Research of risk assessment system on water function areas

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Abstract. Accidents that lead to water pollution are frequent and have seriously affected the aqueous environments of water function areas in recent years. Risk assessments of water function areas at the appropriate scale could provide a useful tool for addressing such accidents. Serious damage is caused to water function areas by water pollution accidents, and an accurate early warning management system for such accidents in water function areas has not been developed. Thus, this study proposes a new method of conducting risk assessments for water pollution accidents in water function areas based on an index system of environmental risk to resolve these problems. Using the analytical hierarchy process and expert scoring, a quantitative index system was constructed using a one-dimensional steady mixed decay model and GIS spatial analysis tools. The method was applied to the water function area of the mainstream in the Taizi River Basin. The results of the risk map show that risk increases along with the direction of flow affected by the upstream industrial point sources. Risk regionalization was performed for water pollution accidents in the water function area of the Taizi River Basin, and five high-risk regions and three moderate-risk regions and three low-risk regions were identified. The results objectively reveal the spatial distribution of the risk of water pollution accidents in the water function area of the Taizi River Basin.

1. Introduction

Water pollution accidents are hazard emergencies characterized by uncertainty and rapid responses, and they have occurred frequently with the rapid development of China's economy and society [1]. Important function areas of water catchment areas, such as drinking water function areas, are located near a large number of high-risk pollution enterprises because of China's unreasonable industrial layout. This situation causes huge potential risks. A total of approximately 35,737 environmental accidents occurred from 1990 to 2007 according to the China Environmental Statistical Yearbook, and among these environmental accidents, water pollution incidents accounted for 55.32\% [2].

Risk assessments of water quality, especially for water pollution accidents, have become the scientific foundation and an important basis for the development of river basin management decisions. Gradually, water environmental quality has been deteriorating and water resource shortages have been growing [3,4]. Globally, water pollution accidents were initially studied with a focus on risk analysis and marine pollution accident assessments [5]. In terms of technical guidelines, many scholars have conducted related research, and these achievements have greatly advanced the development of this field.
In contrast, studies related to water pollution risk assessments are relatively weak in China, and a unified public database on water pollution accidents [8] is lacking. Current research results mostly involve single and scattered case studies, such as the pollutant transport diffusion model established for river systems, safety evaluations of drinking water sources, etc. [9-11]. Moreover, a river basin scale or water pollution accident risk assessment of water function areas have not been performed, and issues related to water pollution accidents must be resolved to assist watershed management departments in the absence of data. Therefore, such assessments can guide management decisions in watershed management departments by providing a clear understanding of the dominant factors that cause water pollution accidents and spatial differences. Such work can effectively guarantee the sustainable development of the water environment [12-14].

The main purpose of the present study is to consider the objectivity of evaluation methods and the availability of data and other factors and propose a method of performing water pollution accident risk assessments in water function areas based on previous research results. This method takes the water function area control unit as the evaluation object and performs a multi-index comprehensive evaluation that includes an analytic hierarchy process (AHP) [15], expert scoring and other methods. The one-dimensional steady mixed decay model is used to establish a calculation model of the water system risk field in a water function area. To verify the practicality and reliability of the method, an effective water pollution accident risk assessment in the water function area of the Taizi River Basin is conducted with a GIS spatial analysis module.

2. Method

2.1. Study area
The Taizi River Basin is located in the central region of Liaoning Province and belongs to the Hun River and Taizi River water systems. The drainage area is 13,883 km², and its approximate position is east longitude 122°26′~124°53′ and north latitude 40°29′~41°39′ (figure 1). A total of 58 reservoirs are in the basin (3 large reservoirs, 5 middle-sized reservoirs, and 50 small reservoirs). The main stream of the Taizi River is 413 km, and it flows through 13 counties with 5 prefecture-level cities, Fushun, Benxi, Liaoyang, Shenyang and Anshan, which are dominated by metallurgy, petrifaction, textile and other industrial sectors.

2.2. Data collection
DEM data are based on ASTER geographic space data cloud data from the Chinese Academy of Sciences. The ground resolution is 30 m × 30 m. Most of the data in this paper are collected from field research and supplemented by information from expert consultation and the literature. The collected data pertain to natural geography, social economy, and irrigation degree. The data on industrial
enterprise pollution sources are obtained from national and local pollution sources, general investigations, and key monitoring companies and other relevant statistical information. Furthermore, the significant risk sources are verified with further field investigations.

2.3. Framework of evaluation description

2.3.1. Core content. The core content of the water function areas of the water pollution accident risk assessment involves the following three aspects: risk receptor, risk source and risk field [16]. The flowchart shown in figure 2 summarizes all core content. A risk receptor is a potential receiving body under water pollution accident risk, and it is similar to a natural disaster hazard-affected body system [17]. A Risk source is an important factor leading to the occurrence of water pollution accidents. A risk field is the transmission medium of a risk factor and represents the foundation of risk area and risk management, and it reflects how a risk factor migrates with changes in the water environment.

![Figure 2. Flowchart showing the evaluation process.](image)

2.3.2. Evaluation of sensitivity in water function areas. In this paper, an effective characterization of sensitivity evaluation systems in water function areas from three aspects are developed: water quality (water function area and water quality status), water quantity (water amount), and water ecology (ecological function regionalization, population density and natural disaster divisions) [18]. The weights of different evaluation indicators are shown in table 1. The results of the sensitivity evaluation in the water function area are divided into three grades: high sensitivity, moderate sensitivity and low sensitivity. The higher the assignment scores, the higher the sensitivity of the water function area. Based on the AHP and expert scoring, the priority and corresponding weight of the indicator are determined. The sensitivity evaluation value in the water function area calculation formula can be expressed as follows:

$$ S = \sum_{i=1}^{n} W_i A_i $$

where $S$ is the sensitivity evaluation value of the water function area, $A$ is the assignment score of each evaluation index, $W$ is the weight of each evaluation index, and $n$ is the number of evaluation indices. $S$ was divided into three grades: $3.00 < S \leq 4.00$ for high sensitivity; $2.00 < S \leq 3.00$ for moderate sensitivity; and $S \leq 2.00$ for low sensitivity.
Table 1. The weights of sensitivity evaluation indicators.

| Evaluation indicators | water function area | water quality status | water amount | ecological function regionalization | population density | natural disaster divisions |
|------------------------|--------------------|---------------------|--------------|------------------------------------|-------------------|--------------------------|
| $W_n$                  | 0.37               | 0.10                | 0.26         | 0.065                              | 0.125             | 0.08                     |

2.3.3. Evaluation of risk source pressure. When evaluating risk source pressure, the sensitivity evaluation results of the water function area were addressed by considering the danger of risk from the source but also the underlying control mechanism. In this paper, fixed risk source as the research object to analyse the risk of industrial enterprises. Based on an investigation of risk source evaluation technology at home and abroad, the evaluation system for risk source pressure on the water function area was constructed under the background of water pollution accidents [19,20]. The danger of the risk source was decomposed into six evaluation indexes: industry category, production process, wastewater quality complexity, rainwater and sewage processing methods, intensity degree and poor industrial enterprise records. The control mechanism was decomposed into two evaluation indexes: safety measures and regional monitoring cross sections. The weights of different evaluation indicators are shown in Table 2. The higher the assignment score, the greater the pressure from risk sources. Based on the AHP and expert scoring, the priority and corresponding weight of the indicator are determined. The calculation formula for the risk source danger and control mechanism evaluation value can be expressed as follows:

$$M = \sum_{i=1}^{n} W_i A_i$$

(2)

where $M$ is the risk source danger and control mechanism evaluation value, $A$ is the assignment score of each evaluation index, $W$ is the weight of each evaluation index, and $n$ is the number of evaluation indices. $M$ was divided into four grades: $0.00 < M \leq 1.00$ for A level; $1.00 < M \leq 2.00$ for B level; $2.00 < M \leq 3.00$ for C level; and $3.00 < M \leq 4.00$ for D level.

Table 2. The weights of risk source danger and control mechanisms evaluation indicators.

| Target layer | Criteria layer ($W_i$) | Indicator layer ($W_{ni}$) |
|--------------|------------------------|---------------------------|
| Risk source danger and control mechanisms | Danger of the risk source (0.60) | Industry category (0.35) |
| | | Production process (0.25) |
| | | Wastewater quality complexity (0.15) |
| | | Rainwater and sewage processing methods (0.15) |
| | Control mechanism (0.40) | Safety measures (0.70) |
| | | Regional monitoring cross sections (0.30) |

An evaluation matrix for the level of risk source was established under the background of water pollution accidents combined with the sensitivity of the evaluation results for water function areas. Specific criteria for the classification are shown in Table 3.

Table 3. Classification table of risk sources.

| Sensitivity of water | Risk source danger and control mechanisms |
|---------------------|-------------------------------------------|

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2.3.4. Evaluation of risk source pressure. When considering the most unfavourable case, multiple risk sources were observed in the water function area control unit; therefore, the impact of risk sources should be accumulated. The steady-state model can be used to calculate this impact because water pollution accidents did not simultaneously occur among all risk sources. A one-dimensional steady river mixed decay model was used for risk the field-index calculations because the width and depth of the river can be ignored on the scale of a river basin and once the risk material enters the water, it will be mixed uniformly throughout the cross section uniformly and then with changes in the flow. The value of the risk source is set to \( q_0 \) when a risk source was observed in the water function area control unit. The risk field index of the downstream control section in the water function area is established based on the one-dimensional steady river mixed decay model:

\[
R_k = \frac{q_0}{Q} \exp\left(-\frac{kx}{86400u_x}\right)
\]  

(3)

where \( R_k \) is the risk field index, \( x \) is the distance between the sewage outlet and downstream control section of water function area (m), \( Q \) is the river discharge of water function area (m\(^3\)/s), \( k \) is a synthetic attenuation coefficient (1/d) and \( u_x \) is the river flow velocity (m/s).

3. Results and discussions

3.1. Control unit

This paper uses the water function area of the main stream of the Taizi River as the research object to conduct a risk assessment of water pollution accidents in water function areas. The main stream of the Taizi River is divided into 2 first-order and 12 second-order regions that involve 6 categories: protection area, drinking water source area, industrial water area, agricultural water area, transition area, and sewage control area. The spatial distribution of the control units of the water function area is shown in figure 3(a).
Figure 3. Water function area control unit (a), water function area sensitivity evaluation (b), risk source pressure evaluation (c) and risk field evaluation (d) in the main stream of the Taizi River basin.

3.2. Sensitivity of water function areas

Based on the above-mentioned evaluation method, the sensitivity of the water function area in the main stream of Taizi River basin is assessed, and its spatial distribution is shown in figure 3(b). The study region includes four high-sensitivity areas, four medium-sensitivity areas and three low-sensitivity areas. The four high-sensitive areas supply drinking water for Benxi, Fushun, and Liaoyang, and the current water quality belongs to class II (Dissolved Oxygen (DO) $\geq$ 6 mg/L, Chemical Oxygen Demand (COD) $\leq$ 15 mg/L, Ammonia Nitrogen (NH$_3$-N) $\leq$ 0.5 mg/L, Total Phosphorus (TP) $\leq$ 0.1 mg/L and Total Nitrogen (TN) $\leq$ 0.5 mg/L). The vegetation coverage rate in the Guanyinge Reservoir, the upper reaches are large, and the habitat quality is favourable. The natural state of the river system in the river channel is relatively complete. The water yield in Yingshui Temple drinking water area and industrial water area is abundant, and the biological diversity is at a high level. Furthermore, Fushun, Benxi and Liaoyang present a low-degree risk for natural disasters and are less affected. The three low-sensitive areas are mainly related to the low water quality requirements of the above three sections. Moreover, the current water quality is of the inferior class V (DO $\geq$ 2 mg/L, COD $\leq$ 40 mg/L, NH$_3$-N $\leq$ 2 mg/L, TP $\leq$ 0.4 mg/L and TN $\leq$ 2 mg/L). The water ecology is affected by the discharge of domestic sewage in Benxi into the industrial water area and sewage control area in the Taizi River Alloy Ditch. Therefore, the water ecological structure has been severely damaged. The Liuhaokou and Ertaizi agricultural water areas belong to the sewage irrigation area, and the soil has been seriously polluted, which leads to soil compaction, low crop yields, decreased agricultural product quantity and quality, and livestock drinking water restrictions. In addition, human activities lead to a greater pollution load; thus, the aquatic habitat is seriously damaged.

3.3. Pressure of the risk source

Based on the field investigation of 419 industrial enterprises in the Taizi River basin, the risk sources pressure is assessed. The 419 industrial enterprises are composed of 29.0% metallurgical industry, 25.9% textile industry, 14.8% papermaking industry, 12.5% petrochemical industry, 3.9% pharmaceutical industry and 3.8% beverage industry. Based on the statistical data of the risk sources in the Taizi River basin, there are 31 serious risk sources (accounting for 7.40% of the total number of risk sources), 183 large risk sources (accounting for 43.68% of the total), and 205 general risk sources among the 419 industrial enterprises (accounting for 48.93% of the total). Based on the spatial distribution (figure 3(c)), the greatest risk sources are observed in the agricultural water area of the Liuha Stream outlet, which accounts for 52.27% of the total number of risk sources, followed by the agricultural water area of Ertaizi and the industrial water area and sewage control area of Alloy Ditch of Taizi River, which account for
13.84% and 13.37% of the total risk sources, respectively. Nineteen serious risk sources are observed in the agricultural water area of the Liuhao stream outlet of the Taizi River, which represents the function area with the greatest risk, and it is followed by the industrial water area and the sewage control area of Alloy Ditch as well as the drinking water source area and industrial water area of Yingshui Temple, which present four and three serious risk sources, respectively.

3.4. Risk field degree
The risk field of the river system of the water function area in the main stream of Taizi River drainage basin is calculated according to formula (3) and its spatial distribution is shown in figure 3(d). The risk field index of the river system of water function area in the main stream of Taizi River gradually increases from the upstream to the downstream. Because of the fewer pollution sources, the risk field degree of the river system in the Guanyinge Reservoir and its upstream water function area is relatively low. A greater number of risk sources are observed in the middle and lower reaches of the water function area because of the location along the river, and the amount of wastewater discharged into the river is large, which leads to serious water environmental pollution. Particularly, the water function areas of the reaches in Benxi, Liaoyang and Anshan are more seriously polluted and the risks of the corresponding water system risk field are also greater. Similar to the sewage control area of Alloy Ditch, many industrial enterprises are located near the main stream in Benxi. As a result, the water quality in this water area is super V class water quality and the water source cannot be used for drinking. Therefore, great risk is observed in this area. The following factors explain the high risk in the drinking water source area and industrial water area of Yingshui Temple, agricultural water area of Beisha River stream outlet, agricultural water area of Liuhao stream outlet, and agricultural water area of Ertaizi: accumulated risk fields are observed in the water system in the upper reaches of the water function area; the industrial enterprises in Liaoyang and Anshan City are mainly concentrated near the mainstream and multiple serious risk sources are observed; and the complex, winding, and gradual channel of the downstream reaches causes a small flow velocity of the river system.

4. Conclusion
A method of performing risk assessments for water pollution accidents in water function areas is proposed based on the sensitivity of the water function areas, the risk source pressure, and the risk field. Thus, links among the points (risk sources), lines (river systems), and surfaces (water function area control units) are realized.

A three-level risk area is realized by using the Taizi River basin as a typical demonstration area and applying the risk assessment method constructed in this paper for water pollution accidents in the water function areas. The results verify the feasibility of the evaluation method and indicate the differences and similarities in water environmental risks between the control units of different water function areas.

The risk assessment method for water pollution accidents in water function areas established in this paper applies a subjective process to determine the weight and selections for the index, and this subjectivity will inevitably lead to certain deviations in the risk areas. However, because of the ubiquity and uncertainty of water pollution accidents as well as the difficulty of obtaining data and the integrity of the acquired data, errors at the watershed scale are acceptable at the risk management level. Therefore, in the case of imperfect data, the evaluation system proposed in this paper represents a practical assessment method that can be widely used. This method can provide theoretical and technical support for the supervision and management of important water function areas in China under the frequent occurrence of water pollution accidents.

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