GROUNDWATER VULNERABILITY ASSESSMENT FOR NITRATE POLLUTION BASED ON MODIFIED DRASTIC METHOD: A CASE STUDY IN SOUTHWEST CHINA

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(Received 1st Jan 2024; accepted 13th Mar 2024)

Abstract. Groundwater vulnerability assessment using DRASTIC is an important tool for groundwater pollution prevention and management. However, traditional DRASTIC methods are not suitable for accurate assessment of groundwater vulnerability in hilly and mountainous regions of southern China. The improved method in this paper retains the basic structure of DRASTIC, and obtains more accurate evaluation results by adding parameters and modifying parameter rating Scale and weights. Comparison of the modified DRASTIC-LY vulnerability map with the map of original DRASTIC-LY method revealed differences in 28.6% of the study area. The risk map shows that the very high vulnerability area decreased from 3.6% to 2.1%, while the high vulnerability area increased from 9.4% to 5.6%. Areas with low vulnerability increased by 10.7%, while areas with medium vulnerability increased by 4.9%. The areas with very high groundwater vulnerability are mainly distributed at the confluence of the Han River and Baojiang River, the areas with high groundwater vulnerability are mainly distributed in the southeast of Mian County, Nanzheng County, Chenggu County and Yang County, while the areas with low groundwater vulnerability are distributed in the northern part of the basin. The Pearson's correlation factor was 0.55 in the original DRASTIC model, 0.58 in the DRASTIC-LY method, and 0.65 in the modified DRASTIC-LY model, which indicated that the revised DRASTIC-LY model was more appropriate than that constructed by the original model. The vulnerability map of the DRASTIC-LY model can assist government planning and decision-making departments to facilitate water resource protection and water quality control.

Keywords: *Aquifer contamination, DRASTIC model, DRASTIC-LY model, nitrate pollution, Hanzhong Basin*

Introduction

In recent years, with economic development and urban expansion, the pressure on the water resources of many countries in the world is gradually increasing (Gemail et al., 2017). As the main natural resource of urban drinking water, groundwater is now facing increasingly serious pollution problems (Tiwari et al., 2016; Tian et al., 2020). In Iran, the groundwater pollution problem is very serious due to population growth and agricultural development (Al-Mallah and Al-Qurnawi, 2018). Argentina's agricultural expansion due to rising international commodity prices and the introduction of new technologies has increased the pressure on natural resources, Land use, especially threats to the quality of groundwater (McLay et al., 2001). China has encountered such problems without exception, coupled with low water resource utilization and large pollution emissions, resulting in an increasingly severe water environment in China, bringing a profound environmental and ecological crisis (Mogaji and San Lim, 2017). Therefore, to protect and improve the groundwater environment and realize the sustainable development and utilization of groundwater resources, we must first determine the areas where groundwater is vulnerable to pollution, that is, the main factors that affect the vulnerability of groundwater in each region.

The term groundwater vulnerability was first proposed by Margat in 1968. In 1987, the International Conference on Soil and Groundwater Vulnerability believed that groundwater vulnerability refers to the sensitivity of groundwater to external sources of pollution and is an inherent characteristic of aquifers. In 1993, the National Research Council of the United States defined groundwater vulnerability as the tendency and possibility of pollutants to reach a specific location above the uppermost aquifer. The groundwater vulnerability is divided into two categories: one is Intrinsic Vulnerability, and the other is Specific Vulnerability. The commonly used models for groundwater vulnerability are DRASTIC (Rezaei et al., 2018; Hao et al., 2017), SINTACS (Baghapour et al., 2016; Hu et al., 2018), GOD (Maqsoom et al., 2020), AVI (Sadat-Noori and Ebrahimi, 2016), SYNTACS (Sinha et al., 2016), SI (Joshi and Gupta, 2018), and EPIK (Ahada and Suthar, 2018). The DRASTIC model is currently the most widely used method in groundwater vulnerability assessment. It was proposed by the U.S. Environmental Protection Agency in 1987 (Aller et al., 1987). It has been applied to groundwater fragility assessment work in various parts of the United States, and has achieved good results, and has been adopted by Canada, South Africa, and European countries. China began to introduce this method in the 1990s. In recent years, the number of scholars conducting research on this method has been increasing, and it has been applied in many places across the country.

In 2008, Wen et al. (2009) used professional model (DRASTIC model) and geographic information system (GIS) technology to evaluate the vulnerability of shallow groundwater in the Zhangye Basin. In 2012, Yin et al. (2013) used the DRASTIC model in the GIS environment to construct a zoning map of groundwater vulnerability in the Ordos Plateau. The results show that 24.8% of the study area has high pollution potential, 24.2% has medium pollution potential, 19.7% has low pollution potential, and the remaining 31.3% of the area has no risk of groundwater pollution. In 2016, Wu et al. (2016) proposed the DRTILSQ model, based on DRASTIC and considering human factors, to assess the risk of groundwater pollution in the northern suburbs of Yinchuan City. In 2017, Yang et al. (2017) used a modified DRASTIC model to assess the vulnerability of groundwater in the Jianghan Plain. The results show that the improved DRASTIC model has a great improvement compared with the conventional model. After the amendment, the correlation coefficient was significantly increased from 41.07% to 75.31%. In 2017, Li et al. (2017) conducted a groundwater vulnerability assessment in the plain area of Tianjin City based on the DRASTIC model and GIS technology containing seven hydrogeological parameters. In 2018, Wu et al. (2018) used a modified DRASTIC model (AHP-DRASTLE model) to assess the vulnerability of groundwater to pollution in Beihai, China, to support the protection of groundwater resources in coastal areas of China. In 2018, He et al. (2018) used the DRACILM model to assess the vulnerability of nitrate pollution in the western

Liaohe Plain. The correlation between vulnerability class and the concentration of NO_3-N in the DRACILM model improved to 0.649, which was 40.6% higher than that obtained by DRASTIC.

In agricultural areas, the use of chemical fertilizers and pesticides is one of the main reasons for the increase of nitrate and chloride in groundwater (Zenebe et al., 2020). The main sources of nitrate are nitrogen fertilizer, domestic sewage, livestock manure and industrial production (Karan et al., 2018). Chloride is partly derived from mineral fertilizers (potassium chloride in a mixture of nitrogen, phosphorus and potassium) and partly from industrial salt used in road maintenance (Wu et al., 2016). In the past 30 years, the amount of groundwater in Hanzhong City has decreased, and the deterioration of water quality is mainly due to the conversion of large areas of dry land to paddy fields, and the excessive use of pesticides and fertilizers by humans (Tian et al., 2020).

Therefore, it is necessary to evaluate the vulnerability of groundwater to determine the health risks of groundwater and to provide references for groundwater development, utilization and management. The special purpose of this study is to (1) improve the DRASTIC model to include land use types and groundwater resources, with emphasis on the impact of nitrate on groundwater vulnerability; (2) determine the weight, grade and category of each parameter, and establish the relationship between the parameter and the concentration of NO_3-N; (3) validate the model and judge the applicability of the model based on sensitivity analysis. The results of the study will help decision-makers to strengthen management and protection of fragile aquifers, thereby greatly improving the efficiency of water use.

Material and methods

Study area

Hanzhong Basin is located in the southwest of Shanxi Province, China. The study area is between 32 ° 56 ‘and 33 ° 19’ N, and 106 ° 36 ‘and 107 ° 41’ E (*Fig. 1*). It is 116 km long from east to west, 18 km wide from north to south, with an area of 1600 km^2 (Li and Zhang, 2010). Because it is located in a subtropical monsoon climate zone, the climate is mild, humid and dry. The annual average temperature is 13℃-14℃, the highest is 37.5℃, the lowest is 1.2℃, and the annual precipitation is between 800-850 mm (Xiao et al., 2019). Evaporation capacity is 900~1200 mm/a (Vandenberghe et al., 2021). The highest temperature was 37.5℃ which appeared in July, and the lowest was 1.2℃ which appeared in January (Zhang et al., 2019). The basin lies between the Qinling Mountains and Daba Mountains, and the Han River flows out from east to west. The terraces in the basin are obvious, which are mainly divided into five types: flood plain, first terrace, second terrace, third terrace and fourth terrace.

There are 6 tributaries of the Han River, of which the Baohe River, Xushui River and Youshui River on the north bank flow into the Han River from north to south, and the Yudai River, Yangjia River and Lengshui River on the south bank flow into the Han River from south to north. There are 9 large and medium-sized reservoirs and more than 50 small reservoirs distributed throughout the Basin. From northwest to the southeast, the terrain gradually decreases, and the landform gradually transitions from low hills and high plains to river terraces and floodplains. The highest altitude is 651 m, the lowest is 420 m, and the average is about 500 m. The soil of Hanzhong Basin belongs to the yellow brown soil zone of the bauxite region in China, with 10 soil categories, 21 sub categories, 38 soil genera and 97 soil species.

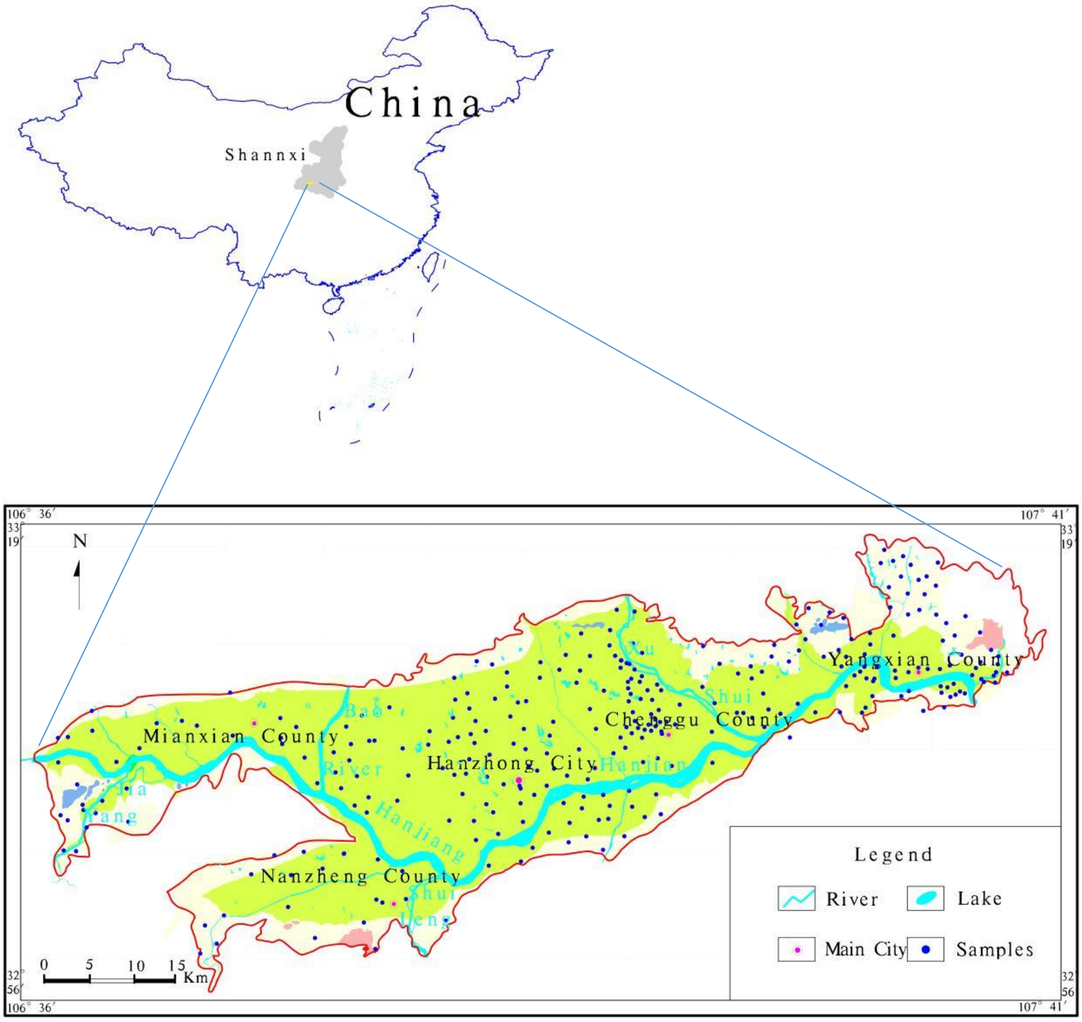


Figure 1. *Location and sampling point distribution map in Hanzhong Basin of China*

Controlled by sedimentary environment and landform, groundwater in the basin is mainly divided into pore water, bedrock fissure water and karst water (*Fig. 2*). Pore water is mainly divided into diving and confined water, which is distributed in Quaternary strata. Affected by the fact that the Quaternary strata are thick in the north and thin in the south, thick in the West and thin in the East, diving aquifers are widely distributed throughout the region. The lithology of the aquifer is mainly composed of alluvial proluvial and alluvial lacustrine sand gravel. Along the banks of each tributary, it is mainly composed of medium fine and medium coarse sand. The thickness of the aquifer is 55~75 m. The buried depth of water level is 0.6~5.5 m in the first terrace and high floodplain, 6~18 m in the second terrace, and 20~35 m in the third terrace and other terraces. Generally speaking, far away from the Han River and its tributaries, the upper burial depth, water yield and distribution characteristics show the law that the water level burial depth changes from shallow to deep, the aquifer particles change from coarse to fine, the water yield property changes from strong to weak, the permeability coefficient changes from large to small, and the aquifer thickness changes from thick to thin. The confined water is widely buried in the Quaternary alluvial lacustrine gravelly medium coarse sand and medium fine sand, mixed with 3-5 layers of cohesive soil. The thickness of the aquifer is about 34.10-46.10 m, and the buried depth of the confined water level is between 6.23-35.07 m. Groundwater in the basin is mainly recharged by surface water and atmospheric precipitation. Bedrock fissure water is mainly distributed in the strongly weathered zone of granite at the bottom of the basin, and also in a small area in the East and south of the basin. The groundwater yield is generally less than 100 m^3/d, which does not have the significance of water supply. Karst water is mainly distributed in the north and west of the basin, with small area and weak water yield. The confined water in the study area moves to the middle of the basin in a gradient of 3~5‰ from the piedmont zone at the edge of the basin along the gradient of the isobaric surface. In the development and utilization of groundwater in the basin, 90.3% of groundwater is used for agricultural irrigation, 4.1% for industrial production, and 3.1% for urban domestic water. Due to the hydraulic connection between surface water and groundwater, pesticides and fertilizers have become the main pollution sources affecting groundwater quality, especially the excessive use of nitrogen and organic pesticides.

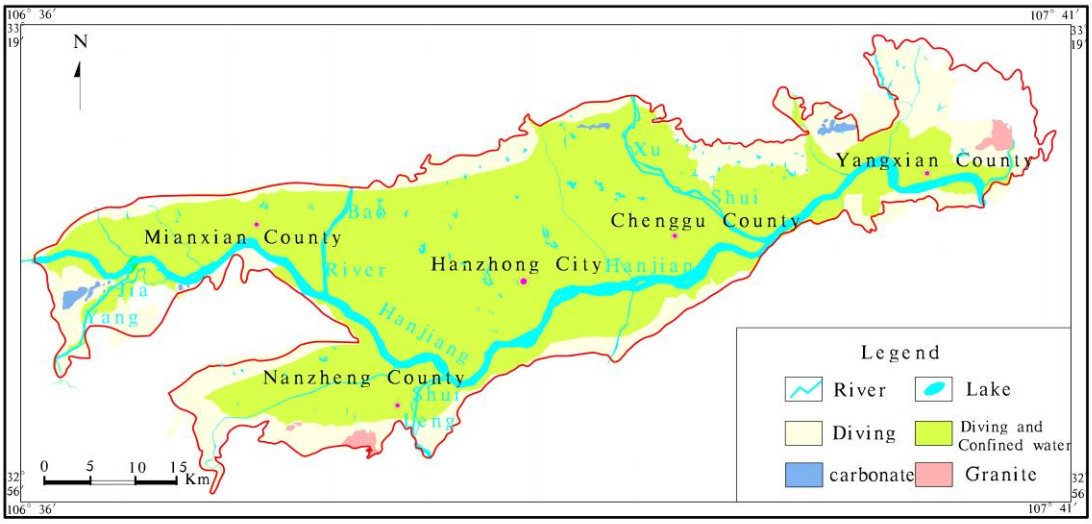


Figure 2. *Groundwater types in the study area*

In order to ascertain the groundwater quality of the basin, 328 shallow groundwater samples were collected from May 2020 to July 2021 (*Fig. 1*). According to the principle of average distribution, the sampling density can reach 2 group/10 km^2 (Tian, 2021).

Methodology

The DRASTIC model was developed by the U.S. Environmental Protection Agency (EPA) to evaluate groundwater pollution potential for the entire United States (Babiker et al., 2005). The acronym DRASTIC stands for the seven parameters used to calculate the DRASTIC index value (*Eq. 1*): the depth to groundwater table (D), net recharge (R), aquifer properties (A), soil properties (S), topography (T), impact of the vadose zone (I), and the hydraulic conductivity of the aquifer (C). Each factor is mainly rated on a scale of 1 to 10, which indicates the relative pollution potential of a given factor (*Table 1*). The seven parameters are then assigned with weights ranging from 1 to 5, reflecting their relative importance (*Table 1*). The DRASTIC index (DI) or vulnerability rating is then computed by applying a linear combination of all factors (Panagopoulos et al., 2006; Mondal et al., 2017):

$$\mathrm{DI} = D_r \cdot D_w + R_r \cdot R_w + A_r \cdot A_w + S_r \cdot S_w + T_r \cdot T_w + I_r \cdot I_w + C_r \cdot C_w \quad \text{(Eq.1)}$$

where D, R, A, S, T, I, and C are the seven parameters and the subscripts r and w are the corresponding rating and weights, respectively. The higher the value of DI index, the greater the groundwater vulnerability to pollution.

Table 1. *Data source and format for the seven parameter data layers*

Parameters	Data source and format	Scale of the map
D	328 monitoring wells, 2020-2021	1:200000
R	precipitation and irrigation data from 2020-2021	1:200000
A	142 hydrogeological drill-hole data, 2020-2021	1:200000
S	50 water penetration test, 2020-2021; World Soil Database (HWSD), 2012	1:200000
T	142 hydrogeological drill-hole data, 2020-2021	1:200000
I	142 hydrogeological drill-hole data, 2020-2021	1:200000
C	142 hydrogeological drill-hole data, 2020-2021	1:200000

More than ten types of data are used to construct the thematic layer of seven parameters of the model (*Fig. 4*). The data format is based on GIS, and ArcGIS 10.2 software is used to perform necessary calculations. The depth to groundwater table (D) was obtained from the water level measurement of 328 shallow groundwater wells in April, 2021. Based on these scattered measured data, a raster map with a pixel size of 20 m is created by using ordinary Kriging interpolation (*Fig. 3a*). Then, according to the definition of DRASTIC model, the depth of groundwater level obtained from the difference is given and assigned a rate of 1 to 10. Net recharge (R) represents the amount of water that reaches the underground aquifer after penetrating the vadose zone. In order to calculate the net recharge parameters, we use the Visual MODFLOW7.0 model. Use hydrological and meteorological data, soil, land use and hydrogeological conditions to calculate R parameters (*Fig. 3c*). The obtained values of net recharge were grouped and rated from 1 to 4. The Aquifer properties (A) refers to aquifer characteristics that affect solute migration and transformation process. The A factor was obtained by using geological map (1:200000), hydrogeological map (1:200000) and 134 borehole data (*Fig. 3d*). Then, the A factor was differed to create parameter map of different hydrogeological units. Finally, the hydrogeological unit were rated from 2 to 10. Soil properties (S) represents the lithological characteristics of the vadose zone and the amount of surface water infiltrating into the groundwater. The Soil media map was mainly based on the global soil database (*Fig. 3e*). The Soil media was rated from 1 to 10 by soil texture. Topography (T) refers to the use of the global digital elevation model (DEM) with a precision of 10 m to determine the percentage slope within a certain range (*Fig. 3f*). Then, according to the slope map, multiple slope equivalent areas were divided and assigned a score from 1 to 10. The influence of vadose zone (I) in DRASTIC model can be defined as the influence of unsaturated zone characteristics. The geological map (200000), hydrogeological map (1:200000) and ecological geological map (1:200000) are used to obtain the impact map of the vadose area (*Fig. 3g*). These data enabled us to accurately depict the cross section of the vadose zone, and then compile it into the DRASTIC model rating system. The hydraulic conductivity (C) of an aquifer indicates the capacity of the aquifer to export and store water. The hydraulic conductivity of the aquifer in the study area is determined by using the pumping experiment and analyzing the hydrogeological data. According to the definition of DRASTIC model, different hydraulic conductivity zones in the study area were assigned with ratings (*Fig. 3h*).

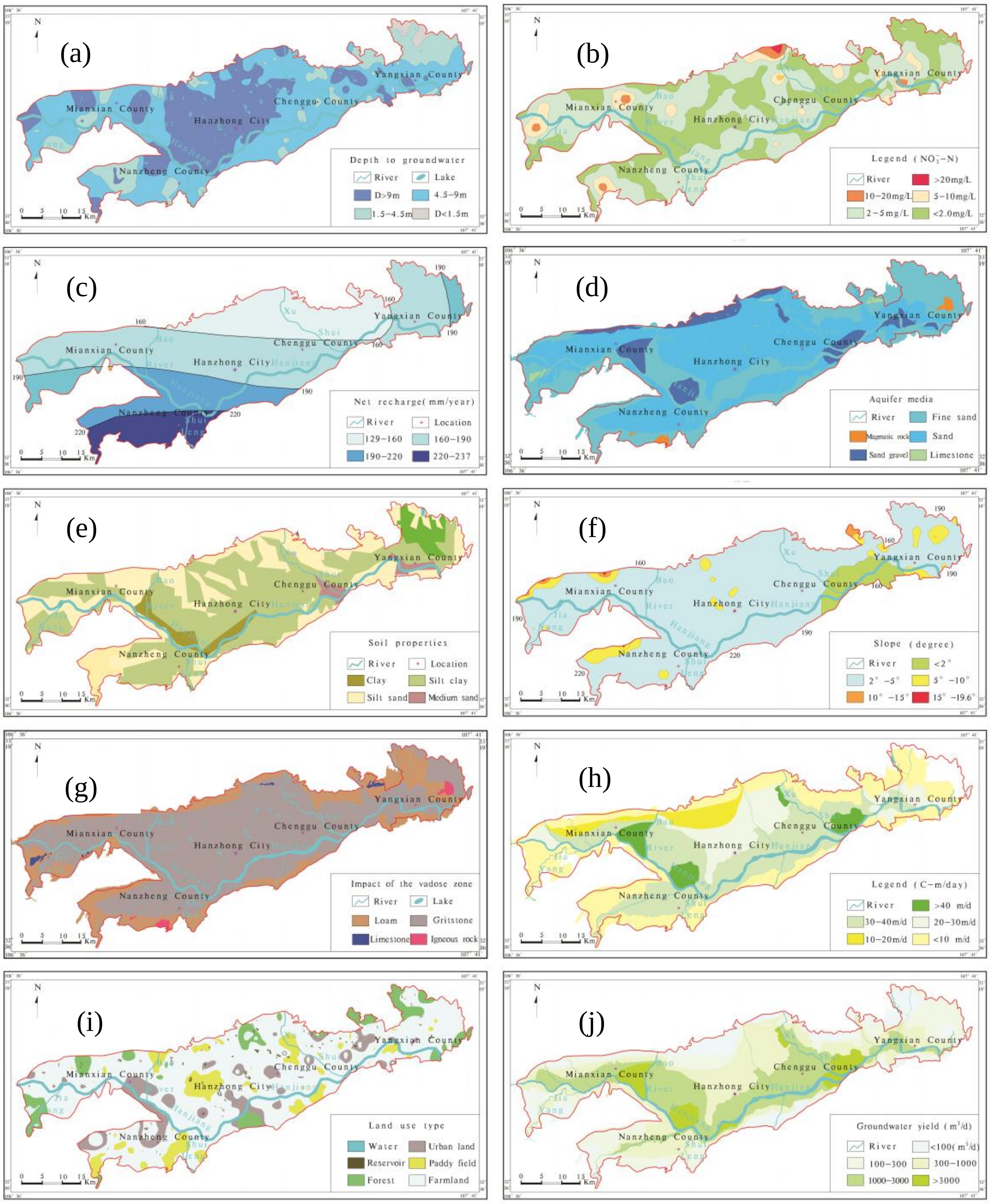


Figure 3. *Seven layers of the DRASTIC-LY model, (a-depth to water, b-NO_3^--N concentration, c-net recharge, d-aquifer media, e-soil, f-topography (slope), g-impact of the vadose zone, h-hydraulic conductivity, i-land use type, and j-groundwater resource yield)*

After the layers of all parameters were created, the value of DI was the weighted sum of the parameters, and the groundwater vulnerability map was obtained by overlaying the thematic maps in ArcGIS (Moghaddam et al., 2018). Generally speaking, the value of DI is between 38 and 183. The smaller the value of DI is, the lower the vulnerability potential is, while the higher the value of DI is, the greater the risk of groundwater pollution in the region (Wei et al., 2021). The DI was divided into four categories, namely very high vulnerability (>153), high vulnerability (153-121), medium vulnerability (121-96), low vulnerability (96-75), and very low vulnerability (<75) (Jhariya et al., 2019; Ahirwar and Shukla, 2018).

DRASTIC-LY model

Based on the original DRASTIC model, in the south of the Qinling Mountains, the potential risks of land use type and groundwater resource yield for pollution identification are mainly considered (Rahman et al., 2008). In agricultural areas, groundwater pollution is mainly caused by human activities and agricultural fertilization, in which the high concentration of nitrate is the main factor affecting groundwater quality (*Fig. 3b*). The land use map was prepared to evaluate the groundwater contamination potential (*Fig. 3i*). The following types of land use were taken into account: Forest, Paddy field, Water, Reservoir, Farmland, and Urban land with ratings 2, 4, 5, 8, and 10 (*Table 2*), respectively (Jafari and Nikoo, 2019). The initial weight of land use parameters in DRASTIC-LY model is set to 5. The model of groundwater resource yield (Y) in a region indicates the rate of groundwater renewal and the ability of self-purification. Based on the systematic analysis of hydrogeological conditions, the threshold of Y parameter in the study area was determined through a large number of pumping tests and reinjection tests (*Fig. 3j*). The initial weight of Y parameters in DRASTIC-LY model is set to 3. The values of DI in DRASTIC-LY model range from 54 to 260 in theory (Mondal et al., 2019).

Table 2. *Rating scales for land use types and model of groundwater resource yield*

Land use type		**Model of groundwater resource yield**	
Types	**Value**	**Range (m^3/day)**	**Value**
Forest	2	< 100	2
Paddy field	4	100-300	3
Water, Reservoir	5	300-1000	5
Farmland	8	1000-3000	7
Urban land	10	> 3000	9

Sensitivity analysis

The DRASTIC model involves a large number of measured data layers, which is regarded as a major advantage (Al-Abadi et al., 2017). With the increase of the number of data layers and the dispersion of weights, the calculation error or uncertainty of a single parameter will have a smaller impact on the final evaluation results. Sensitivity analysis provides information about the impact of ratings and the weight assigned to each factor considered in the model to judge the objectivity of subjective factors (Khan and Jhariya, 2019). The map removal sensitivity analysis and the single-parameter sensitivity analysis are two effective analysis methods. In this study, single parameter sensitivity analysis was used to evaluate the impact on vulnerability index by comparing the effective weight and theoretical weight of each DRASTIC parameter (*Eq. 2*). The effective weight of parameters is calculated as follows (Hosseini and Saremi, 2018):

$$W = \left(\frac{P_r \cdot P_w}{DI}\right) \times 100 \qquad \text{(Eq.2)}$$

where Pr is the rating value of each parameter, Pw is the weight of each parameter, W is the effective weight of each parameter, and DI is the vulnerability index.

Results and discussion

Applying the DRASTIC model to intrinsic vulnerability

The intrinsic vulnerability map of the Hanzhong Basin was created using DRASTIC Model. The vulnerability index of groundwater was calculated on the ArcGIS platform, and the data source is shown in *Table 1*. The weight and rating of vulnerability index were shown in *Table 2*.

The intrinsic vulnerability index (DI) in the Hanzhong Basin was 69-142 and was divided into five classes (Lad et al., 2019; Garewal et al., 2018): very low, medium, high, and very high (*Fig. 4*). The vulnerability classification in the west of the basin is relatively high, which means that this area is more vulnerable to external pollution than other areas; This result is mainly caused by shallow groundwater level, high hydraulic conductivity of aquifer or large proportion of sand and gravel in aquifer and aeration zone. The evaluation results are consistent with the initial concentration map of nitrate (*Fig. 3b*), indicating that the groundwater in this area is vulnerable to human activities. In the central and eastern regions of the basin, due to the shallow groundwater level or high hydraulic conductivity, the vulnerability class is moderate. The low vulnerability areas are scattered, mainly in the north and northeast of the basin. Due to the hydrogeological characteristics of the deep groundwater table, the vadose zone (loam) and aquifer medium (sand), the groundwater vulnerability is low. In general, in the northern, Western and southern regions of the plain, the rapid groundwater runoff, shallow groundwater level and semi open environment are the main reasons for the high vulnerability class. On the contrary, in the northern and northeastern regions of the basin, the main reasons for the low vulnerability class are the deep groundwater level, sluggish flow and closed environment.

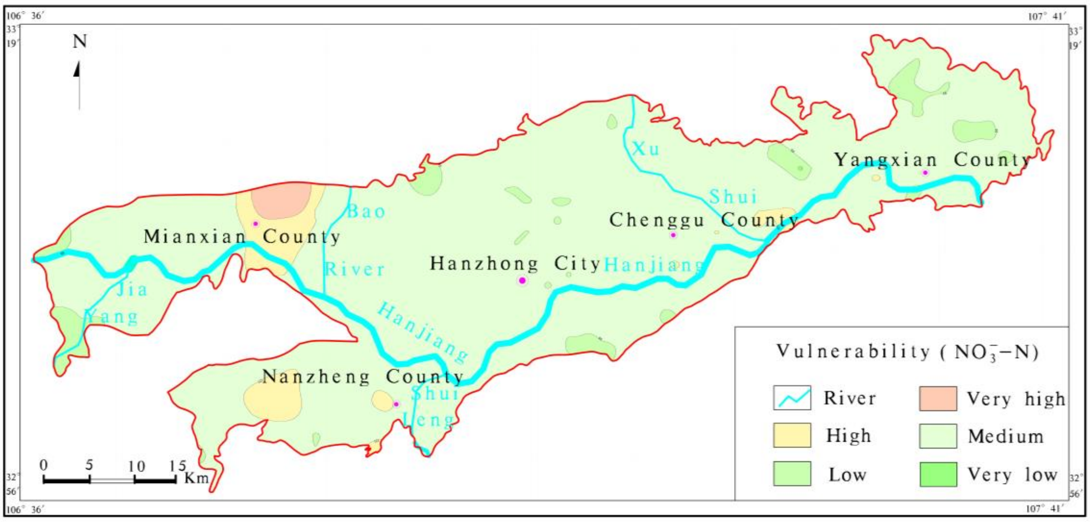


Figure 4. *The map of intrinsic vulnerability based on DRASTIC model*

Assessment of nitrate vulnerability using DRASTIC-LY model

An accurate vulnerability map of the Hanzhong Basin was obtained using the DRASTIC-LY model. Due to the importance of land use types and groundwater resource yield patterns in reflecting human activities, their weights were set to 5 and 4, respectively. The weight and rating of vulnerability index were shown in *Table 2*.

The accurate vulnerability index (DI) in the Hanzhong Basin was 87-228 and was divided into five classes: very low, medium, high, and very high (*Fig. 5*). The southeastern part of Mian County, Nanzheng County, the eastern part of Chenggu County, and the western part of Yangxian County have higher groundwater vulnerability levels, which means that this area is more vulnerable to external pollution than other areas. In the eastern part of Mian County, pumping groundwater along the river and the accumulation of pollutant groundwater along the groundwater flow are the main reasons for the high vulnerability level; In Nanzheng and Chenggu counties, land use type is the main cause of high vulnerability; In western Yangxian County, groundwater vulnerability is mainly affected by groundwater resource yield (*Fig. 3j*) and aquifer medium (*Fig. 3d*). In the north of the Xushui River and the west of Mian County, the nitrate concentration is high, but due to the slow groundwater flow rate, low development and utilization potential, and aquifer medium, the groundwater vulnerability classification is moderate. In the central, northeastern and western regions of the Hanzhong Basin, the groundwater vulnerability classification is low, which is consistent with the evaluation results using the DRASTIC model.

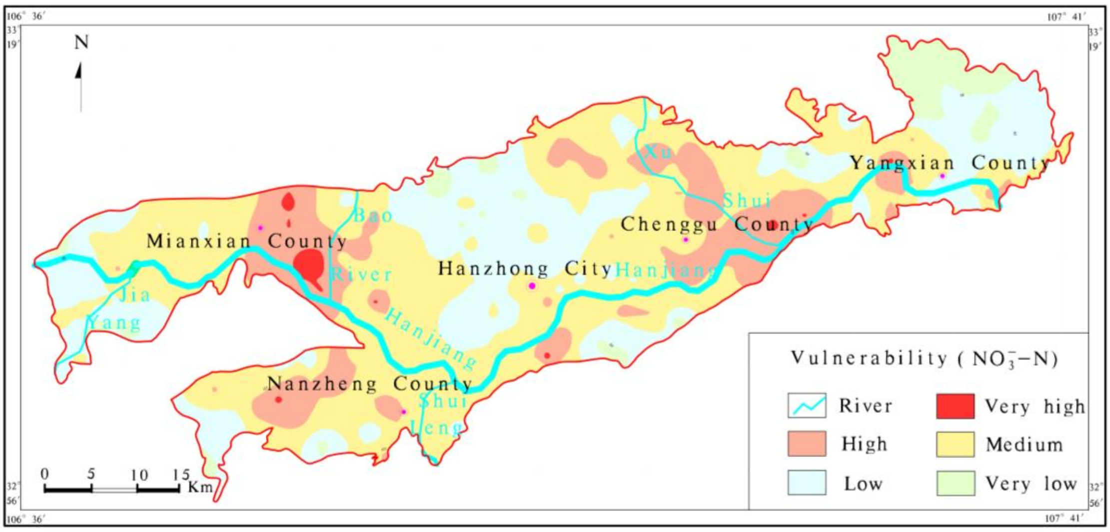


Figure 5. *The map of nitrate vulnerability based on DRASTIC-LY model*

Revising the rating scale of each parameter

Increasing the rationality of rating scales is one of the most effective ways to improve the accuracy of specific vulnerability assessment results. The classification of each parameter defined in the DRASTIC-LY model was associated with the concentration of NO_3-N using statistical methods for the purpose of optimizing the rating scale. For noncontinuous parameters such as soil type, aquifer medium, vadose zone type, groundwater resource yield, land use type, it is necessary to maintain all existing categories in the area. The original and modified values of the parameters in the DRASTIC-LY model, as well as the nitrate concentrations, are shown in *Table 3*. The ratings for each parameter were modified based on the average nitrate concentration in each category, and the ratings were controlled within a 10-grade scale. The original rating of the net replenishment (4) was smaller than the other parameters (9 and 10), so the revised rating had been appropriately modified to 5. Although the revised parameter ratings are not on 10-grade scale (including 5, 9, and 10), the results will be more reasonable and reliable.

Table 3. *Original and modified values of the DRASTIC-LY parameters*

Depth to groundwater				Net recharge				Aquifer media			
Range (m)	**A**	**B**	**C**	**Range (mm)**	**A**	**B**	**C**	**Aquifer media**	**A**	**B**	**C**
> 9	5	6.07	6.90	< 140	1	1.42	0.90	Fine sand	3	6.43	7.33
4.5-9	7	7.02	10.00	140-170	2	7.87	5.00	Magmatic rock	5	2.35	2.67
1.5-4.5	9	6.79	8.77	170-200	3	6.19	3.93	Sand	6	6.47	7.37
< 1.5	10	6.15	7.06	> 200	4	5.92	3.76	Sand gravel	8	8.66	9.87
								Limestone	9	8.77	10.00
Soil type				**Topography**				**Impact of the vadose zone**			
Soil type	**A**	**B**	**C**	**Range slope (%)**	**A**	**B**	**C**	**Geological formation**	**A**	**B**	**C**
Clay	3	4.57	2.85	> 15	1	3.42	2.29	Loam	2	6.88	9.36
silt clay	4	6.04	3.77	10-15	3	7.46	5.00	Gritstone	4	6.53	8.88
silt sand	8	7.85	4.91	5-10	5	6.69	4.48	Igneous rock	7	3.28	4.46
medium sand	10	7.99	5.00	2-5	9	6.58	4.41	Limestone	9	7.35	10.00
				< 2	10	6.79	4.55				
Hydraulic conductivity				**Land use type**				**Model of groundwater resource yield**			
Range (m/d)	**A**	**B**	**C**	**Type**	**A**	**B**	**C**	**Range (m^3/h)**	**A**	**B**	**C**
< 10	1	7.38	5.00	Forest	2	5.56	5.50	< 100	2	5.92	8.65
10-20	2	5.43	3.67	Paddy field	4	6.75	6.68	100-300	3	6.54	9.56
20-30	3	6.29	4.26	Water, reservoir	5	10.10	10.00	300-1000	5	6.63	9.69
30-40	4	6.35	4.30	Farmland	8	5.75	5.51	1000-3000	7	6.84	10.00
> 40	5	6.27	4.24	Urban land	10	6.44	6.37	> 3000	9	5.89	8.61

A: Original rating; B: Mean concentration of NO_3-N (mg/L); C: Modified rating value

Revising the parameter weights

The larger the weight of a parameter, the more important it is in the model than other parameters (Oroji and Karimi, 2018). Different parameters may have different effects on groundwater vulnerability in different regions. For example, Net recharge and Aquifer media that significantly affect NO_3-N concentrations were assigned low and high weights, respectively. However, it is unclear whether theoretical research is applicable to study area practice. This time, it is necessary to study the weights applicable to the model of this study area. The weights of the model in the previous part of the article are based on the parameters obtained in previous research; In order to optimize the DRASTIC-LY model, the weight of each parameter needs to be recalculated. Using Pearson's (r) correlation, the correlation between each parameter and the mean NO_3-N concentration was calculated to achieve the optimized parameters. According to the maximum weight value (5) specified by the model, the new weighting factor is recalculated. If a parameter is not statistically significant, it will be excluded from the vulnerability equation. As shown in *Table 4*, Pearson's r-values and modified weighting factors can clearly be concluded that the "soil type" and "Topography" parameters are not statistically significant and should be excluded from the vulnerability equation. The insignificant correlation between “NO_3-N” concentration and “topography” suggests that topography has less effect on nitrate concentration in groundwater (Saida et al., 2017). The insignificant correlation between “NO_3-N” concentration and “soil type” means that soil adsorption and chemical reaction to NO_3-N can be neglected (Kozlowski and Sojka, 2019). It can also be seen that the weights for the Depth to groundwater, Land use type and Hydraulic conductivity were not changed. However, the weights of the Impact of the vadose zone and the Net recharge parameters have decreased, although they were still relatively high. In addition, the weights of aquifer media and Model of groundwater resource yield were slightly increased. The changed weight shows their increased importance in the evaluation process. Finally, the modified weights for Depth to groundwater, Net recharge, Aquifer media, Soil type, Topography, Impact of the vadose zone, Hydraulic conductivity, Land use type and Model of groundwater resource yield are 5, 3, 4, 1, 1, 4, 3, 5, and 5, respectively (Aslam et al., 2020).

Table 4. *Original and modified rating values of the DRASTIC-LY parameters*

Parameter	**Original weights**	**Pearson’s (*r*) correlation**	**Revised weights**
Depth to groundwater	5	0.461	5
Net recharge	4	0.279	3
Aquifer media	3	0.402	4
Soil type	2	0.113	1
Topography	1	0.102	1
Impact of the vadose zone	5	0.418	4
Hydraulic conductivity	3	0.336	3
Land use type	5	0.484	5
Model of groundwater resource yield	4	0.479	5

Utilities of vulnerability maps for groundwater protection and management

The modified DRASTIC-LY model and actual nitrate concentrations in groundwater in the study area are shown in *Figure 6*. The results show that the revised DRASTIC-LY model has a high correlation with the actual nitrate concentration and is most suitable for understanding the accurate assessment of groundwater pollution vulnerability in different regions. The Nitrate concentration (NO_3-N) values in the shallow groundwater were classified into five classes such as 0.04-5.00 mg/L, 5.00-10.10 mg/L, 10.10-15.14 mg/L, 15.14-20.05 mg/L, and 20.05-31.65 mg/L. Comparison of the modified DRASTIC-LY vulnerability map with the map of original DRASTIC-LY method revealed differences in 28.6% of the study area. The risk map shows that the very high vulnerability area decreased from 3.6% (original model) to 2.1% (modified model), while the high vulnerability area increased from 9.4% to 5.6%. Areas with low vulnerability increased by 10.7% compared to those predicted by the original DRASTIC-LY map. Areas with medium vulnerability increased by 4.9% compared to those predicted by the original DRASTIC-LY map.

At the confluence of the Han River and the Bao River, the groundwater vulnerability is very high, which means that the exploitation of groundwater in the Changlin water source is the main reason for the high vulnerability. Compared with the original

DRASTIC-LY model prediction, there are still high vulnerability areas in the southeast of Mian County, Nanzheng County, Chenggu County and Yang County, but the area is slightly smaller than that predicted by the original model. The main reason is that the area is located in an area of intense human activities, groundwater is exploited while receiving recharge from rainfall and river (Shakoor et al., 2020; Ahmed et al., 2018). It is worth noting that the area of the low vulnerability area in the northern part of the basin increased significantly, mainly because the groundwater in this area is dominated by lateral runoff and receives little recharge from precipitation and river.

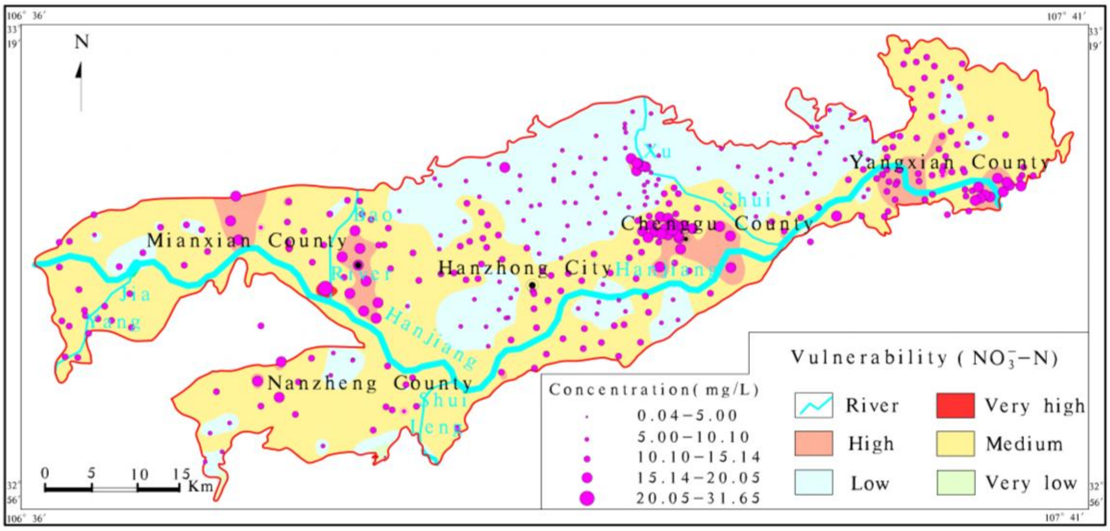


Figure 6. *Map of specific vulnerability using modified DRASTIC–LY model*

Groundwater is an important part of natural resources, and its rational development, utilization and effective management ensure the sustainable use of future generations (Sarkar and Pal, 2017). Assessing groundwater vulnerability is critical for the protection and management of groundwater resources and the environment in the Hanzhong Basin. The Groundwater Vulnerability Assessment Map helps governments make informed decisions to prevent residential, agricultural and industrial impacts on groundwater resources. The modified DRASTIC-LY model is the most suitable model for assessing the specific vulnerability of groundwater in the Hanzhong Basin to nitrate pollution.

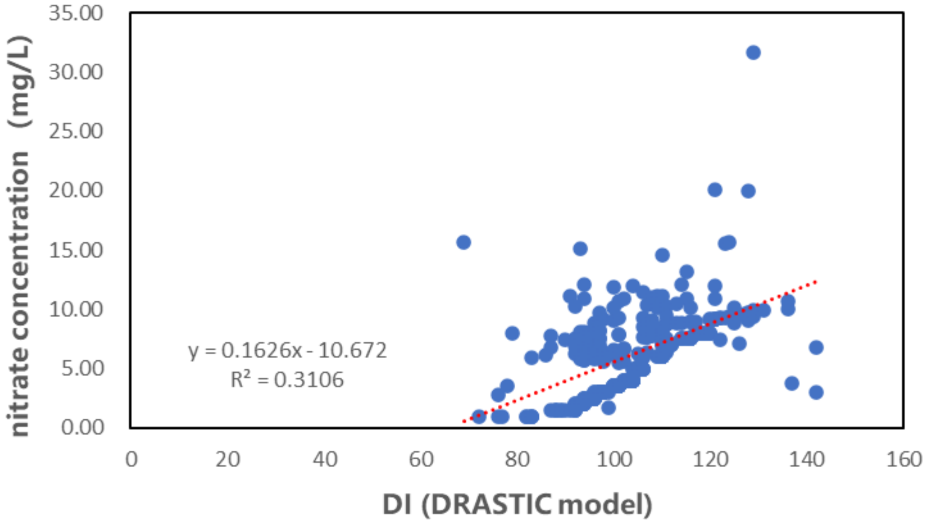
Sensitivity analysis of the modified DRASTIC-LY model

A single-parameter sensitivity analysis was performed by comparing the Revised weight and Effective weight (*Table 5*) (Sarkar and Pal, 2021). The effective weight of a parameter is a function of the relationship between its theoretical weight and the nine parameters in the DRASTIC-LY model. The effective weights of the revised DRASTIC-LY model in this study deviate slightly from the theoretical weights. As shown in *Table 5*, the statistical results of single-parameter sensitivity analysis show that the effective weight is between 2.78% and 19.98%, indicating that the eight indicators in the vulnerability assessment have little difference. The effective weights for D, S, L, and Y (18.58%, 3.52%, 19.98%, and 18.24%, respectively) are higher than their theoretical weights (16.12%, 3.23%, 16.12%, and 16.12%, respectively). Depth to groundwater, land use type, and Model of groundwater resource yield are the three parameters most affected by human activities, which play a key role in groundwater vulnerability assessment. Soil type is a naturally determined parameter, which also plays a role in groundwater vulnerability assessment. The effective weights of the R, A, T, I, and C parameters (6.89%, 12.37%, 2.78%, 9.99%, and 7.65%, respectively) are less than their theoretical weights (9.67%, 12.92%, 3.23%, 12.92%, and 9.67%, respectively, which have standard deviations of 8.33%, 6.41%, 5.31%, 9.62%, and 7.29%, respectively). Topography and soil type parameters had little effect on groundwater vulnerability compared to the other seven parameters.

Table 5. *Statistics of the single-parameter sensitivity analysis*

Parameter	**Revised weight**	**Revised weight (%)**	**Effective weighting (%)**			
			Min	**Max**	**Average**	**Standard deviation**
Depth to groundwater	5	16.13	9.36	34.02	21.25	7.09
Net recharge	3	9.68	2.38	13.03	7.54	3.12
Aquifer media	4	12.90	1.99	24.80	13.22	5.45
Soil type	1	3.23	0.90	7.21	2.66	1.54
Topography	1	3.23	0.87	6.37	2.26	1.08
Impact of the vadose zone	4	12.90	2.03	23.85	10.34	4.69
Hydraulic conductivity	3	9.68	4.91	22.39	9.57	3.84
Land use type	5	16.13	5.83	49.84	18.88	8.09
Model of groundwater resource yield	5	16.13	2.59	26.95	14.25	6.27

Nitrate concentrations in shallow groundwater were tested and analyzed at 328 different villages. The nitrate concentration in groundwater was accurately determined by spectrophotometry method. Measured nitrate concentrations correlated with parameters affecting groundwater flow and confluence were used to modify the original method resulting in the revised DRASTIC-LY model. Pearson’s correlation factor was 0.55 ($R^2 = 0.3106$) in the original DRASTIC model, 0.58($R^2 = 0.3437$) in the DRASTIC-LY method, and 0.65($R^2 = 0.4250$) in the modified DRASTIC-LY model (*Fig. 7*). This indicated that the modified vulnerability map using the revised DRASTIC-LY model was more appropriate than that constructed by the original method.



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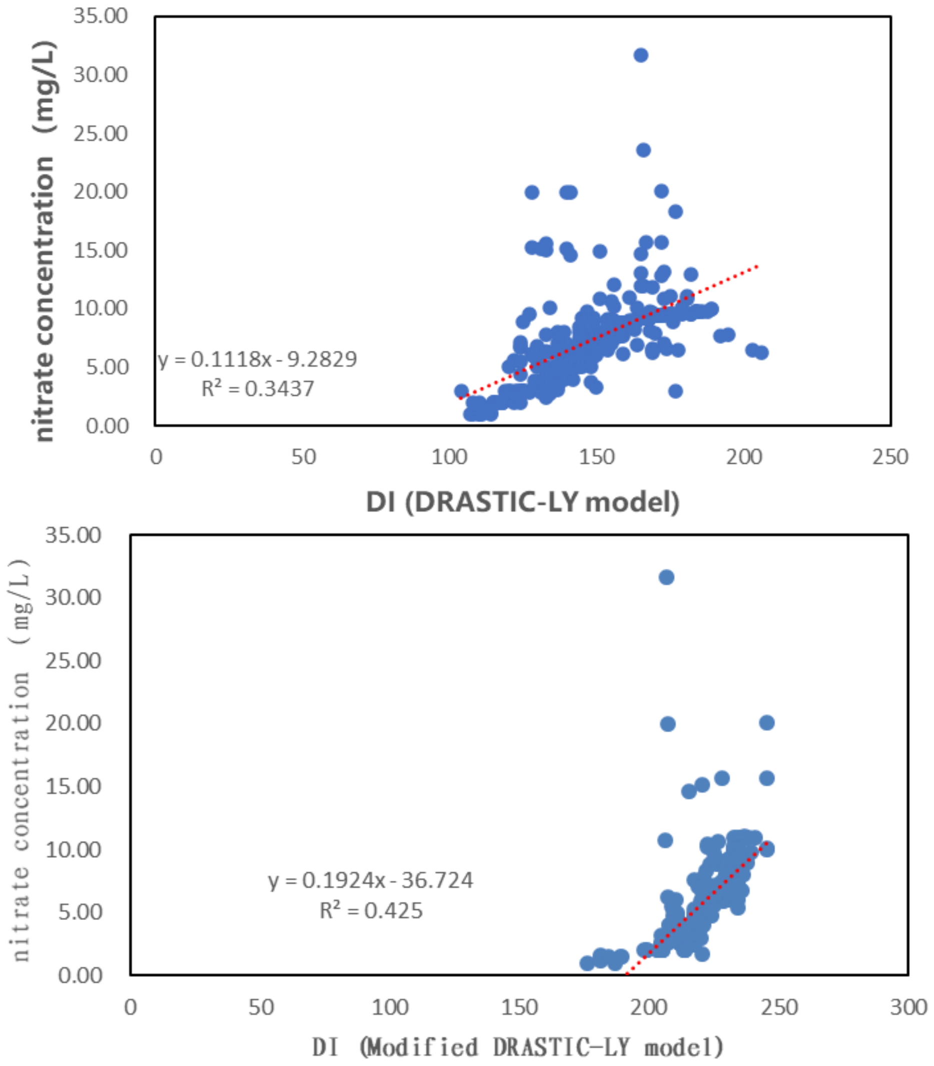

Figure 7. *Relationship between nitrate concentration and DI values: a) original DRASTIC model, b) DRASTIC-LY model, c) modified DRASTIC-LY model*

Conclusions

The traditional DRASTIC method can provide a relatively rapid method for assessing the inherent vulnerability of groundwater. The increase in nitrate concentration in groundwater due to human activities has not been effectively considered. However, this is not the best way to accurately assess groundwater vulnerability in a particular area. In order to solve this problem efficiently, this paper is based on the structure of the DRASTIC model, but (1) took the land use type and model of groundwater resource yield parameters into consider, (2) reduced the weight of Net recharge, Soil type and Impact of the vadose zone parameters, and (3) modified the parameter weightings according to the significance of NO_3-N concentrations associated with the nine parameters. Using the improved DRASTIC-LY model, the vulnerability assessment of groundwater in Hanzhong Basin to nitrate pollution was realized, and a vulnerability map was created.

1. DRASTIC, DRASTIC-LY, and modified DRASTIC-LY models were used to assess the groundwater vulnerability to pollution. Comparison of the modified

DOI: http://dx.doi.org/10.15666/aeer/2203_23392358

DRASTIC-LY vulnerability map with the map of original DRASTIC-LY method revealed differences in 28.6% of the study area. The risk map shows that the very high vulnerability area decreased from 3.6% to 2.1%, while the high vulnerability area increased from 9.4% to 5.6%. Areas with low vulnerability increased by 10.7% compared to those predicted by the original DRASTIC-LY map. Areas with medium vulnerability increased by 4.9% compared to those predicted by the original DRASTIC-LY map.

2. The evaluation results show that the areas with very high groundwater vulnerability are mainly distributed at the confluence of the Han River and Baojiang River, the areas with high groundwater vulnerability are mainly distributed in the southeast of Mian County, Nanzheng County, Chenggu County and Yang County, while the areas with low groundwater vulnerability are distributed in the northern part of the basin. The combined action of human activities and natural conditions affects the vulnerability of groundwater, and household activities, agricultural production and industry in human activities are the main reasons for the increased vulnerability of groundwater.

3. The Pearson's correlation factor was used to determine the statistical relationship between nitrate concentrations in groundwater and groundwater vulnerability maps. The Pearson's correlation factor was 0.55 in the original DRASTIC model, 0.58 in the DRASTIC-LY method, and 0.65 in the modified DRASTIC-LY model, which indicated that the revised DRASTIC-LY model was more appropriate than that constructed by the original model.

Due to the limitation of research funds and the number of samples, the research accuracy is not highly specific. In addition, the analysis and testing of isotopic samples and microbial samples have not been carried out, so it is impossible to determine the exact source of nitrogen and the impact of denitrification on vulnerability. Therefore, the limitation of this study lies in the inability to accurately characterize the physicochemical processes of nitrogen. The study provides a comprehensive description of the inherent and specific vulnerabilities of the Hanzhong Basin, and lays the foundation for future monitoring of nitrogen "dynamic" vulnerabilities.

Acknowledgments. This work was supported by The Project of Comprehensive Investigation of Ecological Restoration in Hilly and Mountainous Areas of South China (No. DD20230097 and No. DD20230480). The author thanks the editors and reviewers of the journal for their valuable comments, which is of great help to the improvement of the paper. Give thanks to Xiujuan Liang, Honggen Xu, Changlai Xiao, Xinhua Bao, Bo Zhang and Shanghai Du, for helping us with data processing skills and writing skills during the writing process.

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