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Article

Study of the Water Environment Risk Assessment of the Upper Reaches of the Baiyangdian Lake, China

Xiaoyan Guan [1,2], Xiaoqiang Ren [1], Yuan Tao [1,2,*], Xiaomin Chang [2] and Bing Li [2]

1 State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
2 Department of Irrigation and Drainage, China Institute of Water Resources and Hydropower Research, Beijing 100048, China
* Correspondence: taoyuanss.good@163.com

Abstract: The risk assessment of water environments provides important references for water environment risk management. In this paper, the water environment risk of the upper rivers of the Baiyangdian Lake is assessed, considering both cumulative and sudden environmental risk. For the cumulative environmental risk assessment of the rivers, the characteristics of pollution transmissibility and accumulation in rivers was considered firstly. Furthermore, suggestions for the control of water environment pollution in the Baiyangdian Basin are given. The results indicate that the cumulative water environment risks of the Xiaoyi River—Dingzhou County, Xiaoyi River—Anguo County, Xiaoyi River—Boye County, and Xiaoyi River—Li County are high. The amount of fertilizer applied per unit of cultivated area, water quality, rate of water quality above the standard in water function zoning, and the ratio of environmental investment to gross domestic product (GDP) are important factors influencing the cumulative water environment risk. For sudden water environment assessments, the Xiaoyi River—Boye County is high. In the future, reducing the intensity of fertilizer application, strengthening the water quality control of the rivers, as well as upgrading the industry, should be carried out to protect the water environment in the Baiyangdian Basin.

Keywords: Baiyangdian Basin; water environment risk assessment; cumulative environmental risk; sudden environmental risk; rivers

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1. Introduction

With the acceleration of social and economic development, more attention has been paid to water environment protection. Water quality is the primary representation of a water environment; many factors may influence the water quality of a river. Surface water pollution, especially river bank pollution, is one of the most serious issues. Jaybhaye, et al. [1] found that the water quality index of the Amba River from the Dolvi Region, Maharashtra, fell under the "poor" category. Snitynskyi, et al. [2] showed that water management and ecological situations may be complicated, especially in water bodies with a significant anthropogenic load, with a deterioration in the water quality due to the limitation of the dilution of polluted wastewater in the Stryi River Basin, Ukraine. Puchlik, et al. [3] pointed out that temperature changes contribute to increased surface water pollution in the northeastern part of Poland. Bridhikitti, et al. [4] studied the surface water quality in the Mun River Basin, Thailand, and showed that the water quality was often found to have high amounts of coliform bacteria during the monsoon season; the water quality in the dry season was even worse, exhibiting high loadings of organic compounds, coliform bacteria, and nutrients, in addition to low dissolved oxygen. The surface water quality was always affected by human activities. Qiao, et al. [5] indicated that, from 2000 to 2019, the water quality was not significantly improved at the non-background sites of

Chengdu's Min Basin, while during the COVID-19 lockdown, the water quality generally improved in the Min Basin. Das, et al. [6] quantified the impact of the COVID-19 lockdown on the water quality parameters of the Buddha Nala located in District Ludhiana in India and found that the impact of the COVID-19 lockdown on the improvement in water quality of Buddha Nala was more evident in the upstream and downstream sections than the middle section, where it was continually impacted by domestic household effluents. Vieira, et al. [7] evaluated the effect of existing domestic, agricultural, and industrial activities on the water quality of the Lis River and pointed that the poor water quality associated mainly with the contamination source from pig-breeding farms.

Water environmental risk analyses provide important references for the protection of water environments. Environmental risk assessment is generally divided into cumulative environmental risk assessment and sudden environmental risk assessment [8,9]. Cumulative environmental risk assessment is a risk assessment of cumulative environmental events usually caused by the long-term discharge of pollutants [10,11]. Sudden environmental risk assessment refers to the leakage of environmental risk materials caused by accidents in industrial production and transportation processes [12]. There were rare studies about the comprehensive consideration of cumulative environmental risk assessment and sudden environmental risk assessment. Many studies of cumulative water environment risk focused on heavy metal pollution in recent years, and the Heavy Metal Pollution Index (HPI), Potential Ecological Risk Index (PERI), and the Comprehensive Risk Index were commonly adopted based on the only parameter of water quality [13–15]. Additionally, there are also many risk assessments of organic micropollutants and sediment contamination in rivers based on the water quality monitoring without pollution source analysis [16,17]. For proposing governance recommendation, more influence parameters during the process of pollutants flowing into rivers should be considered.

In this view, the cumulative water environment risk assessment is difficult to quantify, and the chosen appropriate parameters or indicators are critical. In 1997, the US Environmental Protection Agency (USEPA) published the guidelines of cumulative environmental risk assessment, where the focus of cumulative environmental risk assessment, shifting the assessment from a single risk source to multiple risk sources, was first articulated [18]. The USEPA also divided the cumulative environmental risk assessment process into three parts: planning construction, risk analysis, and risk characterization [19]. To quantize the environment risk, many methods have been studied. Nazar, et al. [20] put forward a quantitative index of water environmental risk instead of a qualitative index. Gottardo, et al. [21] developed an alternative integrated risk assessment (IRA) methodology that provided a more comprehensive, realistic, and flexible ecological status classification based on a weight of evidence approach and applied it in the Llobregat River Basin (Spain) to assess the water environment [22]. Chen, et al. [23] established an assessment index system for accumulative water environmental risks according to the local situation of Changzhou in the Taihu Lake Basin (China) based on the methods of principal component analysis and a comprehensive neural network model, evaluated the accumulative water environmental risks from 2004 to 2009, and pointed out that non-point risk sources are mainly caused by agriculture and livestock farming. Wei, et al. [24] readjusted the proposed evaluation index system of water environment risk by the WWF (World Wide Fund for Nature) to be more suitable for local situations of China, considering the different features of water resources, water environments, water resources' management, and information statistics, and conducted a comprehensive evaluation in the Yangtze River Basin and its seven secondary subareas. Topuz, et al. [25] proposed an environmental risk assessment approach for engineered nanoparticles by integrating the analytical hierarchy process (AHP) and fuzzy inference models, which provide a systematic evaluation of risk factors and reduce the uncertainty about the data and information, respectively. Abedzadeh, et al. [26] carried out a risk-based assessment of water resources development plans under the sustainable development framework using Fuzzy Fault Tree Analysis, which may facilitate decision making for the risk management.

For sudden water environment risk, early studies always focused on the risk assessment of a marine oil spill accident. In order to quantify the sudden environmental risk more objectively, accurately, and concretely, the research focus gradually shifted to quantitative methods, such as establishing an index system and an assessment model. Scott [27] proposed the environment–accident index (EAI) as a tool to assess the risk of chemicals. Dura, et al. [28] used a semiquantitative risk assessment method for the tentative evaluation of a hazardous chemical waste incinerator. Liu [29] used the combined methods of the analytic hierarchy process (AHP) and a fuzzy comprehensive evaluation to build an environment risk source identification technology system, and then applied it in the sudden water environment risk assessment of the main streams of the Songhua River. Yang, et al. [30] combined the drivers–pressures–state–impact–response model, fuzzy comprehensive evaluation method, and coordinated development degree model into a comprehensive risk assessment tool. In China, a regional emergent grid environmental risk assessment method based on the environment risk field has been recommended [31]. Zhou, et al. [32] studied sudden water pollution risk zoning in the Dongjiang River Basin by using this method.

From the above literature, we can see that the studies on water environment risk assessment mainly focused on single cumulative or sudden environmental risk assessments and rarely considered both. In terms of study objects, studies about the environmental risk assessment of rivers were even rarer. The main objective of this paper was to estimate both cumulative and sudden environmental risk assessments, taking the upper rivers of the Baiyangdian Lake as an example. A cumulative risk assessment system with eighteen indexes for the upper rivers of the Baiyangdian Lake was built, considering the characteristics of pollution transmissibility and accumulation in rivers. Then, the risk of sudden water pollution in the upper rivers of the Baiyangdian Lake was evaluated by a grid environmental risk analysis. Additionally, water environment risk prevention and control suggestions were given.

2. Materials and Methods

2.1. Study Area

The Baiyangdian Basin is located in the middle of the North China Plain (113°39′–116°20′ E, 38°39′–40°09′ N), belonging to the Daqinghe River system in the Haihe Basin. The Baiyangdian Lake is the largest plain lake wetland in North China. The Haihe Basin has a complex topography, including middle mountains, low mountains, hills, plains, and a depression lake from west to east. The annual average rainfall is approximately 564 mm and unevenly distributed, concentrated in July to August in the Baiyangdian Basin. There are eight rivers, the Zhulong River, Xiaoyi River, Tang River, Bao River, Fu River, Cao River, Ping River, and Baigou Canal, flowing into the Baiyangdian Lake directly [33]. The Zhulong River and Ping River have no water all year round; the Xiaoyi River, Fu River, Bao River, and Baigou Canal are perennial rivers; and the others are seasonal rivers. The water body of the Baiyangdian Basin is partly maintained by the water diversion from the Yellow River and the South-to-North Water Diversion Project. The major sources of pollution of the upper reaches of the Baiyangdian Lake are chemical oxygen demand, total nitrogen, and ammonia nitrogen.

2.2. Risk Assessment Units

In order to assess the risks of different river segments, the assessment units were divided. Firstly, we marked off the sub-basin of the Baiyangdian Basin, considering topography, administrative divisions, and water function zoning, and then defined the control areas of different river segments. Twenty-four water environment risk assessment units were generated, which were named in the format of "River name–administrative name" (Table 1).

Table 1. Water environment risk assessment units of the rivers.

River Name	Water Environment Risk Assessment Units
Zhongyishui River—Nanyishui River—Baigou Canal (ZNBC)	(1) ZNBC–Yi County, (2) ZNBC–Dingxing County, and (3) ZNBC–Rongcheng County
Cao River	(4) Cao River—Yi County, (5) Cao River—Mancheng District, and (6) Cao River—Xushui District
Bao River	(7) Bao River—Yi County, (8) Bao River—Xushui District
Tang River	(9) Tang River—Hunyuan County, (10) Tang River—Lingqiu County, (11) Tang River—Laiyuan County, (12) Tang River—Tang County, (13) Tang River—Dingzhou County, (14) Tang River—Wangdu County, (15) Tang River—Qingyuan District, and (16) Tang River—Anxin County
Xiaoyi River	(17) Xiaoyi River—Quyang County, (18) Xiaoyi River—Dingzhou County, (19) Xiaoyi River—Anguo County, (20) Xiaoyi River—Boye County, (21) Xiaoyi River—Li County, and (22) Xiaoyi River—Gaoyang County
Fu River	(23) Fu River—Lianchi District and (24) Fu River—Qingyuan District

2.3. Assessment System of Accumulation Water Environment Risk

Considering the characteristics of pollution transmissibility and accumulation in rivers, for the two adjacent reaches of a river, the upstream reaches could be regarded as potential risk sources for the downstream reaches. Taking five parameters of the risk sources, river characteristics, physical geography and social development conditions, and water pollution control ability, as the criterion layer, a water environment risk assessment system was established, where sixteen indexes and eighteen indexes were given for the beginning reaches and the other reaches of a river, respectively (Table 2). For the index of river discharge, the water volume from upstream reservoirs and the supply by the South-to-North Water Diversion Project as well as the Yellow River were additionally added. Among the five parameters of the criterion layer, the parameter of physical geography and social development conditions is the indirect driving factor of water environment risk; water pollution control ability is the main driving factor of water environment pollution control and risk management.

Ten water environment experts were invited to fill in a specially designed questionnaire, which is available in the Supplementary Material; the consultation results were in good agreement. Based on the statistical results, a three-scale analytic hierarchy process (AHP) was used to calculate the index weight, which had a self-regulating function and was more accurate [34]. The scale values were divided into 0, 1, and 2. When index C_i was less important than index C_j, the scale value was 0. When index Ci was as important as index Cj, the scale value was 1. When index Ci was more important than index Cj, the scale value was 2. Then, the calculation process was the same as the traditional analytic hierarchy process [35,36].

Table 2. Index parameters and weights of the water environment risk assessment system.

Criterion Layer	Factor Level	Scheme Layer	Index Layer	Beginning Reaches Weight	Other Reaches Weight
Risk sources	Non-point source pollution within the control range of the reaches	Planting pollution	Amount of fertilizer applied per unit of cultivated area	0.1280	0.1148
		Livestock pollution	Livestock and poultry excretions	0.0657	0.0590
		Rural living pollution	Domestic sewage discharge in rural areas	0.0247	0.0221
			Human excrement and urine emissions in rural areas	0.0091	0.0081
	Point source pollution within the control range of the reaches	Industrial effluents	Industrial wastewater discharge per unit of GDP	0.2276	0.1048
	Water environmental risk impacts of the adjacent upstream reaches	Risk	Risk of the adjacent upstream reaches	-	0.1069
		Distance	Distance to the adjacent upstream reaches*	-	0.0393
River characteristics	Cross-section of river	Water quality condition	Water quality	0.0895	0.0895
			Rate of water quality above the standard in water function zoning	0.0329	0.0329
		Discharge	Perennial average annual discharge	0.0450	0.0450
Physical geography and social development conditions	Social development	Population characteristics	Population	0.0146	0.0146
			Natural population growth rate	0.0054	0.0054
		Economic level	GDP per capita	0.0543	0.0543
	Physical geography	Location of pollution sources	Distance between the pollution source and the Baiyangdian Lake	0.0273	0.0273
Water pollution control ability	Primary control mechanism	Sewage exhaust state	Rate of industrial wastewater discharge up to standard	0.0418	0.0418
		Sewage treatment	Rate of centralized treatment of urban domestic sewage	0.0214	0.0214
		Refuse collection	Urban garbage collection rate	0.0110	0.0110
	Stimulus control mechanism	Risk management investment	Ratio of environmental investment to GDP	0.2018	0.2018

2.4. Grading Standard of Accumulation Water Environment Risk

The accumulation water environment risk was calculated via the method of weighted comprehensive indexes. The greater the calculated result of the comprehensive score of the water environment risk was, the greater the water environment risk was. The details are shown in Table 3 [24].

Table 3. Classification of water environment risk comprehensive scoring value.

Level	Class of Risk	Scoring Value	Risk Characterization
I	No risk or acceptable risk	(0,1]	Probability of risk is extremely low, or destructiveness is weak
II	Low risk	(1,2]	Water use behavior should be regulated to prevent risks
III	Middle risk	(2,3]	Risk may happen or have the potential to cause damage
IV	High risk	(3,4]	Risk happens easily and can cause great damage
V	Very high risk	(4,5]	Risks happens frequently and causes damage that is not easy to recover from

For the index classification, the references of the class division were as follows: (1) firstly, adopt the limit values prescribed in national standards, provincial standards, or municipal standards; (2) secondly, take the literature as a reference, combining it with the local situation in the study area; and (3) if the index dissatisfies both of the above cases, then the Weber–Fechner law (W–F law) could be used to calculated the classification [37–39]. The index classification is shown in Table 4.

Table 4. Classification standard of the river water environment risk assessment index.

Criterion Layer	Index Layer	Unit	Scoring Value					References
			0~1	**1~2**	**2~3**	**3~4**	**4~5**	
Risk sources	Amount of fertilizer applied per unit of cultivated area	kg/ha	0~250	250~450	450~650	650~850	≥ 850	[40]
	Livestock and poultry excretions	10^4 t	0~3.8	3.8~10.4	10.4~28.6	28.6~78.4	≥ 78.4	W–F law
	Domestic sewage discharge in rural areas	10^4 m^3	0~22	22~53	53~126	126~301	≥ 301	W–F law
	Human excrement and urine emissions in rural areas	10^4 t	0~1.4	1.4~3.3	3.3~7.9	7.9~18.7	≥ 18.7	W–F law
	Industrial wastewater discharge per unit of GDP	t/(CNY 10^4)	0~1	1~4	4~14	14~52	≥ 52	W–F law
	Risk of the adjacent upstream reaches	Scoring value	0~1	1~2	2~3	3~4	4~5	[24]
	Distance to the adjacent upstream reaches*	km	≥ 52	34~52	22~34	15~22	0~15	W–F law
River characteristics	Water quality		I	II	III	IV	Others	Standard
	Rate of water quality above the standard in water function zoning	%	100	80~100	60~80	40~60	0~40	[40]
	Perennial average annual discharge	10^8 m^3	≥ 4.72	1.21~4.72	0.31~1.21	0.09~0.31	0~0.09	W–F law
Physical geography and social development conditions	Population	10^4 person	0~3.4	3.4~9.4	9.4~25.9	25.9~71.5	≥ 71.5	W–F law
	Natural population growth rate	‰	≤ −9.9	−9.9~−3.1	−3.1~3.8	3.8~10.6	≥ 10.6	W–F law
	GDP per capita	CNY 10^3	≥ 50.4	30.7~50.4	18.7~30.7	11.4~18.7	≤ 11.4	W–F law
	Distance between the pollution source and the Baiyangdian Lake	km	≥ 268	77~268	22~77	3~22	0~3	W–F law
Water pollution control ability	Rate of industrial wastewater discharge up to standard	%	100	95~100	90~95	80~90	≤ 80	[40]
	Rate of centralized treatment of urban domestic sewage	%	100	95~100	90~95	85~90	≤ 85	[40]
	Urban garbage collection rate	%	100	95~100	90~95	85~90	≤ 85	[40]
	Ratio of environmental investment to GDP	%	≥ 3	2~3	1~2	0.5~1	0~0.5	Standard

2.5. Study Method of Sudden Water Environment Risk

The assessment of sudden water environment risk was conducted based on the method of grid environmental risk assessment, which was recommended as a regional emergent environmental risk assessment method in China [41,42]. The grid environmental risk assessment method could quantize the field intensity of environmental risk sources and the vulnerability of environmental risk receptors for each grid cell. In this paper, grid cells with sizes of 1 km × 1 km were made through the function of Create Fishnet in ArcGis, and the grid cell number was 32,994.

The water environmental risk value of a grid cell could be calculated by the following equation:

$$R_{x,y} = \sqrt{E_{x,y} \times V_{x,y}} \quad (1)$$

where $R_{x,y}$ is the scoring value of the environmental risk of a grid cell, $E_{x,y}$ is the field intensity of the environmental risk of the grid cell, and $V_{x,y}$ is the receptor vulnerability index of the environmental risk. The situations of $R > 80$, $60 < R \leq 80$, $30 < R \leq 60$, and $R \leq 30$, respectively, correspond to high risk, slightly higher risk, middle risk, and low risk [41]. If the cumulative areas of a certain risk classification were larger than 50% of the river's control area, the corresponding risk classification would be the risk of the river.

The water environmental risk field intensity of a grid cell could be expressed as follows:

$$E_{x,y} = \begin{cases} \sum_{i=1}^{n} Q_i P_{x,y} & 0 \leq l_i \leq 1 \\ \sum_{i=1}^{n} (1 - \frac{l_i}{10}) Q_i P_{x,y} & 1 < l_i \leq 10 \\ 0 & l_i > 10 \end{cases} \quad (2)$$

where Q_i is the ratio of the maximum presence and threshold quantity of the environmental risk substance for the *i*th risk source; $P_{x,y}$ is the probability of risk field occurrence in a grid cell, which could be set to 10^{-6} per year; l_i is the distance between the center of a grid cell and the risk sources (km); and n is the number of risk sources.

When an industry enterprise has a variety of risk substances, the ratio of the maximum presence and threshold quantity of the environmental risk substance (Q) could be calculated through summing the Q values of all of the risk substances up. The environmental risk substances of typical industry enterprises are shown in Table 5. The Q values of other industry enterprises could be deduced based on the industry category and enterprise size.

Table 5. Data of environmental risk substances of industry categories.

Serial Numb-er	Type of Risk Source	Registered Size (CNY 10^4)	Environmental Risk Substance	Maximum Presence of Environmental Risk Substance (t)	Threshold Quantity of Environmental Risk Substance (t)	Q
1	Chemical raw materials and chemical products manufacturing	1000	Vitriol	400	10	40
2	Paper products industry	600	Vitriol	0.3	10	0.03
			Oil substances	0.18	2500	0.000072
3	Textile industry	1000	Sodium hydrosulfite	0.029	5	0.0058
			Acetic acid	0.065	10	0.0065
4	Sewage treatment plant	8078	Methyl alcohol	5.329	10	0.5329
5	Food manufacturing industry	3000	Ammonium hydroxide	2.236	10	0.2236
			Methyl alcohol	7.091	10	0.7091
6	Metal products industry	1000	Oil substances	110.32	2500	0.044128
			Ammonium hydroxide	107	10	10.7
			Liquefied petroleum gas	2	10	0.2
			Substances harmful to water environments (Chronic toxicity Category: Chronic 2)	300	200	1.5
			Organic wastewater (concentration of CODcr ≥ 10000 mg/L)	36	10	3.6
7	Service industry	25,417	Oil substances	0.484	2500	0.0001936
			Ethyl alcohol	0.202	500	0.000404
			Hydrochloric acid	0.605	7.5	0.081
			Sodium chlorate	0.806	100	0.00806

8	Leather, fur, and feather products as well as footwear	2000	Health hazards, acute toxic substances (Class 2, Class 3)	6.25	50	0.125
9	Petroleum, coal, and other fuel processing industries	1500	Oil substances	14,600	2500	5.84
10	Wine, beverage, and refined tea manufacturing	1200	Ammonium hydroxide	1.037	10	0.1037
			Vitriol	0.00216	10	0.000216
11	Mining and washing of coal industry	14,260	Oil substances	427.822	2500	0.171
12	Special equipment manufacturing	1488	Additives	1.674	50	0.033
13	Manufacturing of railway, marine, aerospace, and other transportation equipment	2000	Oil substances	1.304	2500	0.0005
			Flammable liquid	0.953	50	0.019
			Acetone	0.00048	10	0.000048
			Ethyl alcohol	0.00048	500	0.00000096
			Hydrochloric acid	0.000027	7.5	0.0000037
14	Motor industry	5000	Oil substances	6.45	2500	0.00258
			Methylbenzene	0.375	10	0.0375
			Xylene	4.375	10	0.4375
			Nickel nitrate	0.625	0.25	2.5
15	Manufacture of non-metallic mineral products	1000	Oil substances	16.667	2500	0.00667
16	Production and supply of electric power and heat power	313972	Oil substances	156.986	2500	0.063

In order to facilitate the comparison of the water environmental risk field intensity in each grid cell, the field intensity of environmental risk was standardized:

$$E_{x,y}{}' = \frac{E_{x,y} - E_{min}}{Emin_{max} \times 100} \quad (3)$$

where $E_{x,y}{}'$ is the field intensity of the environmental risk of a grid cell after standardization, E_{max} is the maximum field intensity of the environmental risk of the region, and E_{min} is the minimum field intensity of the environmental risk of the region.

The receptor vulnerability index of environmental risk mainly considered the impact of the ecological red line. When the grid cell was within the ecological red line, the $V_{x,y}$ value was 80; the $V_{x,y}$ value was 40 on other occasions. The ecological red line is shown in Figure 1.

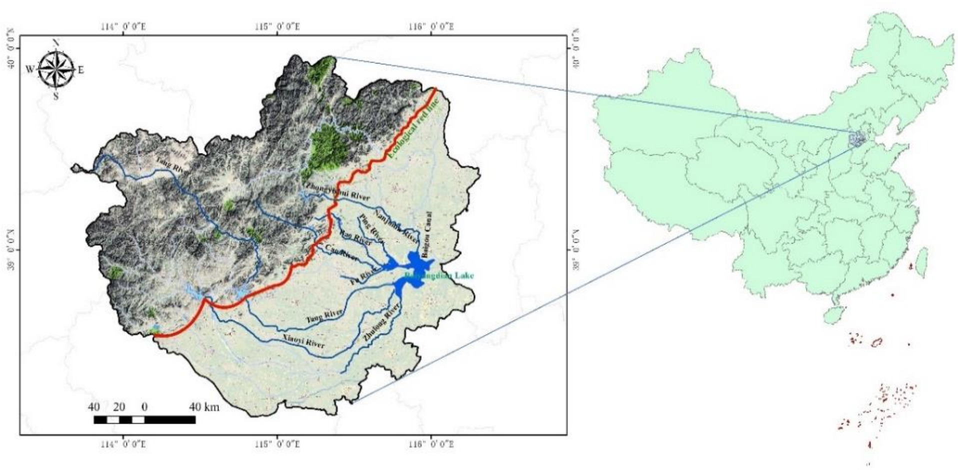

Figure 1. Map of the Baiyangdian Basin and its geographical location in China.

2.6. Data Sources

The data in this paper mainly came from the regional statistical yearbook or economic statistical yearbook, ecological environment departments of provinces and cities, public budgets of the county and district governments, related websites, and monitoring data. In order to keep the time consistency of the data, the data in 2018 were adopted, except for those of water quality. Considering the fact that water quality data were more sensitive to time, the data timeline of the water quality was 2021. The statistical data of the water quality were from monthly reports on the websites of the governments, and the additional data were from field monitoring in March 2021. Additionally, the data of key wastewater discharge monitoring enterprises and sewage treatment plants were from seasonal reports on the websites of the governments.

The key sewage discharge enterprises and sewage treatment plants with large discharges of collected sewage, great potential harm of pollutants, sensitive locations, and that were being monitored by the government were considered the sudden pollution sources. The water quality monitoring points in addition to the key sewage enterprises and urban sewage treatment plants are shown in Figure 2. Two hundred and fifty-four key wastewater discharge monitoring enterprises and sewage treatment plants in addition to thirty-six water quality monitoring points (including statistical data and measured data) were studied. The water quality of the reaches is shown in Table 6.

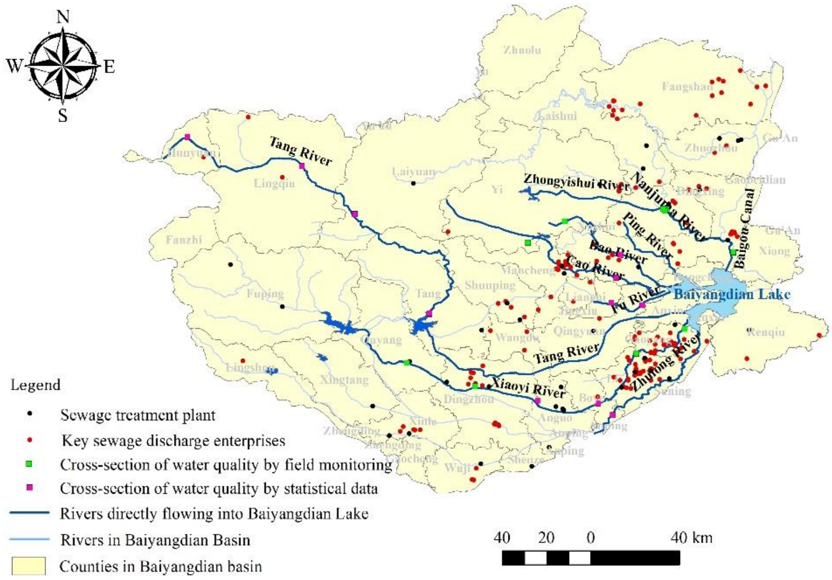

Figure 2. Cross-section of the water quality monitoring and key monitoring point sources of wastewater discharge in the Baiyangdian Basin.

Table 6. Water quality of the upstream rivers of the Baiyangdian Lake in March 2021.

Name of River	Name of County or District	Water Quality
Fu River	Lianchi District	III
Fu River	Qingyuan District	II
Xiaoyi River	Quyang County	II
Xiaoyi River	Dingzhou County	V
Xiaoyi River	Anguo County	V
Xiaoyi River	Boye County	V
Xiaoyi River	Li County	IV
Xiaoyi River	Gaoyang County	IV
Tang River	Hunyuan County	III
Tang River	Lingqiu County	II
Tang River	Laiyuan County	II
Tang River	Tang County	I

Tang River	Dingzhou County	III
Tang River	Wangdu County	III
Tang River	Qingyuan District	III
Tang River	Anxin County	III
Bao River	Yi County	Worse than V
Bao River	Xushui District	III
Cao River	Yi County	III
Cao River	Mancheng District	III
Cao River	Xushui District	III
Zhongyishui River	Yi County	II
Nanyishui River	Dingxing County	II
Baigou Canal	Rongcheng County	Worse than V

3. Results

3.1. Cumulative Water Environmental Risk

The cumulative water environmental risks of the rivers are shown in Figure 3. Totally speaking, the risk levels of the most upper reaches of the Baiyangdian Lake were III, which meant that the water environmental risk of the reaches may happen or have the potential to cause damage. The segments of the Xiaoyi River—Dingzhou County, Xiaoyi River—Anguo County, Xiaoyi River—Boye County, and Xiaoyi River—Li County had a high water environmental risk, where risks may happen easily and could cause great damage, while the segment of the Tang River—Laiyuan County was the only low-risk area.

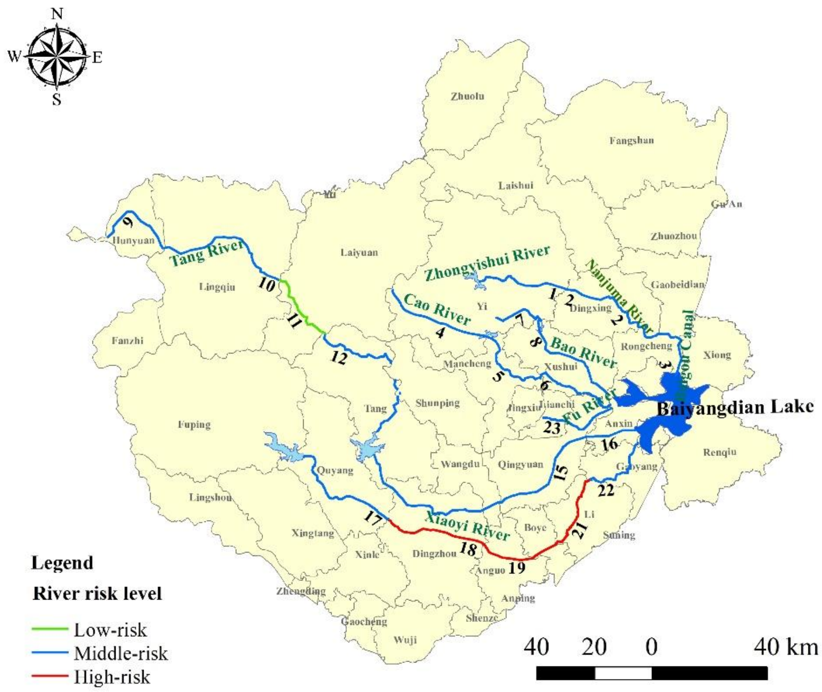

Figure 3. Cumulative water environmental risks of the rivers.

A thermal map of the water environment comprehensive risk assessment index scores in different river segments is shown in Figure 4. We can see that the amount of fertilizer applied per unit of cultivated area, water quality, the rate of water quality above the standard in water function zoning, and the ratio of environmental investment to GDP were important factors influencing the cumulative water environment risk. Most of the counties and districts surrounding the upper reaches of the Baiyangdian Lake did not pay enough attention to water environmental protection; the ratio of environmental investment to GDP was less than 1%, which may make it difficult to control the trend of environmental deterioration. The upstream rivers of the Baiyangdian Lake mainly distribute in the west plain of the Daqinghe Basin, where the agricultural production conditions are good, and the agricultural economy is relatively developed. It is the main grain-producing area in China. The fertilizer application intensities in these areas were much higher and were about three–five times higher than the internationally recognized safety limit (225 kg/hm^2). In particular, in Dingzhou County and Lianchi District, more vegetable and fruits were planted, to which a great deal of fertilizer was applied. The unreasonable fertilization would lead to environmental pressure for the rivers. The water quality and the rate of water quality above the standard in water function zoning were also very important. During the study period, the water qualities of most river reaches were worse than the III grade of the water quality standards, especially for the segments of the Xiaoyi River. Additionally, the perennial average annual discharge in the Tang River—Wangdu County unit and the rate of the centralized treatment of urban domestic sewage in the Tang River—Lingqiu County unit also had larger influences on the environment risk. Furthermore, the livestock and poultry excretions in ZNBC–Yi County also had a great effect on the environment risk.

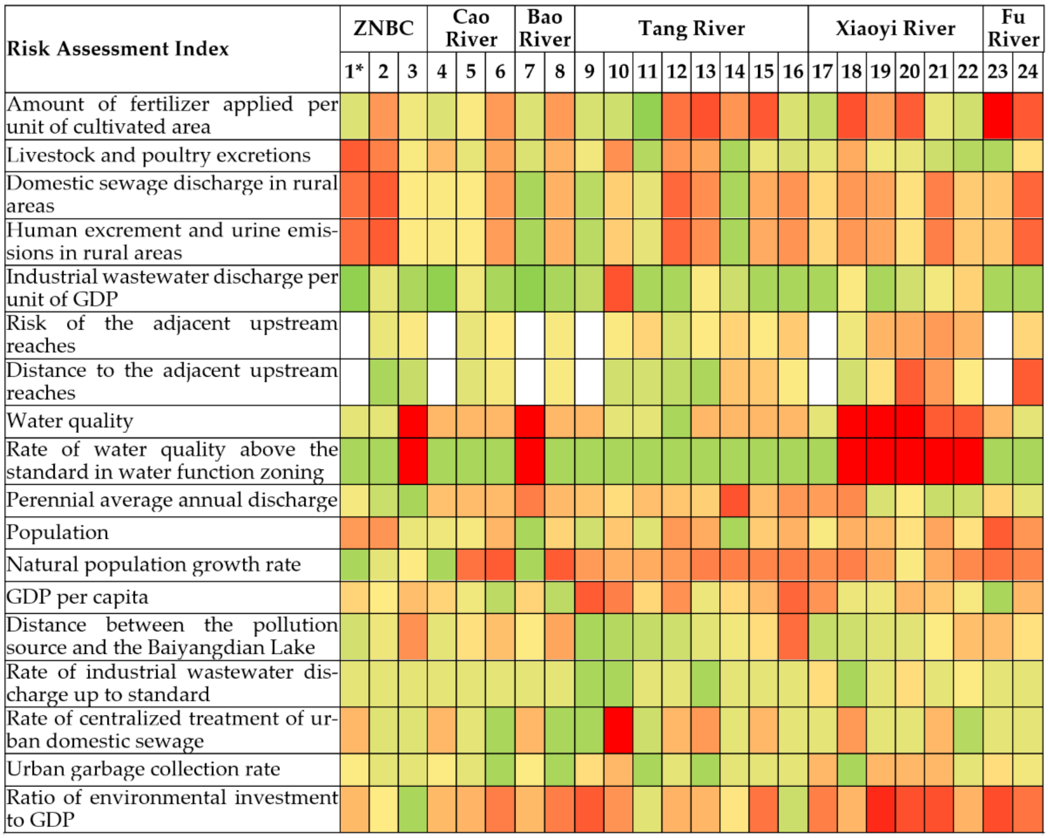

Figure 4. Thermal map of the water environment comprehensive risk assessment index scores. Note: * stands for the number of the river assessment unit; details were given in Table 1. In this Table, the red mesh meant higher risk scores, the green mesh meant lower risk scores, and the yellow mesh showed the middle risk scores.

3.2. Sudden Water Environmental Risk

The calculated field intensity of the water environmental risk in the Baiyangdian Basin is shown in Figure 5. We can see that the areas with a high-risk field intensity were mainly distributed in Mancheng District, Li County, Boye County, and Xinle City. In these areas, large numbers of key monitoring wastewater discharge enterprises existed, accounting for 27.2% of those in the Baiyangdian Basin. The risk field intensity in Mancheng District was higher, mainly because there were more paper and paper products enterprises. For Li and Boye Counties, the main reasons were, respectively, large numbers of textile enterprises as well as papermaking enterprises and several large chemical raw materials and chemical products manufacturing enterprises in and surrounding the two regions. The high field intensity of the environmental risk in Xinle City was mainly due to the large numbers of chemical plants, food processing plants, and sewage treatment plants present. The middle-risk field intensity was mainly the radiation area of the high-risk field intensity.

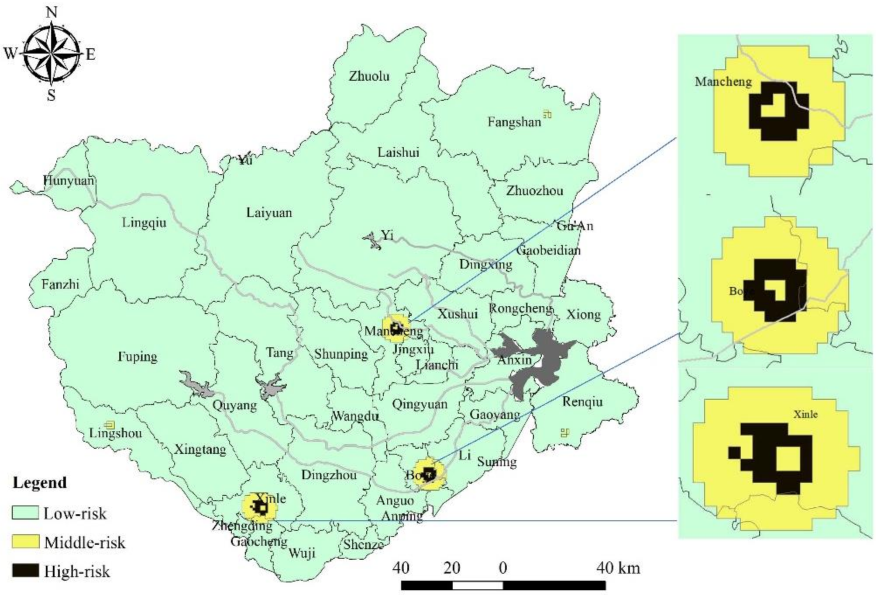

Figure 5. Water environmental risk field intensity in the Baiyangdian Basin.

Taking the receptor vulnerability index of environmental risk into account, sudden water environmental risks of the rivers are shown in Figure 6. The results show that the sudden water environmental risk of the Xiaoyi River—Boye County reaches was high, that of the Cao River—Mancheng District reaches was in the middle, and those of the other reaches were low. For the Xiaoyi River—Boye County reaches, although the control area located outside the ecological red line and the vulnerability of risk receptors were low, the risk field intensity level was relatively higher. There were more water environmental risk substances (sulfuric acid) in the surrounding raw materials and chemical products manufacturing enterprises where the values of Q were much higher than those of other enterprises. For the Cao River—Mancheng District reaches, most of the control area laid within the red line of ecological distribution, and the risk field intensity level was also high. Under the combined effect, the sudden water environmental risk of the rivers presented such a result.

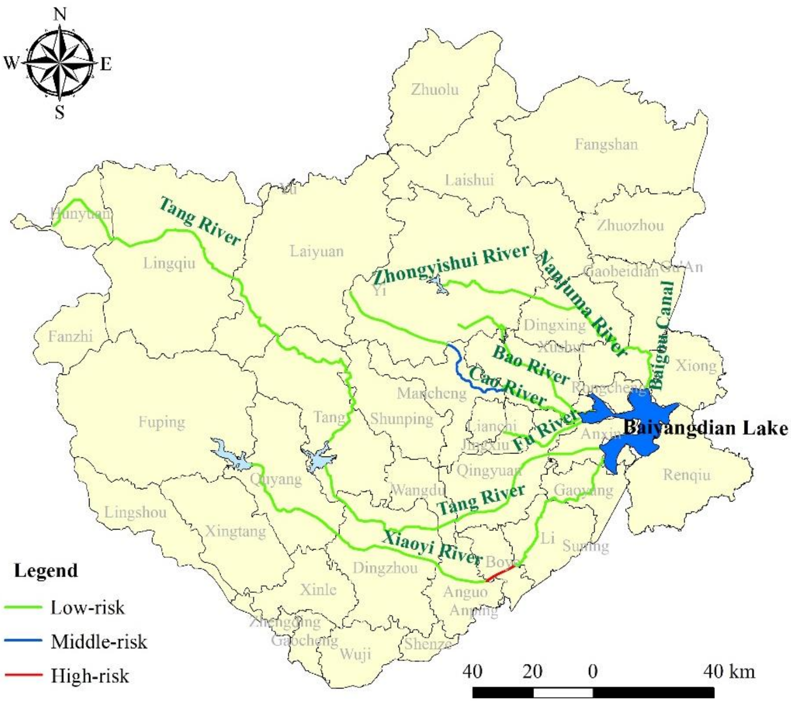

Figure 6. Sudden water environmental risk of the rivers.

3.3. Water Environment Risk Prevention and Control Measures

Based on the analysis of the cumulative water environment risks of the upper rivers of the Baiyangdian Lake, we found that the amount of fertilizer applied per unit of cultivated area, water quality, rate of water quality above the standard in water function zoning, and the ratio of environmental investment to GDP had a great effect on cumulative water environment risks, and that the perennial average annual discharge, urban domestic sewage, and livestock were also important. For the prevention and control of cumulative water environment risk, the following suggestions could be adopted.

Firstly, scientific farming and balanced fertilization could be used in order to reduce the intensity of chemical fertilizer application; at the same time, deep tillage and the deep application of chemical fertilizer, combined with water-saving irrigation technology, should also be promoted to improve the utilization rate of nutrients [43]. Secondly, more attention should be paid to water environment protection in Dingzhou County, Anguo County, Boye County, and Lixian County. The investment in environmental protection should be increased, and the relationship between economic growth and agricultural non-point source pollution should be well-dealt. Thirdly, water environmental protection should be strengthened, and the water quality of rivers should be improved, especially for the Xiaoyi River. To ensure the water quality of the replenishment to the Baiyangdian Lake, the rivers regarded as replenishment paths should also be controlled in regard to their pollution. The investigation and punishment of illegal sewage discharges around rivers should be enhanced, and the vicious circle of cleaning up pollution should be strictly eliminated. Fourthly, optimizing livestock and poultry breeding models as well as implementing the resource utilization of livestock and poultry manure could be carried out to control the pollution of livestock farming.

For the prevention and control of sudden water environment risks, more attention should be paid to the risk sources in Boye County and Mancheng District. To control the sudden pollution in these areas, heavily polluting industries, such as textiles and paper making, should be renovated. Eliminating outdated production capacity, upgrading the industry, and resolutely shutting down heavily polluting enterprises that discharge unqualified wastewater should occur.

4. Discussion

This study can provide a comprehensive suggestion for water environment protection in the Baiyangdian Basin and offer a key reference for local governments.

For the index system of environmental risk, the index selection of the weights of different indexes was very critical.

Compared with the index systems in the literature [23], the objective in this paper was rivers, and Chen's study objective was the basin. The index system in this paper added the indicators of river characteristics as well as physical geography and social development conditions, which directly reflected the current situation of the river environment and the economic effects, respectively. When compared with the index systems of the literature [24], the indicators of policy and reputation have not been considered in this paper, which might be difficult to obtain. While considering the development of the Xiongan New Area, the Baiyangdian Lake will be paid more attention in future. Then, the indicators of policy and reputation could be considered. The index system in this paper may be more realizable, and the data sources are more quantized, which can reasonably reduce the influence of subjective judgment. Additionally, the index system in this paper considered the characteristic of pollution transmissibility and accumulation in rivers by first setting different indicators in the beginning reaches and other reaches. In order to express the effect of the pollutant in upstream reaches on the downstream reaches, the indicators of risk of the upstream reaches and the distance between the upstream reaches and downstream reaches have been used. The transportation of pollutants along rivers could be calculated by simulation and theory calculation [44]. The quantitative characterization of the transportation of pollutants along rivers may be more accurate to the downstream water environment.

In this paper, a questionnaire survey method and analytic hierarchy process (AHP) were used to calculate the weights, which have been used in many pieces of research [45–47]. The APH method is usually combined with other methods for risk assessment in different fields. The questionnaire survey method is usually easier to implement and may be more suitable to reality but is more subjective. Invalid or bad results of a questionnaire survey may cause decision makers to make wrong decisions [48], while there are also some objective methods, such as the entropy weight method, method of the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), statistics models, and neural networks [49–51]. Additionally, there were also some combined subjective methods, such as a combined method of the TOPSIS and the entropy weight method [52]. For further improvement, an objective and reasonable approach should be used.

In addition, for sudden water environmental risk assessments, the pollution sources in this paper were the industry. There have been many other cases producing sudden pollutant, such as hazardous chemicals leaking and dumping accidents during transportation [53]. More pollution sources for sudden water environmental risk should be considered.

Furthermore, both cumulative and sudden environmental risk assessments were conducted, which was an improvement compared to previous research, while the cumulative and sudden environmental risk assessments in this paper did not form a united risk assessment. How to combine the results of cumulative and sudden environmental risk assessments may be a new exploration in the future.

5. Conclusions

Cumulative and sudden environmental risk assessments of the upper rivers of the Baiyangdian Lake were conducted, and water environment risk prevention as well as control suggestions were given, which provided a key reference for water environment protection for local governments in the Baiyangdian Basin. The main conclusions are as follows.

Firstly, an index system that considered the characteristics of pollution transmissibility and accumulation in rivers by setting different indicators in the beginning reaches and other reaches was built. The cumulative environment risk of most of the upper reaches of the Baiyangdian Lake was in the middle. The segments of the Xiaoyi River—Dingzhou County, Xiaoyi River—Anguo County, Xiaoyi River—Boye County, and Xiaoyi River—Li County had a high cumulative environment risk, and the segment of the Tang River—Laiyuan County was the only low-risk area. Secondly, the amount of fertilizer applied per unit of cultivated area, water quality, rate of water quality above the standard in water function zoning, and the ratio of environmental investment to GDP had great effects on cumulative water environment risk. Thirdly, the sudden water environment of the Xiaoyi River—Boye County unit was at high risk, that of the Cao River—Mancheng District unit was at middle risk, and those of other segments were at low risk. Fourthly, for cumulative water environment risk prevention and control, reducing the intensity of chemical fertilizer application, improving the utilization rate of nutrients, and strengthening water environmental protection may be effective measures. In order to prevent sudden water environment risks, eliminating outdated production capacity and upgrading the industry should occur. The objective and reasonable approach should be used to calculate the weight of indicators, quantitative characterization of the transportation of pollutants along rivers may be deepened, and the combined assessment of cumulative and sudden environmental risks may be explored in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14162557/s1, Supplementary Questionnaire.

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