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Suitability assessment of deep groundwater for drinking, irrigation and industrial purposes in Jiaozuo City, Henan Province, north China

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Groundwater has been a major natural resource for human consumption in north China. It is necessary to appreciate the suitability of deep groundwater for drinking, agricultural irrigation, and industrial uses in this region. To this end, a total of 47 groundwater samples were collected from the study area; by comparing the concentrations of different hydrochemical variables with quality standard values, the variable fuzzy set (VFS) was applied to calculate the groundwater quality index (GQI) for various purposes, respectively. Afterward GQI spatial distribution maps were constructed using a geographic information system (GIS) tool to delineate spatial variations of groundwater quality. In this case study, the GQI spatial distribution maps reveal that the areas covered by “Maximum Permissible” groundwater for varying purposes (drinking, irrigation, and industrial) is 1377.2; 2354.7; and 3854.8 km^2, respectively. The groundwater in the eastern part of the study area is suitable for drinking, with the southwestern region as the irrigation water source; the entire study area is acceptable for use in industrial, except the western part of Jiaozuo City. Therefore, the GQI spatial distribution maps can provide useful information for non-technical decision makers for better sustainable groundwater resources management.

drinking water, quality, irrigation, spatial distribution map, variable fuzzy set

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It is well known that groundwater pollution is harmful not only to industrial products and crop yields, but also to public health, which has been reported to cause 43.2% of human disease and 23.7% infant mortality in China [1]. Therefore, it is crucial to ascertain the water quality before its use for human consumption. Motivated by this necessity, many studies are involved in the evaluation of groundwater quality, recharge, circulation, and chemical evolution [2–7]. Ketata et al. [4] employed the geographical information system (GIS) and water quality index (WQI) to assess groundwater quality in the EI Kahairat deep aquifer; the multivariate analysis and WQI were used to classify groundwater from the southern Voltaian for drinking purposes [6]; the groundwater resources were evaluated for drinking, agricultural irrigation, and industrial uses in some north Indian villages by Haritash et al. [7].

Although numerous investigations have gained achievements, they have a number of practical limitations. First, the drinking, irrigation, and industrial water qualities were simultaneously assessed using a single water quality standard and weight coefficient; the difference in the water quality requirements of different regions and their water usage, such as crop patterns, soil structures, and industrial structures, are neglected. Second, traditional methods usually evaluate the quality of irrigation water according to such parameters as residual sodium carbonate (RSC), soluble sodium percentage (SSP), sodium adsorption ration (SAR), percent sodium (Na%), and magnesium hazard [5,7–10]. However, the quality of irrigation water is associated with many other influencing factors, which include not only

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*Corresponding author (email: margroundwater@gmail.com) the aforementioned parameters, but also heavy metal and trace element toxicity. More importantly, it should be noted that these hazards or negative impacts can sometimes occur simultaneously, and therefore it is necessary that all of these parameters must be included in some way to better evaluate irrigation water quality. Third, although Simsek and Gunduz [11] have considered simultaneously the effects of five crucial factors on irrigation water quality during the process of WQI establishment for irrigation use, the calculation flow, as well as the traditional methods, computed the quality rating scale referring to the concentrations of samples' hydrochemical variables and the groundwater quality standard [10,12–14]. In calculating WQI, these methods only used point value, such as "Excellent", "Desirable", or "Maximum Permissible" limit values in groundwater quality standard to calculate. They do not take into consideration the influence of interval values of water quality standard, like [Excellent, Desirable] and [Desirable, Maximum Permissible], on groundwater quality assessments. To overcome these limitations, based on the refereed groundwater guideline value of World Health Organization (WHO), GB/T 14848-09, previous literature, and the influence of hydrochemical variables on the human body, crop yields, and industrial product quality [6,11,15–18], groundwater quality standards and the weight coefficients of each element were established for different purposes (drinking, irrigation, and industrial), respectively. Subsequently, the VFS theory was used to compute a groundwater quality index (GQI) to evaluate groundwater suitability for drinking, irrigation, and industrial uses.

Currently, there have been numerous studies on groundwater quality assessment for drinking use in north China [19–21]; however, the reports simultaneously evaluating north China's groundwater quality for drinking, irrigation, and industrial purposes are few. In view of this fact, it is necessary and urgent to characterize the suitability of deep groundwater for different uses according to this paper.

1 Materials and methods

1.1 Description of the study area

Jiaozuo City is characterized by a semiarid continental climate, with a total area of 4071 km^2. The study area can be divided into four aquifers according to their lithology. The first aquifer can not be used for well construction, because its grain size is so thin that the water amount is very little. Therefore, the second aquifer is the current main exploitation sector for human consumption. This aquifer belongs to the confined aquifer; there is a stable aquitard layer of 30–130 m depth composed of clay and silty clay at the top of this aquifer. The bottom of the second aquifer is 40–210 m (Figure 1). The well discharge is 100–300 m^3/(d m) in the north and south, 50–100 m^3/(d m) in the central part of the study area, and less than 50 m^3/(d m) in the west (Figure 2). The total exploitation of this aquifer system increased from 0.26 Mm^3/a in 1999 to 5.31 Mm^3/a in 2010 [22]. The groundwater in this aquifer is applied unevenly by different anthropogenic activities (drinking, agricultural irrigation, and industrial), drinking water supply is the major and primary use.

1.2 Sample collection and hydrochemical analysis

A total of 47 samples were collected in November, 2011 from the second aquifer for analysis of 26 hydrochemical variables (Figure 2). These samples can be divided into five distinct water types. 38.94% of samples are rich in calcium and bicarbonate reflecting calcium bicarbonate type, which is the dominant water type in Jiaozuo City; both the magnesium bicarbonate and sodium bicarbonate are the second dominant water type. The percent of those samples that fall in the two types can reach 17.02%; the fourth groundwater type belongs to the sodium sulfate type, which is present in 14.89% of the samples. Groundwater rich in magnesium and bicarbonate, which was collected from northeastern

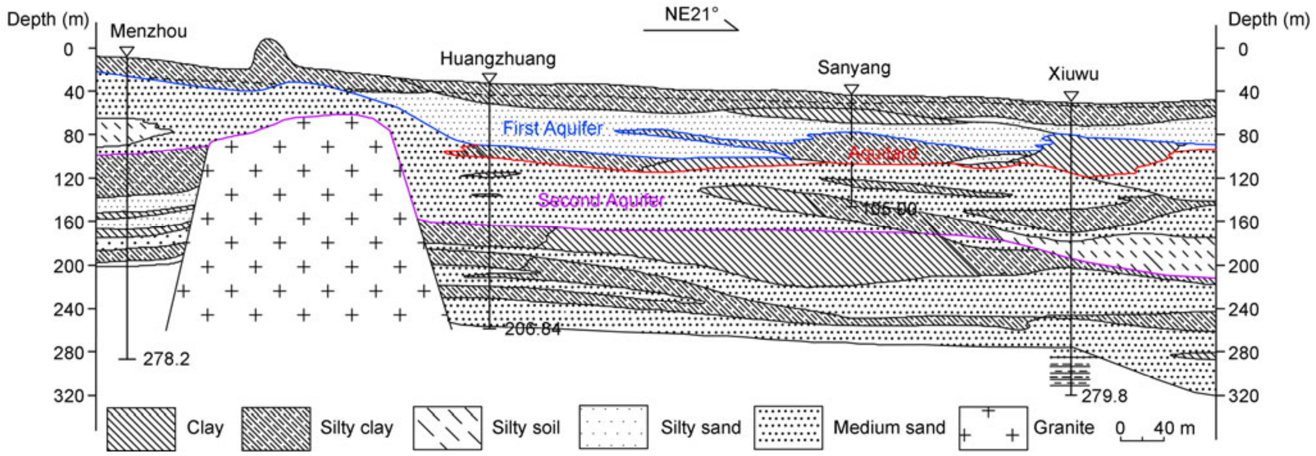

Figure 1 The crosssection of Jiaozuo City.

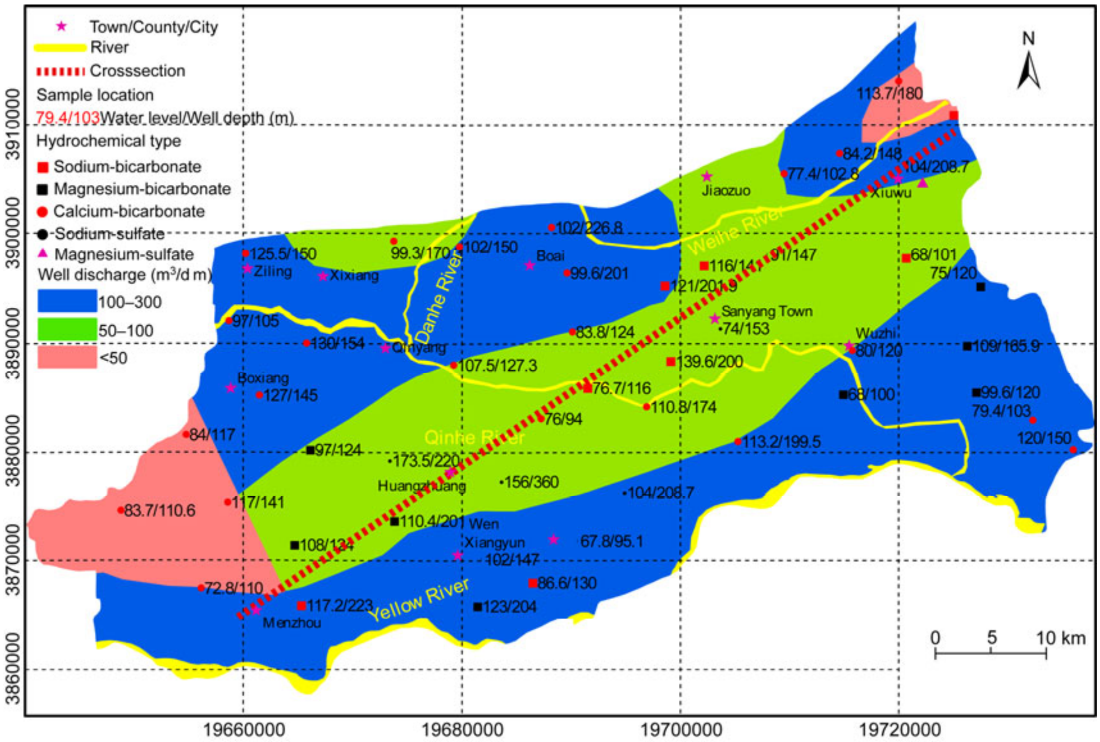

Figure 2 Study area and sample locations.

regions, producing a magnesium bicarbonate type, represents 2.13%. The order of major cation concentrations is sodium> calcium>magnesium>potassium and the order of anion concentrations is bicarbonate>sulfate>chloride>nitrate. According to the hydrochemical analysis and previous studies, the silicate and carbonate minerals dissolution and cation exchange have significant contribution to calcium and magnesium concentrations in groundwater; the higher level of sodium is associated with silicate and halite minerals dissolution and anthropogenic contamination. The chemistry fertilizer and domestic sewage may be the potential sources of potassium in this region.

1.3 Method

The GQI calculation process involves three steps in this work. First, the groundwater quality standard values were constructed for different purposes. Subsequently, weight coefficients were assigned to each hydrochemical variable according to its effect on human body, crop yields, or industrial product quality. Second, according to groundwater quality standards and weight coefficients of each hydrochemical variable, the GQI can be calculated using the VFS technique.

The VFS method can calculate the membership of ith (i=1, 2, … m, m is the number of hydrochemical variables) hydrochemical variable content with every interval value, namely [0, Excellent], [Excellent, Desirable], [Desirable, Maximum Permissible], and [Maximum Permissible, Maximum value]. It fully considered the effects of all classification ranks of quality standards on GQI, rather than that of point value.

The VFS and their related definitions are briefly introduced in this section. VFS, developed by Chen [23], has proven to be a useful tool in dealing with vagueness or fuzziness information. It is widely employed to assess multi-criteria decision making problems [24–26], which consist of probability theory and fuzzy sets. The priority criterion matrix $\boldsymbol{I}_1$, the certain interval matrix $\boldsymbol{I}_2$, the point value matrix $\boldsymbol{M}$, and the optimal relative membership grade matrix $\boldsymbol{U}$ are the most important concepts in VFS. For the length of this article, the calculation process is omitted; details on some of this method and their applications have been described by previous articles [23–26].

Finally, the GQI spatial distribution maps were carried out through a GIS tool, providing groundwater quality distribution information for non-technical decision makers. To examine accuracy of the evaluation results in this article, the distribution maps of WQI, EC, Na%, and total hardness (TH) were also constructed using a GIS tool, which have been widely used in previous studies to assess groundwater quality for drinking, irrigation, and industrial uses.

2 Results and discussions

2.1 Suitability for drinking

The concentrations of copper, zinc, lead, selenium, and ammonia nitrogen in the groundwater of the study area are very low and pH values are always within the guide level range 6.5–8.5 [15,27]. Vasanthavigar et al. [10] have reported that bicarbonate has insignificant effect on human body; therefore, the aforementioned elements were not incorporated into drinking, irrigation, and industrial water suitability assessments. Only the rest of 19 hydrochemical variables (EC, TDS, TH, potassium, sodium, calcium, magnesium, iron, manganese, barium, molybdenum, chromium, arsenic, mercury, chloride, fluoride, sulfate, nitrate, and nitrite) were selected to yield GQI using the VFS technique for the evaluation of drinking, irrigation, and industrial water suitability. Similar to the calculation process of WQI [4,6,10], the GQI also includes the following three steps.

The first step was to build the drinking water quality standard and assign a weight coefficient to each hydrochemical variable for drinking use. It is known that groundwater quality standards and weight coefficients of each element should vary greatly with different uses; it must be established for a specific purpose, rather than a general class. Therefore, the same element should have different weight coefficients and water quality standard values in groundwater suitability assessments for various uses. For example, the arsenic ion plays a key role in drinking water quality assessments. It is one of the most toxic elements to public health, and when humans and animals exposed to arsenic over a long period of time, it can cause cancers of the bladder, liver, kidney, and skin. Therefore, the weight value of 5 was assigned to arsenic regarding the evaluation of drinking water suitability, with maximum permissible limit value equal to 0.05 mg/L set by WHO [15]. Arsenic is not as important as TH, sodium, and calcium in irrigation water quality assessment; its capacity to harm crop is limited, resulting in the retarded growth and metabolic activities of the crop plant. Therefore, this element was given a weight value of 2, since it played an insignificant role in irrigation water suitability assessments; the maximum permissible limit for arsenic in irrigation water was given as 2.0 mg/L [11]. With respect to industrial water quality assessment, the industrial structure includes equipment manufacturing, automobile manufactory, the aluminum industry, and the coal chemical industry in Jiaozuo City, none of which have strict groundwater quality requirements. The arsenic maximum permissible limit value of 0.05 mg/L was set by GB/T 19923-2005 [28], and it was given a weight value of 1. Therefore, based on referencing the WHO, GB/T 14848-09, and previous researches [2,12,15,16,29,30], the groundwater quality standard values of each element for drinking use are listed in Table 1.

Currently, the groundwater standard value for drinking use has been established, and it was required that a weight coefficient was to be assigned to each variable. In this work, the highest weight of 5 was assigned to hydrochemical variables that have a significant impact on body chemistry, health, and disease, other variables were given a weight value between 1 and 4, depending on their influence on public health.

The high values of trace elements have significant adverse effects on public health. According to Table 1, the following trace elements, namely barium, molybdenum, chromium, arsenic, mercury, and fluoride, are found to far exceed their desirable limit. For example, 23.4% of the samples exceed the desirable limit of 1.0 mg/L for fluoride, which may cause mottling of the tooth enamel, especially for children during the formation of their permanent teeth [7]. Mercury is found in the concentration range of 0.0016–0.013 mg/L with an average of 0.005 mg/L for the studied samples, all of the samples are found to be above the desirable limit, and 27.7% of the samples exceed the maximum permissible limit of 0.001 mg/L. It is known that mercury can accumulate in the brain, kidneys, and lungs, causing changes in neurological and renal function. More importantly, it can cause neurological and behavioral disorders in human, and is the most sensitive trace element to the central nervous system [31,32]. Barium levels vary in the range from 0.010 to 0.546 mg/L with a mean value of 0.233 mg/L; 95.7% of the samples' concentrations ranged between the desirable limit (0.1 mg/L) and the maximum permissible limit (1.0 mg/L). Small quantities of barium are highly toxic to human beings, it can lead to several human health problems: muscular paralysis, stomach irritation, swelling of the brain, heart damage, high blood pressure, and in some cases even death [33].

Table 1 indicates that 72.3% and 29.8% of the samples for nitrate and nitrite concentrations exceed the desirable limit of 5.0 and 0.01 mg/L, respectively. High nitrate values can cause blue baby disease or methemoglobinemia in children, and nitrite is more toxic to public health than nitrate [8,34]. The above analysis demonstrates that these hydrochemical variables (barium, molybdenum, chromium, arsenic, mercury, fluoride, nitrate, and nitrite) have the significant impact on human and animal health, which should be given the highest weight coefficient of 5 in this article.

EC and potassium, if present in sufficient quantity, only give an undesirable taste to drinking water, which have no significant influence on the physiological functions of the human body. Therefore, the minimum weight of 1 was assigned to EC and potassium.

Aside from the aforementioned hydrochemical variables, other parameters were given a weight coefficient between 2 and 4 depending on their impact on the human body. It is well known that TH has insignificant adverse effects on human health; a little evidence indicates it has a relationship with heart disease [35]. Therefore, this element was assigned a weight coefficient of 2. Iron was given a weight coefficient of 3 as it plays a relatively important role in the physiological function of the human body. On the basis of the above analysis, each hydrochemical variable gained a weight value (Table 1) according to its influence on human health.

The second step was to calculate the relative weight (*W*) of each hydrochemical variable through eq. (1):

Table 1 Standard values and weight coefficients of hydrochemical variables in the study area for drinking use

Water quality parameter	Standard guideline value			Weight (w_i)	Relative weight $W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$
	Excellent limit	Desirable limit	Maximum permissible limit		
EC (μS /cm)	500	1000	1500	1	0.0145
TDS (mg/L)	300	500	1000	3	0.0725
TH (mg/L)	150	300	450	2	0.0290
K (mg/L)	2	5	12	1	0.0145
Na (mg/L)	20	175	200	3	0.0435
Ca (mg/L)	50	75	200	2	0.0290
Mg (mg/L)	30	50	150	2	0.0290
Fe (mg/L)	0.1	0.2	0.3	3	0.0435
Mn (mg/L)	0.01	0.05	0.1	3	0.0435
Ba (mg/L)	0.01	0.1	1.0	5	0.0725
Mo (mg/L)	0.001	0.01	0.1	5	0.0725
Cr (mg/L)	0.005	0.01	0.05	5	0.0725
As (mg/L)	0.005	0.01	0.05	5	0.0725
Hg (mg/L)	0.00005	0.0005	0.001	5	0.0725
Cl (mg/L)	50	150	250	3	0.0435
F (mg/L)	0.7	1	1.5	5	0.0725
SO_4 (mg/L)	50	150	250	4	0.0580
NO_3 (mg/L)	2	5	20	5	0.0725
NO_2 (mg/L)	0.001	0.01	0.02	5	0.0725
				$\sum w_i = 69$	$\sum w_i = 1.0000$

$$W_i = \frac{w_i}{\sum_{i=1}^{m} w_i}, \qquad (1)$$

where w_i is the weight value of *i*th hydrochemical variable; W_i is the relative weight of *i*th hydrochemical variable, i=1, 2, …, m.

The third step was to calculate the GQI using the VFS theory; more details regarding the calculation process are as follows:

(1) According to Table 1, the priority criterion matrix $\boldsymbol{I}_1$, the certain interval matrix $\boldsymbol{I}_2$, and the point value matrix $\boldsymbol{M}$ were constructed for drinking purposes.

(2) The relative weight W of each hydrochemical variable was calculated using eq. (1).

(3) The optimal relative membership grade matrix $\boldsymbol{U}$ was used to calculate the GQI of each groundwater sample for drinking water suitability assessment.

(4) The GQI spatial distribution map of drinking water (GQID) (Figure 3) was carried out using a GIS tool.

(5) To examine accuracy of the evaluation results of GQID, the WQI spatial distribution map (Figure 4) was also constructed using the traditional methods [4,11].

2.2 Suitability for irrigation application

In this section, the GQI of irrigation water (GQIIR) was generated using VFS, which was based on the consideration of five crucial factors and the influence of interval values of irrigation water quality standards on the irrigation water quality assessment. The calculation process of GQIIR is similar to GQID. The first step was to establish the irrigation water quality standard and assign a weight coefficient to each hydrochemical variable. The water quality standard for irrigation use is described in Table 2, determined according to previous reports [11,36–38]. Meanwhile, the hydrochemical variables were given weight values according to their impact on crop growth in the study area (Table 2). Salinity hazards as well as permeability and infiltration hazards play an important role in soil structure and crop yield, which can decrease the amount of water available to the crop roots and reduce the rate of irrigation water that enters the soil's lower layers. Because EC and TDS are usually used to measure groundwater salinity hazards, a weight value of 5 was assigned to EC and TDS. Jiaozuo City's main agricultural products are wheat, cotton, beans, and fruit. Fruit, such as apple, are sensitive to salinity; wheat and beans are mid-level salt-tolerant crops, and cotton is a highly salt-tolerant crop [39]. The sodium, calcium, and magnesium are all applied to compute SAR; therefore, these elements were given the higher weight coefficient of 4 because they have important effects on crop yield. Higher levels of trace elements can retard the growth and metabolic activities of crop plants and also lead to the accumulation of trace elements in

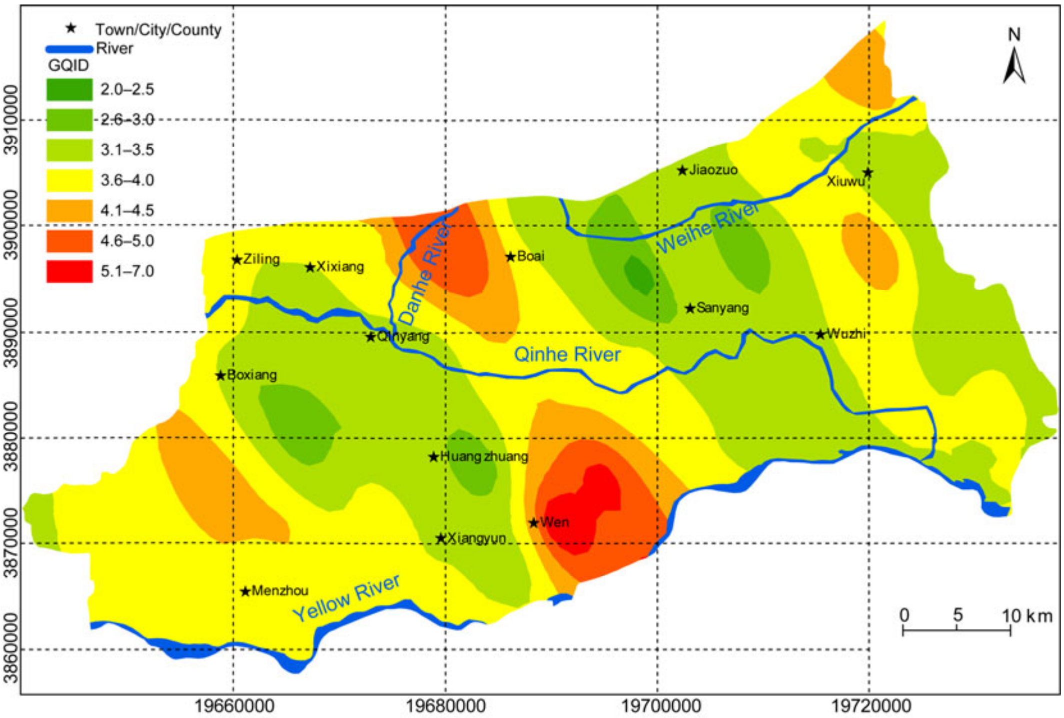

Figure 3 Spatial distribution map of GQID in Jiaozuo City.

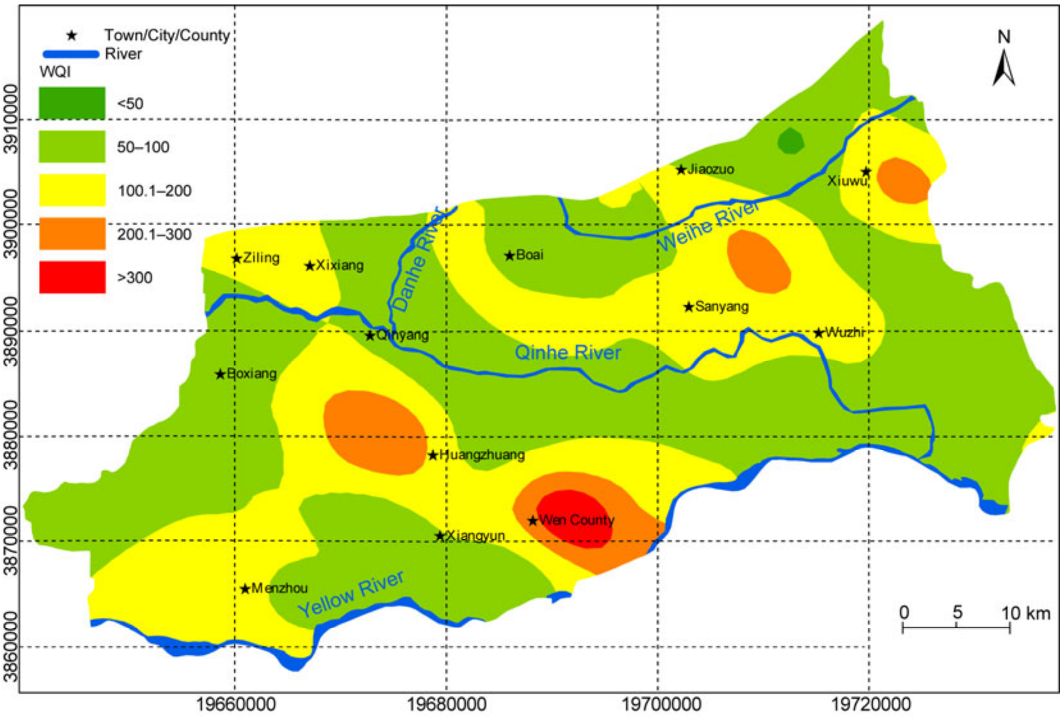

Figure 4 Spatial distribution map of WQI in Jiaozuo City.

the edible part of the crop, the consumption of trace elements contaminated food can result in immunological defense decreasing, intrauterine growth retardation, and impaired psychosocial faculties [40]. It is concluded that the trace elements do not inflict fatal damage to crops themselves; however, the substances are harmful to the human body through the edible part of the plant. Therefore, the trace elements were assigned the weight value of 2 according to its impact on crop yield.

The second step was to calculate GQIIR by VFS theory; its spatial distribution map is demonstrated in Figure 5 using the GIS tool. EC and Na% parameters are widely used to assess irrigation water quality; their distribution maps were also shown in this paper (Figures 6 and 7).

Table 2 Standard values and weight coefficients of hydrochemical variables in study area for irrigation use

Water quality parameter	Standard guideline value			Weight (w_i)	Relative weight $W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$
	Excellent limit	Desirable limit	Maximum permissible limit		
EC (μS/cm)	500	700	3000	5	0.1020
TDS (mg/L)	300	450	2000	5	0.1020
TH (mg/L)	300	450	550	4	0.0816
K (mg/L)	2	5	12	1	0.0204
Na (mg/L)	20	175	200	4	0.0816
Ca (mg/L)	50	75	200	4	0.0816
Mg (mg/L)	30	50	150	4	0.0816
Fe (mg/L)	0.3	5.0	20	2	0.0408
Mn (mg/L)	0.1	0.2	10	2	0.0408
Ba (mg/L)	0.1	1.0	4.0	2	0.0408
Mo (mg/L)	0.001	0.01	0.05	2	0.0408
Cr (mg/L)	0.05	0.1	1.0	2	0.0408
As (mg/L)	0.05	0.1	2.0	2	0.0408
Hg (mg/L)	0.0005	0.001	0.006	2	0.0408
Cl (mg/L)	50	140	350	3	0.0612
F (mg/L)	0.7	1.0	15.0	2	0.0408
SO_4 (mg/L)	0.5	1.0	200	1	0.0204
NO_3 (mg/L)	5	20	30	1	0.0204
NO_2 (mg/L)	0.01	0.02	0.1	1	0.0204
				$\sum w_i = 49$	$\sum W_i = 1.0000$

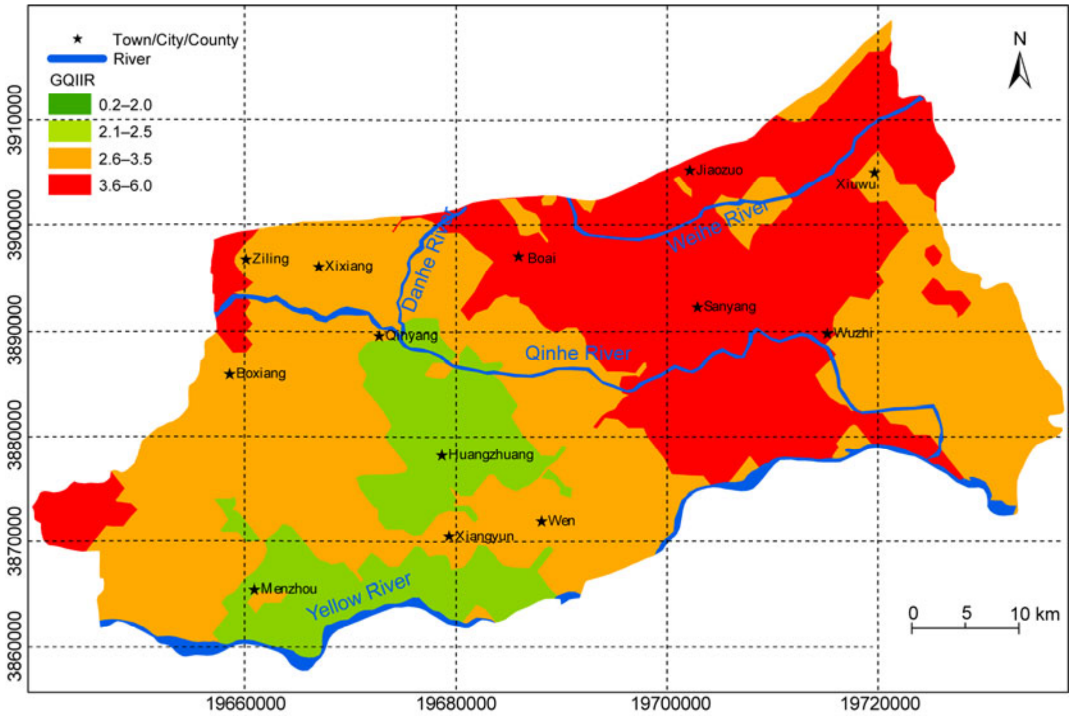

Figure 5 Spatial distribution map of GQIIR in Jiaozuo City.

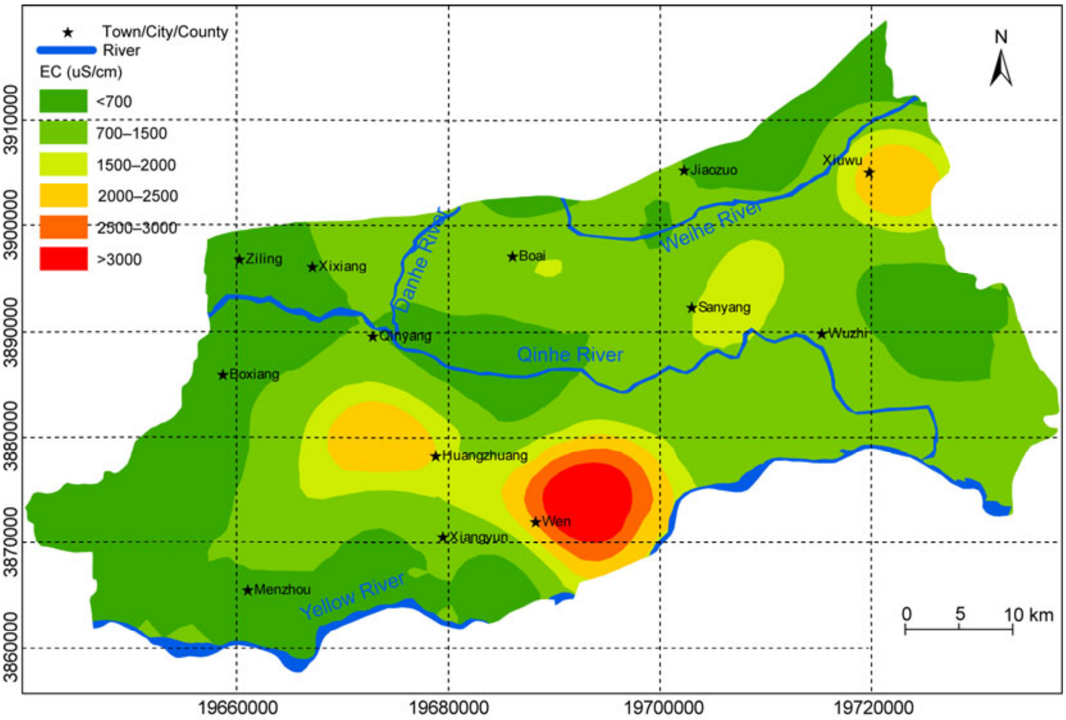

Figure 6 Spatial distribution map of EC in Jiaozuo City.

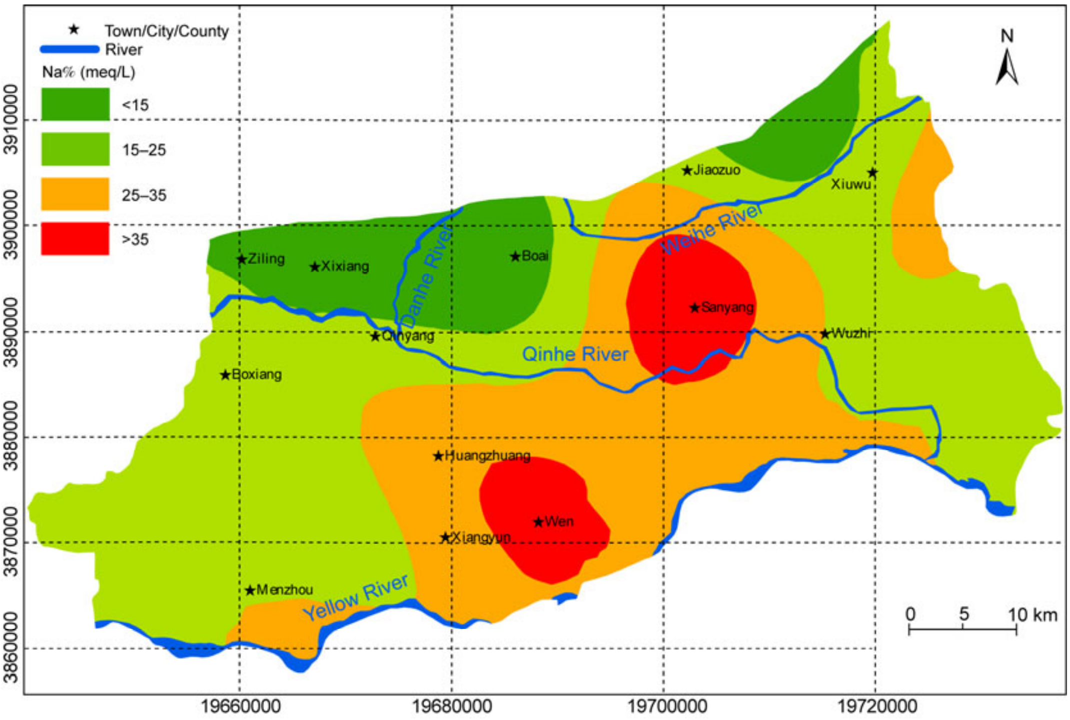

Figure 7 Spatial distribution map of Na% in Jiaozuo City.

2.3 Suitability for industrial application

There is difficulty in constructing the industrial water quality standard; almost every industrial application has its own standards. Parameter values must be established for specific industries, rather than a general class [41]; the industrial structure includes equipment manufacturing, automobile manufactory, the aluminum industry, the coal chemical industry, and energy in Jiaozuo City. Therefore, the quality standard of industrial water in the study area should be established based on the above industries' water quality requirements. With regard to the weight coefficient of each hydrochemical variable, the formation scale effect, the barbotage effect, and the corrosive effect are the most important influencing factors in industrial water quality. These influencing factors involve TDS, TH, calcium, magnesium, sodium, potassium, and iron, and therefore these elements were given the weight value of either 4 or 5. The high concentration of manganese would result in the groundwater turning red, causing a damage dot on the industrial products. Manganese was assigned a weight value of 3. In combination with the actual situation of industrial water requirements in Jiaozuo City, the standard values and weight coefficients of each hydrochemical variable are listed in Table 3. In an application of a similar method, the GQI of industrial water (GQIIN) spatial distribution map is shown in Figure 8, and the TH distribution map is described in Figure 9.

2.4 Discussions

At present, the total values of the GQI for various purposes were obtained; these values were classified into four categories according to three threshold values. The calculation process of threshold values was omitted for the length of this paper, which has been described by Simek and Gunduz [11]. In this paper, let 1.5, 2.5 and 3.5 be the threshold values for drinking, irritation, and industrial uses, these values were used to set the lower and upper limits used in each category specified. The GQI value of 1.5 indicates the excellent limit; 2.5 indicates the desirable limit; 3.5 denotes the maximum permissible limit; a GQI value falling above 3.5 means the groundwater is unsuitable for human consumption.

The spatial distribution map of the GQID (Figure 3) shows that the eastern and central parts of Jiaozuo City is good in drinking water quality, which is found to be suitable for drinking purpose; and its groundwater quality decreases from east to west of the study area, under the impact of the anthropogenic activities and water-rock interaction. Over 51.06% of the samples exceed the "Maximum Permissible" threshold value of 3.5, indicating that groundwater from these wells is unsuitable for drinking, since the groundwater has higher concentrations of some of the sensitive parameters like, nitrate, nitrite, and fluoride.

There are significant differences between Figures 3 and 4. Most of the study areas, with the exception of Wen County,

Table 3 Standard values and weight coefficients of hydrochemical variables in the study area for industrial use

Water quality parameter	Standard guideline value			Weight (w_i)	Relative weight $W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$
	Excellent limit	Desirable limit	Maximum permissible limit		
EC (μS/cm)	500	700	3000	1	0.0189
TDS (mg/L)	500	1000	2000	4	0.0755
TH (mg/L)	300	450	550	4	0.0755
K (mg/L)	2	5	12	5	0.0943
Na (mg/L)	20	175	200	5	0.0943
Ca (mg/L)	30	75	200	5	0.0943
Mg (mg/L)	30	50	150	5	0.0943
Fe (mg/L)	0.3	0.5	1.5	5	0.0943
Mn (mg/L)	0.05	0.1	1.0	3	0.0566
Ba (mg/L)	0.1	1.0	4.0	1	0.0189
Mo (mg/L)	0.01	0.1	0.5	1	0.0189
Cr (mg/L)	0.01	0.05	0.1	1	0.0189
As (mg/L)	0.005	0.01	0.05	1	0.0189
Hg (mg/L)	0.0005	0.001	0.006	1	0.0189
Cl (mg/L)	250	300	350	3	0.0566
F (mg/L)	1.0	2.0	15.0	1	0.0189
SO_4 (mg/L)	30	350	600	3	0.0566
NO_3 (mg/L)	5	20	30	2	0.0377
NO_2 (mg/L)	0.01	0.02	0.1	2	0.0377
				$\sum w_i = 53$	$\sum W_i = 1.0000$

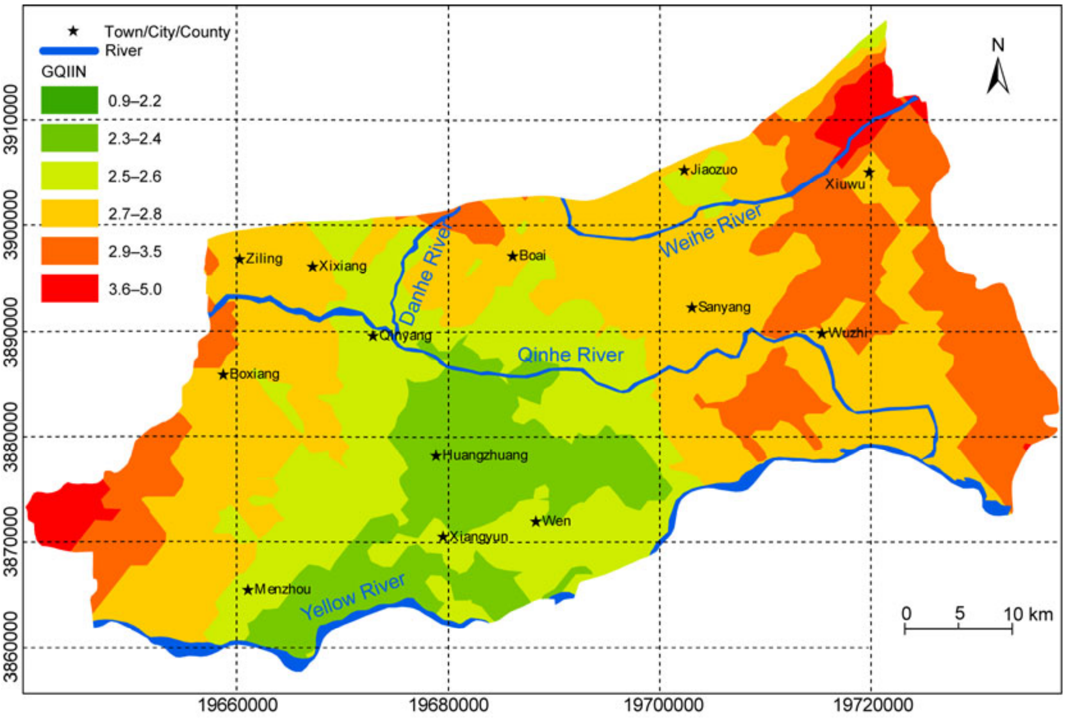

Figure 8 Spatial distribution map of GQIIN in Jiaozuo City.

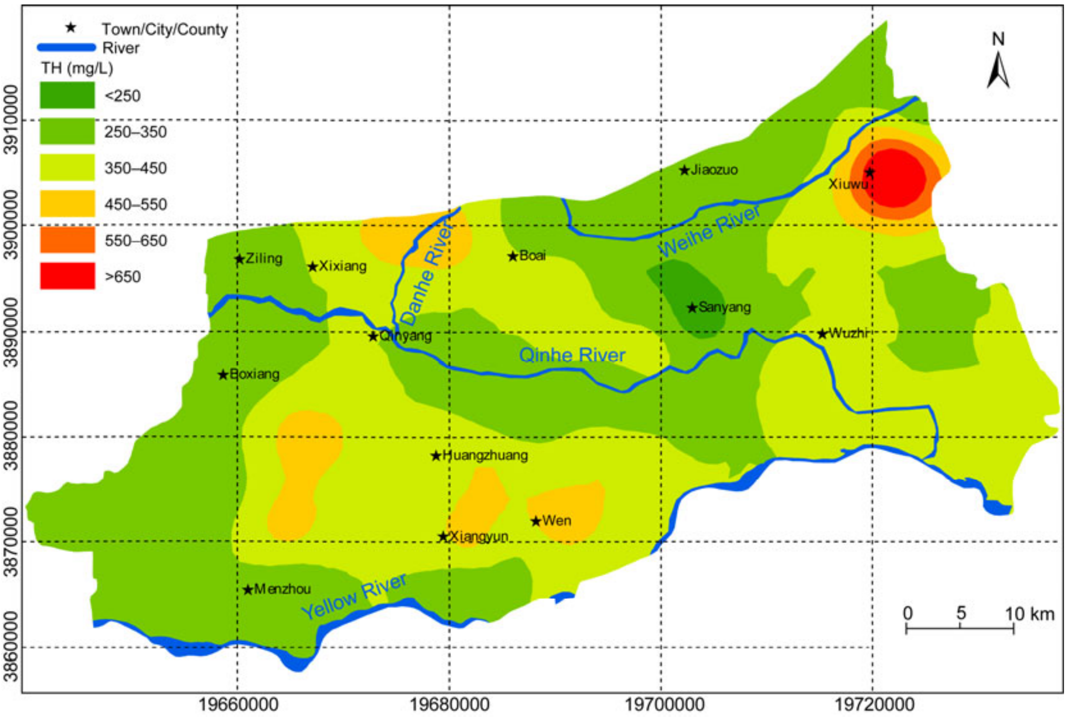

Figure 9 Spatial distribution map of TH in Jiaozuo City.

have water suitable for drinking purpose, as shown in Figure 4. In actual situations, arsenic, iron, and molybdenum have higher concentrations in Xixiang Town and Menzhou City in Jiaozuo City, causing the groundwater unsuitable for drinking. The GQID values of Xixiang Town and Menzhou City range between 3.6 and 4.0, indicating groundwater from these areas is unsuitable for drinking, as indicated in Figure 3. The evaluation effects of GQID are more accurate and reasonable than that of WQI; the major reason for this is that the WQI method does not consider the impact of interval values of a quality standard, like [Excellent, Desirable] and [Desirable, Maximum Permissible], on drinking water suitability assessment.

Figure 5 indicates that groundwater in western and central parts of the study area is suitable for irrigation; however, in the northeastern region, there has been a deterioration in water quality due to high concentrations of EC, TDS, TH, sodium, and fluoride. Near the northwestern boundary of the study area, the groundwater pollution is serious and unsuitable for irrigation. It can be seen that 93.51% of the study area in Figure 6 and 89.22% in Figure 7 have been found to be a suitable irrigation water source, respectively. However, Figure 5 shows only 57.84% of the study area is occupied by "Maximum Permissible" and "Desirable" groundwater for irrigation use. EC and Na% parameters only characterize the adverse effects of salinity hazards and permeability and infiltration hazards on crops; they do not take into account the heavy metal and trace element toxicities. Although it is seen from the figures that the irrigation water quality in Figures 6 and 7 are better than in Figure 5, which does not reflect the actual situation of the irrigation water quality in Jiaozuo City. For example, higher level of heavy metal in the groundwater in Ziling Town, which was due to the arbitrary discharge of industrial effluent, caused crop growth retardation, and even a reduction of yield in some areas, because heavy metals can accumulate unnoticed in extremely high toxic concentrations before affecting a crop. Therefore, it is necessary to take into account five crucial factors for irrigation water suitability assessment.

From the GQIIN assessment (Figure 8), over 94.69% of the study area with GQIIN fall within the "Maximum Permissible" limits (3.5). The overall view of the GQIIN of the present study area shows a lower value, indicating that most of groundwater samples are suitable for use in industry. Only two wells had an unsatisfactory result with GQIIN values exceeding 3.5; it demonstrates that there are sufficient groundwater resources for industrial purposes in Jiaozuo City. The deteriorating trend of industrial water quality comes from the central part to the two sides of study area in Figure 8, and the evaluation results in Figure 9 are the complete reverse. Although hardness plays a key role in boil water quality because it can result in scaling pots and boilers, it has no known adverse effect on other industrial water uses. Jiaozuo City is well known for its energy, aluminum, and coal chemistry industries; it is unsuitable to assess industrial water quality only using the TH parameter.

Figures 3, 5, and 8 indicate that 33.83% of Jiaozuo City is covered by "Maximum Permissible" groundwater for drinking purposes, which covers about 1377.2 km^2. Additionally, 57.84% of the study area is found to be suitable for an irrigation water source; it covers about 2354.7 km^2. Furthermore, 94.69% of the study area with a GQIIN less than 3.5 is covered by "Maximum Permissible" groundwater, with an area of 3854.8 km^2. It concludes that the area covered by "Maximum Permissible" groundwater for the three aforementioned purposes followed the order of drinking <agriculture irrigation < industrial. This is because the quality requirements for drinking water are the strictest. At the opposite extreme, the quality requirement for industrial water supplies range widely. For some specialty industries in Jiaozuo City, such as cooling, concentrating ores and single-pass condensing of steam, almost any water can be used [41]. Therefore, there are more sufficient groundwater resources for industrial use than for drinking and irrigation purposes. These figures show that the area covered by "Maximum Permissible" groundwater for drinking use can be regarded as irrigation and industrial water source. This result is consistent with the public's general understanding; however, there are some significant differences in local areas among the GQI spatial distribution maps. For example, the GQIIR value around Xiuwu County exceed the "Maximum Permissible" limit value of 3.5, signifying the groundwater is unsuitable for irrigation use; the GQIIN is also in the higher range from 2.7 to 3.5, indicating the groundwater is barely suitable for industrial use. On the contrary, this area is occupied by "Maximum Permissible" and "Desirable" groundwater that is suitable for drinking use, the GQID of the groundwater samples in this region is lower, ranging from 2.0 to 3.5. This difference is attributed to Jiaozuo City's hydrodynamic conditions. The Qin-Yellow River alluvial fan is on the northern part of Jiaozuo City; the alluvial fan is primarily partitioned into the proximal fan, the mid fan, and the distal fan areas from Qinyang to Xiuwu County. According to the hydrogeology laws, a significant increase in the concentrations of EC, TDS, TH, sodium, and magnesium were observed in the direction of Qinyang to Xiuwu County of Jiaozuo City following the radius direction of the Qin-Yellow River alluvial fan. These elements play a key role in crop yields and soil structure, because TH and EC are usually used to measure salinity hazards; permeability and infiltration hazards are the functions of sodium, calcium, and magnesium concentrations. The weight values of these elements were so higher (Table 2) that the GQIIR values of these samples fell above the "Maximum Permissible" limit value in Xiuwu County. In addition, TH, sodium, calcium, and magnesium can cause scaling, barbotage, and corrosion effects, and even result in an extra input of energy. These elements were also given higher weight of either 4 or 5 due to their major role in industrial water suitability assessment. Therefore, the qualities of the industrial and irrigation water are gradually deteriorated along this direction; with respect to drinking water quality, although EC, TDS, and TH contents are higher in Xiuwu County, these hydrochemical variables have an insignificant effects on human and animal health. Their weight coefficients are lower in drinking water suitability assessment, and therefore the GQID of these samples are relatively lower. These results indicate that the suitability assessment results of deep groundwater for various purposes in this article are reasonable, accurate, and are in accordance with the hydrogeological laws of the study area.

3 Conclusion

Based on the observed results, it is concluded that (1) the GQI can more accurately characterize the suitability of groundwater for different purposes than traditional methods, such as WQI, EC, Na%, and TH, which provide complete and reasonable information for the general public; (2) the hydrodynamic conditions have an important impact on the evaluation results of groundwater suitability, and better understanding hydrodynamic conditions can help achieve sustainable groundwater resources management in Jiaozuo City over the coming years; (3) the area covered by “Maximum Permissible” groundwater has increased from 1377.2 km^2 for drinking use and 2354.7 km^2 for irrigation to 3854.8 km^2 for industrial purposes, mainly due to stricter quality criteria for drinking water, compared to that for irrigation and industrial water. Accordingly, the eastern Jiaozuo City can be taken as a drinking water source, and the southwestern region as an irrigation water source; finally, the southeastern and near the southwestern portion of the study area is considered as an industrial water source. Therefore, the spatial distribution maps of GQI can make the areas of better and poor water quality easily understood by researchers, policy-makers, and the general public. They could easily decide the purposes of groundwater, either for drinking, irrigation, or for industrial uses in Jiaozuo City. Therefore, the GQI would make sense to a non-technical decision maker and they could use this method without difficulty.

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