



Uncertain in WQI-based groundwater quality assessment methods: a case study in east of Beijing, China

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Abstract

Groundwater is a significance source of freshwater in both urban and rural areas of the world. With the increasing groundwater pollution, it is essential to analysis of groundwater chemical characteristics and evaluate groundwater quality for water supply purpose. The study proposes basic water quality index module (BWQIM) and integrated water quality index module (IWQIM) by combining indicators, weights and model on water quality index (WQI)-based, and evaluated the groundwater quality in Chaoyang District, Beijing. The IWQIM and BWQIM were compared. Fe, HCO_3^- , TDS and TH were identified as key parameters of groundwater quality assessment. The water quality assessment results of BWQIM are scattered. However, the evaluation results of IWQIM are basically consistent and not influenced by indicators and weights. This module solves the problem that the weight of over standard indexes is submerged when multiple indexes are used, it is more reasonable and effective for groundwater quality evaluation, and overall situation of groundwater in the study area was concentrated in good level. Groundwater in aquifers in the study area is weakly alkaline. The Ca– HCO_3 type characterized the general hydrogeochemical composition of Chaoyang district groundwater. Most samples fall in the rock dominance zone, suggesting that rock weathering and rock-water interactions are the primary sources controlling groundwater chemistry and hydrochemical evolution. These findings can provide an effective tool for the groundwater management for drinking and the sustainable development of water resources.

Keywords Groundwater quality · Hydrochemistry · WQI · Uncertainty analysis · Beijing

Introduction

High quality groundwater is crucially important for social and human sustainable development. In some cities, especially in intensive human activities areas, are simultaneously facing groundwater depletion and groundwater pollution. How to control groundwater quality degradation have been paid more and more attention to its widespread distribution

and its potential consequences to human health (Zhang et al. 2020a, 2021; Adimalla and Qian 2021a, b) Among various groundwater resource management tools, groundwater quality assessment is the most basic management approach, providing essential information of groundwater status and trend to solve or reduce the severity of groundwater quality degradation. Numerous studies have been performed regarding groundwater quality assessment around the world with different assessment method (Asadi et al. 2019; Patil et al. 2020; Jha et al. 2020; Nong et al. 2020), which have proved its effectivity on groundwater quality management.

Beijing, being the capital city of China, is a modern mega city with a population over twenty million. In 2019, the total amount of water resources of Beijing is 2.456 billion m^3 , and the per capita amount of water resources is 114 m^3 , which can be classified as shortage of water resources. Groundwater, the largest water resource of Beijing (64.94% in 2019) and the primary source of domestic water, is vital important for the social and economic development of Beijing (Huang et al. 2019). To understand characterize the groundwater

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chemistry and suitability for various uses (drinking, irrigation, and industrial activities), many researchers have conducted groundwater quality assessment of Beijing (Zhai et al. 2015; Zhang et al. 2016). However, a few studies been carried out in Chaoyang District of Beijing, or cover a large spatial scale but without enough details and accuracy at the small scale. In addition, few researches on groundwater quality assessment focused particularly on drinking water purpose.

The most widely used water quality assessment method is water quality index (WQI), which was first developed by Horton (1965). The concept of WQI is using a simple mathematical to obtain a numerical value to express its quality based on physical, chemical and biological measurements. The WQI can provide status of overall water quality over an area based on important water quality parameters with an easily expressible and understood format (a single score) (Ahmed et al. 2019; Lumb et al. 2011). In consequence, it can help decision makers to formulate effective management strategies for protecting aquifers from contamination. However, compare with many of the past researches of WQI on surface water, there are very limited number of studies dealing with groundwater, such as subjective weights (Jehan et al. 2020; Karunanidhi et al. 2021; Vaiphei et al. 2020). Furthermore, some researcher highlighted limitations of WQI and provided recommendations to overcome the drawbacks. To improve the usability and accuracy of WQI in groundwater quality assessment, one important attempt is assigning reasonable weight to each parameter. However, weights are traditionally assigned by subjective approach or objective approach (entropy-weights). Both of the two approaches have its disadvantage need to be improved. To overcome these limits and to incorporate environmental uncertainty in the groundwater quality evaluation process, the application of integrated-weight approach is highly recommended by some researches (Xue et al. 2020). For instance, Gao et al. (2020a) developed the integrated-weight water quality index (IWQI) to assess the suitability of groundwater for drinking purpose. In addition, the IWQI method for determining irrigation water quality has been developed and applied by many researchers (Shaefer and Janardan, 1977; House and Ellis 1987; Rajankar et al. 2009; Logeshkumaran et al. 2015; Adimalla 2020a, b). Moreover, selecting reasonable water quality indicators is important for WQI calculation, the parameters are often weighted according to their importance to water quality (Zhang et al. 2020b), the different number of water quality indicators could produce different classes of WQI.

The present study took Chaoyang District of Beijing as an example to conduct groundwater quality assessment for drinking. The objectives of this study are to (1) Descriptive statistics for the key groundwater chemical parameters; (2) assess suitability of groundwater for drinking purpose

based on basic water quality index approach and integrated-weight approach; (3) compare the effects of the two modules (BWQIM and IWQIM) in dealing with the influence of weight and the influence of indicators in groundwater quality assessment. This study will not only contribute to provide scientific information of groundwater quality variations in the Chaoyang District of Beijing, but also enhances the understanding of effect of different assessment methods, indicators and weight on WQI.

Materials and methods

Study area

Chaoyang District, located in the southeast of Beijing, is the largest district in downtown Beijing. Study area stretches from longitude 116° 21'–116° 38' and latitudes 39° 49'–40° 05' (Fig. 1), with a concentrated district area of 470.8 km². It is sub-divided into 19 townships, population in Chaoyang district is approximately 3.605 million by the end of 2018. The climate of the study area is dominated by temperate continental sub-humid monsoon climate, with annual average temperatures 11.6 °C, annual frost-free period lasted 192 days and annual average precipitation 531 mm over the period from 2001 to 2019 (Huang et al. 2019). The depth to the groundwater table varied from 4 to 40 m, with an average annual value of 24.7 m at the end of 2012 (Hao et al. 2017). The topographic elevation of the area varies from 20 to 46 m, while the layer thicknesses of the quaternary period covering vary between 45 and 100 m, with a slow decline from northwest to southeast, and the average ground slope is about 1/2000, and the annual altitude is 34 m. The aquifer is mainly composed of several layer of quaternary sands and gravels.

The basement structure of Chaoyang District is mainly controlled by the NE-trending structure of the Neocathayian. The western region belongs to the northeast side of the Beijing Depression, and the southeast region belongs to the northern segment of the Daxing District uplift. Cenozoic stratigraphic deposits are formed, and controlled by these two structural units. A thick Tertiary red or purple cemented mudstone, sandstone, sandy mudstone or gravel were deposited in the western depression, accompanied by multiple periods of basalt eruption, with a thickness of about 400 m. The Quaternary system is the main aquifer. The loose sediments of the Quaternary are widely distributed, and the thickness of the Quaternary gradually thickens from west to east. The Quaternary stratum is composed primarily of clay, gravels, silty sands. The phreatic aquifer is generally less than 100 m thick. Due to long-term massive mining, the groundwater level is buried at a depth of 20–30 m. the water output of the confined aquifers is 500–1500 m³/day.

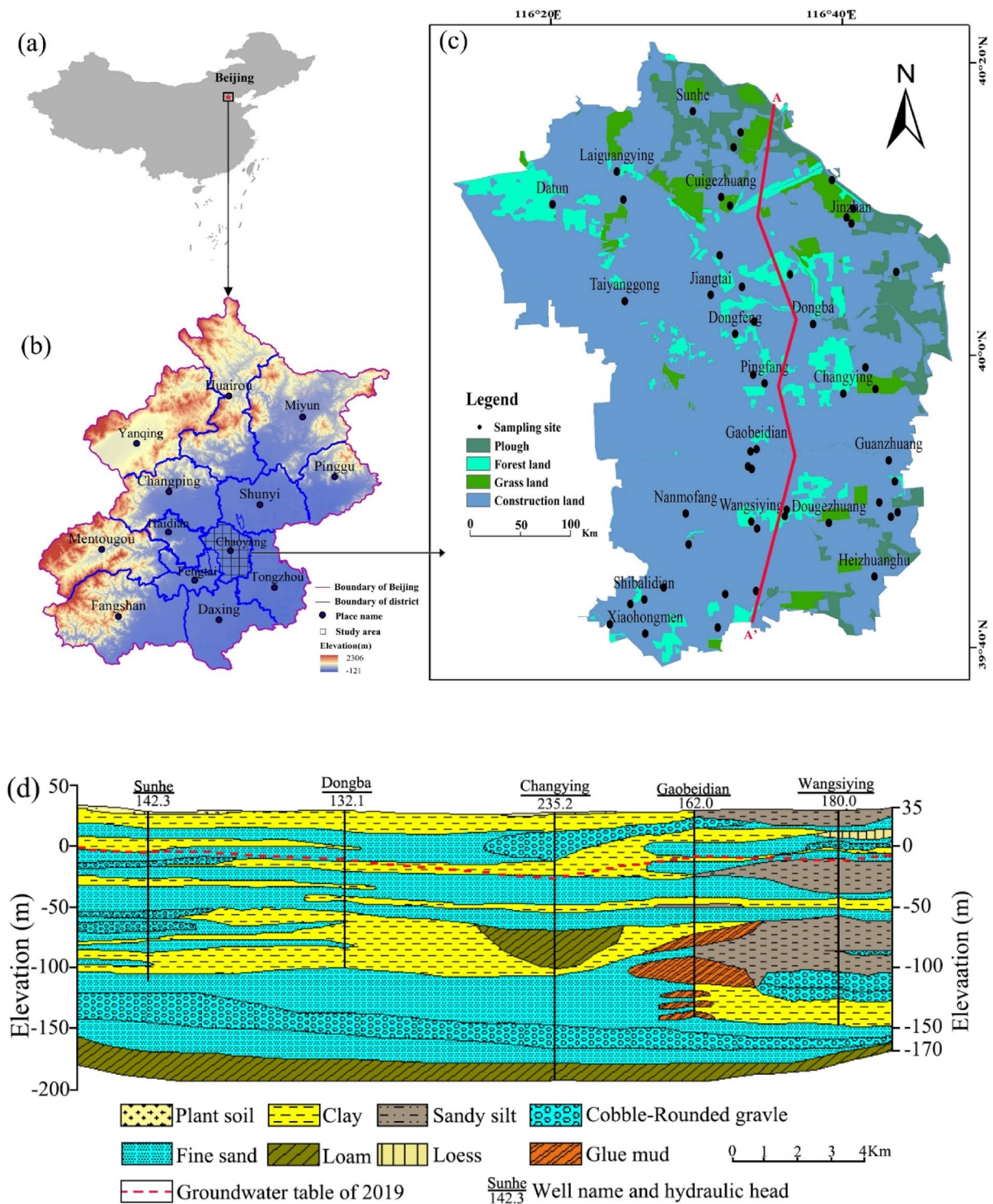


Fig. 1 Study area and groundwater sample sites with the hydrogeological cross section A-A'

Groundwater is mainly recharged by precipitation and lateral runoff, followed by seepage recharge of surface water.

Sample collection and analysis

A total of 51 groundwater samples were collected and tested from domestic tube wells or public water-supply wells with depths < 150 m across the study area in 2019. Before

sampling, wells were pumped for 5–10 min to avoid the effects of stagnant water in the pipeline and the coordinates of each sample were recorded on the GPS system (Gao et al., 2020a). The samples for pH were measured in-situ using the multi-parameter probes (Yinglan et al. 2019). Other samples for the remaining parameters were collected in polyethylene bottles prewashed 2–3 times (> 1000 mL per sample) and stored in refrigerators (0–4°C, protect from light). All the groundwater samples were immediately transferred to the laboratories located nearby the stations for further analysis within 24 h (Wang et al. 2016). All the samples were labelled with detailed information using waterproof markers on the bottles to prevent misdiagnosis. The contents of cation and heavy metal were analyzed using inductively coupled plasma atomic emission spectrometry (ICP-AES 5110). Total hardness (TH) was measured by Na₂EDTA titrimetric method. An electric blast-drying oven, along with an electronic analytical balance (vapour-drying method), was used to measure TDS. The contents of anion were detected by water quality-inorganic anion determination-ion chromatography (Ion chromatograph AQUION). To validate accuracy and reliability of the geochemical data, only water samples with ion balance error of less than ± 5% were accepted. Additionally, blank samples were also used at all the stations to control the accuracy of analyses (Wang et al. 2019a, b).

Water quality assessment method

Water Quality Index is defined as the numeric expression that provides the effect of each of the water quality parameters on the overall water quality for human consumption. First of all, weight values from 1 to 5 are determined for each chemical parameter. Here, 1 the weight value is given to the parameters that will affect the drinking water quality the least, 5 the weight value is given to the parameters that will affect the drinking water quality the most. So, the weighting of water quality parameters and the selecting of water quality indicators are important step when calculating an index. The different weights of water quality parameters and different indicators could produce different values of WQI and different classes of water quality. The aim of comparing the WQI results derived from different methods was to achieve a better understanding of the impacts of different weights allocation and different indicators selection on WQI results (Gao et al. 2020b). In this study, Application of BWQIM and IWQIM for groundwater quality evaluation. BWQIM include total indicator water quality index (TIWQI), common indicator water quality index (CIWQI), local feature indicator water quality index (LFIWQI). IWQIM include total indicator integrated water quality index (TIIWQI), common indicator integrated water quality index (CIIWQI), local feature indicator integrated water quality index (LFIIWQI).

Basic water quality index (BWQI) method

WQI method is widely used in the international evaluate of drinking water quality, it considers whether the monitoring value of each monitoring site exceeds the standard limit value from the three steps. First, each of parameters were assigned a weight w_i between 1 (least effect on water quality) and 5 (highest effect on water quality) based on their effects on relative importance (Abdel-Fattah et al. 2021; Bidhuri and Khan 2020; Ustaoğlu et al. 2020). Second, the relative weight (W_i) of parameters, was calculated as:

$$W_i = \frac{w_i}{\sum_1^n w_i} \quad (1)$$

Third, quality rating scale was computed using the concentration of ions in the groundwater sample divided by WHO standards (2011) for each index and multiplied by 100.

$$\begin{cases} q_i = \frac{C_i - C_{ip}}{S_i - C_{ip}} \times 100 \\ q_{\text{pH}} = \frac{C_{\text{pH}} - 7}{8.5 - 7} \times 100 \end{cases} \quad (2)$$

where C_i is the concentration of each parameter i (mg/L), C_{ip} is the ideal value of the parameter in pure water (consider $C_{ip}=0$ for all, except pH where $C_{ip}=7$), and S_i is the standard value for each chemical indicator according to the Standards for drinking water quality (WHO 2011).

Finally, WQI was calculated using Eq. (3).

$$WQI = \sum_{i=1}^n W_i q_i \quad (3)$$

Integrated-weight water quality index method

In allusion to the calculation result too subjective or objective problem caused by groundwater quality evaluation from the subjective weight and objective weight unilaterally, a method of index calculation for groundwater quality evaluation is applied in this study based on combining the order relation analysis method (also called the G1 method)-Entropy weight method (Kamrani et al. 2016). By optimizing the combination coefficient for subjective and objective weights, both subjective and objective information can be reflected in the index weight. The calculation of IWQI include: subjective weight calculation, objective weight calculation, calculation of integrated weight, and groundwater quality assessment.

Subjective weight based on G1 method

In the early 1990s, Scholars proposed a simple and effective decision analysis methods G1 method, which has obvious advantages and has been gradually recognized in recent years. The specific steps for calculating index weight by G1 method are as follows:

- (i) Determination of order relationship. Parameters are ranked in order by the relative importance for the evaluated object; those results are recorded as:

$$x_1 > x_2 > \dots x_i > x_j \dots > x_n, \tag{4}$$

where $x_i > x_j$ indicates parameter x_i is important (or not less) than parameter x_j for evaluated results.

- (ii) Quantitative analysis of the importance of each index. The relative importance r_j is calculated by Eq. (5) w_j and w_{j-1} are the weight of index x_j and index x_{j-1} , respectively. r_j is the relative importance value.

$$r_j = \frac{w_{j-1}}{w_j} \quad j = 2, 3, 4, 5, \dots, n, \tag{5}$$

- (iii) Calculate parameter weight. The calculation of subjective weight w_j as:

$$w_n = \left(1 + \sum_{k=2}^n \prod_{j=k}^n r_j \right)^{-1}, \tag{6}$$

$$w_{j-1} = r_j w_j \quad j = 2, 3, 4, 5 \dots, n \tag{7}$$

Objective weight based on entropy-weighted method

Information entropy was borrowed from thermodynamics by Shannon, C. E. (Shannon 1948), which solved the problem of quantitative measurement of information. According to the definition of information entropy, the dispersion degree of an index can be judged by the entropy value. The smaller entropy value is, the greater the dispersion degree of the index and the greater the weight of the index. The specific steps are as follows:

- (i) Construct an evaluation matrix. The original data evaluation matrix of the corresponding evaluation index is shown in Eq. (8):

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \dots & \dots & \dots & \dots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix}_{m \times n} = [r_{ij}]_{m \times n}, \tag{8}$$

where r_{ij} represents the evaluation value of i_{th} water sample and j_{th} evaluated parameter, m ($i = 1, 2, 3, \dots, m$) represents water samples and n ($j = 1, 2, 3, \dots, n$) represents the evaluated parameters. The specific gravity of the index value P_{ij} of the i_{th} water sample and j_{th} evaluated parameter is calculated as shown in Eq. (9).

$$P_{ij} = \frac{r_{ij}}{\sum_{i=1}^m r_{ij}} \quad (i = 1, 2, 3, \dots, m; j = 1, 2, 3, \dots, n). \tag{9}$$

- (ii) Calculation of entropy value (e_j) and entropy weight (objective weight: u_j).

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m p_{ij} \ln p_{ij} \quad (1, 2, 3, \dots, m), \tag{10}$$

$$u_j = \frac{1 - e_j}{\sum_{j=1}^n (1 - e_j)} \quad (j = 1, 2, 3, \dots, n). \tag{11}$$

Calculation of integrated weight

Determination of integrated weight is mainly by optimizing the combination coefficient for subjective and objective weights, both subjective and objective information can be reflected in the index weight. The integrated weight can be expressed as follows:

$$\lambda_j = P w_j + (1 - P) u_j, \tag{12}$$

where λ_j is the integrated weight of j_{th} index; w_j is the subjective weight determined by G1 method; u_j is the objective weight determined by entropy-weighted method; where, P is the preference coefficient and $P \in [0, 1]$.

To make the subjective and objective weighted attribute values tend to be consistent, it is necessary to minimize the close degree of subjective and objective attribute values of each water samples, the preference coefficient P are calculated by Eqs. (13) and (14):

$$w_j = \frac{w_j \times u_j}{\sum_j^n w_j \times u_j}, \tag{13}$$

$$P = \sum_{j=1}^n [(w_j - W_{sj})^2 + (w_j - W_{oj})^2]. \quad (14)$$

Groundwater quality assessment based on IWQI

IWQI is an efficient technique to assess the suitability of groundwater for drinking purposes, a rating of quality (q_j) is ascertained using Eq. (15) for every parameter.

$$\begin{cases} q_j = \frac{C_j}{S_j} \times 100 \\ q_{\text{pH}} = \frac{C_{\text{pH}} - 7}{8.5 - 7} \times 100 \end{cases}. \quad (15)$$

In the formula above, c_j is the concentration of species of j parameter (mg/L), C_{pH} is the value of pH, and s_j is permissible limit of the Standards for drinking water quality (WHO 2011) for parameter j (mg/L). The IWQI is determined by Eq. (16):

$$\text{IWQI} = \sum_{j=1}^n \lambda_j q_j, \quad (16)$$

where λ_j and q_j are the integrated weight and rating of quality, respectively. Water quality classification based on WQI value and classified into five excellent, good, medium, poor, extremely poor (Amiri et al. 2014). According to (Muzenda et al. 2019), classification of the evaluation result based on WQI method is shown in Table 2.

Uncertainty analysis

Uncertainty analysis is an efficient method to identify the influents of input indicator factors and weights factors on the assessment results and receive the optimal combination of indicators and weights. Uncertainty analysis was conducted to the influence of different factors on the assessment results according to Eq. (17).

$$U = \frac{|v_{\text{max}} - v_{\text{min}}|}{|V_{\text{max}} - V_{\text{min}}|}, \quad (17)$$

where U is the uncertainty value of indicators or weights, v_{max} is the maximum percentage of evaluation for single factor, v_{min} is the minimum percentage of evaluation for single factor, V_{max} and V_{min} is the maximum and minimum percentage of all factors, respectively.

Results

Descriptive statistics of groundwater hydrochemical characteristics

The statistical analysis of the chemical components for groundwater are helpful for understanding the groundwater chemical characteristics. Statistical information of chemical components, including the maxima, minima, means and coefficient of variation (CV) for each parameter. The hydrochemical characteristics of groundwater are showed in Table 1.

The pH value in the study area ranges from 6.99 to 8.62, indicating a weakly alkaline environment. These values were

Table 1 Statistical analysis of hydrochemical parameters of groundwater samples (units of all parameters are mg/L, except pH)

Parameter	Max	Min	Mean	CV (%)	WHO (2011)	% of SEL
pH	8.62	6.99	7.75	3.51	6.5–8.5	0
K ⁺	3.11	0.07	1.55	43.3	12	0
Na ⁺	110	1.02	47.37	38.7	200	0
Ca ²⁺	170	0.18	64.2	54.7	200	0
Mg ²⁺	56.2	0.02	27.69	50.7	150	0
Fe ³⁺	0.67	0.01	0.03	274.12	0.3	1.96
HCO ₃ ⁻	563	4.88	280.1	30.88	250	56.86
TH	711	0	274.39	52.5	550	3.92
TDS	993	5	421.47	43.1	1000	0
SO ₄ ²⁻	165	0.11	64.4	45	250	0
Cl ⁻	155	0.2	54.1	76.7	250	0
CO ₃ ²⁻	31.2	0	2.35	262.4	–	–
NO ₃ -N	20.3	0	4.39	109.5	20	1.96
NO ₂ -N	0.18	0	0.01	567.3	1	0

CV (%) coefficient of variation, % of SEL % of Samples exceeding acceptable limit, TDS Total dissolved solids, TH Total hardness

found to be in the permissible range of 6.5–8.5. The order of relative abundance of major ions is Total dissolved solids (TDS) > HCO_3^- > SO_4^{2-} > Ca^{2+} > Cl^- > Na^+ > Mg^{2+} > CO_3^{2-} > Fe^{3+} > K^+ , which shows that the major cation of groundwater dominated with Ca^{2+} and Na^+ , and 1.96% of samples had high concentrations of Fe^{3+} , while the major anions dominated with HCO_3^- and SO_4^{2-} , and 56.86% of groundwater was not suitable for direct drinking, owing to the high levels of HCO_3^- (> 250 mg/L). TDS played a major role in changing groundwater quality, the concentrations of TDS with mean values of 456.8 mg/L. The overwhelming majority of CO_3^{2-} is 0 with several exceptions of 6 mg/L, $\text{NO}_2\text{-N}$ is basically under the detection limit (0.01 mg/L).

Total hardness (TH) in groundwater reflects the lithological properties of the strata. The TH ranges from 7 to 711 mg/L with an average 274.39 mg/L. 3.92% of samples were very hard. Nitrogen pollution comes primarily from ammonia nitrogen, nitrate and nitrite pollution (Fulazaky et al. 2015; Adimalla 2020a, b; Adimalla and Qian 2021a, b). Because of intensive fertilizer application and sewage discharges, nitrogen pollution widely occurs in both agricultural regions as well as urban areas. As shown in Table 1 (Wang et al. 2019a, b), $\text{NO}_3\text{-N}$ concentrations were 0–20.3 mg/L with a mean of 4.39 mg/L and levels of $\text{NO}_2\text{-N}$ in groundwater samples were between 0 and 0.18 mg/L with a mean of 0.01 mg/L. Of the samples tested, 1.96%, 0% showed high levels $\text{NO}_3\text{-N}$ and $\text{NO}_2\text{-N}$, respectively. In

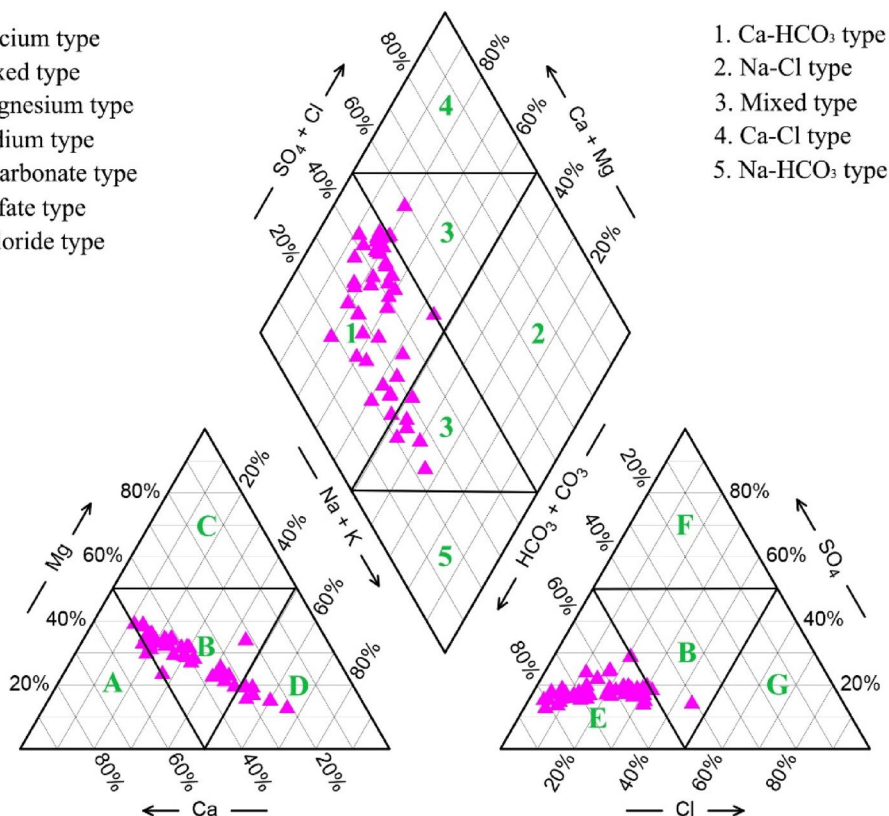
addition, the geochemical mechanisms that influence the chemical composition of groundwater in an aquifer can be inferred by analyzing the correlations between the various chemical components in water samples (Xu et al. 2019a, b; 2021a, b) (Table S1).

Hydrochemical facies and formation mechanism of groundwater chemistry

Piper trilinear diagram was proposed by Piper (1994), which consists of the central diamond field and two triangles plot, a pair of triangles are, respectively, represent the anion and cation diagram (Hajji et al. 2018; Talib et al. 2019). On the cation plot, most samples fall in zone (B), indicating obvious dominance of calcium cation in the groundwater. About 10% of the groundwater samples had relatively higher concentrations of sodium, which appeared in the right corner (Zone D). The anion diagram showed that most samples were found in Zone E, suggesting the dominance of HCO_3^- and signifying the weathering of the carbonate dominated lithology. The central diamond field showed the overall characteristics of groundwater chemistry (Rao and Latha 2019). As shown in Fig. 2, most samples fall in Zone(1), which is mainly dominated by the $\text{HCO}_3\text{-Ca-Mg}$ type or $\text{HCO}_3\text{-Ca}$ type water.

Fig. 2 Piper diagram indicating hydrogeochemical facies of groundwater

- A. Calcium type
- B. Mixed type
- C. Magnesium type
- D. Sodium type
- E. Bicarbonate type
- F. Sulfate type
- G. Chloride type



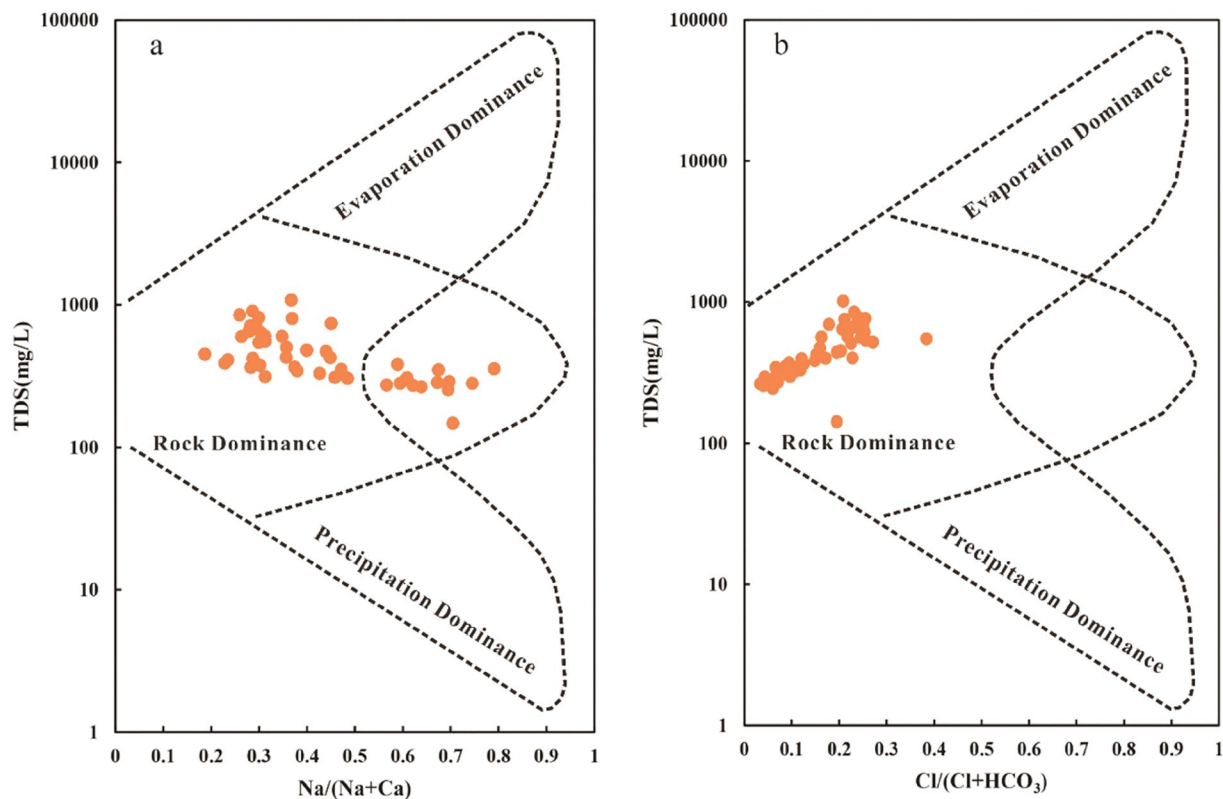


Fig. 3 Gibbs plot shows the principle controlling groundwater chemistry in Chaoyang District

The Gibbs diagrams are helpful to analyze the sources of major ions by identifying the influence of rock weathering, evaporation and precipitation on groundwater (Gibbs 1970). The Gibbs plot is divided into three domains: Rock Dominance, Evaporation Dominance and Precipitation Dominance (Jehan et al. 2020). Gibbs diagrams are obtained through plotting the major ions data of groundwater samples based on $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ and $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ with respect to TDS in groundwater. The Gibbs plot of the groundwater (Fig. 3a, b) shows that the groundwater samples fall in the rock dominance, which suggests that rock weathering and leaching are the major factors dominating the ionic composition of groundwater in Chaoyang district. No sample falls in the precipitation and evaporation dominance field.

Ion ratios

The use of ionic ratios in groundwater can be used to reveal the main factors controlling the hydrochemistry of geochemical processes (Xu et al. 2020; Adimalla and Venkatayogi 2018). In general, the dissolution of rock salt is the main source of Na^+ and Cl^- in groundwater, and releases equal amounts of Na^+ and Cl^- . Figure 4a shows the scatter plot of Na^+ against Cl^- , in which all the groundwater samples are plotted on the upper and lower sides of

the $y = x$ relationship line, indicating that the dissolution of rock salt is not the primary hydrogeochemical process affecting the hydrochemistry components of groundwater. As shown in Fig. 4b, the groundwater samples were distributed near or below the $y = x$ relationship line, reflecting that weathering of carbonate and silicate rocks was the main factor of geochemical processes in the study region. The ratio of $\text{Ca}^{2+} / \text{Mg}^{2+}$ can be used to analyze the influence of carbonate rock and silicate weathering on groundwater hydrochemical characteristics. As shown in Fig. 4c, the groundwater samples were mainly plotted on between the $y = x$ and the $y = 0.5x$ relationship lines, indicating that the weathering of carbonate rock is the main rock weathering process affecting the hydrochemical characteristics of groundwater of the study area. Generally speaking, cation exchange may be one of the important processes affecting the chemical characteristics of groundwater in a region. The groundwater samples mainly fall in the upper sides of the $y = x$ relationship line in Fig. 4d, indicating that Ca^{2+} and SO_4^{2-} in the groundwater of the study area did not mainly originate from the dissolution of gypsum.

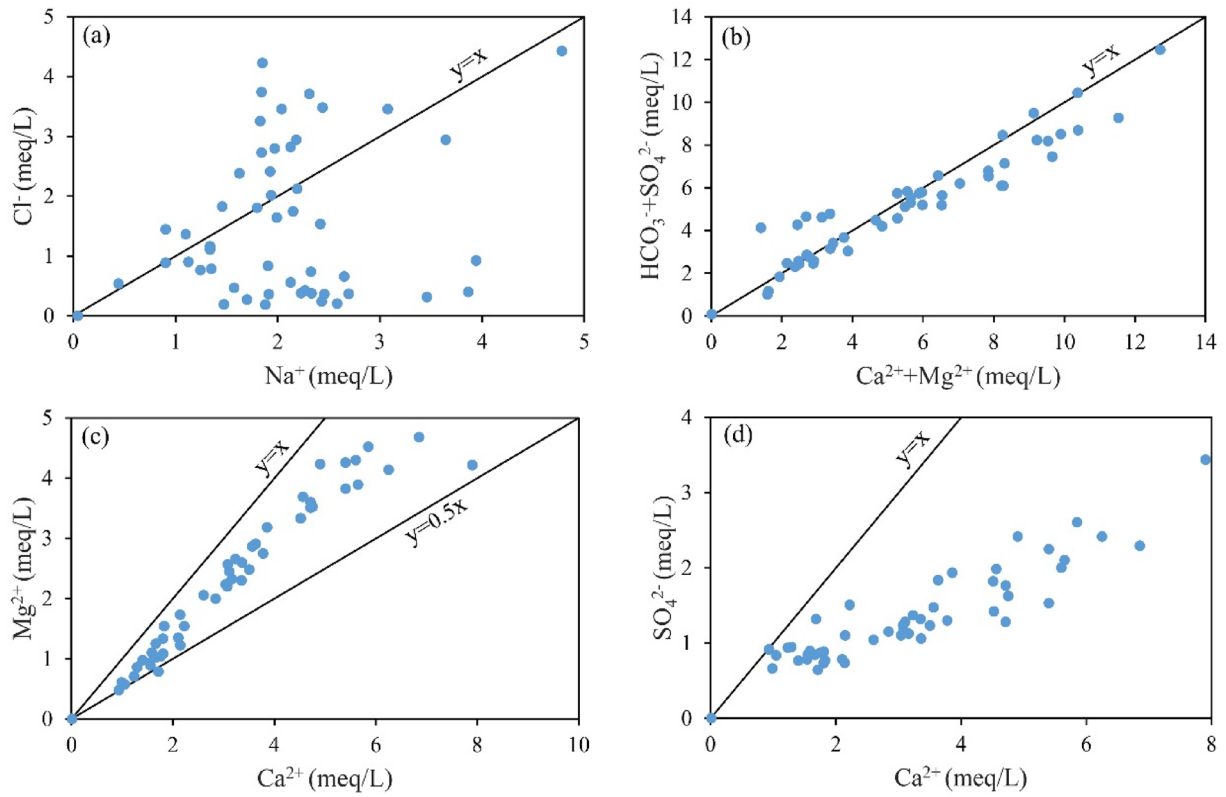
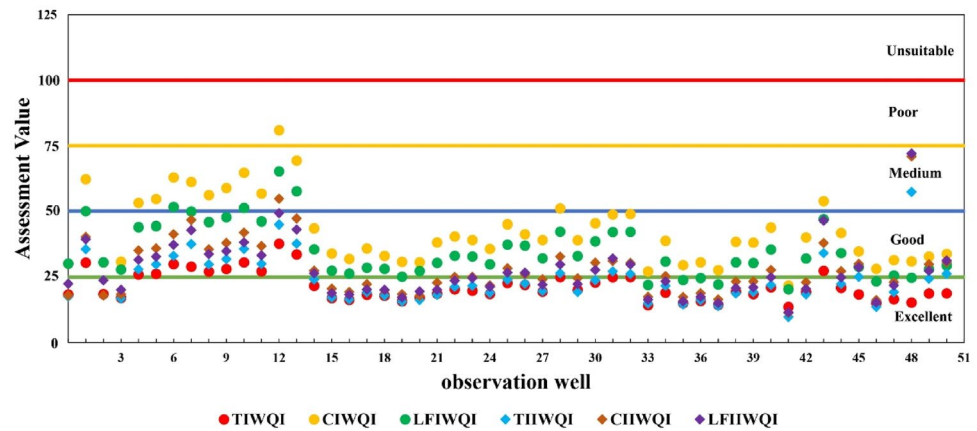


Fig. 4 Ion ratio diagram of groundwater in study area: **a** Na⁺ vs. Cl⁻; **b** Ca²⁺+Mg²⁺ vs. HCO₃⁻+ SO₄²⁻; **c** Ca²⁺ vs. Mg²⁺; **d** Ca²⁺ vs. SO₄²⁻

Table 2 Classification of groundwater quality based on assessment values (Felistas Muzenda 2019)

Methods	WQI range				
	<25	25–50	50–75	75–100	> 100
Type of groundwater					
	Excellent (I)	Good (II)	Medium (III)	Poor (IV)	Unsuitable (V)
TIWQI					
No. of sample	39	12	0	0	0
Percentage (%)	76.5	23.5	0.0	0.0	0.0
CIWQI					
No. of sample	1	37	12	1	0
Percentage (%)	2.0	72.5	23.5	2.0	0.0
LFIWQI					
No. of sample	8	39	4	0	0
Percentage (%)	15.7	76.5	7.8	0.0	0.0
TIIWQI					
No. of sample	33	17	1	0	0
Percentage (%)	64.7	33.3	2.0	0.0	0.0
CIIWQI					
No. of sample	23	26	2	0	0
Percentage (%)	45.1	51.0	3.9	0.0	0.0
LFIIWQI					
No. of sample	28	22	1	0	0
Percentage (%)	54.9	43.1	2.0	0.0	0.0

Fig. 5 Classification of ground-water quality based on different methods



Groundwater quality assessment based on BWQIM

Groundwater quality assessment based on TIWQI

TIWQI is calculated by considering 45 parameters to evaluate the suitability for drinking purpose based on WQI method. W_i value were presented in Table S2. The overall TIWQI value was calculated using Microsoft Excel and the rating of water quality according to this WQI is given in Table 2. According to the TIWQI method, 39 samples (76.5%) had Excellent quality, 12 samples had Good quality. Based on these TIWQI values, the evaluation results were shown in Fig. 5.

Groundwater quality assessment based on CIWQI

In this study, 14 common water quality indicators obtained from the published literatures were used. The relative weights for common water quality indications were given in Table S2. Based on the CIWQI, the number of samples showed that most of the samples (37 samples equal to 72.5%) were placed in the Good quality. The 1 (2.0%), 12 (23.5%), 1 (2.0%) groundwater samples that were classified as Excellent quality, Medium quality, Poor quality, respectively (Table 2). The status of groundwater quality based CIWQI method is shown in Fig. 5.

Groundwater quality assessment based on LFIWQI

Four local feature indicators of Al, As, Hg and Turbidity were added on the basis of the common water quality indicators. Weightings are assigned to the various water quality indicators incorporated into the WQI according to their relative importance in water quality assessment (Table S2). According to the LFIWQI, 15.7% of samples were placed in Excellent quality, 76.5% of samples were placed in Good quality, 4.0% of samples were placed in Medium quality

(Table 2). The LFIWQI evaluation results were drawn in Fig. 5.

Groundwater quality assessment based on IWQIM

Groundwater quality assessment based on TIHWQI

In this study, groundwater quality assessment was evaluated by IWQI, which takes into account of G1 method and objective entropy information. According to G1 method determined the subjective weight of forty-five parameters. Entropy weight method determined the objective weight. The integrated weights are shown in Table S2 and the rating of water quality are as shown in Table 2. Based on TIIWQI method, 64.7% of samples had Excellent quality, 33.3% of samples had Good quality, only 2.0% of samples had medium quality. The evaluation results of TIIWQI were shown in Fig. 5.

Groundwater quality assessment based on CIIWQI

The water quality parameters of CIIWQI the same as CIWQI. The integrated weights are shown in Table S2. 45.1% of samples had Excellent quality, 51.0% of samples had Good quality, 3.9% of samples had medium quality by the CIIWQI method (Table 2). The assessment results were shown in Fig. 5.

Groundwater quality assessment based on LFIWQI

According to long-term monitoring, the indexes of the study area including Al, As, Hg and Turbidity are feature indicators. So, eighteen water quality indicators were selected for groundwater quality assessment based on local feature indicator water quality index. The integrated weights are shown in Table S2 and the rating of water quality are as shown in Table 2. 28 (54.9%), 22 (43.1%), and 1 (2.0%) sample were placed in Excellent quality, Good quality, medium quality,

respectively. Based on LFIWQI method, the evaluation results were shown in Fig. 5.

Discussion

The influence of indicators on groundwater quality assessment

In this study, different water quality indexes were selected to comparison of the influence of indicators based on BWQIM and IWQIM respectively. It can be seen from Fig. 5 that both the BWQIM and IWQIM can reflect the water quality to a certain extent, and in addition to individual monitoring points, the variation trends of evaluation results obtained by selecting different indicators are similar. For using same number of indicators, the weight was computed using preference coefficient for IWQIM. However, the weight calculation of BWQIM is artificially assigned. Different weight calculation methods result in the weight of BWQIM is generally higher than that of IWQIM (Table S2). Further analysis found that BWQIM is able to classify the results into high quality category, while, the IWQIM was placed in low quality category when using the same number of indicators. For using different number of indicators, as the parameter increase, the types of groundwater based on BWQIM were gradually getting better. But, the types of groundwater based on IWQIM were basically unchanged. To explain the reasons for this discrepancy, we analyzed the original data and found that there were 4 indicators exceeding the standard, the main indicators exceeding the standard were HCO_3^- , Fe^{3+} , $\text{NO}_3\text{-N}$, TH, and the number of monitoring data exceeding the standard was 33. For the BWQIM, exceed standard indicators affecting the evaluation results. The IWQIM does not rely excessively on one or a few indicators (Gao et al. 2020b).

The influence of weight on groundwater quality assessment

A comparative evaluation of the BWQIM and IWQIM was performed to examine the influence of weight in predicting actual groundwater quality in the study area. The weight of total indicator, common indicator and local feature indicator are shown in Fig. 6. For BWQIM, the relative weight is calculated using Eq. (1). It can be seen from the calculation process that the weight is mainly assigned according to the importance of parameters to the quality of groundwater, For IWQIM, the integrated weight is determined by combination of subjective and objective weights.

For the total index (Fig. 6a), the weight values of TIWQI varies from 0 to 0.05. However, the weight value of TIIWQI varies from 0 to 0.25, and the weight values of Fe, HCO_3^- ,

Cl^- , Zn, $\text{NO}_2\text{-N}$ vary greatly, which are 0.248, 0.123, 0.084, 0.049, 0.073, respectively. According to TIWQI, the study area was classified into two classes Excellent quality and Good quality for drinking water. However, when TIIWQI evaluated the water quality, medium quality appeared, mainly due to Fe exceed the standard. Considering the calculation method of weight and the exceeding index, TIIWQI can better reflect the actual situation of local water quality.

For the common indicators, the weight values of CIWQI varies from 0.021 to 0.106, the weight values of CIIWQI varies from 0.006 to 0.313 (Fig. 6b). According to CIWQI, the study area was classified into three classes excellent quality, good quality and medium quality for drinking water. However, when CIWQI evaluated the water quality, poor quality appeared, mainly because HCO_3^- , TDS, $\text{NO}_2\text{-N}$ and TH exceed the standard. The weight of HCO_3^- , TDS, $\text{NO}_2\text{-N}$ and TH were 0.106, 0.106, 0.043, 0.106, respectively. When water quality was evaluated by CIIWQI, the weight of HCO_3^- , TDS, $\text{NO}_2\text{-N}$, and TH were 0.106, 0.049, 0.186, 0.041, respectively. Considering the weight and exceed indicators, CIWQI can better reflect the actual situation of groundwater quality.

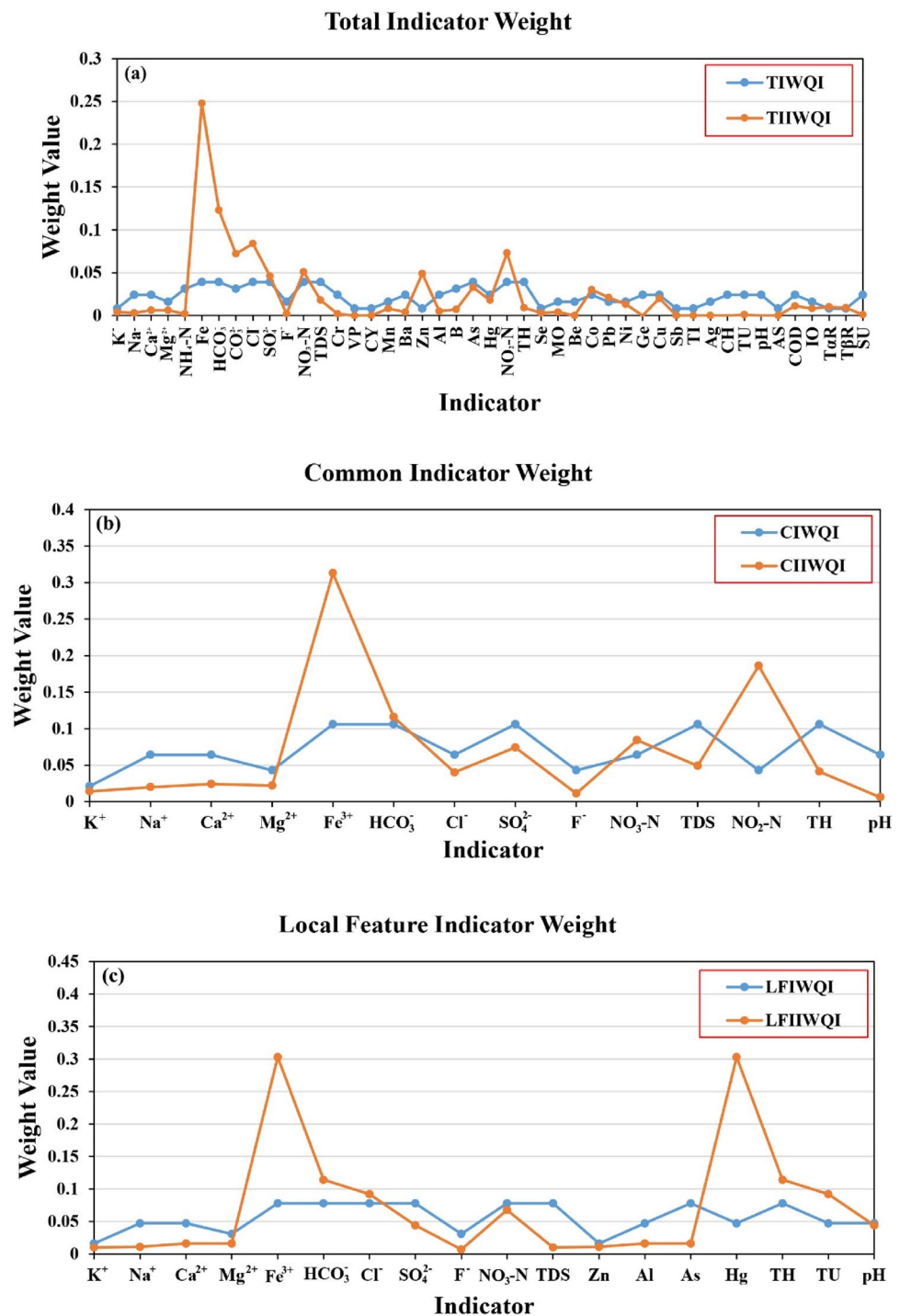
For local feature indicator, the weight values of LFIWQI varies from 0.016 to 0.078. However, the weight value of LFIIWQI varies from 0.007 to 0.303, and the weight values of Fe^{3+} , HCO_3^- , As, Hg and turbidity changed greatly, which are 0.303, 0.114, 0.016, 0.303 and 0.092, respectively. The weight of other indexes changed slightly (Fig. 6c). According to LFIWQI, the water quality of study area was classified at medium level for drinking water. When LFIIWQI evaluated the water quality, the evaluation value of study area is classified into good quality and medium quality. From the results of water quality assessment, there is no significant difference between the two methods.

Based on the above discussion, when using the same number of indicators, the water quality evaluation result based on the IWQIM is one grade lower than the BWQIM (Fig. 5). Through the analysis of the original data, it can be found that the main over-standard indicators are HCO_3^- , Fe^{3+} , $\text{NO}_3\text{-N}$ and TH. As shown in Fig. 6, the weight obtained by the IWQI method is better than the basic WQI method to highlight the important of exceeding the standard indicator. The integrated weight is more reasonable and accurate, while the weight calculation of the basic WQI have strong subjective color.

The comparison of BWQIM and IWQIM based on different methods

For BWQIM based on the basic WQI method showed a noticeable change in most classes. For TIWQI method (Fig. 5), water quality is classified into two classes, where 76.5% of samples were placed in Excellent quality, 23.5%

Fig. 6 The weight comparison of different methods: **a** based on 45 indicators (Total Indicator); **b** based on 14 indicators (Common Indicator); **c** based on 18 indicators (Local Feature Indicator)



of samples were placed in Good quality. For CIWQI method (Fig. 5), water quality is classified into four classes, 2.0% of samples had Excellent quality, 72.5% of samples had Good quality, 23.5% of samples had Medium quality, 2.0% of samples had Poor quality. For LFIWQI method (Fig. 5), water quality is classified into three classes, 15.7% of samples had Excellent quality, 76.5% of samples had Good quality, 7.8% of samples had Medium quality. It means that the increase

of the number of parameters has a significant impact on the evaluation results of basic WQI method. For example, a high value of Cl pollution should make water unsuitable for drinking, and the increase in the number of indicators will result in a decrease in its weight, but a small weight for Cl may be “swamped” in the overall WQI index score, causing large fluctuations in water quality evaluation results.

For IWQIM based on the IWQI method, the TIIWQI method, 33 samples (64.7%) had Excellent quality, 17 samples (33.3%) had Good quality, 1 sample (2.0%) had poor quality. The CIIWQI and LFIIWQI method were close to the TIIWQI method with less samples in excellent category, more samples in good class and almost the same samples in medium type (Fig. 5). As the parameter increase, the value of IWQI decreases gradually, but the change is slight, indicating that the number of parameters has little influence on the IWQI method. According to the above analysis, indicating that IWQIM is not affected by the number of indicators. In the other word, the IWQIM does not rely excessively on one or a few parameters, and all parameters play a role in the water quality assessment.

Although some similar trend of the IWQIM can be observed in the BWQIM evaluation result, the grading of evaluation results significantly different between two methods. Though a comparative evaluation of the BWQIM and the IWQIM was performed to examine the relative performance of two methods in analysis actual groundwater quality status when the number of indicators vary. It can be clearly seen that the evaluation results of IWQIM basically does not change with the vary of the number of indicators, however, the evaluation results of BWQIM were significantly affected by the number indicators. The overall water quality is above medium, and the percentage of each category is given (Table 2). Figure 6 reveals that the IWQIM can highlight the importance of high concentration index and give it higher weight value.

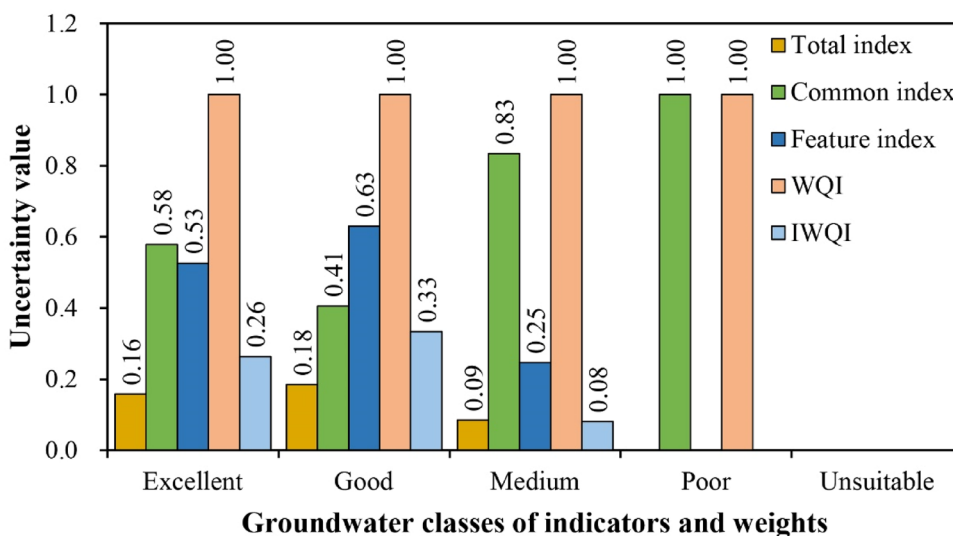
Uncertainty analysis of indicators and weights on evaluation results

The uncertainty results of weights under the action of indicator units are shown in Fig. 7. The results of total index show

that the uncertainty values of the weights under the rating of Excellent, Good and Medium are 0.16, 0.18 and 0.09, respectively. Common indicators results show that 0.58, 0.41, 0.83 and 1 of the uncertainty values of the weights under the rating of Excellent, Good, Medium and Poor, respectively. The results of local feature indicator show that 0.53, 0.63 and 0.25 of the uncertainty values of the weights under the classes of Excellent, Good and Medium, respectively. In the classification of water quality, the uncertainty value of the weight of total index is the smallest, while the uncertainty value of the weight of the common indicator is generally larger. It can be seen from Fig. 6 that when the number of indexes is the same, the over- standard indicators are given greater weight based on the IWQI method. Therefore, IWQI method is more consistent with the actual situation of groundwater quality.

The uncertainty results of indicators under the action of weight units, as shown in Fig. 7. The results of WQI weight units show that the uncertainty values of the indexes under the level of Excellent, Good and Medium is 1. IWQI weight units results show that 0.26, 0.33, and 0.08 of the uncertainty values of the indicators under the rating of Excellent, Good, Medium and Poor, respectively. It can be seen from Fig. 6 that the WQI weight unit fluctuates greatly due to the influence of the number of indicators. However, the IWQI weight unit is basically not affected by the change of the number of indicators. Based on the combination of IWQI method and different indicators, the assessment results are basically the same (Fig. 5). Therefore, the smaller the uncertainty value of the indicator, the more reliable the evaluation result. IWQI method could be used as a suitable method to evaluated groundwater quality for drinking purpose.

Fig. 7 The effect of indicators and weight on the assessment results



Conclusion

Different water quality evaluation methods usually get different evaluation results. Hence, the selection of evaluation method parameters and weight distribution becomes critical. In this study, we discuss the advantages and disadvantages of different methods. In each module, there are three modules based on the number of indicators to analysis the evaluation results of different scenarios. The main conclusions are summarized as follows:

Initially, basic statistical revealed that groundwater in aquifers in the study area is weakly alkaline, the major ions in groundwater of Chaoyang District was in following order: $\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^- > \text{CO}_3^{2-}$ and $\text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+$, and four indicators (Fe, HCO_3^- , TH and $\text{NO}_3\text{-N}$) are critical with concentration values greater than their permissible limits for drinking. Hydrochemical facies were predominantly $\text{HCO}_3\text{-Ca-Mg}$, $\text{HCO}_3\text{-Ca}$ type, which were controlled by rock weathering.

Among three modules of TIWQI, CIWQI and LFIWQI based on the basic WQI method, the best results with the most realistic result came from the CIWQI modules and other modules because of the increase in the number of indicators, the weight of high concentration indicators is submerged in the overall water quality assessment. For three modules of TIIWQI, CIIWQI and LFIIWQI based on the IWQI method, the evaluation results were consistent in grades, the change of index had no influent on IWQI method and the integrated weight showed that HCO_3^- , Fe^{3+} , $\text{NO}_3\text{-N}$ and TH had more important effects on groundwater quality.

Uncertainty analysis indicated that the IWQIM did not rely excessively on one or a few indexes and weight is basically not affected by the change of the number of indicators. The assessment results of IWQIM are basically consistent. However, the evaluation result of BWQIM fluctuates greatly due to the change of the number of parameters. So, the IWQIM evaluation groundwater quality status more accurately.

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CRedit authorship contribution statement YZ: conceptualization, formal analysis, funding acquisition, supervision. RJ: methodology, data curation, software, writing-original draft, writing-review. JW:

methodology, writing—review and editing. WQ: formal analysis, supervision, editing. ZL: data curation, investigation.

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Declarations

Conflict of interest We declare that all authors have no any actual or potential conflict of interest including and financial, personal or other relationships with other people or organizations.

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