Irrigation Water Quality Evaluation in Jiaokou Irrigation District, Guanzhong Basin

Qiying Zhang, Panpan Xu, Hui Qian

***Abstract*—**Groundwater is an important water resource in the world, especially in arid and semi-arid regions. In the present study, 141 groundwater samples were collected and analyzed for various physicochemical parameters to assess the irrigation water quality using six indicators (sodium percentage (Na%), sodium adsorption ratio (SAR), magnesium hazard (MH), residual sodium carbonate (RSC), permeability index (PI), and potential salinity (PS)). The results show that the patterns for the average cation and anion concentrations were in decreasing orders of $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ and $SO_4^{2-} > HCO_3^- > Cl^- > NO_3^- > CO_3^{2-} > F^-$, respectively. The values of Na%, MH, and PS show that most of the groundwater samples are not suitable for irrigation. The same conclusion is drawn from the USSL and Wilcox diagrams. PS values indicate that $Cl^-$and SO_4^{2-}have a great influence on irrigation water in Jiaokou Irrigation District. RSC and PI values indicate that more than half of groundwater samples are suitable for irrigation. The finding is beneficial for the policymakers for future water management schemes to achieve a sustainable development goal.

***Keywords*—**Irrigation water quality evaluation, groundwater chemistry, Jiaokou Irrigation District, Guanzhong Basin.

I. Introduction

GROUNDWATER plays an important role for domestic drinking, industrial production, and agricultural irrigation all over the world, especially in arid and semi-arid regions where surface water and precipitation are usually scarce [1], [2]. The quality of groundwater has been regarded as a decisive factor for a country's sustainable development [3]. Agricultural irrigation requires much higher water quality than industrial water and even household water [2].

Especially for irrigated areas, the variation in groundwater chemistry has a strong effect on plants and soil, potentially damaging plants and reducing crop yields [4], [5]. Specifically, the physical effect of ions is to decrease the osmotic pressure in the structural cells of a plant, preventing water from reaching the branches and leaves [5]. Especially for irrigated areas located in arid and semi-arid areas, groundwater salinization is a common problem [6], [7], where the level of human activities may have significantly increased or disturbed the extent of these processes. This in turn results in crop reduction and subsequent negative impact on the economy and human society. This research has important reference value for regions and countries with food security issues caused by irrigation water quality [8]-[10]. Therefore, it is a prerequisite to understand groundwater quality for irrigation purposes.

The aim of this study is to evaluate the groundwater suitability for irrigation purposes using different indices (sodium percentage (Na%), SAR, RSC, MH, PI, and PS) and to provide information for policymakers to achieve sustainable development.

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II. Study Area

The Jiaokou Irrigation District (34°30′7″–34°52′37″N, 109°12′40″–110°10′1″E), with 60 years of irrigation history, is one of the artificial irrigation areas within the Guanzhong Basin [11]. It is surrounded by water on three sides, with the Shichuan River in the west, Luo River in the east, and Wei River in the south and is located in the east of the Guanzhong Basin (Fig. 1). The climate is classified as warm temperate and semi-arid monsoon with a mean annual temperature of 13.4 °C, a precipitation of 548.5 mm, and annual evaporation of 1003.1 mm. The irrigation water comes from the Wei River with the Canal Head Station of the irrigation area located on the north bank of the river 2.5 km east of Jiaokou Town, Lintong District, Xi'an City (Fig. 1), and the volume of water taken from the river per year is 3.07×10^8 m^3. The canal system is mainly distributed throughout the central and western parts of the irrigation area, which is dominated by cultivated land. However, the dry land is mainly developed in the sandbelt area in the east of the irrigation area. In addition, orchards and residential areas are scattered throughout the study area.

III. Materials and Methods

A. Sample Collection and Laboratory Analysis

A total of 141 phreatic groundwater samples were collected in 2014 from the borewells/hand pumps in the Jiaokou Irrigation District (Fig. 1). The pH and TDS of groundwater samples were measured using a portable device in the field. Ca^{2+}, Mg^{2+}, CO_3^{2-}, and HCO_3^- were measured by titration with a detection limit of 1.0 mg/L, whereas K^+ and Na^+ were measured using flame atomic absorption spectrometry. Cl^- and SO_4^{2-} were determined by ion chromatography. To ensure the appropriate accuracies in the analyses, the ionic-balance-error for the ions in the water samples was within the acceptable limit of ±5% [1], [2], [11].

B. Evaluation Method

Six indicators, sodium percentage (Na%), SAR, RSC, MH, PI, and PS, were calculated to evaluate the status of the groundwater for irrigation purposes [2], [5], [12], [13]. All the parameters used in the following equations were expressed in the milli-equivalent unit.

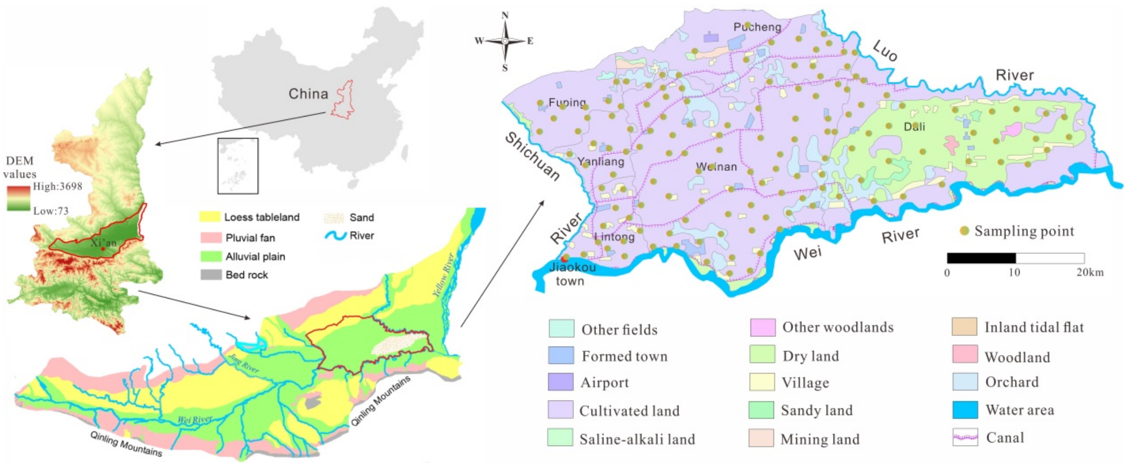

Fig. 1 Map showing the location and land use of study area as well as the distribution of sampling points

$$Na\% = \frac{Na^{+}+K^{+}}{Na^{+}+K^{+}+Ca^{2+}+Mg^{2+}} \times 100 \quad (1)$$

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

$$RSC = \left(CO_3{}^{2-} + HCO_3^{-}\right) - \left(Ca^{2+} + Mg^{2+}\right) \quad (3)$$

$$MH = \frac{Mg^{2+}}{(Ca^{2+}+Mg^{2+})} \times 100 \quad (4)$$

$$PI = \frac{Na^{+}+\sqrt{HCO_3^{-}}}{Na^{+}+K^{+}+Ca^{2+}+Mg^{2+}} \times 100 \quad (5)$$

$$\mathrm{PS} = Cl^{-} + \frac{1}{2} \times SO_4^{2-} \quad (6)$$

IV. Results and Discussion

A. Groundwater Parameters and Groundwater Chemistry

The chemical characteristics of groundwater in this study region are presented in Table I. Seven out of 141 groundwater samples, located west of the study area, have a pH outside the recommended range of 6.5 to 8.5. TDS represents the total dissolved salts in water, and ranged from 237 to 7667 mg/L, with an average value of 2215 mg/L. The patterns for the average cation and anion concentrations were in decreasing orders of $Na^{+} > Mg^{2+} > Ca^{2+} > K^{+}$ and $SO4^{2-} > HCO^{3-} > Cl^{-} > NO^{3-} > CO_3{}^{2-} > F^{-}$, respectively (Table I). Specifically, the Na^{+} content ranged from 23 to 2822 mg/L (mean = 557.43 mg/L) in all groundwater samples, with 83.69% of samples exceeding the allowable limits of 200 mg/L, while the K^{+} concentration ranged from 0.37 to 96.46 mg/L, with an average value of 4.90 mg/L. Ca^{2+} and Mg^{2+} as important indicators of water hardness, showed values from 9.3 to 452.5 mg/L and 20.5 to 435.8 mg/L, respectively. The $SO_4{}^{2-}$ concentrations ranged from 9.4 to 4367 mg/L, with an average value of 625.27 mg/L. Over 70% of samples exceeded the threshold of 250 mg/L for $SO_4{}^{2-}$. HCO^{3-} concentrations varied between 199 and 1249 mg/L, with a mean of 611.19 mg/L, while $CO_3{}^{2-}$ values ranged between 11.6 and 120 mg/L, with an average value of 43.48 mg/L. In this study region, 85.82% of the groundwater samples exceeded the recommended levels of 300 mg/L for HCO^{3-}. The Cl^{-} concentrations varied between 3.16 and 1909 mg/L, with a mean of 379.37 mg/L, with 54.61% of the samples exceeding the threshold of 250 mg/L. NO^{3-} concentrations ranged from 0.1 to 1087 mg/L, with a mean of 156.5 mg/L, while F^{-} concentrations were between 0.2 and 8.92 mg/L, with a mean value of 2.06 mg/L.

TABLE I
STATISTICAL SUMMARY OF CHEMICAL COMPOSITION OF GROUNDWATER IN THE STUDY REGION

Indices	Min.	Max.	Mean	SPL (WHO)	Number of Samples Exceeding the SPL
pH	6.48	9.9	7.68	6.5-8.5	7
TDS	237	7667	2215.01	1000	117
K^{+}	0.37	96.46	4.90	10	12
Na^{+}	23	2822	557.43	200	118
Ca^{2+}	9.3	452.5	62.10	200	3
Mg^{2+}	20.5	435.8	119.78	200	22
CO_3^{2-}	11.6	120	43.48	-	-
HCO_3^{-}	199	1249	611.19	300	121
Cl^{-}	3.16	1901	379.37	250	77
SO_4^{2-}	9.4	4367	625.27	250	104
NO_3^{-}	0.1	1087	156.50	50	99
F^{-}	0.2	8.92	2.06	0.5-1.5	93
COD_{Mn}	0.24	4.35	0.81	3	1

Notes: SPL is standard permissible limit value.

B. Groundwater Quality for Irrigation Purposes

The ion concentration in water will affect the osmotic pressure of water entering the plant cells, which will affect the transportation of water in the plant and finally disrupt plant metabolism [5], [14]. Thus water quality assessment plays an important role in irrigation. In this study, various irrigation water quality indices, Na%, SAR, RSC, MH, PI, and PS were calculated, and the results are summarized in Table II. The spatial distribution maps of these indices are plotted in Fig. 2

TABLE II
IRRIGATION QUALITY PARAMETERS OF JIAOKOU IRRIGATION DISTRICT

IL	WQ	N	P	IL	WQ	N	P
Na%				SAR			
<20	excellent	10	7.09%	<10	excellent	69	48.94%
20-40	good	13	9.22%	10-18	good	59	41.84%
40-60	permissible	28	19.86%	18-26	doubtable	12	8.51%
60-80	doubtable	72	51.06%	>26	unsuitable	1	0.71%
>80	unsuitable	18	12.77%				
RSC				MH			
<1.25	good	80	56.74%	<50	suitable	13	9.22%
1.25-2.5	doubtable	9	6.38%	>50	unsuitable	128	90.78%
>2.5	unsuitable	52	36.88%				
PI				PS			
<25%	unsuitable	0	0	<3	excellent to good	18	12.77%
25-75	moderate	67	47.52%	3-5	good to injurious	9	6.38%
>75%	suitable	74	52.48%	>5	injurious to unsatisfactory	114	80.85%

Notes: IL is indices levels; WQ is water quality; N is the number of groundwater samples; P is the percentage.

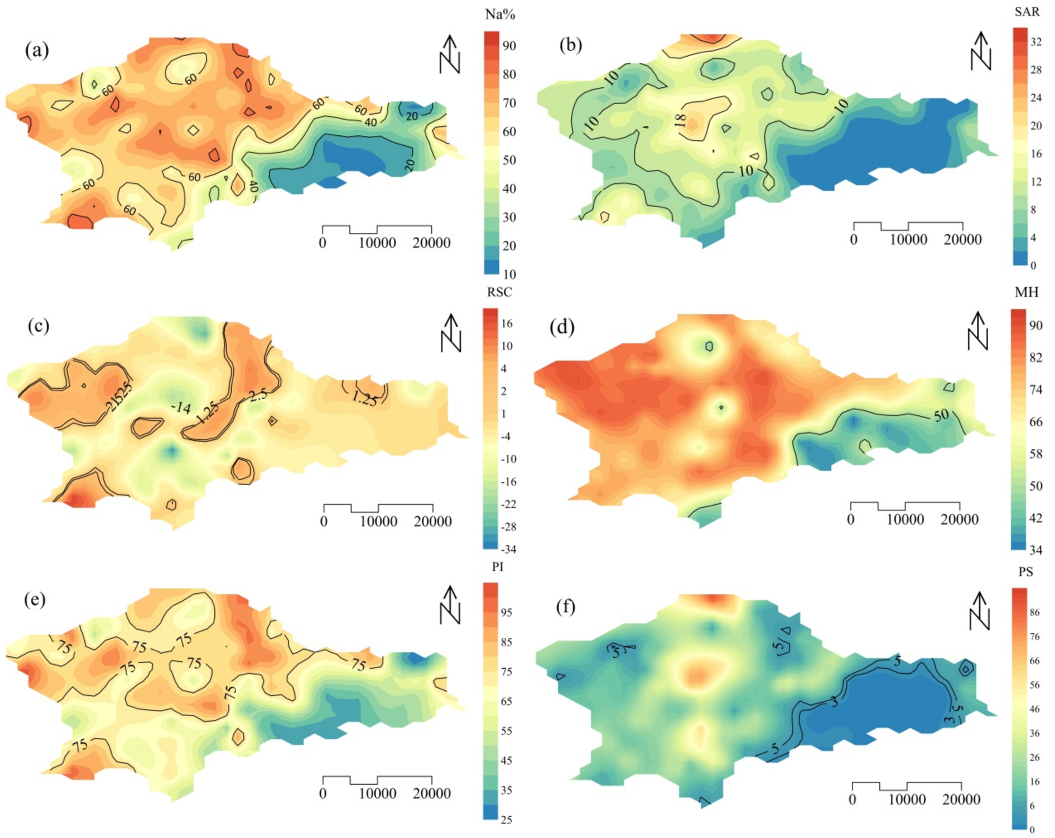

Fig. 2 The spatial distribution maps showing different irrigation indices

Na%, as an evaluation index of irrigation water quality, represents the sodium hazard. High Na% will damage the soil structure, reduce the permeability, and finally result in poor internal drainage in irrigation [12]. Na% is classified into five classes (Table II). The majority of the samples for irrigation are in the doubtable category (51.06%), followed by permissible (19.86%), unsuitable (12.77%), good (9.22%), and excellent category (7.09%). Only 23 groundwater samples meet the regular irrigation. However, 72 and 18 samples have 60% to 80% and > 80% sodium, indicating that these samples are harmful for crops because of their effects on soil permeability and texture. As shown in Fig. 2 (a), except for a small part of the eastern part of the study area, the Na% of the rest of the groundwater has permissible to unsuitable for irrigation.

SAR is used to assess the alkali/sodium level due to the excess sodium or limited calcium and magnesium [15]. Based on the SAR values, irrigation waters are classified into four categories (Table II). A total of 128 out of 141 groundwater samples are good for general irrigation because of limited calcium and magnesium. In addition, increasing the Ca^{2+} and Mg^{2+} concentration in water will improve soil permeability, and this is beneficial for groundwater samples that are not suitable for irrigation (less than 10%). From Fig. 2 (b), only a small part of the central and northern areas of the study area, the SAR values exceeded the specified value (> 18%).

The US Salinity Laboratory (USSL) diagram [16]; (Fig. 3 (a)) and Wilcox diagram [17]; (Fig. 3 (b)), combining both salinity hazard and alkalinity, were used further to analyze the suitability of water for irrigation. Based on these data, most of the water samples fall into zone C3 and C4, indicating a high salinity hazard. Moreover, the SAR values increase with the increase of EC values (Fig. 3 (a)). In addition, as shown in the Wilcox diagram (Fig. 3 (b)), most of groundwater samples belong to the categories "permissible to doubtful" and "doubtful to unsuitable". Moreover, the groundwater samples fall into the zone of "permissible to doubtful" are mainly poor water. The fair groundwater is generally distributed in the category of "excellent to good", indicating that fair groundwater for drinking purposes is a good source for irrigation. Ten samples belong to the category "unsuitable" with EC more than 3000 μS/cm. For groundwater samples with TDS less than 1000, they are mainly distributed in the category of "excellent to good". It can be seen from Figs. 3 (a) and (b), the larger the TDS of the water, the less suitable it is for irrigation.

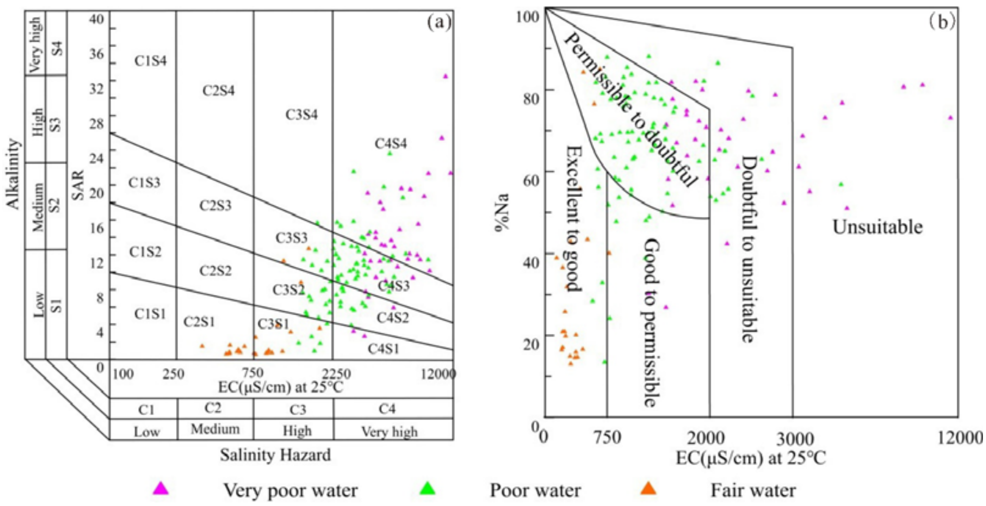

Fig. 3 USSL and Wilcox diagrams demonstrating irrigation water quality: (a) USSL diagram and (b) Wilcox diagram

RSC is defined as the difference of the sum of carbonate and bicarbonate and the sum of calcium and magnesium [2], [18]. In this study, the RSC values of 80 groundwater samples are less than 1.25, i.e., 56.74% of groundwater samples are good for irrigation purpose (Table II). However, 9 and 52 water samples belong to the doubtable and unsuitable category, respectively. Irrigation water with high RSC value may make the soil infertile due to the presence of sodium carbonate [19], [20]. Furthermore, the high-value area of RSC is small and scattered (Fig. 2 (c)). High bicarbonate concentration in irrigation water will raise the RSC values and increase water hardness due to the precipitation of calcium bicarbonate and magnesium bicarbonate [21].

Calcium and magnesium in groundwater generally maintain an equilibrium state. However, when more Mg^{2+} is present in groundwater, the crop yields will decrease due to the alkaline soil [14], [15]. Moreover, high level of magnesium in water can deteriorate soil structure because of exchangeable Na in irrigated soils. MH reflects the damage of magnesium to soil structure. The boundary value of MH for irrigation is 50 [22]. In the Jiaokou Irrigation District, 128 (90.78%) groundwater samples are unsuitable for irrigation based on the MH value (Table II) and these unsuitable samples are basically distributed throughout the study area (Fig. 2 (d)), confirming high magnesium content in the study area.

Long-term irrigation of the soil with mineral-rich (Ca^{2+}, Mg^{2+}, Na^{+}, and HCO_3^{-}) water will reduce soil permeability and eventually make soil to retard the emergence of seedlings [2], [4], [13], [15]. PI, as an indicator to reflect soil permeability, was proposed by [6] and classified into three categories, unsuitable (< 25%), moderate (25-75%), and suitable (> 75%). Some 47.52% of the groundwater samples belong to the moderate category and 52.48% belong to the suitable category (Table II). It can be seen that the impact of irrigation water in the study area is slight on soil permeability. The spatial distribution of PI is shown in Fig. 2 (e).

PS, as an indicator of the impact of Cl^{-} and SO_4^{2-} on irrigation water, is defined as the Cl^{-} concentrations plus half of the SO_4^{2-} concentration [2], [5]. The groundwater samples are classified into three categories, excellent to good, good to injurious, and injurious to unsatisfactory, based on the PS values. The results show that 114 and 9 of groundwater samples belong to categories "injurious to unsatisfactory" and "good to injurious", respectively (Table II). However, only 18 of the samples belong to "excellent to good". This indicates that Cl^{-} and SO_4^{2-} have a great influence on irrigation water. As shown in Figs. 2 (d) and (f), the spatial distribution of PS is basically consistent with MH.

V. Conclusions

Various physicochemical parameters of 141 groundwater samples were analyzed to assess the irrigation water quality using six indicators (Na%, SAR, RSC, MH, PI, and PS). The major conclusions of the study are as follows:

The patterns for the average cation and anion concentrations were in decreasing orders of $Na^{+} > Mg^{2+} > Ca^{2+} > K^{+}$ and $SO_4^{2-} > HCO_3^{-} > Cl^{-} > NO_3^{-} > CO_3^{2-} > F^{-}$, respectively. The majority of the samples for irrigation based on Na% are in the doubtable category (51.06%), followed by permissible (19.86%), unsuitable (12.77%), good (9.22%), and excellent category (7.09%). The USSL and Wilcox diagrams show that most of groundwater samples are not suitable for irrigation. RSC values indicate 56.74% of groundwater samples are good for irrigation purpose, and 128 (90.78%) groundwater samples are unsuitable for irrigation based on the MH value and basically distributed throughout the study area. Based on the PI values, 47.52% of the groundwater samples belong to the moderate category and 52.48% are belong to the suitable category, and 114 and 9 of groundwater samples are belong to categories "injurious to unsatisfactory" and "good to injurious" based on the PS, indicating that Cl^{-} and SO_4^{2-} have a great influence on irrigation water. These findings would provide guidance for spatial management decisions of irrigation groundwater in Jiaokou Irrigation District.

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