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Water Resource Risk Assessment Based on Non-Point Source Pollution

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Abstract: As one of the most important causes of water quality deterioration, NPS (non-point source) pollution has become an urgent environmental and livelihood issue. To date, there have been only a few studies focusing on NPS pollution conforming to the estimation, and the pollution sources are mainly concentrated in nitrogen and phosphorus nutrients. Unlike studies that only consider the intensity of nitrogen and phosphorus loads, the NPS pollution risk for the China's Fuxian Lake Basin was evaluated in this study by using IECM (Improve Export Coefficient Model) and RUSLE (Revised Universal Soil Loss Equation) models to estimate nitrogen and phosphorus loads and soil loss and by using a multi-factor NPS pollution risk assessment index established on the basis of the data mentioned above. First, the results showed that the load intensity of nitrogen and phosphorus pollution in the Fuxian Lake Basin is low, so agricultural production and life are important sources of pollution. Second, the soil loss degree of erosion in the Fuxian Lake is mild, so topography is one of the most important factors affecting soil erosion. Third, the risk of NPS pollution in the Fuxian Lake Basin is at a medium level and its spatial distribution characteristics are similar to the intensity characteristics of nitrogen and phosphorus loss. Nitrogen, phosphorus, sediment, and mean concentrations are important factors affecting NPS pollution. These factors involve both natural and man-made environments. Therefore, it is necessary to comprehensively consider the factors affecting NPS in order to assess the NPS risk more accurately, as well as to better solve the problem of ecological pollution of water resources and to allow environmental restoration.

Keywords: water environment; ecosystems; pollution risk assessment; load; Fuxian Lake

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1. Introduction

The pollution of aquatic environments has had many negative repercussions. Water pollution not only leads to the deterioration of water quality, threatening human health and damaging ecosystems, but also causes serious economic losses [1]. To solve the increasingly serious problem of water pollution, it is necessary to identify the risks of water environmental pollution and take effective risk control measures [2]. In urban water supply systems, the protection of water resource environments is very important for urban water supply and can directly affect urban public security [3]; therefore, it is necessary to establish an assessment level for pollution risk in important water resource areas. In addition, timely control measures should be taken to curb the deterioration of water resources in areas with high levels of pollution. As a major strategic issue that cannot be ignored [4], the protection of water resources is not only related to urban security, but is also related to the ecological environment, which is also the reason why research on the identification and grade assessment of environmental water pollution risks is carried out. Among the different types of environmental water pollution, non-point source (NPS) pollution is difficult to effectively control and prevent due to its unclear effects and complexity, having become an important type of water pollution [5].

The current research on NPS pollution is mostly focused on the pollution load model, which is used to estimate the load of NPS pollution and to analyze the influencing factors of pollutant output, the best management measures for NPS pollution, the temporal and spatial distribution of pollutants, and the risk of pollution occurrence [6–8]. Load models mainly include mechanical models and empirical models. Mechanical models mainly simulate hydrological processes and are used to analyze the characteristics of rainfall runoff and confluence during nutrient migration to water [9,10]. These models include CREAMS [11], ANSWERS [12], GLEAMS [13], AGNPS [14], WEPP [15], EPIC [16], AnnAGNPS [17], BASINS [8], and SWAT [18] models. Although these models can provide accurate results, the values of model parameters cannot be obtained from field data and must be determined through model calibration. The complexity and low computational efficiency of these models limit their application to a certain extent [19,20].

On the other hand, due to their relatively small amounts of data and numbers of parameters, empirical models such as the output coefficient model (ECM) are considered more reliable methods for simulating NPS pollution [21]. The output coefficient model, first proposed by Omernik in 1976 [22], uses multiple linear regression analysis to establish the relationships between N (Nitrogen) and P (Phosphorus) loads and land use types in order to predict eutrophication in water bodies. On this basis, Norvell developed a relatively simple output coefficient model in 1979 to simulate the effects of nitrogen and phosphorus output on the water quality of rivers and lakes to obtain more accurate research results [23]. Since then, the output coefficient model has been continuously improved to obtain more accurate research results. As research increased, Johannes proposed the classical output coefficient model [24] in 1996. Compared with those of the model proposed by Omernik and Norvell, the simulation results of this model are not only more accurate, but also do not rely on a large number of data points, which are difficult to collect, reducing the costs of monitoring and modeling. This model is an effective simulation model and is currently widely used for pollution load calculations [25–27].

Although the output coefficients of different models reflect the uniqueness of the study area, the ECM uses the same output coefficient in different areas, while terrain heterogeneity is not considered when the model is used on a large scale, which limits the ECM [28,29]. Many scholars have improved the ECM, for example by including a precipitation coefficient and terrain factors in the study. It has been shown based on application results that the improved model can optimize the estimation of non-point source pollution [30]. Compared with the traditional empirical model (ECM), the improved empirical model (IECM) shows improvements regarding output coefficients such as terrain and precipitation, which enables the model to provide more accurate calculation results and extends its applications in terms of simulating nitrogen and phosphorus pollution [31].

As nitrogen and phosphorus nutrients are the main causes of water quality deterioration and water eutrophication [32], early NPS pollution risk assessments mainly used the loss of nitrogen and phosphorus to build an index system in order to study NPS pollution [7,33]; however, it has been suggested that NPS pollution is caused by many factors, including land use, runoff, and distance [34,35]. At present, most studies only assess the NPS pollution risk of a basin by estimating nitrogen and phosphorus loads [36], which is not sufficient for analysis. For the assessment of basin pollution risk caused by NPS pollution, comprehensive impact factors need to be considered [37]. By examining the literature and taking into consideration the process of pollutant production and reduction, in this study we select nitrogen, phosphorus, soil erosion intensity, distance, slope, and rainfall levels as the main factors contributing to NPS in order to evaluate the risk of NPS pollution in watersheds [38–40].

The universal soil loss equation (USLE) is an empirical soil loss prediction equation [41,42] that quantifies average annual soil loss. It is based on experimental observation data combined with statistical analysis and generalization of soil erosion impact factors. This equation is widely used mainly because it can be multiplied using a series of simplified variables to determine soil loss in a given area [43]; however, the usefulness of the USLE is affected by survey data, which cannot be effectively combined with soil loss data, and its applications are limited to a certain extent [44]. Conversely, the modified universal soil loss equation improves the process of expanding field data and combining soil erosion data to allow a wider range of applications [45,46].

The loss amounts and spatial characteristics of non-point source pollutants in the Fuxian Lake Basin are analyzed in this study. The pollution risk and spatial distribution of non-point source pollution in the lake are then explored, and the risk levels for different regions are identified. By constructing the output coefficient model and soil erosion model, the pollution loads of nitrogen and phosphorus, the levels of sediment loss, and the spatial distribution of non-point sources are estimated. Then, the risk level of non-point source pollution is evaluated on this basis and the key areas of pollution are determined by using the multi-index comprehensive evaluation method. Finally, the risk levels for non-point source pollution are classified for different regions to analyze the levels and characteristics of non-point source pollution risk in different regions. Compared with previous studies, our study considering the influencing factors of NPS pollution is more comprehensive, while the regional risk level of the basin is further analyzed. In this way, the prevention and control measures of non-point source pollution in the basin can be better implemented and the ecological environment and water resources of Fuxian Lake can be effectively protected.

2. Data and Methods

2.1. Study Area and Data Availability

Located in the central part of Yunnan Province in China, the Fuxian Lake Basin is one of the key protected lakes in Yuxi City. It spans the Chengjiang, Jiangchuan, and Huaning counties of Yuxi City, with a drainage area of 674.69 km^2 and a lake area of 216.6 km^2. Other land use patterns in the study area are shown in Table 1. In recent years, with the development of the livestock industry and tourism in the Fuxian Lake Basin, NPS pollution has become increasingly serious [47], posing a critical threat to the ecological balance of local water bodies. The study area is shown in Figure 1.

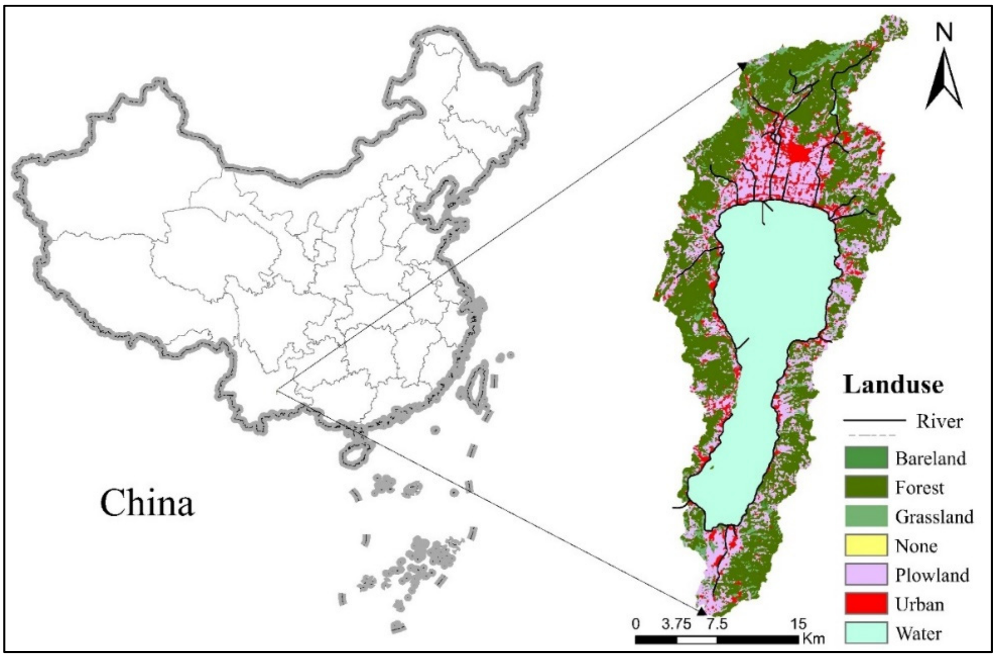

Figure 1. Study area.

Table 1. The proportion of land use types in the study area (km^2/%).

Land Use	Area/Percentage
Urban	44.25/6.56
Water	216.6/32.10
Plowland	141.44/20.96
Grassland	25/3.71
Forest	254.61/37.74
Bare land	0.4/0.06

The data used in this study mainly included the following: (1) a 30 m × 30 m digital elevation model (DEM) provided by the China Geospatial Data Cloud Platform (http://www.gscloud.cn/, accessed on 20 May 2021); (2) Landsat8 Oli-TIRS 2016 satellite remote sensing images provided by the China Geospatial Data Cloud Platform and classified land use type data for 2016 (since the biggest changes in the land use type of the Fuxian Lake Basin in 2008 and 2016 were the conversion of farmland to construction land, representing only 2.2% of the land, and since the other changes were not significant, this study assumed that the land use for the study area had not changed); (3) soil data (soil type and distribution and soil property data) provided by the Scientific Data Center of Cold and Arid Regions; (4) driving data on China's atmospheric assimilation from the Scientific Data Center of Cold and Arid Regions in China (2008–2016 rainfall data from 8 weather stations in the Fuxian Lake Basin and its surrounding areas).

The basic data used in the study included information on the terrain (slope), soil type, precipitation conditions, and intensity of heavy rainfall. The distribution of different influencing factors in the Fuxian Lake Basin is shown in Figure 2.

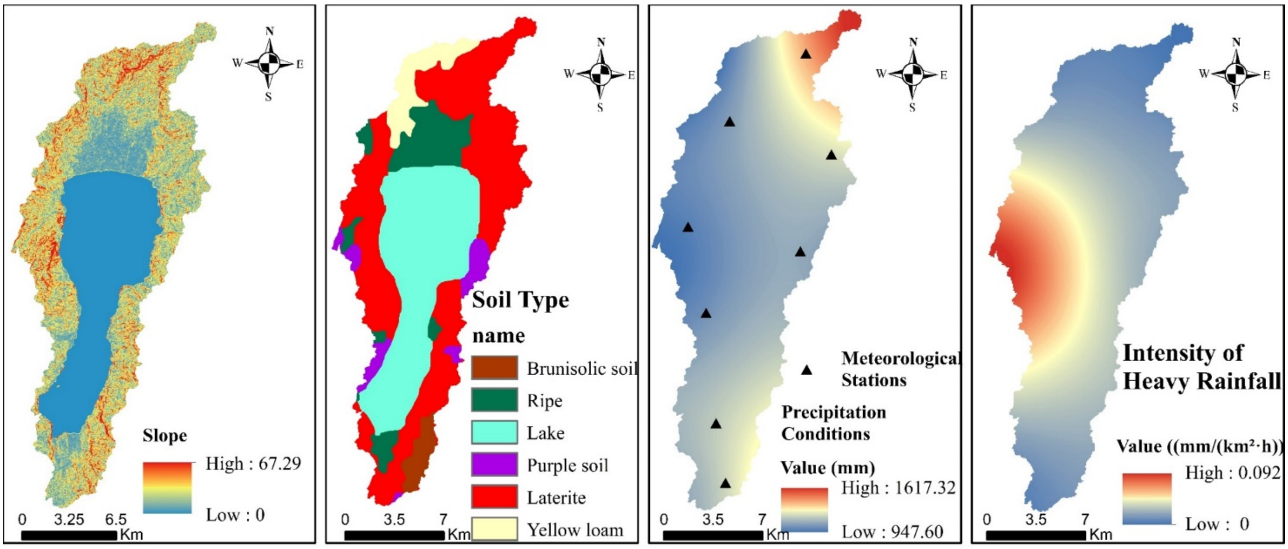

Figure 2. Influencing factors in the Fuxian Lake Basin.

2.2. Improved Export Coefficient Model (IECM)

Precipitation and topography are the main factors affecting NPS pollution; rainfall is the main driving force of NPS pollution, while topography plays a very important role in the transport of NPS pollutants. As such, this study introduced an improved output coefficient model that uses rainfall and terrain impact factors to calculate the pollution load in the study area [48]. The IECM model is expressed as:

$$L = \alpha \cdot \beta \sum_{i=1}^{n} E_i \cdot A_i + P \quad (1)$$

where L stands for the loss value of nutrients in kg; α stands for the precipitation influence factor (precipitation); β stands for the terrain influence factor; E_i represents the output coefficient for the type I nutrient source (kg·km^{-2}·a^{-1}); A_i represents the area of land (km^2) used for category I land use or the number of livestock animals (population) used for category I land use; P stands for the nutrient input value (kg) from rainfall.

Heterogeneity in time and space should be taken into account when considering the influence of factors such as rainfall. The influence of the spatial distribution of rainfall on NPS pollution can be mainly assessed based on the differences in NPS pollution caused by different rainfall levels in different regions within a certain year. The NPS pollution levels are different in different regions due to differences in precipitation. The relationship between pollutants entering the water and rainfall can be expressed by establishing a functional relationship between the annual average rainfall r and the amount of pollutants entering the lake L, as shown in Equation (2):

$$\alpha = \alpha_t \cdot \alpha_s = \frac{L}{L_{ave}} \cdot \frac{r_j}{r_{ave}} = \frac{f(r)}{f(r_{ave})} \cdot \frac{r_j}{r} \tag{2}$$

where α stands for the influencing factor rainfall; L stands for the pollutant load (kg·a^{-1}); r stands for the average annual rainfall in the study area (mm); rave represents the multi-year average rainfall (mm) in the study area; r_j is the annual rainfall (mm) of grid unit J in the study area.

The amount and rate of runoff flow on the slope affect the transport of pollutants. A topographic impact factor is used to reflect the degrees of influence of topographic and geomorphic features on NPS pollution:

$$\beta = \frac{\theta^d}{\theta^d_{ave}} \tag{3}$$

where β stands for the terrain influence factor; d is a constant; θ stands for the slope of spatial cell grids in the basin; θ_{ave} is the average slope of the river basin.

According to relevant studies, the nutrient input value P of rainfall is related to the sedimentation rate of nutrients per unit area of the study area:

$$P = c \cdot a \cdot \lambda \tag{4}$$

$$\lambda = R/p \times 100\% \tag{5}$$

where c stands for the sedimentation rate of a certain pollutant (t·km^{-2}·a^{-1}); a stands for the drainage area (km^2); λ represents the runoff coefficient; R represents the multi-year average runoff depth (mm) in the basin; P is the multi-year average rainfall (mm) in the basin.

2.3. Revised Universal Soil Loss Equation (RUSLE)

The RUSLE is an empirical equation that can comprehensively consider all factors that affect soil erosion [49]; therefore, it is widely used in the estimation of average annual soil erosion in the study area. The equation can be expressed as follows:

$$A = R \times K \times L \times S \times C \times P \tag{6}$$

where A stands for the annual average soil loss, namely the soil erosion modulus (t·hm^{-2}·a^{-1}); R stands for the rainfall erosion factor (MJ·mm·(hm^2·h·a)$^{-1}$); K represents the soil erodibility factor (t·hm^2·h·(hm^2·MJ·mm)$^{-1}$); L stands for the slope length factor; S is the slope factor; C represents the vegetation cover factor; P stands for the soil and water conservation measurement factor.

The rainfall erosivity factor (R) refers to the product of the total kinetic energy of rainstorm events and the maximum rainfall intensity within 30 min. The Wischmeier empirical formula is used to calculate the R factor. This calculation method has the advantages of simplicity, accuracy, and reliability, so it has been widely used globally. The expression is as follows:

$$R = \sum_{i=1}^{12} 1.735 \times 10^{[1.5lg[P_i^2/P]-0.8188]} \quad (7)$$

where P_i is the monthly average rainfall (mm) and P is the average annual rainfall (mm).

The soil erodibility factor (K) is an important indicator of soil resistance upon rainfall and runoff denudation, as well as water erosion and transport. The greater the value, the more vulnerable the soil is to erosion, and vice versa. The factor can be estimated as follows:

$$K = \left\{0.2 + 0.3e^{[-0.0256S_a(1-\frac{S_i}{100})]}\right\}\left(\frac{S_i}{S_i+C_l}\right)^{0.3}\left[1 - \frac{0.25C}{C+e^{(3.72-2.95C)}}\right] \left[1 - \frac{0.7S_n}{S_n+e^{(-5.51+22.9S_n)}}\right] \quad (8)$$

where K stands for the soil erodibility factor; S_a represents the sand content in %; S_i stands for the silty sand content in %; C_l is the clay content in %; C represents the organic carbon content in %; $S_n = 1 - S_a/100$. Here, L, S, C and P are all dimensionless.

The soil data provided by the Cold and Arid Regions Scientific Data Center in this study included the distribution of soil types and soil attributes in the study area. According to the soil classification standard, there are five soil types in the study area, namely brunisolic, ripe, purple, laterite, and yellow loam soils, with different sand, silty sand, clay, and organic carbon contents, as shown in Table 2.

Table 2. Compositions and organic contents of different soil types.

Agrotype	Sand Content (%)	Silty Sand Content (%)	Clay Content (%)	Organic Carbon Content (%)
Brunisolic soil	41	37	22	1.16
Purple soil	42	38	30	1.45
Ripe	29	50	21	1.12
Laterite	49	28	23	0.98
Yellow loam	40	37	23	1.16

2.4. Multiple-Indicator Comprehensive Evaluation Method

At present, research on NPS pollution is mostly concentrated on the estimation of the pollution load or the effects of rainfall and land use changes on pollution; however, if high-load pollution areas in the basin can be identified, the key control areas can be determined, which will better allow the formulation of a reasonable and effective pollution prevention and control plan and increase the efficiency of pollution control work. To determine the spatial distribution characteristics of NPS pollution in the basin and better identify regions with higher risk, in this study we adopted a multiple-indicator comprehensive evaluation method to carry out an NPS pollution risk assessment for pollution sources to provide a decision-making reference for NPS pollution prevention and control [50]. The formula is as follows:

$$NPA = \sum_{i=1}^{n}(P_i \times W_i) \quad (9)$$

where NPA stands for the risk assessment value for NPS pollution; P_i is the ith evaluation factor after standardization; W_i is the weight of the ith evaluation factor.

3. Model Application

3.1. Precipitation Impact Factor α

The regression equation for the NPS pollution load and the average annual rainfall in the Fuxian Lake Basin was established as follows based on rainfall data and NPS pollution inflow data from 2008 to 2016:

$$L_{DN} = 0.0057r^2 - 8.8054r + 4240.7\left(R^2 = 0.7909\right) \quad (10)$$

$$L_{DP} = 0.0006r^2 - 0.8897r + 424.67\left(R^2 = 0.7488\right) \quad (11)$$

According to the rainfall data, the average annual rainfall in the Fuxian Lake Basin is 904.7 mm. Combined with the above regression equation, the influencing factors of rainfall on nitrogen and phosphorus pollutants in the Fuxian Lake Basin were calculated as follows:

$$\alpha_{DN} = \frac{0.0057r^2 - 8.8054r + 4240.7}{925.6} \cdot \frac{r_j}{r} \quad (12)$$

$$\alpha_{DP} = \frac{0.0006Rr^2 - 0.8897r + 424.67}{108.9} \cdot \frac{r_j}{r} \quad (13)$$

The precipitation factor is shown in Figure 3 and the spatial calculation is carried out according to Equations (12) and (13). The obtained precipitation impact factors α_{DN} and α_{DP} are shown in Figure 3. As can be seen from Figure 3, the range of α_{DN} is from 0.00 to 2.33, while the range of α_{DP} is from 0.00 to 1.54.

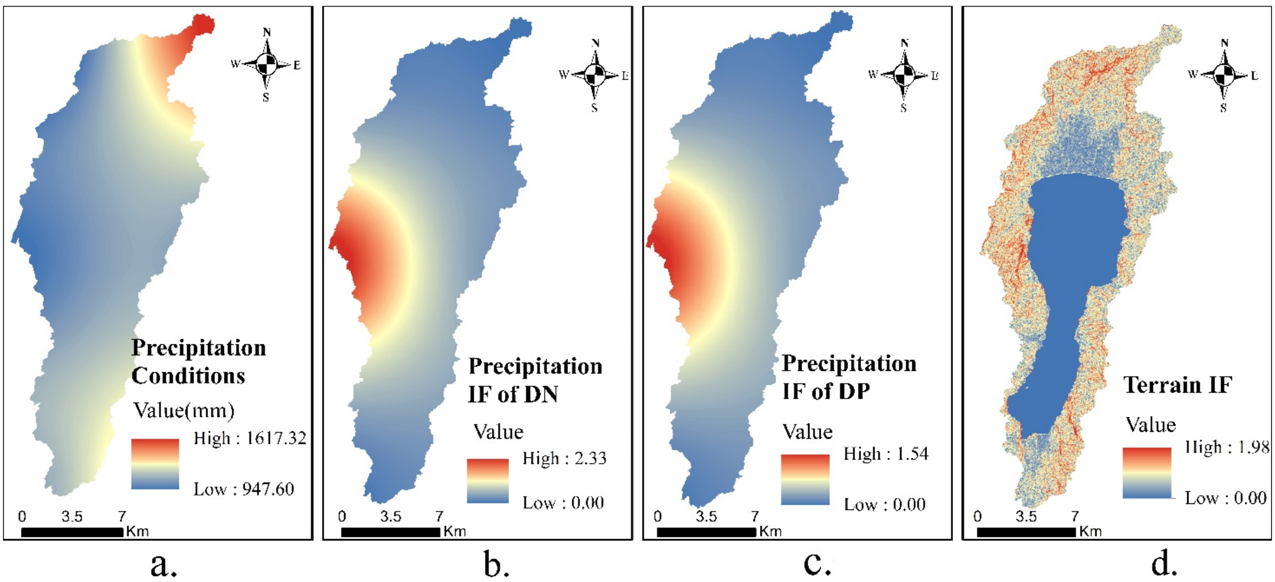

Figure 3. Influencing factors of different coefficients ((**a**): Precipitation Conditions; (**b**): Precipatation IF of DN; (**c**): Precipitation IF of DP; (**d**): Terrain IF).

3.2. Terrain Impact Factor β

According to Equation (3), which has been presented in the literature [27,51,52], the value of d is 0.6014 and the average slope obtained from Equation (3) is 16.37°. The calculated terrain impact factor values from this study are shown in Figure 3d, ranging from 0 to 1.98.

3.3. Export Coefficient

The export coefficient was determined based on the IECM. At present, there are two main methods used to determine the export coefficient values of different pollution sources—one is determination through long-term on-site monitoring, while the other is through literature reviews. Due to the disadvantages of field monitoring, including the long time requirements and high costs, in this study we adopted the literature review method, which has good accuracy and speed. This method is used to determine the export coefficient value by referring to the research results of similar areas based on the actual situation of the study area [53,54].

There are four sources of NPS pollution in the study area: rural life, livestock breeding, land use, and atmospheric precipitation. Land use is divided into cultivated land, forest land, grassland, construction land, and bare land. As shown above, according to the literature, the export coefficients for rural life and livestock breeding were determined. The export coefficients for rural life for N and P were 1.751 kg/year and 0.095 kg/year, respectively. The excretion coefficients for livestock and poultry breeding in the study area were determined according to the excretion coefficient of livestock and poultry breeding provided by the National Environmental Protection Agency of China [55]. The output coefficient for each animal is shown in Table 3.

Table 3. Excretion coefficient of livestock and poultry breeding.

Type of Livestock	Total Nitrogen Content (kg·a^{-1})	Total Phosphorus Content (kg·a^{-1})	Output Scale (%)
Pig	4.51	1.7	16.43
Big livestock	61.1	10.07	16.71
Sheep	2.28	0.45	17.68
Poultry	0.275	0.115	14.89

Based on the current research on NPS pollution in the Southwest China Basin, the land use output coefficient of this study was selected for the Baoxiang Basin, Chenghai Basin, and Yunlong Reservoir, which are similar in nature, geography, and climate to the Fuxian Lake Basin. After taking the average value of these output coefficients, a table showing the land use output coefficients for this study was obtained. Regarding the output coefficient for land use, based on the study of Southwest China, the average value for the research results of Yunnan Basin, Chenghai Basin, and Yunlong Reservoir, which are similar to the natural, geographical, and climatic conditions of Fuxian Lake Basin, was selected [18,56] (Table 4).

Table 4. Land use export coefficient values from different study areas (t·km^{-2}·a^{-1}).

Study Area	Pollutant	Export Coefficient Values			
		Forest Land	Grassland	Construction Land	Bare Land
Yunnan Basin	Nitrogen	0.25	0.6	1.3	1.34
	Phosphorus	0.015	0.165	0.05	0.051
Yunlong Reservoir	Nitrogen	0.28	0.64	/	/
	Phosphorus	0.015	0.036	/	/
Chenghai Basin	Nitrogen	0.41	0.72	1.18	1.36
	Phosphorus	0.03	0.09	0.08	0.21
Fuxian Lake Basin	Nitrogen	0.313	0.653	1.24	1.35
	Phosphorus	0.02	0.097	0.065	0.131

Pollution from rural life mainly includes domestic sewage, garbage, and excrement discharged randomly by residents. According to the investigation results for environmental water protection and water pollution prevention and control planning in the Fuxian Lake Basin, per capita nitrogen and phosphorus emissions in the Fuxian Lake Basin are 0.99 kg·(person·a)$^{-1}$ 0.2 kg·(person·a)$^{-1}$, respectively, while the loss rate is 50%; therefore, the nitrogen and phosphorus output coefficients for domestic sewage are 0.495 kg·(person·a)$^{-1}$ and 0.10 kg·(person·a)$^{-1}$, respectively. The daily garbage output for residents in the Fuxian Lake Basin is 0.5kg person^{-1}, while the nitrogen and phosphorus production levels in garbage account for 0.5% and 0.2% of garbage production, respectively, with a loss rate of 40%; therefore, the nitrogen and phosphorus output coefficients from household garbage for the population in the basin are 0.037 kg·(person·a)$^{-1}$ and 0.015 kg·(person·a)$^{-1}$, respectively. According to the relationship between dietary structure and human excretion in China, the contents of nitrogen and phosphorus in excreta per capita in China are 21.29 g·(person·b)$^{-1}$ and 1.19 g·(person·b)$^{-1}$, respectively. The loss rate of human excrement is 21.9%; therefore, the output coefficients of nitrogen and phosphorus in the study area are 1.751 kg·(person·a)$^{-1}$ and 0.095 kg·(person·a)$^{-1}$, respectively. In conclusion, the nitrogen and phosphorus output coefficients of populations in the basin are 2.483 kg·(person·a)$^{-1}$ and 0.210 kg·(person·a)$^{-1}$, respectively.

According to the existing literature, the output coefficient of the atmospheric deposition rates of nitrogen and phosphorus in the basin are 0.248 t·km^{-2}·a^{-1} and 0.080 t·km^{-2}·a^{-1}, respectively [57,58]. The annual runoff of the Fuxian Lake Basin is 162.18 million m^3, the area is 674.69 km^2, and the average rainfall in 2016 was 893.2mm. According to Equation (5), the runoff coefficient of the basin is 0.268. The nitrogen and phosphorus values from the unit area of atmospheric deposition were determined to be 0.066 t·km^{-2}·a^{-1} and 0.021 t·km^{-2}·a^{-1}, respectively.

To summarize, the export coefficients of various land types in the Fuxian Lake Basin are shown in Table 5.

Table 5. Land use export coefficient values from different studies (t·km^{-2}·a^{-1}).

Source of Pollution	Unit	Category	Nitrogen	Phosphorus
Rural life	kg·a^{-1}	—	2.483	0.21
Livestock and poultry breeding	kg·a^{-1}	Pig	0.741	0.279
		Cow	10.21	1.683
		Sheep	0.403	0.08
		Poultry	0.041	0.017
land use type	t·km^{-2}·a^{-1}	Cultivated land	3.578	0.104
		Forest land	0.313	0.02
		Grassland	0.653	0.097
		Construction land	1.24	0.065
		Bare land	1.35	0.131
Atmospheric deposition	t·km^{-2}·a^{-1}	—	0.066	0.021

3.4. Establishment of an Evaluation System

3.4.1. Selection of Evaluation Factors

Since non-point source pollution in the basin is affected by topography, climate, soil, and other factors, the risks of non-point source pollution are related not only to the output of pollutants, but also to the amount of pollutants transported to the receiving water body. The output loads of nitrogen and phosphorus and the sediment loss of non-point sources reflect the output potential of pollutants. Furthermore, the transport distance, which is the distance between the land unit that produces the pollutants and the river, is an important factor that affects the entry of the pollutants into the receiving water body. Topography is also one of the main factors affecting pollutant migration. Generally, the steeper the gradient is, the faster the migration rate will be and the higher the pollution risk will be. Rainfall is another key factor affecting soil erosion on the surface, which also plays an important role in the migration and diffusion of non-point source pollution. The annual rainfall difference in the study area has a significant impact on river flow within the basin. Regions with a high risk of non-point source pollution have higher pollutant output values and mobility; therefore, in terms of index selection, the process of pollutant generation and reduction was comprehensively considered, and the output loads of nitrogen, phosphorus, and sediment per unit area; the distance factor; the slope factor; and the annual rainfall factor were selected to evaluate the risk of non-point source pollution in the Fuxian Lake Basin.

3.4.2. Determination of Evaluation Factors

Nitrogen factor: The nitrogen factor in the basin represents the intensity of nitrogen loss per unit area, which was estimated by using an output coefficient model for non-point source nitrogen pollution.

Phosphorus factor: The phosphorus factor in the basin represents the intensity of phosphorus loss per unit area, which was estimated by using an output coefficient model for non-point source phosphorus pollution.

Sediment factor: The sediment factor in the basin is the amount of sediment loss per unit area, which was estimated using a soil erosion model for non-point source sediment loss and was obtained using standardized treatment.

Distance factor: The distance factor was determined by calculating the distance between each grid unit and the river.

Slope factor: The slope factor was determined based on the use of the DEM and standardized treatment.

Annual rainfall factor: The annual rainfall factor layer of the Fuxian Lake Basin was calculated by using annual rainfall data for the Fuxian Lake Basin and eight hydrological stations surrounding it.

3.4.3. The Weight of the Evaluation Factors

Different evaluation factors have different degrees of influence on NPS pollution. To determine the degree of influence of each evaluation factor and obtain more accurate risk assessment results, it is necessary to determine the weight of each evaluation factor. In this study, the analytic hierarchy process (AHP) was used to determine the weight of each factor. The AHP is a simple and effective decision-making method used to decompose complex practical problems. According to the steps of the analytic hierarchy process, a judgement matrix was constructed (Table 6) and the relative importance of each factor was judged according to the quantitative scaling method. The random consistency ratio (CR) was 0.0242 < 0.1, which meets the random consistency test standard. Finally, the weight value of each factor in the final non-point source pollution risk assessment index system was determined [58] (Table 7).

Table 6. Judgement matrix of evaluation indices.

B–C	C1	C2	C3	C4	C5	C6
C1	1	1	2	4	5	4
C2	1	1	2	4	5	4
C3	1/2	1/2	1	3	4	3
C4	1/4	1/4	1/3	1	2	1/2
C5	1/5	1/5	1/4	1/2	1	1/3
C6	1/4	1/4	1/3	2	3	1

Table 7. Weight factors of the NPS pollution risk assessment index system.

Target Layer A	Rule Hierarchy B	Evaluation Index C	Weight Value
NPS pollution risk	derived factor B1	Nitrogen factor C1	0.301
		Phosphorus factor C2	0.301
	Migration factor B2	Sediment factor C3	0.188
		Distance factor C4	0.069
		Annual rainfall factor C5	0.046
		Slope factor C6	0.095

4. Results

4.1. Analysis of Nitrogen and Phosphorus Pollution Load Values of NPS Pollution

The improved output coefficient model was used in this study to calculate the loads of nitrogen and phosphorus from NPS pollutants generated by different pollutant types into the lake. The obtained nitrogen and phosphorus load values are shown in the following table (Table 8).

Table 8. Estimated pollution loads of NPS pollution into the Fuxian Lake Basin.

Source of Pollution		Nitrogen/t	Partial Summation/t	Percentage/%	Phosphorus/t	Partial Summation/t	Percentage/%
Rural life	—	238.883	238.883	22.57	21.43	21.43	21.25
Livestock and poultry breeding	Pig	59.569	187.932	17.76	22.222	51.52	51.08
	Big livestock	81.461			12.913		
	Sheep	12.739			2.454		
	Poultry	34.163			13.931		
Land utilization	Cultivated land	474.425	617.025	58.28	13.533	23.214	23.03
	Forest land	73.734			4.571		
	Grassland	16.238			2.373		
	Construction land	51.402			2.62		
	Bare land	1.226			0.117		
Atmospheric deposition	—	14.696	14.696	1.39	4.681	4.681	4.64
Sum	—	1058.536	1058.536	100	100.845	100.845	100

The pollution load of NPS nitrogen (1058.536 t) is much higher than that of phosphorus (100.845 t). The main source of nitrogen is land use. Due to the urbanization of the Fuxian Lake Basin, a large number of rural population areas are changing to urban population areas every year; however, due to the slow speed of economic development in Western China, rural populations still account for the majority of the population. Agricultural activities conducted by a large portion of the rural population related to land use and rural life cause a large amount of nitrogen loss. The total load is 617.025 t, accounting for 58.28% of the total and reaching up to 80.85% of the overall load. This is followed by livestock and poultry breeding (17.76%) and atmospheric deposition (1.39%). The main source of phosphorus is livestock and poultry breeding, with a total load of 51.52 t, accounting for 51.08% of the overall load. The phosphorus pollution loads from land use, rural population, and atmospheric sedimentation account for 23.03%, 21.25%, and 4.64% of the overall phosphorus pollution load from all sources in the Fuxian Lake Basin, respectively.

The main pollution source contribution rate of phosphorus is different from that of nitrogen, and the biggest pollution source of phosphorus load is the use of chemical fertilizers and other fertilizers in livestock and poultry breeding. The contribution rate of livestock and poultry breeding to the phosphorus load (51.08%) is much greater than its contribution rate to the nitrogen load (17.76%). This phenomenon is mainly because 87,000 pigs were produced in the basin by the end of 2016, accounting for 5% of the total number of pigs in Yuxi City. Due to the high output of phosphorus content in the excrement of each pig (0.279 kg), animal husbandry is a key factor related to NPS phosphorus pollution in the Fuxian Lake Basin. Second, land use and rural life are also important sources of phosphorus pollution load; however, the contribution rates of rural life to the phosphorus load (22.57%) and nitrogen load (21.25%) are not significantly different.

It can be seen from the spatial distribution of the nitrogen and phosphorus load intensity levels in the basin in Figure 4 that the spatial variation trend for NPS nitrogen load intensity is high on the east and west sides and low on the north and south sides. The western, eastern, and southeastern regions of the basin are high-intensity areas for NPS pollution loss and the NPS nitrogen load intensity in these areas is relatively high. The northern and southern sides of the lake belong to the plain area of the basin. Although a certain amount of agricultural land is present in this area, there is more nitrogen in the soil and the potential nitrogen loss rate is larger in this area than in other areas; however, the nitrogen load intensity is slightly lower than on the eastern and western sides of the basin because of the simultaneous influences of topography and rainfall.

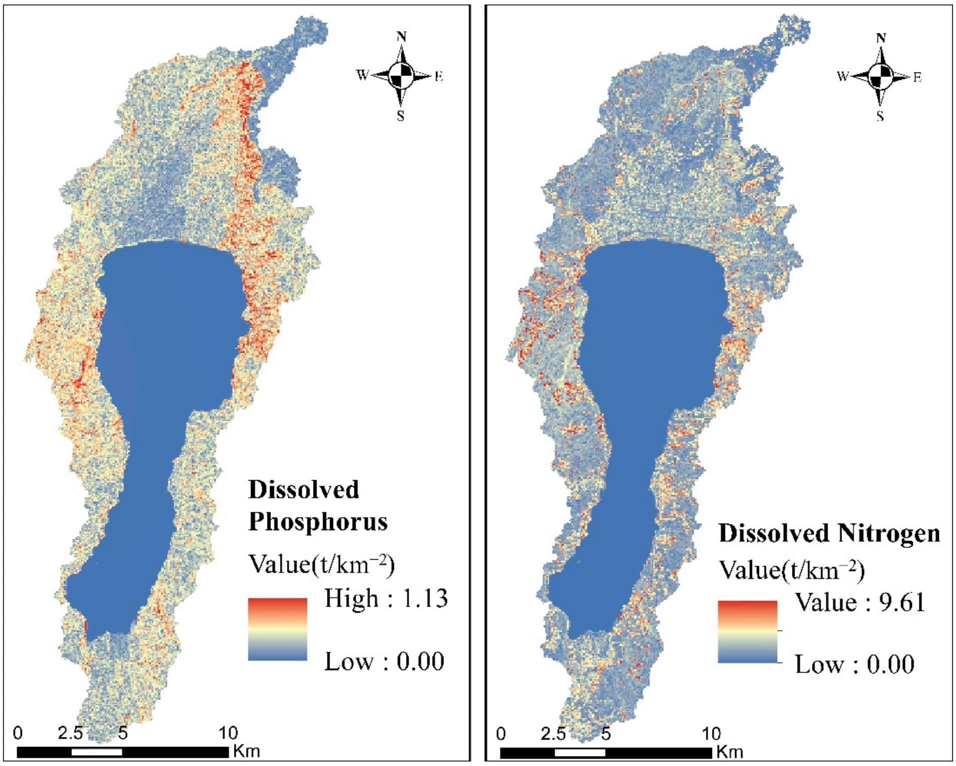

Figure 4. Spatial distribution of nitrogen and phosphorus load intensity levels in the basin.

The phosphorus load intensity of the NPS pollution is highest in the northeast of the basin and the largest source of phosphorus pollution is livestock breeding. In addition, the phosphorus pollution loads caused by land use and rural life are relatively high. The western part of the Fuxian Lake Basin also has a high phosphorus load intensity, which is not only related to the contribution of the main pollution sources to the NPS phosphorus load, but is also affected by topography. The slope range of this area is mostly above 30°, while the rainfall in this area is greater than the average rainfall in the basin; thus, this area is also affected by the influencing factors of rainfall.

4.2. Analysis of the Estimated Results of NPS Sediment Loss

The soil erosion map for the Fuxian Lake Basin in 2016 calculated according to the RUSLE is shown in Figure 5. The soil erosion modulus of the Fuxian Lake Basin for the year 2016 ranged from 0 to 43,838.2 $t \cdot km^{-2} \cdot a^{-1}$, while the average erosion modulus was 1158 $t \cdot km^{-2} \cdot a^{-1}$. The estimated soil erosion results obtained in this study are basically consistent with the monitoring results for soil erosion in the Fuxian Lake Basin [59,60], which indicates that the estimated results in this study are of high credibility.

According to the Standard for Classification and Gradation of Soil Erosion (SL190–2007) issued by the Ministry of Water Resources of China in 2007, the soil erosion intensity in the Fuxian Lake Basin is divided into five categories. The soil erosion classification table and intensity characteristics statistics are shown in Table 8.

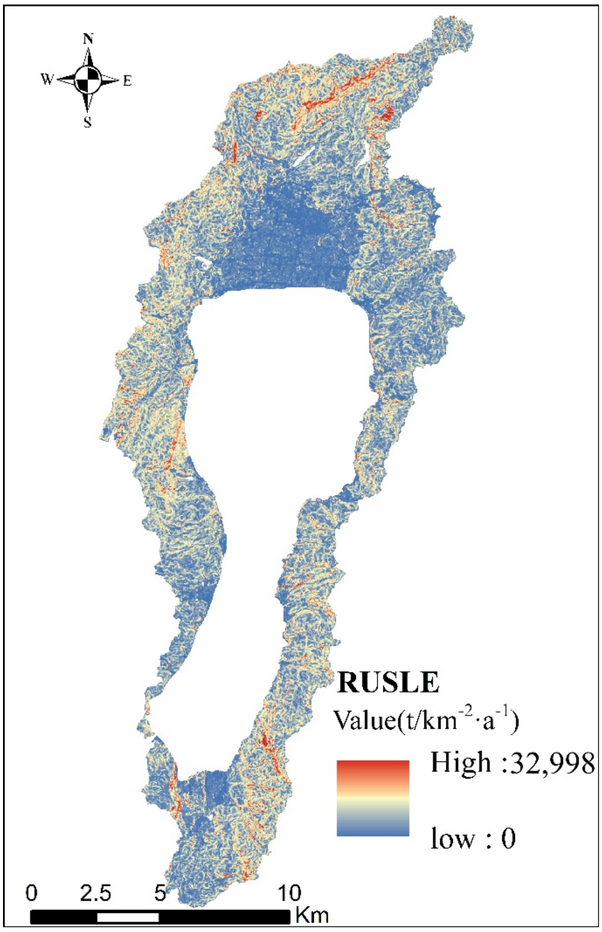

Figure 5. Soil erosion map for the Fuxian Lake Basin.

As shown in Figure 5, the average erosion of the basin in 2016 was 1158 t·km^{-2}·a^{-1}. Combining these data with the classification standard for soil erosion (Table 9), we concluded that Fuxian Lake Basin shows mild erosion intensity. The spatial differences in soil erosion intensity in Fuxian Lake Basin are more obvious than in other areas, with slight and micro erosion being the most widely distributed classes. Among these, micro erosion in the basin mainly occurs on the north bank, south bank, and lake coast. The terrain in these areas is relatively flat, and most of the areas comprise cultivated land, residential areas, or areas of concentrated construction land. The area of light erosion is relatively large and is generally concentrated in planar form in the northern region.

Table 9. Statistical table of soil erosion intensity characteristics in the Fuxian Lake Basin.

Intensity	Range of Soil Erosion	Total Erosion 104 t·a^{-1}	Erosion Percentage %	Erosion Area km^2	Percentage of Area %
Micro	<500	1.891	2.36	104.179	15.37
Mild	500–2500	34.846	43.39	252.455	37.24
Moderate	2500–5000	25.951	32.31	80.249	11.84
Normal intensity	5000–8000	10.805	13.45	17.97	2.65
Extreme intensity	>8000	6.822	8.49	6.527	0.96

The distribution of the moderate erosion is relatively scattered. Overall, the spatial distribution characteristics are similar to the characteristics for normal-intensity and extreme-intensity erosion areas, while the distribution is banded, which is greatly affected by the topographic characteristics. The areas of normal-intensity and extreme-intensity erosion in the Fuxian Lake Basin are relatively small, but they account for 21.94% of the total erosion, which is mainly due to the large soil erosion modulus. These areas are mainly distributed in grassland and bare land areas with steep slopes.

According to the soil erosion intensity characteristics of the Fuxian Lake Basin and the analysis shown in Figure 5, we can see that the majority of soil erosion, i.e., 75.70% of the total erosion, is caused by mild and moderate erosion. From the perspective of the erosion area, the soil erosion in the Fuxian Lake Basin mainly involves micro and light erosion, with the erosion area accounting for 52.61% of the total area of the basin. The moderate erosion area covers 80.249 km^2, accounting for 11.84% of the total area of the basin, while the total area of extreme erosion is 24.497 km^2, accounting for 2.71% of the total area of the basin.

According to the analysis of the sediment loss volume corresponding to different sediment loss intensity levels (as shown in Figure 5 and Table 9), the main sediment loss intensity in the Fuxian Lake Basin is slight loss, while the corresponding sediment loss volume accounts for 43.39% of the total loss volume. The second most prevalent loss intensity is moderate loss (Figure 6), accounting for 32.31% of the total loss. Sediment losses caused by moderate-intensity and extreme-intensity zones account for 13.45% and 8.49% of the total sediment loss, respectively. The micro loss area is the smallest, accounting for only 2.36% of the total sediment loss.

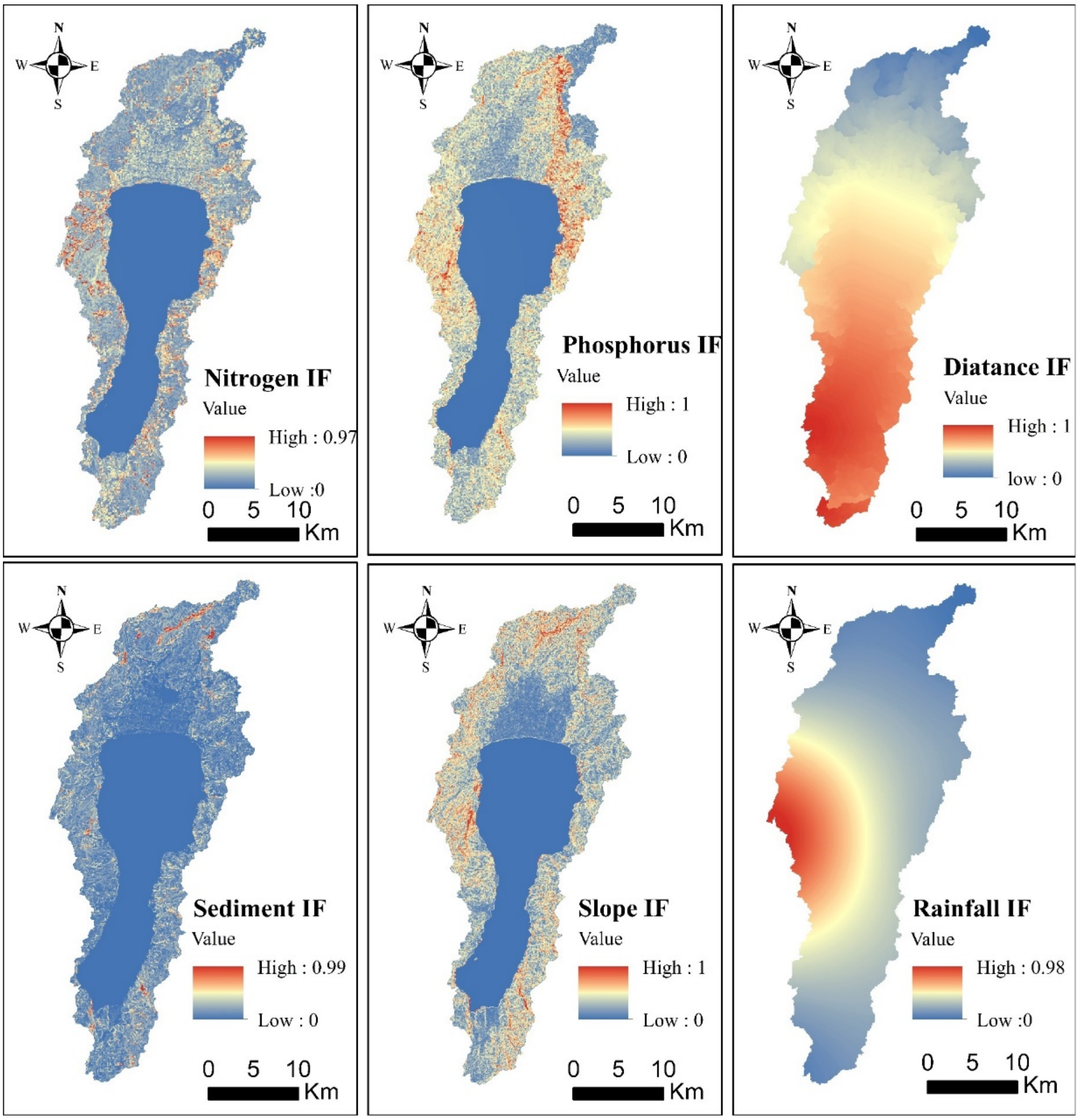

Figure 6. Distribution of influencing factors of NPS pollution in the Fuxian Lake Basin.

4.3. A Risk Assessment of NPS Pollution

The final NPS pollution risk distribution map was obtained by superimposing the six factors, i.e., nitrogen, phosphorus, sediment, distance, slope, and rainfall, as shown in Figure 7. The distribution of the NPS risk level in Fuxian Lake as calculated using six factors is shown in Figure 6. It can be seen from Figure 6 that the higher the risk value of the non-point source pollution, the higher the risk of non-point source pollution is. According to the spatial distribution map of non-point source pollution risk in the Fuxian Lake Basin, it can be seen that the risk values range from 0 to 1.03, while the average risk value is 0.5015.

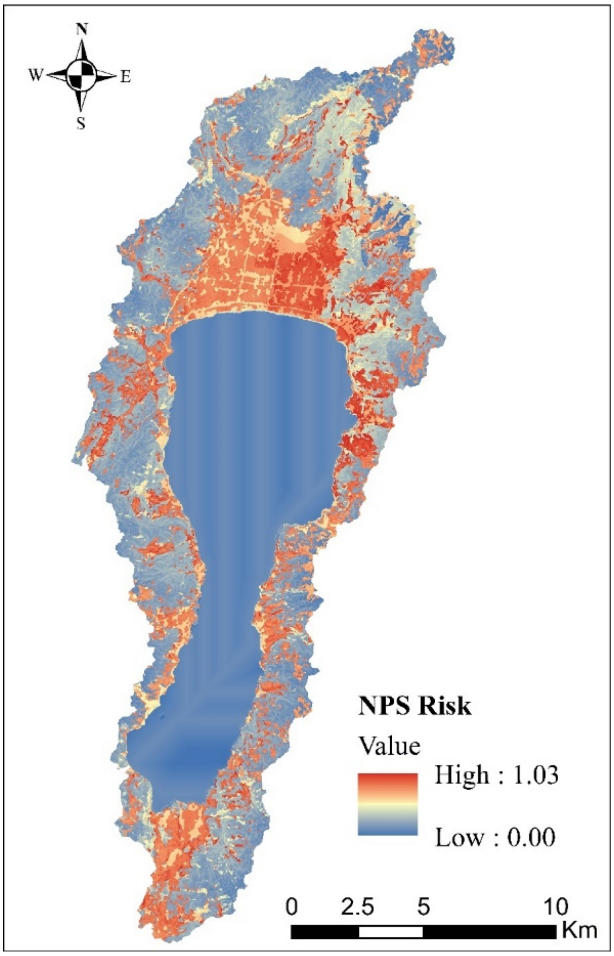

Figure 7. Spatial distribution of NPS pollution risks in the Fuxian Lake Basin.

In terms of the overall spatial distribution of NPS pollution, the risk is highest in the northern plain area, followed by the southern area. The higher risk areas are distributed in narrow strips, which are mainly related to the topography of those parts of the basin. The spatial differences in NPS pollution risk in the Fuxian Lake Basin are determined by various influencing factors.

In terms of pollution source factors, the spatial distributions of nitrogen and phosphorus factors are consistent with the characteristics of comprehensive risk distribution. The overall sediment factor value is small. Areas with larger values are mainly distributed in parts of the north and south, and their distribution is scattered. The spatial distribution of the distance factor shows a trend of higher values in the northern region of the basin than in the southern region. This is mainly because the water network in the region has a higher distance factor value and is more concentrated, while the distance from the lake is shorter, so the migration distance is smaller and the distance factor is larger. The influence characteristics of annual rainfall factors are relatively unclear. The spatial distribution presented by the slope factor is higher in the northern part of the basin than in the southern part and also higher in the western part than in the eastern part. Although the terrain in the northern region is relatively flat, its risk value is relatively high due to the higher loss intensity of nitrogen and phosphorus factors, the denser river network, and the shorter migration distance.

The risk of NPS pollution is affected not only by nitrogen and phosphorus but also by the sediment, migration distance, slope, and rainfall. Basins with high-risk characteristics for NPS pollution are close to rivers and lakes and the migration distances of their pollutants are relatively short. During the rainstorm season, the degree of pollutant loss in runoff is reduced and the ratio of pollutants entering rivers and lakes increases, thereby increasing the risk of water pollution. In the northernmost low-risk watershed area, the migration distance is relatively long, which reduces the risk of pollutants entering rivers and lakes to a certain extent. Unlike nitrogen and phosphorus pollution sources, the sediment factor, slope factor, and rainfall factor have no obvious influence on the risk of NPS pollution.

5. Discussion

As the main form of water pollution, NPS pollution is more difficult to monitor and quantify than point source pollution, and is also more difficult to research, prevent, and control. In this study, IECM and RUSLE models were used to estimate the non-point source nitrogen and phosphorus pollution loads, the sediment loss, and their spatial distribution in the basin. On this basis, the NPS risk level and characteristics of Fuxian Lake Basin were obtained, which makes this study more valuable for reference than previous studies in terms of water source protection.

Although the export coefficient model is an important model for estimating nitrogen and phosphorus pollution [11], rainfall has an important impact on non-point source pollution; therefore, under the premise of considering the temporal and spatial heterogeneity of rainfall factors, in this study we introduced rainfall factors and topographic factors to improve the export coefficient model, which has higher credibility for the average annual pollution load of the basin [14]. Previous NPS risk studies focused more on the generation and transportation of nitrogen and phosphorus pollutants and less on the impact of factors such as soil loss in the NPS pollution study area; however, as is known to all that the differences in topographic slopes and soil erosion resistance levels in different basins, as well as the large-scale soil and water losses in these basins caused by human activities, can cause huge damage to the water resources [8,19]. As such, based on previous studies, in this study we comprehensively considered the nitrogen and phosphorus loads, as well as the amounts of soil and water loss, and estimated the NPS risk within the spatial scope, not only making the estimated results more accurate [33], but also providing practical guidance for water resource protection.

At present, the risk assessment of non-point source pollution tends to focus on changes of water quality [23], the analysis of water pollution characteristics [17], and the protection of ecological environments [41], but less on the calculation and assessment of the risk levels of non-point source pollution loads [2,6]. In addition, in the study of non-point source pollution loads, most scholars mainly focus on the study of nitrogen and phosphorus nutrients as pollution sources [13,30]. Under the premise of comprehensively considering the influence of nitrogen and phosphorus nutrients and sediment as major pollutants on non-point source pollution [33], this study establishes a comprehensive risk assessment index to assess the risk of non-point source pollution, which makes the obtained research results more reliable.

There is no doubt that this study still has some shortcomings. First, this study only discussed the ecological risk assessment of NPS pollution in the Fuxian Lake Basin in 2016 and did not study changes on a long-term scale, meaning that the results of the study are insufficient to influence environmental protection and ecological restoration; therefore, in subsequent research, data from more years will be obtained and NPS pollution in multiple years will be analyzed and simulated to determine the trend for the ecological risk of NPS pollution and its influencing factors.

Second, the migration process for NPS pollutants is extremely complex. It involves many natural and human factors, including the topography, climate, soil, rainfall, and runoff. Although this study comprehensively considered six factors and was very accurate, there is still room for improvement. In future studies, the influences of different factors on NPS pollution should be considered more comprehensively to provide further evidence for the evaluation factors of NPS pollution.

Finally, in the risk assessment and analysis of NPS pollution in this study, the analysis of water characteristics was not sufficient, as pollutants in lakes may also cause differences in NPS pollution to some extent. In future studies, relevant research should be carried out on the sensitivity of lakes to pollutants.

Considering the above deficiencies and prospects [61], future research should focus on China's territorial spatial planning and integrate the risk assessment of the NPS pollution of river basins into territorial spatial planning to better address ecological pollution and environmental remediation [62].

6. Conclusions

This study evaluated the ecological risk of NPS pollution in the Fuxian Lake Basin to improve the empirical model and comprehensively consider the factors that affect NPS pollution. The following main conclusions were reached:

(1) The nitrogen load intensity of the Fuxian Lake Basin is greater than the phosphorus load intensity, while the distributions of NPS nitrogen and phosphorus pollution load intensities have certain spatial differences. The regions with higher nitrogen NPS load intensity are distributed in the west, east, and southeast of the basin. The phosphorus pollution load intensity of the NPS is higher in the northeast and west of the basin;

(2) In 2016, the annual average erosion modulus of the Fuxian Lake Basin was 1158 $t \cdot km^{-2} \cdot a^{-1}$. The average intensity of the Fuxian Lake Basin erosion is classified as mild. The intensity of the sediment loss in the Fuxian Lake Basin is mainly classified as slight, and is mostly distributed on the north bank of the lake and the construction land area along the lake. The intensity of the sediment loss is higher in grasslands and bare land area in the north, west, and southeast of the basin in areas with high topographic relief;

(3) The risk values for NPS pollution in the Fuxian Lake Basin range from 0 to 0.916, with an average risk value of 0.407. Spatially, the risk is higher in the plain area to the north of the lake, mainly due to the joint actions of nitrogen, phosphorus, and distance. Moreover, through the analysis of the risk of NPS pollution in the basin, it was found that the whole basin is primarily medium risk. The risk of NPS pollution is greatly affected by the loss of nitrogen and phosphorus and is affected by other factors to a certain extent.

Through the assessment and analysis of different NPS risks, high-risk areas should be managed and pollution control planning projects and ecological restoration work should be strengthened. Reasonable pollution control planning should be carried out in medium-risk areas to reduce the possibility of increasing pollution. Protection and preventative measures should be taken in low-risk areas and the development intensity of these areas should be rationally planned. The planning and treatment of different risk levels is conducive to NPS risk control in the Fuxian Lake Basin and has a positive guiding role in local ecological restoration and environmental protection.

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