Exposure and Health (2023) 15:825–840
https://doi.org/10.1007/s12403-022-00526-9

ORIGINAL PAPER

Groundwater Quality Assessment Using EWQI With Updated Water Quality Classification Criteria: A Case Study in and Around Zhouzhi County, Guanzhong Basin (China)

Yongqiang Yang[1,2] · Peiyue Li[1,2] · Vetrimurugan Elumalai[3] · Jing Ning[1,2] · Fei Xu[1,2] · Dawei Mu[1,2]

Received: 24 August 2022 / Revised: 22 November 2022 / Accepted: 28 November 2022 / Published online: 9 December 2022

Abstract
The entropy water quality index (EWQI) is a simple method of comprehensively assessing water quality. This method has been widely used in groundwater quality assessment. However, the number of hydrochemical parameters selected for the evaluation can lead to inconsistent classification criteria. In this study, 12 parameters were selected, based on their importance in the groundwater quality, to redefine the classification criteria of EWQI. Therefore, the modified EWQI approach with updated classification criteria was applied to evaluate groundwater quality in the Zhouzhi Country of the Guanzhong Basin, China. The results show that considering heavy metals in the groundwater quality resulted in different EWQI classification criteria from those previously used in other studies due to the large difference in the national standard limits for heavy metals in different water quality categories. In addition, the improved EWQI showed that 1.41, 63.38, and 35.21% of the groundwater samples in the Zhouzhi County were of excellent, good and moderate groundwater quality, respectively. Compared with other classification criteria, the improved EWQI method considering more water hydrochemical parameters and heavy metal elements is more suitable and reliable for comprehensively evaluating groundwater quality.

Keywords Water quality index · Groundwater quality · Heavy metals · Standard limit · Guanzhong Plain

Introduction

In recent years, the rapid development of human society has caused some serious environmental problems, such as unplanned land use, energy shortage, and water pollution (Liu et al. 2020; Luque-Espinar and Chica-Olmo 2020). Groundwater contamination, which is defined as the deterioration of water quality caused by anthropogenic activities, has threatened the survival and development of human beings (He et al. 2022; Li et al. 2014; Subba Rao et al., 2022a, 2022b). Human health may be seriously affected by polluted groundwater as it serves as the primary source of drinking and irrigation water (Li and Wu 2019; Wang and Li 2022). Therefore, the prevention of groundwater pollution has become a high priority for sustainable water resources management (Hu et al. 2020; Zhang et al. 2022a). It is of great significance to carry out first the groundwater quality and pollution degree assessment, and then implement groundwater pollution control policies to reduce and mitigate groundwater pollution (Fida et al. 2022; Zhou et al. 2022).

Researchers have used numerous methods to assess water pollution worldwide, and some of them include improved fuzzy comprehensive evaluation, fuzzy mathematics, multivariate statistical analysis; Nemerow index, set pair analysis, water quality identification index, and water quality index methods (Ali et al. 2021; Maurya et al. 2021; Shankar and Sreevidya 2020; Tian et al. 2021; Tian and Wu 2019; Wang et al. 2014; Qiao et al. 2015; Su et al. 2019; Zhang et al. 2020, 2021a, 2022b). The water quality index (WQI) method has been widely used to determine the overall groundwater quality and its suitability for drinking purposes worldwide (Fadel et al. 2021; Zotou et al. 2019;

✉ Peiyue Li
lipy2@163.com; peiyueli@chd.edu.cn

1 School of Water and Environment, Chang'an University, No. 126 Yanta Road, Xi'an 710054, Shaanxi, China

2 Key Laboratory of Subsurface Hydrology and Ecological Effects in Arid Region of the Ministry of Education, Chang'an University, No. 126 Yanta Road, Xi'an 710054, Shaanxi, China

3 Department of Hydrology, University of Zululand, Kwa-Dlangezwa 3886, South Africa

Mthembu et al. 2022). Li et al. (2010) integrated entropy weights and conventional water quality index (WQI) and developed the entropy water quality index (EWQI), improving the reliability of the water quality assessment results. Since then, EWQI has been widely used for water quality assessment many scholars (Amiri et al. 2014; Ali et al. 2017; Islam et al. 2020). To comprehensively assess groundwater pollution, a large number of physicochemical and biological parameters need to be considered, many of which have been included in the calculation of WQI (Singh et al. 2019). However, the existing EWQI classification criteria vary considerably between studies. Indeed, several researchers have classified the EWQI into five classes, namely < 25, 25–50, 50–100, 100–150, and > 150 (classification criteria one hereafter), corresponding to excellent, good, moderate, poor, and very poor groundwater quality, respectively (Kumar and Augustine 2022; Liu et al. 2022; Zhang et al. 2022c). While other researchers have classified EWQI into < 50, 50–100, 100–150, 150–200, and > 200(classification criteria two hereafter), corresponding to excellent, good, moderate, poor, and very poor groundwater quality, respectively (Egbueri et al. 2020b; Masood et al. 2022; Nguyen et al. 2021; Zhang et al. 2021b). Moreover, a third water quality classification criterion has widely been adopted, namely < 50, 50–100, 100–200, 200–300, and > 300(classification criteria three hereafter), corresponding to excellent, good, moderate, poor, and very poor groundwater quality, respectively (Egbueri et al. 2020a; Ismail and Ahmed 2021; Raheja et al. 2022). These different water quality classification criteria lead to confusing and varying groundwater quality assessment results (Singh et al. 2019; Wang et al. 2020; Panneerselvam et al. 2021). Therefore, using an appropriate EWQI classification is critical for ensuring the reliability of the groundwater quality assessment results. Although heavy metals are harmful to human health, they are rarely considered in the groundwater quality assessment due to the low levels in the analyzed water samples (Ali et al. 2017). Therefore, including heavy metal elements in the EWQI may result in more reliable groundwater quality results, and will be useful for the water quality management (Li et al. 2021).

Zhouzhi County is an important county in the Guanzhong Plain, China, and provides the major water supply for Xi'an. Assessment of groundwater quality of this area is of great importance for water safety and national economic development. Indeed, Qiao et al. (2020) and Zhang et al. (2019) revealed that groundwater is polluted in the entire Guanzhong Plain, showing high nitrate (NO_3^-) and heavy metals concentration is exceeding Chinese groundwater quality thresholds. However, the groundwater quality status around Xi'an city has not been comprehensively assessed. Therefore, this study aims to: (1) to assess the hydrochemical characteristics of groundwater and evaluate its quality using the improved water quality classification criteria; (2) to compare the results obtained using the improved water quality classification criteria with those obtained using the original classification criteria. This study also generated the spatial distribution maps of the main water quality parameters. This study provides suggestions and a basis for local groundwater pollution prevention and control.

Study Area

Location and Geography

Zhouzhi County is located in the central part of the Shaanxi Province, China (107°39′-108°37′ E and 33°42′-34°14′ N) at 68 km from Xi'an City (Fig. 1). The study area is bounded to the west by Mei County, to the east by Huyi District (previous Hu County), to the south by the Qinling Mountains, and to the north by the Wei River, covering a total area of 2974 km^2. Zhouzhi County provides important water supply source for Xi'an City. The study area has a temperate continental climate with an average annual temperature of 13.3 °C (Zhang et al. 2019). The average annual precipitation and evaporation range from 530 to 700 mm and between 1000 and 1200 mm, respectively, with uneven seasonal distribution of precipitation. Indeed, about 45% of the precipitation amount occurs during the month of July and September period (Xu et al. 2019). The overall dry and wet seasons are distinct, with high winds and sandstorms in spring, intense rainfall events occurs in early summer, and limited rainfall occurs during the autumn, winter, and spring. The main rivers in the study area are the Wei River and Hei River. The Hei River is a first-class tributary of the Wei River, characterized by significant seasonal changes in flow. Whereas the highest flow of the mainstream is observed in autumn.

Geological and Hydrogeological Settings

The landform types in the study area are pre-mountain alluvial fans, loess plateau, and valley terraces from the Qinling Mountains to the Wei River, consisting mainly of Quaternary alluvium-lacustrine and loess accumulation (An et al. 2020). The primary terraces are not widely distributed on the north bank of the Wei River, while secondary terraces are continuously developed. Nevertheless, primary and secondary terraces are developed in the Xi'an depression on the south bank of the Wei River, showing narrow terraces with shallow hydraulic gradients (Li et al. 2016a). In addition, the study area is characterized by the presence of two aquifer types, namely the Quaternary sand and gravel aquifer and the Neoproterozoic to Paleoproterozoic bedrock aquifer with a thickness of about 800 m. The main lithological classes are loess, sand, and gravel layers. According to Kong

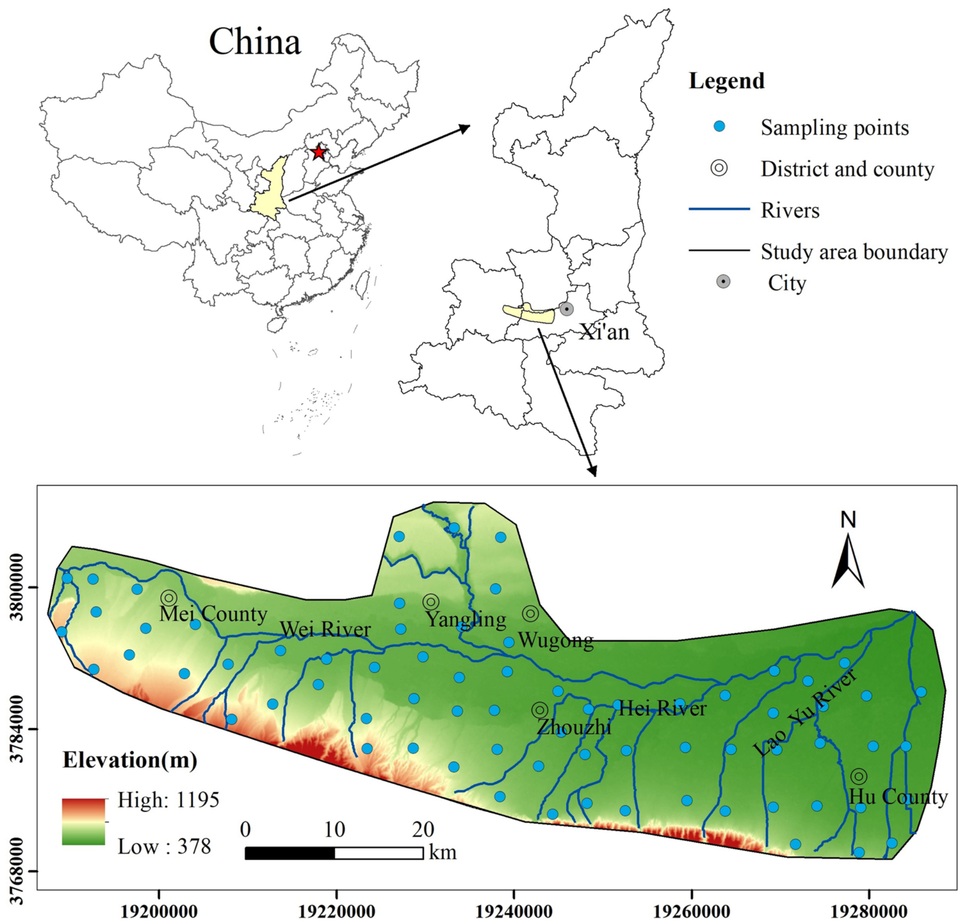


Fig. 1 Location map of the study area and distribution of sampling sites

et al. (2019), the average hydraulic conductivity and the infiltration coefficient of the aquifer is 25.26 m/d and 0.25, respectively. The aquifer is mainly recharged by atmospheric precipitation infiltration and surface runoff, with decreasing recharge rates along both sides of the Wei River, while groundwater discharge occurs mainly by artificial extraction, evaporation, and lateral runoff to the river (Ji et al. 2020). According to the investigation in 2021, groundwater level depth in the study area ranges generally between 8 and 45 m.

Material and Methods

Sample Collection and Analysis

In this study, 71 groundwater samples were collected in polyethylene bottles from well-distributed sampling points in and around Zhouzhi County in June 2021 in the monsoon season. Portable GPS devices were used to record the location of the sampling sites. The groundwater sampling was carried out after pumping groundwater for 3 min and cleaning polyethylene bottles three times with the groundwater to be sampled. In addition, to preserve groundwater samples and ensure the reliability of analytical analyses, concentrated nitric acid was added to the groundwater samples intended for heavy metals analyses. Afterward, groundwater samples were stored and transported according to the Chinese drinking water standards (Ministry of Health of the People's Republic of China and Standardization Administration of the People's Republic of China 2006). On-site measurements of groundwater physicochemical parameters (such as temperature and pH) were conducted using a portable multi-parameter meter (SX723). Whereas fluorine (F^-), chloride (Cl^-), nitrite (NO_2^-), sulfate (SO_4^{2-}), nitrate (NO_3^-), sodium (Na^+), aluminum (Al), arsenic (As), zinc (Zn), total hardness (TH), total dissolved solids (TDS), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) were analyzed in the laboratory of Xi'an Center for Mineral Resources Survey. In addition, the charge balance error percentage (%CBE) of each groundwater sample was checked to ensure the reliable analytical results (Eq. 1). The acceptable standard limit %CBE is set at ± 5%, and in this study all water samples are within this limit, indicating acceptable quality of physicochemical analyses for further study.

$$\%CBE = \frac{\sum \text{Cations} - \sum \text{Anions}}{\sum \text{Cations} + \sum \text{Anions}} \times 100 \quad (1)$$

Correlation Analysis

The degree of correlation between different parameters in groundwater can be quantified by the Pearson correlation coefficient (r), which can be calculated as follows:

$$r = \frac{\sum_{i=1}^{n} (X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \overline{X})^2}\sqrt{\sum_{i=1}^{n} (Y_i - \overline{Y})^2}} \quad (2)$$

where, r is the correlation coefficient between two variables (x and y). $\overline{x}$ and $\overline{y}$ are the mean values of the variables. The value of r ranges between − 1 and 1. A correlation coefficient of 0 indicates that the two variables are not correlated (Wei et al. 2022).

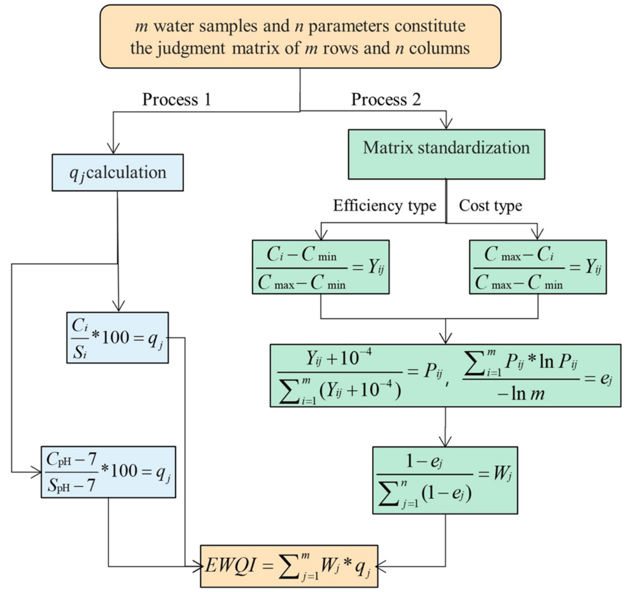


Fig. 2 EWQI calculation process

Introduction to EWQI

EWQI is a comprehensive method for assessing groundwater quality. This method can be used to transform a large water quality dataset into comprehensive water quality scores by assigning objective weights to the hydrochemical parameters (Li et al. 2019; Qiao et al. 2020). Indeed, EWQI has been widely used by numerous researchers (Adimalla 2021; Marghade et al. 2021; Zhang et al. 2022c) due to its calculation simplicity and the ability to integrate multiple hydrochemical parameters. However, the EWQI classification criteria vary considerably between studies, resulting in discrepancies in the results of groundwater quality of the same aquifer. Moreover, differences in the input hydrochemical parameters may result in significant impacts on the EWQI classification criteria. In this study, the main parameters influencing groundwater quality were selected to determine the classification criteria of EWQI. The calculation of EWQI was performed using two main processes (Fig. 2) according to Li et al. (2010) and Wu et al. (2015). The first process consists of calculating the rating scale (q_j) of EWQI for the hydrochemical parameters of groundwater. q_j of pH values was calculated based on the standard pH (S_{pH}) range of 6.5–8.5. Whereas the second process consists of matrix normalization using two different formulae, depending on the different parameters considered (Ali et al. 2017).

The EWQI classification criteria were redefined by considering the 12 parameters, namely F^-, Cl^-, NO_2^-, SO_4^{2-}, NO_3^-, Na^+, Al, As, Zn, pH, TH, and TDS, which were selected based on their pollution characteristics in groundwater. All levels of water quality standard limit value of each parameter were introduced in the EWQI formulae to obtain the new classification criteria. Based on the groundwater quality standard limits of the People's Republic of China (General Administration of Quality Supervision, Inspection & Quarantine of China, and Standardization Administration of China 2017), all hydrochemical parameters and heavy metals can be classified into grades I–V (Table 1).

Results and Discussion

Hydrochemical Characteristics of Groundwater

Groundwater in the study area is mainly used for agriculture, industry and drinking purposes. Therefore, the groundwater pollution in the study area threatens seriously the health of local residents. The concentrations of Cu, Cr^{6+} and Ni in groundwater samples were lower than the detection limits, suggesting that their concentrations were well below the limits for grade I, which would not affect human health (Edokpayi et al. 2018). Therefore, these heavy metals are not discussed in the current study. In this study, 12 parameters were selected to evaluate the groundwater quality. These hydrochemical parameters were selected based on their significant impacts on the groundwater pollution in the study area. Hydrochemical parameter concentrations below the detection limit were considered as half of the detection limit.

The Piper diagram consists of three different zones, in which the anion and cation proportions in water samples are plotted to determine their groundwater facies types, providing a better understanding of the evolution of groundwater

Table 1 Water quality classification standard limits and allowable limits

Parameters	pH	F^-	Cl^-	NO_2^-	SO_4^{2-}	NO_3^-	Na^+	TDS	TH	Al	Zn	As
I	6.5–8.5	1	50	0.01	50	2	100	300	150	0.01	0.05	0.001
II	6.5–8.5	1	150	0.1	150	5	150	500	300	0.05	0.5	0.001
III	6.5–8.5	1	250	1	250	20	200	1000	450	0.2	1	0.01
IV	5.5/9	2	350	4.8	350	30	400	2000	650	0.5	5	0.05
Allowable limits	6.5/8.5	1	250	1	250	20	200	1000	450	0.2	1	0.01

pH standard is divided into alkaline and acidic standards. The alkaline standard limits are 7.5, 8, 8.5, and 9, while the acidic standard limits are 7.5, 7, 6.5, and 5.5

(Piper 1944; He and Li 2020; Su et al. 2020). As shown in Fig. 3, the groundwater sample points in the study area mainly fall in zone 4, indicating that the groundwater chemical type of groundwater is dominated by the HCO_3^-Ca·Mg facies type. Whereas the anions and cations of groundwater samples were mainly distributed in zones E and A, indicating that the anions and cations in groundwater of the study area are dominated by $HCO_3^- + CO_3^{2-}$ and Ca^{2+}, respectively. These results suggest that carbonate mineral weathering (such as calcite and dolomite) is likely to be the main factor controlling groundwater chemistry in Zhouzhi County.

The Gibbs diagrams include two subplots divided into three parts, representing three evolutionary mechanisms of groundwater, namely precipitation dominance, rock dominance and evaporation dominance. These diagrams have, indeed, been applied by many scholars to assess groundwater evolution (Gibbs 1970; He et al. 2021). The results showed that all groundwater samples fall under the rock dominance zone, suggesting that the formation of groundwater chemistry is dominated by water–rock interaction (Fig. 4). As shown in Fig. 4a, there are four groundwater samples falling in the middle left part of the diagram, indicating that these groundwater samples are affected by a combination of the three evolutionary mechanisms. Whereas the remaining groundwater samples suggested a dominance of rock weathering (e.g., carbonate minerals), which influence significantly the groundwater chemical characteristics in the study area. These results are consistent with those obtained using the Piper diagram.

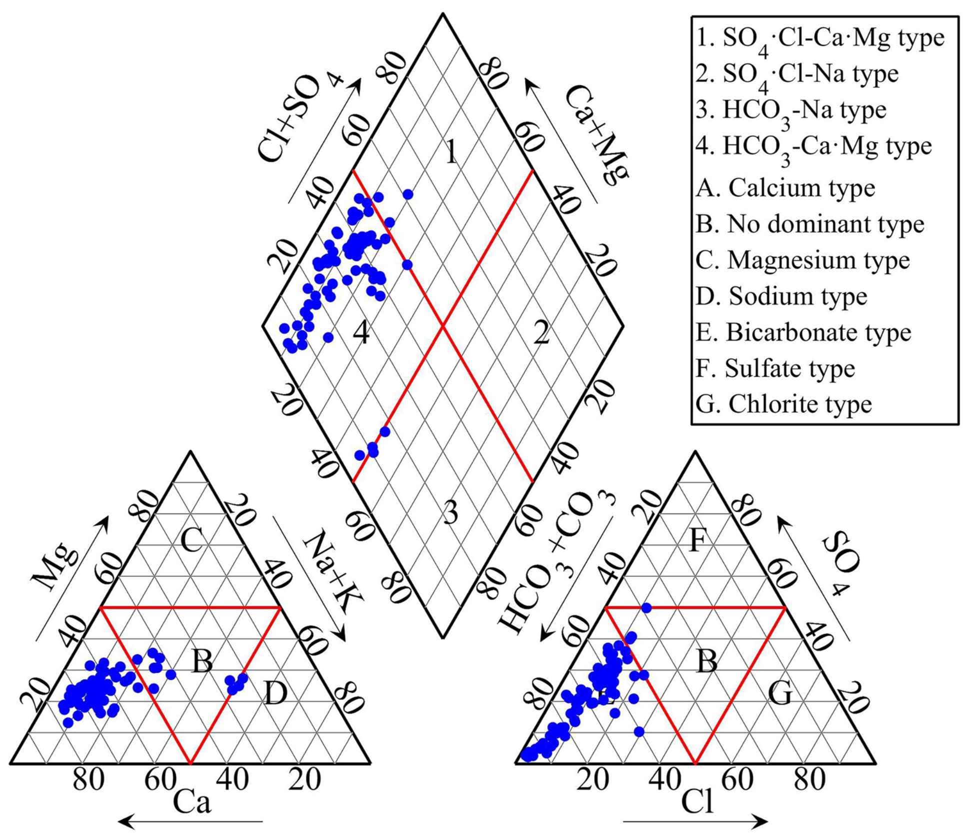


Fig. 3 Piper diagram showing major water types of the groundwater samples

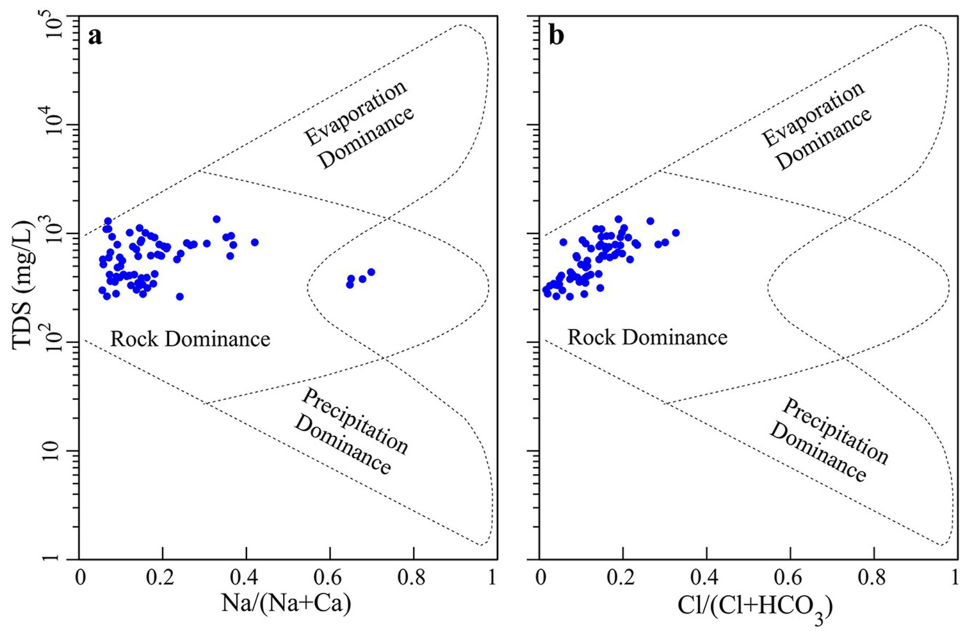


Fig. 4 Gibbs diagrams, **a** TDS versus Na/(Na + Ca), **b** TDS versus Cl/(Cl + HCO3)

Chemical Compositions of Groundwater

For a clear understanding of the hydrochemical characteristics of groundwater. a statistical analysis of the main water quality parameters was carried out. As shown in Table 2, 30.99% of the groundwater samples showed NO_3^- concentrations exceeding the permissible limit, indicating NO_3^- pollution in the study area. Indeed, high NO_3^- concentrations in drinking water are likely to cause methemoglobinemia in infants (Adimalla and Li 2018). The TDS is the sum of inorganic salts and small amounts of dissolved organic matter. The results showed that 11.27% of the groundwater samples exceeded the permissible limit of TDS (1000 mg/L). In fact, high TDS concentrations may affect significantly human health (Ravindra et al. 2019; Tiwari et al. 2016). The TH range was 169–750 mg/L, with a mean concentration of 374.80 mg/L.

Table 2 Statistics of physiochemical parameters of groundwater (Unit: mg/L, except pH)

Parameters	Max	Min	Mean	SD	CV (%)	Allowable Limits	Percentage exceeding the standard (%)
pH	7.94	6.83	7.45	0.23	3.05	6.5–8.5	0
F^-	0.70	0.04	0.19	0.14	69.93	1	0
Cl^-	96.10	2.60	27.73	22.04	79.46	250	0
NO_2^-	1.06	0.63	0.86	0.10	11.23	1	5.63
SO_4^{2-}	250.00	5.59	79.56	61.79	77.67	250	0
NO_3^-	89.65	0.01	19.77	19.54	98.84	20	30.99
TDS	1352.00	262.00	619.38	266.98	43.10	1000	11.27
TH	750.00	169.00	374.80	143.61	38.32	450	35.21
Al	0.80	< 0.0046	0.04	0.11	276.93	0.20	7.04
Zn	0.41	< 0.0027	0.02	0.05	298.66	1	0
As	0.01	0.001	0.003	0.001	47.37	0.01	0
Mg^{2+}	85.10	9.19	27.40	14.62	53.35	–	0
Ca^{2+}	220.00	30.40	112.23	43.70	38.94	–	0
Na^+	100.00	4.83	31.73	25.63	80.76	200	0
K^+	6.68	0.48	2.08	1.13	54.38	–	0
HCO_3^-	498.00	125.00	282.85	89.96	31.81	–	0

< indicates that the parameter concentration is below the detected limit

The results revealed 35.21% of the groundwater samples exceeding the permissible limit of TH (450 mg/L).

The results showed 5.63% of the groundwater samples exceeding the permissible limit of NO_2^- (1 mg/L). The NO_2^- concentrations ranged from 0.63 to 1.06 mg/L, with a mean value of 0.86 mg/L. In fact, high groundwater NO_2^- concentrations pose a high health risk to adults and children (Su et al. 2018; Li et al. 2022). Whereas, Al concentrations ranged from 0.002 to 0.802 mg/L, showing 7.04% of the groundwater samples exceeding the permissible limit of Al. High Al concentrations may cause human health diseases, such as Alzheimer's disease and dialysis encephalopathy in patients with chronic kidney disease (Hart et al. 2021). The As and Zn concentrations in groundwater were within the permissible limits, suggesting low impacts of As and Zn on the groundwater quality in the study area (Tiwari et al. 2017).

Correlation Analysis

The Pearson correlation coefficients between the chemical parameters of groundwater are reported in Table 3. According to the obtained results, TDS was significantly correlated with SO_4^{2-}, K^+, Ca^{2+}, Na^+, Mg^{2+}, Cl^- and HCO_3^-, indicating that these ions are the main components of TDS. These ions were mainly originated from the strong weathering of the rocks in the study area (Wei et al. 2022). Na^+ showed highly positive correlations with Cl^- ($r=0.597$), and was moderately positively correlated with SO_4^{2-} ($r=0.468$), which indicates that Na^+ may come from the dissolution of some evaporites (e.g., halite and mirabilite) in the study area (He et al. 2019; Li et al. 2018). The above reactions can be expressed as formulas (3) and (4).

$$NaCl \rightarrow Na^+ + Cl^- \tag{3}$$

$$Na_2SO_4 \rightarrow 2Na^+ + SO_4^{2-} \tag{4}$$

HCO_3^- showed highly positive correlations with Ca^{2+} ($r=0.522$) and Mg^{2+} ($r=0.810$), SO_4^{2-} showed highly positive correlations with Ca^{2+} ($r=0.683$), and Ca^{2+} and Mg^{2+} are highly positively correlated ($r=0.637$), indicating that they may have the same source, such as weathering and dissolution of gypsum ($CaSO_4 \cdot 2H_2O$), dolomite [$CaMg\ (CO_3)_2$] and calcite ($CaCO_3$) (Li et al. 2016b; Zhang et al. 2018). The above reactions can be expressed in formulas (5)-(7).

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^- \tag{5}$$

$$CaMg(CO_3)_2 + 2H_2O + 2CO_2 \rightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^- \tag{6}$$

$$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \tag{7}$$

F^- is highly correlated with Na^+ ($r=0.598$), because high Na^+ groundwater usually promotes F^- enrichment, and fluorine in groundwater mainly comes from the dissolution of fluoride-bearing minerals (Ali et al. 2016, 2018; Liu et al. 2019; Wu et al. 2020a; Subba Rao et al. 2021). Similarly, F^- and As are positively correlated ($r=0.421$), because in arid and semi-arid regions, alkaline and oxidizing as well as reducing conditions are favorable for the enrichment of As and F^-, and this association is well documented (Guo et al. 2014; He et al. 2020; Kumar et al. 2020; Sathe et al. 2021). Therefore, the weakly alkaline water environment and mineral dissolution in the study area may lead to the coexistence of As and F^- (Li et al. 2021). As and F^- are widely investigated elements in medical geological research (Li and Wu 2022). NO_2^- is an intermediate product of nitrification and will be converted to NO_3^- upon oxidation. NO_2^- and NO_3^- are negatively correlated ($r=-0.145$), and it can be determined that there is a conversion between NO_2^- and NO_3^- (Wu et al. 2020b). As shown in Fig. 5, similar spatial distributions of NO_3^- and TH were observed, indicating that they are homologous, which is consistent with the results of the correlation analysis ($r=0.593$), and this phenomenon can be related to nitrification. The nitrification process favors the dissolution of carbonates in loess sediments, increasing in TH (Hussain et al. 2019).

Improvement in Water Quality Classification Criteria of EWQI

To determine the optimal water quality classification criteria, the allowable water quality limits prescribed in the national groundwater quality standards (Table 1) were composited as virtual water samples to calculate the virtual EWQI. The calculation showed that the highest weight values were for F^- and Cl^-, while the lowest weight values were for Zn and As. The EWQI values obtained in this study showed that the classification limits for grades I, II, III, and IV of the alkaline groundwater ranged approximately within 0–26, 26–50, 50–100, and 100–243, respectively, while those of the acidic groundwater were approximately 0–26, 26–50, 50–100, and 100–258, respectively (Fig. 6). These obtained results also indicate that two factors influenced significatively the EWQI values, namely the weights of the hydrochemical parameters and the threshold limit of each hydrochemical parameter. In fact, compared to other parameters, NO_2^- and heavy metals had relatively higher threshold limits for the IV and V levels than for the first three levels (Fig. 7).

The classification criteria calculated for the alkaline groundwater and acidic groundwater were slightly different from the traditional classification criteria (classification criteria 1 to 3 in Table 4), because the EWQI values are

Table 3 Pearson correlations of major parameters

	F^-	Cl^-	NO_2^-	NO_3^-	K^+	Ca^{2+}	Na^+	Mg^{2+}	HCO_3^-	SO_4^{2-}	TH	TDS	Al	Zn	As	pH
F^-	1															
Cl^-	0.064	1														
NO_2^-	0.443**	0.011	1													
NO_3^-	− 0.318**	0.307**	− 0.145	1												
K^+	− 0.314**	0.295*	− 0.267*	0.529**	1											
Ca^{2+}	− 0.247*	0.691**	0.104	0.629**	0.437**	1										
Na^+	0.598**	0.597**	0.398**	− 0.045	0.054	0.132	1									
Mg^{2+}	0.244*	0.764**	0.341**	0.365**	0.342**	0.637**	0.682**	1								
HCO_3^-	0.400**	0.658**	0.716**	0.062	0.022	0.522**	0.722**	0.810**	1							
SO_4^{2-}	0.044	0.663**	0.024	0.185	0.403**	0.683**	0.468**	0.693**	0.500**	1						
TH	− 0.081	0.787**	0.231	0.593**	0.411**	0.941**	0.372**	0.838**	0.699**	0.745**	1					
TDS	− 0.072	0.744**	0.134	0.741**	0.479**	0.875**	0.400**	0.783**	0.585**	0.680**	0.932**	1				
Al	0.097	0.019	0.163	− 0.138	− 0.021	0.121	− 0.003	0.141	0.138	0.204	0.108	0.046	1			
Zn	0.012	0.130	0.123	0.029	0.085	0.229	0.072	0.170	0.172	0.222	0.221	0.199	0.640**	1		
As	0.421**	0.185	0.208	− 0.287*	− 0.066	0.062	0.402**	0.286*	0.316**	0.436**	0.118	0.087	0.355**	0.219	1	
pH	0.468**	− 0.191	0.195	− 0.423**	− 0.197	− 0.342**	0.238*	− 0.061	0.033	− 0.031	− 0.288*	− 0.310**	− 0.106	− 0.128	0.416**	1

*Indicates correlation is significant at the 0.05 level (2-tailed)

**Indicates correlation is significant at the 0.01 level (2-tailed)

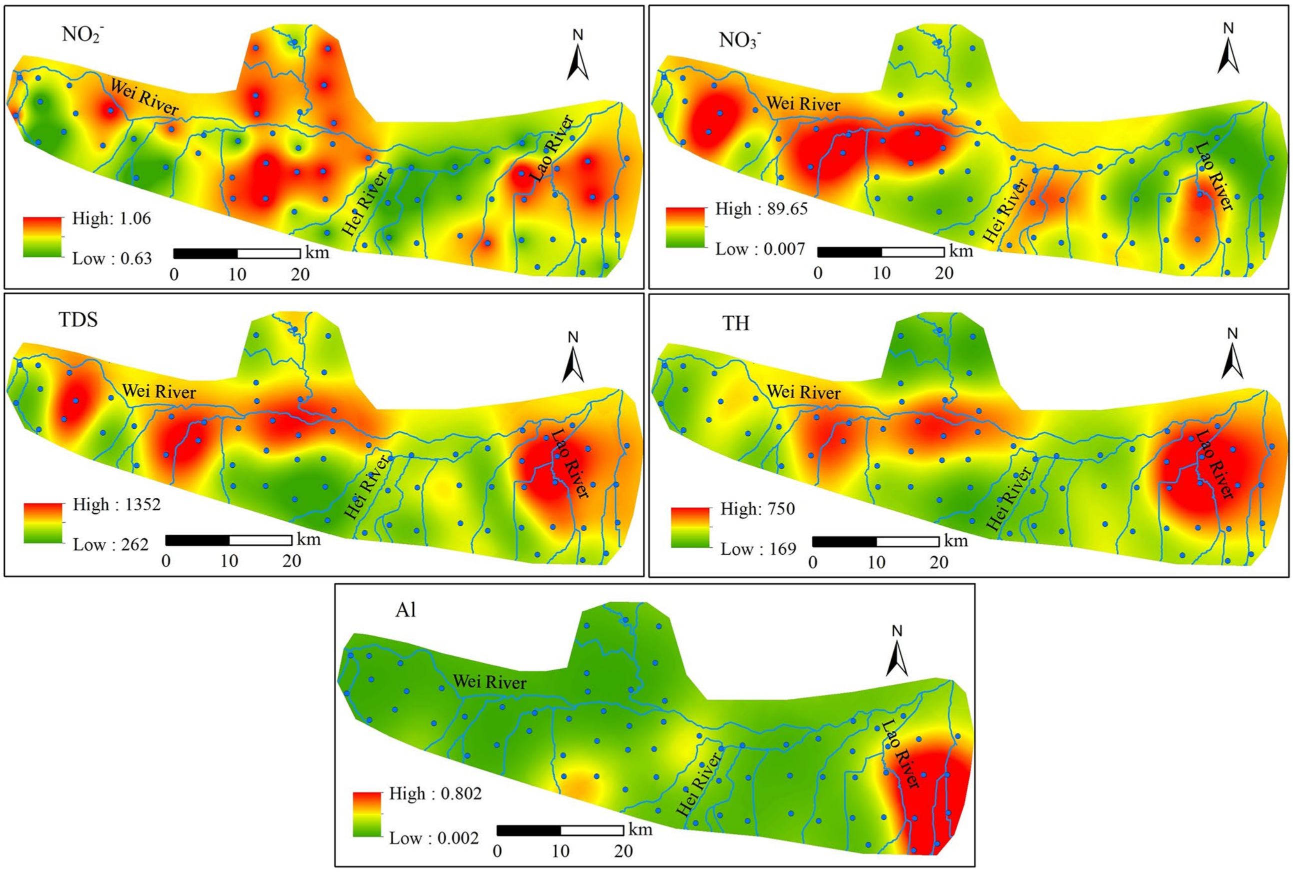
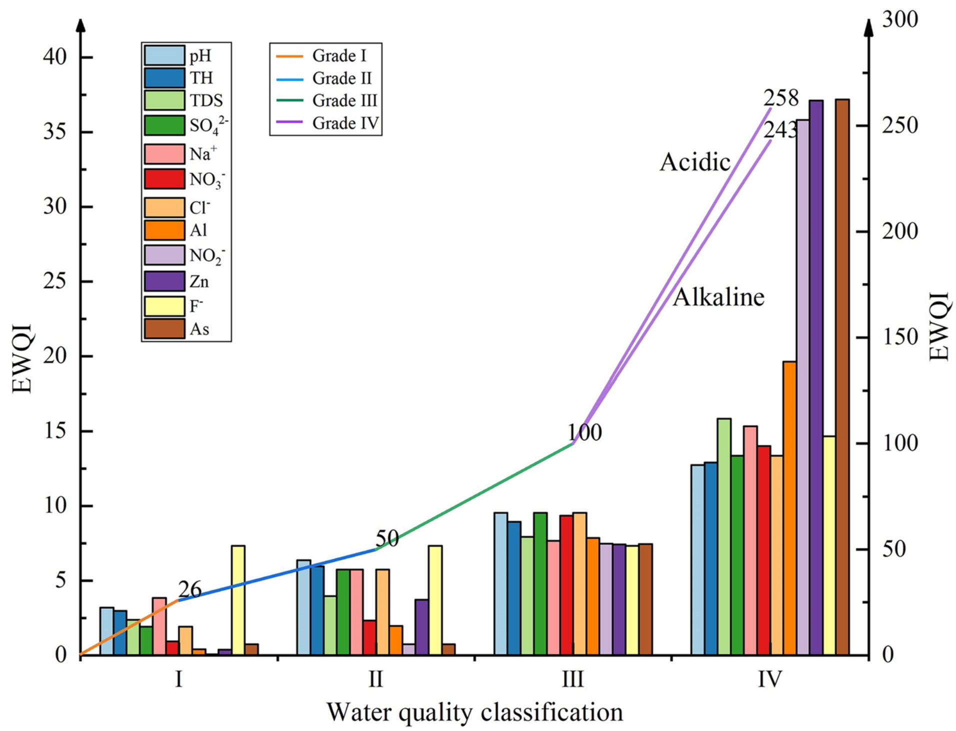


Fig. 5 Spatial distributions of physicochemical parameters

Fig. 6 Proportion of each parameter in the EWQI classification



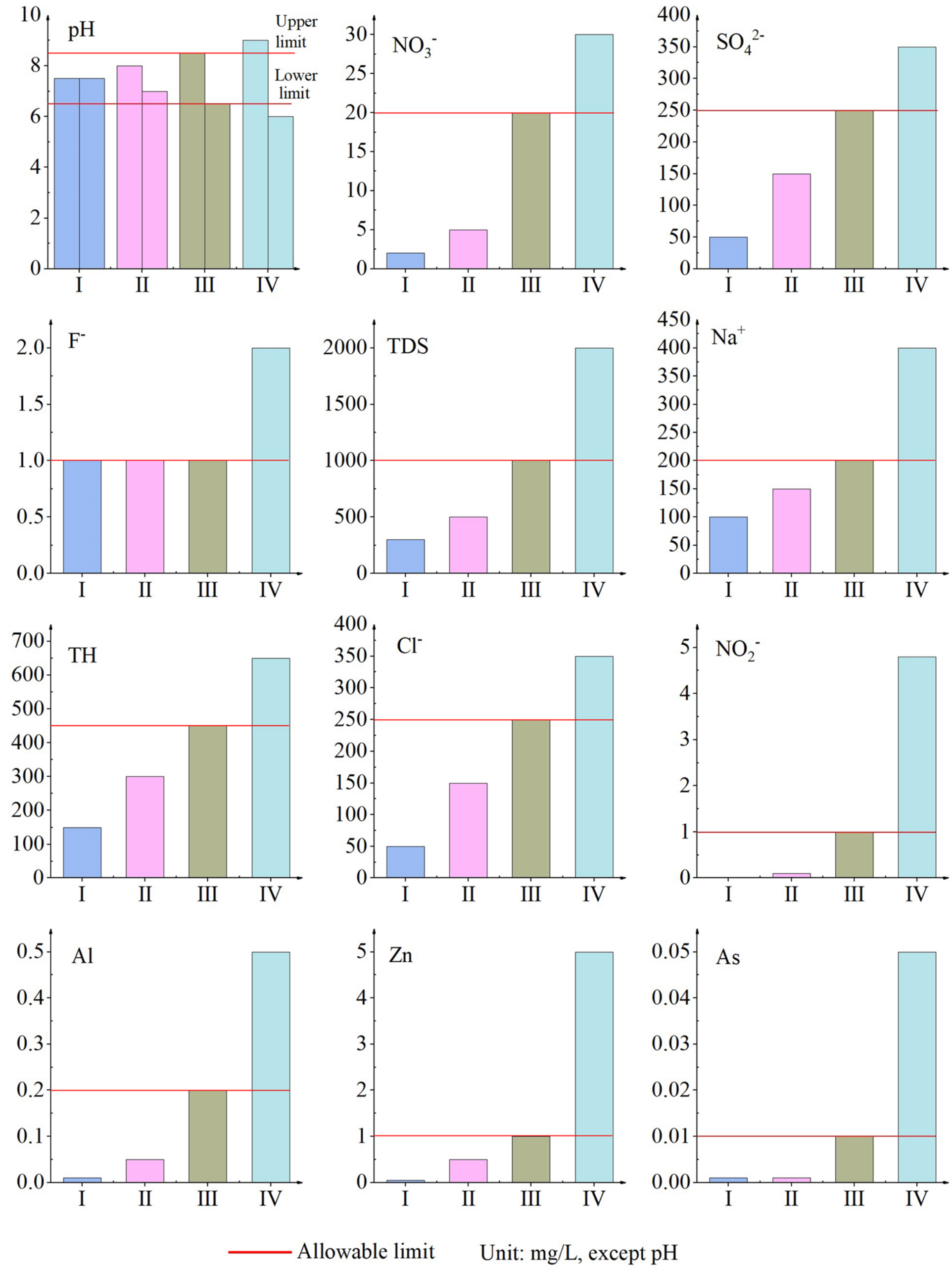


Fig. 7 Limits of each parameter in the groundwater quality standards

Table 4 Overall water quality classification criteria based on EWQI

Rank	I	II	III	IV	V
Water quality	Excellent quality	Good quality	Moderate quality	Poor quality	Very poor quality
Classification criteria 1	< 25	25–50	50–100	100–150	> 150
Classification criteria 2	< 50	50–100	100–150	150–200	> 200
Classification criteria 3	< 50	50–100	100–200	200–300	> 300
New classification criteria	< 25	25–50	50–100	100–200	> 200

typically higher when considering heavy metals in the calculation process. Compared with the traditional classification criteria, the classification values for each water quality level in the obtained criteria in this study are lower, which may be due to the consideration of more hydrochemical parameters and the addition of heavy metals. Based on the calculated EWQI values, the ranges of the grades I, II, and III groundwater quality indices were set as 0–25, 25–50 and 50–100, respectively (Table 4). In addition, since the standard limits of grades IV and V for heavy metals are many times higher than those of the first three grades, the EWQI values showed higher values for grades IV and V. In order to have more strict requirements for water quality, benefiting water quality protection, the EWQI of grade IV Values are set to 100–200 for both alkaline groundwater and acidic groundwater (Table 4). Therefore, the new classification criteria are more suitable for assessing the groundwater quality, combining several hydrochemical parameters and heavy metal elements. In the study, the groundwater quality in Zhouzhi County was assessed using a total of 12 parameters to ensure a comprehensive assessment.

Groundwater Quality Assessment Using Improved EWQI

The entropy weights of hydrochemical parameters were calculated in this study to determine EWQI classes (Table 5). The higher the entropy value, the greater the influence of water chemistry parameters on groundwater quality. According to the obtained results, NO_2^- and pH showed the highest weights of 0.15 and 0.14, respectively, while Al and Zn revealed the lowest weight of 0.02. The EWQI results showed that 1.41, 63.38, and 35.21% were of excellent, good, and medium groundwater quality, respectively, suggesting that groundwater in the study area is suitable for drinking (Sivasankar et al. 2013).

Kriging interpolation of EWQI values were applied to reveal the spatial distribution of groundwater quality in the study area (Fig. 8). The results showed deteriorated groundwater quality in the Wei River Plain area compared to that in the Qinling Mountain Front. Areas closer to the Qinling Mountain Front showed relatively better groundwater quality. In addition, excellent to good groundwater quality (grades I and II) were observed near the Hei River, which may be due to significant recharge from the infiltration of water from the Hei River. Whereas medium groundwater quality (grade III) was particularly observed near the urban area (Wugong, Yangling, Mei County, and Hu County), suggesting that human activities are the main factors affecting the groundwater quality in the study area.

The improved EWQI classification results of this study were compared with those of the three water quality classification criteria mentioned in the introduction (Table 6). According to the comparison results, classification criteria 1 and the improved classification criteria indicated similar groundwater quality results, showing similar numbers of groundwater samples in all groundwater classes. Whereas classification criteria 2 and 3 showed similar groundwater quality, the reason is that the first two levels of water quality EWQI value is the same. Overall, classification criteria 1 and the improved classification criteria are slightly stricter than classification criteria 2 and 3. In addition, the improved

Table 5 Entropy weight of each parameter

Parameters	pH	F^-	Cl^-	NO_2^-	SO_4^{2-}	NO_3^-	Na^+	TDS	TH	Al	Zn	As
Weight	0.14	0.06	0.08	0.15	0.10	0.06	0.11	0.10	0.11	0.02	0.02	0.04

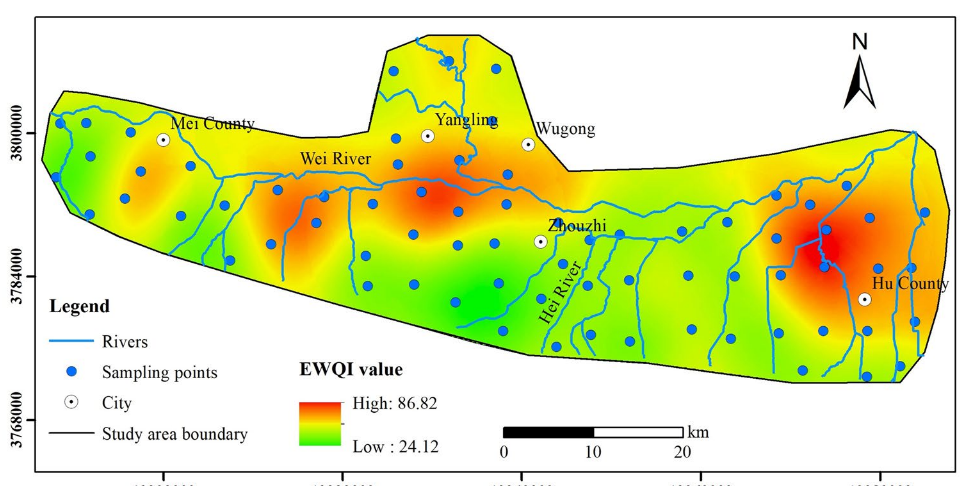


Fig. 8 Groundwater quality distribution map based on EWQI. Higher value indicates worse water quality

Table 6 Number of samples falling into different grades in different classification criteria

Rank	I	II	III	IV	V
Water quality	Excellent quality	Good quality	Moderate quality	Poor quality	Very poor quality
Classification criteria 1	1	45	25	0	0
Classification criteria 2	46	25	0	0	0
Classification criteria 3	46	25	0	0	0
New classification criteria	1	45	25	0	0

EWQI takes heavy metal elements in the evaluation of groundwater quality, making it the most suitable method for comprehensively and accurately assessing groundwater quality.

Recommendations for Groundwater Quality Management

Although there were high groundwater NO_3^- concentrations in some areas of Zhouzhi County, the EWQI results suggested that groundwater in the study area was suitable for human drinking. Nevertheless, some necessary measures must be taken to improve the quality of groundwater and prevent further potential groundwater contamination in the study area.

First, since the study area is covered by a large amount of farmland, the government should support and encourage farmers to substitute industrial fertilizer with organic fertilizers and/or rationalize industrial fertilizer uses to prevent groundwater pollution. In addition, there are piles of livestock manure in the study area, which may lead to groundwater pollution through pollutant leaching. Effective management of manure piles is, therefore, required in the study area.

Second, the presence of intense industrial activities imposes a potential threat to the groundwater resource. Therefore, the government needs to strictly monitor the industrial wastewater effluents and ensure that industrial wastewater meets effluent discharge standards. Moreover, land development activities and drilling production around the water source area need to be reduced to prevent groundwater pollution.

Third, the high numbers of private wells in the study area, the poor awareness of farmers about water quality safety, and the lack of unified government management and water quality monitoring have led to a lack of groundwater protection against pollution. Therefore, it is of great importance to ensure that private well owners and local groundwater management authorities are aware of water quality and potential contamination risks in the study area and ensure that regular maintenance of wells, regular water quality monitoring, and water treatment are carried out (Hynds et al. 2014).

Conclusions

In this study, the overall groundwater quality in Zhouzhi County was assessed using an improved EWQI. In addition, the EWQI classification criteria results were compared with those obtained using other classification criteria. The main conclusions are as follows:

(1) According to the obtained EWQI results, the standard limits of heavy metals for grade IV were higher than those for the first three grades, resulting in higher IV and V EWQI values. The updated groundwater quality classification criteria are excellent quality water (EWQI < 25), good quality water (EWQI within 25–50), moderate quality water (EWQI within 50–100), poor quality water (EWQI within 100–200), and very poor quality water (EWQI > 200).

(2) NO_3^- and TH were the dominant pollution parameters in the groundwater of the study area, followed by TDS, Al, and NO_2^-. In addition, pH, F^-, Cl^-, Na^+, SO_4^{2-}, Zn, and As revealed mean and maximum concentration values within the permissible limit standards.

(3) According to the Kriging interpolation of EWQI, excellent groundwater quality is identified in areas near the Hei River where river water recharge takes place; however, in other areas, human activities are affecting the quality of groundwater.

(4) The improved EWQI results showed that 1.41, 63.38, and 35.21% of the groundwater samples were of excellent, good, and medium groundwater, respectively. Moreover, no groundwater sample showed poor and very poor groundwater quality, suggesting that groundwater is suitable for drinking. Compared with other classification criteria, the improved EWQI is more suitable and comprehensive for assessing the groundwater quality.

Acknowledgements We are grateful for the support and comments from the editors and reviewers.

Author Contributions Y Yang: data collection, data analysis, and original draft preparation. P Li: data review, supervision, data analysis, and revisions. V Elumalai, J Ning, F Xu, and D Mu: reviewing, and editing.

Funding This work was supported by the National Natural Science Foundation of China (42072286 and 41761144059), the Qinchuangyuan "Scientist + Engineer" Team Development Program of the Shaanxi

Provincial Department of Science and Technology (2022KXJ-005), the Fok Ying Tong Education Foundation (161098), and the National Ten Thousand Talent Program (W03070125).

Data Availability The raw data may be provided upon reasonable requests.

Declarations

Conflict of interest All authors of this article declare that they have no conflict of interest.

References

Adimalla N (2021) Application of the entropy weighted water quality index (EWQI) and the pollution index of groundwater (PIG) to assess groundwater quality for drinking purposes: a case study in a rural area of Telangana state, India. Arch Environ Contam Toxicol 80:31–40. https://doi.org/10.1007/s00244-020-00800-4

Adimalla N, Li P (2018) Occurrence, health risks, and geochemical mechanisms of fluoride and nitrate in groundwater of the rock-dominant semi-arid region, Telangana state, India. Hum Ecol Risk Assess 25:81–103. https://doi.org/10.1080/10807039.2018.1480353

Ali S, Thakur SK, Sarkar A, Shekhar S (2016) Worldwide contamination of water by fluoride. Environ Chem Lett 14:291–315. https://doi.org/10.1007/s10311-016-0563-5

Ali A, Strezov V, Davies P, Wright I (2017) Environmental impact of coal mining and coal seam gas production on surface water quality in the Sydney basin, Australia. Environ Monit Assess 189:408. https://doi.org/10.1007/s10661-017-6110-4

Ali S, Shekhar S, Bhattacharya P, Verma G, Chandrasekhar T, Chandrashekhar A (2018) Elevated fluoride in groundwater of Siwani block, western Haryana, India: a potential concern for sustainable water supplies for drinking and irrigation. Groundw Sustain Dev 7:410–420. https://doi.org/10.1016/j.gsd.2018.05.008

Ali S, Shekhar S, Chandrasekhar T, Yadav AK, Arora NK, Kashyap CA, Bhattacharya P, Rai S, Pande P, Chandrasekharam D (2021) Influence of the water–sediment interaction on the major ions chemistry and fluoride pollution in groundwater of the older alluvial plains of Delhi, India. J Earth Syst Sci 130:98. https://doi.org/10.1007/s12040-021-01585-3

Amiri V, Rezaei M, Sohrabi N (2014) Groundwater quality assessment using entropy weighted water quality index (EWQI) in Lenjanat, Iran. Environ Earth Sci 72:3479–3490. https://doi.org/10.1007/s12665-014-3255-0

An Z, Zhang P, Vogel H, Song Y, Dodson J, Wiersberg T, Feng X, Lu H, Ai L, Sun Y (2020) Scientific drilling workshop on the Weihe basin drilling project (WBDP): cenozoic tectonic–monsoon interactions. Scientific Drilling 28:63–73. https://doi.org/10.5194/sd-28-63-2020

Edokpayi JN, Enitan AM, Mutileni N, Odiyo JO (2018) Evaluation of water quality and human risk assessment due to heavy metals in groundwater around Muledane area of Vhembe district, Limpopo province, South Africa. Chem Cent J 12:2. https://doi.org/10.1186/s13065-017-0369-y

Egbueri JC, Ameh PD, Unigwe CO (2020a) Integrating entropy-weighted water quality index and multiple pollution indices towards a better understanding of drinking water quality in Ojoto area. SE Nigeria Scientific African 10:e00644. https://doi.org/10.1016/j.sciaf.2020.e00644

Egbueri JC, Ezugwu CK, Ameh PD, Unigwe CO, Ayejoto DA (2020b) Appraising drinking water quality in Ikem rural area (Nigeria) based on chemometrics and multiple indexical methods. Environ Monit Assess 192:308. https://doi.org/10.1007/s10661-020-08277-3

Fadel A, Kanj M, Slim K (2021) Water quality index variations in a Mediterranean reservoir: a multivariate statistical analysis relating it to different variables over 8 years. Environ Earth Sci 80:65. https://doi.org/10.1007/s12665-020-09364-x

Fida M, Li P, Wang Y, Alam SMK, Nsabimana A (2022) Water contamination and human health risks in Pakistan: a review. Expo Health. https://doi.org/10.1007/s12403-022-00512-1

General Administration of Quality Supervision, Inspection & Quarantine of China, Standardization Administration of China (2017) Standard for groundwater quality (GB/T 14848–2017). China Standards Press, Beijing. (**in Chinese**)

Gibbs RJ (1970) Mechanisms controlling world water chemistry. Science 170(3962):1088–1090. https://doi.org/10.1126/science.170.3962.1088

Guo H, Wen D, Liu Z, Jia Y, Guo Q (2014) A review of high arsenic groundwater in mainland and Taiwan, China: distribution, characteristics and geochemical processes. Appl Geochem 41:196–217. https://doi.org/10.1016/j.apgeochem.2013.12.016

Hart KA, Kennedy GW, Sterling SM (2021) Distribution, drivers, and threats of aluminum in groundwater in Nova Scotia, Canada. Water 13:1578. https://doi.org/10.3390/w13111578

He S, Li P (2020) A MATLAB based graphical user interface (GUI) for quickly producing widely used hydrogeochemical diagrams. Geochemistry 80(4):125550. https://doi.org/10.1016/j.chemer.2019.125550

He B, He J, Sun J, Wang J, Wen D, Jing J, Peng C, Zhang C (2022) Research status and suggestions on the comprehensive evaluation of regional groundwater pollution. Earth Sci Front. https://doi.org/10.13745/j.esf.sf.2022.1.29(inChinese)

He X, Li P, Ji Y, Wang Y, Su Z, Elumalai V (2020) Groundwater arsenic and fluoride and associated arsenicosis and fluorosis in China: occurrence, distribution and management. Expo Health 12(3):355–368. https://doi.org/10.1007/s12403-020-00347-8

He X, Li P, Wu J, Wei M, Ren X, Wang D (2021) Poor groundwater quality and high potential health risks in the Datong basin, northern China: research from published data. Environ Geochem Health 43:791–812. https://doi.org/10.1007/s10653-020-00520-7

He XD, Wu JH, He S (2019) Hydrochemical characteristics and quality evaluation of groundwater in terms of health risks in Luohe aquifer in Wuqi county of the Chinese Loess Plateau, northwest China. Hum Ecol Risk Assess 25:32–51. https://doi.org/10.1080/10807039.2018.1531693

Hu G, Mian HR, Dyck R, Mohseni M, Jasim S, Hewage K, Sadiq R (2020) Drinking water treatments for arsenic and manganese removal and health risk assessment in white rock, Canada. Expo Health 12:793–807. https://doi.org/10.1007/s12403-019-00338-4

Hussain R, Wei C, Luo K (2019) Hydrogeochemical characteristics, source identification and health risks of surface water and groundwater in mining and non-mining areas of Handan, China. Environ Earth Sci 78:402. https://doi.org/10.1007/s12665-019-8350-9

Hynds PD, Murphy HM, Kelly I, Fallon U (2014) Groundwater protection, risk awareness, knowledge transfer and public health: the role of "future custodians." Water Resour Manag 28:5199–5215. https://doi.org/10.1007/s11269-014-0811-z

Islam AMT, Islam HMT, Mia MU, Khan R, Habib MA, Bodrud-Doza M, Siddique MA, Chu RH (2020) Co-distribution, possible origins, status and potential health risk of trace elements in surface water sources from six major river basins, Bangladesh. Chemosphere 249:126180. https://doi.org/10.1016/j.chemosphere.2020.126180

Ismail S, Ahmed MF (2021) GIS-based spatio-temporal and geostatistical analysis of groundwater parameters of Lahore region Pakistan and their source characterization. Environ Earth Sci 80:719. https://doi.org/10.1007/s12665-021-10034-9

Ji Y, Wu J, Wang Y, Elumalai V, Subramani T (2020) seasonal variation of drinking water quality and human health risk assessment in Hancheng city of Guanzhong plain, China. Expo Health 12:469–485. https://doi.org/10.1007/s12403-020-00357-6

Kong FH, Song JX, Zhang Y, Fu GB, Cheng DD, Zhang GT, Xue Y (2019) Surface water-groundwater interaction in the Guanzhong section of the Weihe river basin, China. Groundwater 57:647–660. https://doi.org/10.1111/gwat.12854

Kumar PJS, Augustine CM (2022) Entropy-weighted water quality index (EWQI) modeling of groundwater quality and spatial mapping in Uppar Odai sub-Basin, south India. Modeling Earth Syst Environ 8:911–924. https://doi.org/10.1007/s40808-021-01132-5

Kumar M, Goswami R, Patel AK, Srivastava M, Das N (2020) Scenario, perspectives and mechanism of arsenic and fluoride co-occurrence in the groundwater: a review. Chemosphere 249:126126. https://doi.org/10.1016/j.chemosphere.2020.126126

Li P, Wu J (2019) Drinking water quality and public health. Expo Health 11:73–79. https://doi.org/10.1007/s12403-019-00299-8

Li P, Wu J (2022) Medical geology and medical geochemistry: an editorial introduction. Expo Health 14(2):217–218. https://doi.org/10.1007/s12403-022-00479-z

Li PY, Qian H, Wu JH (2010) Groundwater quality assessment based on improved water quality index in Pengyang county, Ningxia, Northwest China. E-J Chem 7(S1):S209–S216. https://doi.org/10.1155/2010/451304

Li P, Wu J, Qian H, Lyu X, Liu H (2014) Origin and assessment of groundwater pollution and associated health risk: a case study in an industrial park, northwest China. Environ Geochem Health 36:693–712. https://doi.org/10.1007/s10653-013-9590-3

Li P, Wu J, Qian H (2016a) Hydrochemical appraisal of groundwater quality for drinking and irrigation purposes and the major influencing factors: a case study in and around Hua County, China. Arab J Geosci 9:15. https://doi.org/10.1007/s12517-015-2059-1

Li PY, Zhang YT, Yang NA, Jing LJ, Yu PY (2016b) Major ion chemistry and quality assessment of groundwater in and around a mountainous tourist town of China. Expo Health 8:239–252. https://doi.org/10.1007/s12403-016-0198-6

Li PY, Wu JH, Tian R, He S, He XD, Xue CY, Zhang K (2018) Geochemistry, hydraulic connectivity and quality appraisal of multilayered groundwater in the Hongdunzi coal mine, northwest China. Mine Water Environ 37:222–237. https://doi.org/10.1007/s10230-017-0507-8

Li P, He X, Guo W (2019) Spatial groundwater quality and potential health risks due to nitrate ingestion through drinking water: a case study in Yan'an city on the Loess Plateau of northwest China. Hum Ecol Risk Assess 25:11–31. https://doi.org/10.1080/10807039.2018.1553612

Li Y, Li P, Cui X, He S (2021) Groundwater quality, health risk, and major influencing factors in the lower Beiluo river watershed of northwest China. Hum Ecol Risk Assess 27:1987–2013. https://doi.org/10.1080/10807039.2021.1940834

Li P, Wu J, Shukla S (2022) Achieving the one health goal: highlighting groundwater quality and public health. Water 14(21):3540. https://doi.org/10.3390/w14213540

Liu F, Qian H, Shi Z, Wang H (2019) Long-term monitoring of hydrochemical characteristics and nitrogen pollution in the groundwater of Yinchuan area, Yinchuan Basin of northwest China. Environ Earth Sci 78:700. https://doi.org/10.1007/s12665-019-8695-0

Liu J, Gao M, Jin D, Wang T, Yang J (2020) Assessment of groundwater quality and human health risk in the Aeolian-sand area of Yulin City, northwest China. Expo Health 12:671–680. https://doi.org/10.1007/s12403-019-00326-8

Liu L, Wu J, He S, Wang L (2022) Occurrence and distribution of groundwater fluoride and manganese in the Weining plain (China) and their probabilistic health risk quantification. Expo Health 14(2):263–279. https://doi.org/10.1007/s12403-021-00434-4

Luque-Espinar JA, Chica-Olmo M (2020) Impacts of anthropogenic activities on groundwater quality in a detritic aquifer in SE Spain. Expo Health 12:681–698. https://doi.org/10.1007/s12403-019-00327-7

Marghade D, Malpe DB, Duraisamy K, Patil PD, Li P (2021) Hydrogeochemical evaluation, suitability, and health risk assessment of groundwater in the watershed of Godavari basin, Maharashtra, central India. Environ Sci Pollut Res 28:18471–18494. https://doi.org/10.1007/s11356-020-10032-7

Masood A, Aslam M, Pham QB, Khan W, Masood S (2022) Integrating water quality index, GIS and multivariate statistical techniques towards a better understanding of drinking water quality. Environ Sci Pollut Res 29:26860–26876. https://doi.org/10.1007/s11356-021-17594-0

Maurya J, Pradhan SN, Seema GAK (2021) Evaluation of ground water quality and health risk assessment due to nitrate and fluoride in the middle Indo-Gangetic plains of India. Hum Ecol Risk Assess 27(5):1349–1365. https://doi.org/10.1080/10807039.2020.1844559

Ministry of Health of the People's Republic of China, Standardization Administration of the People's Republic of China (2006) Standard Examination Methods for Drinking Water (GB/T 5750-2006). China Standards Press, Beijing (**in Chinese**)

Mthembu PP, Elumalai V, Li P, Sivakumar U, Rajmohan N, Chidambaram S (2022) Integration of heavy metal pollution indices and health risk assessment of groundwater in semi-arid coastal aquifers, South Africa. Expo Health 14(2):487–502. https://doi.org/10.1007/s12403-022-00478-0

Nguyen AH, Pham NTT, Tat VMH, Truong HT, Vo PL (2021) Application of entropy weight in groundwater quality index (EWQI) and GIS for groundwater quality zoning in the southeastern coastal region, Vietnam. IOP Conf Ser: Earth Environ Sci 652:012005. https://doi.org/10.1088/1755-1315/652/1/012005

Panneerselvam B, Muniraj K, Pande C, Ravichandran N, Thomas M, Karuppannan S (2021) Geochemical evaluation and human health risk assessment of nitrate-contaminated groundwater in an industrial area of south India. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-17281-0

Piper AM (1944) A graphic procedure in the geochemical interpretation of water-analyses. Trans Am Geophys Union 25:914. https://doi.org/10.1029/tr025i006p00914

Qiao Y, Liang X-J, Wang Y-B, Yan B-Z, Liu H-Z, Liu J (2015) Evaluation of groundwater quality using improved fuzzy mathematical model. China Water Resour Power 33:27–30 (**in Chinese**)

Qiao J, Zhu Y, Jia X, Shao M, Niu X, Liu J (2020) Distributions of arsenic and other heavy metals, and health risk assessments for groundwater in the Guanzhong plain region of China. Environ Res 181:108957. https://doi.org/10.1016/j.envres.2019.108957

Raheja H, Goel A, Pal M (2022) Prediction of groundwater quality indices using machine learning algorithms. Water Pract Technol 17(1):336–351. https://doi.org/10.2166/wpt.2021.120

Ravindra K, Thind PS, Mor S, Singh T, Mor S (2019) Evaluation of groundwater contamination in Chandigarh: source identification and health risk assessment. Environ Pollut 255:113062. https://doi.org/10.1016/j.envpol.2019.113062

Sathe SS, Mahanta C, Subbiah S (2021) Hydrogeochemical evaluation of intermittent alluvial aquifers controlling arsenic and fluoride contamination and corresponding health risk assessment. Expo Health 13:661–680. https://doi.org/10.1007/s12403-021-00411-x

Shankar BS, Sreevidya R (2020) A novel approach for the formulation of modified water quality index and its application for

groundwater quality appraisal and grading. Hum Ecol Risk Assess 10:2812–2823. https://doi.org/10.1080/10807039.2019.1688638
Singh KR, Dutta R, Kalamdhad AS, Kumar B (2019) Information entropy as a tool in surface water quality assessment. Environ Earth Sci 78:15. https://doi.org/10.1007/s12665-018-7998-x
Sivasankar V, Omine K, Msagati TAM, KumarChandramohan MSA (2013) Evaluation of groundwater quality in Madurai city, south India for drinking, irrigation and construction purposes. Arab J Geosci 7:3093–3107. https://doi.org/10.1007/s12517-013-0994-2
Su H, Kang WD, Xu YJ, Wang JD (2018) Assessing groundwater quality and health risks of nitrogen pollution in the Shenfu mining area of Shaanxi province, northwest China. Expo Health 10:77–97. https://doi.org/10.1007/s12403-017-0247-9
Su F, Wu J, He S (2019) Set pair analysis-Markov chain model for groundwater quality assessment and prediction: a case study of Xi'an City, China. Hum Ecol Risk Assess 25(1–2):158–175. https://doi.org/10.1080/10807039.2019.1568860
Su Z, Wu J, He X, Elumalai V (2020) Temporal changes of groundwater quality within the groundwater depression cone and prediction of confined groundwater salinity using Grey Markov model in Yinchuan area of northwest China. Expo Health 12:447–468. https://doi.org/10.1007/s12403-020-00355-8
Subba Rao N, Dinakar A, Kumari BK (2021) Appraisal of vulnerable zones of non-cancer-causing health risks associated with exposure of nitrate and fluoride in groundwater from a rural part of India. Environl Res 202:111674. https://doi.org/10.1016/j.envres.2021.111674
Subba Rao N, Sunitha B, Das R, Anil Kumar B (2022a) Monitoring the causes of pollution using groundwater quality and chemistry before and after the monsoon. Phys Chem Earth, Parts a/b/c 128:103228. https://doi.org/10.1016/j.pce.2022.103228
Subba Rao N, Dinakar A, Sun L (2022b) Estimation of groundwater pollution levels and specific ionic sources in the groundwater, using a comprehensive approach of geochemical ratios, pollution index of groundwater, unmix model and land use/land cover - a case study. J Contam Hydrol 248:103990. https://doi.org/10.1016/j.jconhyd.2022.103990
Tian R, Wu J (2019) Groundwater quality appraisal by improved set pair analysis with game theory weightage and health risk estimation of contaminants for Xuecha drinking water source in a loess area in northwest China. Hum Ecol Risk Assess 25(1–2):132–157. https://doi.org/10.1080/10807039.2019.1573035
Tian H, Du J, Ma S, Kang Z, Gong Y (2021) Application of water quality index and multivariate statistical analysis in the hydrogeochemical assessment of shallow groundwater in Hailun, northeast China. Hum Ecol Risk Assess 3:651–667. https://doi.org/10.1080/10807039.2020.1749827
Tiwari AK, De Maio M, Singh PK, Singh AK (2016) Hydrogeochemical characterization and groundwater quality assessment in a coal mining area, India. Arab J Geosci 9:177. https://doi.org/10.1007/s12517-015-2209-5
Tiwari AK, Singh PK, Mahato MK (2017) Assessment of metal contamination in the mine water of the west Bokaro coalfield, India. Mine Water Environ 36:532–541. https://doi.org/10.1007/s10230-017-0440-x
Wang Y, Li P (2022) Appraisal of shallow groundwater quality with human health risk assessment in different seasons in rural areas of the Guanzhong Plain (China). Environ Res 207:112210. https://doi.org/10.1016/j.envres.2021.112210
Wang Y, Zhang Y, Wang H, Gong Y, Ran L (2014) Comparative analysis and application of groundwater quality comprehensive evaluation methods. Hebei J Ind Sci Technol 31:3–8. https://doi.org/10.7535/hbgykj.2014yx06001
Wang D, Wu J, Wang Y, Ji Y (2020) Finding high-quality groundwater resources to reduce the hydatidosis incidence in the Shiqu county of Sichuan Province, China: analysis, assessment, and management. Expo Health 12:307–322. https://doi.org/10.1007/s12403-019-00314-y
Wei M, Wu J, Li W, Zhang Q, Su F, Wang Y (2022) Groundwater geochemistry and its impacts on groundwater arsenic enrichment, variation, and health risks in Yongning County, Yinchuan Plain of northwest China. Expo Health 14(2):219–238. https://doi.org/10.1007/s12403-021-00391-y
Wu J, Li P, Qian H, Chen J (2015) On the sensitivity of entropy weight to sample statistics in assessing water quality: statistical analysis based on large stochastic samples. Environ Earth Sci 74:2185–2195. https://doi.org/10.1007/s12665-015-4208-y
Wu J, Li P, Wang D, Ren X, Wei M (2020a) Statistical and multivariate statistical techniques to trace the sources and affecting factors of groundwater pollution in a rapidly growing city on the Chinese Loess Plateau. Hum Ecol Risk Assess 26:1603–1621. https://doi.org/10.1080/10807039.2019.1594156
Wu YT, Bu LJ, Duan XD, Zhu SM, Kong MH, Zhu NY, Zhou SQ (2020b) Mini review on the roles of nitrate/nitrite in advanced oxidation processes: radicals transformation and products formation. J Clean Prod 273:123065. https://doi.org/10.1016/j.jclepro.2020.123065
Xu P, Zhang Q, Qian H, Li M, Hou K (2019) Characterization of geothermal water in the piedmont region of qinling mountains and lantianbahe group in Guanzhong Basin, China. Environ Earth Sci 78:442. https://doi.org/10.1007/s12665-019-8418-6
Zhang YH, Xu M, Li X, Qi JH, Zhang Q, Guo J, Yu LL, Zhao R (2018) Hydrochemical characteristics and multivariate statistical analysis of natural water system: a case study in Kangding county. Southwestern China Water 10:80. https://doi.org/10.3390/w10010080
Zhang Q, Xu P, Qian H (2019) Assessment of groundwater quality and human health risk (HHR) evaluation of nitrate in the central-western Guanzhong basin, China. Int J Environ Res Public Health 16:4246. https://doi.org/10.3390/ijerph16214246
Zhang Y, Hou K, Qian H (2020) Water quality assessment using comprehensive water quality index and modified nemerow index method: a case study of Jinghui canal, north China. IOP Conf Ser: Earth Environ Sci 467:012125. https://doi.org/10.1088/1755-1315/467/1/012125
Zhang W, Li B, Liu Z, Zhang B (2021a) Application of improved fuzzy comprehensive evaluation method in karst groundwater quality evaluation: a case study of Cengong county. Earth Sci Inf 14:1101–1109. https://doi.org/10.1007/s12145-021-00611-8
Zhang Y, Li X, Luo M, Wei C, Huang X, Xiao Y, Qin L, Pei Q, Gao X (2021b) Hydrochemistry and entropy-based groundwater quality assessment in the suining area, Southwestern China. J Chem 2021:5591892. https://doi.org/10.1155/2021/5591892
Zhang Q, Li P, Lyu Q, Ren X, He S (2022a) Groundwater contamination risk assessment using a modified DRATICL model and pollution loading: a case study in the Guanzhong Basin of China. Chemosphere 291:132695. https://doi.org/10.1016/j.chemosphere.2021.132695
Zhang Z, Guo Y, Wu J, Su F (2022b) Surface water quality and health risk assessment in Taizhou city, Zhejiang Province (China). Expo Health 14:1–16. https://doi.org/10.1007/s12403-021-00408-6
Zhang L, Li P, He X (2022c) Interactions between surface water and groundwater in selected tributaries of the Wei River (China) revealed by hydrochemistry and stable isotopes. Hum Ecol Risk Assess 28(1):79–99. https://doi.org/10.1080/10807039.2021.2016054
Zhou Y, Wu J, Gao X, Guo W, Chen W (2022) Hydrochemical background levels and threshold values of phreatic groundwater in the greater Xian region, China: spatiotemporal distribution, influencing factors and implication to water quality management. Expo Health. https://doi.org/10.1007/s12403-022-00521-0

Zotou I, Tsihrintzis VA, Gikas GD (2019) Performance of seven water quality indices (WQIs) in a mediterranean river. Environ Monit Assess 191:505. https://doi.org/10.1007/s10661-019-7652-4