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Impact of Riparian Buffer Zone Design on Surface Water Quality at the Watershed Scale, a Case Study in the Jinghe Watershed in China

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Abstract: This study was conducted to evaluate the impact of riparian buffer zones on water quality in the Jinghe watershed, China. To evaluate the effectiveness of riparian buffers in reducing sediments and nutrients in surface runoff, we employed two validated models: the agricultural non-point source pollution model (AnnAGNPS) and the riparian ecosystem management model (REMM). The AnnAGNPS was used to divide the catchment into homogeneous drainage areas and generate upland loadings for the REMM. The REMM model was then utilized to assess the impact of different riparian buffer designs on sediments and nutrient reduction in surface runoff. We tested five designs, including the recommended standard design by the United States Department of Agriculture (USDA). This design with 20 m herbaceous perennials next to the field (Zone 3), followed by a 20 m wide harvestable deciduous forest in the middle (Zone 2), and a 10 m wide non-harvestable deciduous forest adjacent to the river (Zone 1). We also evaluated alternative designs, such as removing Zone 3, removing Zone 2, and reducing the widths of the buffer zones further. For the entire Jinghe watershed, we calculated, compared, and analyzed the annual totals of water inflow, sediment yields, and dissolved nitrogen in surface runoff into and out of Zone 1, 2, and 3 for all the designs. The analysis indicated that the removal efficiency of sediments ranged from 85.7% to 90.8%, and the removal efficiency of dissolved nitrogen in surface runoff ranged from 85.4% to 91.9% for all the designs. It is also indicated that riparian buffer zones are highly effective in reducing sediments and nutrients in agricultural runoff, even with reduced buffer widths. This finding underscores the importance of implementing riparian buffer zones as a valuable approach in the agricultural intensive watershed with constraints for allocating for the creation of standard riparian buffers.

Keywords: AnnAGNPS; dissolved nitrogen; REMM; riparian buffer; river water quality; sediment

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1. Introduction

Food security has always been a critical issue for our society [1]. In China, food security is a high-priority issue, and it is challenged by several factors, including population growth, urbanization, industrialization, etc. [2]. These factors have generated inevitable pressure on agricultural production [3]. During the past decades, more and more lands have been converted to crop fields, and many agricultural lands have been expanded to the edge of riverbanks [4]. Direct discharge of chemicals and sediments into the surface water system has resulted in water pollution on a large scale, which in turn has reduced the usable water in China [5]. In China, water resources and watershed processes have become a top research priority.

The Jinghe watershed is a typical agricultural-intensive area with rapid urbanization in the last decades, which is suffering from serious soil erosion and facing ecological challenges between urbanization and conservation [6]. The non-point sources (NPS) pollution emphasized by human activities is a major challenge to improving the aquatic environment [7,8]. The whole Jinghe watershed is the key area to improve the water quality and to protect the watershed ecosystem in the loess plateau area in China.

Riparian buffer zones are revealed to be effective in reducing pollutants and sediment loadings into the surface water systems and managing water resources [9–12]. Riparian buffer zones act as ecological safeguards for surface water bodies by mitigating non-point source pollutants emanating from terrestrial ecosystems [13]. The riparian buffer zone can modify the overland flow, promote sediment deposition, and enhance nutrient filtering [14]; converting riverside croplands into riparian buffers is assumed to be beneficial to surface water systems.

The design and management of these zones at a landscape scale are significantly influential to their effectiveness in improving water quality [15]. While riparian buffers are widely recognized for their ecological services, their implementation at a landscape level and its consequent effects on water quality can be influenced by a variety of complex and interacting factors, including land use, vegetation type, and climate conditions (Fischer and Fischenich, 2000) [16].

Studies show that the design and management of these zones significantly impact their effectiveness in protecting surface water quality, particularly at the watershed scale [17].

Many factors influence the effect of riparian buffers on runoff and pollutant reduction [18], and buffer width is one of the most important ones [19]. Most studies have proven that wider buffers with denser vegetation have a higher protection capability [20]. On the other hand, Richardson et al. (2012) [21] suggested that a narrow buffer is effective in mitigating environmental pollution. In the U.S., studies of simulating riparian buffer zones have been conducted for a long time; however, few studies have been conducted in China, which is the largest agricultural country in the world. Studies are needed to find an optimized design for converting riverside crop fields to riparian buffers in the Jinghe watershed based on its typical natural and agronomic management conditions.

While the importance of riparian buffers in preserving water quality is globally recognized, understanding the intricacies of their impact, particularly in varying land use, vegetation, and climate conditions, has been complex [22,23].

Computational modeling has emerged as an important tool in understanding and predicting these complexities, enabling the assessment of potential impacts of varying buffer zone designs under different scenarios.

Several sophisticated watershed-scale hydrological models, such as SWAT (soil and water assessment tool), HSPF (hydrological simulation program—Fortran), and Mike SHE, have been utilized to study the effects of riparian buffers on water quality [24–26]. However, these models often fall short of providing detailed simulations of riparian-specific processes.

In light of the complexity of riparian processes, our study employs the integrated use of the AnnAGNPS (annualized agricultural non-point source) and REMM (riparian ecosystem management model) models. AnnAGNPS provides a comprehensive simulation framework for agricultural non-point source pollution, including the transport of sediments and nutrients under varying land use scenarios [27,28]. In China, the AnnAGNPS is widely applied to simulate hydrological processes and non-point source pollution. Jiang et al. (2019) [18] used the AnnAGNPS model in the Wucun watershed, China, with a focus on selecting the optimum buffer width for the implementation of riparian reforestation. Zhang et al. (2019) [29] used the AnnAGNPS model to evaluate the effectiveness of best management practices (BMPs) for control of non-point source pollution in the Three Gorges Reservoir Area in China. In general, the AnnAGNPS seems to be an appropriate option for NPSP modeling in China at large study areas and long-term temporal scales [30]. Most importantly, the AnnGGNPS model even has a component to evaluate the contribution of riparian zones to sediment/nutrient trapping efficiency.

Meanwhile, REMM is a process-oriented model that accurately simulates biogeochemical transformations within riparian zones. REMM has been used to simulate the effect of riparian buffers on reducing sediment, nitrogen (N), and phosphorus (P) at the field scale, allowing a thorough examination of riparian buffer designs [31,32].

In this study, we combine the capabilities of AnnAGNPS and REMM to evaluate the impact on water quality by converting riverside crop fields to riparian buffer zones in the Jinghe watershed, China. The objectives include (1) to evaluate the reduction of water, sediments, and nitrogen of a standard riparian buffer, (2) to assess the impact of reducing sediments and nutrients of narrower riparian buffers by reducing zones width, and (3) to estimate the effect of vegetation types on reducing sediments and pollutants.

2. Materials and Methods

2.1. Study Area

The study area is the Jinghe watershed (106°14′ to 108°42′ E, 34°46′ to 37°19′ N) of the Weihe River basin in the middle part of the Yellow River basin in China (Figure 1). The Jinghe River is the primary tributary of the Weihe River, with a total length of 483 km. The Jinghe watershed is the second largest catchment of the three catchments of the Weihe basin, and it drains 45,421 km^2, which accounts for 33.85% of the total drainage area of the Weihe basin [33].

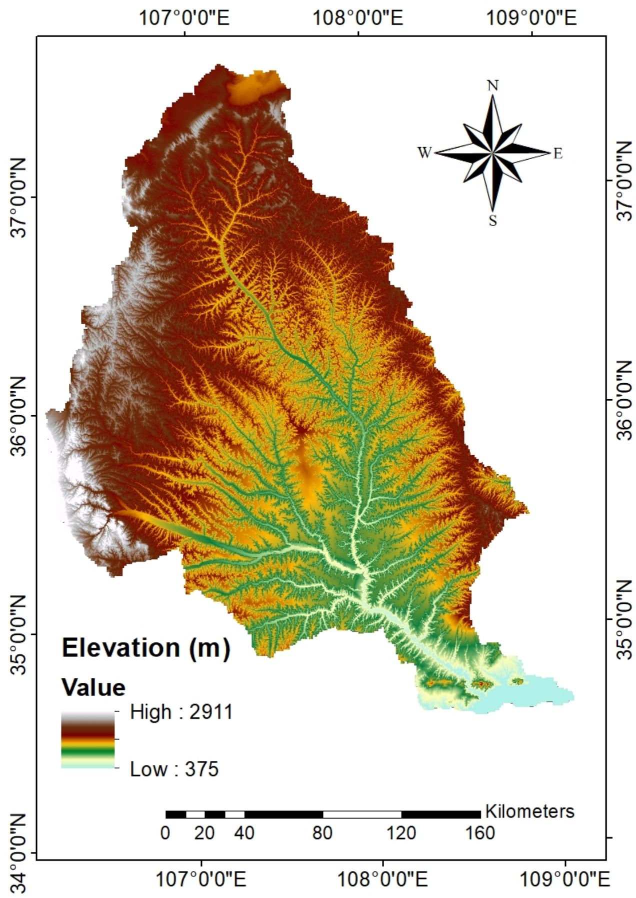

Figure 1. The Jinghe watershed.

In the Jinghe watershed, the average annual temperature is 8 °C and the annual amount of precipitation is 350 to 600 mm. The major crops grown in the Jinghe watershed are corn and winter wheat. The dominant soil is Loess soil (Huangmian soil), which occupies most of the catchment [33].

2.2. AnnAGNPS Model Description

AnnAGNPS is a continuous-simulation, daily time step, and watershed-scale model developed to evaluate non-point source pollutants from agricultural fields based originally on the single-event model AGNPS [34]. It mainly simulates runoff, sediments, and nutrient loadings exiting from agricultural fields through drainage channels. With the use of the model, a watershed could be divided into user-identified homogeneous, drainage-area-determined cells based on the topographic information. From individual cells, runoff can be predicted from precipitation events. The required input data for the model includes topography data, land use and management data, soil data, and climate data.

2.2.1. Topography Data

A 90 m × 90 m digital elevation model (DEM) of the Jinghe watershed was acquired from the Loess Plateau Data Center (LPDC) [35].

The overall terrain of the Jinghe River Basin is tilted from the northwest and east to the southeast with an elevation of 689–2789 m; however, the most sensitive area with intensive agriculture is distributed in the valley plain. The mountain region in the east and west edges only accounts for less than 15% of the total area, and these areas are mostly covered by forest without many pollution and erosion issues. It has been widely reported that runoff modeling is sensitive to the resolutions of the DEMs; the finer the DEM resolution, the more the runoff. However, the changes in the DEM resolution did not show a certain pattern with runoff output [36,37]. As reported by Nazari-Sharabian et al. (2019) [38], the 30 m DEM generated 1.97% more runoff compared with the 90 m DEM, but the overall distribution of runoff in the sub-watersheds has not shown a significant difference. Our study aims to evaluate the effectiveness of different buffer designs based on the comparison, and the magnitude of the runoff with an accuracy of no more than 5% will not affect the result. We, therefore, used 90 m × 90 m of DEM to enhance the efficiency of the modeling.

The DEM was used to identify the topographic information, define surface drainage channels described as "reaches" and subdivide watersheds into multiple drainage areas along the channels described as "cells".

The size of the cell depends on two important parameters, the critical source area (CSA) and the minimum source channel length (MSCL). The CSA is defined as the minimum upstream drainage area above which a source channel is maintained. The MSCL is the minimum acceptable length of the cell for the source channel to exist. In this study, a CSA of 1000 ha and an MSCL of 2000 m were decided to divide the Jinghe watershed into 4290 cells with an average cell area of around 1050 ha.

2.2.2. Land Use and Management Data

The land use data were obtained from the LPDC [35]. In the Jinghe watershed, two typical deciduous trees, willows and poplars, constitute most non-agricultural areas. Corn and winter wheat are the dominant crop types in arable areas. In this study, there were a total of four land use types classified: "deciduous forest", "corn", "winter wheat" and "developed" (Figure 2).

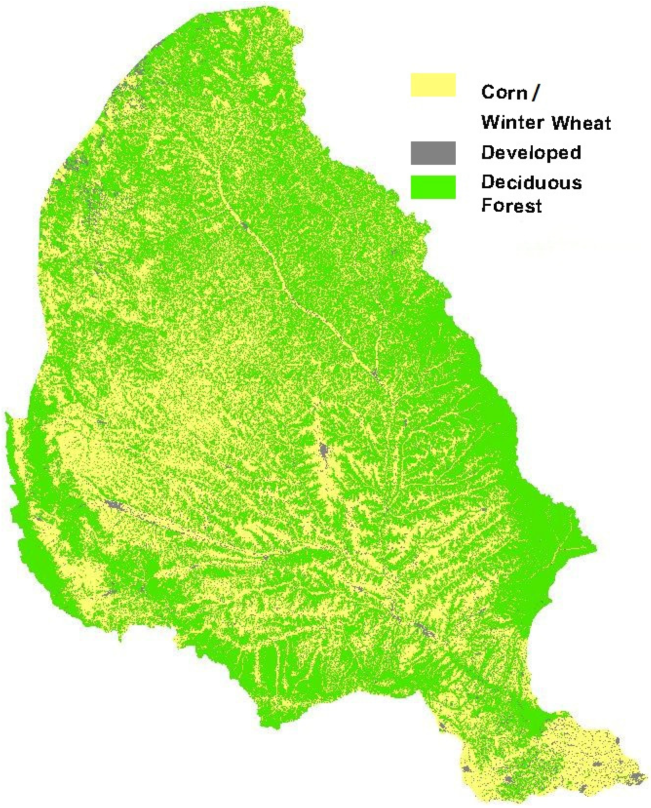

Figure 2. Land use in the Jinghe watershed.

The land management information includes tillage, fertilizer, seeding, and harvesting, which was obtained from the Revised Universal Soil Loss Equation (RUSLE) database provided by the Natural Resources Conservation Service (NRCS) [39]. For the 'corn' and the 'winter wheat' land use types, the detailed management operations are listed in Table 1.

Table 1. Management operations in the Jinghe watershed for AnnAGNPS.

Date (Day/Month)	Operations of Corn	Operations of Winter Wheat
1/11	Tillage	
10/4	Fertilizer	
1/5	Tillage	
10/5	Seeding	
10/6	Fertilizer	
20/10	Harvesting	
11/10		Tillage
13/10		Seeding
10/3		Fertilizer
1/7		Harvesting

2.2.3. Soil Date

The soil data were obtained from LPDC [35]. There are 10 major soil types in the Jinghe watershed: red soil, Rhogosol, aquic soil, Fluvent soil, Huang mian soil (Loessent), light brown earth, Heilu soil, cinnamon soil, Solonchak, and Aeolian sand soil.

For each soil type, AnnAGNPS requires data on different physical and chemical properties of all the soil layers. These properties include layer number, layer depth, bulk density, clay, silt, sand, rock and very fine sand ratio, $CaCO_3$ content, saturated conductivity, field capacity, wilting point, pH, and organic matter ratio. Properties of each soil type were obtained from the China Soil Database [40].

2.2.4. Climate Date

The AnnAGNPS required daily climate data consisting of maximum and minimum air temperatures, precipitation, dew point temperature, sky cover or solar radiation, and wind speed. Except for solar radiation data, all other climate data were obtained from the National Oceanic and Atmospheric Administration [41]. Solar radiation data were obtained from OpenEI Datasets [42].

Due to the large site spatial variation of the Jinghe watershed, four climate stations (HUNGTE, PINGLIANG, XIFENGZHEN, and CUIMU) were selected to generate the climate input files. Using the Thiessen Polygon method in ArcGIS, the Jinghe watershed was divided into four polygons, where each polygon contains one climate station. Any AnnAGNPS cells within the same polygon used the climate data for the station in that polygon.

All the climate data were selected for the historical period from January 1973 to December 1977. The historical climate data were further processed to daily typical climate data of one typical meteorological year using the climate generation models preGEM and agGEM provided by USDA [43]. As an example, Figure 3 shows the daily maximum and minimum air temperatures and precipitation of the typical meteorological year of the CUIMU climate station.

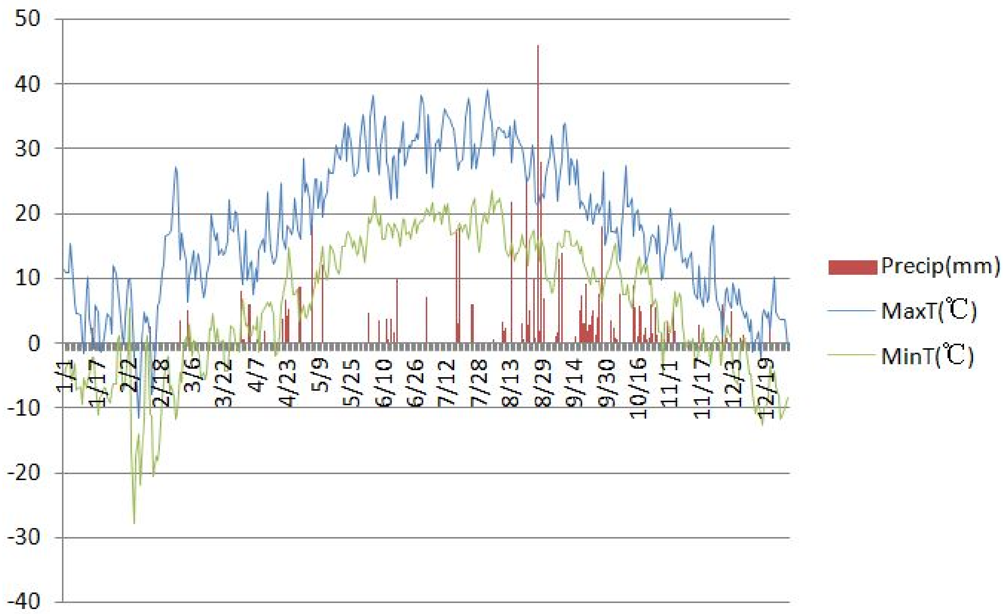

Figure 3. Daily max and min air temperatures and precipitation of CUIMU station.

2.2.5. AnnAGNPS Output

The AnnAGNPS output data include runoff, sediments, and nutrient loadings on a daily, monthly, and yearly basis. Output parameters can be specified for any user-designated watershed source location, such as specific cells and reach [44]. In this study, daily output data of runoff depth, sediments, and nutrient yields for each cell were obtained and used as the upland loadings for REMM.

2.3. REMM Model Description

REMM [45] was developed by USDA-ARS to simulate surface and subsurface hydrology, movement and deposition of sediments, dynamics of carbon, nitrogen and phosphorus, and vegetation growth at the field scale [46]. The riparian ecosystem characterized in the model consists of three buffer zones (Zone 3, Zone 2, and Zone 1) parallel to the stream [45], which are shown in Figure 4. Required input data for REMM include climate data, upland loadings, buffer structure parameters, and vegetation data for each buffer zone.

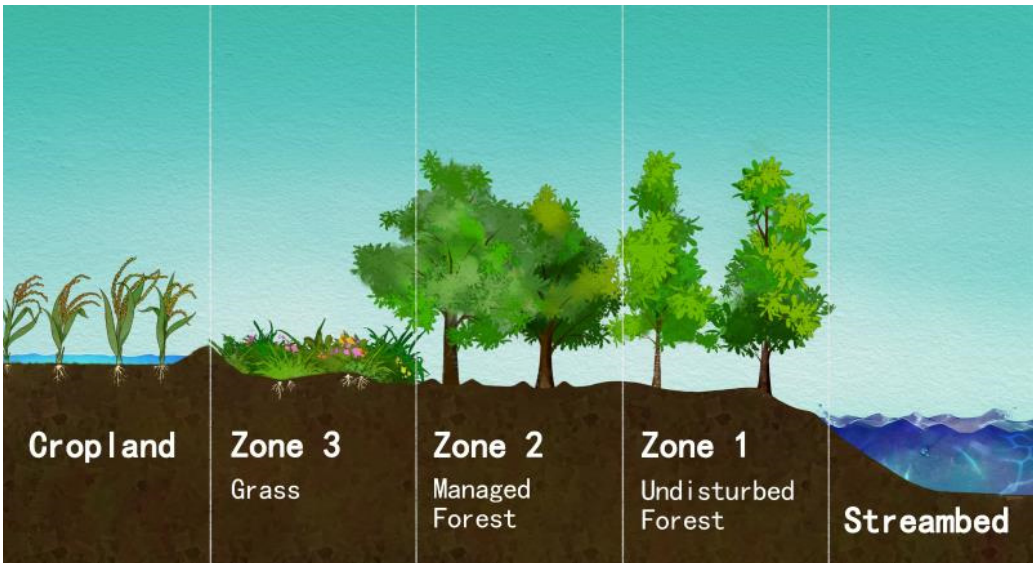

Figure 4. Three buffer zones (Zone 3, Zone 2, and Zone 1) parallel to the stream.

The climate data for REMM were the same as the climate data for AnnAGNPS. The upland loadings were obtained from the outputs of AnnAGNPS. For the buffer structure parameters, two major parameters, "buffer width" and "vegetation type", were designed for each zone. For the vegetation data, the default value for the most basic information on vegetation, such as the percent area covered in each zone and the dry weight of different plant organs, was used [45].

2.3.1. Buffer Widths and Vegetation Types

To evaluate the effectiveness of riparian buffers in reducing sediments and nutrients, five designs of the riparian buffer with different buffer widths and vegetation types were conducted in the study.

Following the suggestions of USDA [47] on buffer width design, the standard design (Design 1) was constructed with 20 m herbaceous perennials, 20 m harvestable deciduous upper canopy forests, and 10 m non-harvestable deciduous upper canopy forests for Zones 3 (next to the field), 2 (zone in the middle), and 1 (next to the river), respectively.

In China, a relatively small per capita land area calls for testing the effectiveness of narrower riparian buffers. In this study, Design 2 was conducted by taking out Zone 3, and Design 3 was conducted by taking out Zone 2 from the standard design. For Designs 4 and 5, the vegetation types were kept the same, and the widths of Zone 3 and Zone 2 were further reduced by 50% from Designs 2 and 3. In all the designs, Zone 1 was kept as a 10 m non-harvestable deciduous upper canopy. Table 2 shows the details of the five designs concerning buffer widths and vegetation types.

Table 2. Designs of the riparian buffer zones.

Zones	Designs	Design 1	Design 2	Design 3	Design 4	Design 5
Zone 3	Zone Width (cm)	20	0	20	0	10
	Vegetation Type	A	none	A	none	A
Zone 2	Zone Width (cm)	20	20	0	10	0
	Vegetation Type	B	B	none	B	none
Zone 1	Zone Width (cm)	10	10	10	10	10
	Vegetation Type	C	C	C	C	C

Notes: A herbaceous perennial. B harvestable deciduous upper-canopy forests. C non-harvestable deciduous upper canopy forests.

2.3.2. Process of Running REMM

REMM was run for each cell for 365 days of the typical meteorological year for all five designs. REMM provides users with annual, monthly, and daily output data. For this study, the annual outputs of REMM were selected. All outputs for each cell generated from REMM were unit-area (per hectare drainage area above the measurement point) data. The unit-area output data for each cell were multiplied by the cell area, and results were further summed up to obtain the total value for the Jinghe watershed. The total value was then divided by the total area of the Jinghe watershed to obtain the grand average of output variables of water inflow, sediments, and dissolved nitrogen over the whole catchment.

2.4. Test of the Model

The models were evaluated on an experimental riparian site at the Gibbs Farm in Tifton, Georgia, using data published by Yuan et al. (2007) [48]. The area of the contributing upland field to the riparian site was 0.31 ha. The upland field was mainly cultivated with corn, and the dominant soil type was Tifton loamy sand. With the use of a 1 arc-sec resolution DEM of a small watershed named the Little Watershed, a single cell was defined by AnnAGNPS. Then, this single cell was assigned with the land use type as corn and the soil type as Tifton loamy sand according to the condition of the upland field. The AnnAGNPS outputs of the cell were then used as the upland inputs for REMM to simulate the riparian buffer zone.

The DEM data were obtained from the National Hydrography Dataset (NHD) of the United States Geological Survey (USGS) [49]. The land use data were obtained from the Cropland Data Layer (CDL) of USDA [50]. The soil data were obtained from the Soil Survey Geographic (SSURGO) Database of USDA [51]. The same climate input data collected at the riparian site were used for both AnnAGNPS and REMM. The buffer characteristics of the riparian site were designed by using the REMM editors based on the detailed description provided by Inamdar et al. (1999) [52,53].

3. Results

3.1. Evaluation of Model Performance

For the experimental riparian site at the Gibbs Farm in Tifton, Georgia, the output results of AnnAGNPS and REMM were compared with published results. Table 3 shows the AnnAGNPS and the REMM simulated results compared with the published results [30].

Table 3. AnnAGNPS and the REMM simulated results compared with the published results.

Date (Month/Day)	AnnAGNPS Simulated	REMM Simulated	Published [48]
Surface runoff (mm)	229.7		216.9
Sediment Loading (kg/ha)	990.6		1236.8
N in surface runoff (kg/ha)	7.8		8.5
Into Zone 3 (mm)		235.6	216.9
Into Zone 2 (mm)		142.1	141.3
Into Zone 1 (mm)		85.4	88.0

The errors between the published data and the AnnAGNPS simulated results of surface runoff, sediment loading, and nitrate in surface runoff are 0.06, 0.2, and 0.08, respectively, while the errors between the published data and the REMM simulated results of surface runoff into Zone 3, Zone 2, and Zone 1 are 0.07, 0.006, and 0.03, respectively. Based on these comparisons, both models were considered acceptable for this study.

3.2. Reduction in Water, Sediments, and Nitrogen for the Standard Design

3.2.1. Total Water Inflow

For the standard design, the annual total water inflow goes into Zones 3, 2, and 1 and out of Zone 1 for the whole catchment, as shown in Figure 5. The reduction of water inflow through the riparian buffer zones over the whole catchment is 24.61 mm, with a reduction rate of 6.6%. The reduction of water is low because of the saturation of the soil. The water inflow in terms of watershed hydrology and groundwater recharge plays a significant role in re-establishing the balance between the amount of groundwater withdrawal and, therefore, ensuring longer-term ecosystem health and function across the watershed [54]. Our result indicates that the reduction of water inflow through the riparian buffer zones over the whole catchment is 24.61 mm, with a reduction rate of 6.6%. Compared with the reduction of sediment and dissolved nitrogen in surface runoff, it is also indicated that the effect of the buffer is not functioning by the reduction of water.

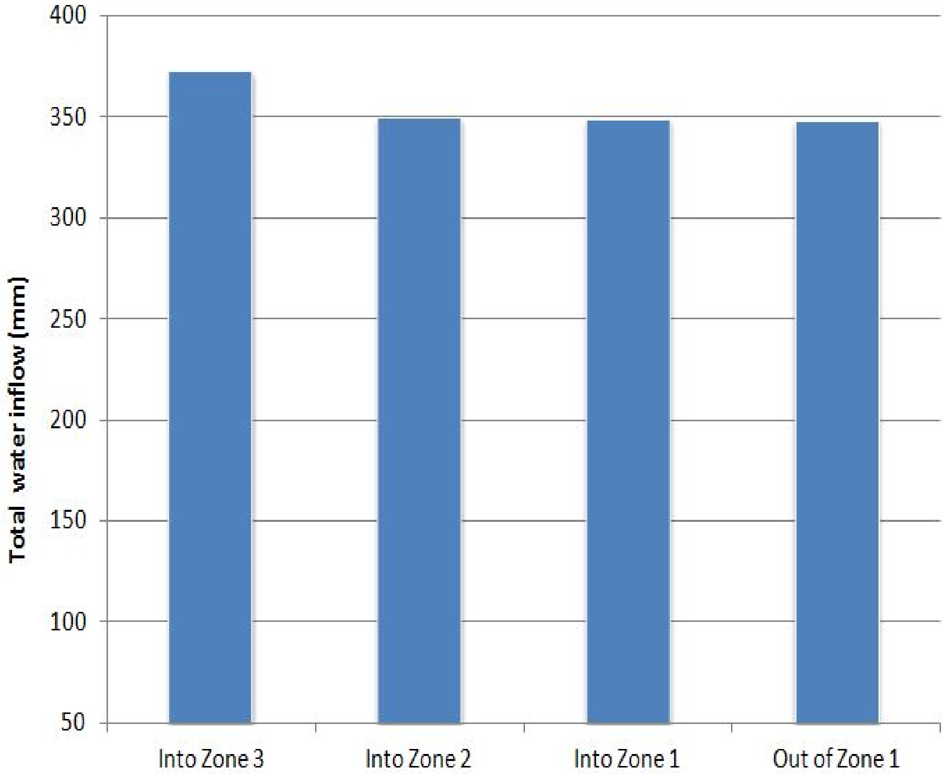

Figure 5. Annual total water inflow into Zones 3, 2, 1, and out of Zone 1 for the whole Jinghe watershed for the standard design.

3.2.2. Sediments and Dissolved Nitrogen in Surface Runoff

In agricultural-intensive areas such as the Jinghe Watershed, nitrogen is usually the most concern for water quality because nitrogen is used in agriculture to grow crops. The Jinghe River flows over the most erosive area in the yellow river; sediment from upland and channel erosion is always a serious concern. Excessive sediment input can have detrimental effects on the catchment ecosystem and health, control of sediment input to the watershed is a crucial matter [55]. Our result indicates that the riparian buffer plays a significant role in reducing sediment and nitrogen in the river. For the standard design, annual total sediments and annual total dissolved N in surface runoff flow into Zones 3, 2, and 1 and out of Zone 1 for the whole catchment are shown in Figures 6 and 7. The annual total reduction of sediments through the buffer zones for the whole catchment is around 6.02 million tons, with a reduction rate of 90.8%, while the annual total reduction of dissolved N in surface runoff is around 0.07 million tons at a rate of 91.9%.

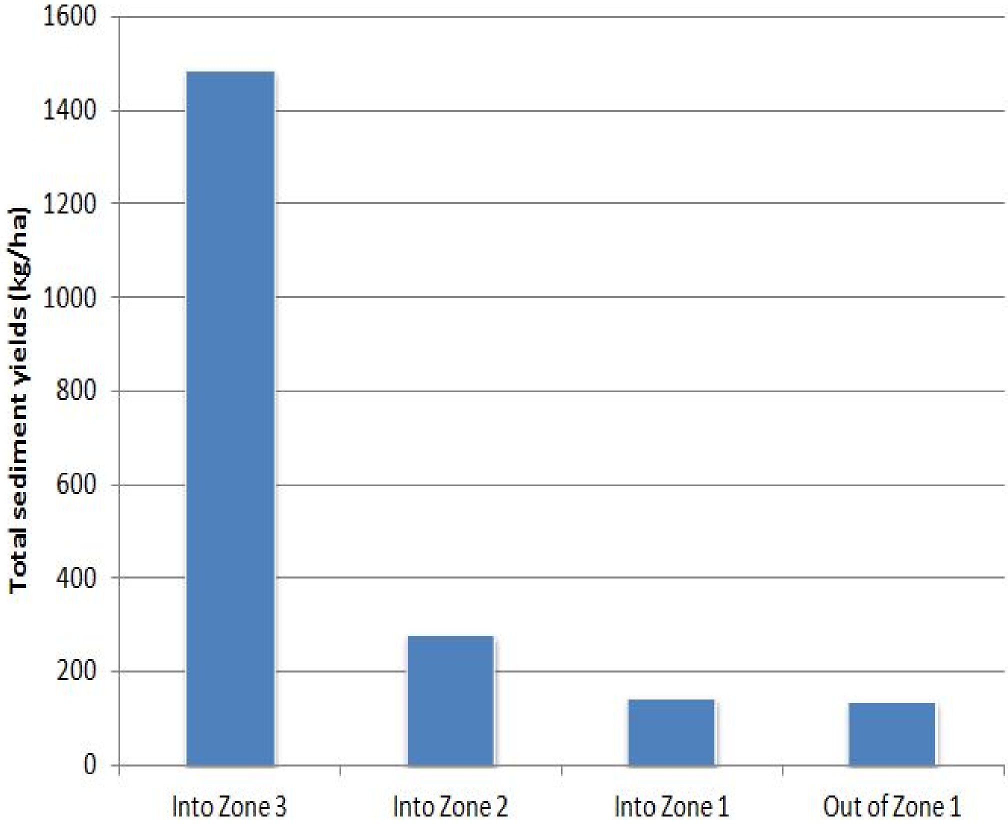

Figure 6. Annual total sediments into Zones 3, 2, 1, and out of Zone 1 for the whole Jinghe watershed for the standard design.

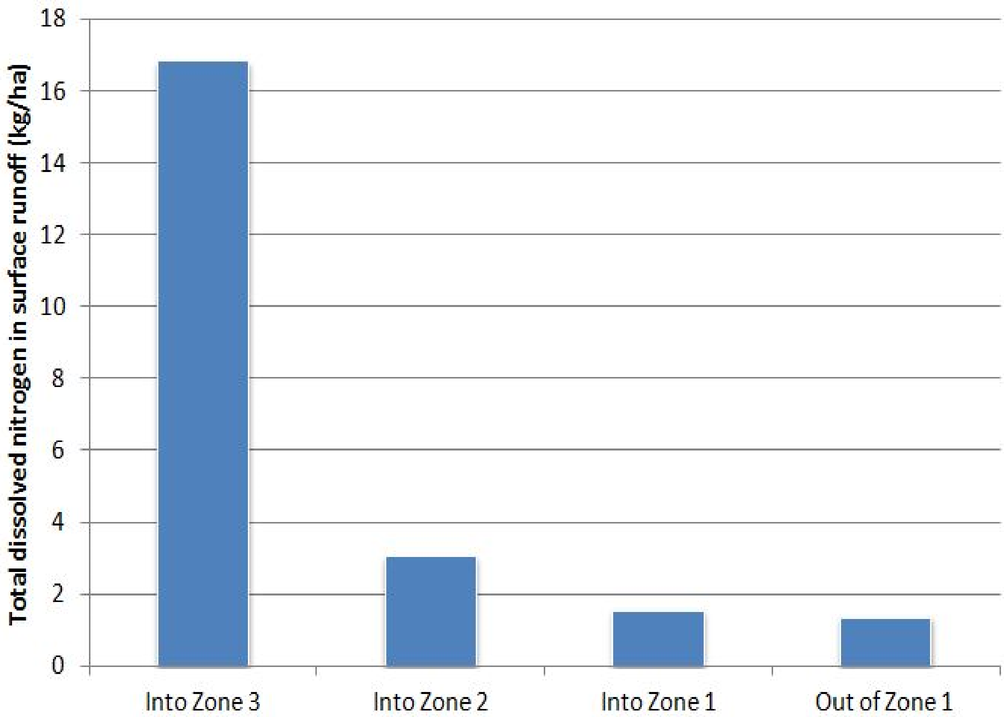

Figure 7. Annual total dissolved N in surface runoff into Zone 3, 2, 1, and out of Zone 1 for the whole Jinghe watershed for the standard design.

In riparian buffers, trees and grasses help to trap sediments by slowing down the runoff from the upland, making the sediment settle out. Plants in riparian buffers are able to maintain nitrogen by having denitrifying bacteria on the roots. The denitrification process is innocuous, which allows the excess nitrogen to be used by the vegetation of the riparian buffer rather than enter the river. Our result indicates that the riparian buffer plays a significant role in reducing sediment and nitrogen in the river.

With the reduction results, more than 90% of the sediments and dissolved N were reduced by the designed riparian buffers. The effectiveness of the standard design of riparian buffers is great for the whole Jinghe watershed.

3.3. Effect of Riparian Buffer Zone Designs

3.3.1. Effect of Reducing Numbers of Zones

The effect of reducing the number of zones on removing sediments and N was estimated by comparing Designs 2 and 3 with the standard design (Figures 8 and 9). Reduction of sediments and N for Design 2 is around 5.75 million tons and 0.066 million tons, with rates of 86.7% and 87.4%, respectively. Reduction of sediments and N for Design 3 is about 5.8 million tons and 0.067 million tons, with the rate of 87.4% and 88.7%, respectively. For the whole catchment, the reduction indicates that reducing the number of zones is effective in removing sediments and dissolved N, and it is an acceptable way to save lands by taking out one zone without much impacting the effectiveness of riparian buffers.

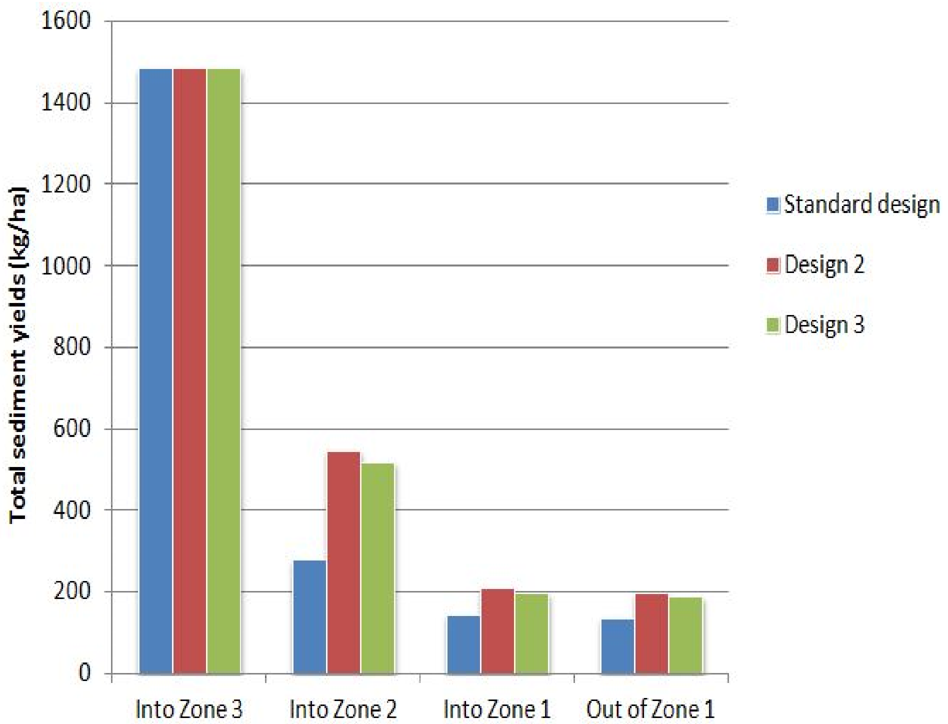

Figure 8. Comparison of reduction of total sediments among standard design, and Design 2 and Design 3.

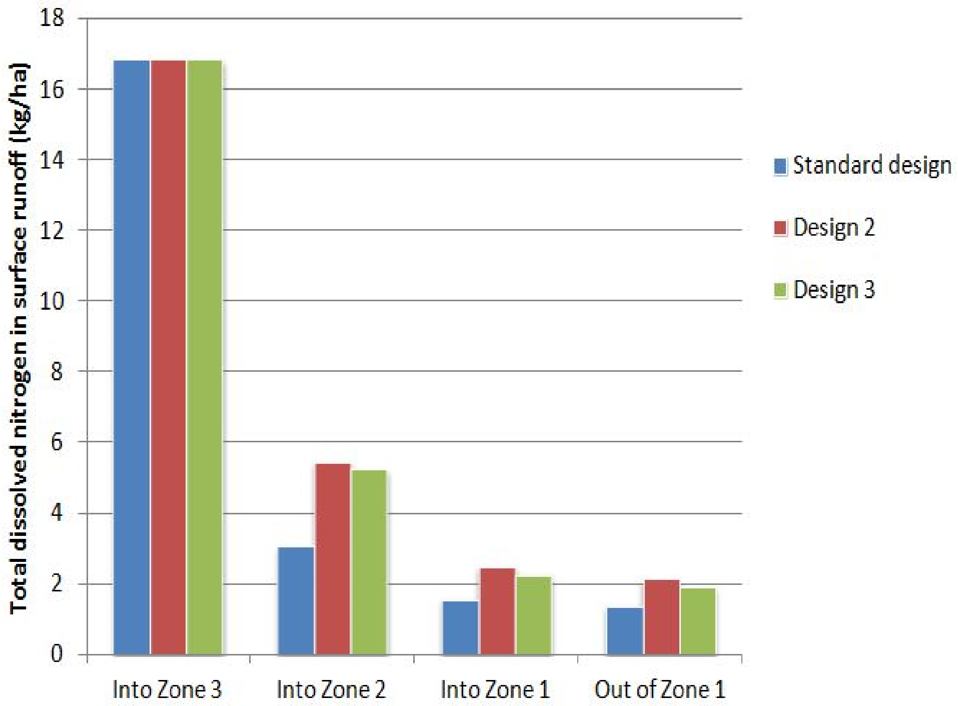

Figure 9. Comparison of total dissolved N reduction in the surface runoff among standard design, Design 2, and Design 3.

3.3.2. Effect of Zone Width

Within the same zone number, the efficiency in reducing sediments and nitrogen of riparian buffers with different zone widths was compared and analyzed (Figures 10–13). Reducing the zone width to half (10 m) based on Designs 2 and 3 and Designs 4 and 5 show more desirable results. The reduction of sediments and N for Design 4 is around 5.68 million tons and 0.064 million tons, with the rate of 85.7% and 85.4%, respectively, while the reduction of sediments and N for Design 5 is about 5.69 million tons and 0.065 million tons with the rate of 85.8% and 86.2%, respectively. The reduction rate of sediments for Designs 4 and 5 is only 1% and 1.6% lower than for Designs 2 and 3, while the reduction rate of nitrogen is only 2% and 2.5% lower.

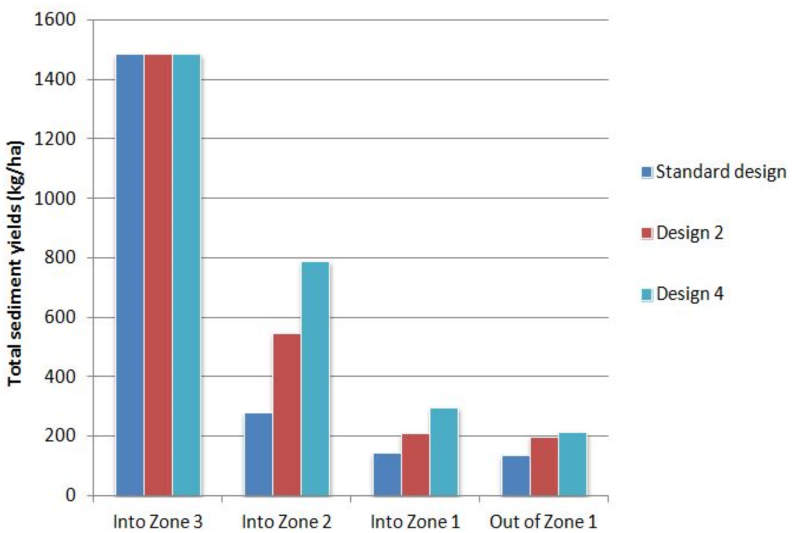

Figure 10. Comparison of reduction of total sediments among standard design, Design 2, and Design 4.

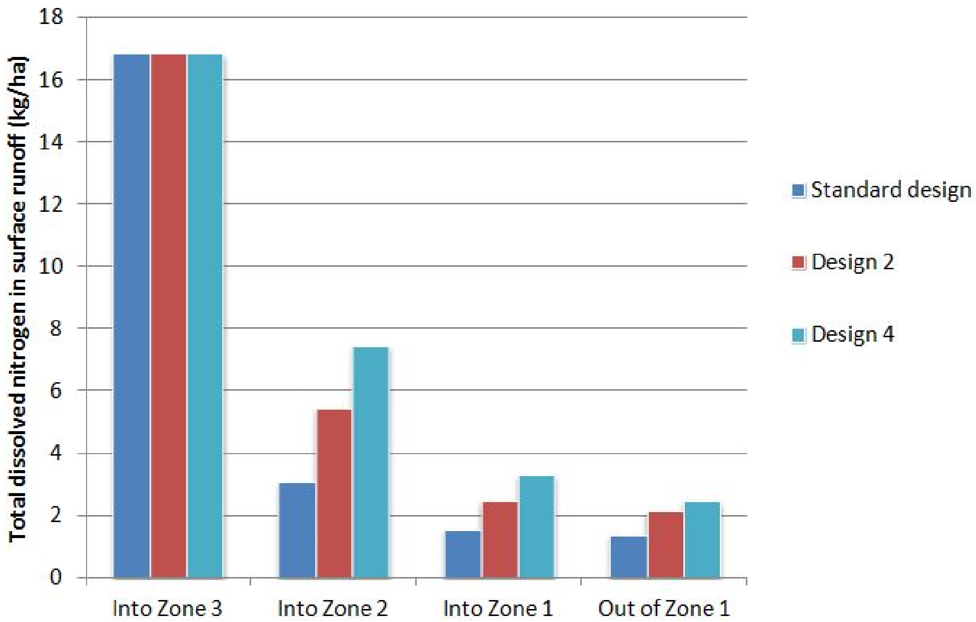

Figure 11. Comparison of total dissolved N reduction in the surface runoff among standard design, Design 2, and Design 4.

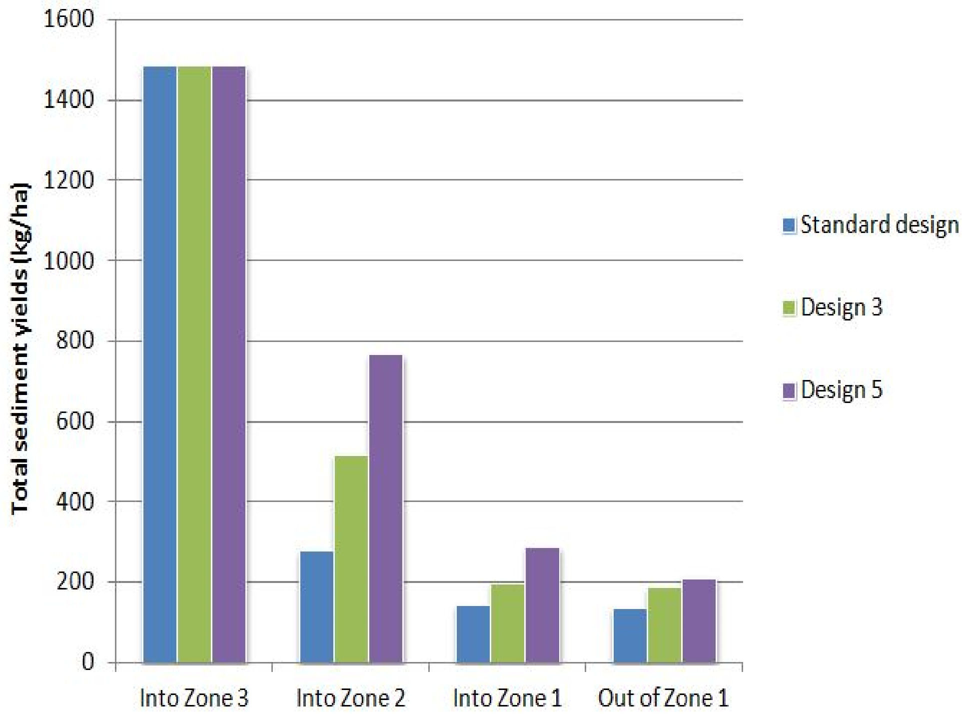

Figure 12. Comparison of reduction of total sediments among standard design, Design 3, and Design 5.

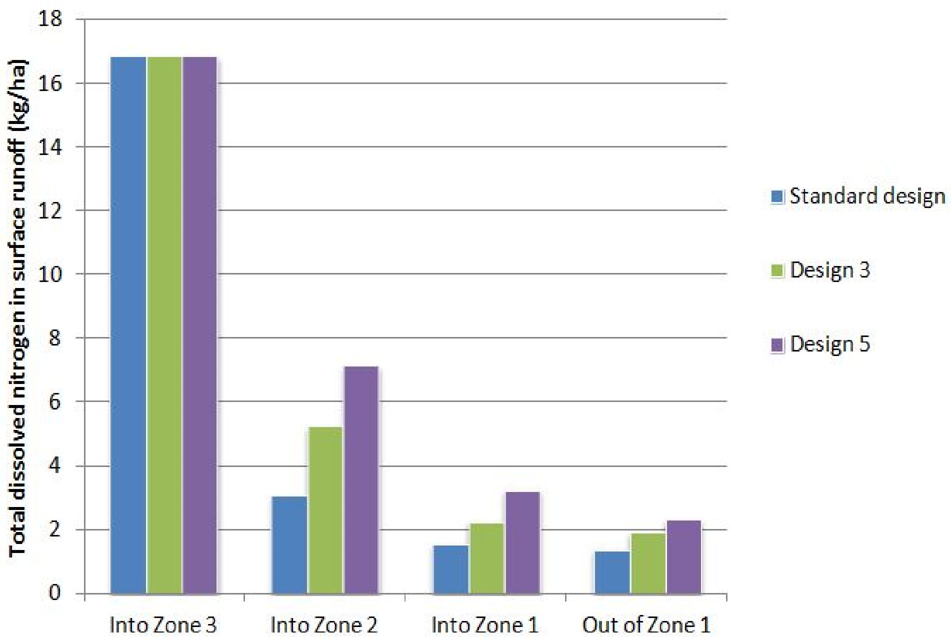

Figure 13. Comparison of total dissolved N reduction in the surface runoff among standard design, Design 3, and Design 5.

With this performance, reducing the width of Zone 3 and Zone 2 to 10 m is proved acceptable, and a buffer with a total width of 20 m (Zone 3 or 2 plus Zone 1) effectively reduces sediments and dissolved N.

3.3.3. Effect of Vegetation Types

The difference in the reduction of sediments and nitrogen between Designs 2 and 3 was around 50,000 tons and 980 tons, respectively, while the difference in the reduction of sediments and nitrogen between Designs 4 and 5 was around 4800 tons and 670 tons, respectively. For the whole catchment, between vegetation types, the difference in the reduction of sediments and nitrogen is small, considering the total reduction. Vegetation type has little impact on the effectiveness of riparian buffers.

4. Discussion

4.1. Comparison with Other Studies on the Buffer Zone Design

Several studies have examined the effectiveness of riparian buffer zones in reducing non-point source pollution in surface water. A literature review studied the streamside forest buffer width and concluded that forest buffers no less than 30 m wide are needed to protect the physical, chemical, and biological integrity of small streams [19]. Mayer et al. (2007) [56] found that buffer effectiveness increased with buffer width, but width explained a small but significant ($R^2 = 0.09$, $p < 0.01$) fraction of the variance in removal efficiency. Studies of riparian buffers to trap sediment show that buffers 10 m wide can trap about 65% of sediment delivered by overland flow [57,58]. While buffers 30 m wide can be expected to trap about 85% of sediments [19,59,60]. It seems that the increased sediment trapped by the wider riparian buffer only accounts for a small portion (by mass).

In comparison, our study found that riparian buffer zones with a width of 20 m were effective at reducing sediment and nutrient loads in surface water in the Jinghe watershed. Our study also tested different riparian buffer zone designs and found that removing Zone 3 or reducing the widths of the buffer zones had a limited impact on the effectiveness of the riparian buffer zones. It could be evidence to encourage the build-up of the riparian buffer in agricultural-intensive watersheds, even if only a narrow buffer is feasible concerning land shortage for conservation purposes.

4.2. The Role of Riparian Buffer for Soil and Water Conservation

Based on our study, it is evident that riparian buffer zones are highly effective in reducing sediments in surface water. We, therefore, believe that preventing the off-site consequence of soil erosion is essential for good watershed management. For a long time, the focus of soil and water conservation practices and research has been primarily on hillslope and channel management in the form of on-site measures. The idea is also supported by a review by Mekonnen et al. 2015 [61], in which the effect of sediment trapping on soil and conservation was studied.

According to a study in Europe [62], a great relevance of existing riparian vegetation in controlling sediments in streams for watersheds where pressure from agriculture is highest. The riparian vegetation could prevent the sediment concentration in the stream from surpassing the limits set in the EU Water Framework Directive.

In Virginia, US, Upper James River basin, the average sediment trapped by the streamside riparian (24.8 Mg ha^{-1} y^{-1}) is 38 times higher than the control treatment (0.65 Mg ha^{-1} y^{-1}) [63].

Suspended sediment concentration and loads were 90% lower after the riparian buffer was created on an agricultural catchment in Australia with a gentle slope, sandy soils, and average annual rainfall of 799 mm [64]. In a study in Iowa in the US, where the soil and topography (loess soil at 5–20% slope) is like Jinghe watershed in our study, riparian buffers trapped 4.8 Mg ha^{-1} y^{-1} of sediment from a 27.6 ha catchment [65].

In a small watershed in Brazil (77 ha), with gentle slopes (mean slopes of 10%), the riparian buffers were found to trap 54% of the total sediment yield (12 Mg ha^{-1} y^{-1}) [66]. Our study also showed that riparian buffer zones are effective in reducing sediment from soil erosion to river flow. The study also emphasized the importance of incorporating riparian buffer zones into the region's soil and water conservation practices and policies. At the catchment scale, particularly for the Jinghe watershed, we highly suggest integrating riparian buffers with other conservation measures that are mainly designed for reducing on-site soil erosion can help to reduce river sediment loads and benefit the ecosystem and the communities that depend on it.

4.3. Limitations and Suggestions for Future Study

AnnAGNPS is a suitable upland model to directly provide the required upland input data for the riparian buffer model. REMM is an appropriate model for riparian buffer simulation and prediction. For watershed scale simulation, AnnAGNPS properly divides the watershed into homogeneous drainage areas and makes it possible for REMM to simulate at the field scale. Using AnnAGNPS and REMM is an applicable way for large-scale riparian buffer simulations. However, for large watersheds, it is time-consuming because there has not yet been an automatic procedure for importing AnnAGNPS outputs into REMM. For future studies, it is recommended to develop a built-in function for automatically importing the AnnAGNPS output variables into REMM and processing the models.

In our study, we only consider the design of an effective risperidone buffer from the perspective of hydrological and conservational benefits. In fact, there are many other factors that affect the adoption and success of respiration buffers, such as socioeconomic factors, regulatory and legal factors. Areas with heavy agricultural or industrial land use may need larger and more effective riparian buffers, but these are also the areas where land is most likely to be occupied by agricultural land and, therefore, difficult to allocate for buffer creation. Implementing riparian buffers may involve navigating complex legal and regulatory hurdles, such as zoning laws, water rights, and environmental regulations. This can slow down the implementation process and make it more difficult to create effective buffers.

5. Conclusions

In our study, we have integrated the REMM with the AnnAGNPS model in an agriculture-intensive watershed to evaluate riparian zones as BMP. The results of this study indicated that riparian buffer zones are highly effective in reducing sediments and nutrients in agricultural runoff. Converting riverside crop fields to riparian buffers has the potential to improve surface water quality for watersheds while providing new land use for economic benefits. The results of this study are anticipated to be helpful in guiding land use changes in restoring ecosystems and promoting sustainability by preventing water pollution from agricultural fields.

Overall, our study adds to the body of knowledge on the effectiveness of riparian buffer zones in reducing non-point source pollution in surface water, particularly in the context of the Jing River watershed in China.

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References

1. Godfray, H.C.; Garnett, T. Food security and sustainable intensification. *Philos. Trans. R. Soc. Ser. B* **2014**, *369*, 20120273. [CrossRef] [PubMed]
2. Khan, S.; Hanjra, M.A.; Mu, J. Water management and crop production for food security in China: A review. *Agric. Water Manag.* **2009**, *96*, 349–360. [CrossRef]
3. Van Bavel, J. The world population explosion: Causes, backgrounds and -projections for the future. *Facts Views Vis. ObGyn* **2013**, *5*, 281–291. [PubMed]
4. Zhou, X.; Helmers, M.J.; Asbjornsen, H.; Kolka, R.; Tomer, M.D. Perennial filter strips reduce nitrate levels in soil and shallow groundwater after grassland-to-cropland conversion. *J. Environ. Qual.* **2010**, *39*, 2006–2015. [CrossRef]
5. Balcerzak, A.M.; Smiley, P.C.; Kalcic, M.M. Evaluating the Effects of Riparian Habitat Type on Nutrient Concentrations in Agricultural Headwater Streams. *J. Am. Water Resour. Assoc.* **2022**, *58*, 1497–1809. [CrossRef]
6. Zheng, T.; Zhou, Z.; Zou, Y.; Pulatov, B.; Biswas, A. Analysis of Spatial and Temporal Characteristics and Spatial Flow Process of Soil Conservation Service in Jinghe Basin of China. *Sustainability* **2021**, *13*, 1794. [CrossRef]
7. Sliva, L.; Williams, D.D. Buffer zone versus whole catchment approaches to studying land use impact on river water quality. *Water Resour.* **2001**, *35*, 3462–3472. [CrossRef]
8. Shen, Z.; Liao, Q.; Hong, Q.; Gong, Y. An overview of research onagricultural non-point source pollution modelling in China. *Sep. Purif. Technol.* **2012**, *84*, 104–111. [CrossRef]
9. Stang, C.; Gharabaghi, B.; Rudra, R.; Golmohammadi, G.; Mahboubi, A.A.; Ahmed S, I. Conservation management practices: Success story of the Hog Creek and Sturgeon River watersheds, Ontario, Canada. *J. Soil Water Conserv.* **2016**, *71*, 237–248. [CrossRef]
10. Anbumozhi, V.; Radhakrishnan, J.; Yamaji, E. Impact of riparian buffer zones on water quality and associated management considerations. *Ecol. Eng.* **2005**, *24*, 517–523. [CrossRef]
11. Jaja, N.; Mbila, M.; Codling, E.; Tsegaye, T.; Odutola, J. Landscape Variability of Riparian Buffers and Its Impact on Soil and Water Chemistry of an Urbanized Watershed. *Ecol. Indic.* **2022**, *137*, 108777. [CrossRef]
12. Momm, H.G.; Bingner, R.L.; Yuan, Y.; Locke, M.A.; Wells, R.R. Spatial characterization of riparian buffer effects on sediment loads from watershed systems. *J. Environ. Qual.* **2014**, *43*, 1736–1753. [CrossRef]
13. Lee, P.; Smyth, C.; Boutin, S. Quantitative Review of Riparian Buffer Width Guidelines from Canada and the United States. *J. Environ. Manag.* **2004**, *70*, 165–180. [CrossRef]
14. Liu, X.; Zhang, X.; Zhang, M. Major factors influencing the efficacy of vegetated buffers on sediment trapping: A review and analysis. *J. Environ. Qual.* **2008**, *37*, 1667–1674. [CrossRef]

15. Zhang, X.; Liu, Y.; Zhou, L. Correlation Analysis between Landscape Metrics and Water Quality under Multiple Scales. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1606. [CrossRef]
16. Fischer, R.A.; Fischenich, J.C. Design Recommendations for Riparian Corridors and Vegetated Buffer Strips; Technical Note (Ecosystem Management and Restoration Research Program (U.S.)). 2000. no. ERDC TN-EMRRP-SR-24. Available online: http://www.elkhornsloughctp.org/uploads/files/1381443282Fischer%20and%20Fischenich%202000%20buffer%20design.pdf (accessed on 20 March 2017).
17. Mayer, P.M.; Reynolds, S.K., Jr.; McCutchen, M.D.; Canfield, T.J. *Riparian Buffer Width, Vegetative Cover, and Nitrogen Removal Effectiveness: A Review of Current Science and Regulations*; EPA/600/R-05/118; United States Environmental Protection Agency: Washington, DC, USA, 2005.
18. Jiang, K.; Li, Z.; Luo, C.; Wu, M.; Chao, L.; Zhou, Q.; Zhao, H. The reduction effects of riparian reforestation on runoff and nutrient export based on AnnAGNPS model in a small typical watershed, China. *Environ. Sci. Pollut. Res.* **2019**, *26*, 5934–5943. [CrossRef]
19. Sweeney, B.W.; Newbold, J.D. Stream side forest buffer width needed to protect stream water quality, habitat, and organisms: A literature review. *J. Am. Water Resour. Assoc.* **2014**, *50*, 560–584. [CrossRef]
20. Liu, Z.; Tong, S.T.Y. Using HSPF to model the hydrologic and water quality impacts of riparian land-use change in a small watershed. *J. Environ. Inform.* **2011**, *17*, 1–14. [CrossRef]
21. Richardson, J.S.; Naiman, R.J.; Bisson, P.A. How did fixed-width buffers become standard practice for protecting freshwaters and theirriparian areas from forest harvest practices? *Fresh Water Sci.* **2012**, *31*, 232–238. [CrossRef]
22. Sharma, A.; Tiwari, K.N.; Bhadoria, P.B.S. Effect of Land Use Land Cover Change on Soil Erosion Potential in an Agricultural Watershed. *Environ. Monit. Assess.* **2011**, *173*, 789–801. [CrossRef]
23. Tilahun, A.; Asmare, T.; Nega, W.; Gashaw, T. The Nexus between Land Use, Land Cover Dynamics, and Soil Erosion: A Case Study of the Temecha Watershed, Upper Blue Nile Basin, Ethiopia. *Environ. Sci. Pollut. Res.* **2023**, *30*, 1023–1038. [CrossRef] [PubMed]
24. Gassman, P.W.; Sadeghi, A.M.; Srinivasan, R. Applications of the SWAT Model Special Section: Overview and Insights. *J. Environ. Qual.* **2014**, *43*, 1–8. [CrossRef] [PubMed]
25. Roostaee, M.; Deng, Z. HSPF-Based Watershed-Scale Water Quality Modeling and Uncertainty Analysis. *Environ. Sci. Pollut. Res.* **2019**, *26*, 8971–8991. [CrossRef] [PubMed]
26. Ma, L.; He, C.; Bian, H.; Sheng, L. MIKE SHE Modeling of Ecohydrological Processes: Merits, Applications, and Challenges. *Ecol. Eng.* **2016**, *96*, 137–149. [CrossRef]
27. Qi, H.; Altinakar, M.S.; Vieira, D.A.N.; Alidaee, B. Application of Tabu Search Algorithm with a Coupled AnnAGNPS-CCHE1D Model to Optimize Agricultural Land Use1. *J. Am. Water Resour. Assoc.* **2008**, *44*, 866–878. [CrossRef]
28. Guo, Y.; Peng, C.; Zhu, Q.; Wang, M.; Wang, H.; Peng, S.; He, H. Modelling the Impacts of Climate and Land Use Changes on Soil Water Erosion: Model Applications, Limitations and Future Challenges. *J. Environ. Manag.* **2019**, *250*, 109403. [CrossRef]
29. Zhang, J.; Li, S.; Dong, R.; Jiang, C.; Ni, M. Influences of Land Use Metrics at Multi-Spatial Scales on Seasonal Water Quality: A Case Study of River Systems in the Three Gorges Reservoir Area, China. *J. Clean. Prod.* **2019**, *206*, 76–85. [CrossRef]
30. Xue, J.; Wang, Q.; Zhang, M. A Review of Non-Point Source Water Pollution Modeling for the Urban–Rural Transitional Areas of China: Research Status and Prospect. *Sci. Total Environ.* **2022**, *826*, 154146. [CrossRef]
31. Zhang, C.; Li, S.; Qi, J.; Xing, Z.; Meng, F. Assessing Impacts of Riparian Buffer Zones on Sediment and Nutrient Loadings into Streams at Watershed Scale Using an Integrated REMM-SWAT Model. *Hydrol. Process.* **2017**, *31*, 916–924. [CrossRef]
32. Vidon, P.; Allan, C.; Burns, D.; Duval, T.P.; Gurwick, N.; Inamdar, S.; Lowrance, R.; Okay, J.; Scott, D.; Sebestyen, S. Hot Spots and Hot Moments in Riparian Zones: Potential for Improved Water Quality Management1. *JAWRA J. Am. Water Resour. Assoc.* **2010**, *46*, 278–298. [CrossRef]
33. Qi, Q.; Wang, T.; Kou, X.; Ge, J. Temporal and spatial changes of vegetation cover and the relationship with precipitation in Jinghe watershed of China. *Chin. J. Plant Ecol.* **2009**, *33*, 246–253.
34. Bingner, R.L.; Theurer, F.D. AnnAGNPS: Estimating sediment yield by particle size for sheet and rill erosion. In Proceedings of the Seventh Interagency Sedimentation Conference, Reno, NV, USA, 25–29 March 2001; Volume 1, pp. 1–7.
35. LPDC (Loess Plateau Data Center). Data of 90 meter resolution digital elevation model (DEM) in Weihe River Basin. Available online: http://loess.geodata.cn (accessed on 3 March 2017).
36. Dixon, B.; Earls, J. Resample or Not?! Effects of Resolution of DEMs in Watershed Modeling. *Hydrol. Process.* **2009**, *23*, 1714–1724. [CrossRef]
37. Bosch, D.D.; Sheridan, J.M.; Batten, H.L.; Arnold, J.G. Evaluation of the swat model on a coastal plain agricultural watershed. *Trans. ASAE* **2004**, *47*, 1493–1506. [CrossRef]
38. Nazari-Sharabian, M.; Taheriyoun, M.; Karakouzian, M. Sensitivity Analysis of the DEM Resolution and Effective Parameters of Runoff Yield in the SWAT Model: A Case Study. *J. Water Supply Res. Technol.-AQUA* **2019**, *69*, 39–54. [CrossRef]
39. Theurer, F.D.; Cronshey, R.G. AnnAGNPS-reach routing processes. In Proceedings of the First Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV, USA, 19–23 April 1998; pp. 19–23.
40. CSD (China Soil Database). Soil Science Database. Available online: http://vdb3.soil.csdb.cn/ (accessed on 20 March 2017).
41. NOAA (National Oceanic and Atmospheric Administration). Global Summary of the Month. Available online: https://www.ncdc.noaa.gov/cdo-web/datasets (accessed on 20 March 2017).

42. OpenEI Datasets. Summary World Solar Energy Data (Updated 29 July 2014). Available online: https://en.openei.org/datasets/dataset?tags=China (accessed on 17 April 2017).
43. Richardson, C.W.; Wright, D.A. *WGEN: A Model for Generating Daily Weather Variables*; US Department of Agriculture, Agricultural Research Service: Washington, DC, USA, 1984; 83p.
44. Bingner, R.L.; Theurer, F.D.; Yuan, Y. AnnAGNPS Technical Processes. 2003. Available online: http://www.sedlab.olemiss.edu/AGNPS (accessed on 20 March 2017).
45. Lowrance, R.; Altier, R.S.; Williams, R.G.; Inamdar, S.P.; Sheridan, J.M.; Bosch, D.D.; Hubbard, R.K.; Thomas, D.L. REMM: The Riparian Ecosystem Management Model. *J. Soil Water Conserv.* **2000**, *55*, 27–34.
46. Altier, L.S.; Lowrance, R.R.; Williams, R.G.; Inamdar, S.P.; Bosch, D.D.; Sheridan, J.M.; Hubbard, R.K.; Thomas, D.L. *Riparian Ecosystem Management Model (REMM): Documentation*; USDA Conservation Research Report; USDA: Washington, DC, USA, 2000.
47. Welsch, D.J. *Riparian Forest Buffers: Function and Design for Protection and Enhancement of Water Resources*; NA-PR-07-91; U.S. Department of Agriculture, Forest Service, Northern Area State & Private Forestry: Broomall, PA, USA, 1991.
48. Yuan, Y.; Bingner, R.; Williams, R.; Lowrance, R.; Bosch, D.; Sheridan, J. Integration of the models of AnnAGNPS and REMM to assess riparian buffer system for sediment reduction. *Int. J. Sediment Res.* **2007**, *22*, 60–69.
49. United States Geological Survey (USGS). National Hydrography Dataset (NHD). Available online: https://www.usgs.gov/national-hydrography/national-hydrography-dataset (accessed on 3 March 2017).
50. USDA.Cropland Data Layer (CDL). Available online: https://www.nass.usda.gov/Research_and_Science/Cropland/SARS1a.php (accessed on 3 March 2017).
51. Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online: https://websoilsurvey.nrcs.usda.gov/ (accessed on 3 March 2017).
52. Inamdar, S.P.; Sheridan, J.M.; Williams, R.G.; Bosch, D.D.; Lowrance, R.R.; Altier, L.S.; Thomas, D.L. Riparian Ecosystem Management Model (REMM): I. Testing of the hydrologic component for a coastal plain riparian system. *Trans. ASAE* **1999**, *42*, 1679–1689. [CrossRef]
53. Inamdar, S.P.; Lowrance, R.R.; Altier, L.S.; Williams, R.G.; Hubbard, R.K. Riparian Ecosystem Management Model (REMM): II. Testing of the water quality and nutrient cycling component for a coastal plain riparian system. *Trans. ASAE* **1999**, *42*, 1691–1707. [CrossRef]
54. Noori, R.; Maghrebi, M.; Jessen, S.; Bateni, S.M.; Heggy, E.; Javadi, S.; Nouri, M.; Pistre, S.; Abolfathi, S.; AghaKouchak, A. Decline in Iran's Groundwater Recharge. *Res. Sq.* **2023**. *Preprint*. [CrossRef]
55. Malekmohammadi, B.; Uvo, C.B.; Moghadam, N.T.; Noori, R.; Abolfathi, S. Environmental Risk Assessment of Wetland Ecosystems Using Bayesian Belief Networks. *Hydrology* **2023**, *10*, 16. [CrossRef]
56. Mayer, P.M.; Reynolds, S.K.; McCutchen, M.D.; Canfield, T.J. Meta-Analysis of Nitrogen Removal in Riparian Buffers. *J. Environ. Qual.* **2007**, *36*, 1172–1180. [CrossRef]
57. Dunn, A.M.; Julien, G.; Ernst, W.R.; Cook, A.; Doe, K.G.; Jackman, P.M. Evaluation of Buffer Zone Effectiveness in Mitigating the Risks Associated with Agricultural Runoff in Prince Edward Island. *Sci. Total Environ.* **2011**, *409*, 868–882. [CrossRef] [PubMed]
58. Meador, M.R.; Goldstein, R.M. 2003. Assessing Water Quality at Large Geographic Scales: Relations among Land Use, Water Physicochemistry, Riparian Condition, and Fish Community Structure. *Environ. Manag.* **2003**, *31*, 504–517. [CrossRef] [PubMed]
59. Clausen, J.C.; Guillard, K.; Sigmund, C.M.; Martin Dors, K. Water Quality Changes from Riparian Buffer Restoration in Connecticut. *J. Environ. Qual.* **2000**, *29*, 1751–1761. [CrossRef]
60. Ziegler, A.D.; Negishi, J.; Sidle, R.C.; Preechapanya, P.; Sutherland, R.A.; Giambelluca, T.W.; Jaiaree, S. Reduction of Stream Sediment Concentration by a Riparian Buffer: Filtering of Road Runoff in Disturbed Headwater Basins of MontaneMainland Southeast Asia. *J. Environ. Qual.* **2006**, *35*, 151–162. [CrossRef]
61. Mekonnen, M.; Keesstra, S.D.; Stroosnijder, L.; Baartman, J.E.M.; Maroulis, J. Soil Conservation Through Sediment Trapping: A Review. *Land Degrad. Dev.* **2015**, *26*, 544–556. [CrossRef]
62. Aparício, B.A.; Nunes, J.P.; Bernard-Jannin, L.; Dias, L.F.; Fonseca, A.; Ferreira, T. Modelling the Role of Ground-True Riparian Vegetation for Providing Regulating Services in a Mediterranean Watershed. *Int. Soil Water Conserv. Res.* **2023**, *11*, 159–168. [CrossRef]
63. Lakel, W.A.; Aust, W.M.; Holding, M.C.; Dolloff, C.A.; Keyser, P.; Feldt, R. Sediment trapping by streamside management zones of various widths after forest harvest and site preparation. *For. Sci.* **2010**, *56*, 541–551.
64. McKergow, L.A.; Weaver, D.M.; Prosser, I.P.; Grayson, R.B.; Reed, A.E.G. Before and after riparian management: Sediment and nutrient exports from a small agricultural catchment, Western Australia. *J. Hydrol.* **2003**, *270*, 253–272. [CrossRef]
65. Tomer, M.D.; Moorman, T.B.; Kovar, J.L.; James, D.E.; Burkart, M.R. Spatial patterns of sediment and phosphorus in a riparian buffer in western Iowa. *J. Soil Water Conserv.* **2007**, *62*, 329–338.
66. Sparovek, G.; Beatriz Lima Ranieri, S.; Gassner, A.; Clerice De Maria, I.; Schnug, E.; Ferreira Dos Santos, R.; Joubert, A. A conceptual framework for the definition of the optimal width of riparian forests. *Agric. Ecosyst. Environ.* **2002**, *90*, 169–175. [CrossRef]