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RESEARCH ARTICLE

Assessment of groundwater vulnerability by applying the improved DRASTIC model: a case in Guyuan City, Ningxia, China

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Abstract
Groundwater is the main source of production and living in most arid and semi-arid areas, and it plays an increasingly critical role in achieving local urban development. There is a serious issue regarding the contradiction between urban development and groundwater protection. In this study, we used three different models to assess the groundwater vulnerability of Guyuan City, including DRASTIC model, analytical hierarchy process-DRASTIC model (AHP-DRASTIC) and variable weight theory-DRASTIC model (VW-DRASTIC). The groundwater vulnerability index (GVI) of the study area was calculated in ArcGIS. Based on the magnitude of GVI, the groundwater vulnerability was classified into five classes: very high, high, medium, low, and very low using the natural breakpoint method, and the groundwater vulnerability map (GVM) of the study area was drawn. In order to validate the accuracy of groundwater vulnerability, the Spearman correlation coefficient was used, and the results showed that the VW-DRASTIC model performed best among the three models (ρ=0.83). The improved VW-DRASTIC model shows that the variable weight model effectively improves the accuracy of the DRASTIC model, which is more suitable for the study area. Finally, based on the results of GVM combined with the distribution of F^- and urban development planning, suggestions were proposed for further sustainable groundwater management. This study provides a scientific basis for groundwater management in Guyuan City, which can be an example for similar areas, particularly in arid and semi-arid areas.

Keywords Guyuan City · Semi-arid · DRASTIC · AHP · VW · Groundwater vulnerability

Introduction

Groundwater is an important natural water resource for human production and life, particularly in arid and semi-arid areas (Li et al., 2019; Chakraborty et al., 2022). It supports economic, social and environmental development in variety of ways, including drinking, industrial production, irrigated agriculture and ecological services (Li et al., 2018). However, there is an increasing risk of groundwater contamination. Maintaining groundwater security while developing cities has become a critical global challenge (Kalhor and Emaminejad, 2019; Li et al., 2021; Zaryab et al., 2022). If groundwater is not appropriately managed and protected, the quality of groundwater may be significantly influenced by intensive human activities (Chidambaram et al., 2018; Xiong et al., 2022). Moreover, as groundwater is the final receiver of the water cycle, the contaminated groundwater is always difficult to clean up, so the prevention of groundwater is always preferable to post-contamination cleanup (Patel et al., 2022).

Over the past two to three decades, clean drinking water resources have declined in both quality and quantity due to frequent human activities such as urbanization and increased population density (Rashid et al., 2021). Globally, numerous studies have reported on groundwater contamination, such as Brazil (Hirata et al., 2020; Tedesco et al., 2021), Canada (Gardner et al., 2020),

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Pakistan (Rashid et al., 2020; Rahman et al., 2021; Din et al., 2022), Bangladesh (Bodrud-Doza et al., 2020), and Russia (Kolupaeva et al., 2020; Lebedeva et al., 2020). Similarly, there are large areas of contaminated groundwater in China. Studies have been conducted in Beichuan River basin (Zhang et al., 2023), Heilongdong Spring Basin (Liu et al., 2022), Guanzhong Basin (Wang et al., 2022), Zhangjiakou (Wang et al., 2021) and Yongning county (Wei et al., 2022), etc. As we know, urbanization is the main trend of human social development in the future. The unreasonable exploitation of groundwater resources has already led to groundwater contamination in some areas with earlier coastal development (Akshitha et al., 2021; Boumaiza et al., 2022; Kumar et al., 2022). Also, studies have shown that long-term consumption of contaminated groundwater can cause serious harm to humans and induce a range of diseases (Ali et al., 2019; Ali et al., 2021; Khattak et al., 2021; Rashid et al., 2022a,b). Therefore, it is important to develop a sustainable management plan for groundwater to ensure safety and reduce health risks (Rashid et al., 2022a,b; Rashid et al., 2023).

Groundwater vulnerability assessment is an efficient and non-engineering approach to prevent groundwater contamination (Deepesh et al., 2018; Oke, 2020). It is possible to identify groundwater vulnerabilities using groundwater vulnerability maps (GVM), as well as provide practical guidelines for minimizing groundwater contamination and providing a scientific basis for groundwater quality restoration (Barbulescu, 2020; Kirlas et al., 2022). By reviewing past studies, researchers have developed a variety of models to assess groundwater vulnerability, including AVI model (Putranto et al., 2018; Adetya et al., 2019), EPIK model (Nekkoub et al., 2020; Omotola et al., 2020), GOD model (Taazzouzte et al., 2020), GALDIT model (Mahrez et al., 2018; Ma et al., 2020), SINTACS model (Oroji, 2019), etc. Among them, DRASTIC model is a very common and reliable method, which has been widely used and highly recognized in GVM (Barbulescu, 2020; Patel et al., 2022; Zhang et al., 2022). However, the traditional DRASTIC model uses Delphi method to determine the weight of indicators, which has the weakness of using fixed weights for various indicators (Khosravi et al., 2018). Therefore, it is essential to make reasonable corrections to the DRASTIC model. By using variable weight theory (VW), it is possible to calculate weights that are proportional to the rate value of indicators and thus obtain a more reasonable distribution of weights in multi-objective decision-making (Lin et al., 2020). In this way, it is possible to establish a relationship between weights and indicators which is well suited to improving the DRASTIC model.

Arid and semi-arid regions are experiencing extreme groundwater stress (Sreedevi et al., 2022). In these regions, groundwater is an important resource to ensure the water security and sustainable economic development. Guyuan City belongs to the arid water-scarce region in Northwest China. With the growth of population, industrialization and urbanization, the contradiction between socio-economic development and groundwater protection is very prominent (Yu et al., 2021). To assess groundwater vulnerability in Guyuan City, Lu et al. (2016) used DRASTIC model to assess the groundwater vulnerability in Guyuan City. They reported that the areas were divided into key prevention area and general prevention area based on the GVM, and corresponding prevention and control measures were proposed. Li et al., (2021); Li (2021) constructed a DRATI-LE model to assess the groundwater vulnerability in Guyuan City and proposed the corresponding strategies to protect groundwater quality. At present, there are few studies on groundwater vulnerability assessment in Guyuan City. Guyuan City's groundwater quality is under serious threat due to the long-term lack of rational planning for managing water resources and the lack of advanced and efficient water utilization technologies.

Currently, how to achieve groundwater sustainable management combined with groundwater vulnerability in the context of expanding urbanization has been a critical challenge, and there is a lack of research on this issue. Studies on the assessment of groundwater vulnerability mainly focus on the intrinsic vulnerability or special vulnerability, with little consideration on how to guide local groundwater management. The urbanization of Guyuan City is slated to have a greater impact on groundwater with future economic development and population growth. The objective of this study, using the improved DRASTIC model, is to integrate urban development and groundwater vulnerability assessment in Guyuan City, which in turn will guide local groundwater management. The results of this study can provide a scientific basis for the rational development, protection and management of groundwater in Guyuan City, which is of great significance for the sustainable development of groundwater.

Study area

Location and Range

Guyuan City is located in the northwestern part of China and the south of Ningxia, including Yuanzhou District, Longde County, Xiji County, Pengyang County, and Jingyuan County, within the geographic coordinate of 105°19′-106°57′ E and 35°14′-36°31′ N (Fig. 1).

Geology and topography

The study area is located at the northwest edge of the Loess Plateau, with elevations ranging from 1303-2923m. The landforms from west to east are alpine hills, mountains,

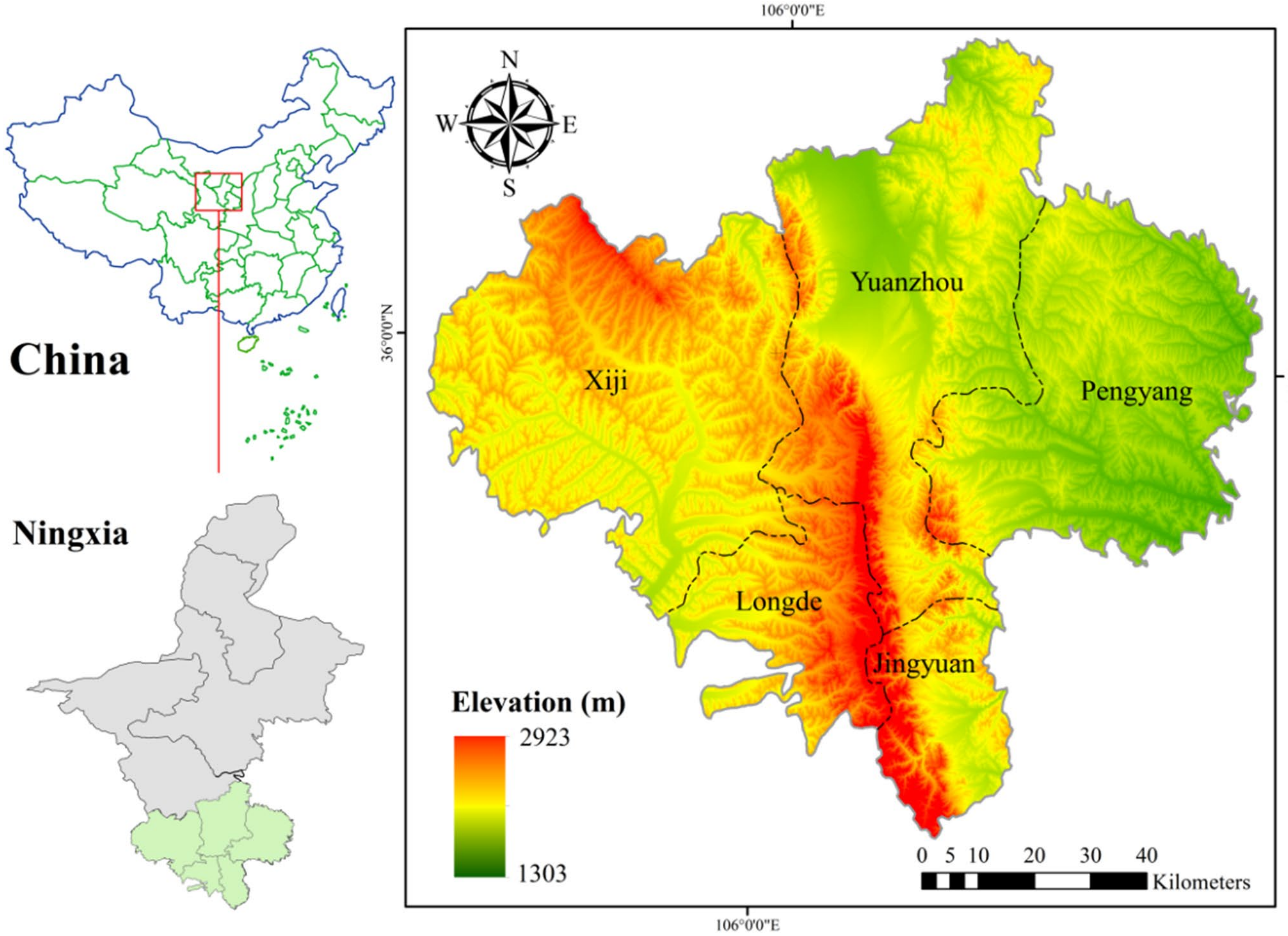


Fig. 1 Location of the study area

alluvial plains and loess hills. Most of the study area is covered by Quaternary loess, and the lithology is mainly sandstone, mudstone and glutenite.

Geography and climate

The study area belongs to the warm-temperature semi-arid climate zone of Loess Plateau, with variations in precipitation. According to statistics, the annual average of temperature is 6.1°C, and the annual average of evaporation is 1753.2mm.

Hydrogeology

The study area consists of several aquifers, including loose rock type water-bearing group, clastic type water-bearing group, bedrock type water-bearing group, and carbonatite type water- bearing group. The thick, loose, pore-rich Quaternary sediments are the main reservoirs. The sources of groundwater recharge are mainly rainfall recharge, surface water infiltration, lateral recharge in mountainous areas and irrigation recharge, of which rainfall recharge is the main source of recharge. The discharge routes are artificial exploitation, evaporation and discharge to surface water, among which artificial exploitation and evaporation are the main routes (Fig. 2).

Urban development and groundwater environmental problem

In the study area, endemic fluorosis is an endemic disease that widely distributed in the study area, which is closely related to the specific primary geochemical environment (Luo et al., 2018; Mwiathi et al., 2022). In the 1980s, the study area worked on water conversion to prevent fluorosis and promoted facilities such as eaves catchment projects. However, due to the relative dispersion of villages, there are still some villages that use shallow groundwater as drinking water (Li et al., 2020).

Currently, the study area is accelerating industrial restructuring and vigorously promoting urbanization. One type I city (0.2-0.5 million people) and three type II cities (<0.2 million people) are expected to be planned (Fig. 3).

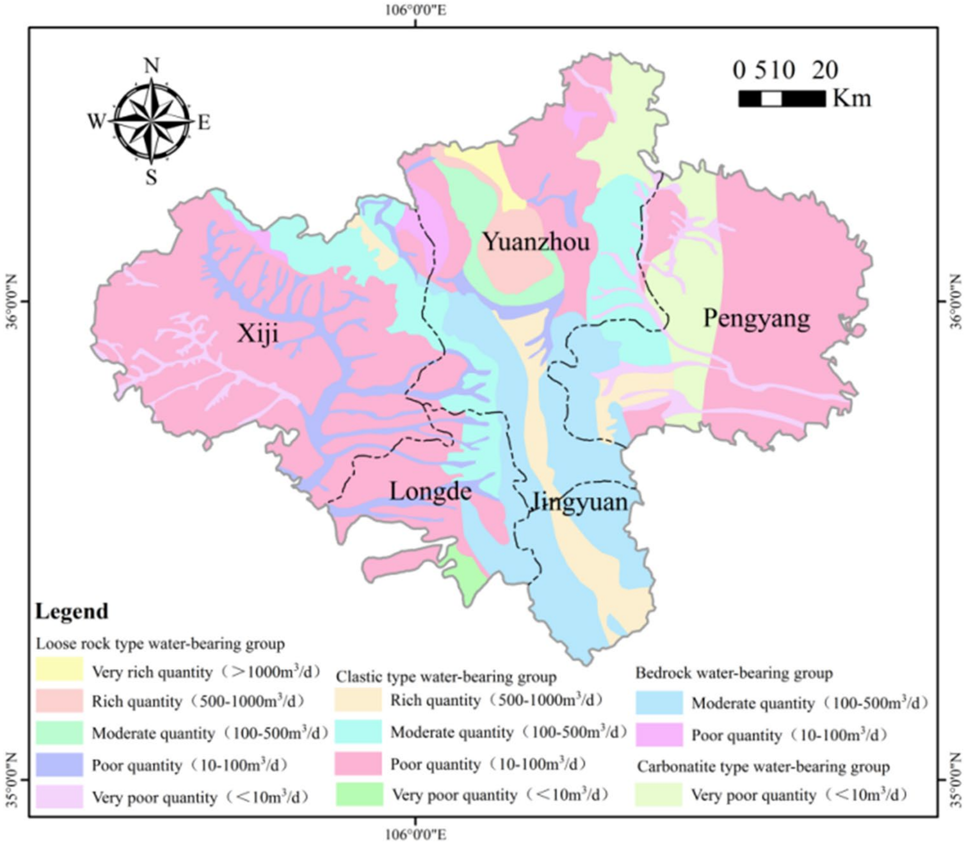


Fig. 2 Hydrogeological map of the study area

Methods

Technical route

In this study, the traditional DRASTIC model was improved by applying AHP and VW methods. And the GVM of the study area was drawn by DRASTIC, AHP-DRASTIC, and VW-DRASTIC models, respectively. Finally, the suggestions are made for sustainable development of groundwater to the study area. All the data for groundwater vulnerability assessment were obtained from different sources (Appendix 1).

Sampling collection

To determine the groundwater quality of the study area and prepare for the model validation. Thirty-two sampling points were selected, and all groundwater samples were taken from different sources such as tube wells, hand pumps, and dug wells. Each sample was collected after 5 minutes of water flow and stored in polyethylene bottles that were rinsed with samples. After sealing and immediately sent to the laboratory for testing, the nitrate has been measured by UV spectrophotometric method.

Quality control and quality assurance

In order to obtain the accuracy and precision of the results, nitrate testing was performed in strict accordance with the relevant standards. And each groundwater sample was analyzed in triplicate, and the average value was recorded in the final results. The experimental steps were carried out in accordance with groundwater quality testing methods (Appendix 2). The weights of the model were calculated by Yaahp software, and data superimposition and processing were performed in ArcGIS 10.5.

DRASTIC model

The DRASTIC model was developed by Aller et al. (1985), and it was found to be applicable for GVM in arid and semi-arid areas by several hydrogeologists (Nazzal et al., 2019; Dizaji et al., 2020; Taghavi et al., 2022; Patel et al., 2022). Seven important hydrogeological indicators are considered in this model, including depth to the groundwater table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C). These indicators are assigned different weights, and the rate values

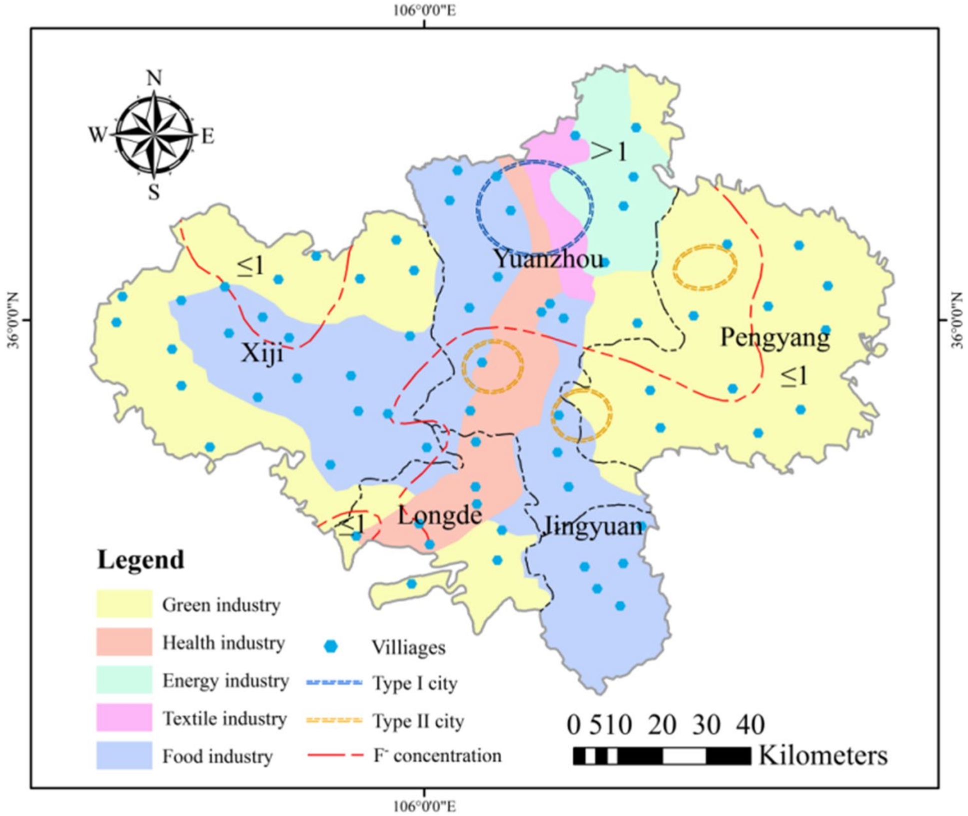


Fig. 3 Urban development and groundwater environmental problem of the study area

are assigned from 1 (least significant) to 10 (most significant) for each indicator (Ata et al., 2018; Khashei-Siuki et al., 2020). The groundwater vulnerability index (GVI) is calculated as Eq. (1), the higher the GVI, the higher the groundwater vulnerability.

$$DRASTIC \cdot \text{index(DI)} = \sum\nolimits_{i=1}^{7} R_i W_i \tag{1}$$

Where: DI is the value of GVI in DRASTIC model, R_i is the rate value of the i-th indicator, and W_i is the weight of the i-th indicator.

AHP method

AHP method was conceived to solve multi-criteria decision making problems (Wu and Yu, 2021). The judgment matrix was constructed by the importance provided by experts (Appendix 3). The eigenvector of the judgment matrix is used as the weight of each indicator. By calculating the judgment matrix, the corresponding weight of each indicator are obtained. The calculation formula is shown as Eq. (2) and Eq. (3).

$$CI = \frac{\lambda_{\max} - m}{m - 1} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

Where: CI is the consistency index, $\lambda_{\max}$ is the maximum eigenvalue, m is the number of indicators, and RI is the average random consistency index.

According to the AHP method, the GVI is calculated by Eq. (4).

$$AHP - DRASTIC \cdot \text{index(AI)} = \sum\nolimits_{i=1}^{7} V_i W_i \tag{4}$$

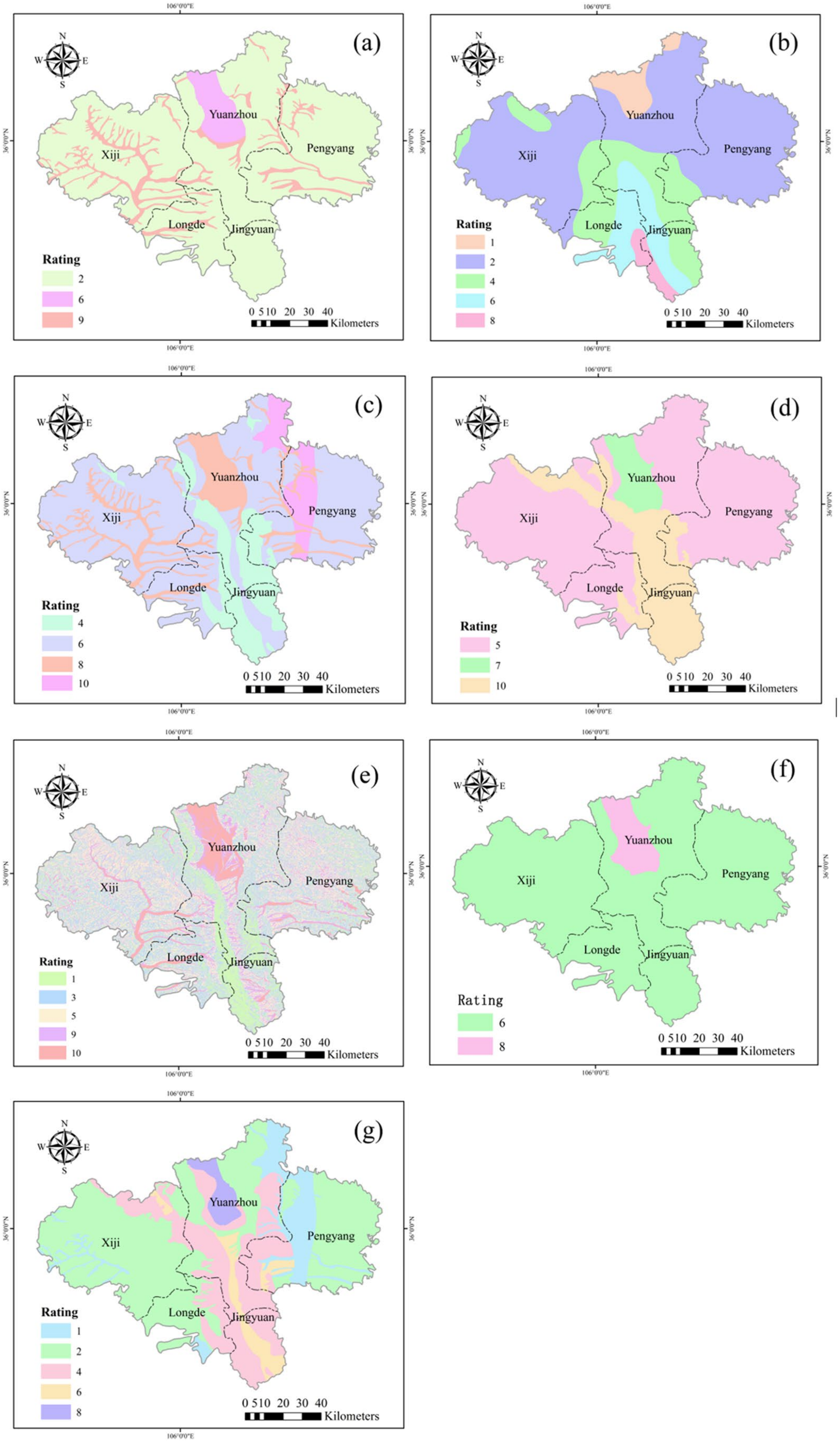
Where: AI is the value of GVI in AHP-DRASIIC model, V_i is the rate value of the i-th indicator, and W_i is the weight of the i-th indicator.

Variable weight theory

VW is an integrated decision-making method pioneered by Wang et al. (1985). The VW strives to make the weight of indicators change with the rate value of indicators, so that the weight of indicators can closely reflect the role of corresponding indicators in decision-making.

The state variable weight vector is defined by Eq. (5).

$$S_i = \left(x_i\right)^{\alpha - 1} \tag{5}$$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◂**Fig. 4** The thematic map of the indicators: (**a**) depth to groundwater table, (**b**) net recharge, (**c**) aquifer media, (**d**) soil media, (**e**) topography, (**f**) impact of the vadose zone, (**g**) hydraulic conductivity

The calculation method of the variable weight vector is shown as Eq. (6).

$$W_i' = \frac{W_i S_i}{\sum_{i=1}^{n} W_i S_i} \quad (6)$$

Where: x_i is the rate value of the i-th indicator, S_i is the state variable weight vector of the i-th indicator, α is the equilibrium coefficient, W_i is the constant weight of the i-th indicator, and W_i' is the variable weight of the i-th indicator. In this study, α is assigned a value of 0.2 (Huang et al., 2022).

Finally, the GVI is given by Eq. (7).

$$VW - DRASTIC \cdot \text{index(VI)} = \sum_{i=1}^{n} w_i' x_i \quad (7)$$

Where: VI is the value of GVI in VW-DRASTIC model, x_i is the rate value of the i-th indicator, and W_i' is the variable weight of the i-th indicator.

Spearman correlation coefficient

Using Spearman correlation coefficient between nitrate content and groundwater vulnerability is an effective validation method to ensure the model performance of GVM (Lin et al., 2021). The Spearman correlation coefficient is a good way to measure the closeness between two variables, the specific equation is shown as Eq. (8).

$$\rho = 1 - \frac{6\sum_{i=1}^{N} d_i^2}{N\left(N^2 - 1\right)} \quad (8)$$

Where: ρ is the value of Spearman correlation coefficient, d_i is the rank difference between the ranking of No_3^- at point i and the ranking of groundwater vulnerability, N is the number of groundwater samples (Appendix 3).

Results

Rating values of indicators

Depth to groundwater table (D)

The D reflects the distance of contaminant migration from the surface to the aquifer, and helps to determine the time of contaminant contact with the surrounding media. Usually, the deeper the groundwater is buried, the greater the chance of contaminant attenuation. Based on the data of the study area, the D can be classified into 0-10, 10-50 and >50m. According to the ranges defined by Aller et al. (1985), the rate values were assigned of 9, 6 and 2, respectively, and the weight is 5 in DRASTIC model (Fig. 4a).

Net recharge (R)

Contaminants can be carried into the aquifer by water recharge. Therefore, the R is the main carrier of contaminant transport to aquifers. In general, the greater the recharge, the greater the potential for groundwater contamination. Since the climate of the study area is arid and the main source of groundwater recharge is precipitation, the annual average of rainfall is used to represent R. In this study, R was classified into 400-450, 450-500, 500-550, 550-600 and >600mm. The rate values were assigned of 1, 2, 4, 6, and 8, respectively, and the weight is 4 in DRASTIC model (Fig. 4b).

Aquifer media (A)

The A is a reflection of the ability of the aquifer to control the attenuation of contaminants (Yu et al., 2022). Since different types of A have different sizes of particles and pores, they can significantly affect the diffusion rate of contaminants. The larger the particles or fractures of A, the more permeable it is and the less dilutive to contaminants. According to the ranges defined by Aller et al. (1985), the aquifer media in the study area were assigned a rate value of 4 for metamorphic, 6 for sandstone, 8 for sand and gravel, and 10 for karst limestone. The weight in DRASTIC model is 3 (Fig. 4c).

Soil media (S)

The S is the top of vadose zone that has significant biological activity, where has a significant impact on the infiltration of contaminants. Generally, the smaller the soil particles, the weaker the characteristics of swell-shrink. Thus, it leads to a reduction in the amount of contaminants that enable reach the aquifer. Based on the data of S in the study area, loess was assigned a rate value of 5, shrinking and aggregated clay of 7, and gravel of 10, and the weight is 2 in DRASTIC model (Fig. 4d).

Topography (T)

The T is the change in surface slope. The degree of T determines whether contaminants are washed away or have sufficient time to seep into the ground within a certain area. In this study, T is divided into five classes ranging from 0-2°, 2-6°, 6-12°, 12-18°, and >18°, the rate values were assigned of 10, 9, 5, 3, and 1, respectively, and the weight is 1 in DRASTIC model (Fig. 4e).

Impact of the vadose zone (I)

I refers to the part between the ground and the groundwater level. This zone is the main site of dilution, biodegradation, neutralization, and chemical reactions of contaminants before they enter the aquifer, thus influencing the groundwater vulnerability. According to the ranges defined by Aller et al. (1985), the I was assigned a rate value of 6 for sandstone and limestone, 8 for sand and gravel. The weight in DRASTIC model is 5 (Fig. 4f).

Hydraulic conductivity (C)

C is the capacity of the aquifer to pass through groundwater, which reflects the hydraulic transport properties of the aquifer. Usually, the higher the C, the easier it is for contaminants to infiltrate the aquifer. In this study, the gushing capacity of a single well is used to represent C (WU et al., 2018). In this study, C is divided into five classes ranging from 0-10, 10-100, 100-500, 500-1000, and >1000m^3/d, the rate values were assigned of 1, 2, 4, 6, and 8, respectively, and the weight is 3 in DRASTIC model (Fig. 4g).

The results from the original DRASTIC model

The thematic maps were overlaid in ArcGIS 10.5, and the GVI of each cell was calculated by Eq. (1). Then, the groundwater vulnerability was classified according to the magnitude of the GVI. The higher the rank, the higher the risk of groundwater contamination. In this study, the GVI was calculated as 73-166 in the DRASTIC model, and it was classified into five classes by using the natural breakpoint method, namely very low, low, medium, high and very high vulnerability (Fig. 5a).

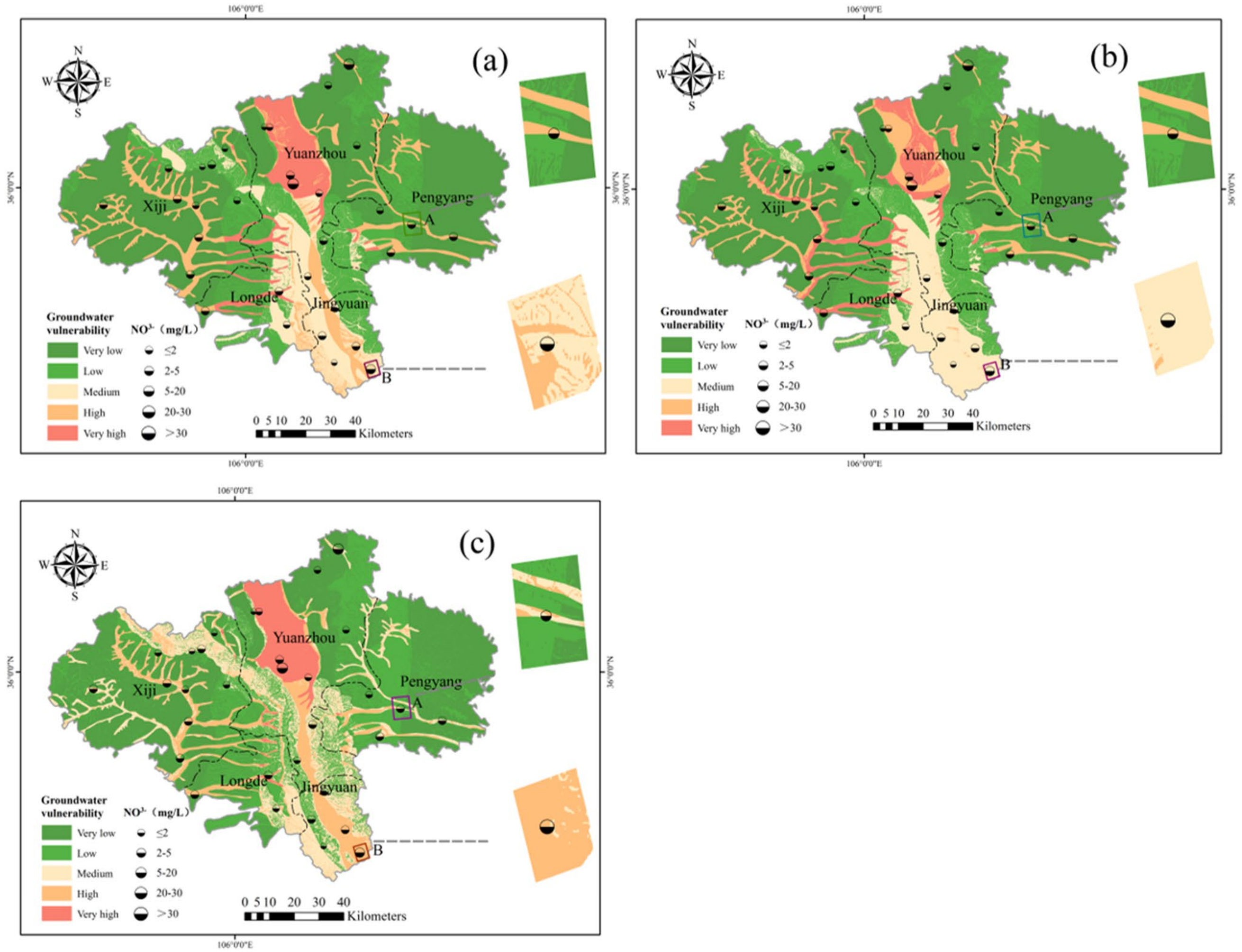

Fig. 5 Results of groundwater vulnerability map: (**a**) DRASTIC model, (**b**) AHP-DRASTIC model, (**c**) VW-DRASTIC model

The results from the AHP-DRASTIC model

Different from subjective weighting, AHP is based on the pair-wise comparison matrix to compare the importance of different indicators. In the improved AHP-DRASTIC model, the initial weights of the seven indicators were modified by using the AHP method (Table 1). The CR value is 0.01, which is satisfied with the consistency requirement, indicating reasonable results (Saaty, 2003). The GVI was calculated by Eq. (4), and the GVM was drawn by using the natural breakpoint method (Fig. 5b).

The results from the VW-DRASTIC model

The VW is to amplify the influence of low-value indicators by increasing their weight, so that the risk represented by the indicators can be objectively reflected in groundwater vulnerability (Teng et al., 2018). The GVI was calculated according to Eq. (7). The results show that the distribution of groundwater vulnerability calculated by the VW-DRASTIC model is more reasonable (Fig. 5c). As the groundwater vulnerability decreases, the increase trend of area is more gentle compared with other models (Appendix 4).

Discussion

Distribution of groundwater vulnerability

It can be seen from Fig. 5a that the very high vulnerability areas are mainly distributed in the northern part of Yuanzhou District and the north-central part of Longde County, with an area of 232.46 km^2 (2.21%). The high vulnerability areas are mainly distributed in Yuanzhou District, Xiji County, Pengyang County and Jingyuan County, with an area of 883.07km^2 (8.41%). The medium vulnerability areas are mainly distributed in the south of mountainous area, including Yuanzhou District, Longde County and Jingyuan County, with an area of 358.96km^2 (3.42%). The low vulnerability areas are mainly distributed in the southern part of Yuanzhou District, Longde County and Pengyang County, with an area of 2108.36km^2 (20.08%). The very low vulnerability areas are mainly distributed in the northern part of Yuanzhou District, western of Xiji County and eastern of Pengyang County, with an area of 6917.15km^2 (65.88%). According to the GVM, the high and very high vulnerability areas are mainly distributed in Yuanzhou district, with fragmented distribution in Xiji County, Longde County and Pengyang County. It indicates that the groundwater in these areas is most vulnerable to the effects of contamination. The D in these areas is less than 50m and the A is mainly consisted of sand and gravel, which represents the high net recharge conditions in these areas. The area covered by very

Table 1 Weight of different models

Rate value of indicators	Weight of DRASTIC model	Weight of AHP model	Weight of VW-DRASTIC model	Rate value of indicators	Weight of DRASTIC model	Weight of AHP model	Weight of VW-DRASTIC model	Rate value of indicators	Weight of DRASTIC model	Weight of AHP model	Weight of VW-DRASTIC model
R	4	0.19		T	1	0.05		C	3	0.10	
1			0.43	1			0.50	1			0.43
2			0.25	3			0.21	2			0.25
4			0.14	5			0.14	4			0.14
6			0.10	9			0.09	6			0.10
8			0.08	10			0.08	8			0.08
A	3	0.12		D	5	0.31		S	2	0.08	
4			0.36	2			0.58	5			0.43
6			0.26	6			0.24	7			0.33
8			0.21	9			0.18	10			0.25
10			0.17								
I	5	0.16									
6			0.56								
8			0.44								

low vulnerability is the largest, mainly distributed in the north and east of the study area, and these areas are not susceptible to the influence of contamination. Due to the high depth and low recharge rate, D in these areas are typically above 50m, reducing the probability of contamination.

Comparison the results of different model

Although the improved AHP-DRASTIC model optimized the weight of indicators in groundwater vulnerability assessment. However, it is not reasonable to apply the same weight to an indicator throughout the study area, and the model needs to be improved in this regard. It can be seen from Table 1, on the basis of a constant weight, the larger the value of the indicator, the smaller its weight after VW. On the contrary, the smaller the value of the indicator, the greater its weight after VW. The VW links the weight of indicators to their value and gives more reasonable weight to different values. And comparing the GVM of constant weight with variable weight, it can be seen that the results are generally consistent, but there are some differences in local areas.

In this study, two typical inconsistent areas were selected to analyze the influence of VW on the assessment results (Fig. 5a-c). In area A, the rate values of D, R, A, S, T, I and C are 9, 2, 8, 5, 3 6 and 1 respectively. The variable weight of D is smaller than its constant weight, while the weight of others is the opposite. Compared with other assessment units, the incentive effect caused by the variation of weight in this unit is greater. Therefore, the groundwater vulnerability in DRASTIC model and AHP-DRASTIC model are high vulnerability, while the groundwater vulnerability in VW-DRASTIC model is medium. The level of No_3^- is III at the water quality sample point corresponds to medium vulnerability, which verifies the reasonableness of the VW-DRASTIC model. In area B, the rate values of D, R, A, S, T, I and C are 2, 4, 6, 10, 5 6 and 6 respectively. The variable weight of R and C are smaller than their constant weight, and the others are the opposite. Compared with other assessment units, the penalty effect caused by the variation of weight in this unit is greater. Therefore, the groundwater vulnerability in DRASTIC model and AHP-DRASTIC model are medium vulnerability, while the groundwater vulnerability in VW-DRASTIC model is high. The level of No_3^- is IV at the water quality sample point corresponds to high vulnerability, which once again verifies the reasonableness of the VW-DRASTIC model. The comparative analysis of constant weight and variable weight showed that the VW-DRASTIC model can better reflect the complex groundwater vulnerability assessment process under the influence of multiple indicators, and the results are better than the constant weight vulnerability assessment.

Model Validation

Although groundwater does not contain nitrate in its native environment, as human activities increase, large quantities of effluent containing No^{3-} seep down into it. Therefore, the degree of contamination of an area can be visually reflected by the concentration of No_3^-. To validate the model accuracy, the Spearman correlation coefficients was used to validate and compare the results of three models. The correlation coefficient of DRASTIC model is 0.71, AHP-DRASTIC model is 0.75, and VW-DRASTIC model is 0.83.

According to Spearman correlation coefficient criteria classification (Spearman et al., 1904), the results were classified as uncorrelated (<0.3), weakly correlated (0.3-0.5), moderately correlated (0.5-0.8), and strongly correlated (≥0.8) (Appendix 4). The results of the Spearman correlation coefficient showed that all the models could describe the distribution of groundwater vulnerability accurately. Among them, the VW-DRASTIC model is the best, followed by the AHP-DRASTIC model and DRASTIC model. The DRASTIC model gave the smallest degree of correlation. The correlation coefficients of AHP-DRASTIC and VW-DRASTIC models are increased, indicating that the performance of the optimized weights was improved by model modification. Meanwhile, according to the classification of Spearman correlation coefficient, the DRASTIC model and AHP-DRASTIC model are moderately correlated while the VW-DRASTIC model is strongly correlated. The VW significantly improves the correlation of groundwater vulnerability in the study area. The optimized weighting method is more accurate and reasonable than the original method.

Single-indicator sensitivity analysis

Single-indicator sensitivity analysis can be used to check the spatial importance of each indicator and improve the uncertainty of model accuracy (Huang et al., 2022). The calculation method for effective weight is shown in Eq. (9).

$$E_i = \frac{r_i \times w_i}{V} \tag{9}$$

Where: E_i is the effective weight of the i-th indicator; r_i and w_i are the rating and weight of the i-th indicator, respectively; V is the vulnerability index.

The analysis results showed that VW significantly increased the effective weight of D and decreased the effective weight of A. The effective weights of other indicators were close to the theoretical weights, indicating that the accuracy of the VW-DRASTIC model was relatively high (Table 2). In Table 2, the theoretical weight is the constant weight calculated by the AHP-DRASTIC model. The

Table 2 Results of single-indicator sensitivity analysis

Indicator	Theoretical weight (%)				Effective weight (%)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
D	13.39	52.02	19.88	8.50	2.24	14.06	33.72	3.10
R	2.90	21.09	9.86	2.55	0.40	2.34	10.04	0.32
A	11.02	31.78	20.23	4.64	5.62	17.67	10.74	3.13
S	5.74	23.41	11.33	3.43	10.15	25.05	12.82	4.69
T	0.84	14.58	7.36	3.71	0.46	7.92	4.05	2.42
I	14.37	35.18	24.88	3.35	18.59	28.41	20.28	1.19
C	1.63	16.96	6.20	2.95	0.41	5.09	11.91	0.79

effective weights of D, R, S, and C in the VW-DRASTIC model (33.72%, 10.04%, 12.82% and 11.91%, respectively) are greater than the theoretical weights (19.88%, 9.86%, 11.33% and 6.20%, respectively), and the other indicators appear to have lower effective weights than the theoretical weights. In the AHP-DRASTIC model, the indicators with higher weights are D, A, and I (19.88%, 20.23% and 24.88%, respectively). In the VW-DRASTIC model, the indicators with greater weights are D and I (33.72% and 20.28%, respectively). The effective weights and theoretical weights of D and I are relatively large, indicating the importance of the accuracy of these data for vulnerability assessment. Among them, the largest effective weight of D indicates that D has the greatest impact. Figure 5 also shows this influence.

Suggestions for the sustainable development of groundwater

Long-term consumption of highly fluoridated groundwater can seriously endanger human health and lead to diseases such as fluorosis and stomach cancer (Chen et al., 2021). According to the China Groundwater Quality Standard, the limit value of F^- is 1.0 mg/L in groundwater. Based on the results of GVM, the assessment principles for sustainable development of groundwater in the study area were proposed in conjunction with the distribution of F^- and urban development planning (Appendix 5). The study area was divided into key monitoring area, reasonable exploitation area, scale exploitation area, priority relocation area, and improvement

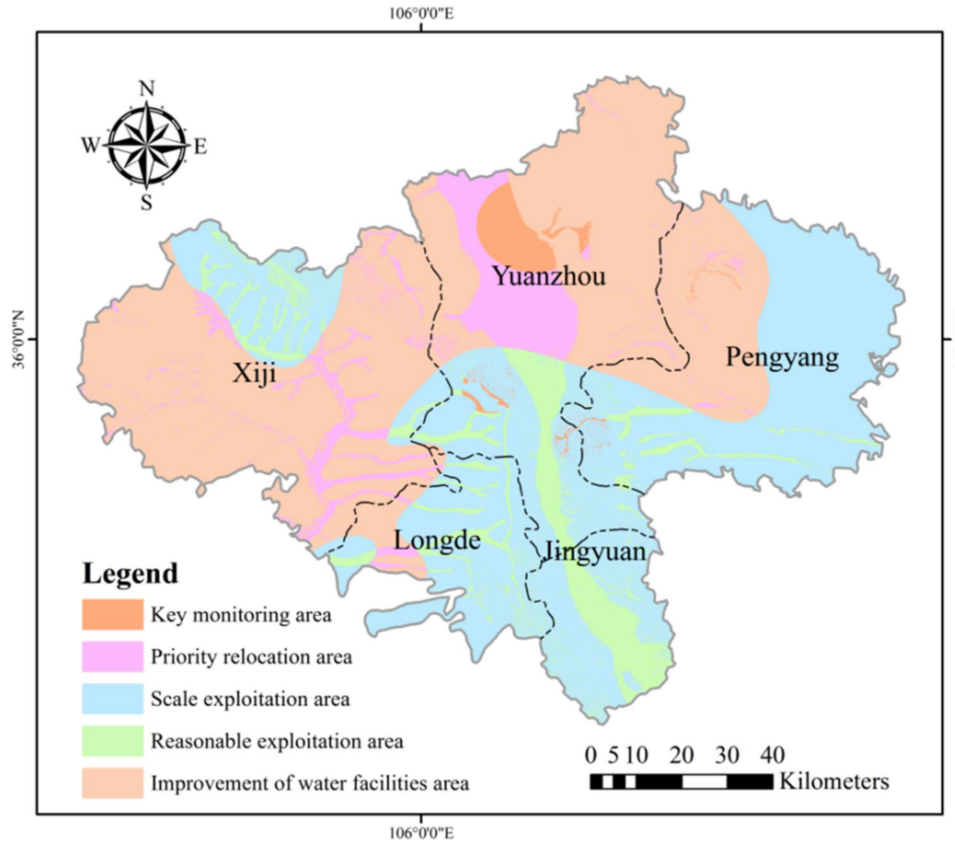

Fig. 6 Groundwater management zoning map of the study area

of water facilities area (Fig. 6). The following suggestions were made for further groundwater management.

(1) The villages in Xiji County, Longde County, Yuanzhou district where the groundwater vulnerability is high or very high, and $F^{-}>1$ mg/L should priority relocation. And the villages that cannot be relocated temporarily should promote projects (such as eaves catchment project, etc) to protect the quality of water for the residents' production and living.
(2) Improve the water facilities in the remaining areas with high or very high vulnerability of groundwater, enhance the use of surface water, and gradually promote urbanization after completing the relocation of priority areas.
(3) Since there are high and very high vulnerability areas of groundwater in Type I and II cities, advance planning should be done before urban construction. In the meantime, when developing and utilizing groundwater, avoid these areas as much as possible.
(4) In the process of Type I and II urban planning, water resources should be used in multiple channels. Meanwhile, the construction of facilities such as rainwater collection (Yu et al., 2021), recycled water recycling within the city should be strengthened.

Conclusion

In this study, DRASTIC, AHP-DRASTIC, and VW-DRASTIC model were used to assess groundwater vulnerability in Guyuan City. The main findings are as follows:

(1) The accuracy of the optimized DRASTIC model results was all improved to different degrees, indicating the importance of optimizing the DRASTIC model.
(2) The VW-DRASTIC model overcomes the deficiency of using fixed weight and gives the best correlation among the three models, which is more suitable for Guyuan city.
(3) This study proposes a method that is applicable to the sustainable development of groundwater management in Guyuan City. Other areas can modify it according to the actual situation.
(4) Considering the complexity of the actual situation, effective engineering and non-engineering measures should be taken in practice to monitor groundwater quality in order to prevent further groundwater contamination.
(5) Due to the wide range of indicators affecting groundwater vulnerability, as much data as possible should be collected for further research in order to obtain more accurate assessment results.

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Declarations

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