Article

Risk Assessment of Upper-Middle Reaches of Luanhe River Basin in Sudden Water Pollution Incidents Based on Control Units of Water Function Areas

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Abstract: Upper-middle reaches of Luanhe River Basin belongs to Haihe River Basin and it is a pretty important water source to North China, especially to Tianjin and Tangshan Cities, Hebei. Based on control units of the water function areas and the sub-basins the working units were produced. The index system for environmental risk source hazard was constructed by adopting the pressure state response (PSR) environmental analysis model. The environment risk sources are identified, and their hazard grade assessment is performed. In the environmental risk source hazard an assessment index system, namely "downstream characteristics of environmental risk sources" is added by taking the fact into account that environmental risk sources themselves are affected by different functional areas (working units) downstream of the rivers. Through collecting hazard data, determining their standards and weights for environment risk sources, the fuzzy comprehensive evaluation method is used to calculate the risk source hazard grades and the vulnerability grades of the working units. Using the one-dimensional exponential decay river model for pollutants in rivers, the hazard grade evaluation method of working units is established. This consists of two parts: (1) The risk source hazard grade of the working unit itself, and (2) the impact of the risk sources upstream on the working unit downstream of the rivers. Combining the hazard grade with the vulnerability grade of the working unit, the risk grade of the working unit is evaluated through the risk matrix. The risk zones of the watershed are realized by merging working units in the same control units of the water function areas with the same risk grades. The risk zoning of sudden water pollution incidents in the upper and middle reaches of Luanhe River Basin is obtained by applying the above risk zoning method. It is found that there are 55 risk zones in total, including three highest risk zones, 15 higher risk zones, 14 lower risk zones, 23 lowest risk zones. These results indicate that the upper and middle reaches of River Luanhe are overall at low risk. The corresponding management methods for the different risk zones are suggested.

Keywords: sudden water pollution incidents; Luanhe River; risk; control units of the water function areas

1. Introduction

In recent years, due to the fast development of economy, more frequent incidents in water pollution occur in China, for instance, the 2005 Songhua River serious water pollution incident, the Taihu lake

water pollution incident in 2007, Changzhi, Shanxi aniline leakage in 2012 [1]. Although these sudden incidents occur at low probability, it can cause irreparable consequences due to its sudden strong destructive characteristics at large scale. This together with its characteristics of multiple sources and receptors makes it very difficult to research.

There are two definitions of risk [2]. The first is defined as the product of the probability of occurrence of an event and the result or consequence of the event [3,4], and it is used for risk assessment in insurance, security fields in most cases [5,6], and also used for environmental risk sources, such as enterprises, construction projects, which is called "accident risk" [7–9]. The second is defined as the combination of hazard and vulnerability [10–12]. We construct environmental risk assessment model or system for environmental risk assessment of regional or watershed scale according to the second definition [13–17].

There are many types of basic units in risk zoning. The grid is used as the basic units [15], and all the risk evaluation indexes need to be obtained by interpolation. Administrative districts can also be used as basic units [10]. The social economic evaluation index can be obtained directly, but due to the existence of several scattered reaches in the basic unit the regional natural factors are not fully considered in the region.

There is a little study on risk assessment and regionalization of sudden water pollution events in the basin scale. Paul, et al. (2004) used 2-D surface water flow model CE-QUAL-W2 Version 3.1 to effectively study the risks associated with accidental or intentional releases of a hazardous material into an inland waterway [18]. Liu, et al. (2012) use a fuzzy fault tree model and the comprehensive influence index model to carry out sudden water pollution risk assessment in the region, which is lack of data, and establish multi-scale evaluation model to the river unit of the whole region [19]. In this study, the water function area is examined as an index of the receptor, but the interaction of the environmental risk between the upstream and downstream units of the river is not considered. Mehmet, et al. (2013) used modified pollution indices to evaluate the pollution status in the middle section of the Lower Seyhan River Basin and the water quality index (WQI) was utilized to evaluate water pollution levels [20]. Zhang, et al. (2014) introduced relative risk model (RRM) to quantify model evaluation factors, and undertook risk assessment to the old river basin. This study treats the sub basin as an evaluation unit, taking full account of the natural features of the watershed [21]. Most importantly, these studies have identified "Zoning units", and the risk of the units are evaluated, but it is not made in the true sense of the "risk zoning", because the zoning unit should satisfy the maximum risk similarity in the unit, while the risk difference is the biggest between the units [22].

Luanhe River Basin belongs to Haihe River basin, China, and Luanhe River is the second largest river into the Bohai Sea of north China, and belongs to typical semi-arid and seasonal wind climate region. It is an important natural barrier and drinking water resource for Beijing, Tianjin and Tangshan Region with more than 50 million populations. In the past, most researches were focused on the temporal and spatial distributions of water and sediment yield in the Luanhe River Basin [23] and landscape ecological risk response to land use change in the basin [24]. Little attention is paid to assess the risk of Luanhe River basin in sudden water pollution incidents. So this paper aims to improve the current risk assessment method and apply this new method to study the risk of the upper and middle reaches of Luanhe River Basin in sudden water pollution incidents in view of increasingly sudden water pollution incidents.

2. Research Area

The upper and middle reaches of Luanhe River Basin is the local basin in front of the dam of Daheiting Resivior, which is mainly across two provinces (autonomous regions): The Inner Mongolia Autonomous Region and Hebei Province, 18 counties/cities/districts/banners (CD County means Chengde County, FN County means Fengning County, KC County means Kuancheng County, LH County means Longhua County, LP County means Luanping County, PQ County means Pingquan County, Sl district means Shuangluan district, SQ district means Shuangqiao District, YSYZ Mining

District means Yingshouyingzi Mining District, WC County means Weichang County, XL County means Xinglong County, QX County means Qianxi County, DL County means Duolun County, GY County means Guyuan County) (Figure 1).
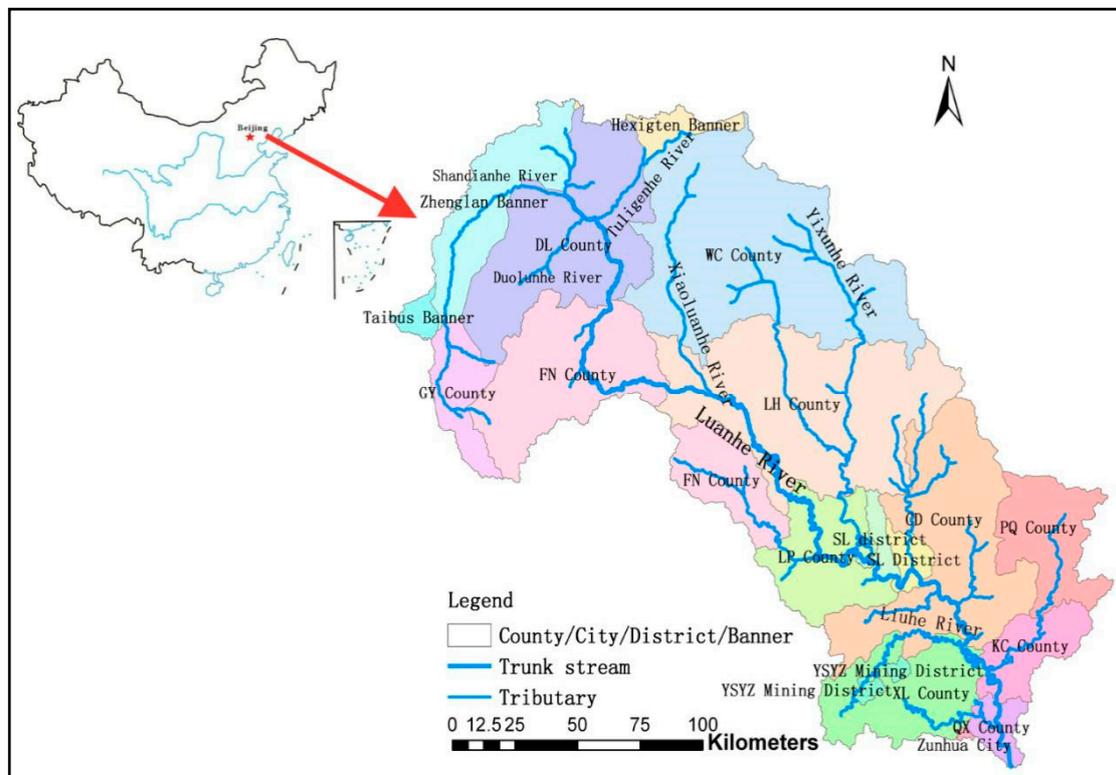

Figure 1. Upper-middle reaches in the Luanhe River.

3. Research Method

3.1. Data Source

Digital Elevation Model (DEM) data comes from the United States Geological Survey (USGS), the resolution is 90 m × 90 m, and the Albert equal projection, and GCS_Bejing_1954 geographic coordinate system is used. The data of the basin landform, water function areas, the environmental risk sources and regional natural economic and social information are obtained through the statistical yearbook, literature search, field investigation, visiting to relevant departments and expert consultation.

3.2. Water Function Area and Control Units

Water function area is the waters delimited according to its dominant function and carried out the corresponding water environment quality standard, which is based on natural conditions and development and utilization of water resources, comprehensive river basin planning, water resources and water ecosystem protection and economic and social development requirements to meet the demand of rational development, utilization, saving, and protection of water resources.

Control unit is obtained by superimposing the spatial data of the catchment area, water system distribution and its flow direction, boundary of water function area, control section distribution, administrative boundary and other indexes on a digital map, which is based on the principle of division of pollution control unit.

The relationship between the water functional area and control unit: (1) The water function area is the premise and basis for dividing the control unit, which is combined with three other elements (see Figure 2) to obtain a control unit; and (2) The water function area includes only the water area, and the control unit comprises the water area and the corresponding land area.
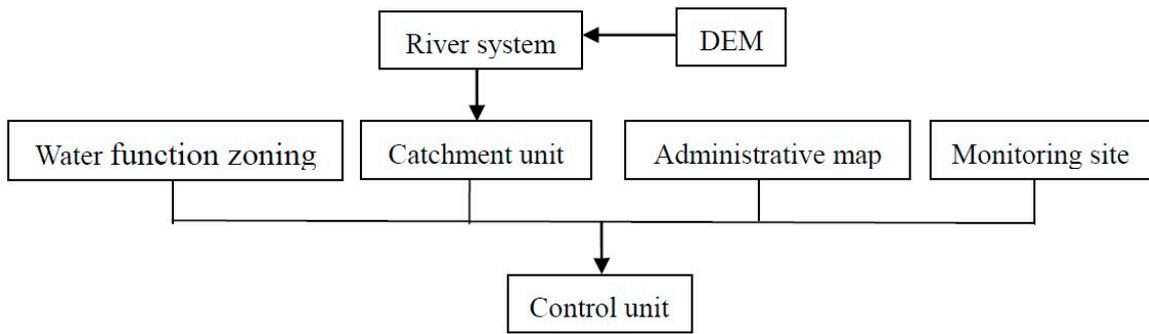
Figure 2. Schematic diagram of control unit division.

According to the control unit division method for water function areas, the upper-middle reaches of Luanhe River Basin includes 34 water function areas, and the corresponding control units, as shown in Figure 3 and Table 1.
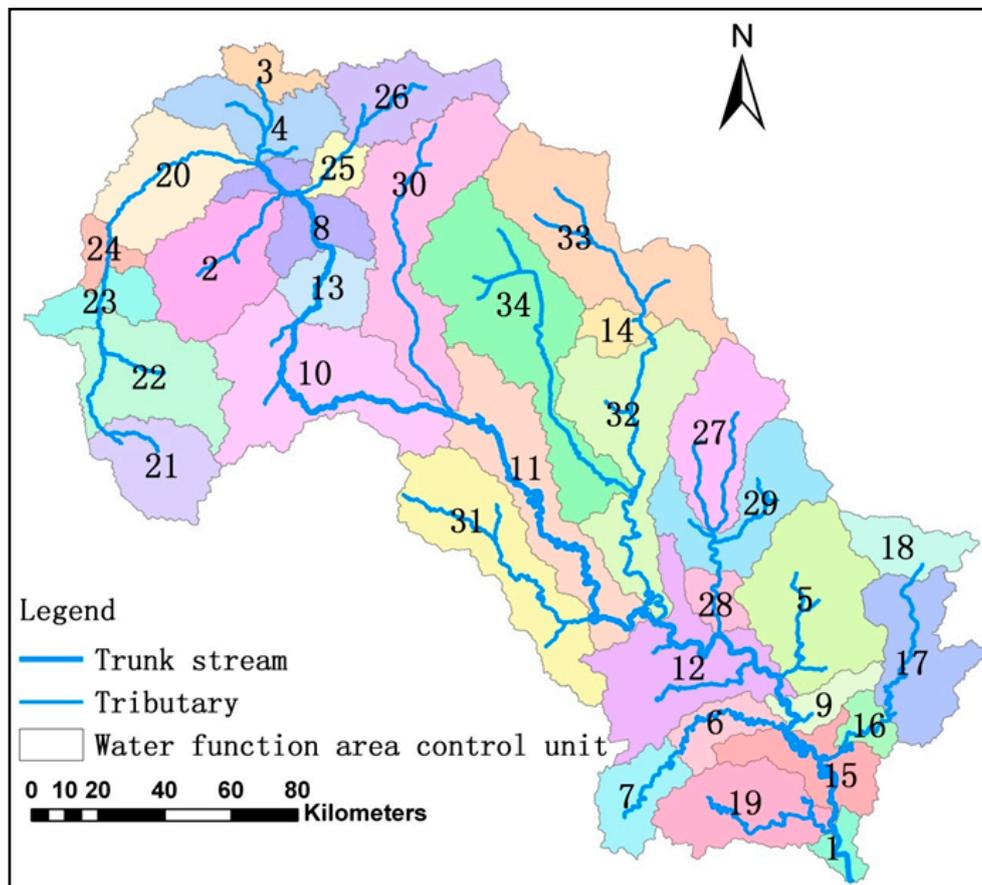

Figure 3. The upper-middle reaches of Luanhe River and water function area distribution map.

3.3. The Division of Working Units and its Advantages

Each sub basin within the water function area control unit is defined as a working unit for risk assessment transition units based on the water function area control units, which are determined by the river basin management institution. All indexes are represented on the working units, and the indexes that are not in the working unit need to be interpolated to the working units. The advantages are that: (1) The risk assessment indexes associated with rivers within the working unit are complete, and there is no artificial cutting water bodies; (2) it is generally believed that once a sudden water pollution event occurs, the pollutant will diffuse in the sub basin where the environmental risk source

lies and transmit through the river to the downstream; and (3) it is consistent with the current water management unit in China and easy to manage.

Table 1. Water function area control unit name.

No.	The Name of the Water Function Area Control Unit	No.	The Name of the Water Function Area Control Unit
1	Daheiting reservoir	18	Baohe River Water source protection area
2	Duolun River Agricultural water area	19	Sahe river reserve area
3	Heifeng river reserve area	20	Duolun county Agricultural water area
4	Heifeng River Agricultural Water area	21	Shandian River Water source protection area
5	Laoniu River drinking water source area	22	Mongolia Hebei Shandian River buffer area
6	Liuhe river buffer area	23	Shandian river reserve area
7	Liuhe river drinking water source area	24	Shuluun Huh Agricultural water area
8	Luanhe River Agricultural water area	25	Tuligen River industrial water area
9	Luanhe river buffer area	26	Tuligen River Water Conservation area
10	Luanhe river reserve area 1	27	Wulie river reserve area
11	Luanhe river reserve area 2	28	Wulie River industrial water area
12	Luanhe river drinking water source area	29	Wulie river drinking water source area
13	Mongolia Hebei Luanhe River buffer area	30	Xiaoluanhe River Water source protection area
14	Temple palace reservoir	31	Xingzhou River Water source protection area
15	Panjiakou reservoir	32	Yixun river drinking water source area
16	Baohe river buffer area	33	Yixun River Water source protection area
17	Baohe river drinking water source area	34	Yimatu river reserve area

The upper, middle reaches of Luanhe River Basin are obtained by entering the DEM and using the ArcGIS hydrological analysis model and they are divided into 107 working units by combining the water function area control unit with the sub basin, as shown in Figure 4.
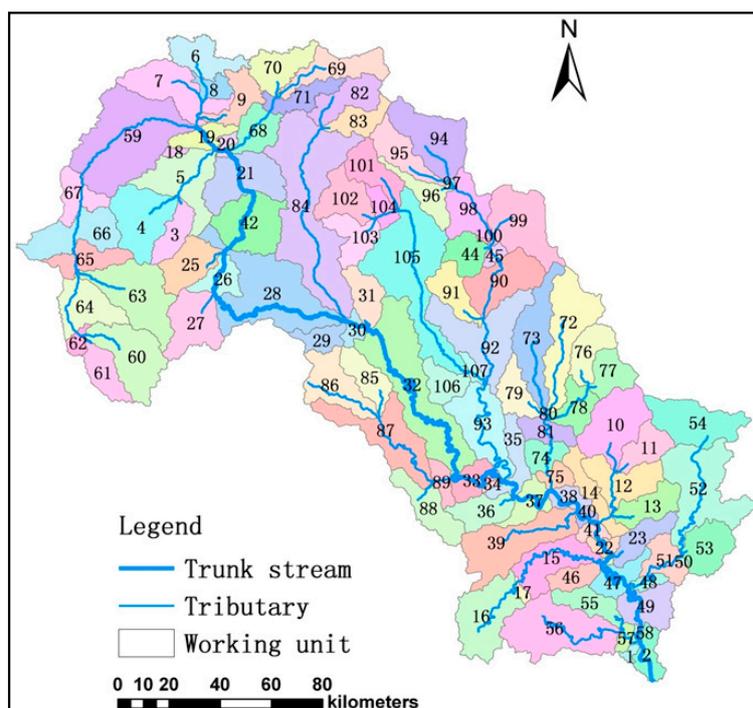

Figure 4. Working unit partition map in upper-middle reaches of Luanhe River.

3.4. Environmental Risk Sources Hazard Grade Assessment

The environmental risk sources of sudden water pollution incidents are divided into four grades: Major risk sources, big risk sources, general risk sources and slight risk sources by referring to the *National Emergency Plan for Environmental Emergencies* [25]. Environmental risk source hazard assessment is identified through environmental risk source identification, hazard index system construction, quantification, index weight determination and grade calculation.

3.4.1. Establishing Environmental Risk Sources Hazard Index System

Environmental risk source data are obtained through the establishment of questionnaires, field research and visiting relevant departments. Referring to previous work [26], the pressure state response (PSR) environment analysis model is adopted, and the environmental risk sources hazard evaluation index system is constructed from three aspects: (1) Environmental risk sources hazard (pressure), (2) hazard receptor (state), and (3) risk control ability (response). As shown in Figure 5, it includes target, topic and index layers.
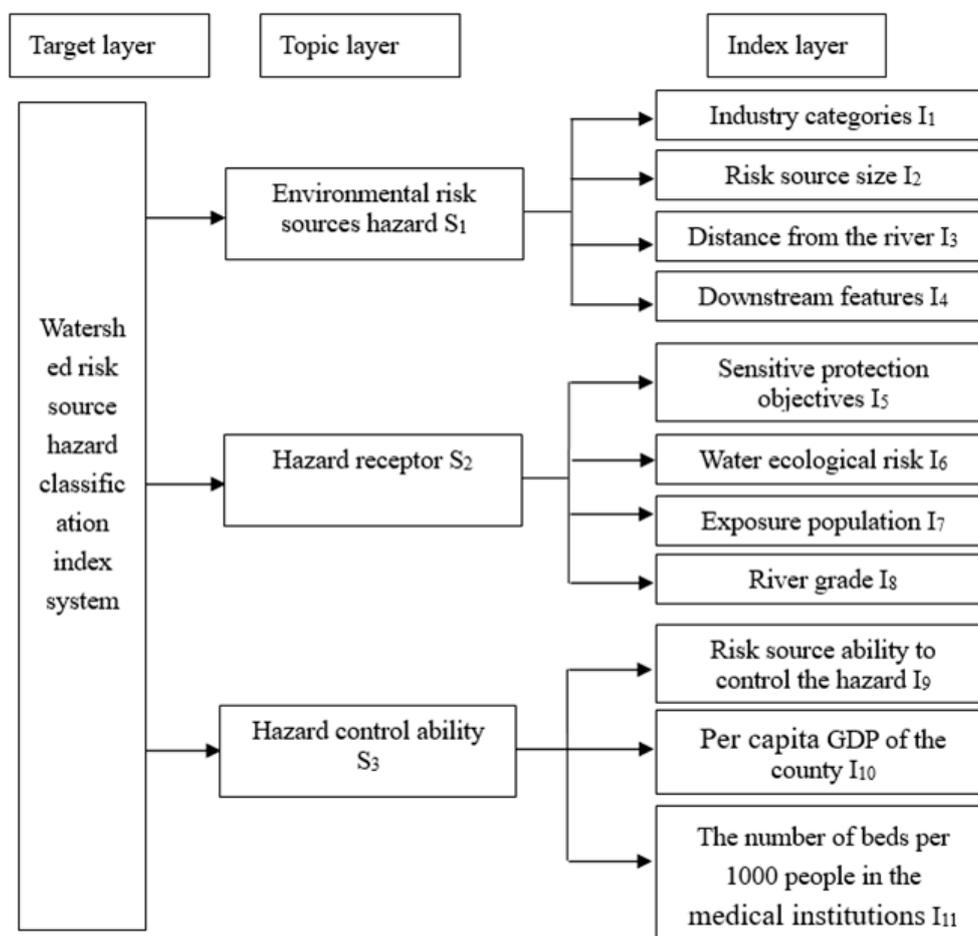

Figure 5. Risk source hazard index system.

3.4.2. Quantifying Environmental Risk Sources Hazard Index System

As the target, it consists of three topics, as shown in Figure 5, and they are Environmental risk sources hazard S_1, Hazard Receptor S_2 and Hazard Control Ability S_3. Following is an explanation about the system.

A Environmental Risk Sources Hazard S_1

A1. Industry Categories I_1

Risk sources in different industry categories have varying degrees of hazard. For example, "chemical raw materials and chemical products manufacturing" and petroleum processing, coking and nuclear fuel processing" have a higher score of 0.8; and "the food manufacturing industry", "water production and supply industry" and "beverage manufacturing industry" have a low score of 0.2. Corresponding to the four grades of the risk sources, this paper divides the risk sources into four grades, and determines quantitative standards as listed in Table 2.

Table 2. Index classification standard and weight of the hazard index.

Topic Layer	Index Layer	Weight	1st	2nd	3rd	4th
Risk of environmental risk sources	industry categories	0.0485	0.8	0.6	0.4	0.2
	Risk source size (Ten million yuan)	0.0882	100	50	10	1
	Distance from the river (km)	0.0514	0.1	0.8	1.5	3
	Downstream features	0.0267	10	6	3	1
Hazard receptor	Sensitive protection objectives	0.0797	18	12	6	0
	Water ecological risk	0.0274	1	0.8	0.6	0.4
	Exposure population (ten thousand people)	0.1483	15	10	5	1
	River grade	0.0416	1	0.8	0.6	0.4
Risk control ability	Risk source ability to control the hazard	0.2519	1	2	3	4
	Per capita Gross Domestic Product (GDP) of the county (dollar/person)	0.1498	4800	8600	12,300	16,100
	The number of beds per 1000 people in the medical institutions(Bed/thousand people)	0.0514	1	3	6	10

A2. Risk Source Size I_2

Generally, the bigger the size of the risk sources, the higher the risk. Because most companies' employees, sales and total assets that can measure risk sources size can't be known, and the scale of the enterprise has a good correlation with the risk sources of "registered capital", the registered capital is used as a measure of risk sources index scale, and the grades are established according to [22] and [26], as shown in Table 2.

A3. Distance from the River I_3

In general, the closer the risk sources to the river, the easier the pollutant entering the river and polluting the water environment, and the higher the hazard of the risk sources. Based on Arc-GIS software, a distance measurement (near) tool is used to obtain the nearest distance of each risk sources to the river. The grades are established according to [26], as shown in Table 2.

A4. Downstream Features I_4

Referring to the influence of the pollutant produced by the risk sources to the downstream working units through river transportation and diffusion, we consider the two aspects: The distances between the risk source and the downstream working units, and the importance of the downstream working units. The more important the downstream working units (score based on the water function area characteristics of the working units shown in Table 3, and the shorter the distance between the risk source and the downstream working units, the greater the hazard. The following equation is used to describe I_4:

$$I_{4j} = \frac{\omega_1}{\theta_1} + \frac{\omega_2}{\theta_2} \ldots + \frac{\omega_n}{\theta_n}, \tag{1}$$

where I_{4j} is the score of downstream features; j is a number; *n* represents the number of risk sources flowing through the working units; ω_n stands for the score of the risk sources flowing through the working units, showing in Table 3; θ_n is the distance between the risk sources and the working units (10 km).

Table 3. Statistical table of risk sources risk index.

Working Unit Water Function Area Characteristic	Drinking	Protection, Reservation	Buffer	Industry, Agriculture
Score *	1	0.8	0.5	0.3
Sensitive protection objectives	200 thousand population drinking water source or National Nature Reserve	150 thousand population drinking water source or provincial nature reserve	100 thousand population drinking water source or municipal Nature Reserve	Other or no nature reserves
Score *	9	6	3	0
Characteristic pollutants	COD	Nutriment	Other chemicals	Chromium (six valence)
Score *	0.4	0.4	0.6	1
River grade	Trunk stream	tributaries of level one	tributaries of level two	tributaries of level three
Score *	1	0.8	0.6	0.4
Risk source ability to control the hazard	Pollution source category	Signing the letter of environmental protection undertaking	Environmental protection illegal information	Pollutant discharge permit
Score *　1　0	National grade　Other grade	Yes　No	No　Yes	Yes　No

* Score in the table shows the quantitatively relative importance, and is generally judged subjectively [7,26].

B Hazard Receptor S_2

B1. Sensitive Protection Objectives I_5

Two aspects are considered: Whether the water function area to, which the working units belongs are the drinking water source and its population [27], as well as whether there are natural reserves, and their grades are shown in Table 3.

B2. Water Ecological Risk I_6

Water ecology means the water effects on biology and the adaptation of biology to various water conditions [28]. When water bodies contain certain characteristic pollutants, they may have different hazards to the water environment. According to the Comprehensive Wastewater Discharge Standards and Sanitary Standards for Drinking Water, the characteristic pollutants are used for grading, as shown in Table 3, and the standard is listed in Table 2.

B3. Exposure Population I_7

Use population size of the working units as the exposure population of risk sources. The standard is referred National Emergency Plan for Environmental Emergencies, as shown in Table 2.

B4. River Grade I_8

It is generally believed that the higher the river grade that the risk sources pollutant flows into, the greater the possibility of pollutant transport and diffusion, and the greater the influences of the possibility on low-grade rivers. According to the study of [29], river grades are shown in Table 3, and the standard is in Table 2.

C Hazard Control Ability S₃

The ability to control the hazard of sudden environmental incidents in a region can be evaluated from two aspects: The hazard control ability of the area and the hazard control ability of the risk sources. The regional hazard control ability is evaluated by the number of beds per 1000 people in the medical institutions where the risk sources lie and the per capita Gross Domestic Product (GDP) in the county. The risk sources ability to control the hazard is evaluated by the superposition of several factors as follows.

C1. Risk Source Ability to Control the Hazard I₉

It is superimposed by the following factors, such as Pollution source category, whether to sign the letter of environmental protection undertaking et al. as shown in Table 3.

C2. Per Capita GDP of the County I₁₀

Per capita GDP of the county to which the risk source belongs represents the level of economic development in the region to a certain extent [13]. Generally speaking, the higher the per capita GDP, when the sudden water pollution accidents occur in the region, the more dangerous control capability, the lower corresponding risk grade is, as shown in Table 2.

C3. The Number of Beds per 1000 People in the Medical Institutions

According to the "Standard of Medical Institutions (Trial)", the more the number of beds per 1000 people in medical institutions means the better health care in the area. Once the sudden water pollution accidents occur, hazard control ability is stronger, and the lower the hazard grade [22], as shown in Table 2.

3.4.3. Determination of Weights of Environmental Risk Sources Hazard Assessment Indexes and Calculation of Results

An improved analytic hierarchy process (AHP) is adopted to determine the weight of the index through expert investigation, and the fuzzy comprehensive evaluation method is used to calculate the hazard grade of the environmental risk source [26].

3.5. Working Unit Hazard Assessment

Most previous work has considered that the working unit hazard grades are equal to the risk sources hazard grade in the unit [19,21]. The present research differs from that. Because once the upstream risk sources release a lot of pollutants in a short period of time and cause the sudden water pollution, leaked dangerous substances will flow through river systems and spread to the downstream, impacting on the downstream working units. Apparently, the downstream working unit hazard grade will be affected by upstream risk sources.

Due to the influence of upstream risk sources on downstream units, the working unit hazard grade is divided into two parts, as shown in Equation (2), one part is the greatest hazard grade of the risk sources in the unit, and the other part is the influence of the upstream risk sources on it.

$$F = G_{MAX} + \sum_{i=1}^{m} C_x \ (I = 1, \ 2, \ 3 \ \ldots \ldots \ m), \tag{2}$$

where F is the total hazard scores of the working unit; G_{MAX} is the largest hazard value of each risk sources score in the working unit (because the sudden water pollution is generally caused by only one risk source although there may be several risk sources in the unit); C_x is the effect of one upstream risk source on the working unit through rivers; m is the total number of upstream working units of the working unit under consideration.

The hazard grade of the risk source can be used as a generalized substance or pollutant, such as water quality index BOD or COD. Due to extremely shortage of data, and for simplification purposes,

the effect of the upstream risk source on a downstream working unit through rivers is approximated to one-dimensional exponential decay river model as

$$C_x = C_0 \exp\left(-K\frac{x}{\mu}\right) \tag{3}$$

where C_x is the influence of upstream risk sources on the working unit through rivers; x is longitudinal distance along the river; C_0 is the upstream risk source grade; μ is the mean velocity (m/s) of the channel under design flow; K is the comprehensive attenuation coefficient of pollutants (1/s).

As indicated above, probabilities that pollutant coincides with all risk sources in a working unit are quite low and usually there exists only one risk source of practical pollution, and hence the highest value of risk grade scores of all risk sources in a working unit is considered. Hazard grades and corresponding scores are shown in Table 4.

Table 4. Risk source grade and working units hazard grade and score corresponding table.

Risk Source Grade	G	Working Units Hazard Grade	F
major risk source	10	Higher hazard	$F \geq 8$
big risk source	6	High hazard	$4.5 \leq F < 8$
general risk source	3	Moderate hazard	$2 \leq F < 4.5$
slight risk source	1	Low hazard	$0 \leq F < 2$

3.6. Working Unit Vulnerability Assessment

Vulnerability refers to the extent to which something is vulnerable or injured [30]. Corresponding to the hazard grade, the study divides the vulnerability into four grades, which are higher vulnerability, high vulnerability, moderate vulnerability and low vulnerability. Working unit vulnerability needs to be identified through vulnerability index system construction, quantification, index weight determination and grade calculation.

3.6.1. Establishment of Vulnerability Index System for Working Units

The index system of vulnerability is divided into three layers: Target, topic, and index layers, as in Figure 6.
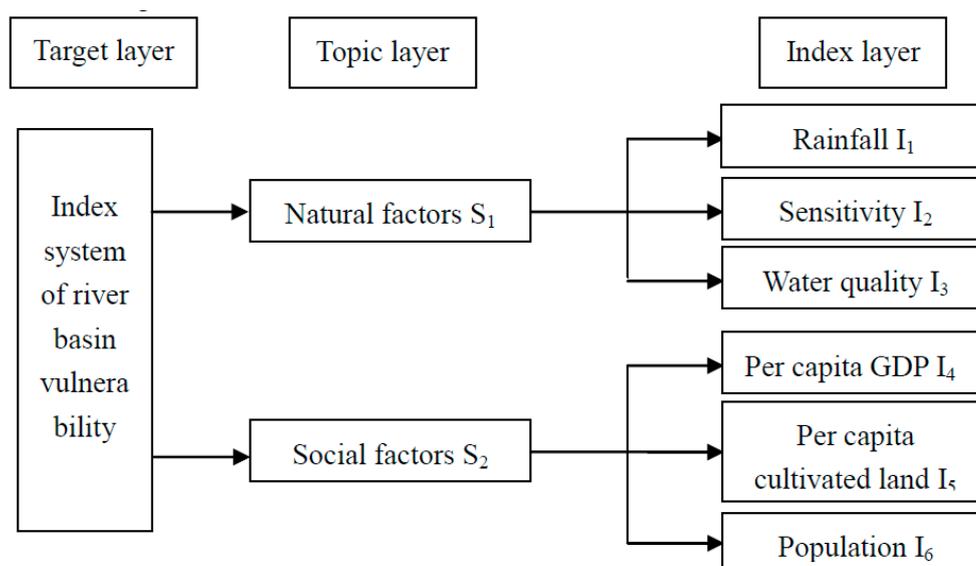

Figure 6. Index system of working unit vulnerability.

3.6.2. Working Unit Vulnerability Index System Quantification

D Natural Factors S_1

D1. Rainfall I_1

The amount of rainfall is related to the amount of biomass in the ecological resources. The more the rainfall in a region, the more complex the biological networking and the stronger stability of the ecosystem, and the less vulnerable the region [26], as shown in Table 5.

Table 5. Vulnerability index classification standard and weight table.

Vulnerability Index	Weight	1st	2nd	3rd	4th
Rainfall (mm)	0.12121	390	490	600	700
Sensitivity	0.18092	1.8	1.3	0.7	0.2
Water quality	0.14813	2	3	4	5
Per capita Gross Domestic Product(GDP) (dollar/person)	0.15874	16,100	12,300	8600	4800
Per capita cultivated land area (mu/person)	0.16965	6.2	3.5	2.8	1.1
Population density (person/square kilometer)	0.22156	392	280	165	52

D2. Sensitivity I_2

Determined by the nature of the load-bearing body itself, the sensitivity of the hazard receptor is mainly reflected by sensitive targets. When the sensitivity is different in the face of the same water pollution incident, the impact is also different. Taking into account the impact of sudden water pollution incidents on residents, and other organisms in the working unit, the two scores are superimposed as a sensitivity score of the working unit as given in Table 6.

Table 6. Working unit sensitivity assignment table.

Sensitive Target	Score	Nature Reserve Grade	Score
Drinking	1	National	1
Protection, reservation	0.8	provincial	0.5
buffer	0.5	Below the provincial	0
Industry, agriculture	0.3	/	/

D3. Water Quality I_3

The better the water quality, the weaker the ability to resist hazard and the higher the vulnerability. According to the Surface Water Environment Quality Standard, and considering that there is no river reach meeting the first grade of the national water quality standard in the study area, the index is defined as the four grades standard, as shown in Table 5.

E Social Factors S_2

E1. Per Capita GDP I_4

Per capita GDP is an important component of socio-economic factors, and indicates the economic level of an area. Economic factors are closely related to the vulnerability of working units. The more developed the economy, the greater the risk of loss [13], as shown in Table 5.

E2. Per Capita Cultivated Land Area I_5

Water resources are vital to cultivated land. The dependence of cultivated land on water resources determines that the per capita cultivated land area is a component of the vulnerability of working

units. Per capita cultivated land area is closely related to the vulnerability of regional ecological environment [31]. The more the per capita arable land area, the more vulnerability the ecological environment, and the lower the per capita cultivated land area, the lower the vulnerability is, as shown in Table 5.

E3. Population Density I_6

The higher the population density index, the more vulnerable people are affected by the risk, the higher the vulnerability is [15] as shown in Table 5.

3.6.3. Working Unit Vulnerability Index Weight Determination and Result Calculation

An improved analytic hierarchy process (AHP) is adopted through expert investigation to determine the weight of the index, and the fuzzy comprehensive evaluation method is used to calculate the working unit vulnerability [26].

3.7. Risk Assessment

The risk grade of each working unit can be obtained from the risk grade matrix [32], which is based on the evaluation of working units hazard grade and vulnerability grade, as shown in Figure 7.

	Grade I (Higher vulnerability)	Grade I (Higher vulnerability)	Grade I (Higher vulnerability)	Grade I (Higher vulnerability)
Grade I (Higher hazard)				
Grade II (High hazard)				
Grade III (Moderate hazard)				
Grade IV (Low hazard)				

Higher risk I　　　　High risk II　　　　Moderate risk III　　　　Low risk IV
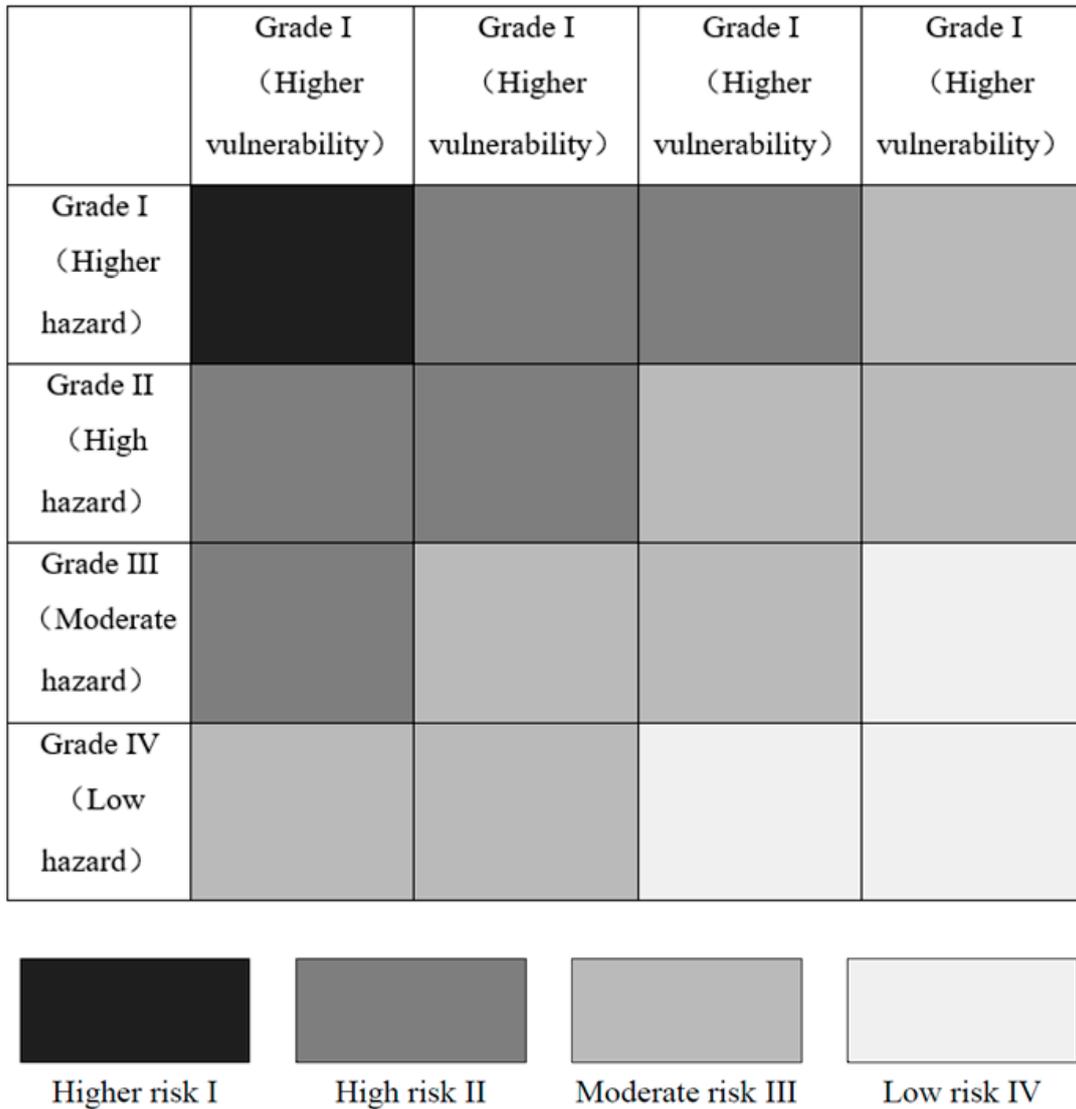
Figure 7. Risk grade matrix diagram.

According to the environmental risk zoning theory [22], the adjacent working units belong to the same water function control unit and the same risk grade are merged, and the watershed risk zoning is obtained.

4. Results Analysis

4.1. Environmental Risk Sources Hazard Assessment Result

Combined with the standard in Table 2 and the fuzzy comprehensive evaluation method, the environmental risk sources risk grade results of the upper-middle reaches of the Luanhe River are obtained. Risk sources evaluation results are shown in Figure 8 and Table 7. There are 43 risk sources that have 15 major risk sources, 14 big risk sources, six general risk sources and eight slight risk sources. From the point of view of the risk level, most risky sources belong to the larger risk. From Figure 8 we can see that in the upper-middle reaches of the Luanhe River, risk sources distribution is concentrated, mainly distributed in the middle and lower segment of the study area.
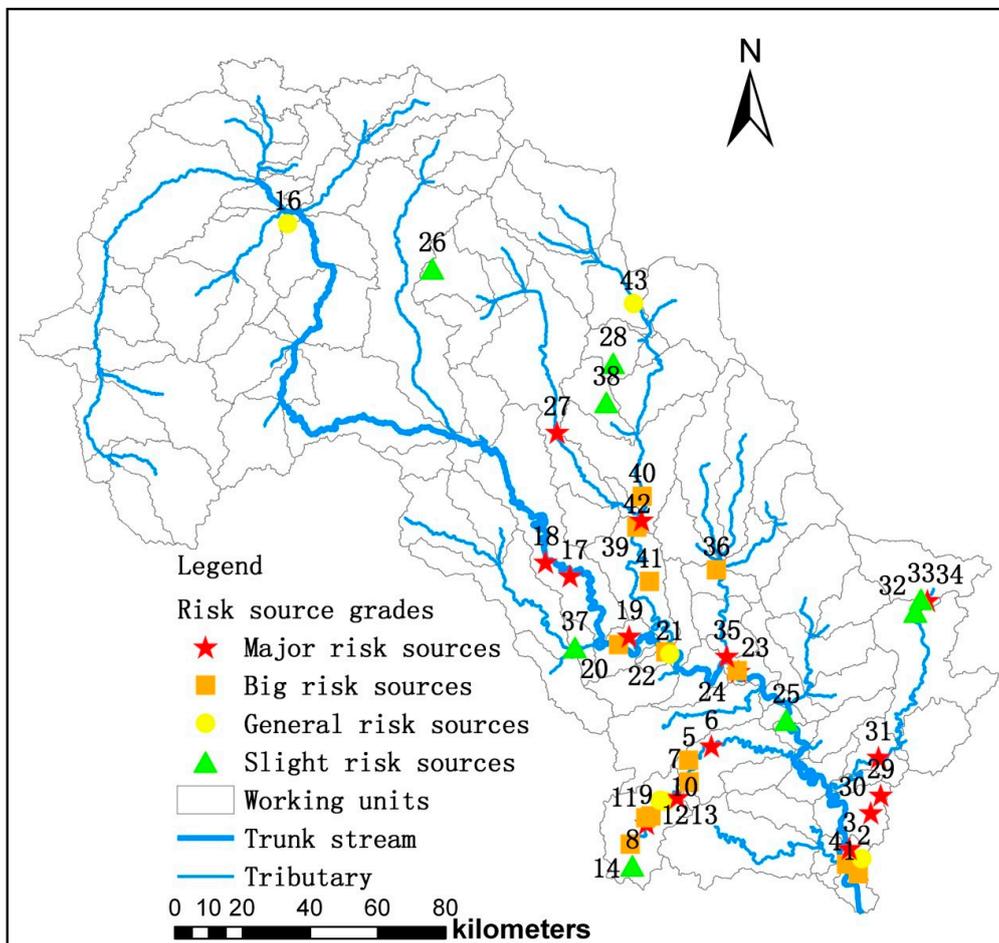
Figure 8. Risk sources hazard grade map.

4.2. Working Units Hazard Assessment Result

Combining the environmental risk sources risk assessment result in Section 4.1 with the calculation method in Section 3.3 the conclusion of hazard assessment of 107 working units in the upper reaches of Luanhe River is obtained, as shown in Figure 9. Most working units in the study area have low grade hazard, i.e., 75 are low hazard working units, eight moderate hazard working units, five high hazard working units, and 19 higher hazard working units, and hence the overall hazard is low.

Table 7. Environment risk source name.

No.	Environment Risk Source Name	No.	Environment Risk Source Name
1	Tianbao cement Ltd.	23	Chengde city sewage treatment Co., Ltd.
2	Jidong Cement Co., Ltd.	24	Chengde municipal wastewater treatment plant
3	Sheng Feng Steel Co., Ltd.	25	Chengde county sewage treatment plant
4	Fuzhenquan Mining Co. Ltd.	26	Changhong Potato Starch Co. Ltd.
5	New brewing Co., Ltd.	27	Weichang County heating company
6	Sihai develops Limited by Share Ltd.	28	Binfa Potato Starch Co., Ltd.
7	Tongxing mining limited liability company	29	Hengmao Paper Co. Ltd.
8	Shuang Fu Mining Co., Ltd.	30	Jianfeng mining
9	Ring energy thermoelectric Co., Ltd.	31	Jiujiang coal storage and Transportation Co., Ltd.
10	Kaixing energy Co. Ltd.	32	Pingquan sewage treatment plant
11	Pingan coal mine	33	Bishushangzhuang group Wine Co., Ltd.
12	Hangyang gas Co. Ltd.	34	Yingke Fine chemicals Limited by Share Ltd.
13	Wang Zhuang collective economy company	35	China traction group Chengde crankshaft connecting rod Co., Ltd.
14	Xinglong County Sewage treatment plant	36	Heishan Iron Mine
15	Liu Yuan sewage treatment Co., Ltd.	37	Luanping sewage treatment plant
16	Datang Duolun Coal Chemical Co., Ltd.	38	Yushijindan Pharmaceutical Co. Ltd.
17	Longxiao heating limited liability company	39	Jiangyuan Liquor Co., Ltd.
18	Jianlong Special Steel Co., Ltd.	40	Fuze Food Co. Ltd.
19	Green Food Co., Ltd.	41	Hongyuan fruit industry Co., Ltd.
20	Qixing Mining Group Co. Ltd.	42	Longhua County sewage treatment plant
21	Guodian Chengde Thermal Power Co., Ltd.	43	Weichang County wastewater treatment plant
22	Chengde iron and Steel Group Co., Ltd.		
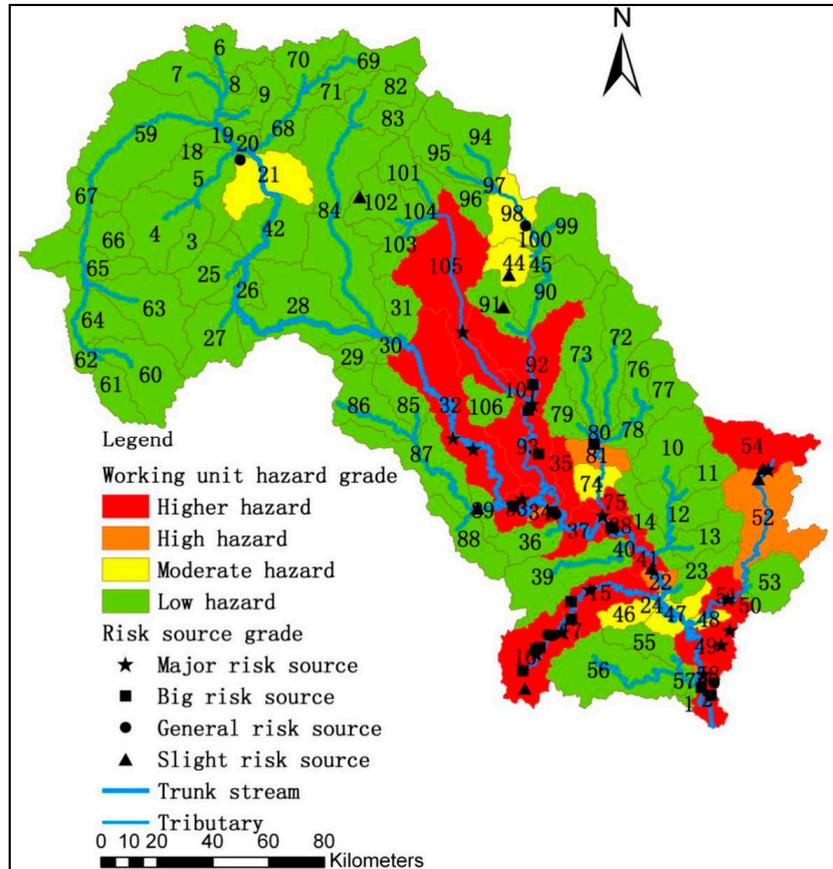
Figure 9. Working unit hazard grade distribution map.

4.3. Working Units Vulnerability Assessment Result

Combined with the standard in Table 5 and the fuzzy comprehensive evaluation method, the vulnerability assessment results are shown in Figure 10. This shows that there are eight higher vulnerability working units, six high vulnerability working units, 22 moderate vulnerability working units and 71 low vulnerability working units in the upper-middle reaches of Luanhe River Basin, indicating that the study area is overall in lowest vulnerability and the upper-middle reaches of Luanhe River Basin have strong ability to resist risks. High vulnerability areas are mainly located in the upper part of the study area, due to their fragile ecosystem and high sensitivity scores. It is worth noting that the working units for Daheiting reservoir is in high vulnerability, which needs to focus on investigation into protection.
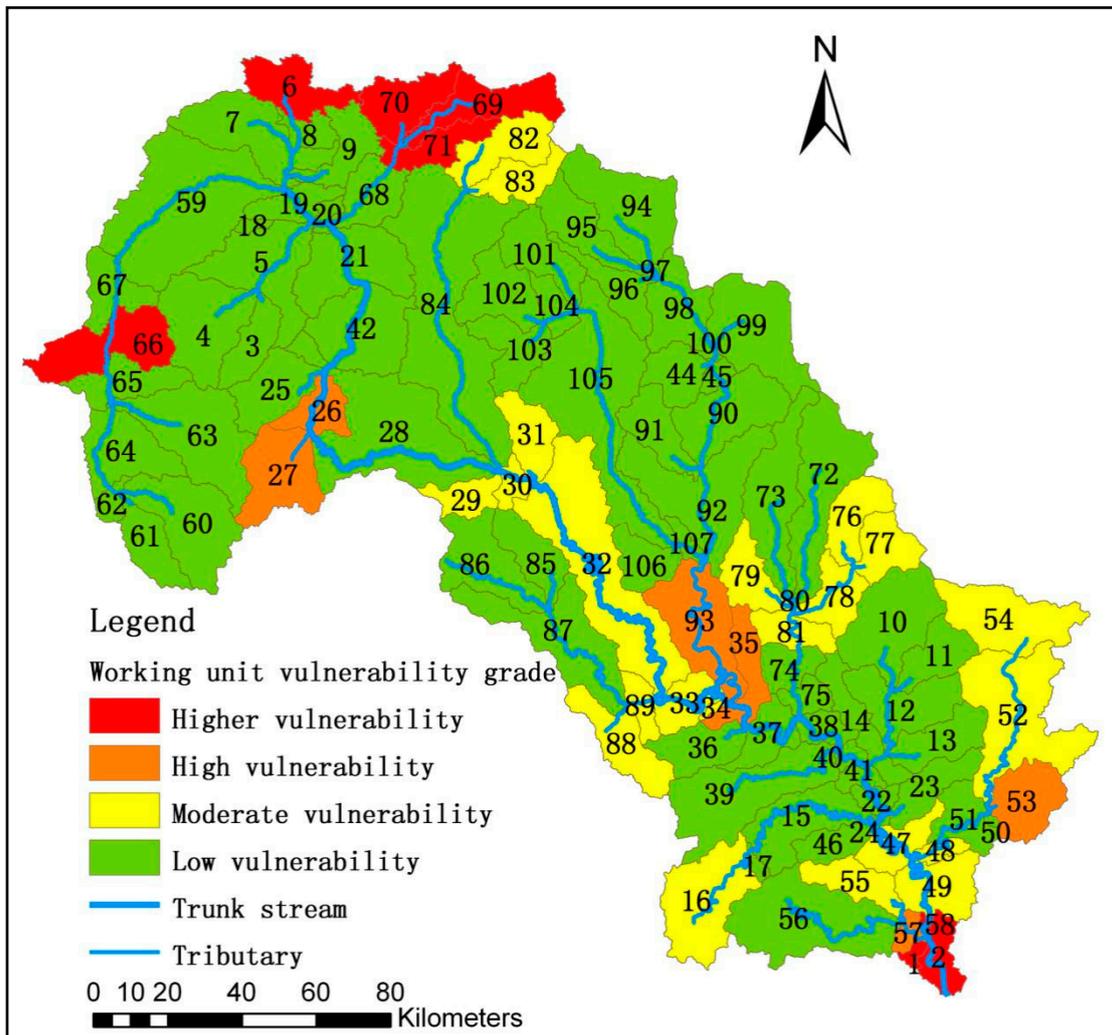
Figure 10. Working units vulnerability grade distribution map.

4.4. Working Units Risk Assessment Result

The risk grade of working units can be obtained by evaluating the hazard and vulnerability grade of the working units with the risk matrix. Figure 11 shows that the study area is at low risk (53 units), followed by moderate risk (25 units) and high risk (25 units), least for higher risk (four units), indicating overall low risk in the upper-middle reaches of Luanhe river.
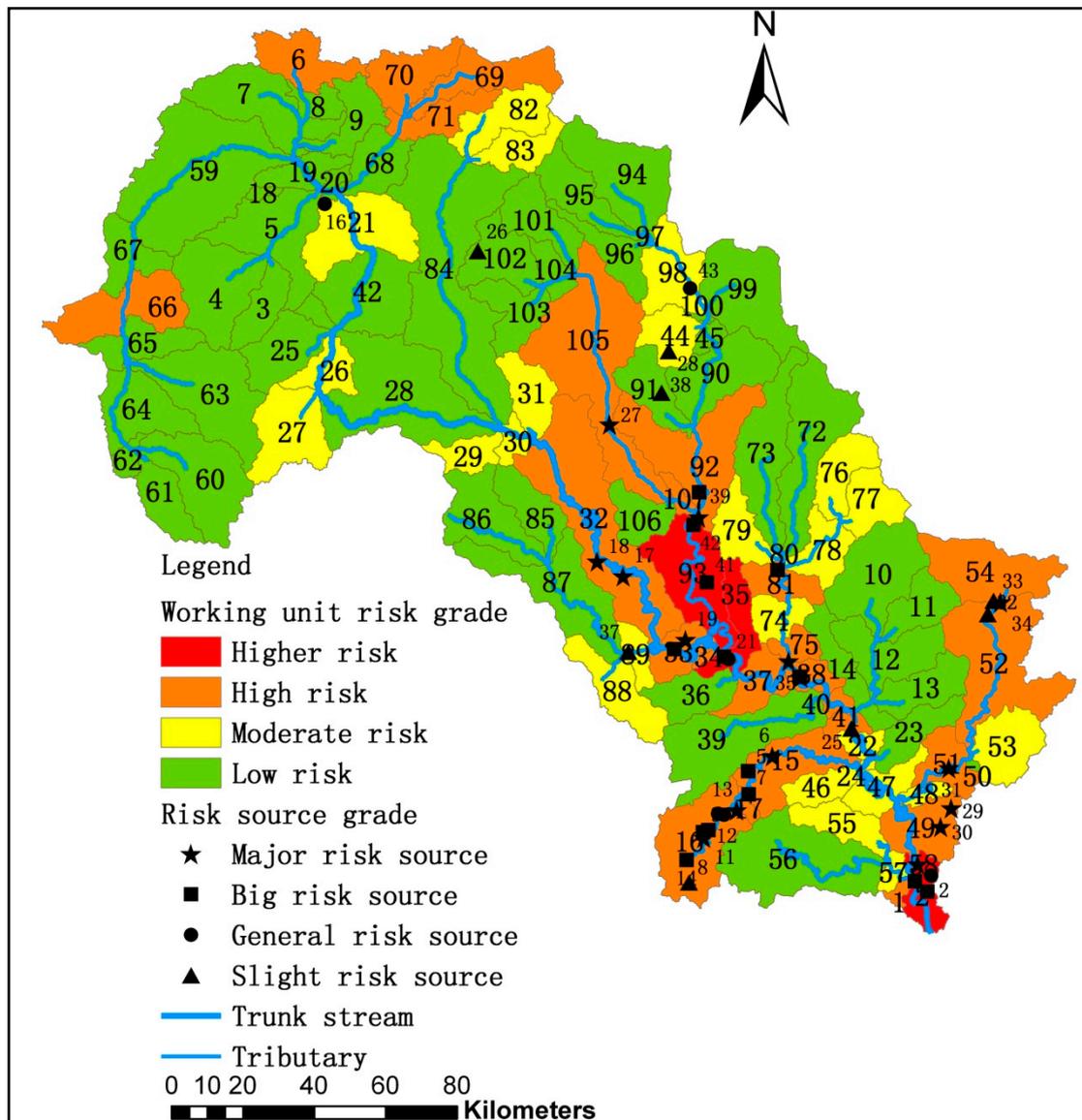
Figure 11. Working unit risk grade distribution map.

4.5. Risk Zoning Results Based on Water Function Area Control Unit

After obtaining the working units risk grade, according to the environmental risk zoning theory, merging the working units with the same risk grade in a water function area, four risk grades zones are obtained, and they are higher risk zone I, high risk zone II, moderate risk zone III and low risk zone IV, as shown in Figure 12. The risk zoning is scattered distribution in the upper-middle reaches of the Luanhe River, and there are three higher risk zones I, 15 high risk zones II, 14 moderate risk zones III, and 23 low risk zones IV, which illustrate that the risk in the upper reaches of Luanhe River is generally low.
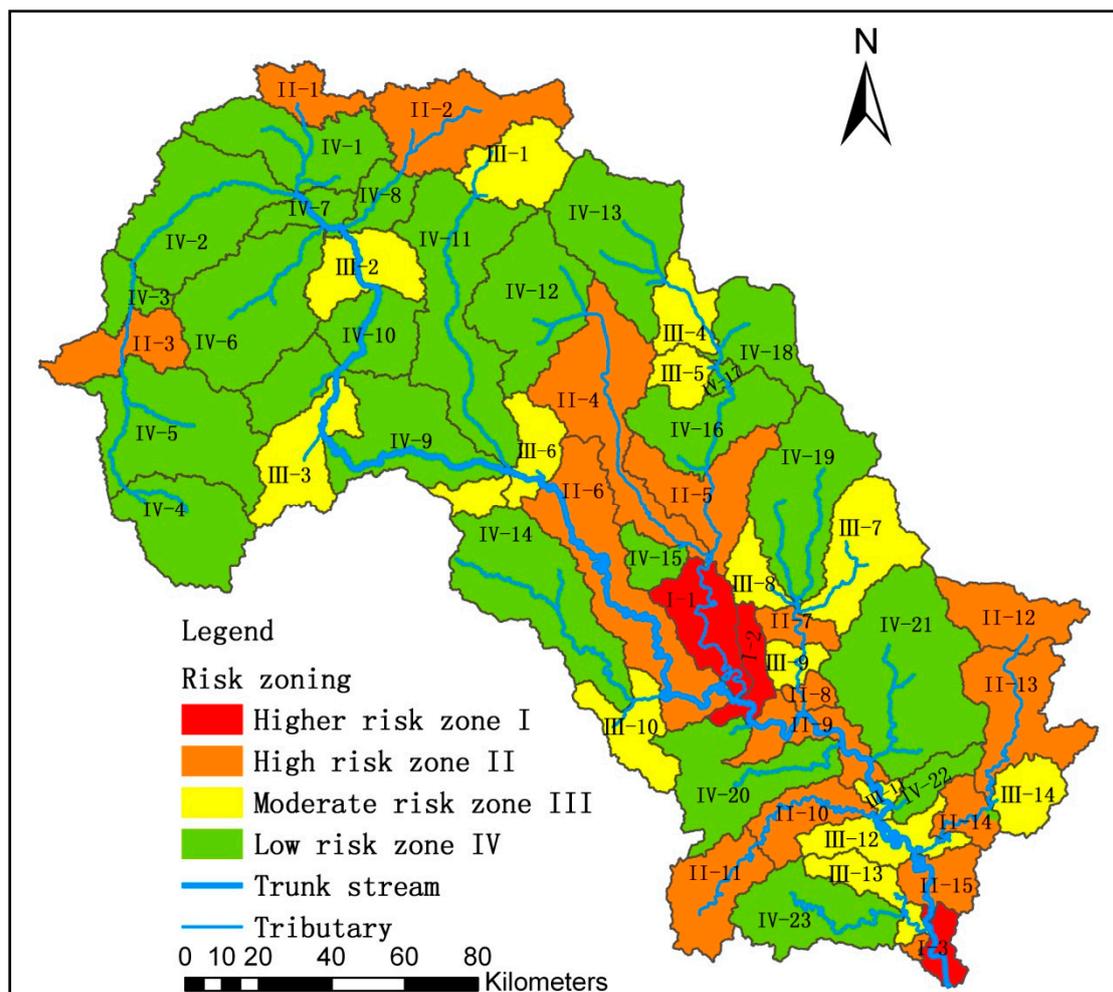
Figure 12. Risk zoning in the upper-middle reaches of Luanhe River based on water function area.

5. Discussion

The risk zoning results for the upper-middle reach of the Luanhe River from sudden water pollution incidents have been recognized by the relevant departments and they apply the methods to practical works. For example, the major risk source "Chengde iron and Steel Group Co., Ltd.", which is located in Daheiting reservoir and near the drinking water source are identified by the relevant departments and has been shut down.

When studying the downstream features I_4 for a very large river basin area, the risk sources hazard upstream to downstream working units generally requires a coupled one-dimensional, two-dimensional or three-dimensional hydrodynamic and water quality model. In particular, in the study area the Panjiakou Reservoir belongs to deep water reservoir and a three-dimensional numerical simulation model is necessary; the Daheiting reservoir is wide with a relatively small water depth and a two-dimensional numerical simulation model is appropriate; and between these two reservoirs, there is a narrow river and a one-dimensional river network model is sufficient. At the same time, the coefficients in those equations need to be determined through actual observations and experiments.

The information about the distribution of water conservancy infrastructures in the study area fails to fully investigate and obtain. For example, a dam may have a hysteresis effect to mitigate the adverse effects of water pollution incidents, including interception, temporary storage, by impounding water when sudden water pollution incidents occur. Therefore, the quantity, quality and distribution of the dam in the area can be used as an index of environmental risk source in hazard control capability. Similarly, the role of other structures can be considered. For instance, tailings dams actually exist in

the Luanhe River Basin and it should be taken as risk sources. However, detailed data of tailings dams, such as distribution and quantities in the Luanhe River Basin are not available, and thus the present analysis cannot take them as the environmental risk sources into account.

After identification and obtaining the risk zoning results of sudden water pollution incidents in the upper and middle reaches of Luanhe River Basin, the prevention and control technical measures and schemes of the sudden water pollution events in the upstream of Luanhe River could be proposed based on the national and local policies and regulations, the basic principles of water pollution control, the constituent factors of the risk level of risk zones and the actual situation. They are as follows: (A) Different management measures and schemes should be proposed according to different risk and vulnerability levels in the risk area; (B) mitigate risk levels through controlling risk sources; (C) control risks from multi-aspects, such as legal, social, economic, political and technological factors; and (D) strengthen the protection of risk receptors to reduce vulnerability. For high risk area, for example, because the hazard and vulnerability are in general very high, it is necessary to ban on the construction of new risk sources (e.g., new chemical plants and factories), to prohibit the introduction of new sensitive receptors, to shut down or move major risk sources out in the area, to establish strict and comprehensive environmental pollution monitoring system, to strengthen risk prevention and supervision, as well as to increase the construction of protective barriers for high sensitive receptors.

It is noteworthy to point out that the proposed risk assessment method is based on the water function area control unit, a Chinese and scientific concept and a practical tool in effectively managing water resources and fighting water pollution according to Chinese experience. We strongly believe that this concept could be applied and extended in many other countries and regions, especially with a water shortage and severe water pollution.

6. Conclusions

The risk of water pollution incidents of upper-middle reaches of Luanhe River Basin is assessed in the process of regionalization, leading to the following improvement: (1) Each sub basin within a water function area control unit is identified as a working unit, and taken as the transition unit of the risk assessment regionalization in a sudden water pollution event; (2) in environmental risk source hazard assessment index system, the risk source flows through the downstream different water function areas (working units) and it will affect the environmental risk source hazard grade itself, and thus increase the "Downstream features" of environmental risk sources index; (3) the calculation method of hazard from risk source to working unit is established and the working unit hazard grade is composed of two parts: The risk source hazard grade of the working unit and the influence of the upstream risk source to the downstream working unit hazard; and (4) the risk zoning theory is applied to combine the working units with the same risk grade in the same water function control unit for obtaining the final risk zoning unit.

In the upper-middle reaches of Luanhe River Basin area there are 34 control units. Combining with the sub basin, it is further divided into 107 working units. There are 43 environmental risk sources, among which 15 are the major risk sources, and 14 are the big risk sources which are concentrated and distributed in the middle and lower reaches of the study area. However, there are 75 low hazard working units and the overall hazard is low. Almost working units are in low vulnerability, which means that the upper-middle reaches of Luanhe River basin has the strong ability to resist risks. The risk grade of each working unit is obtained through risk matrix. Working units are combined with those of the same risk grades and the water function area control units, resulting in 55 risk zones, including three higher risk zone I, 15 high risk zone II, 14 moderate risk zone III, and 23 low risk zone IV. This indicates that the risk of the upper-middle reaches of Luanhe River Basin is low, and the corresponding management methods for the different risk zones are suggested. The Daheiting reservoir as one of drinking water sources of Tianjin belongs to the higher risk zone I, and its management is required, which includes separating and cutting off its risk sources, and at the same time increasing the protective barriers of its high-sensitivity receptors.

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