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# **Evaluation of the Groundwater Safety and Analysis of the Spatial-Temporal Evolution in the Lower Plain of the Liaohe River, Northeast China based on the Improved DRASTIC** Model

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Abstract - The deterioration of the groundwater safety may lead to a series of ecological and social problems. In this study, we select relevant hydrogeological and anthropogenic parameters to construct the groundwater safety evaluation method for the lower plain of the Liaohe River based on the improved DRASTIC model. By spatially weighted overlay and Getis-Ord Gi\* analysis of groundwater safety distribution maps, the main governance regions and main factors causing groundwater deterioration were identified. On this basis, the evolution trend of the groundwater key management area was quantitatively analyzed using the standard deviation ellipse (SDE) method. The results show that groundwater safety in the north and south of the lower plain of the Liaohe River are continuing to deteriorate. The correlation test between the groundwater safety index and the measured nitrogen concentration verified the scientific accuracy of the proposed groundwater safety evaluation method.

#### 1. Introduction

Groundwater is an important natural resource for safe drinking water and social and economic development [10]. While the demand for water is increasing due to the rapid development of modern industry, and the discharge of pollutants is also increasing at the same time. Most countries are facing different levels of groundwater pollution and overexploitation, which threaten ecosystems and humans [4, 11]. Therefore, assessing the safety level of groundwater and grasping trends in its evolution are urgently required for the protection and treatment of groundwater.

Increasing numbers of studies have comprehensively evaluated the safety of groundwater by combining the essential characteristics of groundwater and external disturbance factors. Xu et al. [15] constructed groundwater safety evaluation indicators from the five dimensions of nature, ecology, environment, society, and economy, and then used fuzzy comprehensive evaluation methods to evaluate

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the safety of groundwater ecosystems, which reflected the relationship between human activities and groundwater systems. Based on the superimposed analysis of groundwater quality, water quantity, and land-use patterns in different regions, Liang et al. [8] evaluated regional groundwater safety according to groundwater quality standards and provided a reference for comprehensive groundwater management. With a focus on shale gas, Lu et al. [9] established a reliability–resilience–vulnerability and gas migration index based on probabilistic and conditional probability-based algorithms, which provided a groundwater safety assessment strategy for areas under shale gas development. All these studies established a linear relationship between groundwater safety assessment. Although researchers have selected various parameters from different aspects for weighted overlay analysis to obtain a map of groundwater safety in the comprehensive evaluation of groundwater based on the index system method, most of them lack failed to consider spatial correlation patterns and internal driving forces. As a result, defining the main controlling factors and critical areas for management or prevention of groundwater pollution is challenging.

The objectives of this study are to: (1) construct an evaluation system of groundwater safety by integrating hydrogeological conditions and human factors; (2) identify the main influencing factors and key prevention areas of groundwater safety according to the spatial quantitative analysis methods.

# 2. Study area and data preprocessing

## 2.1. Study Area

The lower plain of the Liaohe River is located in the middle and lower reaches of the Liaohe River in Northeast China. It straddles the middle of Liaoning Province from the northeast to the southwest. The geographical coordinates are  $40.3^{\circ}$ – $42.0^{\circ}$  N and  $121.0^{\circ}$ – $123.5^{\circ}$  E. From southwest to northeast, the slope is about 240 km long, and the east–west expanse is 120–140 km, with a total area of about 26,500 km<sup>2</sup> (Fig. 1). The administrative areas of the lower plain of the Liaohe River include Shenyang, Liaoyang, Tieling, Panjin, Fuxin, Fushun, Jinzhou, Yingkou, and Anshan, including a total of 9 cities and 22 counties in Liaoning Province. The lower plain of the Liaohe River is not only the most essential grain commodity production area in Liaoning or even China, but also the core area of the old industrial base in Northeast China; thus, the intensity of production and activity in this region is high [14].



Figure 1 Location of the lower plain of the Liaohe River.

# 2.2. Data Acquisition and Pre-Processing

Hydrogeological parameter data were mainly obtained from the "Water Resources in Liaoning" and "Land Resources Atlas of Liaoning Province", DEM, as well as measured data from monitoring points. These sources are hydrological and geological statistical books compiled by the Liaoning Provincial Department of Water Resources.

The scales of different parameters differed widely; therefore, it is necessary to form a unified research scale [6]. All parameter layers were standardized according to the rules of each parameter's contribution to groundwater safety. Finally, we comprehensively considered the study area based on the data density and work efficiency and created uniform mesh layers with a grid size of  $1 \times 1$  km for further calculation and analysis based on the center value of each grid unit.

## 3. Methodology

#### 3.1. DRASTIC based groundwater safety evaluation method

The DRASTIC model [1] is one of the most versatile methods currently used to assess groundwater vulnerability. The model consists of seven hydrogeological parameters: depth to groundwater (D), net recharge (R), aquifer type (A), soil type (S), topography (T), impact of vadose zone type (I), and conductivity (C). These parameters have fixed grading standards (Tables 1) and fixed weights. The weights of the seven parameters are 5, 4, 3, 2, 1, 5, and 4, respectively. The DRASTIC-based vulnerability index (VI) is computed using the following equation [7]:

 $VI = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r$ (1) where the subscripts *r* and *w* refer to their rating and weight, respectively.

The groundwater vulnerability index calculated by DRASTIC can reflect groundwater safety from hydrogeological aspects, the more vulnerable the groundwater system, the more likely it is to be polluted or damaged, and the lower the safety of the groundwater. Based on this principle, four anthropogenic parameters, water resources per capita (W), proportion of cultivated land (P), fertilization intensity (F), and industrial wastewater discharge per unit area (U), are combined with the DRASTIC model to construct a groundwater safety index (GSI), where W reflects the resource endowment of the study area, P reflects the main human activities in the study area, F and G reflect the principal source of groundwater contamination in the study area. We rate and weight the four parameters according to the DRASTIC rules (the rating criteria are shown in Table 2), and the weights of W, P, F, and U were 6, 7, 6, and 7, respectively. The weights of these four humanistic parameters are greater than the weights of the DRASTIC parameters because they have a stronger impact on groundwater safety. The coercive index (CI) can be obtained by adding the four parameters linearly, which is expressed by the following equation:

$$CI = W_w W_r + P_w P_r + F_w F_r + U_w U_r$$
<sup>(2)</sup>

As with the vulnerability results obtained by DRASTIC, the higher the score, the lower the safety of groundwater. Therefore, the *GSI* can also be constructed by linear addition of *CI* and *VI*. The *GSI* is computed using the following equation:

$$GSI = \frac{1}{VI_w VI_r + CI_w CI_r} \times 1000$$
<sup>(3)</sup>

Since CI is an active destructive pressure on the groundwater system with a large variation and VI is relatively stable, we determine the weight of CI is 0.6 and the weight of VI is 0.4. To visually compare the results, these values can be multiplied by 1000, yielding an index value closer to 1. Table 1 Bange and rating for parameters D = R + S = T I and C

Table 1 Kange and fatting for parameters D, K, A, S, T, T and C.							
D		R		T	Т		
Range	Rating	Range	Rating	Range	Rating	Range	Rating
(m)		(mm)	-	(%)	_	(m/day)	_
0-1.5	10	0–50	1	0–2	10	0.01-1.3	1
1.5-4.5	9	50-100	3	2–6	9	1.3-3.9	2
4.5–9	7	100 - 180	6	6-12	5	3.9-8.6	4
9–15	5	180-250	8	12–18	3	8.6-13	6
15-23	3	≥250	9	≥18	1	13-24.2	8
23-30.5	2					≥24.2	10
≥30.5+	1						
	A		S			Ι	

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Туре	Rating	Туре	Rating	Туре	Rating
Holocene	5	Clay	1	Holocene deposits	8
Conglomerate	4	Clay loam	3	Conglomerate	6
Karstic	8	Sandy clay loam	4	Flysch	3
Pleistocene	7	Loam	5	Tyrrhenian sea terraces	6
Marl	6	Sandy clay	5	Limestone	6
Flysch	3	Sandy loam	6	Mart	2
		Silty clay	2	Pleistocene deposits	6

Table 2	Range	and ratir	ig for parar	meters W (	water reso	urces per	capita), P	' (proporti	ion of cu	ultivated
la	and), $F$	(fertilizat	tion intensi	ty), and $U$	(industrial	wastewa	ter discha	rge per u	nit area)	).

W		1	р		F	U	
Range (1000	Rating	Range (%)	Rating	Range	Rating	Range	Rating
m3/person)				(ton/km <sup>2</sup> )		$(1000 \text{ ton/km}^2)$	
>1.1	1	< 0.05	1	<5	1	<1	1
1-1.1	2	0.05-0.1	2	5-10	2	1–2	2
0.9–1	3	0.1 - 0.15	3	10-15	3	2–3	3
0.8-0.9	4	0.15-0.2	4	15-20	4	3–4	4
0.7 - 0.8	5	0.2-0.25	5	20-25	5	4–5	5
0.6 - 0.7	6	0.25-0.3	6	25-30	6	5–6	6
0.5 - 0.6	7	0.3-0.35	7	30-35	7	6–7	7
0.4 - 0.5	8	0.35-0.4	8	35–40	8	7–8	8
0.3–0.4	9	0.4-0.45	9	40-45	9	8–9	9
≤0.3	10	≥0.45	10	≥45	10	≥9	10

Global Spatial Autocorrelation: Moran's I

Spatial autocorrelation analysis is a measure of the degree of potential interdependence of the spatial distribution of certain elements or variables [13], we adopt global Moran's I to measure the overall correlation of groundwater safety distribution, the equation for the global spatial autocorrelation index is as follows:

$$GlobalMoran'sI = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{s^2 \sum_{i=1}^{n} \sum_{j=1}^{m} W_{ij}}$$
(4)

where  $S^2 = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2$ ,  $\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$ ,  $x_i$  represents the observation value of the *i*th unit,  $\bar{x}$  is the average observation values, and *n* is the number of units.  $W_{ij}$  is a binary adjacent space weight matrix, indicating the adjacency relationship of the spatial object, if regions *i* and region *j* are adjacent,  $W_{ij} = 1$ . Otherwise,  $W_{ij} = 0$ .

#### 3.2. Local Spatial Autocorrelation: Getis-Ord Gi\*

Getis-Ord Gi\* is one of the most widely used local spatial autocorrelation statistics to investigate the specific spatial distribution and local clusters of various spatial phenomenon [5]. The Getis-Ord Gi\* for groundwater safety can be expressed as:

$$G_i(d) = \sum_{j=1}^n W_{ij}(d) x_j / \sum_{j=1}^n x_j$$
(5)

The standard form of Equation (5) can be obtained by standardizing the  $G_i(d)$ :

$$Z[G_i(d)] = \frac{G_i(d) - E[G_i(d)]}{\sqrt{VAR[G_i(d)]}}$$
(6)

where *n* is the number of units,  $x_j$  is the groundwater safety index in the *j*th unit,  $W_{ij}(d)$  is the spatial weights matrix indicating the spatial adjacency relations between the unit *i* and its neighboring unit *j*, and  $E[G_i(d)]$  and  $VAR[G_i(d)]$  are mathematical expectation values and variance values respectively.

# *3.3. Standard Deviation Elliptic Method*

The standard deviational ellipse (SDE) was originally proposed by Lefever to analyze the distribution characteristics of discrete data sets [2], which is widely used to measure the trend in discrete points and reflects the average distribution of a specific attribute over a certain period. It has particular application value in the spatial analysis of tourism resources, water resources distribution, and pollution potential evolution [3]. We use SDE to analyze quantitatively the temporal and spatial evolution of groundwater safety and derive the distribution direction, evolution direction, and evolution scale in the study area.

# 4. Results and discussion

# 4.1. Spatial Distribution of Groundwater Safety

Based on Equations 1–3, we plotted the groundwater safety distribution map with the grid of  $1 \times 1$  km for years 1991, 2005 and 2020 (Fig. 2). The groundwater safety index was classified into five ranges based on the natural breaks method, and the distribution maps were classified as high, moderate-high, moderate, moderate-low, and low safety areas in order of the safety index from high to low. Table 3 summarizes the area ratios of every level of groundwater safety in the lower plain of the Liaohe River in different years.

Fig. 2 and Table 3 show that the low and moderate-low safety areas showed a trend of decreasing first and then increasing from 1991 to 2020, which changed from northern part only to a more distributed pattern in the northern and southern. In 1991, the groundwater safety distribution was polarized, with low and moderate-low safety zones mainly distributed in the north, and high and moderate-high safety zones primarily distributed in the south and west. In 2020, the low safety and moderate-low safety areas increased significantly; the areas achieving these two levels accounted for 61.4% of the entire study area.

We observed that the corresponding cities in the north, Shenyang, Xinmin, and Liaozhong, have higher levels of agricultural activity; the average proportion of cultivated land in these cities during the study period was 0.491 and the average fertilization intensity was 45.675 t/km2, ranking the areas first among all cities or urban agglomerations, and far exceeded the values in other regions. Therefore, the main factor controlling groundwater safety in the northern region is agricultural pollution. The southern cities, Panjin, Panshan, Dawa, Yingkou, are all located in the coastal area, the geological landscape and water resource endowment of these coastal cities are poor, mainly reflected in the low elevation, seawater erosion, soil salinization, etc. Therefore, the main factors affecting the unsafe groundwater in the southern region are harsh geological environments and industrial pollution.



Figure 2 Annual groundwater safety distribution map in the Lower plain of the Liaohe River.

	(unit. 70).								
Year	High	Moderate-high	Moderate	Moderate-low	Low				
	safety	safety	safety	safety	safety				
1991	10.15	36.50	19.03	2.99	31.32				
2005	14.35	20.81	49.76	15.06	0.02				
2020	4.10	13.32	21.17	30.84	30.56				

Table 3 Area ratio of each degree of groundwater safety in the lower plain of the Liaohe River  $(unit \Re)$ 

#### 4.2. Rationality of Groundwater Safety Evaluation Results

We tested the rationality of the proposed groundwater safety evaluation method by verifying the correlation between the nitrogen concentration and the groundwater safety index, which is based on the principle that the concentration of nitrogen in groundwater is positively correlated with the risk of groundwater pollution [12]. According to the data availability, the data of nitrogen concentration in groundwater in 1991, 2005, and 2020 were obtained and input into the coordinate system with the groundwater safety values in the corresponding sampling points in these years (Fig. 3). The analysis of these two variables showed that the Pearson correlation coefficients of the three years were 0.722, 0.790, and 0.770, respectively, which were significantly correlated at the 0.01 level. The results prove that the proposed groundwater safety evaluation method and the evaluation results are scientific and reasonable.



Figure 3 Pearson correlation test of groundwater safety and nitrogen concentration for the years 1991, 2000, and 2005

#### 4.3. Global Spatial Autocorrelation

The global Moran's I of groundwater safety was calculated at the  $1 \times 1$  km scale. As shown in Fig. 4, global Moran's I was 0.9596, 0.9347, and 0.9435 in 1991, 2005, and 2020, respectively. Therefore, the groundwater safety in the lower plain of the Liaohe River was strongly spatially correlated during the years studied.



Figure 4 The global Moran's *I* scatter map of groundwater safety index *Hot and Cold Spots* 

With the center distance of the adjacent grid units as the distance weight, the Getis-Ord Gi\* of the central value of the groundwater safety index in each unit was calculated, and the hot and cold spot distribution maps of groundwater safety in the lower plain of the Liaohe River were created (Fig. 5).

Fig. 5 shows that the northern urban agglomerations (Shenyang, Xinmin, and Liaozhong) had long centers of cold and sub-cold spots, which were more obvious than other areas in terms of spatial neighbor

effects. Therefore, the northern regions of the lower plain of the Liaohe River are the primary regions requiring pollution prevention and management to strengthen the degree of governance and control. The groundwater in the southern region has gradually changed from sub-hot to sub-cold spots, this is the main region requiring governance or pollution prevention, which is second only to the north in terms of pollution treatment. The southeastern region of the study area mainly included hot and sub-hot spots, which were locally congregated on a small scale. The degree of groundwater safety in this region was significantly better than other areas, which can provide a reference for groundwater safety management in other areas.



Figure 5 Distribution of hot and cold spots of groundwater safety in the lower plain of the Liaohe River.

# 4.4. Spatial-Temporal Evolution of Groundwater Safety

The cold and sub-cold spots are the areas that need to be urgently treated and managed. Therefore, we evaluated the cold and sub-cold spot regions as the research objects, exploring their temporal–spatial evolution trends to provide theoretical support for prevention and control of pollution in low-safety groundwater regions. As shown in Fig. 6 and Table 4, there was a large southward movement from 1991 to 2005, the center in 2005 shifted to south by 26.3092 km from the center in 1991, during this period, the problem of low groundwater safety had developed from a local to a more regional problem. By 2020, the size and distribution of the SDE and the location of the center were very close to those in 2005, the deterioration of groundwater safety has stabilized. Therefore, we concluded that the groundwater safety in the lower plain of the Liaohe River is deteriorating overall, and the situation is becoming increasingly serious. The prevention and control of groundwater pollution must urgently be addressed.



Figure 6 Evolution of SDE and gravity of cold spots.

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Tuble 1 Statisties of standard deviation empse and gravity center.								
Year	Latitude (N)	Longitude (E)	Long axis	Short axis	Displacement	Rotation		
			(km)	(km)	distance (km)	Angle		
1991	41°52′58.073″	123°0'33.683"	79.0097	68.6366	-	58.73°		
2005	41°40′10.254″	122°46'44.122"	152.0481	74.5277	26.3092	41.71°		
2020	41°41′24.155″	122°45′22.303″	156.1315	67.1027	1.4600	45.87°		

Table 4 Statistics of standard deviation ellipse and gravity center.

## 5. Conclusion

In this study, a number of geological parameters and humanistic parameters were selected to establish the groundwater safety assessment method with DRASTIC model. On this basis, the main prevention regions were identified by Getis-Ord Gi\* method. Then, SDE method to quantitatively analyze the spatial-temporal evolution trend of main focused areas. The results of the correlation test between the groundwater safety index and the measured nitrogen concentration data verifies the groundwater safety index in this study. The proposed study can provide a reference for groundwater management for water resource managers in the lower plain of the Liaohe River. The parameters selected in this study may not be sufficient and will be enriched in future studies.

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# References

- Aller, L.T., Bennett, T., Lehr, J.H., Petty, R.J., Hackett, G., DRASTIC: A standardized system for evaluating groundwater potential using hydrogeological settings, Washington, D.C.: U.S. Environmental Protection Agency, 1987.
- [2] Butt, A., Ahmad, S.S., Shabbir, R., Erum, S., GIS based surveillance of road traffic accidents (RTA) risk for Rawalpindi city: A geo-statistical approach, Kuwait Journal of Science, 2017, vol. 44, pp. 129-134.
- [3] Fang, Y., Huang, Z., Yu, F., Tu, W., Evolution Analysis of Relative Efficiency of Provincial Tourist Resources, Scientia Geographica Sinica, 2013, vol. 33, pp. 1354-1361.
- [4] Fatemeh, F., Hossein, Z., GIS-Based Groundwater Potential Mapping in Khorramabad in Lorestan, Iran, using Frequency Ratio (FR) and Weights of Evidence (WoE) Models, Water Resources, 2019, vol. 46, pp. 679–692.
- [5] Getis, A., Ord, J.K., Spatial analysis and modeling in a GIS environment, in A Research Agenda for Geographic Information Science, Boca Raton: CRC Press, 1996.
- [6] Güler, G., Kurt, M.A., Korkut, R.N., Assessment of groundwater vulnerability to nonpoint source pollution in a Mediterranean coastal zone (Mersin, Turkey) under conflicting land use practices, Ocean & Coastal Management, 2013, vol. 71, pp. 141-152.
- [7] Hamerlinck, J.D., Arneson, C.S., Assessing Ground Water Vulnerability to Pesticides, in Wyoming Ground Water Vulnerability Assessment Handbook, Wyoming: Spatial Data and Visualization Center Publication, University of Wyoming, 1998.
- [8] Liang, C., Hsu, W., Chien, Y., Wang, S., Chen, J., The Combined Use of Groundwater Quality, Drawdown Index and Land Use to Establish a Multi-Purpose Groundwater Utilization Plan, Water. Resour. Manag., 2019, vol. 33, pp. 4231-4247.
- [9] Lu, H., Kang, Y., Liu, L., Li, J., Comprehensive groundwater safety assessment under potential shale gas contamination based on integrated analysis of reliability–resilience–vulnerability and gas migration index, Journal of Hydrology, 2019, vol. 578, pp. 124072.
- [10] Moench, M. Groundwater and poverty: exploring the connections, in Intensive use of groundwater: Chanllenges and opportunities, Llamas, M. R and Custodio, E., Eeds.; Colorado: Balkema, 2003, pp. 441-456.
- [11] Qiu, J., China faces up to groundwater crisis, Nature, 2010, vol. 466, pp. 308.

- [12] Rupert, M.G., Calibration of the DRASTIC ground water vulnerability mapping method, Ground Water, 2001, vol. 39, pp. 625-630.
- [13] Wang, Q., Yang, S., Zheng, M., Han, F., Ma, Y., Effects of Vegetable Fields on the Spatial Distribution Patterns of Metal(loid)s in Soils Based on GIS and Moran's I, International Journal of Environmental Research and Public Health, 2019, vol. 16, pp. 4095.
- [14] Xi, X., Zhang, X., Sun, C., Bao, J., Assessment and Soft Zoning of Groundwater Vulnerability in the Lower Reach of the Liaohe River Plain Under Uncertainty Condition, Scientia Geographica Sinica, 2017, vol. 37, pp. 1439-1448.
- [15] Xu, B., Zhang, Y., Assessment of groundwater ecosystem security in arid oasis Shihezi reclamation area in Xinjiang, Research of Environmental Sciences, 2018, vol. 31, pp. 919-926.