

Article

Groundwater Vulnerability Assessment and Protection Strategy in the Coastal Area of China: A GIS-Based DRASTIC Model Approach

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Abstract: Groundwater vulnerability reflects the risk level of groundwater contamination and its self-repairing ability, as well as its sustainability for use. Therefore, it provides significant scientific support for implementing measures to prevent groundwater contamination, especially in coastal areas. In this study, considering the lithology of vadose in valley plains and the extent of karst subsidence areas, a GIS-based DRASTIC model was employed to assess groundwater vulnerability in Tangshan City, a coastal area in China. The assessment results were presented and mapped using GIS, based on a comprehensive evaluation of seven parameters, including “Depth of groundwater, Vertical net recharge, Aquifer thickness, Soil media, Topography, Impact of vadose zone, and Hydraulic conductivity”. The identified groundwater vulnerability zones included the highest, higher, moderate, low vulnerability those four zones, which accounted for 4%, 53%, 25%, and 18%, respectively. In addition, according to the results of field investigation, the karst subsidence area and the mined-out coastal area were directly classified as the highest vulnerable areas and covered 1.463 km²; more attention is required here in subsequent groundwater protection processes and strategies. Finally, the groundwater pollution index was used to validate the groundwater vulnerability distribution results, and these two were in high agreement, with an R^2 coefficient of 0.961. The study is crucial for the rational utilization and protection of water resources in Tangshan City.

Keywords: groundwater; vulnerability assessment; GIS-based DRASTIC model; protection strategy; coastal areas



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1. Introduction

Water resources are a vital and irreplaceable natural asset for human survival and development. With the rapid progress of national economic construction and the improvement of living standards, the demand for groundwater resources continues to increase, leading to an increasingly prominent imbalance between supply and demand. Simultaneously, the issue of water pollution has become more pronounced due to the continuous development of industry and agriculture, posing a serious threat to human development. Shallow groundwater systems are highly susceptible to changes in precipitation levels since their recharge primarily comes from surface sources [1]. Groundwater, as a crucial water source, has garnered significant attention.

Under recent climate change, groundwater resources have been increasingly exploited and utilized worldwide, resulting in pollutant issues, particularly in highly vulnerable areas [2]. Groundwater extraction, which serves as a widespread and accessible method for obtaining high-quality freshwater, accounts for up to 30% of total global freshwater

utilization [3,4]. However, excessive groundwater exploitation often leads to a continuous decline in the water table [5–7], posing risks of land subsidence and collapse, especially in densely populated urban areas such as Tianjin, Jakarta, Konya, Mashhad, and Hanoi [8–12]. Moreover, groundwater exploitation significantly contributes to vulnerability associated with high levels of human activity [13,14]. The exploitation of groundwater and its impact on ecological systems pose challenges to global economic and social development [15,16].

Groundwater vulnerability reflects both the extent of contamination and the ability of groundwater to self-repair and maintain sustainability. As a complex black box system, groundwater vulnerability factors are diverse, and various research methods are available. For example, Chaves et al. [17], Van Dijck et al. [18], and Cui et al. [19] employed Mann–Kendall’s Test, Poisson Distribution, End-member mixing analysis, and other relevant models based on land use change and soil infiltration. These studies revealed that groundwater responses to precipitation weaken or even disappear due to the thickened vadose zone and reduced permeability caused by declining groundwater levels and the conversion of natural grasslands to artificial farmland [20]. In a recent study in Nigeria, GLSI and LC models were used to conduct a case study of the Ijero mining site, examining the comparative effect of lateritic shield on groundwater vulnerability [21,22]. Groundwater vulnerability assessment provides significant scientific support for implementing measures to prevent groundwater pollution [23,24]. Vaezihir and Tabarmayeh [25] and Wen et al. [26] selected environmental parameters such as vadose zone impact, hydraulic conductivity, population density, and river recharge, utilizing the DRASTIC model to evaluate aquifer vulnerability.

The DRASTIC model aims to use seven factors such as “Depth to water, Net recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and Hydraulic Conductivity”, and allocates the ratings to all factors according to the range of factors [27], which is simple and widely used in evaluating groundwater contamination vulnerability. However, previous studies tend to assess groundwater vulnerability subjectively and refer only to a small number of factors, or have reported only a weak correlation between water pollutant concentrations (commonly nitrate) and the calculated DRASTIC index [28,29], which provided difficulties in obtaining conclusion accurately. This research integrated DRASTIC with additional methods like the GIS techniques, PCA (Principal Component Analysis), and other statistical approaches, which improve the evaluation systems to be modified to obtain more accurate results based on local hydrogeological conditions [30–32]. Furthermore, regression analysis is also applied in the DRASTIC model which has developed a new system for evaluating groundwater vulnerability, thereby enhancing scientific rigor and accuracy in utilization.

Groundwater vulnerability studies are crucial foundational work for the rational development, utilization, and protection of groundwater resources. To establish timely zoning systems for groundwater pollution prevention and control, it is necessary to evaluate the pollution resistance of groundwater systems. In this study, a GIS-based DRASTIC model was employed to assess groundwater vulnerability, with emphasis on the lithology of the vadose in the valley plain and the extent of karst subsidence areas. Comprehensive evaluation results based on seven parameters were presented and mapped using GIS to reflect the typical characteristics of coastal areas, enabling the efficient formulation of protection strategies. The aim of this study is to construct a set of groundwater vulnerability evaluation index systems and methods in the coastal area, to characterize the spatial distribution of vulnerability, and to propose corresponding protection measures and environmental protection strategies for highly vulnerable areas.

2. Study Area and Data

2.1. Location and Meteorology

Tangshan City is situated in the northeast of Hebei Province, with geographical coordinates ranging from 117°31′ to 119°19′ east longitude and 38°55′ to 40°28′ north latitude. The total land area of Tangshan City is 13,472 km², comprising 5131 km² (38.09%)

of mountainous terrain and 8341 km² (61.91%) of plains. Additionally, it has a sea area spanning 4472 km², with a coastline stretching 229.72 km in length. Tangshan experiences a typical warm temperate sub-humid continental monsoon climate characterized by cold and dry winters with northerly winds, and hot and rainy summers with southerly winds. The annual average temperature is 10.6 °C, while the average precipitation from 1956 to 2020 amounts to 608.7 mm.

2.2. Hydrogeology

Based on the occurrence conditions of groundwater and the characteristics of aqueous media in Tangshan, three types of groundwater can be identified: pore water in loose rocks, carbonate karst water, and bedrock rock fissure water. Pore water is primarily found in the piedmont plain, coastal plain, inter-mountain basin, and valley zones of the Yan Mountain region (Figure 1). The main source of recharge for this groundwater type is atmospheric precipitation, and its dynamics closely follow the annual distribution of rainfall. Karst water is predominantly present in the southern foothills of the Yan Mountain, concealed within sloping plains, piedmont areas, and intermountain basins. The degree of karst development varies and is closely associated with the local geological structure and geomorphology. Individual well yields typically range from 40 to 25 m³/h·m, while spring water flow rates vary between 0.3 and 3.0 L/s. Fissure water is located in the northern hilly area, characterized by a recorded fracture rate of 1.3%. The weathered zone has an approximate depth of 50 m, with some localized fractures exceeding 100 m due to significant geological influences [33].

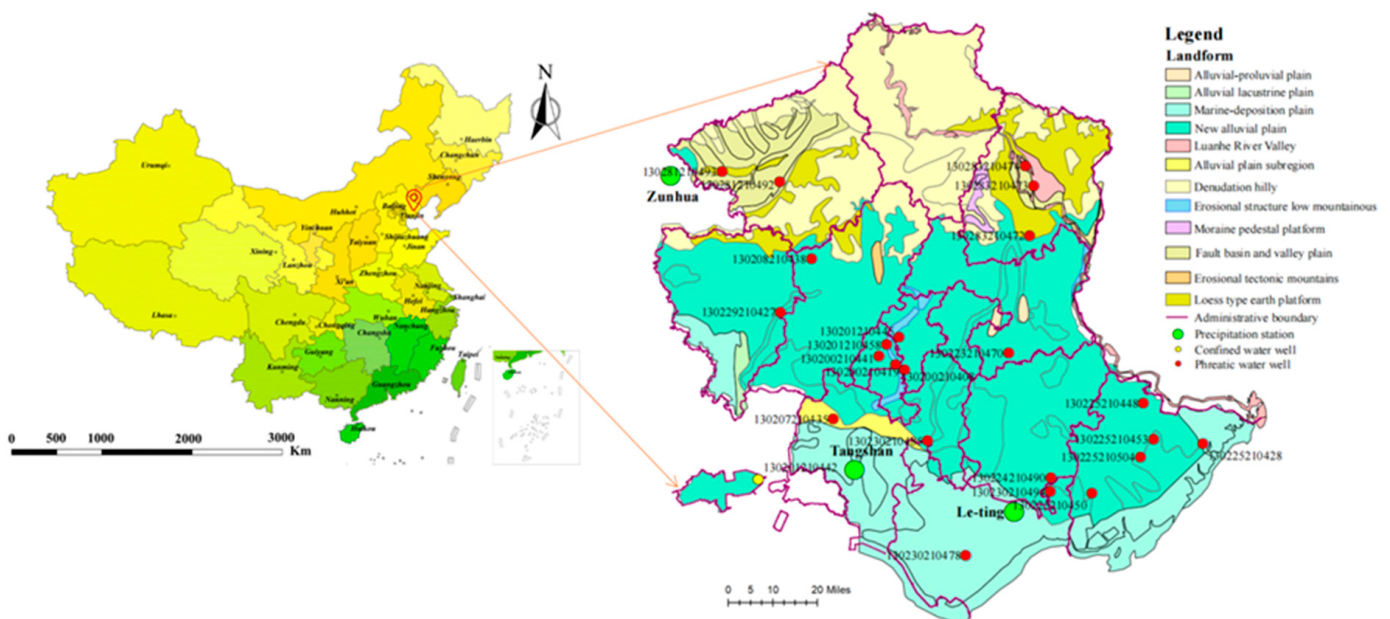


Figure 1. The location of study area and its hydrogeological condition.

2.3. Data Availability

This study is a significant component of the zoning and technical research for groundwater pollution prevention and control in Tangshan City, encompassing two main aspects: the analysis of groundwater dynamics and the evaluation of groundwater vulnerability.

In the investigation of groundwater dynamics, a total of 75 government-monitored wells with long-term observation data were carefully selected to ensure completeness, control, and representativeness. For each district or county level, 1–2 monitoring wells were chosen for analysis, ensuring a uniform distribution across the study area. Specifically, this study focused on analyzing the response of unconfined groundwater, directly recharged by precipitation. Based on these principles, data from 24 monitoring wells were ultimately

determined. To complement this analysis, three precipitation stations in Zunhua, Tangshan, and Leting were selected to match similar monitoring wells based on their proximity.

In the evaluation of groundwater vulnerability, data acquisition was conducted through indoor data collection and gathering relevant information about the study area's geology, hydrogeology, and drilling. This included parameters such as groundwater depth, vertical net recharge, aquifer thickness, soil medium, terrain slope, vadose medium type, and permeability coefficient. A total of 1599 boreholes and associated information were gathered from various sources, including survey reports on land pollution from key industries in Hebei Province, China (974 cases), hydrogeology and engineering geology borehole construction and in-situ tests (28 cases), comprehensive geological surveys of major cities and towns (19 cases), the national important geological borehole database service platform (55 cases, <https://zk.cgsi.cn/> (accessed on 28 August 2023)), groundwater level surveys (164 cases), and geotechnical investigation reports (359 cases). Aquifer permeability data were obtained by combining the aquifer media type with empirical values from the Hydrogeological Manual [34]. All data collected are accurate, providing strong support for the reliability of this study.

3. Methodology

3.1. Description of the GIS-Based DRASTIC Model Framework

In this study, a GIS-based DRASTIC model was employed to assess the vulnerability of groundwater in Tangshan City, a coastal area in China. The DRASTIC model, initially developed by the US Environmental Protection Agency (EPA) to evaluate groundwater pollution potential across the United States [35], considers intrinsic vulnerability based on hydrogeological characteristics while disregarding the specific contaminants. The use of a GIS-model interface facilitates data input, and the GIS can also serve as a common platform for transferring information between different examples of software. By combining various data sets within the GIS framework, thematic maps can be generated for utilization by the DRASTIC model. Furthermore, the GIS enables the conversion of these maps into raster mode, dividing them into pixels with dimensions of 300 m × 300 m. Each pixel is assigned a numerical value corresponding to the resulting grid, which serves as a basis for the seven parameters of the DRASTIC model, as detailed in the following equation:

$$DRASTIC_{index} = W_D R_D + W_R R_R + W_A R_A + W_S R_S + W_T R_T + W_I R_I + W_C R_C \quad (1)$$

where, the parameters in Equation (1) include the following: depth of groundwater (D), vertical net recharge of groundwater (R), aquifer thickness of media (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C).

Consequently, vulnerability is calculated at a high resolution for each individual pixel. The GIS is further utilized to overlay the seven thematic maps, thereby generating a groundwater vulnerability map. The DRASTIC index computation involves assigning weights (W) to each parameter and using the assigned values (R).

3.2. Description of the GIS-Based DRASTIC Model Parameters

The seven parameters in Equation (1) that affect and control groundwater flow and pollutant transport are adopted in DRASTIC to constitute the factor system for vulnerability assessment. Based on the "Delineation of Priority Areas for Groundwater Pollution Prevention and Control Technical Guideline" published by the China Geological Survey in 2022 [36], different parameter weights have been assigned by investigation experience and field experiment. According to the influence of each parameter on groundwater vulnerability, different weight values are assigned to them in Table 1.

Table 1. Description of DRASTIC model parameters and its weights.

Parameter	Description	Relative Weight
Depth of groundwater (D)	Depth to groundwater table is the distance from the surface to the submerged surface; unit is m.	5
Vertical net recharge (R)	Approximate using precipitation infiltration recharge instead of vertical net recharge; unit is mm/a.	4
Aquifer thickness (A)	Aquifer thickness can be analyzed from borehole data; refers to the saturated zone material properties, which controls the pollutant attenuation processes; unit is m.	3
Soil media (S)	The soil media is a weathered layer with a thickness of 2 m or less at the surface, which controls the amount of recharge that can infiltrate downward.	2
Topography (T)	Slope values can be automatically generated in GIS after DEM extraction from 1:50,000 or 1:10,000 topographic maps.	1
Impact of Vadose Zone (I)	The unsaturated zone material: it controls the passage and attenuation of the contaminated material to the saturated zone.	5
Hydraulic conductivity (C)	Indicates the ability of the aquifer to transmit water, and hence determines the rate of flow of contaminant material within the groundwater system.	3

Based on the aforementioned seven parameters, an evaluation level is assigned to each parameter. As the local groundwater depth increases, vertical net recharge decreases, aquifer thickness increases, soil and vadose zone cutoff particles become finer, topographic slope increases, and aquifer permeability coefficient decreases, the scores for each parameter will decrease. A lower score indicates a smaller contribution of that parameter to the groundwater vulnerability assessment index, suggesting a reduced susceptibility to pollution. Conversely, higher scores indicate a greater contribution of the parameter to the groundwater vulnerability assessment index, indicating a higher vulnerability to pollution. The scores for each indicator range from 1 to 10, with specific classifications provided in Table 2.

Table 2. The parameter Ranking and Assignment in DRASTIC.

Parameter	Grade									
	1	2	3	4	5	6	7	8	9	10
D (m)	>30	(25, 30]	(20, 25]	(15, 20]	(10, 15]	(8, 10]	(6, 8]	(4, 6]	(2, 4]	≤2
R (mm/a)	0	(0, 51]	(51, 71]	(71, 92]	(92, 117]	(117, 147]	(147, 178]	(178, 216]	(216, 235]	>235
A (m)	>50	(45, 50]	(40, 45]	(35, 40]	(30, 35]	(25, 30]	(20, 25]	(15, 20]	(10, 15]	≤10
S	rock	clay loam	silt loam	loam	sandy loam	swelling or condensing clay	silt-sand/ fine sand	medium sand/coarse sand	gravel-cobble	thin layer or missing
T(%)	>10	(9, 10]	(8, 9]	(7, 8]	(6, 7]	(5, 6]	(4, 5]	(3, 4]	(2, 3]	≤2
I	clay	loam	sandy loam soil	silt-sand	silty, fine sand	fine sand	medium sand	coarse sand	sand gravel	gravel-cobble
C (m/d)	[0, ≤4]	(4, 12]	(12, 20]	(20, 30]	(30, 35]	(35, 40]	(40, 60]	(60, 80]	(80, 100]	>100

A step wise flow diagram representing the data processing, preparations of layers, and assigning of weights has been demonstrated below in Figure 2.

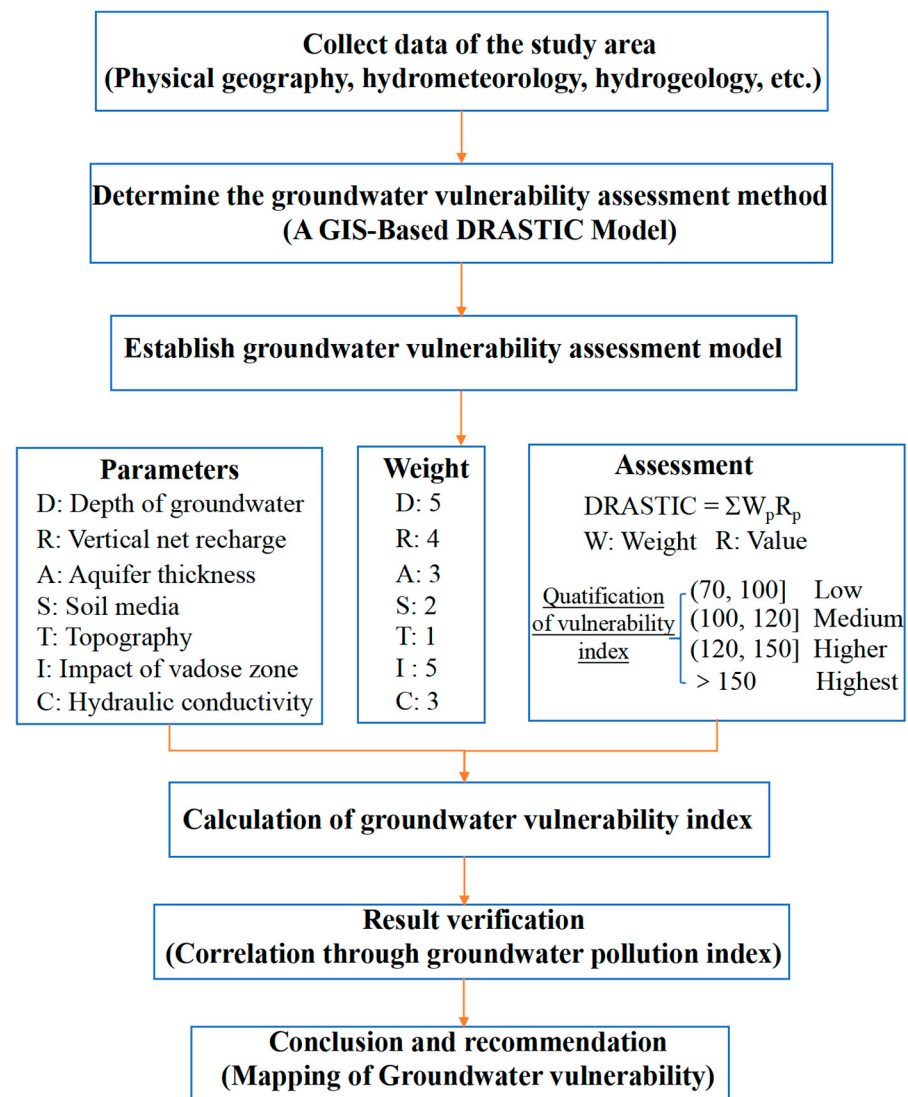


Figure 2. Flowchart of groundwater vulnerability assessment.

4. Results and Discussion

4.1. Results of Single Parameter Evaluation

4.1.1. Depth of Groundwater

A total of 1867 data points were collected for groundwater depth. The depth at which groundwater is located primarily determines the depth of the transmission medium through which pollutants migrate to the aquifer [37]. Generally, a greater groundwater depth requires more time for pollution to reach the aquifer. This results in a smaller amount of pollution entering the aquifer and weaker levels of contamination within the aquifer, with the opposite being true as well.

The method for analyzing the zoning map of buried depths differs between mountainous and plain areas. In the plain and valley regions, water level data collected and supplementary surveys are interpolated and adjusted based on hydrogeological and river conditions. In mountainous areas, characterized by significant topographic variations and complex geological conditions, underground water depths are mainly classified according to aquifer types. The same type of water-bearing medium within an area is assigned an average value based on measured groundwater levels. Additionally, for valleys within mountainous regions where groundwater exists within loose rock formations, score values are determined by interpolating the buried depths observed in plain areas.

Once the above analysis is completed, the mountainous and plain areas are superimposed using GIS, ensuring uniform layer attributes. Gradation mapping (Figure 3a) is then assigned based on Table 2.

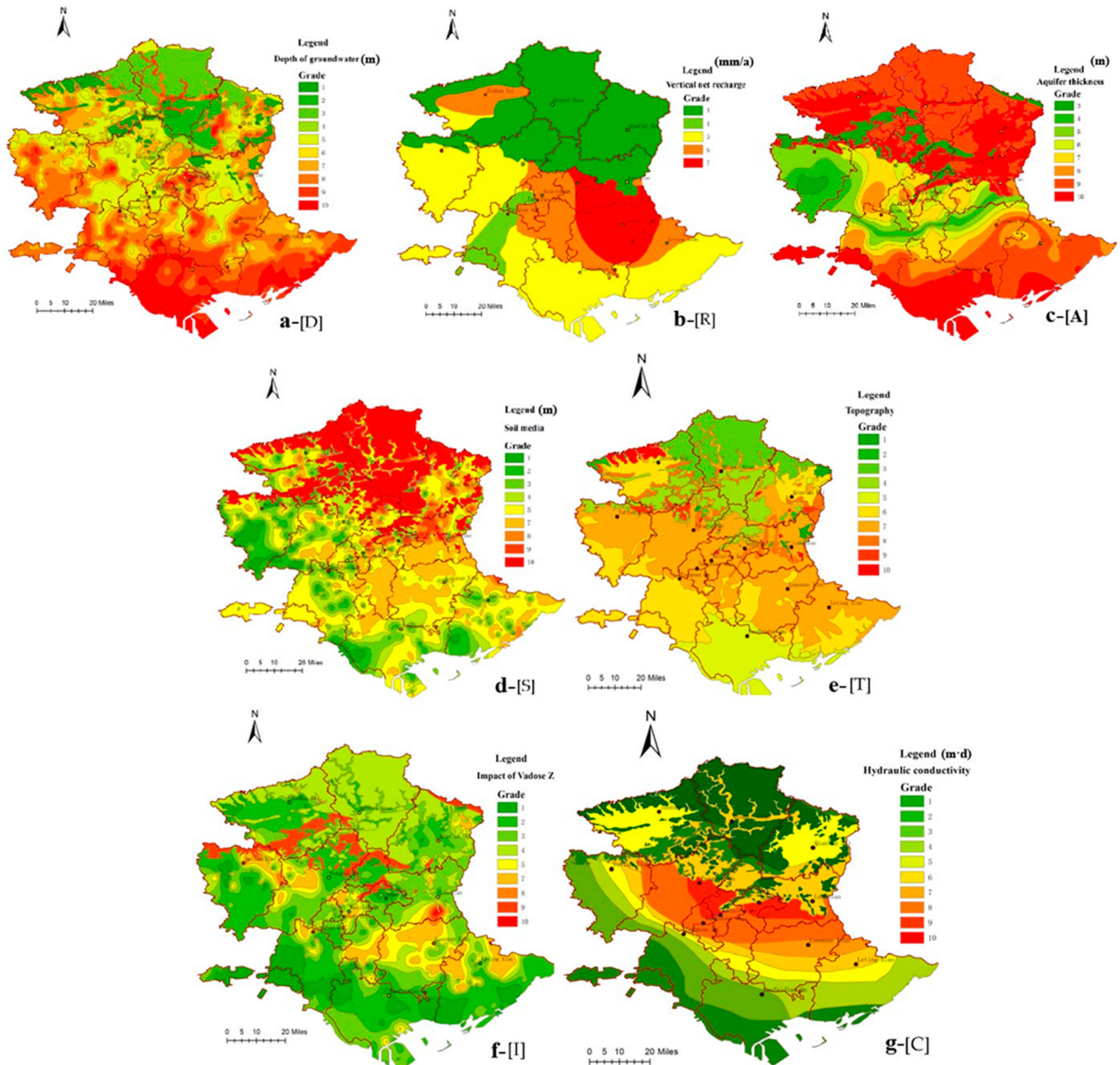


Figure 3. Mapping of DRASTIC parameters ((a) Depth of groundwater; (b) Vertical net recharge; (c) Aquifer thickness; (d) Soil media; (e) Topography; (f) Impact of vadose zone; (g) Hydraulic conductivity).

4.1.2. Vertical Net Recharge

Net recharge refers to the amount of water per unit area that infiltrates the surface and reaches the aquifer. Contaminants can enter the aquifer vertically through this recharge water [38]. In the DRASTIC model, net recharge represents the total amount of water applied to the surface and infiltrated into the aquifer. In Tangshan City, atmospheric precipitation serves as the primary source of regional recharge, and therefore, the vertical net recharge can be estimated using precipitation infiltration [39]. Generally, the equation

$R = P \times \alpha$ is used, where R denotes the vertical net recharge, P represents the precipitation infiltration coefficient, and α represents the annual precipitation.

The annual precipitation data for the region were obtained from the 2020 precipitation records of four gauging stations. In 2020, Tangshan City experienced rainfall ranging from 480–720 mm, with higher precipitation observed in the northern mountainous area compared to the southern plain area. Notably, Luannan County in the southern plain area received relatively higher precipitation. In the study area, the values of α range from 0.15–0.2 in the plain area, 0.09 in the igneous and metamorphic rock area, and 0.08 in the carbonate rock area. The empirical values of the precipitation infiltration coefficient were adjusted based on field seepage test results (30 groups) to ensure accuracy. The resulting vertical net recharge is illustrated in Figure 3b.

4.1.3. Aquifer Thickness

Aquifer thickness (Figure 3c) is determined by combining groundwater depth measurements with borehole data [40]. The data sources include the national important geological borehole database service platform (55 points), Geo-technical Investigation Reports (359 points), and borehole data collected during field investigations (30 holes), totaling 444 points.

In the bedrock mountain areas, the thickness of the weathered fissure layer is primarily considered, and it is obtained by subtracting the groundwater depth. The average value is then calculated for different regions. In the metamorphic rock and igneous rock mountain areas of Tangshan City, the thickness of the weathering layer ranges from 40–50 m, with some areas reaching up to 60 m. For the bare leaky karst mountains, the thickness of the strong water-bearing zone identified through borehole data is used to determine the aquifer thickness. Again, the average value is calculated for different regions. For example, in the northern part of Yutian County, Tangshan City, the thickness of the Jixian dolomite strong water-bearing zone is 40–45 m. In the plain area, the shallow aquifer thickness in the coastal region is relatively thin, mostly less than 10 m. This is determined based on calculations using borehole data and groundwater depth measurements.

4.1.4. Soil Media

Soil refers to the biologically active upper layer of the seepage zone. The influence of soil on groundwater vulnerability primarily relies on the physicochemical properties of different soil types [41]. In the study area, there are various soil media, with sandy loam and swelling or condensing clay being widely distributed. In the northern mountainous area of Tangshan City, the surface soil layer is very thin in some areas, while the lower part consists of weathered bedrock crust. This results in predominantly thin or deficient soil media. In the middle region, sandy loam, silty sand, and fine sand are widely distributed. In the coastal area, clay loam (clay), and silty loam are prevalent. The soil media were classified into different grades as shown in Figure 3d.

4.1.5. Topography

Topographic slope plays a significant role in groundwater migration and subsequently affects groundwater vulnerability [42]. In this study, a digital elevation model (DEM) of the research area was acquired through a measurement system. The DEM had an accuracy of 12.5 m, which met the guidelines' requirements. Using the GIS's slope tool, the slope was calculated based on the projected DEM map. Then, according to the scoring standard, each zone's attributes were determined through reclassification (Figure 3e). Due to the high resolution of the data, fragmentation zones were formed considering the impact of rivers and dams in the plain area on slope classification. This evaluation utilized the geomorphic zones of the study area as a reference, and the average terrain slope within each zone was considered the representative slope value.

The study area exhibits significant variations in topographic slope, generally decreasing from north to south. High topographic slope values are concentrated in the northern

mountainous area, while the intermountain basin, piedmont plain, and coastal plain exhibit relatively low slopes. The highest topographic slope values are found along the northern edge of Yutian County, the southern part of Zunhua City, the northern part of Fengrun District, the southern part of Qianxi County, the western part of Qian'an City, and the northwestern part of Luanzhou City. Conversely, the lowest slope values are primarily distributed in Caofeidian District along the southern coast.

4.1.6. Impact of Vadose Zone

The unsaturated zone, also known as the vadose zone, refers to the area between the Earth's surface and the water table. The type of vadose zone medium plays a crucial role in controlling water exchange between the soil layer and aquifer, the migration and transformation of pollutants, as well as various physicochemical and biological processes [43]. Additionally, the vadose zone medium determines the length and path of percolation. Therefore, it serves as an important indicator for evaluating groundwater vulnerability.

In the plain area of the study region, the vadose zone mainly consists of Quaternary sediments, which can be categorized into nine types. When assessing the self-purification capacity of the vadose zone, factors such as particle size and permeability of the Quaternary sediments are primarily considered. The assigned values range from 1 to 10. In the mountain aquifers, the vadose zone comprises regolith with varying degrees of metamorphic rocks and igneous rocks, as well as dissolution layers of dolomites and limestone in karst areas. Based on vulnerability assessments conducted in different mountainous regions in China, the medium score for the vadose zone in bedrock regolith is determined to be 4 points.

This determination takes into account the extent of fracturing and dissolution observed in the surface regolith of the Tangshan mountain area, finally showed in Figure 3f. For dolomite or limestone vadose zones, the medium score is set at 8 points.

4.1.7. Hydraulic Conductivity

The permeability of an aquifer is influenced by the type of aquifer medium, and the permeability coefficient partially reflects the lithological composition of the aquifer [44]. Generally, larger particle sizes or more voids in the aquifer medium indicate greater permeability, lower dilution capacity, and higher potential for pollution [45]. The aquifer's permeability coefficient is determined based on the type of aquifer medium, combined with empirical values, and adjusted using data obtained from field exploration and pumping tests (30 groups). The classification of aquifer medium types refers to the data source of aquifer thickness.

In the plain area, the permeability coefficient was obtained by interpolating the collected drilling data using Kriging interpolation with software such as Golden Surfer. For mountain aquifers, the permeability coefficient is classified based on weathered fissure aquifers in metamorphic rocks, weathered fissure aquifers in igneous rocks, and karst fissure aquifers. The assignment of permeability coefficients is performed according to the aquifer types derived from pumping test results from hydrologic boreholes. GIS technology is utilized to overlay the mountain and plain areas, harmonize layer attributes, and assign values to each partition following evaluation guidelines.

In the northern mountainous area of Tangshan City, the permeability coefficient mostly ranges from 0.5–5 m/d, with some areas reaching up to 10 m/d. In the southern coastal area, where silt is the predominant aquifer type, the permeability coefficient is relatively low, mostly below 12 m/d. The Shanqian area in central Tangshan exhibits higher permeability coefficients, with the lowest values observed in the north of Zunhua City, Qianxi County, and the northwest of Qian'an City. Conversely, the highest values are found in the east of Fengrun District, the south of Kaiping District, the south of Guye District, and the south of Luanzhou City. The assignment result for hydraulic conductivity in the DRASTIC parameter is presented in Figure 3g.

4.2. Results of Comprehensive Vulnerability Assessment and Its Validation

4.2.1. Results of Groundwater Vulnerability

Vulnerability mapping was conducted using the Geographic Information System (GIS) based on hydrogeological data of the study area and with reference to the DRASTIC model, as shown in Figure 4. The groundwater vulnerability index values for Tangshan City range from 85 to 173, classified into four levels according to the DRASTIC classification principle (refer to Table 3). Higher vulnerability assessment index values indicate a higher susceptibility to pollution, while lower values suggest a lower vulnerability and reduced susceptibility to pollution. Additionally, karst collapse areas and regions affected by mining subsidence are directly classified as the highest vulnerability areas.

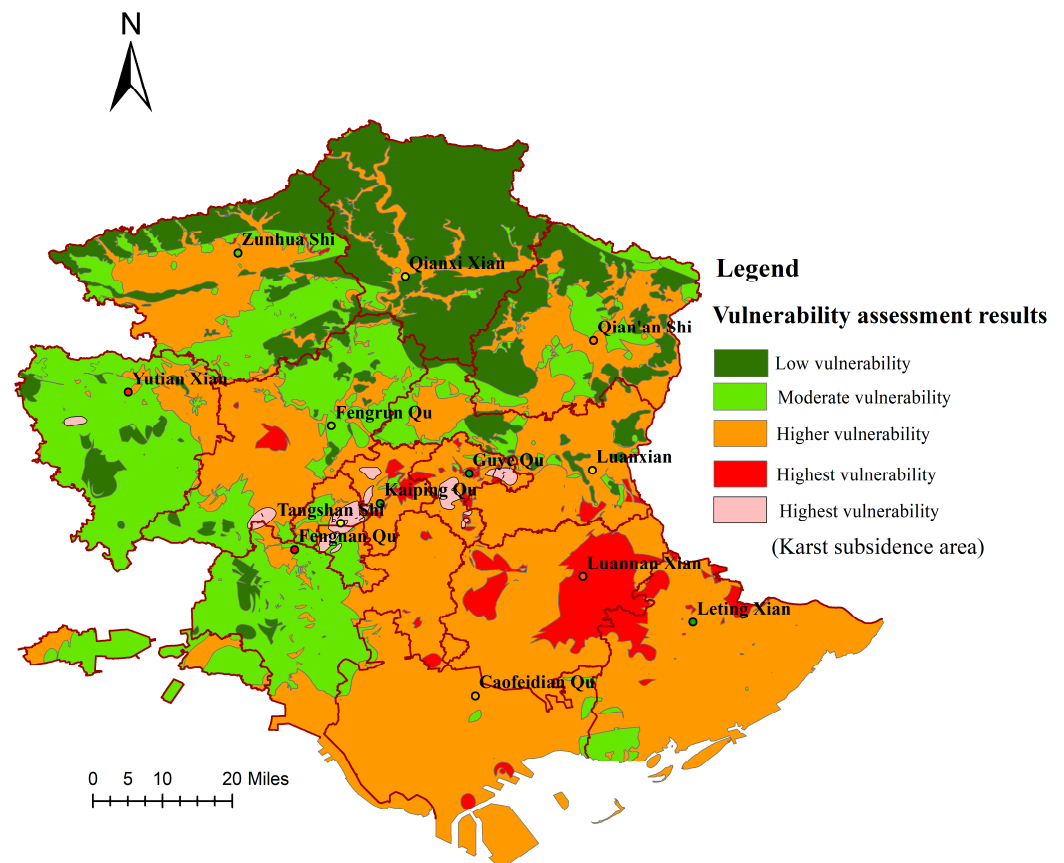


Figure 4. Comprehensive evaluation of vulnerability of groundwater in Tangshan.

Table 3. Classification of vulnerability of shallow groundwater in Tangshan City.

Groundwater Vulnerability Composite Index Value	Vulnerability	Level
(70, 100]	Potentially contaminated	Low
(100, 120]	Easily contaminated	Moderate
(120, 150]	highly prone to be contaminated	Higher
>150	Particularly vulnerable to be contaminated	Highest

The vulnerability assessment map of shallow groundwater in Tangshan City reveals the following distribution results. Firstly, the shallow groundwater in Tangshan City exhibits high vulnerability, with the highest vulnerability area accounting for 4% of the total study area, the higher vulnerability area accounting for 53%, and the moderate vulnerability area accounting for 25%. Together, these three categories account for 82% of the area, while the low vulnerability area only accounts for 18%. This highlights the weak protection performance of shallow groundwater in the region, making it susceptible to pollution.

Secondly, the spatial variability and causes of groundwater vulnerability in the study area are complex. The area around Luannan County has relatively shallow groundwater depth, significant vertical recharge, and a thick aquifer, leading to its classification as an area with high underground vulnerability. The valley area in the study region is also classified as a high vulnerability area due to its homogeneous lithology, simple rock structure, and strong permeability. These areas experience frequent agricultural activities and have well-developed aquaculture, resulting in a high pollution load and easy pollution of groundwater [46]. Similarly, highly vulnerable areas are also found in the central and southeastern regions of Tangshan, characterized by high vertical net recharge, relatively high permeability coefficients, good water permeability, and limited self-purification capacity. In addition, the karst subsidence area and the mined-out coastal area were directly classified as the highest vulnerable areas, covering 1.463 km². These factors contribute to weak anti-pollution capabilities of groundwater, making it prone to pollution. Additionally, these areas are marked by intense human activities, including urban industrial and domestic sewage discharge from Tangshan City, as well as excessive fertilization and sewage irrigation in agricultural regions. Therefore, they should be prioritized as key areas for groundwater protection.

Thirdly, low-vulnerability areas are scarce and mainly concentrated in the northern part of Tangshan, such as the northern edge of Zunhua City, Qianxi County, and the northwest of Qian'an City. In these areas, groundwater depth is significant, the vadose zone exhibits fine lithology, and recharge amounts are limited, reducing vulnerability to external pollutants.

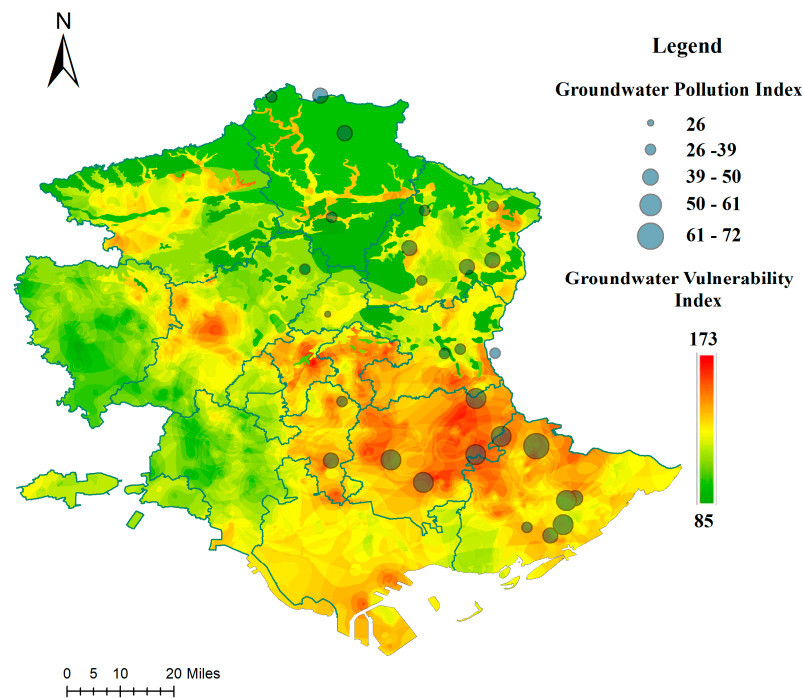
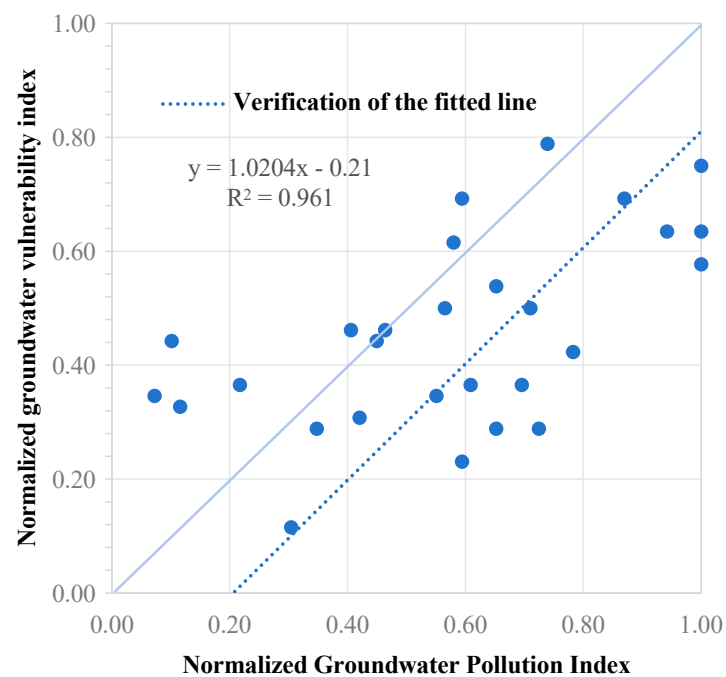
4.2.2. Validation for the Mapping of Groundwater Vulnerability

Groundwater with high vulnerability is more easily contaminated and thus more likely to have poorer water quality conditions. Currently, there are fewer methods to validate the vulnerability of groundwater, and the pollution distribution of " NO_3^- , NO_2^- , NH_4^+ " is generally used to compare with the vulnerability distribution of groundwater [47,48]. Xu et al. utilized single and combined factors to evaluate the water quality of groundwater, and then examined the correlation between the evaluation level and the vulnerability index [49]. Chao et al. chose typical water quality indicators characterizing groundwater taste, color, and scaling, which were selected to calculate the value of the groundwater pollution index according to the "Groundwater Quality Evaluation Standards" [50], and then compared them with the spatial distribution of groundwater vulnerability. Since this study also addresses the vulnerability of shallow groundwater, and there are similarities with the above studies, similar validation methods were selected.

We selected 11 water quality indicators (in Table 4) from nearly 30 well sites to calculate the Groundwater Pollution Index (GPI), which summed every index up after assigned number based on different categorization criteria in Table 4. The GPIs, ranging from 26 to 72, were used to validate the groundwater vulnerability and mapped in Figure 5, which demonstrates that high groundwater vulnerability corresponded to a high groundwater pollution index. These two were in high agreement, with a R^2 coefficient of 0.961, as shown in Figure 6. This certificated that the GIS-based DRASTIC model for groundwater vulnerability assessment was scientific and reliable, and could provide reliable experience for groundwater pollution prevention and management.

Table 4. Assignment criteria of groundwater pollution index.

Assigned Index	pH	TH mg/L	TDS mg/L	F [−] mg/L	Cl [−] mg/L	SO ₄ ^{2−} mg/L	NO ₃ [−] mg/L	NO ₂ [−] mg/L	Fe mg/L	Cu mg/L	Mn mg/L
1	6.5–8	150	300	0.2	50	50	2	0.005	0.1	0.01	0.01
3	6–6.5; 8–8.5	300	500	0.5	150	150	5	0.01	0.2	0.05	0.05
5	5.5–6.0; 8.5–9	450	1000	1	250	250	20	1	0.3	1	0.1
7	1–5.5; 9–13	650	2000	2	350	350	30	4.8	2	1.5	1.5
10	0–1; 13–14	>650	>2000	>2	>350	>350	>30	>4.8	>2	>1.5	>1.5

**Figure 5.** The mapping of groundwater vulnerability index and groundwater pollution index.**Figure 6.** Groundwater vulnerability assessment and verification index correlation.

4.3. Groundwater Protection Strategy in Coastal Area

4.3.1. Groundwater Protection Objectives Based on Groundwater Vulnerability

According to the results of the vulnerability assessment of shallow groundwater in Tangshan City, the following medium- and long-term objectives for groundwater protection have been formulated in view of the current water quality and water environment.

1. To guarantee water safety and prevent groundwater pollution. Groundwater is one of the important sources of drinking water, and protecting groundwater means guaranteeing people's drinking water safety and basic usage of water.
2. To maintain ecological balance on this basis. Protecting groundwater can maintain the water supply of wetlands, keep the stability of the ecological environment, and promote the maintenance of species diversity and the balance of the natural ecosystem.
3. To pay attention to the protection of water sources for agricultural irrigation to ensure the sustainability of agricultural irrigation and maintain the normal growth of crops, paying particular attention to reducing the adverse effects on soil salinization in the coastal area.
4. To prevent the decline in groundwater level and ground subsidence. Over-exploitation of groundwater will lead to the decline in groundwater level and ground subsidence, which will in turn lead to geological disasters and ground subsidence. One of the objectives of groundwater protection is to avoid these problems and maintain the stability of the groundwater system.

To realize the sustainable management and utilization of groundwater and to support the sound economic development of Tangshan City, groundwater resources are non-renewable resources, and the protection and rational utilization of groundwater is an important part of realizing the sustainable development of the region, which is also an important goal of this study.

4.3.2. Groundwater Protect Measures in Study Area

Based on the results of vulnerability assessment of groundwater in Tangshan City and the above protection objectives, we have clarified that the protection performance of shallow groundwater is weak, and the current status of shallow groundwater pollution is serious, so we propose the following protection measures for the current situation characteristics.

1. Reasonable land use and control of new highly polluting enterprises to reduce groundwater pollution: Urban planning, especially industrial zoning, should consider vulnerable areas and restrict the establishment of industrial zones in areas vulnerable to groundwater pollution, such as the center of Tangshan City, Kaiping District, Guye District, and Luannan County. In addition, wastewater discharge from industrial zones must be strictly managed to ensure that standards are met and groundwater pollution is controlled [51]. By controlling the sources of pollution, restricting the discharge of hazardous substances, and rationally managing groundwater extraction, it is possible to ensure that the quality of groundwater meets safety standards.
2. Balanced control of groundwater exploitation: Over-exploitation of groundwater will lead to increased water hardness, groundwater pollution, and even ground subsidence. At this stage, deep wells with serious over-exploitation should be closed, the amount of groundwater extraction should be limited, and the number of new wells should be controlled.
3. Regulate sewage irrigation and fertilizer use: It is important to control the amount of fertilizers used in agricultural areas and promote their effective use in order to minimize the amount that enters groundwater. Additionally, effluent used for irrigation should be analyzed and tested to ensure that it does not adversely affect soil and groundwater quality [52].
4. The establishment of a comprehensive groundwater monitoring network and early warning system throughout the region is essential. Regular water quality monitoring should be carried out to detect early warning signs in time for timely interventions

to mitigate serious consequences and to report data to ecological and environmental authorities.

4.3.3. Rigorous Implementation Plans for Groundwater Exploitation in High Vulnerability Area

Based on the above groundwater protection objectives and implementation methods, this study suggests that the Tangshan area should follow the following most stringent groundwater exploitation plan to ensure the sustainable development of groundwater resources.

- (1). Key groundwater pollution sources such as chemical and metal products industrial clusters, landfills, hazardous waste disposal sites, and other key groundwater pollution sources should be investigated and evaluated as soon as possible to map out the status of groundwater pollution, establish a system of seepage and leakage prevention for key groundwater pollution sources, carry out seepage and leakage prevention inspections every year, formulate seepage prevention and renovation plans for seepage prevention measures that do not satisfy the corresponding seepage prevention specification requirements, and take technical and management measures in a timely manner to eliminate hidden dangers.
- (2). For areas where groundwater pollution exists, detailed investigation and assessment of groundwater shall be further carried out, and where groundwater treatment and remediation or risk control is required after detailed investigation and assessment, control shall be strengthened and appropriate management shall be carried out in a timely manner. In areas where the health risk of groundwater pollution is unacceptable, the use of groundwater should be prohibited, and drainage methods such as pits and ponds should be restricted to reduce the disturbance of the polluted area; if drainage is really needed, it should be discharged in compliance with the standard after treatment.
- (3). Penalties should be established for enterprises and individuals who do not comply with the rules on groundwater protection, and they should be ordered to rectify the situation thoroughly before continuing production.
- (4). In areas where karst is strongly developed and where there are many fallout holes and karst funnels, construction projects that may cause groundwater pollution shall not be newly built, altered, or expanded.

5. Conclusions

Being a typical coastal city, Tangshan City exhibits a high level of vulnerability in its shallow groundwater system. The highly vulnerable area accounts for 4% of the total study area, while the areas classified as moderately and highly vulnerable account for 25% and 53%, respectively. Collectively, these three categories encompass 82% of the study area, leaving only 18% categorized as having low or minimal vulnerability. The groundwater pollution index was used to validate the groundwater vulnerability distribution results, and these two were in high agreement, with an R^2 coefficient of 0.961.

The study area, characterized by complex hydrogeological conditions and high vulnerability, is situated along the coast. The valley regions, with their homogeneous lithology, simple rock structure, and high permeability, are particularly vulnerable according to the assessment results. Additionally, the karst subsidence area and the mined-out coastal area were directly classified as the highest vulnerable areas, covering 1.463 km², where more attention is required in subsequent groundwater protection processes and strategies.

Based on the vulnerability assessment outcomes for shallow groundwater in Tangshan City, it is evident that the current state of shallow groundwater pollution is severe, indicating a weak performance in safeguarding the quality of shallow groundwater resources. Therefore, it is recommended that relevant departments address these concerns by taking appropriate actions informed by the evaluation results. These actions should focus on improving and developing groundwater resources in a rational manner, implementing

effective measures to control groundwater pollution, and undertaking remediation efforts to restore polluted groundwater.

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