RESEARCH ARTICLE

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Assessment of groundwater vulnerability by applying the modified DRASTIC model in Beihai City, China

Xiaoyu WU[1] · Bin LI[1] · Chuanming MA[1]

Abstract
This study assesses vulnerability of groundwater to pollution in Beihai City, China, as a support of groundwater resource protection. The assessment result not only objectively reflects potential possibility of groundwater to contamination but also provides scientific basis for the planning and utilization of groundwater resources. This study optimizes the parameters consisting of natural factors and human factors upon the DRASTIC model and modifies the ratings of these parameters, based on the local environmental conditions for the study area. And a weight of each parameter is assigned by the analytic hierarchy process (AHP) to reduce the subjectivity of humans to vulnerability assessment. The resulting scientific ratings and weights of modified DRASTIC model (AHP-DRASTLE model) contribute to obtain the more realistic assessment of vulnerability of groundwater to contaminant. The comparison analysis validates the accuracy and rationality of the AHP-DRASTLE model and shows it suits the particularity of the study area. The new assessment method (AHP-DRASTLE model) can provide a guide for other scholars to assess the vulnerability of groundwater to contamination. The final vulnerability map for the AHP-DRASTLE model shows four classes: highest (2%), high (29%), low (55%), and lowest (14%). The vulnerability map serves as a guide for decision makers on groundwater resource protection and land use planning at the regional scale and that it is adapted to a specific area.

Keywords Beihai City, China · Groundwater · Vulnerability assessment · Analytic hierarchy process · DRASTIC method

Introduction

Groundwater vulnerability defines the tendency or possibility of groundwater to contamination under the influence of natural conditions and human activities, reflecting the sensitivity of groundwater to changes of natural conditions and human activities. The assessment result of groundwater vulnerability can identify areas that are more likely to be polluted than others as a result of human activities and provide a scientific basis for groundwater protection program. The groundwater vulnerability assessment, as an important fundamental work for the exploitation, utilization, and protection of groundwater resources, is an important basis for taking measures to prevent and control groundwater pollution (Sun et al. 2007; Wang

et al. 2015). In Beihai City, groundwater is an important resource of domestic water supply in suburb and rural area and agricultural irrigation water, and the supply of domestic water and industrial water in urban area all relies on the exploitation of groundwater. With the development of economy and rapidly urbanization, the demand for water grows sharply. According to the geo-environmental survey results, the groundwater quality in this region has been deteriorating in recent years mainly because of waste emissions and fragmented land use patterns. It is a common phenomenon that "three nitrogen" do not meet standard for groundwater quality in China, and nitrate contamination is one of the major characteristics of groundwater pollution in the study area. It is challenging that groundwater can meet demand for water supply with increasing population for long term in the study region. Therefore, the assessment of groundwater vulnerability is a prerequisite for the groundwater resource protection and rational exploitation, the land use planning, and the groundwater resources management.

At present, various methods have been developed for assessing the vulnerability of groundwater; of all the models, the DRASTIC method is the most widely used method for

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assessing the vulnerability of groundwater (Denny et al. 2007; Krishna et al. 2015; Tiwari et al. 2016) because of the using of simple principles and the easily accessible parameters. It has made a great progress at home and abroad (Lynch et al. 1997; Dong et al. 2002; Lei and Zhang 2003; Pacheco et al. 2015; Victorine Neh et al. 2015). However, this method is increasingly criticized for the selection of hydrogeological parameters, and the weight and rating are not in good agreement with the actual conditions of the study area and its specificity, because each parameter was assigned the same weight and rating (Denny et al. 2007; Dhar 2013), which result in high obvious subjectivity. Moreover, one of important limitations of the DRASTIC method is that it does not take into account the impact of human activities on the groundwater pollution. Thus, to optimize and adapt the DRASTIC method to specific conditions of the study area, it is necessary to improve the DRASTIC method to get more objective result. Some scholars have optimized the DRASTIC method by adopting various techniques (Allouche et al. 2017; Kazakis and Voudouris 2015; Sener and Davraz 2013). Different methods have their own comparative advantage and limitations; however, identifying and applying the most appropriate one in the study area are crucial. The analytic hierarchy process (AHP) is a multi-objective decision analysis method by adopting qualitative and quantitative analysis (Saaty 1990). It makes use of less quantitative information to quantize decision-making process of policy makers based on analyzing essence, influence factors, and internal relations of complex decision-making problem. This method not only does not cut off relative effect of each factors on the result but also does analyze complex elements of study object with a recursion order hierarchy structure and decrease subjective. It applies to analyze interrelated, interdependent multi-factor complex problems, such as the vulnerability assessment of groundwater, because its result remains to overcome subjectivity of the weighting factor. Thus, this paper has improved the DRASTIC method based on taking into account the impact of human activities on groundwater, and combined it with analytic hierarchy process by MapGIS software, named AHP-DRASTIC, which reflects specific conditions of the study area. To ensure the precision and reliability of outcomes for the vulnerability assessment in the AHP-DRASTIC model, comparative analysis between the DRASTIC vulnerability assessment and assessment result of AHP-DRASTIC model has been used to validate this model.

MapGIS is universal geographic information system software with independent intellectual property right, developed by the China University of Geosciences (Wu 2004). It is based on MAPCAD, a famous map editing and publishing system, and it can collect, store, retrieve, analyze, and graphically represent spatial data. It is a advanced graphics and image processing technology and has various functions, including graphics processing, data management, spatial analysis, image processing, practical

services five modules. The software is easy to learn and operate with beautiful figure, high precision, and mapping speed.

The study aims to assess groundwater vulnerability by using improved DRASTIC method to provide a strategic basis for regional groundwater resource protection and management, and provides scientific guidance for exploitation of groundwater resource.

The study area

The study area is located in Beihai City, in the south of Guangxi Zhuang minority Autonomous Region, China, and covers an area of 3378 km^2, near the Beibu Bay, between 20° 54′~21° 55′ N latitude and 108° 50′~109° 47′ E longitude. It includes one county and three districts (Hepu County, Haicheng District, Yinhai District, Tieshangang District), along with two islands, Weizhou Island and Xieyang Island (Fig. 1).

The study area is subtropical monsoon climate, characterized by mild climate and abundant rainfall. The average annual precipitation is 1607.1 and 1689.8 mm in the municipal district and Hepu County, respectively (Fig. 2). There are many rivers and reservoirs in this area, mainly distributed in Hepu County, and the surface water resource zone belongs to the coastal watersheds of the southern part of Guangxi.

The whole terrain is high in the northeast and low in the southwest, the northeast and northwest are the hills, and the southern coastal area is the platform and the plain; there are many harbors in the coastal area and the coastal area is affected by the tide. Weizhou Island and Xieyang Island are located on the southern sea, where the main terrain is the volcanic low hill (Fig. 3).

According to the characteristics of aquifer media, occurrence conditions of groundwater, and hydraulic characteristics, groundwater for the study area can be divided into four types: loose rock pore water, red layer clastic rock pore-fissure water, carbonate karst water, and bedrock fissure water. Among them, the bedrock fissure water can be divided into three types of structure fissure water, granite weathering net-like fissure water, and basalt pore-fissure water (Fig. 4). The aquifers is generally recharge by precipitation, irrigation water, canal water, and surface water. Groundwater runoff trends from north to south, southwest, and southeast coast or harbor, from inland to sea area. Groundwater runoff in the island trends from the center of island to the surrounding. In addition to the impact of exploitation, the equitential line of the phreatic water and confined water keeps the same trend with the terrain.

As of 2010, the total land area of the study area was 398,866.95 ha, agricultural land covers an area of 265,750.17 ha, construction land area covers an area of 57,264.08 ha, and the remaining land covers an area of
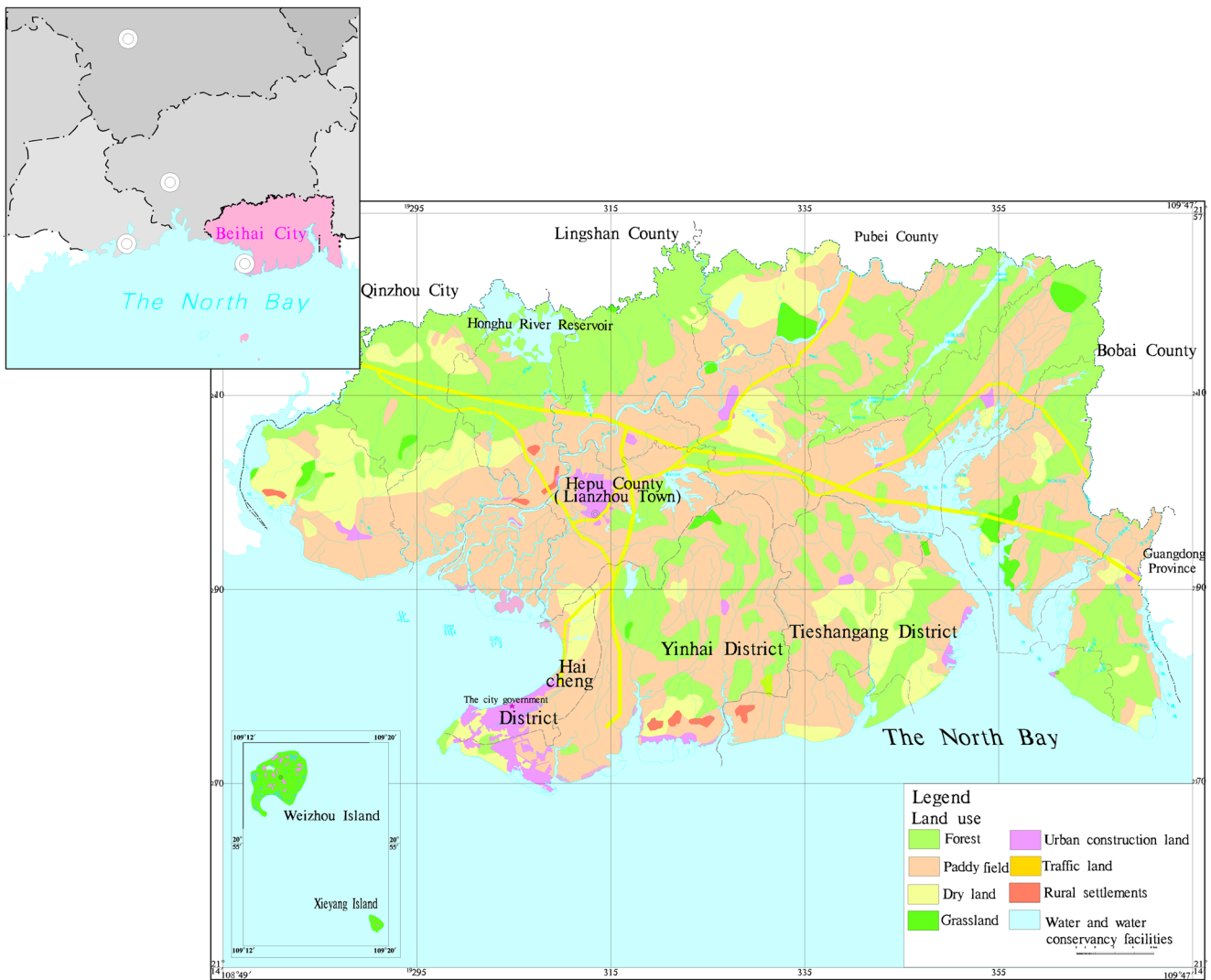
Fig. 1 Location and land use of the study area

75,852.7 ha, accounting for 67, 14, and 19% of the total land area, respectively (Fig. 1). Hepu County is mainly agriculture development area, which abounds in food, peanuts, sugar cane, subtropical fruits, vegetables, sericulture, and so on. The main used chemical fertilizers consist of urea and potassium fertilizer; the average amount of chemical fertilizer is about 0.0028 kg in per square meter farmland. Tieshangang District is industrial development area; industrial activities are represented essentially by chemical fertilizers, textiles, food, construction materials, petrochemicals, and other chemical products.

The study area has a long history of exploiting groundwater. At present, groundwater provides main water source for industrial production and domestic water of the urban area, and water supply facilities are dominated by mixed exploitation well, with the concentrated and large exploitation. The well groups are too concentrated in the offshore area, causing intensive groundwater extraction and resulting in seawater intrusion in some areas; shallow groundwater is exploited by civil wells in rural areas, mainly used for drinking water and domestic water. The distribution of exploitation wells is scattered, so these wells are administrated systematically for groundwater protection. Intensity of groundwater exploitation for the study area is shown in Fig. 5.

Materials and methods

Source of data

Data sources were provided by Geological Survey Center, Wuhan. Database was obtained by digitizing the existing maps of the study area, collected from Geological Survey Center, Wuhan. Water samples from the entire study region were taken in the year 2010 from 38 sample points and
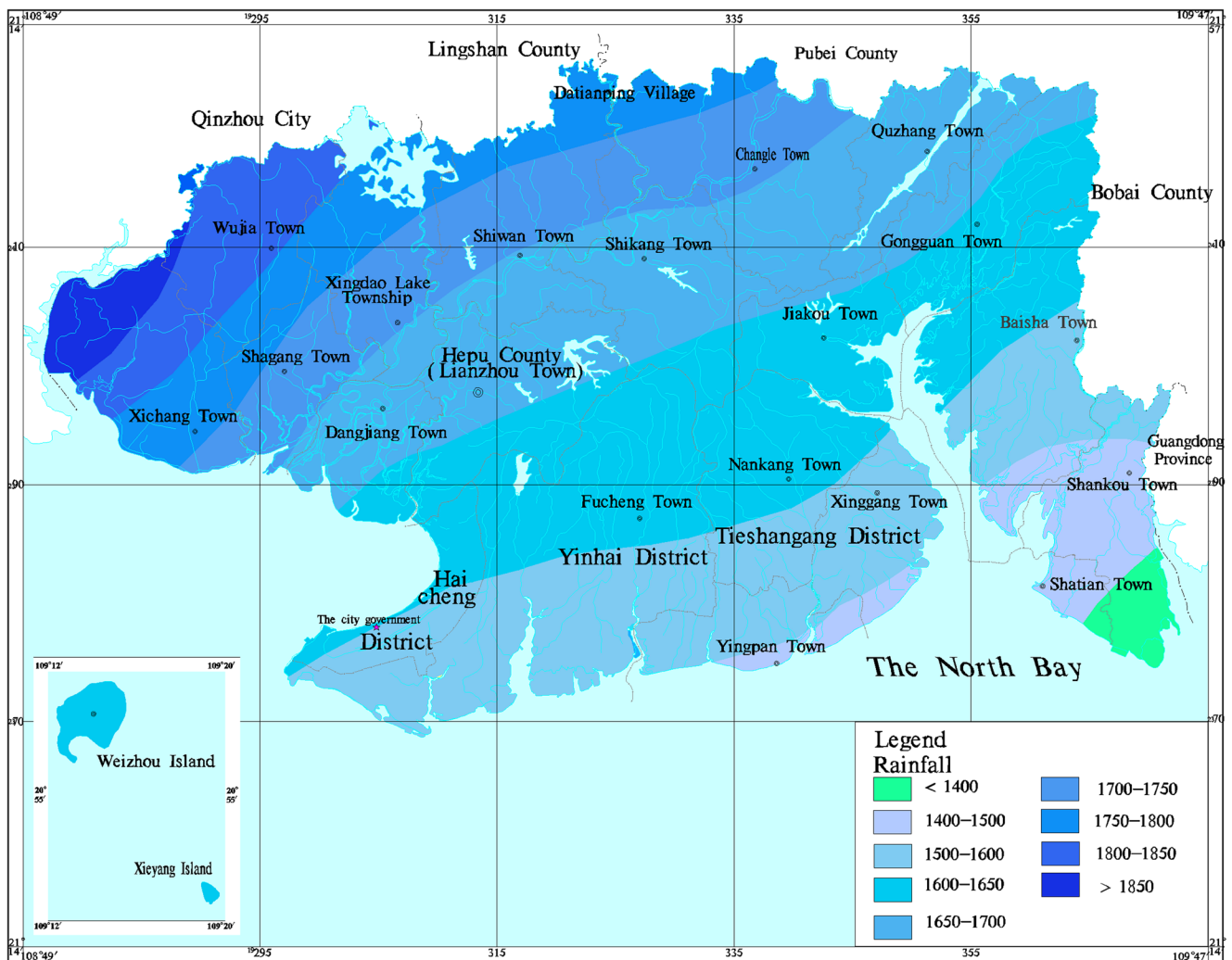
Fig. 2 Distribution map of rainfall in the study area

completed by the actual analyses. And nitrate has been measured by UV spectrophotometric method.

The DRASTIC method

The DRASTIC method was developed by Aller et al. (1987a, b) based on weights and rating for different parameters. The term DRASTIC refers to the acronym of seven geological and hydrogeological parameters; these parameters are Depth to groundwater table (D), net Recharge (R), Aquifer medium (A), Soil type (S), Topography (T), Impact of the vadose zone (I), and hydraulic Conductivity (C). Each of the seven parameter is assigned a value ranging from 1 to 10 based on their relative effect on the aquifer vulnerability, and each parameter is determined a weight, ranging from 1 to 5, that reflects the importance of this factor to the vulnerability of groundwater. Then, the DRASTIC index is computed by summing up the product of rating and weight according to Eq. (1). The higher

the DRASTIC pollution index is, the greater the vulnerability of groundwater to pollution is.

$$\text{DRASTIC} \quad \text{index(DI)} = \sum_{i=1}^{7} R_i W_i \qquad (1)$$

where R and W are ratings and weights for seven parameters of DRASTIC model.

Modified DRASTIC model (AHP-DRASTLE model)

Optimization of the assessment factors

The selection of parameters is considered as the key of assessing the groundwater vulnerability; the rational index system is contributed to increase the veracity and objectivity of the evaluation result. The assessment index system should be established based on the local environmental conditions of the study area, and follows the important principles, i.e.,
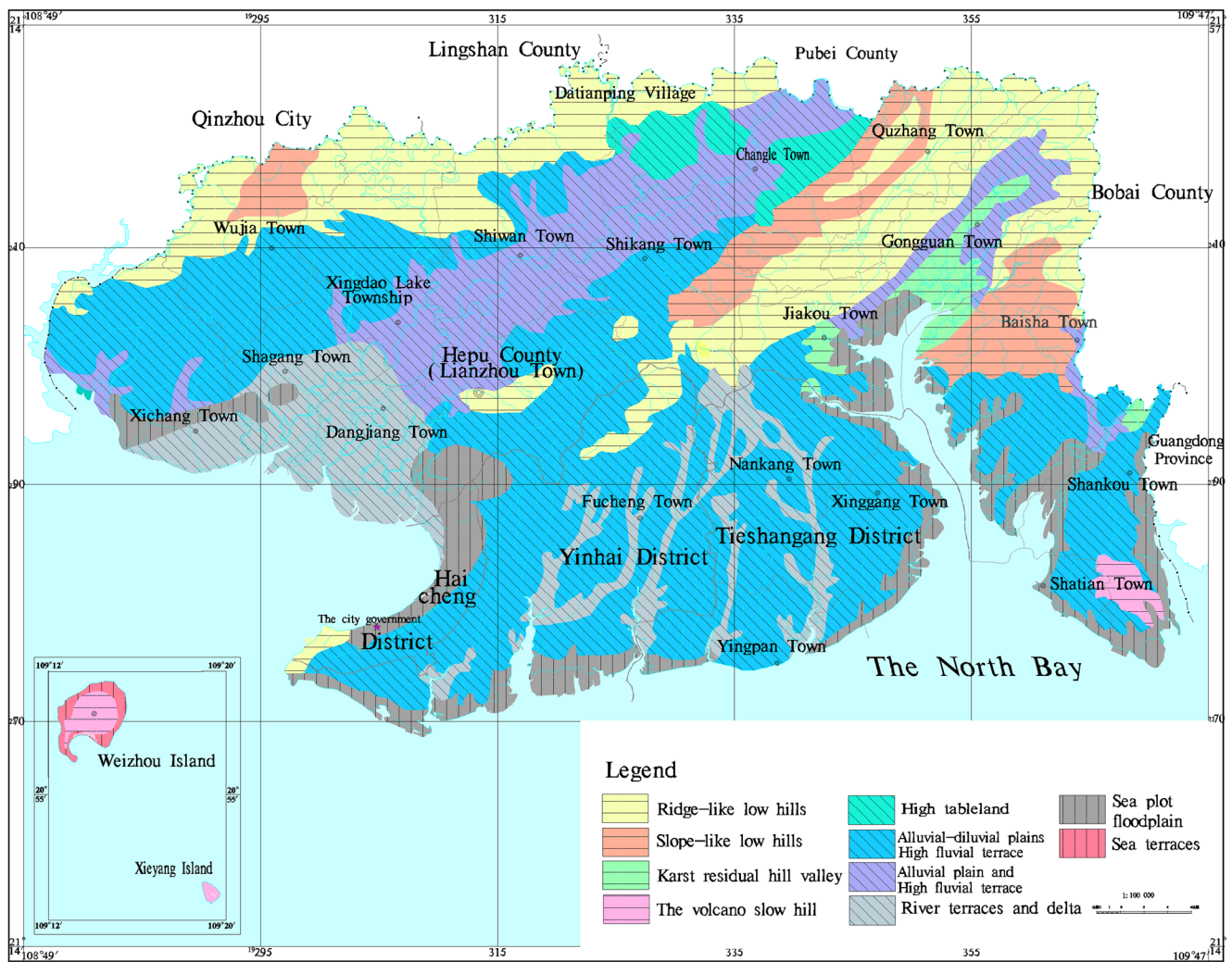
Fig. 3 Topographic conditions of the study area

pertinence, typicality, objectivity, easy data acquisition, and easy quantize, instead of applying the original evaluation model blindly. The assessment of groundwater vulnerability not only should consider instinct hydrogeological characteristics of the groundwater system but also does not ignore the impact of human activities on groundwater. Thus, this study considers hydrogeological parameters based on the DRASTIC model, and integrates human factors into the assessment of the groundwater vulnerability. In addition, the presence of nitrate in groundwater is often used as an index of groundwater vulnerability assessment (Huan et al. 2012). In the study area, the depth to groundwater is shallow, soil media and impact of vadose zone have a degree of similarity, and impact of vadose zone on the groundwater vulnerability can be reflected by soil media and impact of vadose zone was integrated into soil media. Considering the local environmental conditions and obtained data, the Pearson correlation coefficient between score of each parameter for the DRASTIC model and the mean nitrate concentration measured has been

analyzed for confirming the important hydrogeological factors that have obvious impact on the groundwater vulnerability.

The groundwater system is an open system, groundwater environment is closely related to human activities, and human factors that have an effect on groundwater vulnerability include land use planning, groundwater exploitation intensity, and contaminant load. Land use represents an important parameter in assessing the vulnerability of aquifers (Zhou and Li 2008). Some areas are subject to human activities, including agriculture, urban planning, and industrial development, which change natural features (Maanan et al. 2014). There are significant sources of groundwater pollution from land use activities, particularly agricultural practices, with an increasing consumption of chemical fertilizers, and urbanization. Increasing emission of domestic sewage densely populated urban area also will result in the groundwater pollution. The perturbation of human activities to groundwater is concentrated in the exploitation of groundwater. The study has proved that overexploitation of aquifers and the dissolution
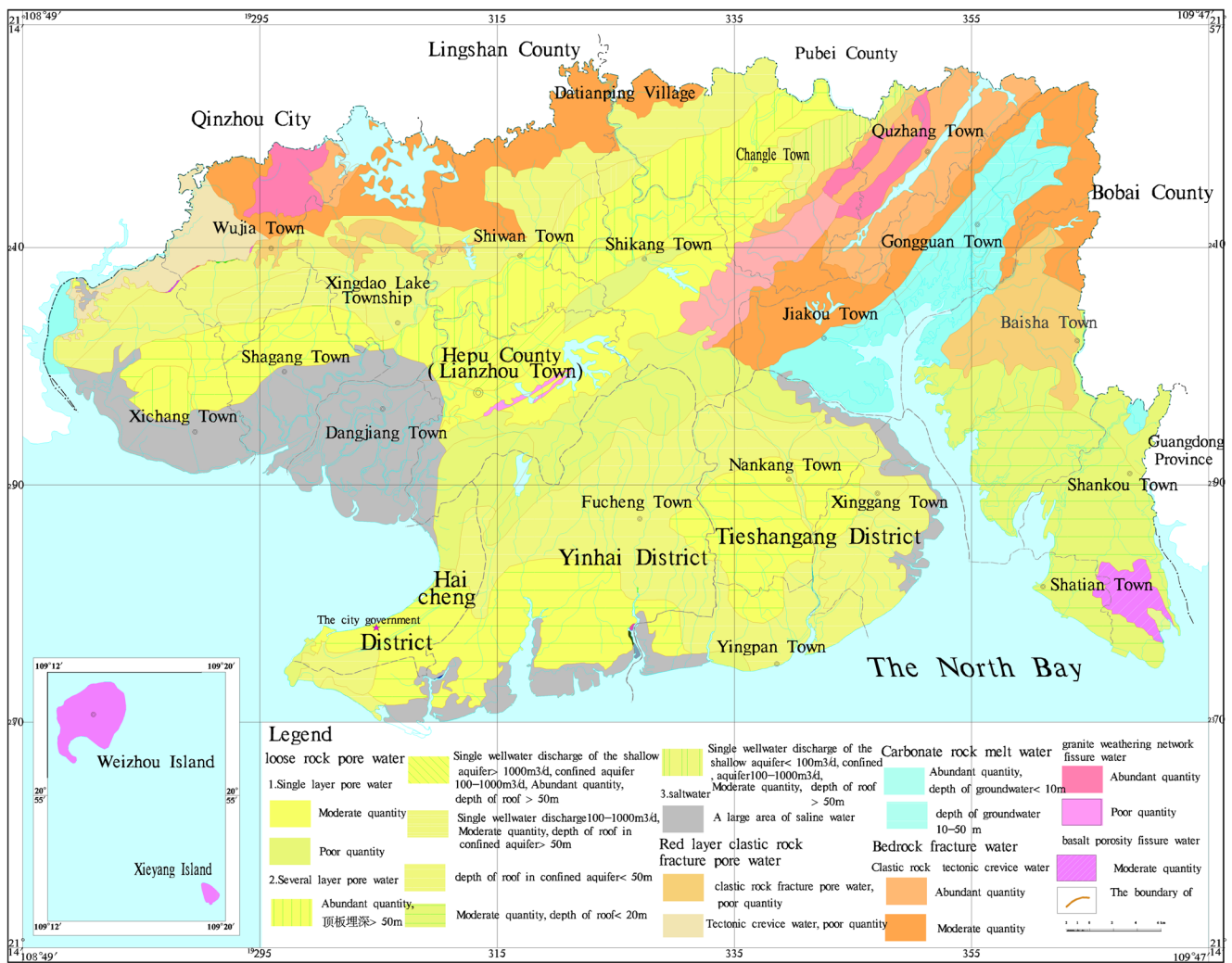
Fig. 4 Hydrogeological map of the study area

of natural harmful substances may impair groundwater quality and increase salinization (Ben Hamouda et al. 2010; Zhou et al. 2012). The extensive pumping of coastal wells contributes to the intrusion of seawater into the mainland freshwater porous aquifer, and seawater intrusion occurred in the coastal area of the study region because of overexploitation of groundwater. The greater the intensity of groundwater exploitation is, the easier it is to contaminate the groundwater, and the dilution of contaminates also trend to decrease due to the reduction in groundwater. Two human factors including land use and groundwater exploitation intensity are used to assess impact of human activities on the groundwater vulnerability.

Depth to water table (D). Groundwater table depth is the distance between the uppermost layer of unsaturated zone and groundwater static level. It controls the distance that pollutant pass-through before reaching the aquifer and reaction time of contaminant with surrounding media; thus it affects possibility of contaminant to infiltrate into groundwater. When this distance is high, it is more difficult for surface water with

contaminants to reach groundwater, and the vulnerability of groundwater to contaminants also is small.

Rainfall recharge (R). Rainfall recharge is the rainfall that flows from ground surface to groundwater. It can easily bring contaminants into groundwater. The pollutants infiltrate and migrate to the aquifer, along with the recharge of rainfall to groundwater. And the pollution is increased. The greater the rainfall recharge is, the greater the possibility of pollutants reaching the aquifer is, that is, the vulnerability of groundwater to pollution trends to became large.

Aquifer media (A). The aquifer is also designated as a geological or hydrogeological formation which can produce enough water for consumption (Anwar and Rao 2003). The aquifer media not only governs infiltration path and length for contaminants in an aquifer but also determines duration of time available for attenuation (such as sorption, biodegradation, dispersion, and volatilization) and size of contact area between contaminants and media. Generally speaking, the greater aquifer media particle sizes stand for greater porosity
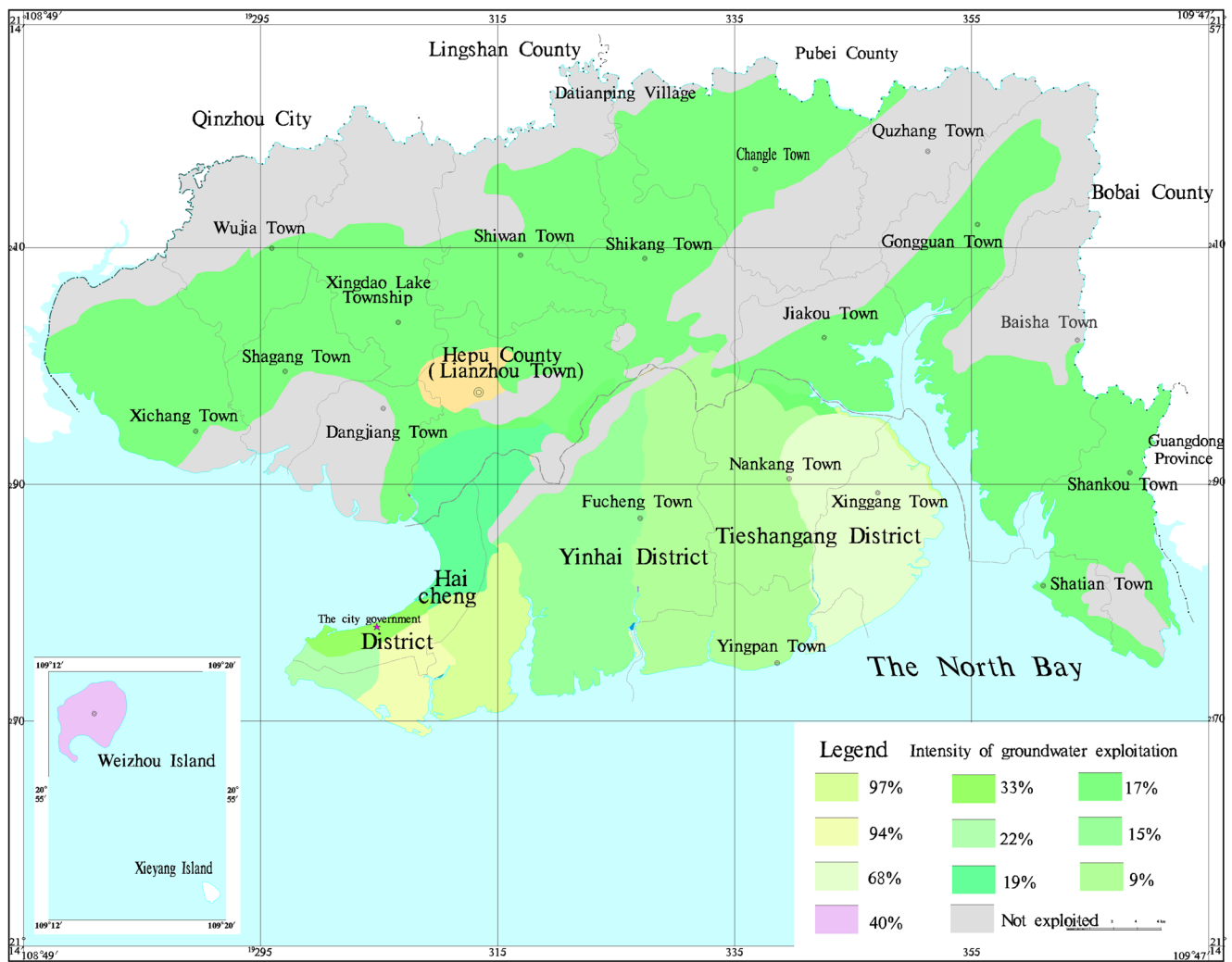
Fig. 5 Intensity of groundwater exploitation in the study area

and permeability, and may speed migration of contaminants in the aquifer and reduce the attenuation capacity of pollutants, so the groundwater is more susceptible to contamination, that is, the groundwater vulnerability is higher.

Soil media (S). Soil media is the ground surface with biological activity characteristics of the vadose zone. It influences groundwater movement, potential dispersion, and pollutant migration in the vadose zone. The vulnerability of soil is mainly affected by soil grain type, shrink/swell capacity of clay in soil, and soil grain size. When shrink/swell capacity of clay in soil and soil grain size is small, it is more easy for contaminants to infiltrate into the aquifer, and it is contributed to enhance biological and physico-chemical reactions (sorption, biodegradation, volatilization, etc.), so the vulnerability of groundwater to pollution trends to became small.

Topography (T). Topography of an area accounts for the change in slope, it determines runoff and infiltrate of rainfall, and the steeper topography is in an area, the greater the possibility of creating surface runoff is, the greater the chance for

infiltration is. Gentler slopes (slopes of 0–2%) have higher retaining capacity for water, the probability of creating surface runoff is very, the chance for infiltration is greater, and the groundwater is prone to pollution. When the slope is more than 18% in an area, the groundwater potential for pollution is high. The higher values indicate more vulnerability of groundwater to contamination.

Application of the analytic hierarchy process

The analytic hierarchy process is a multi-objective decision analysis method combining qualitative and quantitative analysis; this method is contributed to reduce obvious subjectivity when it is used to assign the weight of factor. The weighting factor reflects the relative importance of each factor. The same factor has different impacts on groundwater vulnerability in various areas, so the weight is different in various study areas (Shao et al. 2014). In form of one limitation of the DRASTIC method in the sense that its weight is fixed value and based on

human subjective opinion, this paper applies the analytic hierarchy process (AHP) to determine the weighting factor of each parameter based on a certain function of groundwater vulnerability with each class, which reflects actually relative importance of each parameter to the groundwater vulnerability for the study area.

The vulnerability index for AHP-DRASTLE model is calculated by the following equation:

$$V\_index(DI) = \sum_{i=1}^{7} R_i W_i \qquad (2)$$

Result and discussion

The vulnerability assessment result for the DRASTIC method

According to ratings of parameters of the DRASTIC model, the DRASTIC index score and distribution for the study area are shown in Table 1, and the DRASTIC index was calculated by using Eq. (1) and with help of data management in MapGIS, with a range of 102–206, and was classified into four types: highest, high, low, and lowest, with the equidistant division; the final vulnerability map of DRASTIC model is created by using graphics processing of MapGIS (Fig. 6). It is clear that the highest vulnerability is in the northern hilly areas, and a very few area part of the study area has a low vulnerability. It is also noted that the northern parts of the study area are more vulnerable than the south.

The vulnerability assessment result for the improved DRASTIC method

Optimization of the assessment factors and its ratings

The Pearson correlation coefficient between score of each parameter for the DRASTIC model and the mean nitrate concentration measured is shown in Table 2; it shows that depth to groundwater table, soil media, topography, aquifer media, and rainfall recharge are the most dominant factors associated with the intrinsic vulnerability for groundwater. In our implementation of DRASTIC model, seven parameters, consisting of Depth to water table (D), Rainfall recharge (R), Aquifer media (A), Soil type (S), Topography (T), Land use (L), and Groundwater exploitation intensity (E), are considered as the most critical indexes for the evaluation of the groundwater vulnerability, and named it as DRASTLE.

Then, each parameter has been assigned a typical range and a rating value scale to a ten-graded relative scale (r) based on the relevant research (Fan et al. 2007; Liao et al. 2016; Antoine et al. 2017; Nabila et al. 2017) and the susceptibility of local environmental conditions to groundwater for the study area (Table 3).

Optimization of the weight of each parameter

The assignment of the weight in the present study composed four general steps: (1) Establishing the hierarchy structure of the evaluation index system, all indexes have been classed into three levels (Table 4); (2) constructing a series of pair-

Table 1 The rating and weight of DRASTIC parameters in the study area

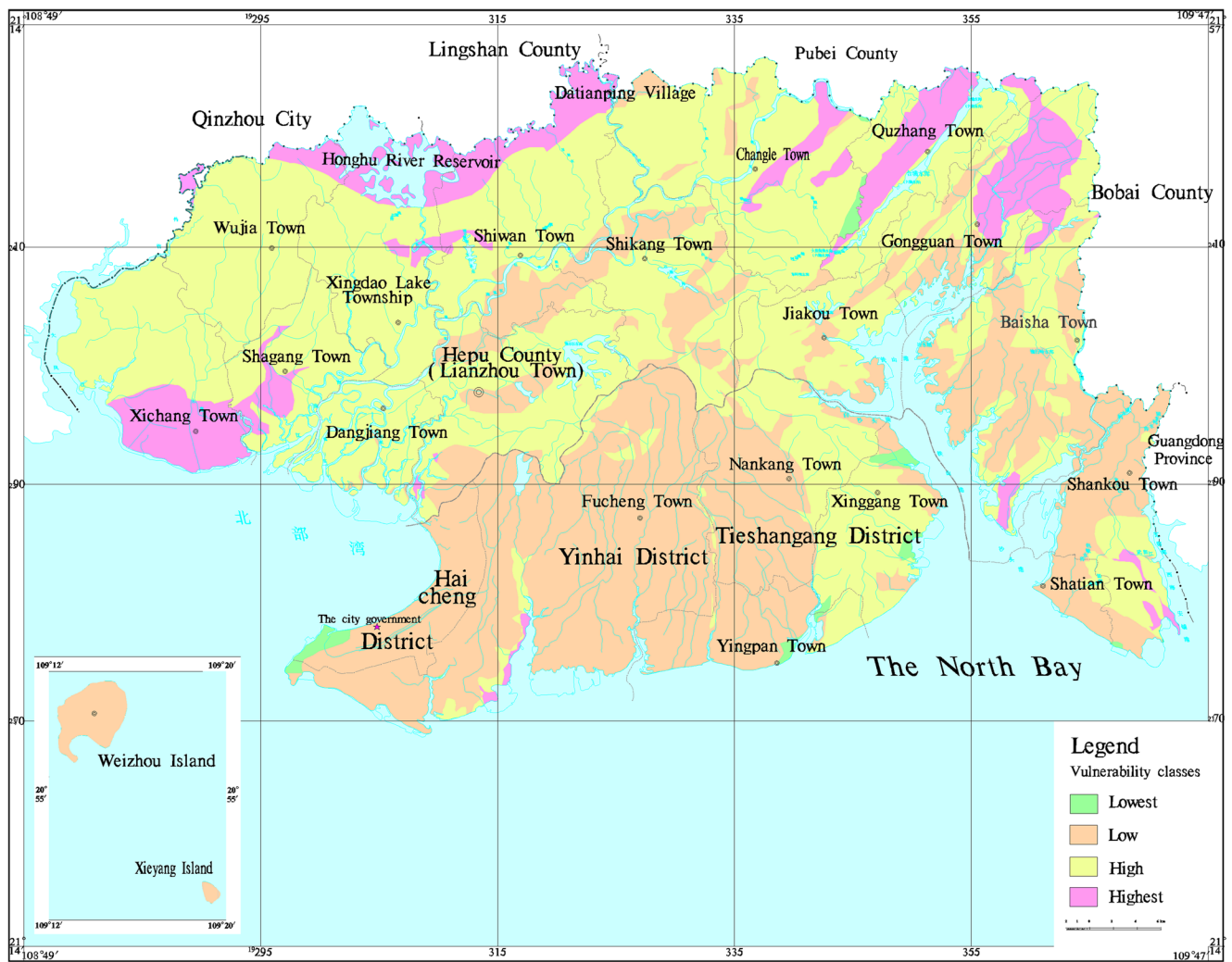| Serial number	Depth to groundwater table (D)		Net recharge (R)		Aquifer media (A)		Soil media (S)	
	Range (m)	Rating	Range (mm)	Rating	Range	Rating	Range	Rating
1	0–1.5	10	101.6–177.8	6	Weathered metamorphic rocks, Igneous rock	4	Sand	9
2	1.5–4.6	9	177.8–254	8	Thin-layer sandstone, limestone, shale	6	Sandy loam	7
3	4.6–9.1	7	> 254	10	Massive sandstone, gravel	8	Loam	5
4	9.1–15.2	5			Basalt	9	Silty loam	4
5							Clay loam	3
Weights	5		4		3		2	
Serial number	Topography (T)		Impact of vadoze zone (I)				Hydraulic conductivity (m/day)	
	Range (%)	Rating	Range		Rating		Range (%)	Rating
1	0–2	10	Metamorphic rocks, igneous rock		4		0.04–4.1	1
2	2–6	9	Layered limestone, sandstone, shale		6		4.1–12.2	2
3	6–12	5	Gravel		8		12.2–28.5	4
4	12–18	3	Basalt		9		28.5–40.7	6
5							28.5–40.7	8
Weights	1		5				3	

Fig. 6 The DRASTIC vulnerability map

comparison judgment matrices by comparing indexes of same level one by one (Table 5), and estimating importance of each weighting in contributing to the vulnerability; (3) in order to make certain consistency of pairwise comparison matrix, the consistency judgment was checked, CR = 0.032 < 0.1, which certified the estimated normalized weights (Huang 2009); and (4) the final value of the weight factor was obtained by multiplying the weight of each index by the weight of the criterion layer (Table 6).

Based on the partition and selection of above-stated parameters, graphics processing of MapGIS (Fig. 7) is used to create the thematic maps depending on given rating values ranging from 1 to 10. Some thematic maps are derived from maps in the study area, i.e., land use and intensity of groundwater exploitation, so Fig. 8 only shows others rating distribution map. Then, the vulnerability index was calculated with the weight and the rating value of each parameter by using Eq. (2) in the MapGIS 6.7 software to produce the vulnerability map for the AHP-DRASTLE model. Based on equidistant

division (Table 7), the vulnerability index can be graded into four classes: lowest, low, high, and highest, and the study area is classified into four environmental vulnerability areas accordingly. The spatial analyst tool of MapGIS is used to elaborate the groundwater vulnerability map by overlaying the thematic maps; the final vulnerability map is shown in Fig. 8.

From Fig. 8, about 70% of the study area has been classified within low to lowest vulnerability; a small part of the study area fall into highest vulnerability zone. Area under vulnerability classes and their distribution are depicted in Table 8.

Discussion

From the vulnerability map of DRASTIC model (Fig. 6), we found 11% for highest vulnerability areas, 51% for high vulnerability zone, 37% for low vulnerability areas, and only 1% for lowest vulnerability areas. For the AHP-DRASTLE model (Fig. 8), highest vulnerability areas are situated in Hepu

Table 2 The correlation analysis between the index and nitrate concentration

Index	Range	The rating	Mean NO$_3^-$ (mg/L)	Spearman rho coefficient
Depth to groundwater (m)	0–1.5	10	10.00	0.37
	1.5–4.6	9	27.29	
	4.6–9.1	7	3.02	
	9.1–15.2	5	10.65	
Soil type	Sand	9	25.10	0.60
	Sandy loam	7	53.80	
	Loam	5	23.40	
	Silty loam	4	12.99	
	Clay loam	3	19.37	
Topography (%)	0–2	10	50.00	0.59
	2–6	9	7.60	
	6–12	5	11.37	
	12–18	3	11.37	
Hydraulic conductivity (m/day)	0.04–4.1	1	25.37	0.31
	4.1–12.2	2	16.90	
	12.2–28.5	4	12.85	
	28.5–40.7	6	11.02	
	40.75–80.1	8	36.34	
Aquifer media	Weathered metamorphic rocks, igneous rock	4	10.00	0.44
	Thin-layer sandstone, limestone, shale	6	8.87	
	Massive sandstone, gravel	8	31.89	
	Basalt	9	11.64	
Rainfall recharge (mm)	100–150	2	18.67	0.52
	150–200	4	12.97	
	200–250	6	11.431	
	250–300	8	18.15	
	> 300	10	24.70	

Table 3 The rating of AHP-DRASTLE model

Depth to groundwater table (D)		Rainfall recharge (R)		Aquifer media (A)	
Range (m)	Rating	Range (mm)	Rating	Range	Rating
0–1.5	10	< 100	1	Massive shale	1–3 (2)
1.5–4.6	9	100–150	2	Metamorphic rocks, igneous rock	2–5 (3)
4.6–9.1	7	150–200	4	Weathered metamorphic rocks, igneous rock	3–5 (4)
9.1–15.2	5	200–250	6	Layered sandstone, limestone, shale, sand	5–9 (6)
15.2–22.9	3	250–300	8	Massive sandstone, Limestone, shale, silt	4–9 (7)
22.9–30.5	2	> 300	10	Gravel	4–9 (8)
> 30.5	1			Basalt	2–10 (9)
				Karst development limestone	9–10 (10)

Soil media (S)		Topography (T)		Land use (L)		Groundwater exploitation intensity (E)	
Range	Rating	Range (%)	Rating	Scoring range	Rating	Range (%)	Rating
Thin layer or missing	10	0–2	10	Woodland	1	< 20	2
Saline soil	9	2–6	9	Wetlands	2	20–40	4
Sand	9	6–12	5	Grassland	3	40–60	6
Sandy loam	7	12–18	3	Waters	5	60–80	8
Sandy clay	6	> 18	1	Arable land	7	> 80	10
Loam	5			Unused land	8		
Silty, clay loam	3			Urban construction land, industrial land, residential land	10		
Clay	1						

Table 4 The hierarchy structure of the evaluation index

Target layer A	Criteria layer B	Index layer C
Groundwater vulnerability	Internal factors B_1	Depth to groundwater table C_1
		Rainfall recharge C_2
		Aquifer media C_3
		Soil media C_4
		Topography C_5
	Human factors B_2	Land use C_6
		Groundwater exploitation intensity C_7

County and the western coastal areas of Yinhai District with 2% of the study area, the high vulnerability areas cover 29% of the study area, and low and lowest vulnerability areas occupy 54 and 14%, respectively. It is clear that both DRASTIC and AHP-DRASTLE models produce different vulnerability maps, but they have something in common. Yinhai District is the low vulnerability area in both maps. The northern areas are low or lowest vulnerability in AHP-DRASTLE model, while they are high vulnerability in DRASTIC model. AHP-DRASTLE model applies land use and intensity of groundwater exploitation, whereas DRASTIC model neglects these parameters. The northern areas are forest, and groundwater is not exploited, which generated lowest vulnerability compared to DRASTIC model.

Taking the Honghu River reservoir area as an example, where the depth to groundwater table is relatively shallow, topography is relatively sheer, and the aquifer media consists of enhance sorption and biodegradation. The area is characterized to rich fresh water and groundwater resource, groundwater runoff modulus is more than 6 L/s km², and the aquifer is not exploited by humans, which strengthen dilution capacity. Moreover, there are less pollution sources in the area because of weak human activities on the groundwater. The susceptibility of groundwater to contamination is relatively small in the Honghu river reservoir area. This area is characterized with highest vulnerability from DRASTIC model final map, while the vulnerability map of AHP-DRASTLE model shows this area is low vulnerability area.

From the general comparison between DRASTIC model and AHP-DRASTLE model, it is obvious AHP-DRASTLE model better suits the case of Beihai City than DRASTIC model. This is because it takes into account human factors that play an important role in groundwater contamination; these factors are land use and intensity of groundwater exploitation. Agricultural land accounts for 67% of the total study area, and the seawater intrusion occurred in the the coastal areas due to exploitation. And it adopts optimized parameters and its ratings and weights that reflect the influence of each parameter on the final vulnerability accurately. The comparative analysis confirmed that AHP-DRASTLE model can better assess the groundwater vulnerability to pollution and enhance the objectivity and rationality of the final groundwater vulnerability assessment for the study area.

The vulnerability map (Fig. 8) can be used for groundwater resource protection. The highest vulnerability zone is situated particularly in the Hepu County and the western coastal area of the Yinhai District. The groundwater is polluted by organic matter as result of increasing domestic pollution sources in Hepu County, so the necessary measures are taken to avoid dumping of garbage, sewage discharge, and further contamination of groundwater. The high vulnerability zone in Yinhai District is exposed to seawater intrusion as a result of overexploitation of groundwater. To control the extent of seawater intrusion, amount of groundwater exploitation should be decreased and some exploited wells are supposed to be closed. The low or lowest vulnerability class does not imply that the groundwater pollution does not occur in the low or lowest vulnerability areas. Compared to high vulnerability areas, these vulnerability areas are not susceptible to pollution from human activities and natural environment. It also is necessary to strengthen monitoring of water quality and water quantity in the low or lowest vulnerability areas to prevent the further groundwater pollution in the future. The major local groundwater source should be planned in the lowest vulnerability area in which the groundwater is rich; the establishment of different sizes of centralized water supply sources will avoid the groundwater pollution from the process of groundwater decentralized exploitation.

Table 5 The weight of each index

Index A	B_1 0.67	B_2 0.33
Depth to groundwater table C_1	0.36	
Rainfall recharge C_2	0.24	
Aquifer media C_3	0.12	
Soil media C_4	0.10	
Topography C_5	0.18	
Land use C_6		0.33
Intensity of groundwater exploitation C_7		0.67

Table 6 The weight of AHP-DRASTLE model

Index	Depth to groundwater table	Rainfall recharge	Aquifer media	Soil medium	Topography	Land use	Intensity of groundwater exploitation
Weights	0.242	0.158	0.084	0.065	0.118	0.111	0.222

Single-parameter sensitivity analysis

The objective of single-parameter sensitivity analysis is to determine the effective weight of each parameter in the groundwater vulnerability map. The effective weight, also called coefficient of variation, was calculated by using the following equation:

$$W = \frac{P_r \cdot P_w}{V} \cdot 100 \tag{3}$$

where W is the effective weight of the parameter P, P_r is the rating, P_w is the weight, and V is the vulnerability index.

The single-parameter sensitivity analysis result is shown in Table 9. Table 9 reveals that the depth to groundwater table and rainfall recharge trend to be the most effective parameter in the vulnerability assessment, because their effective weights, 32.9 and 20.5%, respectively, are higher than their respective theoretical weights (24.2 and 15.8, respectively). The aquifer media and topography (9.6 and 15.9%, respectively) also show higher effective weight in comparison to their theoretical weight (4.8 and 11.8%, respectively). The other parameters present less effective weights than the theoretical weight. The significance of depth to groundwater table, rainfall recharge, aquifer media, and topography layers

Fig. 7 Rating distribution map of groundwater vulnerability other indexes: (a) depth of groundwater table, (b) rainfall recharge, (c) aquifer media, and (d) soil media
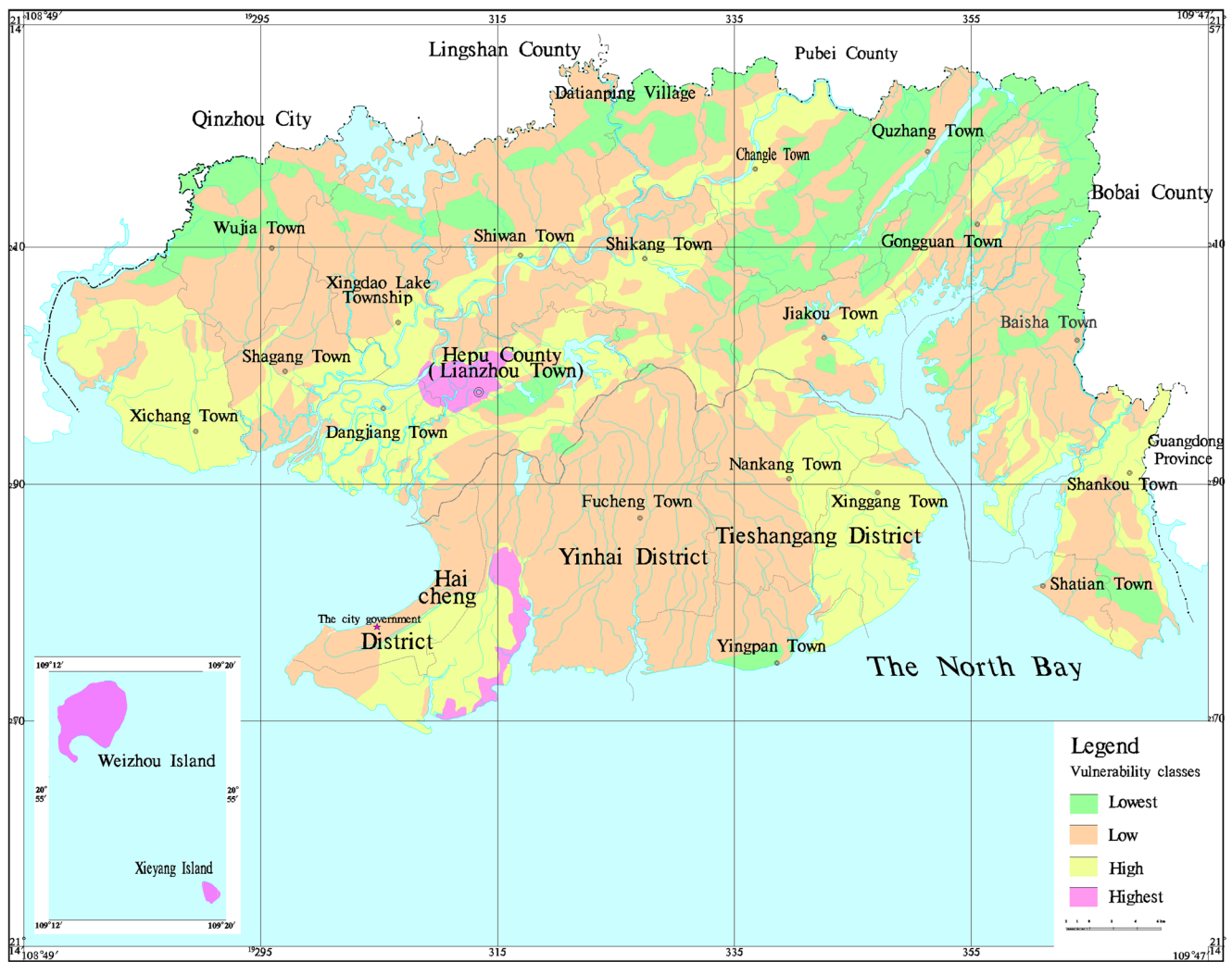
Fig. 8 The vulnerability map for AHP-DRASTLE model in the study area

highlights the importance of obtaining accurate and detailed information about these factors.

Conclusions

This paper evaluates the groundwater vulnerability to pollution by applying both DRASTIC models (AHP-DRASTLE) for Beihai City, China. In form of limitation of the DRASTIC model, this study improves and modifies the DRASTIC model to adapt the modified DRASTIC model to the particularity of the study area. The Pearson correlation coefficient between the parameter score values and the mean nitrate concentrations

Table 7 Evaluation degree of the vulnerability index

Rank	Lowest	Low	High	Highest
Index	< 5.0	5.0–6.5	6.5–8.0	8.0–9.0

declares that depth to water table, rainfall recharge, aquifer media, soil type, and topography are the critical parameters that influence groundwater hydrogeological vulnerability to contamination. And human factors, i.e., land use and intensity of groundwater exploitation, are considered in the assessment process, named DRASTLE. Moreover, this paper optimizes the ratings of parameters based on the local environmental conditions and relative researches, and modifies the weights of parameters by applying the analytic hierarchy process to better assess the groundwater vulnerability. Further, the comparative analysis concluded that AHP-DRASTLE model suits the study area more than the DRASTIC model and can reflect influence of the individual characteristic on the vulnerability of groundwater to pollution.

From the vulnerability assessment of the modified DRASTIC model, a great majority of areas in Beihai City are low and lowest vulnerability. This study provides an important tool for decision makers at groundwater resource protection and scientific land use planning. The resulting

Table 8 The assessment result of the groundwater vulnerability in the study area

Evaluation grade	Area (km²)	Area ratio (%)	Distribution area	The influencing factor
Highest vulnerability	49.8	2	Hepu County and the western coastal areas of Yinhai District	Larger rainfall recharge, overexploitation of groundwater, the shallow depth of groundwater, groundwater was polluted from domestic pollution sources
High vulnerability	979.36	29	Xichangt Town, Dangjiang Town—Changle Town area, Shankou Town southeast of Yinhai, and east of Tieshangang District	Rainfall is heavy, terrain slope less than 2%, the degradation of pollutants in gravel aquifers is weak
Low vulnerability	1894.21	55	Wujia Town, Xingdao Lake, Shiwan Town, Haicheng District, west of Tieshan gang, Baisha Town and Shatian Town—Gongguan Town Area	Depth of groundwater table is deep, the steep is large, low groundwater exploitation intensity, the aquifer consists of sand and gravel sand, weak degradation to pollutants
Lowest vulnerability	493.33	14	West and northwest of the study area	Rich groundwater resources, strong autopurification, low groundwater exploitation intensity, weaker human activity

Table 9 Single-parameter sensitivity analysis (effective weights)

Parameters	Theoretical weight (%)	Effective weight (%)			
		Max	Mean	Min	SD
D	24.2	58.5	32.9	14.5	8.5
R	15.8	43.5	20.5	4.2	6.6
A	4.8	26.5	9.6	5.1	2.1
S	6.5	46	5.7	2.9	2.9
T	11.8	46.5	15.9	4.3	5.4
L	11.1	33.1	9.2	1.4	5.4
E	22.2	37.1	10.0	5.9	6.5

vulnerability map can be used for plan of groundwater exploitation; it also can be used for design of groundwater monitoring networks.

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