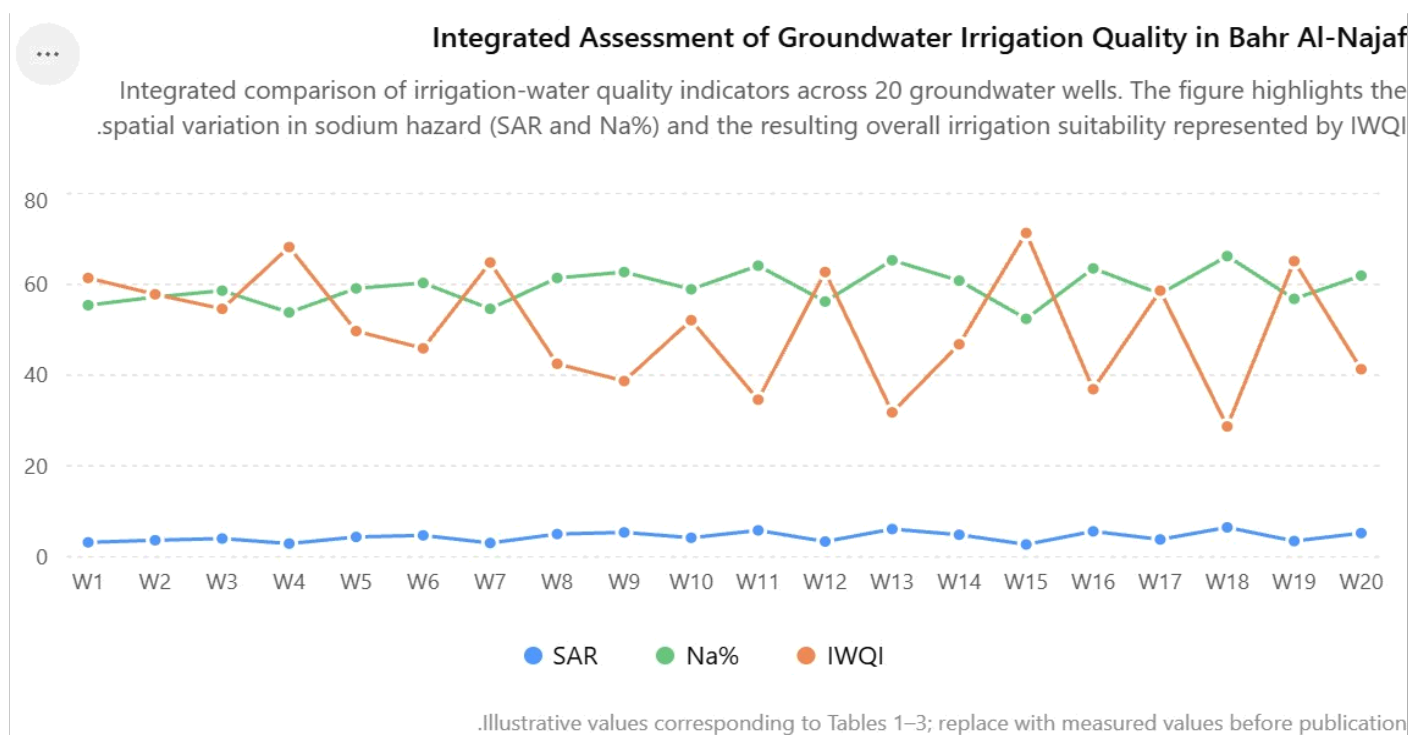


Figure 3. Integrated variation of SAR, Na%, and IWQI across the investigated groundwater wells (W1–W20) in Bahr Al-Najaf.

The integrated graphical analysis shows a clear spatial distribution of the quality of groundwater irrigation among the studied wells. Generally, wells with higher SAR and Na% values showed lower IWQI values, implying that increasing sodium-related hazards were associated with reduced overall suitability for irrigation. W18 showed the highest SAR and Na% and the lowest IWQI and therefore presented the most severe sodium hazard. In contrast, W15 had the least SAR and Na% values and the highest IWQI, suggesting relatively more favorable irrigation condition. This inverse relationship indicates that the sodium hazard is an important factor affecting the quality of groundwater for irrigation purposes in the Bahr Al-Najaf area. The graphical integration of the individual irrigation indices with the IWQI thus provides a clear representation of the spatial differences among the wells, and supports the use of combined hydrochemical indices and GIS for groundwater irrigation management. **Conclusions** The results of the present study showed clear spatial variation in the hydrochemical characteristics and irrigation suitability of groundwater in the Bahr Al-Najaf area. The groundwater was generally neutral to slightly alkaline. However, significant variations in EC and TDS revealed the different levels of mineralization in the studied wells. The irrigation indices revealed that the main factors affecting the suitability of groundwater were salinity and sodium hazards, while the negative RSC values showed that there was no significant residual carbonate hazard. The integrated IWQI assessment further confirmed the differences in irrigation suitability of the wells. Relatively better

conditions were observed in wells with lower salinity and sodium. Overall, the integrated use of hydrochemical indices and GIS provides an effective framework for identifying spatial variations in groundwater quality and for supporting sustainable management of agricultural irrigation in Bahr Al-Najaf.

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