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Spatial Layout of Vegetation Buffer Zones around Water Bodies to Avoid Non-Point Source Pollution in a Mining Area

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Abstract: The riparian vegetation buffer zone plays an important role in the prevention and control of non-point source pollution, and consideration should be given to selecting one with a lower cost and better effect. The SWAT model was used to simulate the regulation ability of riparian vegetation buffer zone layout on runoff, nitrogen, and phosphorus in the Jiawang Basin, and five different vegetation buffer zone layout scenarios were set up. The results showed that (1) the SWAT model has good applicability in simulating runoff and water quality in the Jiawang Basin; (2) the reduction rates of runoff, total nitrogen, and total phosphorus in continuous forest riverbank buffer zones reached 2.46%, 6.63%, and 9.18%, and their regulatory effects were better than those in grasslands; (3) there is not much difference in the inhibitory effect of forest and grassland on total nitrogen, but the discontinuous forest buffer zone has a better reduction effect on total phosphorus than grassland. Therefore, in the actual arrangement of vegetation buffer zones, it should be tailored to local conditions to achieve ideal non-point source pollution prevention and control effects at a lower cost.

Keywords: riparian vegetation buffer zone; non-point source pollution; SWAT model; scenario simulation

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1. Introduction

Different land use patterns will change the allocation of material resources, thus affecting the input, output, and types of regional material flows and the function of ecosystems [1]. With the enhancement of human activities, the spatial allocation of land use will also change, and the hydrological cycle, as a kind of material flow, is closely related to it. Therefore, optimizing the spatial allocation of land use and regulating the virtuous cycle of ecological material flow are the key issues that should be paid attention to.

In recent years, various pollutants stemming from agricultural cultivation, aquaculture, urban development, and other land-use practices have been introduced into water bodies as non-point source pollution through diverse surface-loading mechanisms, leading to water eutrophication [2,3]. After many years of research, the riparian vegetation buffer zone adopted in the process of material flow has been identified as a method with low cost, high efficiency, easy operation, and the most natural ecology [4]. These buffer zones play a pivotal role in mitigating non-point source pollution, regulating runoff, preserving biodiversity, and promoting soil and water conservation. The effectiveness of riparian vegetation buffer zones is intricately linked to factors such as their width and layout [5].

The main methods for delimiting the buffer zone width at home and abroad include the outdoor experiment method [6], empirical value method, simple mathematical model method, complex mechanism model method, and GIS-based mathematical model method [7,8]. In the exploration of the layout of the riparian buffer, researchers such as Wang Min and Qian Jin have experimentally demonstrated that the layout of these zones on different slopes can influence the retention efficiency of pollutants [9]. Utilizing the SWAT model, Chang Jian established five scenarios involving source control measures and interception measures [10]. The interception measures included planting trees and grass in the river channel and defining vegetation filter strips around farmland in the HRU. The results indicated the effective control of soil erosion and a reduction in the loss of nutrients such as nitrogen and phosphorus. Through field experiments, Lv Jian and colleagues found varying efficiencies in nitrogen removal for different densities of poplar artificial forests, with the best interception effect observed at a density of 1000 plants per hectare [11].

While existing research has predominantly focused on the investigation of riparian buffer zone vegetation types, density configurations, and slope layouts through field experiments, there has been relatively less attention from a macroscopic perspective on whether the length of riparian buffer zones needs to be continuously deployed along the riverbank.

The original river system of Jiawang District is developed, and a large area of stagnant water has been formed due to coal mining. With the acceleration of urbanization, water pollution needs to be paid attention to [12]. Therefore, taking Jiawang coal mining subsidence area as an example, this paper uses a SWAT model to simulate the reduction effect of land use change on non-point source pollution under different layout scenarios of vegetation buffer zones around a riverbank, so as to provide a scientific basis for the treatment of non-point source pollution in Jiawang watershed.

This paper opens with a depiction of the function of the riparian buffer zone and the necessity of deploying a riparian buffer zone using the SWAT model. Next, we describe our Materials and Methods, present our findings, discuss them, provide recommendations, and provide a Conclusion and Discussion.

2. Materials and Methods

2.1. Study Area

The research area is located in Jiawang District in the northeast of the main urban area of Xuzhou City (34°17′~34°32′ N, 117°17′~117°42′ E) (as shown in Figure 1a), covering an area of 496.59 km^2. It is located in the transitional zone between the North China Plain and the alluvial plain of the Yellow River, characterized by low hills, hillside plains, and alluvial plains. The topography in the study area exhibits a northwest high-to-southeast low pattern. The region experiences a humid and semi-humid monsoon climate, with an average annual temperature of 13.8 °C and annual precipitation of 896 mm. Abundant water resources are present in the area, including the Grand Canal, Bulao River, Tuntou River, Pan'an Lake, and other water systems and lakes. Additionally, there are coal mines such as Qishan, Xinzhuang, Wazhuang, and Quantai, with prolonged and intensive mining leading to ground subsidence. The coal mining subsidence area covers 104.33 km^2. Due to the expansion of subsidence water area, the acceleration of urbanization, and the increase in agricultural fertilizer application, the water quality pollution problem in Jiawang coal mining subsidence area is prominent. It is necessary to provide ideas for the optimization of the water environment in this area, and also to provide evidence for water quality pollution problems in other high-diving mining areas in the east. In order to quantitatively simulate hydrological processes and non-point source pollution, specific research areas are divided, as shown in Figure 1.

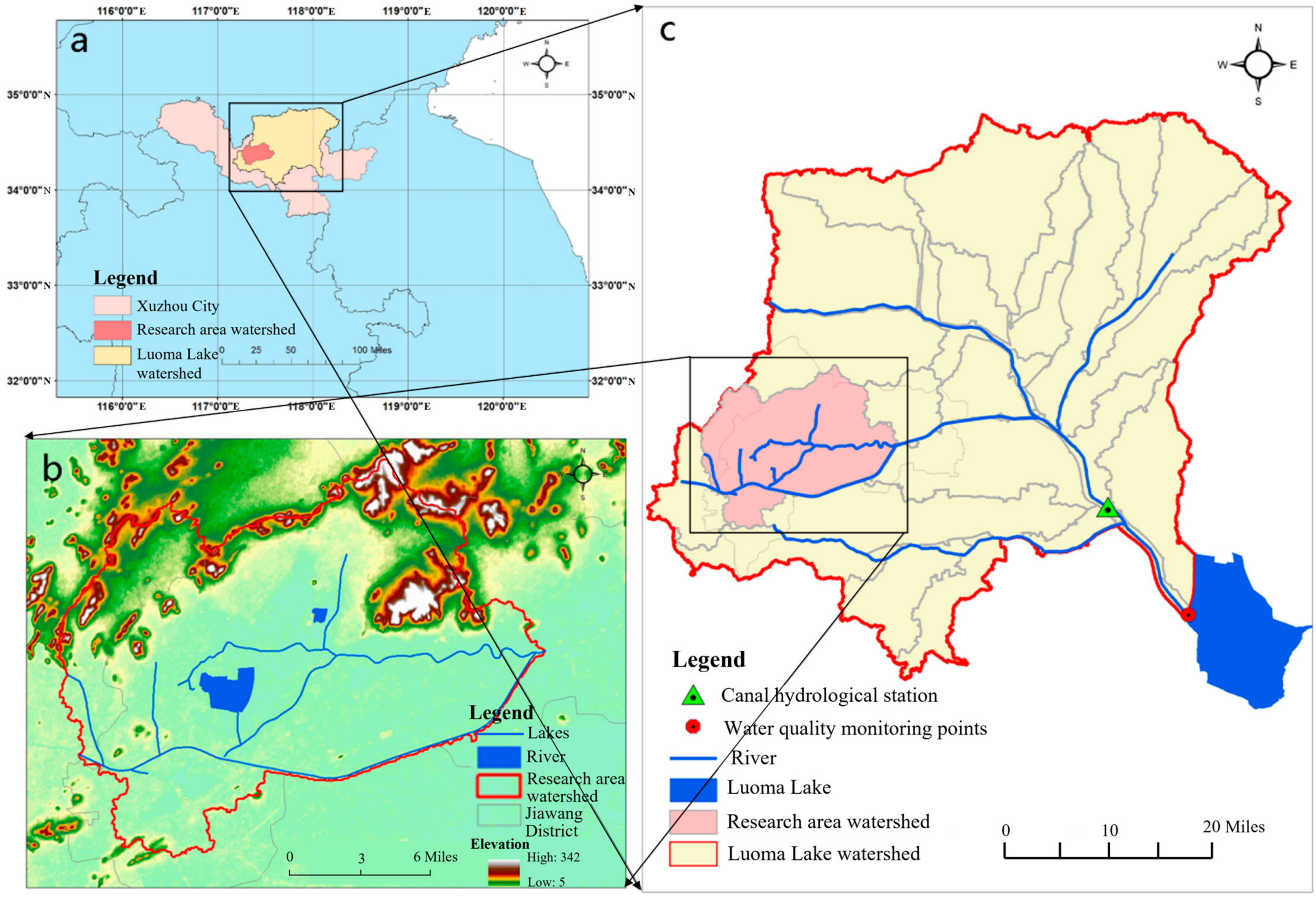


Figure 1. (**a**) The location of the study area in Xuzhou City. (**b**) The location and topography of the Jiawang watershed. (**c**) The spatial relationship between the Luoma Lake watershed and the Bujawang watershed.

2.2. Data Sources

The primary utilized datasets encompass remote sensing imagery, digital elevation model (DEM) data, soil data, meteorological data, runoff data, water quality data, and others. The sources of these datasets are primarily delineated in the following table (Table 1).

Table 1. Basic data collection statistics table.

Data Sources	Data Set Name	Data Content
National Earth System Science Data Sharing Platform (https://www.geodata.cn/ (accessed on 5 January 2024))	1:1,000,000 Soil Type Data of Jiangsu Province	Soil Type Raster Map
Wanfang Data Resource System (https://www.wanfangdata.com.cn/ (accessed on 5 January 2024))	Soil Records of Jiangsu Province	Soil Type Attribute Data
Cold and Dry Region Scientific Data Center (http://bdc.casnw.net/ (accessed on 7 January 2024))	China Soil Dataset Based on the World Soil Database	Soil Type Data Raster Map
91 Satellite map (https://www.91weitu.com/ (accessed on 7 January 2024))	Digital Elevation Model (DEM)	8 m × 8 m Resolution DEM Raster

Table 1. *Cont.*

Data Sources	Data Set Name	Data Content
National Meteorological Science Data Center (https://data.cma.cn/ (accessed on 7 January 2024))	Daily Climate Data Set for China Surface	Daily Precipitation, Temperature, Relative Humidity, Wind Speed, etc. Data from 2000 to 2019
Xuzhou Water Resources Bulletin and Xuzhou Hydrology Records (https://sw.xz.gov.cn/ (accessed on 6 January 2024))	Monthly Streamflow at Canal Hydrological Station	Measured Monthly Streamflow Data for the Years 2015–2018
Xuzhou City Water Resources Bureau (https://sw.xz.gov.cn/ (accessed on 9 January 2024))	Nitrogen and Phosphorus Water Quality Monitoring Data	Measured Water Quality Data for Each Month in the Years 2017–2019

2.3. Data Analysis

2.3.1. SWAT Model

The Soil Water and Assessment Tools (SWAT) is a semi-distributed physical hydrological model developed by the United States Department of Agriculture in the late 20th century [13,14]. Following extensive scrutiny by numerous scholars, the SWAT model has gained widespread recognition as a reliable tool for simulating non-point source pollution at the watershed scale [15–17]. The SWAT model mainly includes a hydrological process submodule, soil erosion submodule, pollution load submodule, and nutrient migration submodule; this article mainly involves the hydrological process and pollution load submodules.

This study utilizes the SWAT model to simulate annual and monthly runoff, total nitrogen, and total phosphorus in the research area. The required data include elevation data, land use data, soil data, meteorological data, and measured hydrological data (as shown in Table 1). In the process of establishing the model, the watershed is defined first, and the "burn-in" algorithm is used to correct the real river based on DEM data. The threshold value of the catchment area is closer to the real situation as seen in several experiments. Then, the river network is edited to determine the water outlet position. The hydrologic response unit is determined by the method of dominant ground cover/dominant soil type. Finally, meteorological and soil data can be imported into the model to run the simulation [18].

After running the simulation, it is essential to calibrate and validate the model's applicability. In the SWAT model, there are numerous parameters influencing runoff, total nitrogen, and total phosphorus. Building upon the parameters selected based on the experience of previous studies, a parameter sensitivity analysis is conducted using the SUFI-2 algorithm within SWAT-CUP [19]. Parameters with p values less than 0.5 are chosen as calibrated parameters, and the iteration is repeated 1000 times to ultimately determine the optimal parameter values.

2.3.2. Time Model

The width of riparian buffer zones influences their functional performance [20], and therefore it is crucial to determine the width of riparian vegetation buffer zones before conducting scenario simulations. In this study, we employed a time model established by Phillips [21] to assess the mitigation of non-point source pollution by riparian vegetation buffer zones. This model measures the pollution removal efficiency of the vegetation buffer zone by comparing the time and energy losses required for runoff to pass through it. Taking into account factors such as topography, soil physicochemical properties, and surface roughness, we utilized geographic information systems (GISs) to draw the variable width of riparian vegetation buffer zones in the study area [22]. The formula for the time model is as follows:

$$\frac{T_b}{T_r} = \frac{B_b}{B_r} = (n_b/n_r)^{0.6}(L_b/L_r)^2(K_b/K_r)^{0.4}(s_b/s_r)^{(-0.7)}(C_b/C_r) \quad (1)$$

In the formula, b and r represent the relevant variables for the planned and reference riparian vegetation buffer zones, respectively. Tb/Tr represents the ratio of the retention time of pollutants in overland and underground overflows in the planned riparian vegetation buffer zone and the reference riparian vegetation buffer zone. Bb/Br represents the ratio of pollutant removal efficiency in the planned and reference riparian vegetation buffer zones. n is the Manning's coefficient for the land surface. L represents the width of the riparian vegetation buffer zone (m), K is the saturated hydraulic conductivity (cm/h), S is the slope (%), and C is the soil water holding capacity (cm). The input parameters are illustrated in Figure 2 [23].

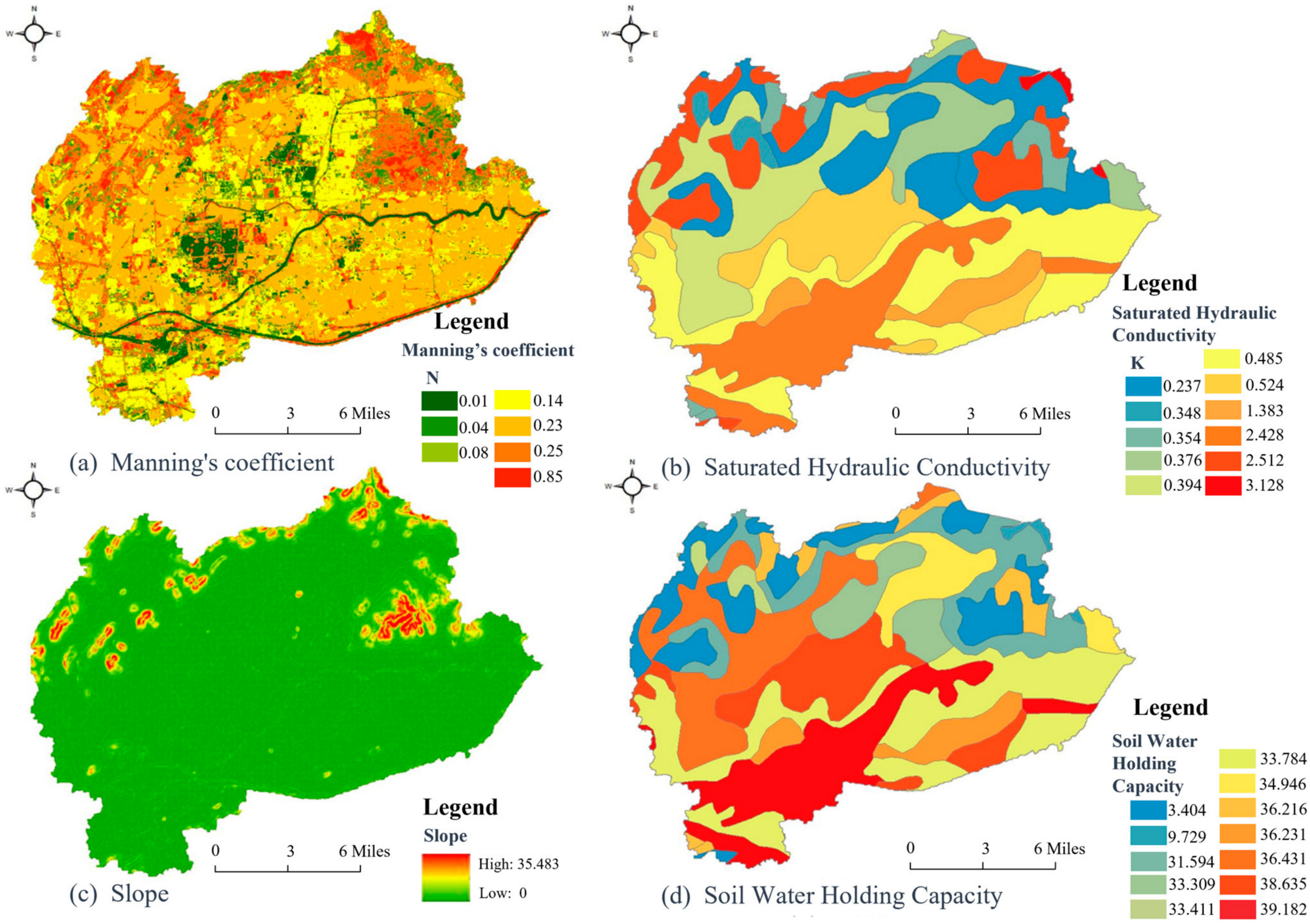


Figure 2. Input data for the time model of the Jiawang watershed. (**a**) Manning's coefficient. (**b**) Saturated hydraulic conductivity. (**c**) Slope. (**d**) Soil water holding capacity.

Substituting the formula p = Bb/Br into Equation (1) and replacing Lp with Lb, we obtain

$$L_p = p^{0.5} L_r \left[(n_r/n_b)^{0.6}(K_r/K_b)^{0.4}(s_r/s_b)^{(-0.7)}(C_r/C_b)\right]^{0.5} \quad (2)$$

2.3.3. Scenario Settings

After the SWAT model meets the accuracy requirements and determines the width of the riparian vegetation buffer zone, the layout scenarios of 5 types of riparian vegetation buffers are set to simulate their effectiveness in preventing and controlling surface source pollution. How to optimize the configuration of riparian vegetation buffer zones is also analyzed.

(1) Simulate the effects of different types of continuous vegetation buffer zones on the mitigation of non-point source pollution. To analyze the impact of riparian vegetation buffer types on non-point source pollution control, the simulated riparian vegetation

buffer zones are converted into forest and grassland and embedded into the current land use raster map to design three scenarios. Based on this, compare the responses of runoff, total nitrogen, and total phosphorus under different scenarios:

Scenario 1: Simulate the current situation of land use (2019) and assess the source pollution status below;

Scenario 2: Embed the calculated vegetation buffer zone in the land use status grid map of the Jiawang River Basin and convert it into forest land;

Scenario 3: Convert the vegetation buffer zone in Scenario 2 to grassland.

(2) Simulate the effects of different types of intermittent vegetation buffer zones on the mitigation of non-point source pollution. Considering that nutrients may enter water bodies with runoff, it is assumed that setting riparian vegetation buffer zones in areas with runoff can intercept most pollutants. To verify this assumption, two scenarios are designed by setting vegetation buffer zones in areas with runoff flow while not setting or setting different types of vegetation buffer zones in other areas:

Scenario 4: The construction land, bare land, and cultivated land within 150 m to 300 m runoff length of simulated vegetation buffer zone were converted into forest land, and the vegetation buffer zone in some areas was restored;

Scenario 5: The vegetation buffer zones in Scenario 4 were converted into grassland.

3. Result and Analysis

3.1. Model Calibration and Validation

The data required for modeling include Digital Elevation Model (DEM) data; daily precipitation, temperature, relative humidity, and wind speed data from four meteorological stations in Xuzhou, Pizhou, Suining, and Feixian for the period 2000–2019; land use data obtained through supervised classification; soil data from the Harmonized World Soil Database (HWSD); measured runoff data from the canal hydrological station; and water quality monitoring data at selected cross-sections.

In this study, the SWAT model was used to simulate the runoff and water quality of the Luoma Lake watershed and Jiawang watershed from 2013 to 2019. Ultimately, the Luoma Lake watershed was divided into 39 sub-watersheds, and the Jiawang watershed was divided into 19 sub-watersheds. Due to the lack of measured runoff and water quality data in the study area's watershed, model parameters were calibrated using nearby Luoma Lake watersheds with similar topography, climate, soil, and land use conditions. The calibrated parameters were then applied to construct the SWAT model for the study area.

Based on the runoff data from the canal hydrological station and water quality monitoring data at the junction of the canal and Luoma Lake, the SWAT-CUP with SUFI2 algorithm was used for global parameter sensitivity analysis, calibration, and validation. The pre-warming period was set as 2013–2014, the flow calibration period as 2015–2017, and the flow validation period as 2018. After flow parameter calibration, the water quality calibration period was set as 2017–2018 and the water quality validation period as 2019. Due to the significant water transfer from the south to north in the study area and Luoma Lake watershed, negative flow values occurred during the dry season. Some months' data were excluded during parameter calibration. The simulated results for monthly runoff rate, monthly total nitrogen load, and monthly total phosphorus load are shown in Figure 3.

Calibration period- and validation period-specific R^2 and Ens evaluation results are shown in Table 2. According to the research on model evaluation standards in the relevant literature (Feng, A.P, 2020) [24], the R^2 of runoff in this study is greater than 0.5, and Ens is greater than 0.35, indicating that the model accuracy meets the requirements.

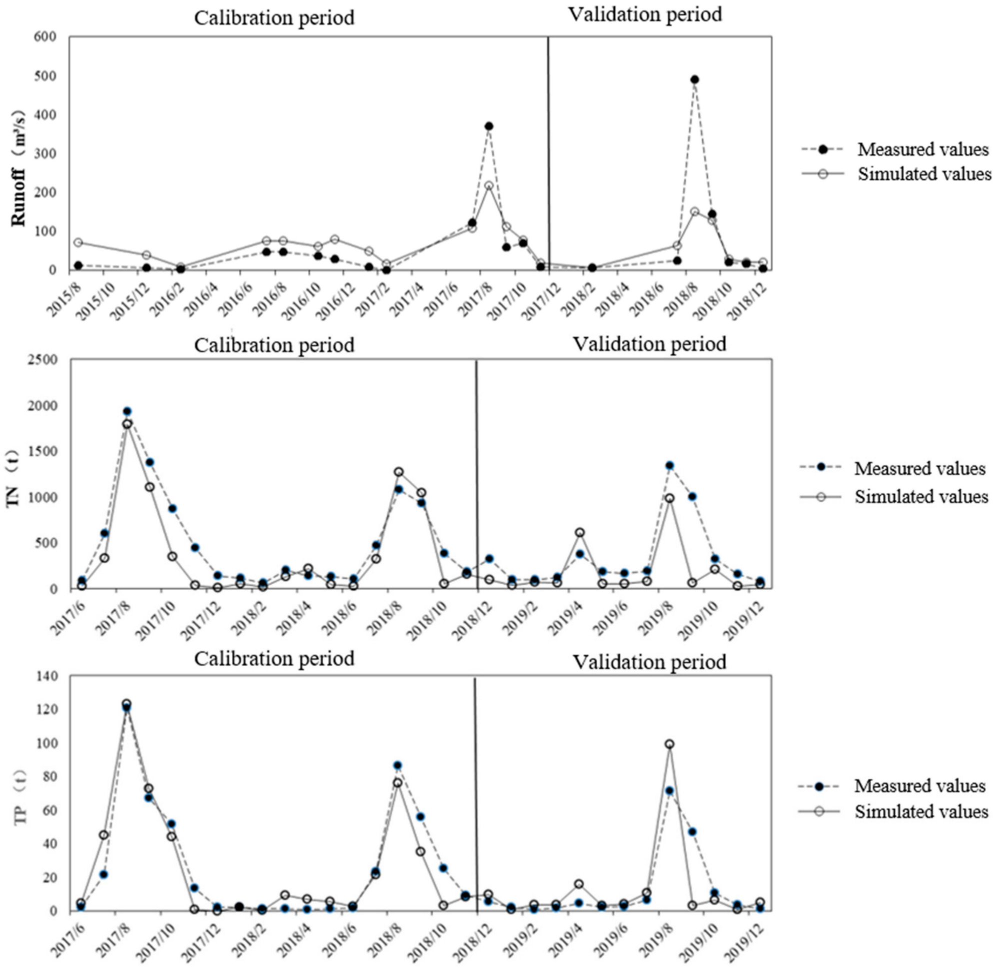


Figure 3. Comparison of estimated and measured values of various parameters during the verification period.

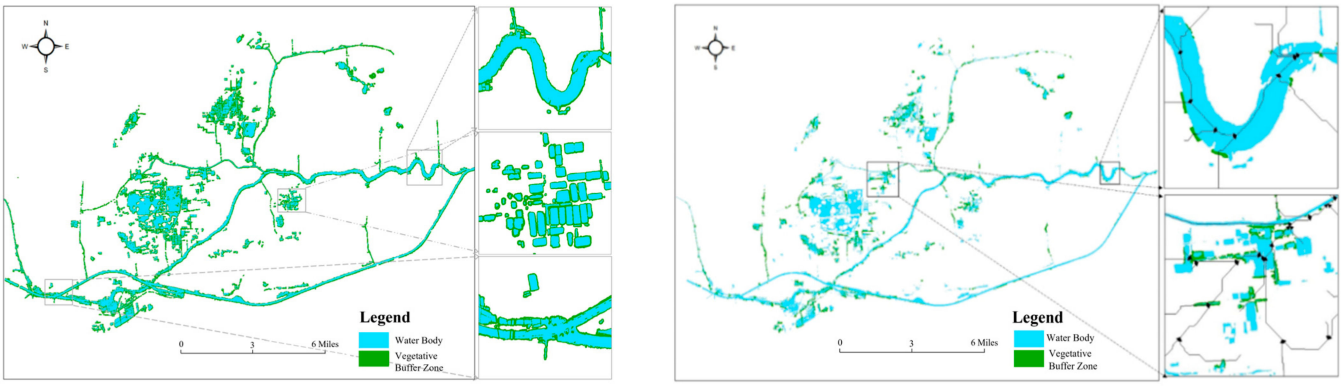
Table 2. Evaluation of runoff and water quality simulation results.

Output Type	Rate Regular		Verification Period	
	R^2	Ens	R^2	Ens
Runoff	0.84	0.68	0.73	0.40
TN	0.89	0.81	0.52	0.36
TP	0.91	0.91	0.65	0.47

3.2. Vegetative Buffer Strip Simulation Result

Based on the time model, the variable riverbank ecological buffer strip in the Jiawang watershed is mainly distributed in the width range of about 28 m to 110 m. According to the simulated results, a total of 25.05 km^2 of the riverbank vegetation buffer strip needs to be constructed in the Jiawang watershed, as shown in Figure 4a.

The riparian vegetation buffer zone has the function of blocking the flow of harmful substances and improving water quality. According to the Time Model, the riparian buffer zone simulated is continuously distributed. In order to study whether the riparian buffer zone needs to be continuously laid out, based on the assumptions of Scenario 4 and Scenario 5, and according to the surface runoff path in the study area, the 150 m to 300 m length riparian vegetation buffer zone with runoff passing through is retained as the area for non-point source pollution prevention and control, as shown in Figure 4b.



(**a**) (**b**)

Figure 4. (**a**) Simulation results of riparian vegetation buffer zone in Jiawang watershed. (**b**) Discontinuous riparian vegetation buffer zone in the Jiawang watershed.

3.3. Scenario Simulation Analysis

(1) Simulating the Effects of Different Types of Continuous Vegetation Buffer Zones on Non-Point Source Pollution Control.

In Scenario 1, the runoff was 6.55 m^3/s, the total nitrogen load was 182,240 kg, and the total phosphorus load was 15,382 kg. Comparing Scenarios 2 and 3 with Scenario 1, it can be observed that the addition of 25.05 km^2 (an increase of 5.05%) of forest and grassland vegetation buffer zones resulted in a reduction in runoff, total nitrogen, and total phosphorus. The runoff in Scenarios 2 and 3 decreased by 0.16 and 0.12 m^3/s, respectively. The total nitrogen load decreased by 12,080 kg and 11,840 kg, and the total phosphorus load decreased by 1412 kg and 518 kg, respectively. The forested buffer zone in Scenario 2, compared to the grassland in Scenario 3, exhibited higher reduction rates in runoff, total nitrogen, and total phosphorus by 0.6%, 0.14%, and 5.81%, respectively. This indicates that both forest and grassland vegetation buffer zones can intercept runoff and mitigate nitrogen and phosphorus pollution. Therefore, the establishment of vegetation buffers is effective in regulating runoff and reducing non-point source pollution. The comparison between Scenarios 2 and 3 shows that, under the same area and form, the forested buffer zone has a stronger capacity for runoff interception and nitrogen and phosphorus reduction, especially in controlling total phosphorus, making it a preferable choice for different regions based on the predominant type of pollutant.

(2) Simulate the effects of different types of vegetation buffer zones on spatial configuration for the prevention and control of non-point source pollution.

When the vegetation type remains unchanged, only buffer zones are set up in the areas where the original vegetation buffer zone runoff passes through. After the area is reduced to 38.48% of the original, it still has the function of intercepting and reducing pollution in the watershed. The setting of vegetation buffer zones in the forest land of the runoff area in Scenario 4 and the grassland of the runoff area in Scenario 5 reduces runoff by 0.05 and 0.03 m^3/s, reduces total nitrogen load by 4700 kg and 4200 kg, and reduces total phosphorus load by 548 kg and 156 kg. Comparing Scenario 4 with Scenario 3, it can be seen that 38.48% of the area of the vegetation buffer zone can achieve the same or an even better interception effect on phosphorus as the grassland vegetation buffer zone. Therefore, it is more important to construct forest vegetation buffer zones for phosphorus interception. Scenario 6 is based on Scenario 4, where the remaining vegetation buffer zone area is set as grassland. It can be seen that compared to Scenario 2, which has the best effect, the interception effect of runoff reaches 84%, and the reduction rates of total nitrogen and phosphorus reach 97% and 58%, respectively. Therefore, considering the cost of vegetation buffer zones and the long time required for forest formation, similar to Scenario 6, a small part of the area is set with forest land, while the remaining areas are set with grassland. This aids in achieving optimal non-point source pollution control while saving costs (Table 3).

Table 3. Simulation results of runoff, total nitrogen, and total phosphorus under different vegetation buffer zones in the Jiawang watershed.

Scenario	Annual Average Runoff (m^3/s)		Total Nitrogen Load (kg)		Total Phosphorus Load (kg)	
/	Simulated Values	Reduction (%)	Simulated Values	Reduction (%)	Simulated Values	Reduction (%)
Scenario1	6.55	—	182,240	—	15,382	—
Scenario2	6.39	2.46	170,160	6.63	13,970	9.18
Scenario3	6.43	1.86	170,400	6.49	14,864	3.37
Scenario4	6.5	0.84	177,540	2.58	14,834	3.56
Scenario5	6.52	0.53	178,040	2.3	15,226	1.01

4. Conclusions and Discussion

This study employed the SWAT model to construct a hydrological model for the Jiangwan area. After calibration and validation, six scenario analyses were conducted to assess the effects of different arrangements of riparian vegetation buffer zones on non-point source pollution prevention and control. The specific conclusions are as follows:

(1) After correcting model parameters using the parameter transfer method in the Jiawang watershed, the evaluation results of the SWAT model were consistent with other relevant studies. Therefore, the SWAT model demonstrates good applicability in simulating runoff, nitrogen, and phosphorus in this region.

(2) A quantitative analysis of the effects of riparian vegetation buffer zones on non-point source pollution prevention and control reveals the following: Compared to the baseline Scenario 1, the introduction of vegetation buffer zones in Scenarios 2 and 3 resulted in respective average annual reductions of 2.46% and 1.86% in runoff, 6.63% and 6.49% in total nitrogen, and 9.18% and 3.37% in total phosphorus. Continuous vegetation buffer zones can regulate runoff and alleviate non-point source pollution, with forested areas exhibiting better control over total phosphorus and total nitrogen compared to grassland.

(3) Simulation results for vegetation buffer zones set only in areas where runoff passes through indicate that in Scenarios 4 and 5, the average annual runoff decreased by 0.84% and 0.53%, total nitrogen decreased by 2.58% and 2.30%, and total phosphorus decreased by 3.56% and 1.01%, respectively. Although vegetation buffer zones without continuous deployment still play a role in preventing and controlling non-point source pollution, their interception efficiency decreases. However, in scenarios without the continuous deployment of vegetation buffer zones, forested areas exhibit slightly better efficiency in intercepting total phosphorus compared to continuously deployed grassland vegetation buffer zones. Therefore, when arranging vegetation buffer zones in practice, it is advisable to adapt the strategy based on the types of main non-point source pollutants and the available area for buffer zone deployment, achieving optimal non-point source pollution prevention and control effects at a relatively lower cost.

But with population growth and economic development, the demand for water resources continues to increase, leading to the excessive exploitation and utilization of water resources. This can lead to a decrease in groundwater level, wetland degradation, and river drying, affecting the stability and sustainability of aquatic ecosystems. Fertilizers and pesticides used in agricultural activities can also enter water bodies through runoff, causing water quality deterioration and ecosystem imbalance. Therefore, while considering economic benefits, social and ecological benefits also need to be considered.

The riparian vegetation buffer zone, composed of forests, grasslands, and shrubs on both sides of a river, plays a crucial role in preventing pollutants from runoff entering water bodies. Its significance extends to the long-term development of water and ecological environments, garnering widespread attention from both the academic community and government agencies. The effectiveness of riparian buffer zones is influenced by various factors such as width, vegetation types, and layout.

The zoning of a territory based on surface runoff by the type of land use is a critical aspect of hydrological management, particularly in assessing the impacts of human activities on water resources. This zoning typically involves categorizing areas such as reserves, agricultural land with considerations for erosion processes, recreational areas, and zones earmarked for residential and industrial development. Such categorization often relies on available statistical data, which are influenced by factors like population density, income levels, and other socio-economic indicators [25].

Numerous scholars globally have conducted extensive research on the width of riparian buffer zones, ranging from 15 m to 200 m. However, there is currently no unified standard as different requirements may dictate different widths, with a prevailing belief that wider buffer zones are more effective than narrower ones [26,27]. Regarding vegetation types, studies by Noe, Boomer, Gillespie, and others suggest that forests are more effective than grasslands in trapping nitrogen, aligning with the simulated results in this paper. However, divergent opinions exist; for instance, Hill et al. [28]. found that grasslands have a stronger ability to remove nitrogen than forests. These discrepancies may stem from differences in regional soil and geological conditions, variations in the growth conditions of herbaceous and woody plants, and different research methodologies.

While much research has focused on the width and vegetation types of riparian buffer zones, attention to buffer zone length has been relatively limited. Stanford et al. discovered that in situations where land availability is limited, long and narrow riparian buffer zones can effectively alleviate aquatic pressure sources. LM de Oliveira et al. [29]. also recommend continuous riparian buffer zones. Addressing the issue of discontinuous placement, Brumberg Hilary et al. [30] argued, based on a case study in Costa Rica, that riparian buffer zones should be at least 500 m long to protect water quality. They emphasized that buffer zone length has a more significant impact than width because land use along the riverbanks significantly affects water quality within 1 km downstream. While this conclusion has not been universally confirmed, it underscores the need for riparian buffer zones to be of a certain length to achieve the desired effects. In the absence of continuous deployment, the effectiveness of each short segment of the riparian buffer zone in preventing and controlling non-point source pollution diminishes.

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