

Article

Study on the Generation and Output Characteristics of Non-Point Source Pollution in the Process of River Migration

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Abstract

After the non-point source pollutants are generated at the source position and migrate to the target water body, they will have different degrees of loss under the action of precipitation, adsorption, or absorption by plants, resulting in differences in pollution output load and generation amount. Taking the Xin'an River Basin as an example, this study analyzes the spatial distribution characteristics of non-point source pollution generation and output in the process of river migration and explores the influence of river migration on non-point source pollution based on the soil and water assessment tool (SWAT) model and mathematical statistical methods. The results showed that the spatial distribution intensity of total nitrogen and total phosphorus in different sub-basins of Xin'an River Basin is between 3.88 and 29.16 kg/ha and 0.11–1.18 kg/ha, respectively. The high intensity areas of non-point source pollution generation and output are mainly concentrated in the hydrologically sensitive areas in the southern part of the basin and the erosion-sensitive area in the southeastern part of the basin, and the critical source areas of non-point source pollution are a result of comprehensive effects of crop fertilizer input, soil nitrogen, and phosphorus storage as well as hydrology and soil erosion. There are differences in the spatial distribution of non-point source pollution generation and output in the process of river migration. Some sub-basins have significant changes in their generation and output, and the sub-basin output coefficients of total nitrogen and total phosphorus are between 0.856 and 1.014 and 0.998–1.061, respectively. The change intensity of pollutants after river migration is affected by the combined effects of migration time, runoff intensity, material adsorption, and desorption, etc. The research findings will provide scientific support for zonal management and targeted measures of non-point source pollution in the Xin'an River Basin.

Keywords: object-oriented river migration; non-point source pollution; generation and output; spatial distribution; SWAT model



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1. Introduction

Xin'an River is the third largest water system in the Anhui Province and the largest inbound river in the Zhejiang Province, and its water quality directly affects the water quality of Qiandao Lake, an important water source in the Zhejiang Province. The CPC Central Committee, the State Council, and all sectors of society have attached great importance to the protection of the water environment in the Xin'an River Basin; they launched and implemented China's first trans-provincial water environment compensation pilot project

in Xin'an River. In addition, they have also requested for the Anhui Province to speed up the process of water pollution prevention and control in the upstream of the Xin'an River, promote the continuous improvement of water quality, and ensure that the water quality of the outbound river reaches meet the water quality standards required by the downstream. Xin'an River is located in an agricultural area and previous studies have shown that it is currently facing many problems of non-point source pollution, such as serious soil erosion and elevated water nitrogen load, etc. [1]. Therefore, the prevention and control of non-point source pollution in the basin should be strengthened to improve the water environment of Xin'an River. In view of this, the study on the characteristics of non-point source pollution in the Xin'an River Basin is of great significance for the scientific and effective control of non-point source pollution in the basin.

There is a certain difference in spatial distribution in the loss of non-point source pollution. The critical source areas (CSAs) are the areas with the maximum pollution load output per unit area and are also the main areas for the control and treatment of non-point source pollutants [2]. Ruan et al. discovered that 49.4% of the total phosphorus is from 26.8% of the basins in the critical source areas [3]. Ma et al. concluded that agricultural land is the main component of the critical source area of non-point source pollution through the risk level and spatial distribution of the source area [4]. The identification of critical source areas is the primary task of the control of non-point source pollutants, and the analysis of spatial distribution characteristics is the basis for determining critical source areas. The SWAT model can perform the continuous and long-time sequenced agricultural basin simulation and accurately analyze the loss distribution by the aid of the spatial data information provided by the Geographic Information System (GIS) and Remote Sensing (RS), so it has become one of the mainstream tools for identifying critical source areas by model methods. The SWAT model, applied and improved by Zeiger and others, has identified the potential critical source areas of pasture source pollution load in a large karst basin of the central USA [5]. Somaye et al. has identified the critical source areas of non-point source pollution in the Zrebar Lake watershed in Iran with the SWAT model under limited data conditions, and pointed out that alfalfa, apple, and tobacco are the most polluted plants [6]. Based on the SWAT model for identifying critical source areas of non-point source pollution loss, most studies are confined to macro-scale simulations and fail to systematically analyze the internal mechanisms of their spatial differentiation by deeply integrating watershed underlying surface characteristics (such as slope, drainage density, and land use). Additionally, scant research has quantitatively assessed the retention (attenuation) or release (promotion) effects of river channels themselves on the transport of non-point source pollutants [7–9].

After the non-point source pollutants such as nitrogen and phosphorus are lost (generated) at the source position and migrate to the target water body, they will have different degrees of loss under the action of precipitation, adsorption, or absorption by plants, which changes the loss load of pollutants and causes the differences in pollution output load and generation amount [10,11]. The retention and loss of pollutants in the river are affected by factors such as topography, surface coverage, and migration paths, etc. [12–14]. Due to different loss source locations of nitrogen and phosphorus pollutants in the basin and different action intensities of the river in the migration and transformation process, pollutants have different retention and loss conditions in the river. Compared with the spatial distribution characteristics of pollutant generation amount, the spatial distribution characteristics of the actual output amount will change [15,16]. A review of current research in the Xin'an River Basin and similar hydrological environments reveals a predominant focus on identifying the spatial distribution characteristics of either non-point source pollutant generation (i.e., entry into rivers) or export (i.e., outflow from sub-basins) as isolated

processes. However, few studies have spatially coupled and compared the “generation” and “export” processes or deeply examined the influence of in-stream transport processes on these patterns [17–19]. There is a lack of systematic, spatially explicit analysis in this regard [20–22]. Identifying critical source areas based solely on generation or export loads may fail to accurately reflect their ultimate pollution contribution to downstream water bodies, as river channels play a dynamic role as either a “sink” or “source” during pollutant transport [23,24].

This study focuses on the Xin'an River Basin within Huangshan City, Anhui Province, as the research area. After constructing and validating an SWAT model, we analyze the spatial distribution characteristics of non-point source pollutant generation and export, with emphasis on comparing their spatial similarities and differences. A “river attenuation coefficient” is introduced to quantify the impact of in-stream transport processes on the increase or decrease in non-point source pollutants. Furthermore, we comprehensively explore the synergistic effects of environmental factors such as pollution generation intensity and runoff migration time on spatial differentiation patterns. This research not only deepens the understanding of the entire “generation–transport” process of non-point source pollutants but also provides a solid scientific basis for precise prevention and efficient control of non-point source pollution in the Xin'an River Basin.

2. Materials and Methods

2.1. Overview of the Study Area

Xin'an River Basin, which originates in Liugujian, Xiuning County, Huangshan City, Anhui Province, passes through the Qiandao Lake, the Fuchun River, and the Qiantang River, and flows into the East China Sea through Hangzhou Bay, is the source of the Qiantang River and the inbound river with the largest catchment area in the Zhejiang Province. Meanwhile, it is the third largest water system in the Anhui Province, behind the Yangtze River and the Huaihe River, and it is located at 117°38'27"–118°55'16" east longitude and 29°24'55"–30°19'08" north latitude. The basin in the Anhui Province covers a total area of about 6736.8 km², of which the basin in Huangshan City is 5856.1 km². The topography is dominated by hills and middle and low mountainous areas, with an overall terrain tilt from southwest to northeast and an elevation of 700–1200 m. The basin has a monsoon moist climate, with abundant precipitation and rich heat, and its multi-year average precipitation is 1733 mm. The period from April to July is the wet season, accounting for about 78% of the total annual rainfall. Therefore, the Xin'an River Basin in Huangshan City, Anhui Province was selected as the study area, and the geographical location is shown in Figure 1.

The main land use type of the basin is forest lands, accounting for 72.17% of the total area of the basin. As the tea industry is a local characteristic industry, the occupied area of tea garden ranks second, accounting for 11.11% of the total area of the basin. The occupied area of cultivated land ranks third, accounting for 10.50% of the total area of the basin (Figure 1). The soil types are mainly yellow soil, yellow brown soil, and red soil, and the distribution varies vertically with the altitudes. The yellow soil is mostly concentrated in the middle and low mountainous areas. Concentrated in the lower mountainous areas, the yellow brown soil is characterized by a thicker soil layer, higher fertility, higher stone content, and good air and water permeability. The red soil is mainly concentrated in the hilly areas, in which the soil texture is heavy and the fertility is relatively poor, but the heat and light conditions are good. There are about 1.48 million permanent residents in the basin. Agriculture and tourism are the main industries, and the industrial level is low.

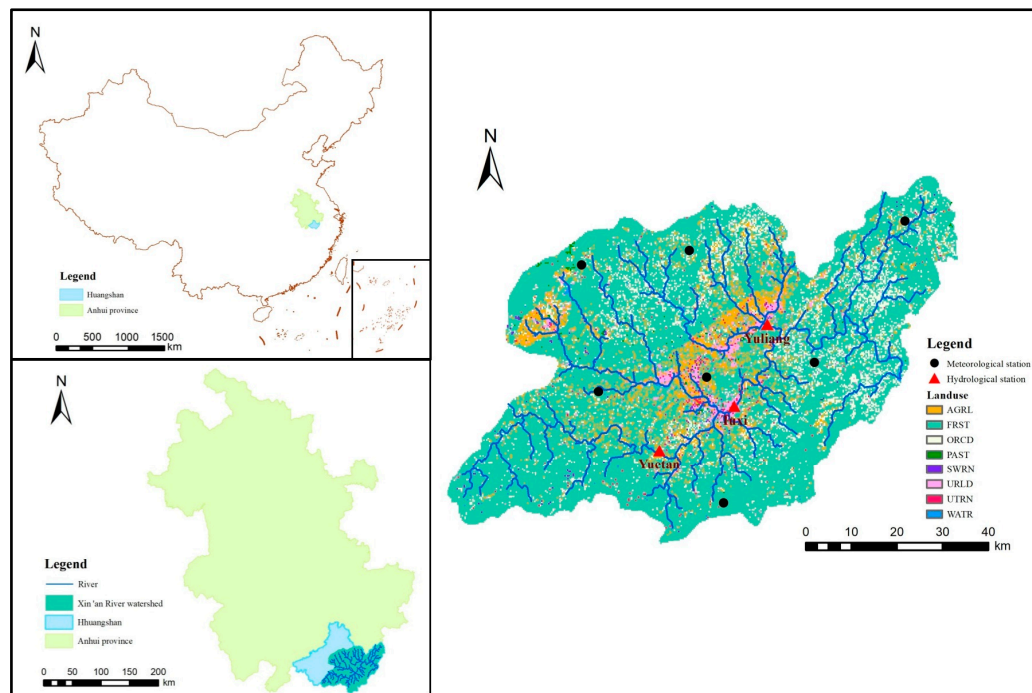


Figure 1. Location diagram of the study area.

2.2. SWAT Model Construction

2.2.1. Model Database Construction

The database required for the operation of the SWAT model includes a spatial database and an attribute database. The spatial database includes the digital elevation model (DEM), present land use map, soil type distribution map, and basin drainage map, etc. (Table 1); the attribute database includes soil property, meteorological data, and crop management data, as well as hydrological and water quality measured data for model calibration and validation, etc.

Table 1. Model-required data information table.

Data	Resolution	Format	Source
DEM	30 m	ESRI Grid	International Scientific Data Service Platform
Land Use Map	30 m	ESRI Grid	Chinese Academy of Environmental Planning
Soil Type Distribution Map	1 km	ESRI Grid	The Second National Soil Census
Meteorological Data	1/4°	.xls	The China Meteorological Assimilation Driving Datasets for the SWAT model
Water Quality Data	Month	.xls	Chinese Academy of Environmental Planning

The soil data required by the SWAT model include physical and chemical properties. The physical properties of soil determine the accuracy of model simulation, which includes soil name, number of soil layers, and structure of soil layers, etc.; the chemical properties determine the assignment of the initial values of the model, including organic nitrogen content, soluble phosphorus content, and organic phosphorus content, etc. The data values were calculated by consulting the Harmonized World Soil Database (HWSD) constructed by the Food and Agriculture Organization of the United Nations and were combined with the Soil-Plant-Air-Water (SPAW) model developed by the University of Washington.

The meteorological data required by the SWAT model were derived from The China Meteorological Assimilation Driving Datasets for the SWAT model (CMADS) released by China Institute of Water Resources and Hydropower Research, with the time scale of

2008–2018 and the spatial resolution of $1/4^{\circ} \times 1/4^{\circ}$. The elements such as daily mean temperature, daily maximum/minimum temperature, and daily cumulative rainfall, etc., were included. In the CMADS V1.1 dataset, a total of 6 stations in the Xin'an River Basin were extracted as the meteorological input data for the SWAT model. The station distribution is shown in Figure 1, and the details about the station are shown in Table 2.

Table 2. Distribution of CMADS stations in the study area.

Station Name	Latitude/ $^{\circ}$	Longitude/ $^{\circ}$	Elevation/m
119–234	29.53	118.28	490
120–233	29.78	118.03	183
120–234	29.78	118.28	156
120–235	29.78	118.53	309
121–233	30.03	118.03	869
121–234	30.03	118.28	627
121–236	30.03	118.78	387

The agricultural management data required by the SWAT model include crop type, farming mode, management mode, and fertilizing amount, which were derived from field investigation and the Huangshan Agricultural Statistical Yearbook. The crops in the basin are mainly tea, oilseed rape, and rice. The farming mode is paddy-upland rotation and dry land planting. The fertilizers are mainly nitrogen fertilizer (urea) and phosphate fertilizer (superphosphate). The statistics of the time and amount of chemical fertilizer application during the crop growth period are shown in Table 3.

Table 3. Crop management information in the study area [25].

Code	Name	Date	Management	Fertilizer Amount/(kg·hm ^{−2})	
				Urea	Superphosphate
RICE	Rice	10 May	Seeding	No fertilizer needed	
		20 June	Transplanting/Base fertilizer	210	225
		5 July	Tillering fertilizer	105	0
		1 August	Panicle fertilizer	210	0
		25 October	Reaping	Harvesting and removing	
CANP	Oilseed rape	1 October	Seeding/Base fertilizer	120	750
		1 November	Fertilizer for accelerating seedling growth	90	0
		20 December	Fertilizer for winter crops	45	0
		20 January	Fertilizer applied during the oilseed rape bolting stage	45	0
RNGB	Tea tree	10 May	Reaping	Harvesting and removing	
		1 November	Base fertilizer	500	375
		1 February	Flushing manure	300	0
		25 March	Spring manuring	225	0
		15 July	Summer manuring	225	0

2.2.2. Sensitivity Analysis, Calibration, and Validation of the SWAT Model

According to the operational requirements of the SWAT model, relevant data were collected and organized to construct the SWAT model database of the basin. By taking the period from 2008 to 2010 as the warm-up year, the period from 2011 to 2014 as the calibration year, and the period from 2015 to 2016 as the validation period, the division method of the basin–sub-basin–hydrological response unit was used to gradually realize the basin spatial discretization and simulate the output of basin runoff, sediment, and water quality (TN, TP).

After the model was successfully run, global sensitivity analysis of the model's runoff parameters was performed using the SWAT-CUP software (version 2012). This method evaluates parameter sensitivity through the p -Value and t -Stat values from the t -test, where a p -Value closer to 0 or a larger absolute t -Stat value indicates higher parameter sensitivity [26]. The results of the global sensitivity analysis for runoff parameters are presented in Table 4.

Table 4. Global sensitivity analysis results of runoff parameters.

Sensitivity Ranking	Parameter	p -Value	t -Stat
1	SOL_K	0	1
2	ESCO	0.412	0.825
3	CN2	0.845	0.196
4	SOL_AWC	0.884	−0.147
5	CH_N2	0.938	−0.078
6	GW_DELAY	0.940	−0.075
7	ALPHA_BF	0.949	0.064
8	GWQMN	0.956	0.055
9	REVAPMN	0.982	0.022
10	GW_REVAP	0.988	−0.015
11	CANMX	1	0

After the calibration of runoff parameters was completed, sediment and water quality parameters were further analyzed. Due to their relatively narrow range of variation and more manageable impact on the objective function variables, the sensitivity analysis of sediment and water quality parameters was generally performed using a trial-and-error adjustment method. By adjusting individual parameters one by one and analyzing the output results, the parameters identified as most sensitive to sediment and water quality, in order, were USLE_C, USLE_P, SPCON, CDN, SDNCO, NPERCO, ERORGN, PSP, and ERORGP, etc.

The SUFI-2 algorithm within the SWAT-CUP software was employed to calibrate and validate the simulated results at the Tunxi Station and the watershed outlet. Through continuous iterations of the algorithm, an optimal parameter set was ultimately obtained. The coefficient of determination R^2 and Nash–Sutcliffe efficiency coefficient Ens were adopted to evaluate the applicability of the model:

$$R^2 = \frac{\left[\sum_{i=1}^n (S_i - \bar{S})(M_i - \bar{M}) \right]^2}{\sum_{i=1}^n (S_i - \bar{S})^2 \sum_{i=1}^n (M_i - \bar{M})^2} \quad (1)$$

$$Ens = 1 - \frac{\sum_{i=1}^n (S_i - M_i)^2}{\sum_{i=1}^n (S_i - \bar{S})^2} \quad (2)$$

where R^2 refers to the coefficient of determination, Ens refers to the Nash–Sutcliffe efficiency coefficient, S_i refers to the measured data, M_i refers to the simulated data, $\bar{S}$ refers to the average of all the measured data, and $\bar{M}$ refers to the average of all simulated data. The R^2 and Ens values can be directly viewed in the Summary_Stat.txt output file of SWAT-CUP (see supplementary materials).

The simulated results of the Tunxi Railway Station and basin outlet were calibrated with the measured values, showing that the R^2 between the simulated and measured values of runoff, sediment, total nitrogen, and total phosphorus at the Tunxi Railway

Station are 0.95, 0.87, 0.87, and 0.77, respectively, and the *Ens* reach 0.83, 0.84, 0.79, and 0.71, respectively; the R^2 and *Ens* of total nitrogen at the basin outlet are 0.89 and 0.87, respectively, and the R^2 and *Ens* of total phosphorus are 0.78 and 0.70, respectively, which meet the calibration requirements of the model. The calibrated models were verified at different time periods without changing the parameter values of the model, and the results showed that the R^2 between the simulated and measured values of runoff, sediment, total nitrogen, and total phosphorus at the Tunxi Railway Station are 0.96, 0.89, 0.76, and 0.69, respectively, and the *Ens* reach 0.87, 0.86, 0.71, and 0.58, respectively; the R^2 and *Ens* of total nitrogen at the basin outlet are 0.95 and 0.89, respectively, and the R^2 and *Ens* of total phosphorus are 0.77 and 0.75, respectively. The optimal values of the sensitive parameters finally determined by the model are shown in Table 5, and the fitting of simulated values and measured values is shown in Figure 2.

Table 5. Table of parameter values for model calibration.

Variable	Parameter	Description	Lower Limit	Upper Limit	Final Value
Flow	CN2	SCS moisture condition II curve number for pervious areas	−0.25	0.25	−0.108
	CH_N2	Main channel Manning coefficient	0	3	0.134
	ESCO	Soil evaporation compensation coefficient	0	1	0.875
	CANMX	Maximum canopy storage	0	10	8.550
	SOL_AWC	Available water capacity of the soil layer	−0.25	0.25	0.118
	SOL_K	Saturated hydraulic conductivity of the first layer	−0.25	0.25	0.183
	ALPHA_BF	Baseflow recession coefficient	0	1	0.905
	GW_DELAY	Groundwater delay (days)	0	100	2.500
	GWQMN	Threshold water level in the shallow aquifer for the base flow	0	500	82.500
	REVAPMN	Shallow groundwater runoff coefficient	0	500	27.500
	SLSUBBSN	Average slope length	94	108	94.283
Sediment	SPCON	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	0.007	0.009	0.008
	SPEXP	Exponent parameter for calculating sediment re-entrained in channel sediment routing	0.78	0.92	0.915
	USLE_P	USLE equation support practice factor	0.18	0.35	0.191
	USLE_C	Min value of USLE C factor applicable to the land cover/plant	0	0.5	AGRL: 0.348 ORCD: 0.245 FRST: 0.285 PAST: 0.041
TN	CDN	Denitrification rate coefficient	0	0.78	0.012
	SDNCO	Soil water content threshold for denitrification to occur	0.63	0.97	0.836
	NPERCO	Nitrogen percolation coefficient	0.10	0.40	0.372
	ERORGN	Organic nitrogen enrichment ratio	1.88	3.75	2.656
	RCN	Nitrogen concentration in rainfall	3.50	11.17	10.518
TP	SOL_ORGP	Initial organophosphorus concentration in the soil layer	49.44	71.84	57.614
	P_UPDIS	Phosphorus absorption distribution	52.89	100.0	64.715
	PSP	Phosphorus availability index	0.55	0.70	0.687
	ERORGP	Organophosphorus enrichment ratio	0	1.09	0.486
	PPERCO	Phosphorus flow coefficient	10.0	15.07	14.589

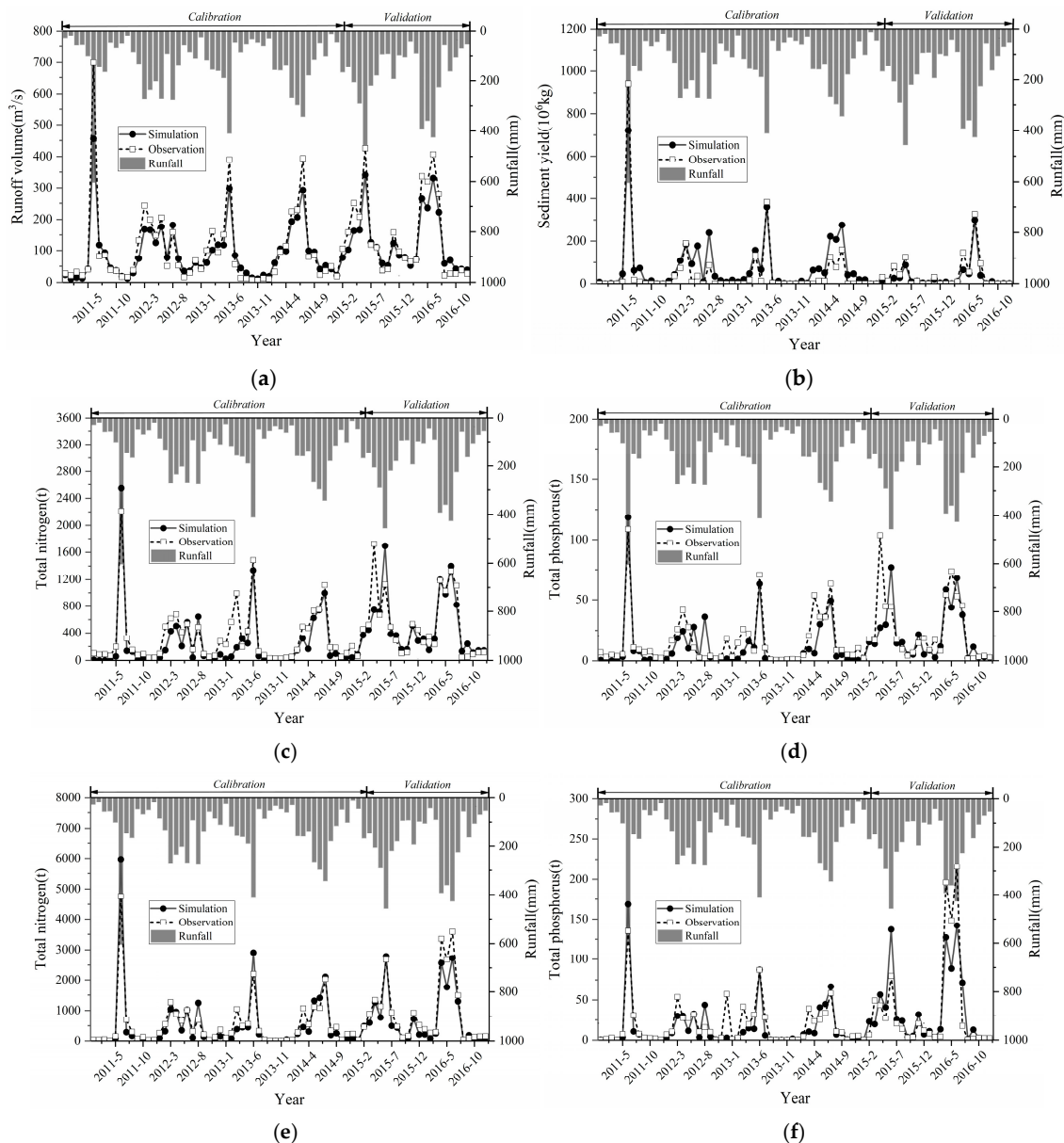


Figure 2. The fitting of simulated values and measured values: monthly runoff of the Tunxi Railway Station (a); monthly sediment of the Tunxi Railway Station (b); monthly total nitrogen of the Tunxi Railway Station (c); monthly total phosphorus of the Tunxi Railway Station (d); monthly total nitrogen of the basin outlet (e); monthly total phosphorus of the basin outlet (f).

2.2.3. Simulation and Key Parameter Calculation of the SWAT Model's Construction

The models after validation were applied to simulate the changes in non-point source pollution in the process of river migration in the study area from January 2011 to December 2016, so as to obtain the generation and output amount of runoff, sediment, total nitrogen, and total phosphorus in each sub-basin. The multi-year average of each index was calculated through statistics and the area of the sub-basin was combined to obtain the generation amount, output amount, and distribution characteristics of the sub-basin per unit area. The generation amount refers to the amount that enters into the sub-basin river in the process of river migration, while the output amount refers to the amount that exports from the sub-basin outlet after river migration.

The runoff, sediment, total nitrogen, and total phosphorus will deposit or be absorbed by plants in the process of river migration, resulting in different degrees of loss. The sub-basin output coefficient (R) is used to reflect the retention and loss of runoff, sediment, total

nitrogen, and total phosphorus of the sub-basin in the river. The sub-basin output coefficient can be obtained by dividing the output amount of runoff, sediment, total nitrogen, and total phosphorus at the sub-basin outlet by the generation amount entering the river, the calculation formula is as follows:

$$R = SUBoutput / SUBexport \quad (3)$$

where R refers to the sub-basin output coefficient, $SUBexport$ refers to the generation amount (kg) entering the sub-basin river within the time step, and $SUBoutput$ refers to the output amount (kg) at the sub-basin outlet after river migration.

3. Results and Discussion

3.1. Spatial Distribution Characteristics of Pollutants Generation Intensity

This study employed the Jenks Natural Breaks method for data classification to optimally reveal natural groupings and spatial patterns within the data [27]. To facilitate comparison, the output values adopted the same middle breakpoint values as the generation values. Some sub-basins, due to their relatively small area proportion, could not be numerically labeled at the selected map scale; however, this does not affect the analytical conclusions. The high generation intensity areas of total nitrogen in the basin were mainly distributed in the No. 39 and No. 42 sub-basins in the southeast, with a total nitrogen generation amount per unit area of 25.00–29.16 kg/ha; the secondary high-generation intensity areas were the No. 5 and No. 18 sub-basins in the north, the No. 30 and No. 47 sub-basins in the southeast, and the No. 44 sub-basin in the southwest, with an intensity of 19.50–25.00 kg/ha; other areas had low generation intensity (Figure 3a). Areas with high generation intensity featured relatively steep terrain slopes, which induced high soil erosion rates [28]. Furthermore, the prevalence of grassland and slope farmland in these regions, combined with the application of pesticides and fertilizers, provided ample “sources” of pollutants for these sub-basins.

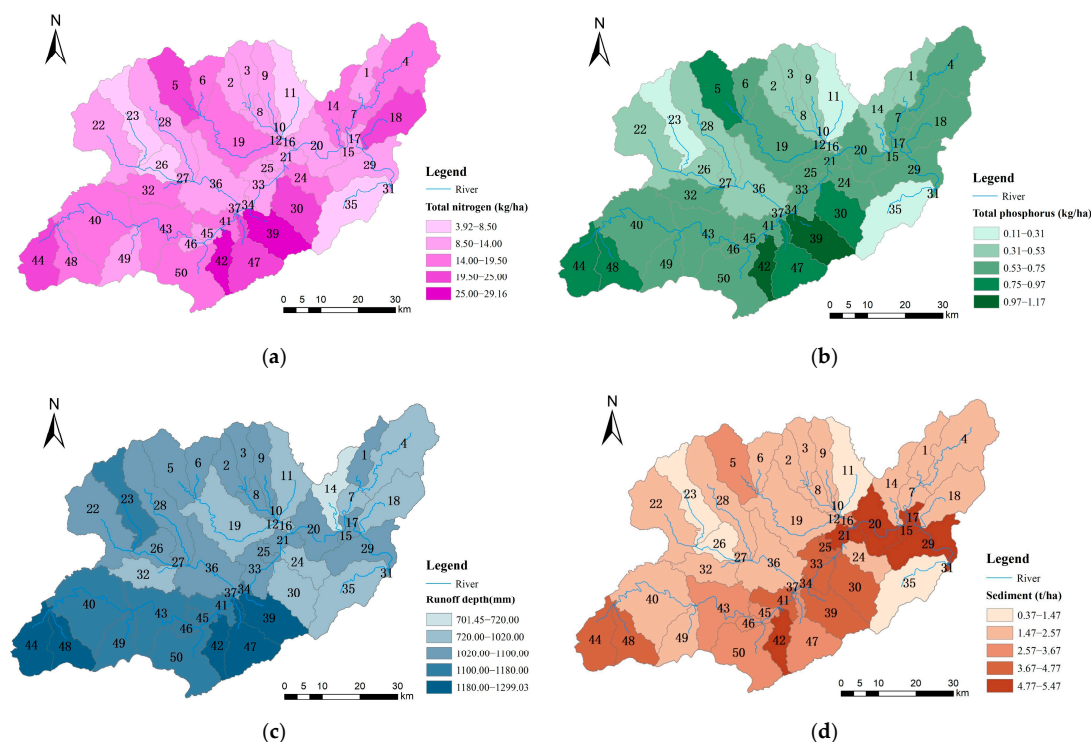


Figure 3. Spatial map of generation of total nitrogen (a), total phosphorus (b), runoff (c), and sediment (d).

The high generation intensity areas of total phosphorus were distributed in the No. 39 and No. 42 sub-basins in the southeast, with the generation amount per unit area of 0.97–1.17 kg/ha; the secondary high-generation intensity areas were the No. 5 sub-basin in the north, the No. 30 and No. 47 sub-basins in the southeast, and the No. 44 and No. 48 sub-basins in the southwest, with an intensity of 0.75–0.97 kg/ha; other areas had low generation intensity (Figure 3b). The areas with high total phosphorus generation intensity largely coincided with those of high total nitrogen, a pattern primarily driven by the combined effects of land use types, terrain slope, and agricultural management practices. The steep slopes in these regions increase the risk of soil erosion. Moreover, the extensive distribution of slope farmland, coupled with agricultural activities such as tillage, disrupts soil structure and reduces erosion resistance, thereby accelerating the loss of soil particles and associated nitrogen and phosphorus elements adsorbed to them via surface runoff [29]. In contrast, sub-basins with lower generation intensity exhibit relatively higher coverage of woodland, grassland, and orchard areas. Here, the interception and buffering effects of the vegetation canopy and litter layer effectively reduce the generation intensity of nitrogen and phosphorus pollutants [30].

The high and secondary high generation intensity areas of runoff were concentrated in the No. 39, No. 40, No. 41, No. 42, No. 43, and No. 44 sub-basins in the southern part of the basin and the No. 23 sub-basin in the northwestern part of the basin (Figure 3c). The high generation intensity areas of sediment were the No. 15, No. 17, No. 20, No. 21, No. 29, and No. 31 sub-basins in the central and eastern part of the basin and the No. 42 sub-basin in the southern part of the basin; the secondary high-generation intensity areas of sediment were the No. 25, No. 30, No. 33, No. 34, No. 37, No. 39, No. 41, No. 44, and No. 48 sub-basins. Other areas had low intensity (Figure 3d). On the whole, the southern part of the basin has high runoff depth and large runoff potential and belongs to the hydrologically sensitive area of the basin. With a large slope, the southeast part of the basin mainly uses its lands as forest lands and reclaims part of its lands for cultivated lands and garden lands (Figure 1). It also has serious soil erosion and large sediment generation intensity (3.67–5.47 t/ha), as it is the soil erosion-sensitive area of the basin. Furthermore, the areas with high generation intensity of total nitrogen and total phosphorus overlap (the No. 39 and No. 42 sub-basins). These sub-basins are also located within regions of high runoff generation intensity and high sediment generation intensity (No. 42) or sub-high intensity (No. 39). This indicates that areas sensitive to soil erosion and hydrologically sensitive areas are at high risk for non-point source pollutant loss. This phenomenon is the combined result of high fertilizer input in agriculture, high soil nitrogen and phosphorus reserves, and the integrated effects of hydrological and erosion factors [31].

3.2. Spatial Distribution Characteristics of Pollutant Output Intensity

The high-output intensity areas of total nitrogen were mainly distributed in the No. 39 and No. 42 sub-basins in the southeast part of the basin, with an output intensity of 25.00–29.12 kg/ha; the secondary high-output intensity areas were the No. 5 sub-basin in the north, the No. 30 and No. 47 sub-basins in the southeast, and the No. 44 sub-basin in the southwest, with an intensity of 19.50–25.00 kg/ha; other areas had low output intensity (Figure 4a). Areas with high pollutant export share common characteristics: a sparse river network, steep slopes, and rapid flow velocity. These factors result in an excessively short pollutant transport time, preventing the river's self-purification process from being fully effective. Meanwhile, intense hydrodynamic conditions cause the resuspension of river sediment, releasing previously deposited nitrogen and phosphorus pollutants back into the overlying water. Ultimately, these processes enhance the export of nitrogen and phosphorus pollutants [32]. The high-output intensity areas of total phosphorus and total nitrogen

coincided with each other, the No. 39 and No. 42 sub-basins had the maximum output per unit area and the output intensity was 0.97–1.18 kg/ha; the secondary high-output intensity areas were the No. 5 sub-basin in the north, the No. 30 and No. 47 sub-basins in the southeast, the No. 40, No. 44 and No. 48 sub-basins in the southwest, and the No. 18 sub-basin in the northeast, with an intensity of 19.50–25.00 kg/ha; other areas had low output intensity (Figure 4b). In areas with low pollutant exports, forest interception and river self-purification are key factors reducing the output of nitrogen and phosphorus pollutants in these sub-basins. These regions contain extensive water conservation forests, which research shows can effectively intercept runoff and sediment, significantly reduce the export of nutrient elements, and perform ecological functions such as regulating flow and improving water quality [33].

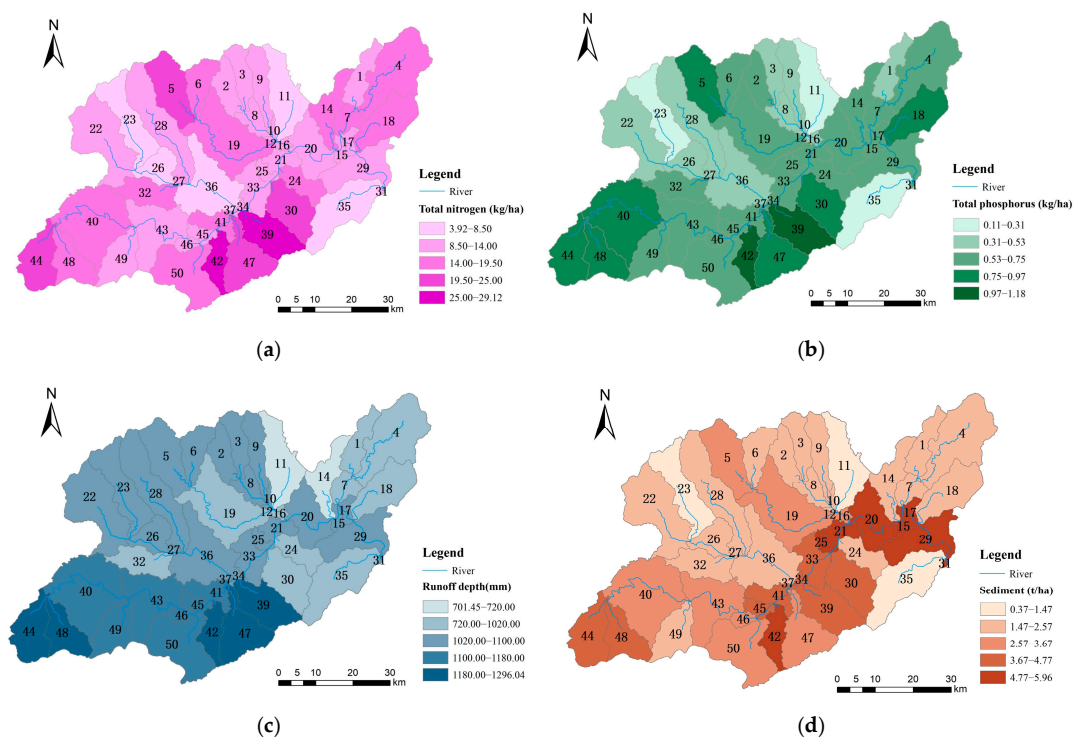


Figure 4. Spatial map of export of total nitrogen (a), total phosphorus (b), runoff (c), and sediment (d).

The secondary high and high output intensity areas of runoff were concentrated in the No. 39, No. 40, No. 41, No. 42, and No. 43 sub-basins in the southern part of the basin (Figure 4c). The high-output intensity areas of sediment were the No. 15, No. 17, No. 20, and No. 21 sub-basins in the central and eastern part of the basin and the No. 42 sub-basin in the southern part of the basin, while the secondary high-intensity areas were the No. 25, No. 30, No. 33, No. 34, and No. 39 sub-basins in the southeast part of the basin and the No. 44 and No. 48 sub-basins in the southwest of the basin. Other areas had low intensity (Figure 4d). The No. 39 and No. 42 sub-basins with high-output intensity of total nitrogen and total phosphorus coincided with the high intensity area of runoff as well as the high and secondary high-intensity areas of sediment, respectively, indicating that soil erosion is the main reason for the output of non-point source pollutants of nitrogen and phosphorus.

Compared to the spatial distribution of pollutant generation intensity within the basin, the export intensity shows significant changes in some sub-basins. For example, the total nitrogen export intensity in the No. 18, No. 36, and No. 43 sub-basins decreased markedly compared to their generation intensity (Figures 3a and 4a), indicating that the riverine systems in these areas have a significant retention and transformation effect on nitrogen. The primary mechanisms include microbially driven processes such as ammonification,

nitrification, and denitrification, as well as the adsorption and uptake of nitrogen by aquatic and riparian vegetation. In contrast, the total phosphorus export intensity in the No. 14, No. 18, and No. 40 sub-basins increased compared to their generation intensity (Figures 3b and 4b). This rise may originate from the release of phosphorus from sediment induced by flow disturbance. It is noteworthy that the No. 18 sub-basin exhibited a simultaneous decrease in total nitrogen and increase in total phosphorus, indicating that the transport and transformation mechanisms within the same river system can be distinctly different—even opposite—for different pollutants. This conclusion is supported by findings from other similar studies [34,35]. In contrast, the export and generation intensities per unit area of total nitrogen and total phosphorus in other sub-basins remained largely unchanged, with pollutants being transported almost without attenuation from the slopes to the watershed outlet.

3.3. The Influence of River Migration on Pollutant Output

The sub-basin output coefficients of runoff, sediment, total nitrogen, and total phosphorus in each sub-basin were analyzed and calculated (Figure 5). The sub-basin output coefficients of runoff were all above 0.99, showing that there is basically no loss of runoff in the process of river migration. Most of the sub-basin output coefficients of sediment reached 1.00 and above, and the maximum sub-basin output coefficient of sediment in the No. 12 sub-basin reached 1.534, indicating that the sediment in most sub-basins does not decrease but increases in the process of river migration. The increase in sediment output was mainly caused by large runoff, rapid migration, and decreased deposition of sediment as well as the increase in river erosion caused by large runoff in the study area.

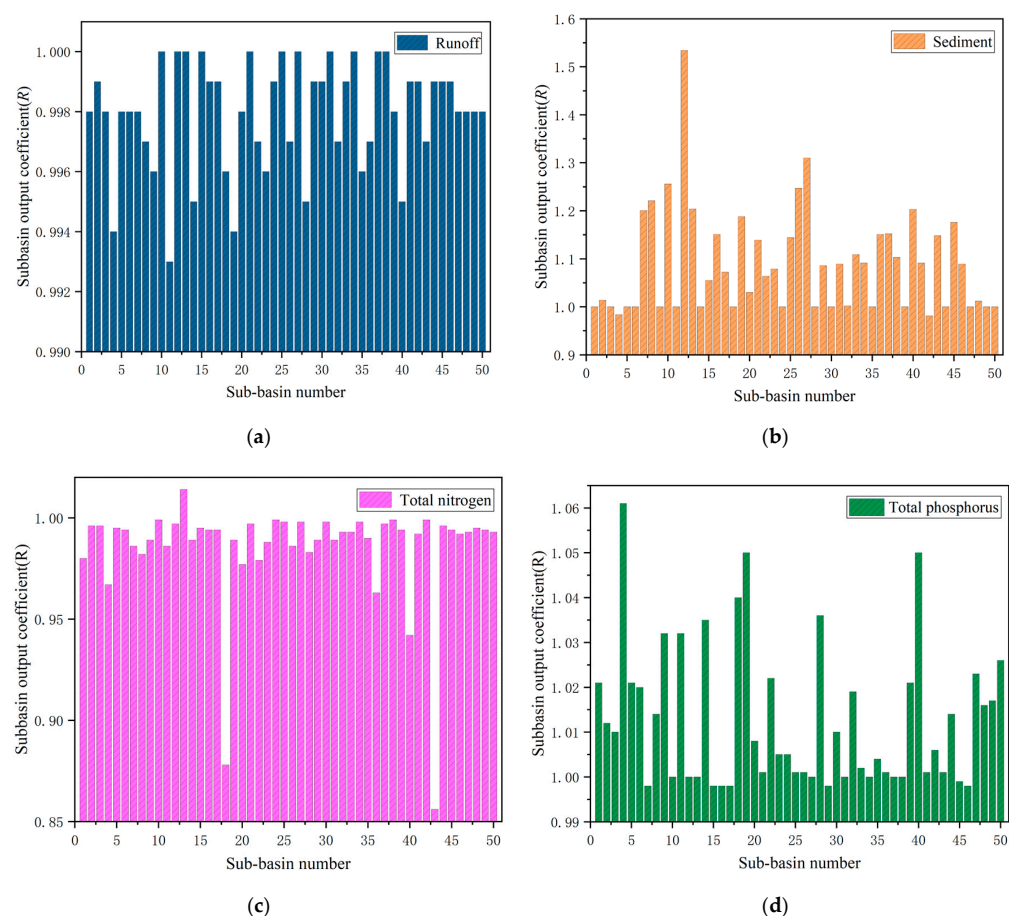


Figure 5. Sub-basin output coefficient of runoff (a), sediment (b), total nitrogen (c), and total phosphorus (d).

Nitrogen in the river exists in two forms: organic nitrogen and inorganic nitrogen. During the migration and transformation process, ammoniation, nitrification, and denitrification occurred, and absorption by plants and sediment adsorption were included as well [36]. Ammoniation, nitrification, and denitrification are irreversible processes in which nitrogen is spilled and permanently removed in the form of gas. The intensity of the effects of river migration processes on nitrogen transformation was mainly related to migration time, migration distance, and flow velocity [37,38]. The sub-basin output coefficient of total nitrogen in the basin ranged from 0.856 to 1.014, and there was no significant change in the sub-basins as a whole, but nitrogen in most sub-basins attenuated during migration; the sub-basin output coefficients of total nitrogen in the No. 18 and No. 43 sub-basins were 0.878 and 0.856, respectively, which were smaller than those in other sub-basins. The main reason was that the rivers in these two sub-basins are longer, and the No. 43 sub-basin is located in a hydrologically sensitive area with a dense river network. Although nitrogen has longer migration time in the river, it is mostly retained and transformed, so river migration has a reducing effect on nitrogen loss.

Phosphorus is mainly present in the form of particles in the water body. Part of the phosphorus is adsorbed on the surface of the suspended solids in water body and enters the sediment with the sedimentation of the suspended solids, and the other part is absorbed by the plants and microorganisms in the water [39]. The process of river migration and transformation mainly includes the adsorption and desorption of sediment, and the absorption and assimilation of plants and microorganisms. Adsorption and desorption are dynamic equilibrium processes. The phosphorus adsorbed by the sediment may be re-released into the water during the process of migration and transformation, and the greater the turbulence intensity of water flow is, the more phosphorus is released into the overlying water [40]. The sub-basin output coefficient of total phosphorus in the basin was between 0.998 and 1.061, indicating that the total phosphorus in some sub-basins is deposited and retained in the process of river migration, but the total phosphorus load in most sub-basins will increase in varying degrees during migration, which is mainly caused by the river erosion and the release of sediment in the river. The sub-basin output coefficient of total phosphorus in the No. 4, No. 14, No. 18, and No. 40 sub-basins increased significantly. The reason might be that these sub-basins have high terrain and large water flow; the water disturbance under large runoff is enhanced, which accelerates the diffusion of phosphorus in pore water of sediment and increases the release amount of phosphorus. Therefore, river migration promotes its output.

4. Conclusions

Based on ArcGIS 10.2 and SWAT 2012, this paper constructs a non-point source pollution model that matches the actual situation of the Xin'an River Basin and analyzes the model's simulation results to obtain the generation and output characteristics of non-point source pollution in the process of river migration. The spatial distribution intensity of total nitrogen and total phosphorus in different sub-basins of the Xin'an River Basin was between 3.88 and 29.16 kg/ha and 0.11–1.18 kg/ha, respectively. The high intensity areas of non-point source pollution generation and output were mainly concentrated in the hydrologically sensitive areas in the southern part of the basin and the soil erosion-sensitive areas in the southeast part of the basin (the No. 39 and No. 42 sub-basins, etc.), where the topographic slope is large, the cultivated land is widely distributed, the river runoff potential is large, and the soil erosion is serious. Therefore, the critical source areas of non-point source pollution in the basin are a result of the comprehensive effects of crop fertilizer input, soil nitrogen and phosphorus storage, hydrology, and soil erosion.

There were differences in the spatial distribution of non-point source pollution generation and output in the process of river migration. Some sub-basins had significant changes in their generation and output, and the sub-basin output coefficients of total nitrogen and total phosphorus were between 0.856 and 1.014 and 0.998–1.061, respectively. The total nitrogen in most sub-basins of the Xin'an River Basin is retained and transformed in varying degrees after river migration, and river migration has a reducing effect on nitrogen loss. The total phosphorus is retained and attenuated in some sub-basins, the phosphorus adsorbed in the sediment of most sub-basins is re-released into the water with water disturbance, and river migration promotes phosphorus loss. The changing intensity of pollutants in different sub-basins after river migration is affected by the combined effects of migration time, runoff intensity, material adsorption, and desorption, etc.

Based on the findings of this study, it is recommended to adopt differentiated management strategies for non-point source pollution control in the Xin'an River Basin. In the hydrologically sensitive areas in the southern part of the basin and the soil erosion-sensitive areas in the southeast, priority should be given to implementing farmland ecological interception measures, such as establishing riparian buffer strips and grassed filter strips, to reduce the risk of nitrogen and phosphorus entering rivers directly with runoff. In regions with active phosphorus release, it is essential to strengthen the control of internal pollution sources within river channels by carrying out sediment-stabilization engineering and hydrological regulation to inhibit the resuspension and release of phosphorus from sediments. Additionally, Best Management Practices (BMPs) should be promoted across the entire basin, including optimizing fertilizer application structures and advocating for conservation tillage, to systematically enhance the effectiveness of non-point source pollution control from three aspects: source reduction, process interception, and end-of-pipe treatment.

The present study has several limitations. First, although the SWAT model was calibrated and validated, the accuracy of its simulations remains dependent on the quality and resolution of the input data. The soil, land use, and other datasets used in the study may not fully capture fine-scale spatial heterogeneity, thereby introducing uncertainty. Second, while the study identified significant nitrogen retention or phosphorus increase in certain sub-basins and attributed these phenomena to microbial processes (e.g., denitrification) or physical processes (e.g., sediment resuspension), the analysis remains largely inferential. There is a lack of field-measured data on key parameters such as in-stream hydrodynamics, sediment properties, and nitrogen/phosphorus speciation to validate and quantify these mechanisms. Future research should focus on integrating multi-source, high-resolution data to enhance the spatial detail of simulations, and employ in situ monitoring of key river reaches combined with laboratory analysis to clarify the driving mechanisms of nitrogen and phosphorus release from sediments under varying hydrological conditions. This will enable more precise quantification and delineation of critical source areas.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w17233333/s1>, File S1: SWAT model files for the Xin'an River Basin study area in this paper.

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