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Assessing the Effects of Land Use Changes on Non-Point Source Pollution Reduction for the Three Gorges Watershed Using the SWAT Model

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ABSTRACT. This study presents a new attempt of applying the hydrological model SWAT to the Three Gorges watershed in China for addressing its non-point source (NPS) pollution control issues. The model was calibrated and validated using the monitoring data collected during 2002-2008, and satisfactory values of R^2 and E_{NS} (Nash-Suttclife Efficiency) were obtained. The calibrated SWAT model was then used to simulate 6 different land use scenarios for investigating the effects of each scenario on the non-point source (NPS) pollution control in the watershed. Six scenarios were designed with distinct land use focuses and include five newly-designed scenarios (Q1-Q5) representing 5 different land use alternatives and a baseline scenario (Q6) representing the land use pattern the watershed had in 2005. It was identified that the farmland is the dominant contributor to the NPS pollution in the watershed in terms of yields of sediment, TN and TP. If the farmland is changed to the woodland, grassland or shrubland, a better control and reduction over the NPS pollution could be achieved. This study provides a good understanding of the interactions between different land use patterns and the NPS pollution control for decision-makers to make sound decisions. Changing the land use pattern and implementing alternative management practices could help reduce the non-point source pollution effectively and thus play a significant role in improving reservoir water quality of the watershed.

Keywords: land use, management, non-point source, SWAT, Three Gorges watershed

1. Introduction

The Three Gorges Dam (TGD) spans the Yangtze River by the town of Sandouping, located in the Yiling District of Yichang City, in Hubei province, China. It is a hydroelectric dam and the world's largest power station in terms of installed capacity (21,000 MW). The TGD construction started in 1994 and the dam body was completed in 2006 while all the originally planned components of the project (except a ship lift) were completed on October 30, 2008. Since then, the dam had gradually raised the water level behind the dam and reached its designed maximum level of 175 m in October 2010. When the water level is at its maximum, the dam reservoir is stretching about 660 km in length upstream along the Yangtze River and has an average of 1.12 km in width. The dam reservoir contains 39.3 billion m^3 of water with a total surface area of 1,045 km^2, and the reservoir watershed has a total area of 58,000 km^2.

The dam project has been regarded as a remarkable engineering, social and economic success in China, and a move toward limiting greenhouse gas emissions, through producing hydro-electricity, increasing the Yangtze River's shipping capacity and reducing the potential for floods downstream by providing flood storage space in the dam reservoir. However, it has been a controversial project since the very beginning in terms of flooding many archaeological and cultural sites, displacing and relocating 1.3 million people, causing significant ecological changes, and environmental concerns in the reservoir.

One major environmental concern facing the region is the water quality deterioration issue in the reservoir caused by the non-point source (NPS) pollution due to intensive land development and mainly agricultural activities. At current levels, 80% of the land in the area is experiencing erosion, depositing large amount of sediments associated nutrient inputs into the reservoir annually. Meanwhile, the hydraulics of water flow in the reservoir has changed dramatically since the completion of the dam body, and has thus adversely affected the natural assimilative capacity of the receiving water body. All these facts have

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led to gradual and serious deterioration of water quality in the reservoir, and as a result, local authorities have been undertaking the enhanced stresses for effectively responding to NPS pollution issue through planning different land use patterns and using alternative land management practices in the watershed. This requires a sound understanding of the interactions between the non-point pollution sources and water quality, and of the way how the reservoir system will react to particular land use policies. For responding to this need, hydrological watershed models have been widely used for decades to evaluate regional non-point source pollution and the short- and long-term impacts of alternative land use and management practices (Tsihrintzis et al., 1996, 1997).

Previously, various hydrological models have been developed for simulating surface runoff, sediment transport and nutrient distribution in watershed settings (Arnold et al., 1998; Hassen et al., 2004; Bhuyan et al., 2004; Barco et al., 2008; Goncu and Albek, 2010; Laurent and Ruelland, 2011; Zhang et al., 2011a; Zhang et al., 2011b; Zhang et al., 2012). In this study, we have chosen the Soil and Water Assessment Tool (SWAT) to examine the NPS pollution issues in the Three Gorges reservoir. The SWAT model is a semi-distributed watershed model developed particularly for application to large complex watersheds over long periods of time (Neitsch et al., 2002; Arnold and Fohrer, 2005). It can simulate and estimate NPS pollution generation at the source and its movement from the source area to the receiving water body, providing flow and concentration histograms at various points in the watershed and entry points into the receiving water body. A key strength of SWAT is its flexible framework that not only allows the user to divide a large watershed into any number of small sub-basins, but also allows the simulation of a wide variety of land use and management practices with straightforward parameter changes (Gassman et al., 2007).

Since its creation in early 1990s, the SWAT has been continuously revised and has been used extensively to study stream flow, sediment yields and nutrient transport (Arnold et al., 1998; Neitsch et al., 2002). Many researchers in Europe and North American have used SWAT to evaluate various NPS pollution issues and assess the effects of land use scenarios and management practices (Saleh et al., 2000; Shanti et al., 2001; Vache et al., 2002; Shanti et al., 2003; Chaplot et al., 2004; Pandey et al., 2005; Arabi et al., 2006; Cheng et al., 2006; Rode et al., 2008; Volk et al., 2009; Panagopoulos et al., 2011a, b). For the Three Gorges watershed, some Chinese researchers have used the SWAT model to simulate the hydrological processes and evaluate the NPS pollution problems for several tributaries along the Yangtze River, and promising results have been obtained (Ding et al., 2009; Ma et al., 2009; Wang et al., 2011; Xu et al., 2006). However, to the best of our knowledge, the SWAT model has not yet been used to the entire region of the Three Gorges watershed for addressing land use pattern changes and associated non-point source pollution issues.

This study presents an application of the hydrological model SWAT as an effective planning and management tool for the large-scale Three Gorges watershed. The objectives of this study include: (i) model configuration and performance assessment through model calibration and verification – configuring the SWAT model to our particular case and assessing its performance and ability to simulate relevant land use management practices; (ii) evaluation of existing land use pattern and management practices – using the verified SWAT model to evaluate the current land use and management practices and identify the major non-point pollution sources within the Three Gorges watershed; and (iii) design and analysis of alternative land use and management scenarios – using the verified SWAT model to analyze the designed land use scenarios as the alternatives to the existing practices and their effects on water quality control and improvements. Six alternative land use scenarios were considered and analyzed, and the results could provide scientific information for sound decision-making supports related to regional non-point source pollution control and Three Gorges watershed land management plan.

2. The Study Watershed

The Three Gorges watershed covers a region within 106°16' ~ 111°28' E and 28°56' ~ 31°44' N, as shown in Figure 1. The watershed includes 20 cities and towns, counties, districts starting from Jiangjin City of Metro Chongqing in the west to Yiling District of Yichang City in the east, Hubei Province. The total population in this region is over 20 million in 2008. The eastern watershed is part of the hilly Sichuan Basin, and the most western part of the watershed has mountainous terrain and topography. Hilly and mountainous terrains account for 94% of the total watershed area while only 4% is plain area. There are 40 main tributary streams flowing into the Yangtze River within the boundary of the watershed. The region has a yearly average precipitation of 1,000 mm with 90% occurring from July to September. The current land use practices include four main categories, i.e., farmland, woodland, shrubland, and grassland, among which the farmland and woodland account for over 70% of the total.

3. Model Description and Input Data

3.1. Model Description

SWAT is a process-based distributed-parameter simulation model developed by the United States Department of Agriculture (USDA) to predict the impacts of watershed management on water, sediment and nutrients in either meso-scale or macro-scale basins (Knisel, 1980; Leonard et al., 1987; Arnold et al., 1990; Arnold et al., 1998; Williams, 1995). SWAT could be divided into a number of components and modules, including weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, stream routing, and pond/reservoir routing module (Arnold and Fohrer, 2005). Simulation of the hydrology of a watershed contains two major phases of the hydrologic cycle: the land phase and the water or routing phase. The former simulates the amount of water, sediment, nutrient, and pesticide loadings carried by surface runoff from sub-basin to corresponding main channel. The latter contols the movement of water, sediment, nutrients and pesticides through the channel network of the watershed to the

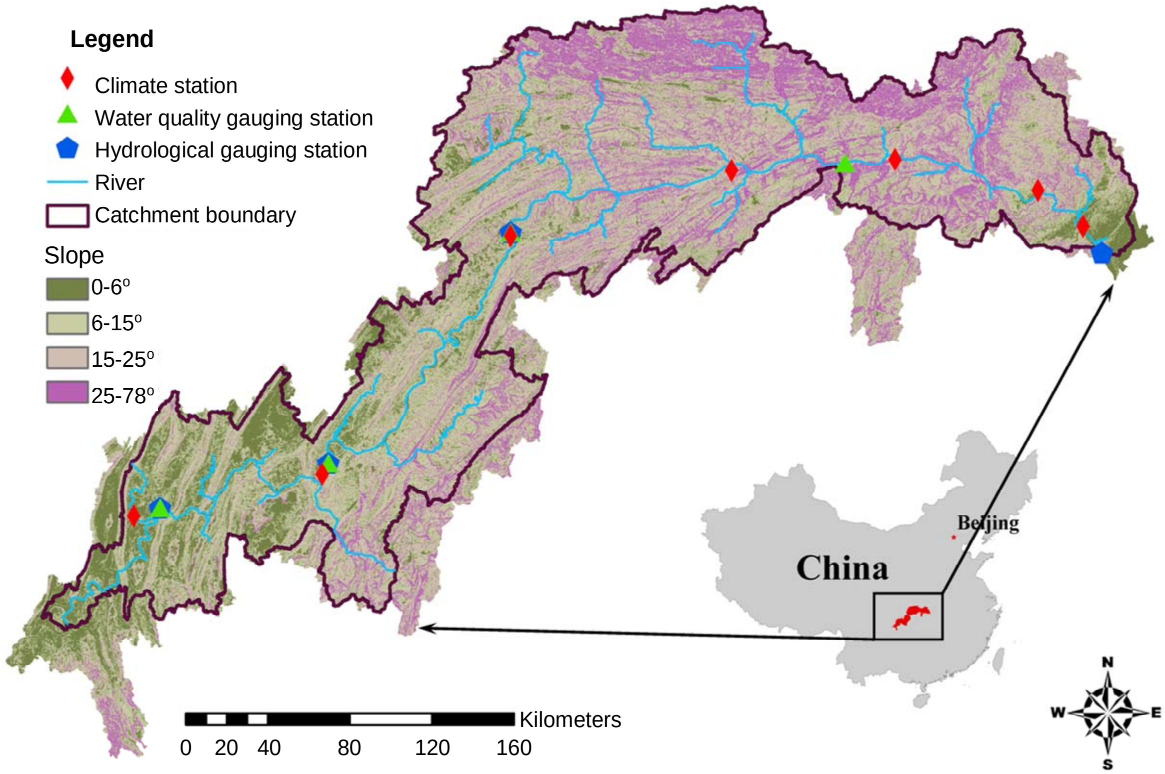

Figure 1. Location and map of the Three Georges Reservoir and watershed.

outlet (Neitsch et al., 2005). The water balance equation is the core basis of hydrologic cycle simulation in SWAT, as presented below:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (1)$$

where SW_t is the final soil water content (mm); SW_0 is the initial soil water content on day i (mm); t is the time (day); R_{day} is the amount of precipitation on day i (mm); Q_{surf} is the amount of surface runoff on day i (mm); E_a is the amount of evapotranspiration on day i (mm); w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm); and Q_{gw} is the amount of return flow on day i (mm).

The Modified Universal Soil Loss Equation (MUSLE) was used to estimate the erosion and sediment yield through Hydrologic Response Units (HRUs) in SWAT based on the amount of runoff (Williams, 1975). The Equation is expressed as below:

$$sed = (11.8 \times Q_{surf} \times q_{peak} \times area_{hru})^{0.56} \times K_{usle} \times C_{usle} \times P_{usle} \times LS_{usle} \times CFRG \quad (2)$$

where *sed* is the sediment yield on a given day (ton); Q_{surf} is the surface runoff volume (mm /ha); q_{peak} is the peak runoff rate (m^3/s); $area_{hru}$ is the area of the HRU (ha); K_{USLE} is the USLE soil erodibility factor; C_{USLE} is the USLE cover and management factor; P_{USLE} is the USLE support practice factor; LS_{USLE} is the USLE topographic factor, and *CFRG* is the coarse fragment factor.

Nutrients cycles are predicted in association with diverse management practices involving planting, pesticide application, irrigation, harvesting, and tillage. Both N and P could be divided into organic and inorganic forms in the process of transport and transformation. The forms of N tracked by SWAT include nitrates, organic nitrogen, and ammonia, while P is simulated as the forms of soluble phosphorus and organic phosphorus. Nutrients are introduced to the main channel and transported downstream through surface runoff and lateral subsurface flow (Williams, 1975).

3.2. Input Data for SWAT Setup

Major data categories required by the SWAT modeling include topographic data, land use, soil map, daily weather data, soil attributes, hydrological data, water quality data, and agriculture management. The details are proved in the following context.

Watershed topography is represented by a 90 × 90 m digital elevation model (DEM) dataset (Figure 2a) which was downloaded from the International Scientific Data Service Platform website. Land use (1:250000) for 2005 and soil vector map (1:4000000) for 1990s are both obtained from Data Sharing Infrastructure of Earth System Science which is supported by the Institute of Geographic Sciences and Natural Resources Research (IGSNRR) and the Institute of Soil Science (ISS), Chinese Academy of Sciences (CAS). Both graphs are presented in Figure 2 (2b and 2c), and details of land use and soil types in the study watershed are also provided in Table 1 and Table 2, respectively. They were used together for delineating the sub-basins and hydrologic response units (HRUs), as shown in Figure 2d.

Table 1. Summary of Land Use Types in the TGR Watershed

ID	SWAT Code	Name	Area(ha)	Land Use
11	FOEC	Forest-Evergreen-conifer	1122161	Wood land
12	FOEH	Forest-Evergreen-hardwood	156042	
13	FODC	Forest-Deciduous-conifer	47485	
14	FODH	Forest-Deciduous-hardwood	259284	
15	FOMX	Forest-Mixed	440970	
16	BOSK	Bosk	824109	Brush land
21	MEGR	Meadow grass	27158	Grass land
22	TYGR	Typical grass	356538	
26	BOGR	Bosk grass	289248	
31	PAFI	Paddy field	637864	Farm land
32	IRLA	Irrigable land	84415	
33	DRLA	Dry land	1455999	
41	STLT	Structural land	48010	Structural
42	COUN	Country	16875	land
53	WATE	Water (river, pond etc.	89841	Water
54	BOLA	Bottomland	3358	
61	NAKE	Naked	626	Barren land

Table 2. Soil Types in the TGR Watershed

ID	SWAT Code	Name	Area (ha)
161	PTzongR	General brown soil	63100
201	PThuangzongR	General yellow-brown soil	708200
203	nianpanhuangzongR	Planosol yellow-brown soil	72800
231	PThuangR	General yellow soil	1463800
253	huanghongR	Yellow-red soil	23200
531	PTzongseshihuiT	General brown rendzina soil	403700
563	shenyushuidaoT	Percogenic paddy soil	243800
611	PTchongjiT	General alluvial soil	192700
651	PTziseT	Neutral purple soil	1774300
652	shihuixingziseT	Calcareous purple soil	678800
653	bubaoheziseT	Unsaturated purple soil	29700

Daily time-series of measured precipitation, air temperature, relative humidity as well as wind velocity were provided by National Meteorological Information Center from 7 meteorological stations for the years of 2001 ~ 2008. Monthly observed river flow and sediment yields data from the stations of Cuntan, Qingxichang, Wanxian, Yichang (Figure 1) were obtained from the Ministry of Water Resources of China, Hydrology Bureau for the period of 2001 ~ 2008. Seasonal observed water quality data from the stations of Cuntan, Qingxichang, and Wanxian (Figure 1) were provided by the local environmental protection departments in the watershed.

Agricultural management practices and details with respect to corn/spring-canola rotation in dry land and rice in paddy land were collected through field investigation, expert consultation and literature search. Dry land is plowed in May and then corn is planted thereafter and harvested in September with 250 kg/ha N-fertilizer and 100 kg/ha P-fertilizer being applied; spring canola is then seeded and grows through October to next April with an application rate of 250 kg/ha for N-fertilizer and 100 kg/ha for P-fertilizer. Rice is cropped in the paddy lands twice a year in April and August, respectively, with a fertilization rate of 250 kg/ha for N and 200 kg/ha for P. All of the crops are irrigated by weather.

In this study, the Three Gorges watershed was divided into 79 sub-basins, as shown in Figure 2d, with the threshold area being set at 40,000 ha. The land slope was grouped into four grades (≤ 6°, 6 ~ 15°, 15 ~ 25°, ≥ 25°). The land use, soil map and land slope were then overlapped onto each other to define the threshold of HRU. In total, 2985 HRUs were defined with uniform parameters and variables being used in each unit. Data of hydrology and water quality from upstream inlets including Yangtze River, Jialing River and Wu River were also added to the SWAT for enhancing the simulation accuracy.

4. Model Calibration and Validation

4.1. Model Calibration

Before the SWAT model is applied to land use scenario analysis, it has to be properly calibrated and validated for improving its reliability and accuracy in future simulation (Klaus et al., 2005). SWAT model contains a large number of parameters. On the one hand, this could significantly facilitate and enhance the hydrological modeling process; on the other hand, inevitably, they are frequently over-parameterized. Therefore, identification of the sensitive parameters is an essential step for calibrating the model effectively. Once identified, these sensitive parameters are the ones to which most of the calibration effort should be devoted. In this study, the trial-and-error method was used to calibrate the SWAT model, and the sensitive model parameters were adjusted manually through the ArcGIS-based interface of SWAT model, so that the satisfactory agreements between the measurements and simulations for all the variables of interests are achieved simultaneously. The sequence of model variables we used to calibrate the SWAT model is the surface runoff, then the sediment yields, followed by the nutrient transport. The satisfactory agreements between the measurements and simulations were evaluated using the following two formulas, i.e., the Nash-Sutcliffe model efficiency (E_{NS}) and the coefficient of determination (R^2) (Gikas et al., 2006):

$$E_{NS} = 1 - \frac{\sum_{i}^{n}\left(Q_{s,i} - Q_{o,i}\right)^2}{\sum_{i}^{n}\left(Q_{s,i} - \overline{Q_s}\right)^2} \qquad (3)$$

$$R^2 = \frac{\left[\sum_{i}^{n}\left(Q_{s,i} - \overline{Q_s}\right)\left(Q_{o,i} - \overline{Q_o}\right)\right]^2}{\sum_{i}^{n}\left(Q_{s,i} - \overline{Q_s}\right)^2 \sum_{i}^{n}\left(Q_{o,i} - \overline{Q_s}\right)^2} \qquad (4)$$

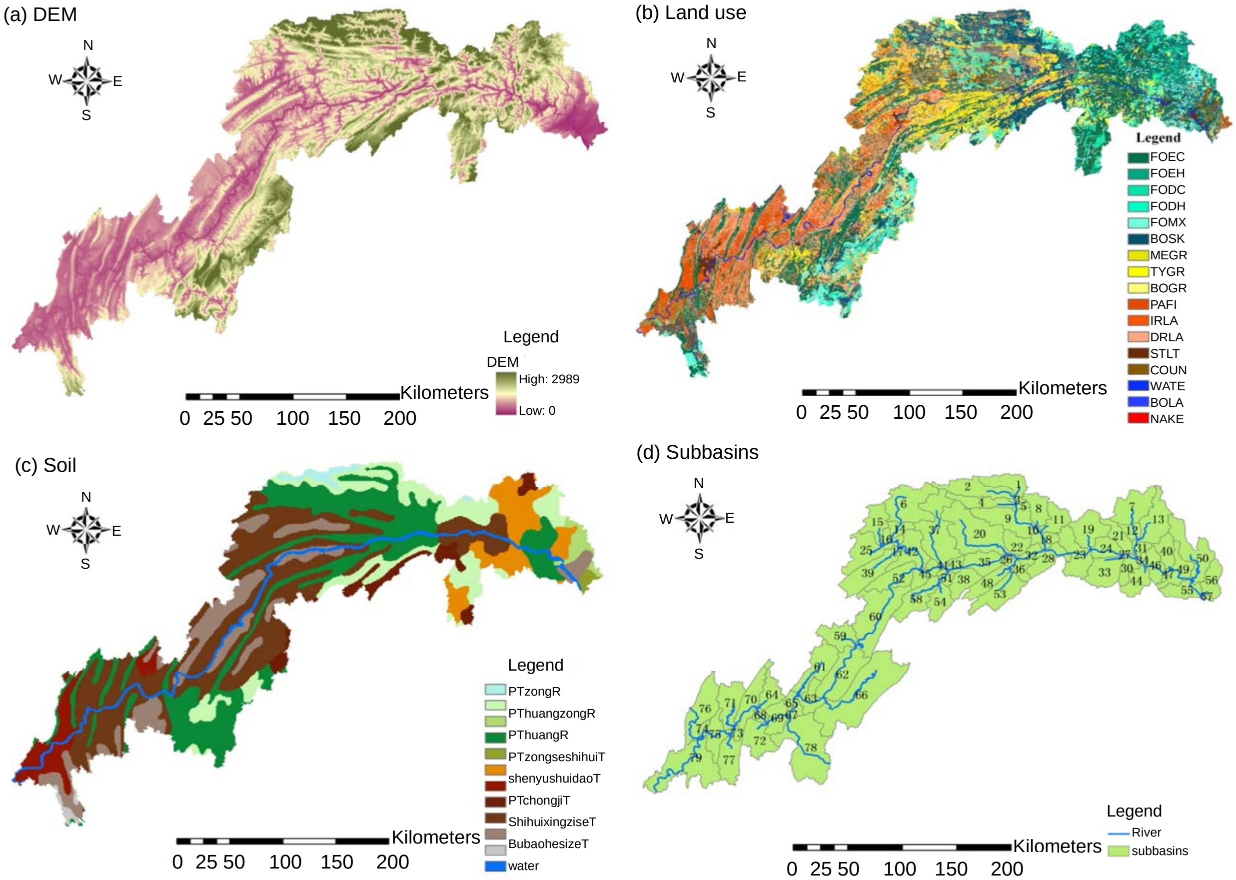

Figure 2. Spatial presentations of SWAT input data and division of sub-basins of the watershed.

In Equations (3) and (4), $Q_{s,i}$ and $Q_{o,i}$ represent the simulated and observed values of specific state variable, respectively; $\overline{Q_s}$, $\overline{Q_o}$ are the average values of the simulated and observed state variable; n is the total number of data recorded; E_{NS} gives the level of agreements between the observed and simulated values of the state variable, and it indicates how satisfactorily the simulations and observations agree to each other; R^2 is the coefficient of determination, indicating correlations between the observed and simulated state variables. The values of E_{NS} range from $-\infty$ and 1, and the values of R^2 change from 0 to 1. Their magnitudes are often used to express how accurately the model simulation could achieve, i.e., closer to one, more accurate the simulation results are. In this study, SWAT model performance on a monthly average was classified as: excellent if R^2 or $E_{NS} \geq 0.90$; very good if $0.75 \leq R^2$ or $E_{NS} < 0.90$; good if $0.50 \leq R^2$ or $E_{NS} < 0.75$; fair if $0.25 \leq R^2$ or $E_{NS} < 0.50$; poor and unsatisfactory if $0 \leq R^2$ or $E_{NS} < 0.25$ or $E_{NS} < 0$ (Moriasi et al., 2007; Parajuli et al., 2009; Parajuli, 2010).

In this study, three state variables of SWAT model, i.e., runoffs, sediment yields, and nutrient yields in the watershed, were used to calibrate the most sensitive parameters. These parameters are described in Table 3. Among these parameters, Curve Number (CN) and Soil_Available Water Capacity (SOL_AWC) have been found to be the most sensitive parameters that affect all three state variables and their values were adjusted by multiplying 0.9 in the calibration process. The parameters of Soil Evaporation Compensation Factor (ESCO), Base Flow Alpha Factor (ALPHA_BF) and Evapotranspiration Rate Factor (REVAPMN) were found to be sensitive to the runoff simulation and were adjusted delicately to fine-tune the flow simulation in the hydrologic cycles in the watershed. The channel sediment parameters SPCON and SPEXP were found to be very sensitive to the sediment yield and transport and their values were set to 0.0015 and 1, respectively. For calibrating nutrient-related parameters, including Nitrogen Percolation Coefficient (NPERCO), Soluble Phosphorus Percolation Coefficient (PPERCO) and Phosphorus Soil Partitioning coefficient (PHOSKD), these values were adjusted within their own ranges repeatedly and their default values were found to be the best fits ultimately.

4.2. Model Calibration and Validation Results

Monthly hydrological data and seasonal water quality data collected from the specific monitoring stations during the years of 2001 to 2008 were used for SWAT model calibration and validation. Four hydrological measuring stations along the Yangtze River section within the Three Gorges watershed from upstream to downstream are Cuntan Station (S1), Qingxichang

Table 3. Descriptions and Value Calibrations of Sensitive Parameters in SWAT Model

Variable	Item	Description	Normal Range	Actual Value
CN2	Flow, Sediment, Nutrient	Curve number	35 - 98	67 - 97
SOL_AWC	Flow, Sediment, Nutirent	Soil available water capacity (mm H_2O/mm soil)	0 - 1	0.5 - 0.1
ESCO	Flow	Soil evaporation compensation factor	0 - 1	0.8
ALPHA_BF	Flow	Base flow alpha factor (days)	0 - 1	0.048
REVAPMN	Flow	Threshold depth of water in the shallow aquifer for revap to occur (mm H_2O)	0 - 500	50
SPCON	Sediment	Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing	0.0001 - 0.01	0.0015
SPEXP	Sediment	Exponential parameter for calculating sediment reentrained in channel sediment routing	1 - 2	1
NPERCO	Nutrient	Nitrogen percolation coefficient	0 - 1	0.2
PPERCO	Nutrient	Soluble phosphorus percolation coefficient	10 - 18	10
PHOSKD	Nutrient	Phosphorus soil partitioning coefficient	100 - 200	175

Table 4. The Values of R^2 and ENS Calculated from the Model Calibration and Validation

Station	Item	Calibration				Validation			
		Flow	Sediment	TN	TP	Flow	Sediment	TN	TP
Cuntan, S1	R^2	0.988	0.980	0.725	0.656	0.999	0.996	0.838	0.939
	E_{NS}	0.980	0.905	0.417	0.555	0.998	0.977	0.720	0.381
Qingxichang, S2	R^2	0.990	0.957	0.854	0.621	0.998	0.989	0.860	0.914
	E_{NS}	0.983	0.930	0.365	0.498	0.993	0.986	0.320	0.861
Wanxian, S3	R^2	0.989	0.931	0.847	0.311	0.993	0.958	0.963	0.836
	E_{NS}	0.981	0.683	0.778	0.270	0.993	0.938	0.722	0.811
Yichang, S4a	R^2	0.984	0.649	0.662	0.684	0.967	0.746	0.906	0.621
Peishi, S4b	E_{NS}	0.981	0.384	0.520	0.661	0.966	0.594	0.873	0.110

Table 5. Sediment Loads and Nutrient Loads in Runoff over Different Land Use Types for Scenario Q6

Land Use	Area	Proportion	Sediment		TN		TP	
	ha	%	10^4t/a	%	10^4t/a	%	10^4t/a	%
Farmland	1870403	39.29	9063.57	88.75	5.82	82.66	1.56	86.55
Woodland	1472564	30.93	178.07	1.74	0.41	5.80	0.06	3.29
Shrubland	766988	16.11	136.28	1.33	0.40	5.72	0.07	3.85
Grassland	503766	10.58	308.74	3.02	0.38	5.38	0.06	3.20
Others	147058	3.09	525.71	5.15	0.03	0.43	0.06	3.11
Total	4760778	100	10212.37	100	7.04	100	1.81	100

Station (S2), Wanxian Station (S3), and Yichang Station (S4a). Four water quality monitoring stations along the same route are Cuntan Station (S1), Qingxichang Station (S2), Wanxian Station (S3), and Peishi Station (S4b). The data sets include monthly averages of flow rate, sediment yield, TN yield, and TP yield. Due to lack of more frequent water quality data from the 4 stations, we assumed that the observed monthly average TN and TP yields are consistent from one month to another within a specific season. Among all the data sets we collected, the data from 2002 through 2005 were used for model calibration and the determination of model parameters, and the data from 2006 through 2008 were used for model validation and assessment of model's simulation performance. The model calibration and validation results were plotted together in Figures 3 to 6, which compare the plots between the observed and simulated monthly averages of runoffs, sediment yields, TN and TP yields, respectively. The Nash-Sutcliffe model efficiency coefficient and the coefficient of determination were also calculated based on Equations (3) and (4), and they are given in Table 4.

The model calibration and validation results as presented in Figures 3 to 6 and Table 4 show that a satisfactory goodness of fit has been reached for each state variable of interest. In general, the model performs better in simulating hydrological cycles than water quality in terms of TN and TP yields. It is observed that the values of R^2 and E_{NS} for runoff simulation at all 4 stations are greater than 0.96, indicating an excellent level of simulation performance. The model performance on sediment simulations is excellent for upstream section (S1 and S2) while being fair to good for downstream section (S3 and S4a), with the values of R^2 and E_{NS} being ranged from 0.384 ~ 0.996. The model performance of nutrient simulation changes from poor to excellent, with TN simulation performing considerably better than TP. This is due mainly to the unavailability of sufficient water quality monitoring data. The model calibration and validation results imply that the SWAT model performs gene-

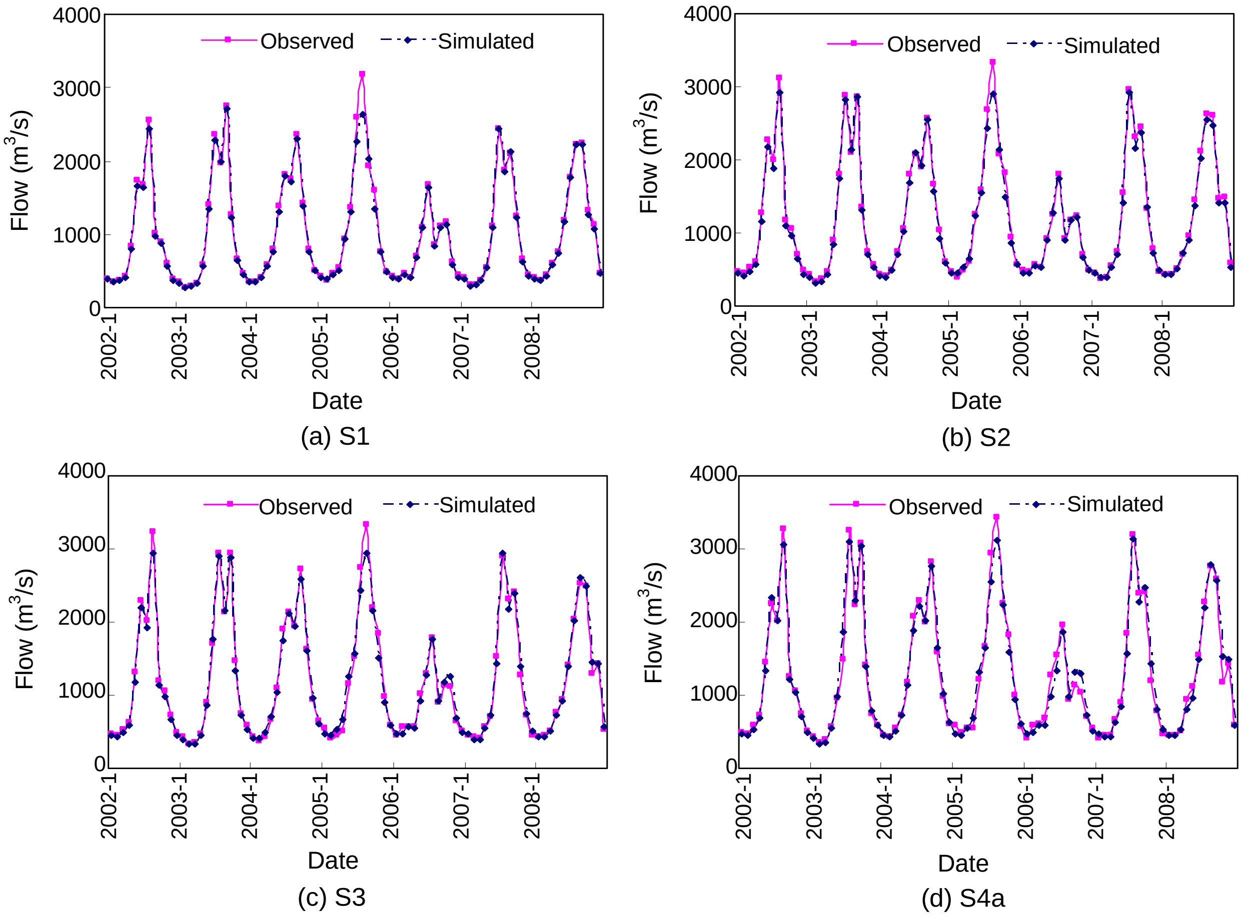

Figure 3. Comparison between the observed and simulated monthly flow rate at 4 Stations for the years of 2002-2008.

rally satisfactorily in simulating the hydrological cycles as well as the sediment and nutrient yields caused by the NPS. It is believed that the calibrated SWAT model can be applied to the large-scale Three Gorges watershed.

5. Land Use Scenario Design and Analysis

5.1. Scenario Design

In this study, the calibrated SWAT model was then applied to the study watershed through simulating different land use and management scenarios and examining the impact of each scenario on reservoir water quality due to non-point source pollution. A total of six scenarios were designed on the basis of field investigation results, local expert consultations, and case studies from literature surveys (Nie et al., 2011; De Girolamo and Lo Porto, 2012). They represent six different land use patterns which could be feasibly adopted by local authorities. The details of the six scenarios are provided below.

[Scenario Q1] – Reforestation through changing the farmland with a slope greater than 25° in the watershed to forest land (woodland). This scenario was designed for echoing Central Government's reforestation policy which encourages the whole country to implement for improving ecological and environmental protection and conservation.

[Scenario Q2] – Enhanced reforestation through changing all the farmland with a slope greater than 15° in the watershed to forest land (woodland). This scenario was designed to examine the best results which could be achieved through returning and converting the majority of cultivable farmland in the watershed to woodland.

[Scenario Q3] – Reforestation through converting most of the grassland in the watershed to forest land (woodland). The transformed grassland accounts for 9.53% of the total area of the watershed.

[Scenario Q4] – Agricultural development through converting most of the grassland (9.53% of the total area) in the watershed to cultivable farmland for supporting local farmers.

[Scenario Q5] – Best forest coverage scenario through converting most of the grassland and part (13.22%) of the farmland in the watershed to forest. This will make the region of the Three Gorges watershed become a better conservation area with fewer agricultural activities. The forest coverage ratio in the watershed could reach as high as 57.33% of the total watershed area.

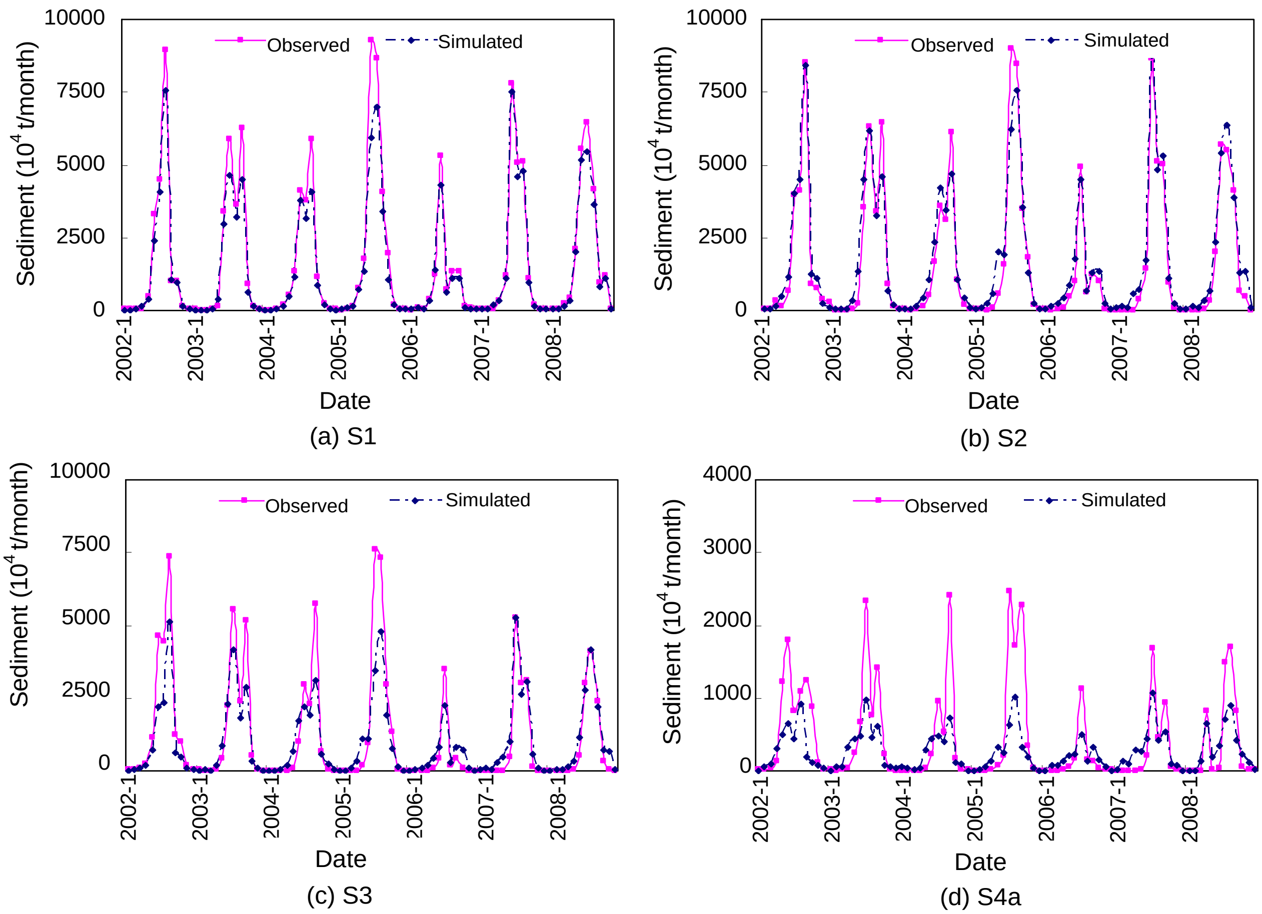

Figure 4. Comparison between the observed and simulated monthly sediment yields at 4 Stations for the years of 2002-2008.

[Scenario Q6] – Baseline scenario representing the land use activities and management practices implemented by the local governments and authorities in 2005, and it was simulated first in this study to identify the dominant non-point pollution source in the current land use practices within the Three Gorges watershed.

Among six scenarios, Q1 to Q5 represent 5 distinct directions with their respective focus in formulating the land use and management policies toward the NPS pollution control. Q1 and Q2 target on enhancing the reforestation efforts through converting part of the farmland to forest land in the watershed. However, Q1 focuses on the farmland with a slope greater than 25° while Q2 focuses on the farmland with a slope greater than 15°. The farmland with a slope less than 25° (in Q1) or 15° (in Q2) remains for maintaining a certain level of agricultural activities in the region. Q3 is designed to evaluate the response of the NPS pollution control to the policy that all the grassland is converted to forest land; and for this scenario, all the farmland in the region will remain to sustain its production. Being distinct from Q3, Q4 suggests converting all the grassland to farmland instead of forest land, and this scenario aims to examine how the NPS pollution will evolve if the local government weights up the agricultural activities and development. In this study, Q5 represents an ideal policy scenario with all of the grassland and most of the farmland being converted to the forest land in the watershed. It is anticipated that the best NPS pollution control performance in terms of sediment and nutrient yield reductions might be achieved under this scenario. The simulation results obtained from Q1 ~ Q5 will be compared with the baseline scenario Q6 to examine their effectiveness and soundness.

5.2. Scenario Analysis and Results

5.2.1. Baseline Scenario Q6

Baseline scenario Q6 was simulated using the SWAT model to examine the loads of sediment, TN and TP from different land use types in the watershed in the year of 2005, and the simulation results are presented in Table 5 and Table 6. Table 5 gives the existing land use pattern in the watershed as well as the loads of sediment, TN and TP in the runoff over different land use types. The land use types in the watershed could be divided into 5 groups with a total area of 4,760,778 ha. They are listed in Table 5 in a sequence from the biggest to the smallest according to their sizes, i.e., farmland, woodland, shrubland, grassland and other land uses (such as bared land and con-

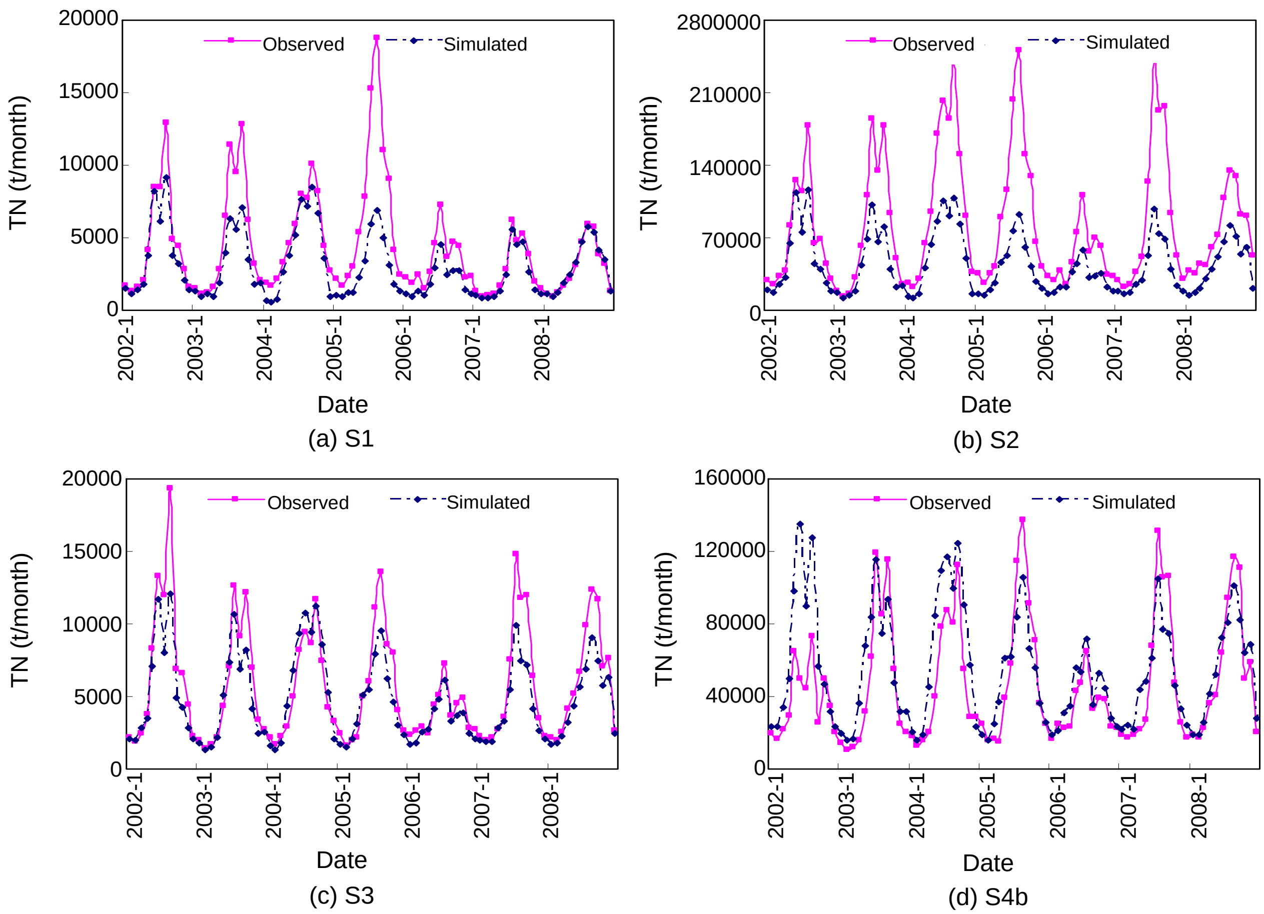

Figure 5. Comparison between the observed and simulated monthly TN yields at 4 Stations for the years of 2002-2008.

struction land). Among them, the farmland and woodland have the largest and second largest area, accounting for 39.29% and 30.93% of the total, respectively. In terms of the sediment load in surface runoff, the farmland is the dominant land use type and contributes 88.75% of total sediment yields, followed by the other land uses with a contribution ratio of 5.15%. This is consistent with the common knowledge that vegetation covers (grass, shrub and forest) could significantly prevent soil erosion and loss from precipitation and surface runoff. In term of TN loads in surface runoff, the farmland is also the dominant contributor of nitrogen yield and loss into the reservoir, with a ratio of 82.66% of the total, followed by the woodland (5.80%), shrubland (5.72%), and grassland (5.38%). Similar trends could be observed for the TP loads and the contribution ratios of farmland, shrubland, woodland, and grassland are 86.55%, 3.85%, 3.29% and 3.20%, respectively. It is not surprising that agricultural activities on farmland could contribute significantly to the non-point source pollution in the watershed. In the study watershed, the farmland only accounts for 39.29% of the total land use area however contributing over 80% to the total sediment, TN and TP loads, and this fact makes the farmland particularly stand out in terms of non-point sources in the region. Changing the land use types or implementing alternative land management practices might be able to help alleviate this problem, and the farmland is of particular importance in land use changes. This fact also helps guide the design of Q1 ~ Q5 scenarios in this study.

Table 6. Annual Sediment and Nutrient Loads Per Unit Area for Different Land Use Types for Scenario Q6

Land Use	Sediment	TN	TP
	t/(ha·a)	kg/(ha·a)	kg/(ha·a)
Farmland	46.48	30.89	8.03
Woodland	1.21	2.78	0.40
Brushland	1.78	5.26	0.91
Grassland	3.34	5.87	0.96
Others	—	—	—
Watershed Average	21.45	14.80	3.80

Table 6 gives the annual loads of sediment, TN and TP per unit area of different land use type in 2005, and it represents the output intensity of NPS pollution from the different types of land use in the watershed. In term of runoff intensity, surprisingly, the woodland produced the biggest runoff intensity of approximate 700 mm per ha per year, followed by the shrubland, farmland and grassland. This is due mainly to the fact that

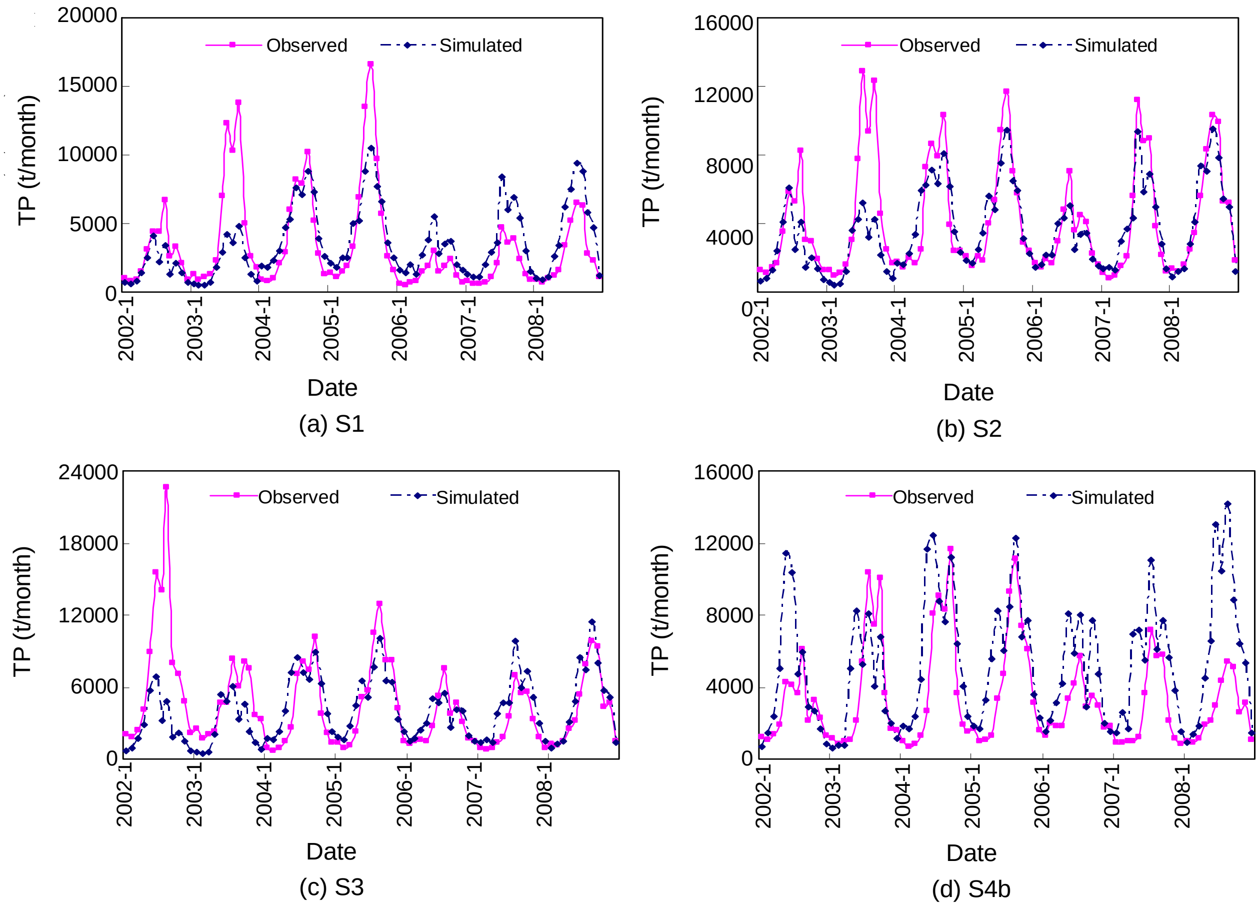

Figure 6. Comparison between the observed and simulated monthly TP yields at 4 Stations for the years of 2002-2008.

the canopy cover of the woodland in the watershed is generally above a certain threshold height, which makes the woodland have higher rainfall-runoff conversion coefficient. This finding is consistent with other previous local works (Huang et al., 1999; Li et al., 2009; Liu et al., 2011). In terms of the annual NPS pollution contributions per unit area, the farmland produced a sediment rate of 46.48 t/(ha·a), a TN rate of 30.89 kg/(ha·a), and a TP rate of 8.03 kg/(ha·a), which doubles the average loading rates for the watershed. It can be concluded that the reforestation will play a crucial role in water-soil conservation and non-point source pollution control. This result is of significance to the decision making related to the changes of land use policies and land management practices.

5.2.2. Simulation of Land Use Change Scenarios (Q1 ~ Q5)

Figure 7(a ~ f) gives a graphical presentation of different land use patterns specified by the six scenarios. Among these scenarios, Scenario Q5 has the largest woodland size (57.33% of the total land use area) while the baseline scenario Q6 has the smallest woodland size (34.57% of the total); Scenario Q6 has the largest grassland size accounting for 11.48% of the total land use area while Scenario Q5 has the smallest grassland size (1.95% of the total); Scenario Q4 has the largest farmland size (46.87% of the total) and Q2 has the smallest farmland size (26.21% of the total). It is observed that Q1 land use map (Figure 7a) looks similar with Q6 land use map (Figure 7f) since only 3.64% of the total farmland (i.e., the farmland with a slope greater than 25°) is converted to the woodland; the middle portion of Q2 land use map (Figure 7b) is apparently different with that of Q6 land use map (Figure 7f) since all the farmlands with a slope greater than 15° being converted to woodland are located in the middle portion of the watershed. Scenarios Q2 and Q3 have similar woodland size and similar spatial distribution, 45.70% and 44.11%, respectively. However, they have different sizes of grassland and farmland. The simulation results for Q2 and Q3 could help explain the effects of grassland and farmland on the non-point source pollution control under the same woodland setting. Scenarios Q3 and Q4 compare two different land use patterns through changing the grassland to the woodland and farmland, respectively, in terms of their effects on NPS pollution control. Scenarios Q4 and Q5 represent two extreme situations of land use patterns and their potentials in reducing the NPS pollution in the watershed.

In this study, the calibrated SWAT model was then used to simulate the land use scenarios (Q1 to Q5) to examine the impact of each scenario on reservoir water quality due to non-

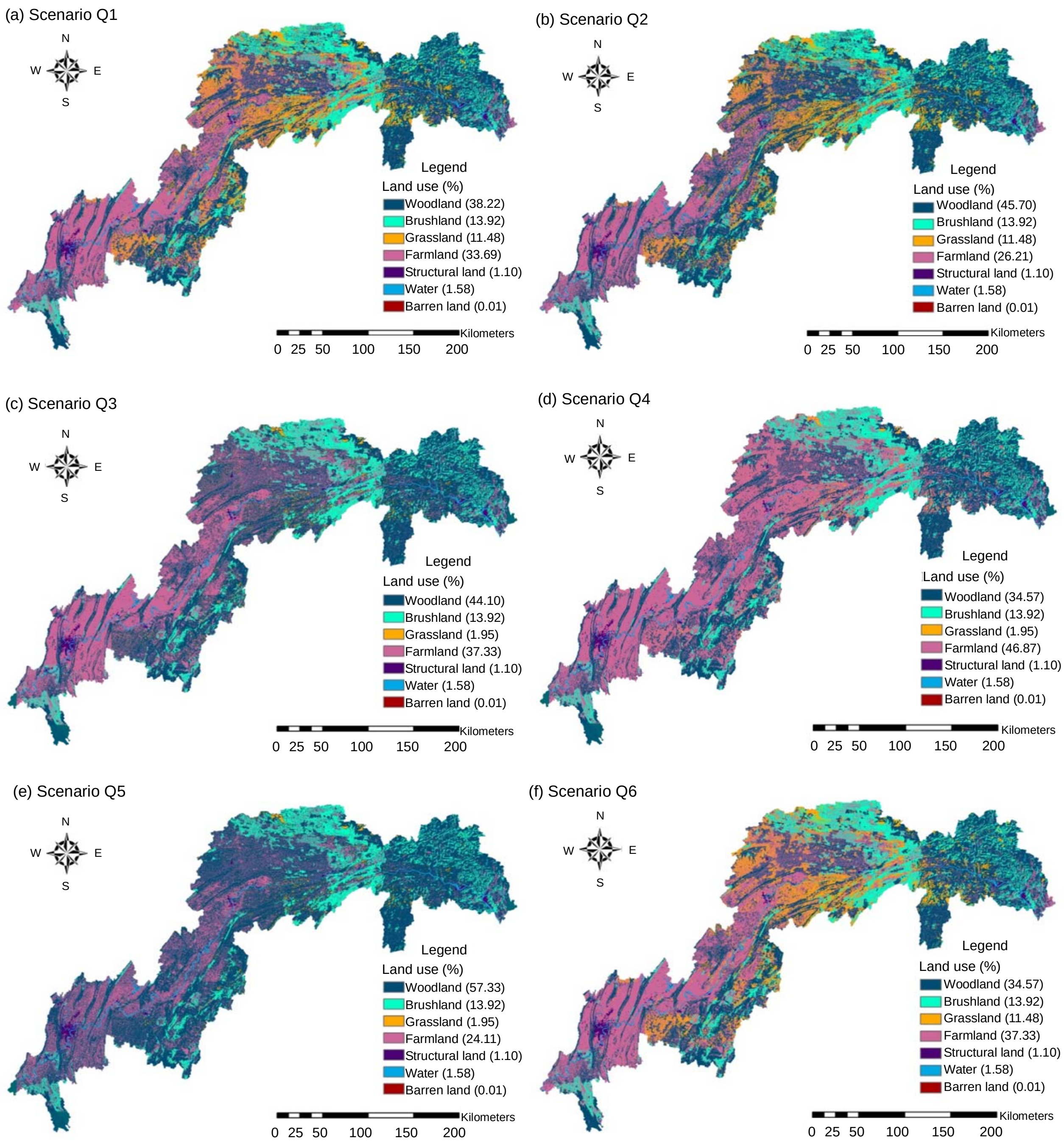

Figure 7. Land use patterns specified for the six scenarios.

point source pollution in term of multi-year average of the yields of runoff, sediment and nutrients (TN and TP). The results were also compared to the baseline scenario simulation results, as presented in Figures 8 and 9. Figure 8 gives a yield comparison among all six scenarios. Figure 9 presents the reduction or increase ratio of NPS pollution yields of Scenarios Q1 ~ Q5 when compared to the baseline scenario Q6. It is observed that the land use changes could significantly affect the yields of runoff, sediment and nutrients. For example, the sediment yield from Q4 is the largest with a value of 1.662 million ton per year and it increases 62.37% over the baseline scenario. The sediment yield from Q2 is only 0.346 million ton per year with its reduction ratio of 66.15% being highest. Similar significant changes could be observed for the yields of TN and TP. However, this is not the case for runoff generation, and a small change rate of 0.30% to 2.07% was observed. It can be concluded that changing the land use pattern and implementing alternative management practices could help reduce the non-point source pollution effectively and thus play a significant role in improving reservoir water quality of the watershed.

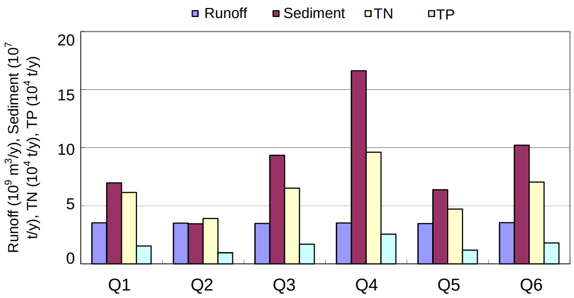

Figure 8. Multi-year averages of yields of runoff, sediment, nutrients for six scenarios.

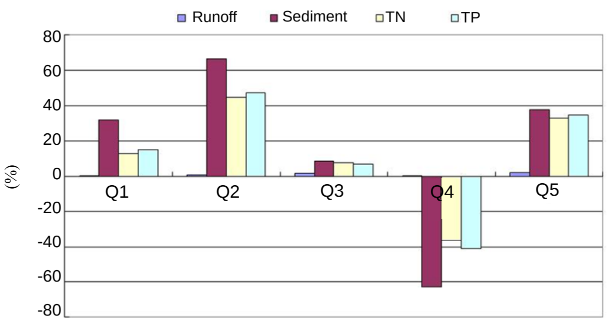

Figure 9. Reduction or increase ratio of Scenarios Q1 ~ Q5 in comparison to the baseline scenario Q6 (Note: bar graphs above 0-axis indicate yield reduction; bar graph below 0-axis indicates yield increase).

The SWAT modeling results also reveal different effects on the reduction of non-point source pollution control among designed land use scenarios. Scenario Q1 has yield reduction ratios of 31.71% for sediment, 12.78% for TN, 14.92% for TP, while Scenario Q2 has substantial increases for the yield reduction ratios with 66.15% for sediment, 44.46% for TN, and 44.96% for TP. It is indicated that the farmland has been the major contributor to the watershed NPS pollution. Figure 9 shows that the yield reduction ratio for Q2 is 6 to 8 times bigger than Q3. This implies that, when the woodland size is fixed, changing the farmland to other types will be able to better control the NPS pollution. The results for Q3 and Q4 show that a totally different NPS pollution control effect will be observed when the same grassland is converted to woodland and farmland, respectively. If the 9.53% grassland is converted to the woodland type, it would reduce the NPS pollution by less than 10%; however, if the same grassland is converted to the farmland type, it would increase the yield of NPS pollution by 50%. Therefore, the practice of changing the grassland to the farmland in the watershed should be strictly regulated and restricted. Scenario Q5 has the largest woodland size among all the scenarios, however, its effects on the NPS pollution control is not the best. Q5 has a similar reduction of sediment as Q1 and a close reduction of nutrients to Q2. It is indicated that the existing woodland should be well conserved and protected; however, extra pre-cautions should be given when making decisions related to the increase of woodland area from other land use types.

6. Conclusioins

In this study, the SWAT model was applied to the large-scale Three Gorges watershed in China for evaluating the effects of land use types on the non-point source pollution control. This study is a first-time attempt of applying the SWAT model to the NPS pollution control study for the entire region of the Three Gorges watershed, and represents a new contribution to the SWAT modeling community. The model was firstly calibrated and validated using the data collected from the hydrological and environmental monitoring stations along the Three Gorges reservoir for the years of 2002 ~ 2008. Although the calculated values of R^2 and E_{NS} vary among the runoff, sediment yield and nutrient yields, the results show that these values are in the acceptable ranges and a satisfactory goodness of fit between the simulated and observed state variables has been achieved. In general, the model performs better in simulating hydrological cycles than water quality expressed as TN and TP yields. The calibrated SWAT model was then applied to the study watershed through simulating 6 different land use scenarios and examining the effects of each scenario on the non-point source pollution control in the watershed. Six scenarios include a baseline scenario (Q6) representing the land use pattern the watershed had in 2005 and five newly-designed scenarios (Q1 ~ Q5) representing 5 different land use alternatives. The baseline scenario simulation results identify the dominant role of the farmland in contributing to the non-point source pollution in the watershed. In 2005, the farmland only accounts for 39.29% of the total land use area, however, it contributes over 80% to the total sediment, TN and TP loads. Scenarios Q1 to Q5 were simulated to investigate the possible effects of five alternative land use patterns on the non-point source pollution issue in the watershed through comparing their yields of runoff, sediment, and nutrients with the baseline scenario. The simulation results of Scenarios Q1 to Q5 once again indicate that the farmland is the major contributor to the watershed NPS pollution. If the farmland is changed to woodland, grassland or shrubland, a better control over the NPS pollution could be achieved. It is believed that the land use changes could significantly affect the yields of runoff, sediment and nutrients. This study provides a good understanding of the interactions between different land use types and the NPS pollution for making sound decisions. For example, the policies and practices of changing the grassland to the farmland in the watershed should be strictly regulated and restricted. Also, the existing woodland should be well conserved and extra pre-cautions should be given when making decisions related to the increase of woodland area from other land use types. It can be concluded that changing the land use pattern and implementing alternative management practices could help reduce the non-point source pollution effectively and thus play a significant role in improving reservoir water quality of the watershed.

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