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Effect of reforestation on nitrogen and phosphorus dynamics in the catchment ecosystems of subtropical China: the example of the Hanjiang River basin

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Abstract

BACKGROUND: To enable effective management and decision making for the sustainable use of water resources, we successfully integrated factors such as dams, land use and soil properties as well as management factors in the Hanjiang River basin, a subtropical catchment of China, into the SWAT model to simulate water cycles as well as the distribution, movement, and transformations of nutrients.

RESULTS: The accuracy of the model was validated by monitoring data over the Hanjiang River. The validated model was then used to evaluate the effects of the Reforestation of Cultivated Land (RFCL) initiative. The simulation results showed that RFCL would cause an obvious decrease in surface runoff (−23.6%, $P < 0.01$) but an increase in groundwater (71.8%, $P < 0.01$) and percolation out of the soil (24.7%, $P < 0.01$). The total water yield does not change significantly (−4.4%), but the decrease in total sediment loading is substantial (−56.2%, $P < 0.01$). The simulation results also show that RFCL would greatly decrease the organic N (−42.6%, $P < 0.01$), NO_3 yield in surface flow (−37.1%, $P < 0.01$), and the NO_3 yield in subsurface flow (−25.5%, $P < 0.01$), whereas the NO_3 yield in groundwater flow would increase (107%, $P < 0.01$). In terms of phosphorus, RFCL would cause both organic phosphorus (−38.2%, $P < 0.01$) and the phosphorus yield from the soil (−33.3%, $P < 0.01$) to decrease.

CONCLUSION: The results suggest that RFCL is an effective policy for watershed environment management, which might have a relatively small effect on river discharge but that the purification effects on water quality in the river would be remarkable.

Keywords: nitrogen and phosphorus; catchment ecosystems of subtropical China; Reforestation of Cultivated Land (RFCL); Hanjiang River

INTRODUCTION

With China's rapid economic development, population growth, and dramatic changes in lifestyle, its water environment is constantly worsening. According to regular water quality monitoring by the Datong hydrological station located along the lower reaches of the Changjiang (Yangtze) River, nitrate concentrations increased 10-fold between 1968 and 1997,[1] and nitrogen contamination has increased dramatically over last 40 years.[2,3] For example, extensive proliferation of blue-green algae in many lakes and dams and frequent outbreaks of red tide along the coast are causing environmental and health problems.[4] Concurrently, in the subtropical catchments of China, wide areas of watersheds are suffering from serious floods and high levels of soil and nutrient losses due to heavy rainfall and intensive human activities. Immediate implementation of best management practices is required in these critical areas to control soil and nutrient losses. However, to do so, it is first necessary to identify the critical areas and quantify the movement fluxes of sediments (soil erosion) and nutrients therein. Thus, to enable effective management and decision making for the sustainable use of water resources, it is essential to conduct scientific catchment–ecosystem assessments with emphasis on biophysical and biogeochemical processes.

For this purpose, we initially investigated nitrogen (N) flow, largely in relation to food production and consumption, in different agricultural regions in China. We especially targeted

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the Changjiang River basin by using a database of county-level agricultural statistics and field investigations.[5–8] However, these examinations were limited to the use of inventory budget models to determine past and current issues rather than dynamic process models that would allow for prediction of future changes and scenarios for effective management and decision making at the catchment scale. Here, we attempted to use an integrated catchment ecosystem model – the Soil and Water Assessment Tool (SWAT) – to simulate the spatial and temporal characteristics of water and nutrient dynamics among the atmosphere, soil, vegetation, and water bodies as well as to evaluate the effect of the Reforestation of Cultivated Land (RFCL) policy on ecosystem functions and the water environment over a catchment scale.

The SWAT model is a dynamic model that was developed at the University of Texas and by the United States Department of Agriculture (USDA) in the early 1990s.[9] It was developed to assist water resource managers in assessing the impact of land use, management and climate on water supplies and non-point-source pollution in watersheds and river basins. The model has been extensively used, mostly by hydrologists for watershed hydrology-related issues.[10–14] It has been well validated and applied to assess long-term effects of land use changes on stream flow. For example, Fohrer *et al*. used the SWAT model to predict the impact of land use changes on water balance for four meso-scale watersheds in Germany,[15] and Mishra *et al*. used it to study the impact of land use changes in a mixed land use watershed located in a subtropical region in India.[16] These studies revealed that sub-watersheds with relatively high forest cover exhibit less runoff and lower sediment yields, whereas those with relatively more cultivated area showed higher levels of runoff and sediment. Cao *et al*. used SWAT to simulate two land cover scenarios in the Motueka River catchment, New Zealand, to assess the impacts of land cover change on total water yield, groundwater flow, and quick flow.[17]

Because the algorithm of SWAT is open to the public online (http://swatmodel.tamu.edu/), it is easily verified and modified. A comprehensive description of all the components of SWAT can be found in the literature.[9,10,18–20] For this study, we successfully integrated factors such as large dams, land use patterns, and soil properties along with some parameters related to lifestyle, including socioeconomic conditions, from inventory data and field surveys conducted in the catchment of the Hanjiang River, a typical watershed of subtropical China. It can be used to evaluate the effects of climate changes and human activities, such as the RFCL initiative, fertilizer over-application, and increased atmosphere deposition, on water flux variables such as evapotranspiration (ET), surface runoff (SURF Q), and lateral flow (LAT Q). Water quality factors such as sediments (SED), biochemical oxygen demand (BCOD), ammonium nitrogen (NH4-N), nitrate nitrogen (NO3-N), dissolved oxygen (DO), total nitrogen (T-N) and total phosphorus (T-P) can also be evaluated. The Hanjiang River basin, the largest sub-catchment of the Changjiang River in subtropical China, was used as an example target area.

CASE STUDY AREA

The Hanjiang River is one of the largest tributaries of the Changjiang River, with a length of 1577 km and a watershed area of 159 000 km^2 (Fig. 1). To the north are the Qinling Mountains, and the Daba Mountains are to the south. The average elevation above sea level is 739.4 m, with a maximum of 3549 m, and the total drop of the river is 1964 m. The river rises in southwestern Shaanxi Province and flows east across the southern part of Shaanxi Province into Hubei Province. It crosses through most of Hubei Province from northwest to southeast before finally flowing into the Changjiang River in the provincial capital city, Wuhan. The Hanjiang River basin exhibits a humid subtropical climate, with a relative humidity $>60\%$. The annual distribution of rainfall is influenced by the Asia–Pacific monsoons, with the northwest monsoon prevailing from October to April and the southeast monsoon from May to September. The wet months are May to September, and the dry months are October to April. The average annual rainfall is 700–1100 mm and increases gradually from north to south.

Land use within the study area was classified into 11 classes, the major types being forest–deciduous (occupying 24.5%), agricultural land-row crops (22.0%), grassland (20.7%), paddy fields (11.1%), forest–mixed (10.1%), forest–needle leaf (9.3%), water (1.3%), and urban and built-up land (0.5%; Fig. 2). The

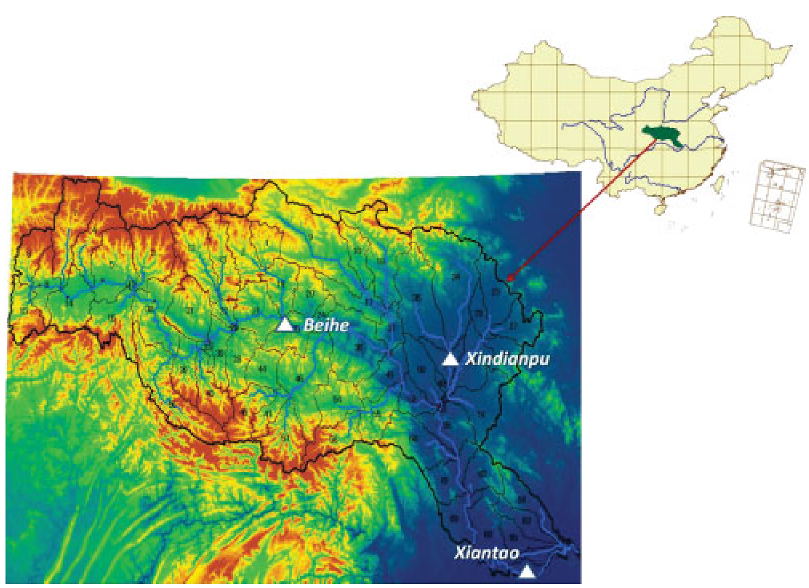

Figure 1. Location and topography of the Hanjiang River basin.

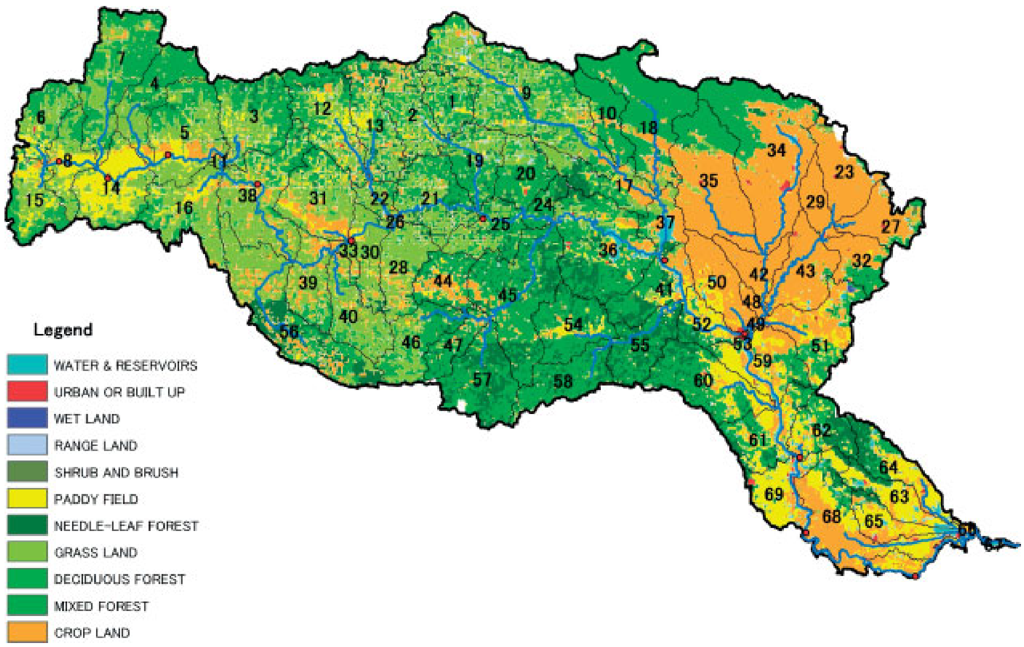

Figure 2. Land use map of the Hanjiang River basin.

soil of the study area consisted mainly of yellow, yellow-brown, yellow-cinnamon, purple, peaty, and paddy soils according to soil classification systems of China. Land use, topography, rainfall, and drainage network patterns are thought to be the major factors affecting hydrological processes, such as evapotranspiration, surface runoff, and river discharge. Fertilizer application, soil organic matter, and waste disposal are the main factors affecting biogeochemical processes such as carbon, nitrogen, and phosphorus fluxes. Since the late 1980s, land use in China has changed drastically. In addition to expansions of urban areas, there have been obvious increases in forestation, largely as a result of the Chinese land use policy entitled Reforestation of Cultivated Land (RFCL). These land use changes are considered to be important factors affecting both hydrological and biogeochemical processes.

MODEL DESCRIPTION AND DATA COLLECTION

Description of model

SWAT is a theoretical model that operates on a daily time step. In order to adequately simulate hydrologic processes in a basin, the basin is divided into sub-basins through which streams are routed. The subunits of the sub-basins are referred to as hydrologic response units (HRUs), which are the unique combination of soil and land use characteristics as well as slope, and are considered to be hydrologically homogeneous. The model calculations are performed on a HRU basis and flow and water quality variables are routed from HRU to sub-basin and subsequently to the watershed outlet. The SWAT model simulates hydrology as a two-component system, comprised of land hydrology and channel hydrology. The land portion of the hydrologic cycle is based on a water mass balance.

The water balance of each HRU in the watershed contains four storage volumes: snow, the soil profile (0–2 m), the shallow aquifer (2–20 m) and the deep aquifer (>20 m). The soil profile can contain several layers. The soil–water processes include infiltration, percolation, evaporation, plant uptake, and lateral flow. Surface runoff is estimated using the soil conservation service (SCS) curve number. Percolation is modeled with a layered storage routing technique combined with a crack flow model. Potential evaporation can be calculated using the Hargreaves, Priestly–Taylor or Penman–Monteith method.[9]

The SWAT watershed model contains algorithms for simulating erosion from the watershed, which is estimated using the modified universal soil loss equation (MUSLE). After the sediment yield is evaluated using the MUSLE equation, the model further corrects this value considering snow cover effect and sediment lag in surface runoff. The SWAT model also calculates the contribution of sediment to channel flow from lateral and groundwater sources. Eroded sediment that enters channel flow is simulated to move downstream by deposition and degradation.[19]

Soil N is also simulated in the SWAT model. It is partitioned into five N pools, two being inorganic (ammonium-N (NH4-N) and nitrate-N (NO3-N)) and three being organic (active, stable, and fresh). The SWAT model simulates movement between N pools, such as mineralization, decomposition/immobilization, nitrification, denitrification, and ammonia volatilization. Other soil N processes such as N fixation by legumes and NO3-N movement in water are also included in the model. Once N enters channel flow, the SWAT model partitions N into four pools: organic N, NH4-N, nitrite-N (NO2-N), and NO3-N. The algorithms used to describe N transformations in channel flow were adapted from the QUAL2E model by SWAT model developers.[19]

Another nutrient simulated in the soil profile is P. Soil P is divided into six P pools. Three of the pools are characterized as mineral P and three are characterized as organic P. Transformations of soil P between these six pools are regulated by algorithms that represent mineralization, decomposition, and immobilization. Other soil P processes included in the SWAT model are inorganic P sorption and leaching. P that enters stream channels is evaluated similar to N. Two pools of P are simulated for channel processes: organic P and inorganic/soluble P. The algorithms used in channel P calculations by the SWAT model were adapted from the QUAL2E model and are available in the SWAT model theoretical documentation.[19]

The SWAT model development primarily emphasizes climate and management impacts, water quality loadings and fate, and continuous time simulation. Although the SWAT model simulates on a daily time step, the model has options for the output that allow us to define the output time step (daily, monthly, or annual). Output variables include flow volume, nutrient yields, sediment yield, and plant biomass yields. These variables are provided on the sub-basin or HRU spatial level depending on the output time step selected.

The pond/reservoir routing allows for sediment settling and simplified nutrient and pesticide transformation routines. The command structure for routing runoff and chemicals through a watershed is similar to the structure for routing flows through streams and reservoirs. However, huge reservoirs, such as Danjiangkou Dam over the Hanjiang River, might change the structure for routing flows. In this study, we have changed most parameters concerning reservoirs suitable for huge dams, and integrated land use and soil properties along with some parameters related to lifestyle, including socioeconomic conditions, from inventory data and field surveys conducted in the catchment of the Hanjiang River Basin.

Collection of data

The SWAT model requires sufficient data to be defined. Basic data include topography (DEM: Digital Elevation Model), climate (daily and monthly meteorological data), soil and land use data (digital maps and physical and chemical parameters). The availability and quality of the watershed data can increase the accuracy of the model predication. Here we used data as follows: meteorological data from 15 weather stations for 1998–2008 were collected from the Climatic Data Center, National Meteorological Information Center, China Meteorological Administration (http://data.cma.gov.cn/). Hydrological data for 1998–2008 were measured by the Changjiang Water Resources Commission. The land cover map (1 : 1 000 000) in approximately 2000 was developed by the Institute of Geographical Sciences and Natural Resources Research (IGSNRR), Chinese Academy of Sciences (CAS). The map of soil types (1 : 1 000 000) and soil properties of each type originated from the Institute of Soil Science, CAS. The DEM (90 × 90 m) was obtained from the Shuttle Radar Topography Mission (SRTM), located within the US Geological Survey (USGS) website (seamless.usgs.gov).

For modeling purposes, the input data (i.e. DEM, land use map, soil map, weather data, and management parameters) were extracted and generated using Version 2009.93.5 for the SWAT 2009 model built within the ArcGIS 9.3 SP1 platform. The first step was watershed delineation, which split the Hanjiang River basin into 69 sub-watersheds (Fig. 1) according to the terrain and river channels. The next step was to upload the monthly and daily meteorological data, including air temperature (TEMP), precipitation (PRECIP), humidity (HUMI), wind speed (WIND), and solar radiation (RAD). Snow is simulated so TEMP drops below zero in winter. The final stage was to write the input files that contained the required input data for the project. General channel parameters, plant growth parameters and management operations were adjusted according to the local statistical or field survey data. The most important data of water quality such as NH_4-N, T-N and T-P for model calibration and validation at three observation stations – Xindianpu, Beihe and Xiantao – as shown in Fig. 1, were obtained from a cooperative project with the Changjiang Water Resources Commission (CWRC) of China.

Table 1. Best parameters selected by the calibration process at three stations – Baihe, Xindianpu, and Xiantao – on the Hanjiang River as shown in Fig. 1

Parameter	Min.	Max.	Baihe	Xindianpu	Xiantao
ALPHA_BF	0.00	1.00	0.96	0.96	0.54
CH_K2	0.00	150.00	139.30	138.30	125.50
CH_N2	0.03	0.07	0.05	0.05	0.07
CN2	−30.00	30.00	−12.50	−29.21	16.83
ESCO	0.00	1.00	0.04	0.15	0.01
GW_REVAP	0.02	0.20	0.08	0.20	–
GWQMN	0.00	2000.00	143.70	1506.00	1899.90
REVAPMN	0.00	200.00	142.00	141.60	29.55
SOL_AWC	−25.00	25.00	14.60	6.56	7.79
SURLAG	0.00	10.00	0.31	0.31	0.31

ALPHA_BF, base flow alpha factor (days); CH_K2, effective hydraulic conductivity of channel (mm h^{-1}); CH_N2, Manning's roughness coefficient for the main channel; CN2, initial SCS curve number for moisture condition II (%); ESCO, soil evaporation compensation factor; GW_REVAP, groundwater 'revap' coefficient; GWQMN, threshold depth of water in the shallow aquifer required for return flow to occur (mm); REVAPMN, threshold depth of water in the shallow aquifer for 'revap' or percolation to the deep aquifer to occur (mm); SOL_AWC, available water capacity of the soil layer (%); SURLAG, surface runoff lag time (days).

Calibration and validation of the model

The model was calibrated and validated against observation data from several tributaries in the upper, middle, and lower reaches of the Hanjiang River. Sensitivity analysis was conducted to guide the calibration process. The model calibration was performed for the daily and monthly observed flows and the concentration of nutrients from the hydrological stations at Xindianpu Station at the outlet of sub-basin 42, Beihe Station at the outlet of sub-basin 25, and Xiantao Station at the outlet of sub-basin 68, for the period 1998–2003. The coefficient of determination (R^2), Nash–Suttcliffe simulation efficiency (ENS) (Nash and Suttcliffe, 1970), and root mean square error (RMSE) were used to check model performance. The R^2 value is an indicator of the relationship between the observed and simulated values. It describes the proportion of the total variance in the observed data that can be explained by the model, and ranges from 0.0 to 1.0, with higher values indicating better agreement. The ENS indicates how well the plot of observed *versus* simulated values fits the 1 : 1 line. RMSE provides an indication of the error between the observed and simulated values. The calibration was stopped when the average measured and simulated values were within 15% and R^2 was >0.6. The parameters were adjusted several times and compared with observed data, and the most sensitive and best parameters were identified and are shown in Table 1; the rest of the parameters remained in the range set by the original SWAT model.

The calibration process was based on a comparison of monthly data measured hydrodynamic and water quality variables against model estimates during 1998–2003 ($n = 72$). For the river discharge calibration process, measured and simulated monthly flows were well matched or slightly under- or over-predicted in some months. Figure 3 provides a comparison between simulated values and observation data at Xindianpu Station in the sub-watershed, Baihe Station in the main stream of the upper reaches of the Hanjiang, and Xiantao Station in the lower reaches of the river. This comparison shows that the actual river discharge values

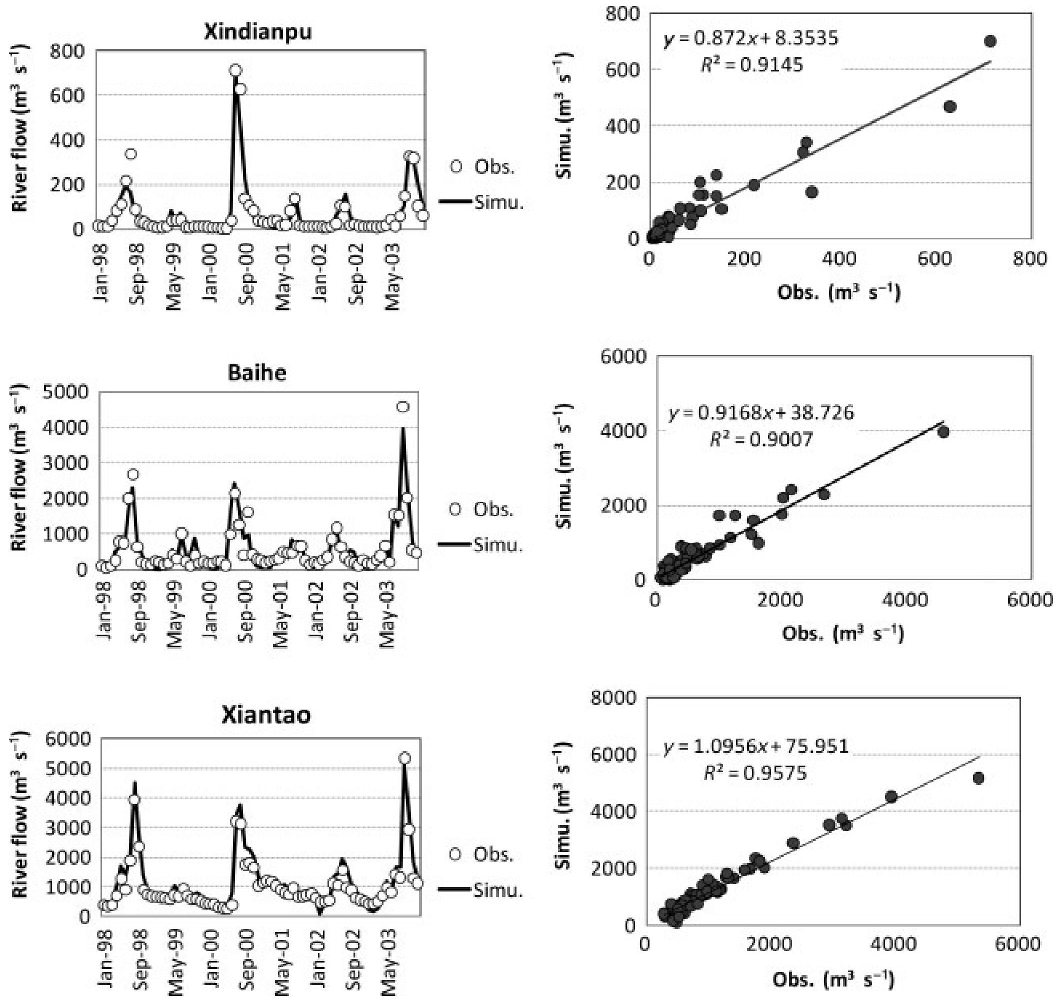

Figure 3. Observed and simulated flows during the calibration period.

agree with the simulated values very well, with a high regression coefficient in the sub-watershed ($R^2 = 0.92$, ENS $= 0.91$, RMSE $= 80.87$) and the upper reaches ($R^2 = 0.90$, ENS $= 0.88$, RMSE $= 249.46$). Given that the parameters for agricultural water use and the dam reservoir were coupled with the model, the variance between the observed data and simulated values remains small, with a high regression coefficient, even in the lower reaches ($R^2 = 0.96$, ENS $= 0.90$, RMSE $= 278.67$). Thus we are sure that the model behaves very well in all reaches.

For the validation process, the model was operated with input parameters during the calibration process without any changes for the period from 2004 to 2008 ($n = 60$). Figure 4 provides a comparison of simulated values and observation data at Xindianpu Station in the sub-watershed, Baihe Station in the main stream of the upper reaches of the Hanjiang, and Xiantao Station in the lower reaches of the river during the validation period. This comparison shows that the actual river discharge values agree with the simulated data with a high regression coefficient in the sub-watershed ($R^2 = 0.817$, ENS $= 0.50$, RMSE $= 52.10$), upper reaches ($R^2 = 0.76$, ENS $= 0.72$, RMSE $= 346.97$), and even the lower reaches ($R^2 = 0.89$, ENS $= 0.70$, RMSE $= 427.60$). The regression coefficient results for both the calibration and the validation were higher than the minimum values recommended in the literature ($R^2 > 0.60$ and ENS > 0.50), indicating that the model simulates the entire watershed process with sufficient agreement between the simulated and observed output data.

The simulation of nitrogen and phosphorus loads in the river flow was calibrated and validated in the next step. Figure 5 provides a comparison of simulated values and observation data at Baihe Station in the upper reaches and Xiantao Station in the lower reaches of the Hanjiang River during the validation period. This comparison shows that the measured total nitrogen (T-N) values agree with the simulated data, with a high regression coefficient at Baihe Station in the upper reaches ($R^2 = 0.71$, ENS $= 0.64$, RMSE $= 97.90$) during the validation period for 2005–2008 ($n = 48$). The correlation between the measured and simulated monthly average loads of NH_4-N for 2003–2005 ($n = 36$) at Xiantao Station in the lower reaches of the river showed an R^2 of 0.42 and an ENS of 0.30. The positions of the high and low peaks were correct, but the agreement was poor for the fluctuation. This may be due to unstable of NH_4-N, given that it is easily nitrified into nitrate nitrogen (NO_3-N) in soil and water. Unfortunately, we were unable to obtain NO_3-N or T-N data at Xiantao Station. However, the results for the monthly averaged loads of total phosphorus (T-P) were better than those for the NH_4-N loads at the lower reaches of the river. Specifically, the correlation between the measured and simulated monthly averages of T-P showed a very high R^2 of 0.82

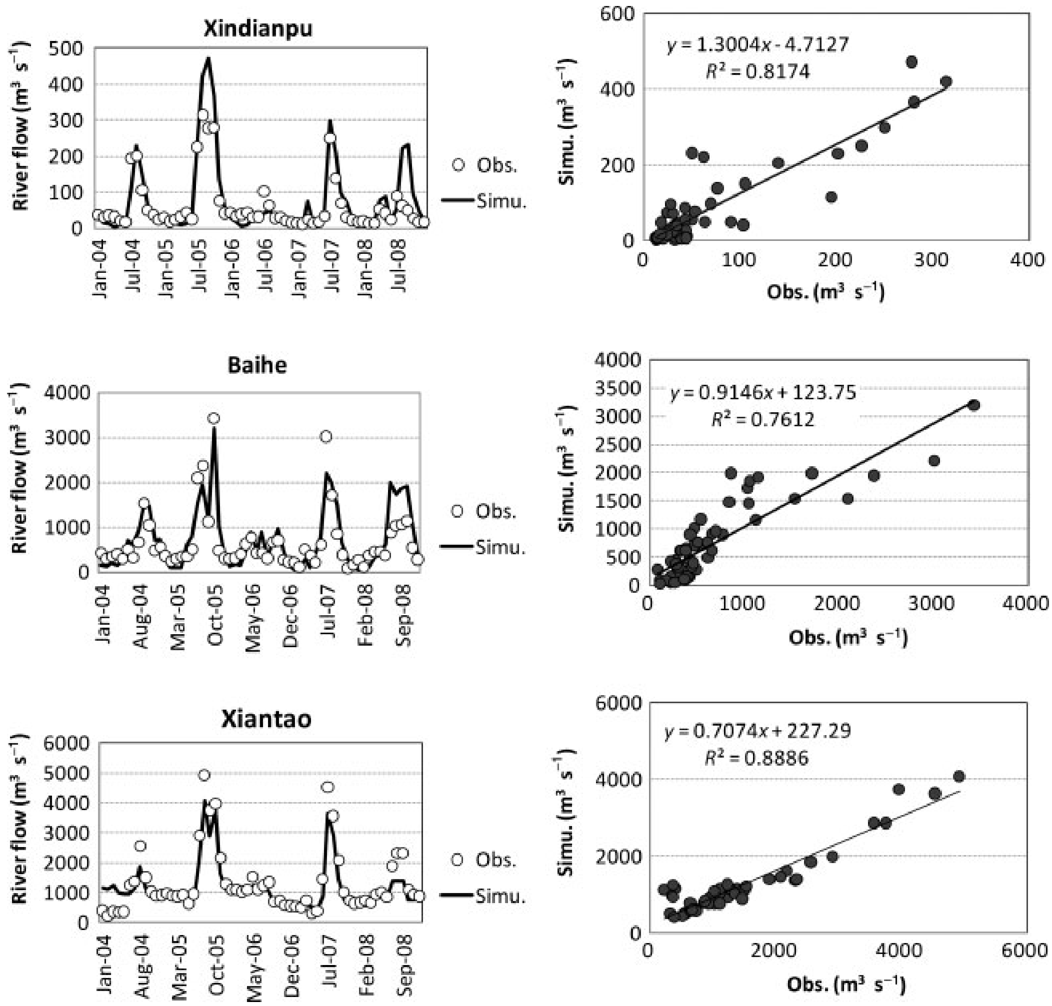

Figure 4. Observed and simulated flows during the validation period.

and an ENS of 0.74, as shown in Fig. 5. These results revealed a realistic model that can be used for current simulations and future predictions of nutrient fluxes.

RESULTS AND DISCUSSION

Simulation of water fluxes

By using the validated model, we were able to estimate the daily, monthly, and annual distribution of water fluxes, including potential evapotranspiration (PET, mm), actual evapotranspiration (ET, mm), surface runoff (SURQ, mm), lateral flow (LAT Q, mm), and water yield (WATER YIELD, mm) for the entire catchment or for each sub-catchment. Table 2 shows the monthly and annual values averaged from 1997 to 2008 over the total catchment of the Hanjiang River. From this table, it is clear that ET accounts for the greatest water loss (54.9%), and WATER YIELD accounts for 33.4% of the total rainfall in this catchment.

Figure 6 gives an example of annual outputs, showing the distribution of precipitation (PRECIP, mm) and simulated evapotranspiration (ET, mm), SURQ and groundwater flow (GW Q, mm) in 2008. From this figure, we can see that precipitation (390–1763 mm) and surface runoff (13–669 mm) have similar distribution patterns, whereas evapotranspiration (220–673 mm) increases gradually from the upper reaches to the lower reaches. As expected, the maximum ET is in the Danjiangkou Reservoir, and groundwater flow (0–178 mm) mainly occurs in the area surrounding the middle reaches of the Danjiangkou Reservoir, and the maximum groundwater flow is within the Danjiangkou Reservoir. The most interesting phenomenon is that the surface runoff (SURQ, mm) mainly occurs in mountainous areas both in the upper and especially in lower reaches, where precipitation is greater than that in other areas.

Simulation of nutrient fluxes

By using the validated model, we were also able to estimate the daily, monthly, and annual distribution of water quality variables in the catchment, such as sediment yield (SED YIELD, t ha^{-1}), nitrate in surface runoff (SURQ NO3, kg N ha^{-1}), nitrate in lateral flow (LATQ NO3, kg N ha^{-1}), nitrate in water percolating out of the root zone (PERC NO3, kg N ha^{-1}), nitrate in the crops (CROP NO3, kg N ha^{-1}), organic nitrogen (ORG N, kg N ha^{-1}), soluble phosphorus (SOL P, kg P ha^{-1}), and organic phosphorus (ORG P, kg P ha^{-1}). Table 3 shows the annual averages of both water resources and water quality from 2000 to 2008 over the total catchment of the Hanjiang River. From this table, it is clear that PERC NO3 and CROP NO3 are larger than in other nitrates.

Figure 7 gives an example of the annual outputs, showing that the distribution of simulated nitrogen, e.g. ORG N, ranges from

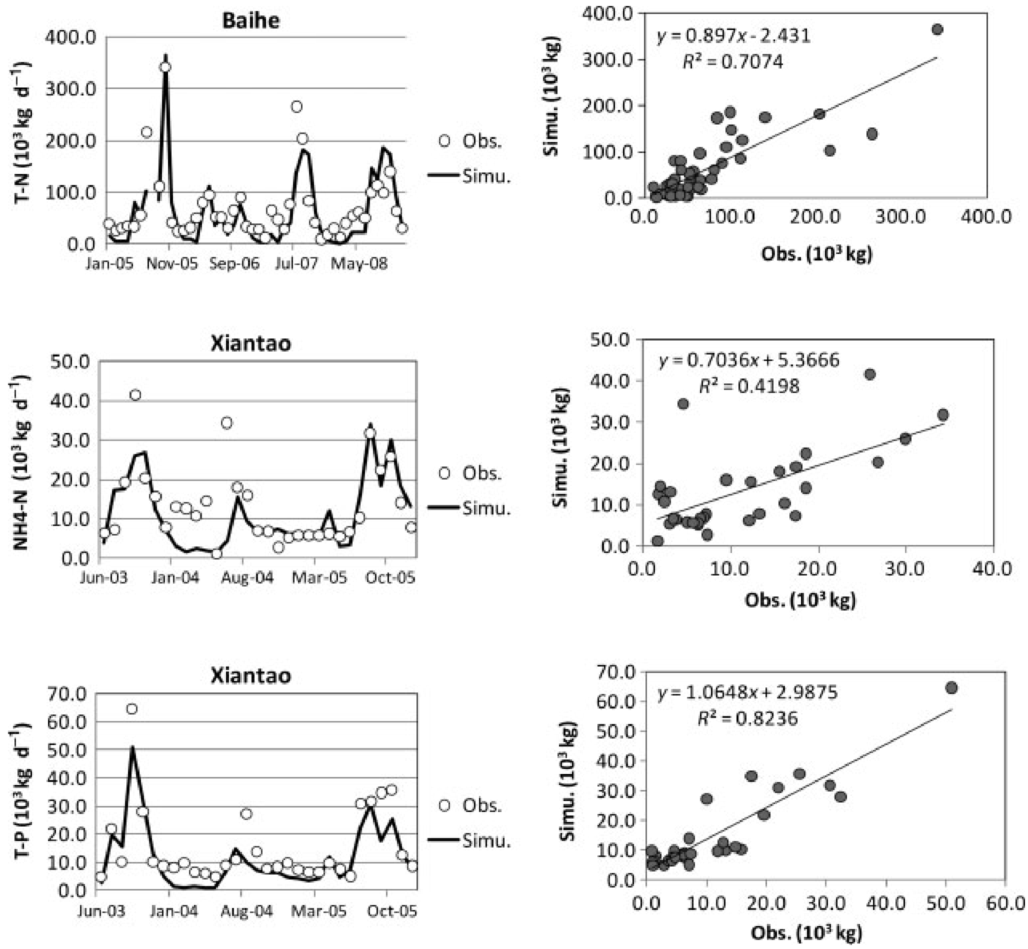

Figure 5. Observed and simulated water quality during the validation period.

Table 2. Simulated monthly water balances during 1997–2008 over the Hanjiang River basin

Time	RAIN (mm)	SNOW (mm)	SURFQ (mm)	LAT Q (mm)	WATER YIELD (mm)	ET (mm)	PET (mm)
JAN	12.01	5.25	1.67	1.01	3.20	9.16	12.34
FEB	19.67	2.28	1.66	1.64	3.53	14.91	21.49
MAR	32.87	1.21	2.48	3.84	6.52	29.84	42.67
APR	57.19	0.06	5.10	6.44	11.64	42.79	67.05
MAY	98.81	0.02	10.45	11.54	22.22	59.88	90.45
JUN	101.77	0.00	13.79	11.89	25.81	64.96	100.68
JUL	172.41	0.00	33.78	21.27	57.27	76.82	111.35
AUG	138.65	0.00	32.09	18.22	54.16	61.79	99.72
SEP	87.24	0.00	22.23	14.19	40.23	41.17	67.43
OCT	72.40	0.03	16.45	13.99	34.03	29.76	42.94
NOV	26.27	0.19	6.58	4.77	13.67	17.16	23.59
DEC	14.33	1.88	3.00	1.99	6.31	9.90	13.18
ANNUAL	833.62	10.92	149.28	110.79	278.59	458.14	692.89

0.01 to 12.47 kg N ha^{-1}, SURQ NO3 ranges from 0.08 to 3.49 kg N ha^{-1}, LATQ NO3 ranges from 0.01 to 2.69 kg N ha^{-1}, and NO_3 GW ranges from 0.00 to 29.77 kg N ha^{-1} in 2008. From this figure, it is apparent that organic nitrogen is mainly distributed in cultivated areas and forestland in the upper and middle reaches, whereas the nitrate in surface runoff is mainly distributed in the areas with high rainfall in the lower reaches. The nitrate in lateral flow is present in the forest areas in the upper reaches, whereas that in groundwater mainly occurs in the middle reaches of agricultural areas.

Figure 8 gives an example of annual outputs, showing the distribution of simulated phosphorus loads, such as organic phosphorus (ORG P, 0.00–1.05 kg P ha^{-1}), soluble phosphorus yield (SOL P, 0.00–0.04 kg P ha^{-1}), and sediment phosphorus yield (SED P, 0.00–0.04 kg P ha^{-1}) in 2008. This figure illustrates

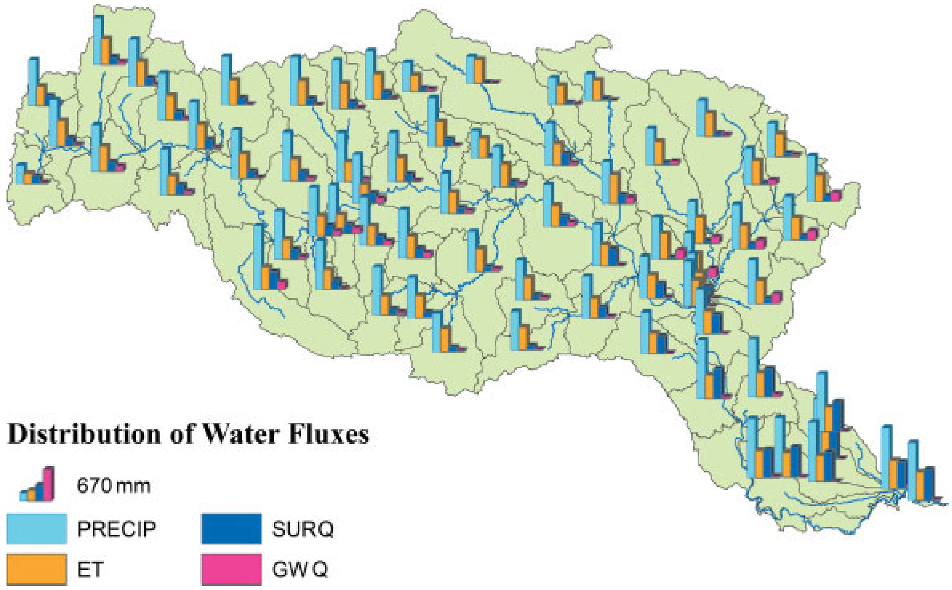

Figure 6. Distribution of precipitation (PRECIP), actual evapotranspiration (ET), surface runoff (SURQ), and groundwater flow (GWQ) in 2008.

Table 3. Simulated annual water quantities and qualities from 1997 to 2008

Time	PREC (mm)	SURQ (mm)	LAT Q (mm)	GW Q (mm)	PERCO LATE (mm)	SW (mm)	ET (mm)	WATER YIELD (mm)
2000	1093.00	216.61	149.32	5.12	202.47	97.61	518.29	361.75
2001	622.53	67.77	85.27	5.43	47.66	102.36	422.10	153.69
2002	775.60	129.96	93.25	9.02	86.30	99.76	466.69	226.90
2003	995.63	183.81	147.89	32.12	195.68	112.39	454.83	357.19
2004	811.28	135.96	110.42	21.88	98.40	112.04	462.96	262.74
2005	1021.00	230.48	142.68	90.72	203.63	98.39	461.21	457.05
2006	712.59	98.84	90.83	20.57	52.33	100.66	471.55	205.31
2007	889.18	215.75	107.59	49.73	118.09	96.67	448.49	367.00
2008	923.47	204.35	123.18	55.07	115.23	94.48	481.82	376.52
MEAN	871.59	164.84	116.71	32.18	124.42	101.60	465.33	307.57
Time	SED YIELD (t ha^{-1})	SURQ NO3 (kg N ha^{-1})	LATQ NO3 (kg N ha^{-1})	PERC NO3 (kg N ha^{-1})	CROP NO3 (kg N ha^{-1})	ORG N (kg N ha^{-1})	SOL P (kg P ha^{-1})	ORG P (kg P ha^{-1})
2000	6.37	0.99	0.77	18.12	22.97	2.62	0.003	0.30
2001	1.86	0.42	0.41	5.95	25.86	0.58	0.002	0.07
2002	3.68	0.64	0.39	17.39	21.72	1.11	0.004	0.14
2003	8.69	1.00	0.52	20.24	18.58	2.32	0.005	0.28
2004	3.70	0.62	0.53	11.25	19.71	1.04	0.006	0.13
2005	7.69	1.02	0.56	15.14	18.88	2.23	0.004	0.26
2006	3.99	0.50	0.44	5.53	19.31	0.84	0.003	0.11
2007	5.82	0.93	0.37	11.50	20.23	1.45	0.007	0.19
2008	6.65	0.96	0.44	13.84	16.10	1.62	0.005	0.19
MEAN	5.38	0.79	0.49	13.22	20.37	1.53	0.004	0.19

that organic phosphorus and sediment phosphorus are mainly distributed in the mountainous areas in upper and lower reaches, which is the same distribution pattern as sediment yield. However, SOL P is much less than ORG P and mainly occurs in the lower reaches with large surface flow.

Evaluation of the effects of reforestation

The Conversion of Farmland to Forests (RCFF) regulations were adopted at the 66th Executive Meeting of the State Council of China on 6 December 2002, and were effective as of 20 January 2003. These regulations were formulated for the purposes of standardizing conversion of farmland to forests, protecting the lawful rights and interests of those who convert their farmland to forests, consolidating the achievements made in the conversion of farmland to forests, optimizing the structure of rural industries, and improving the ecologic environment. By 2009, a total area of 27.70 million ha had been reforested, including 9.30 million ha of cultivation land and 17.40 million ha of unused or mountainous lands, particularly lands exhibiting a slope greater than 15°.

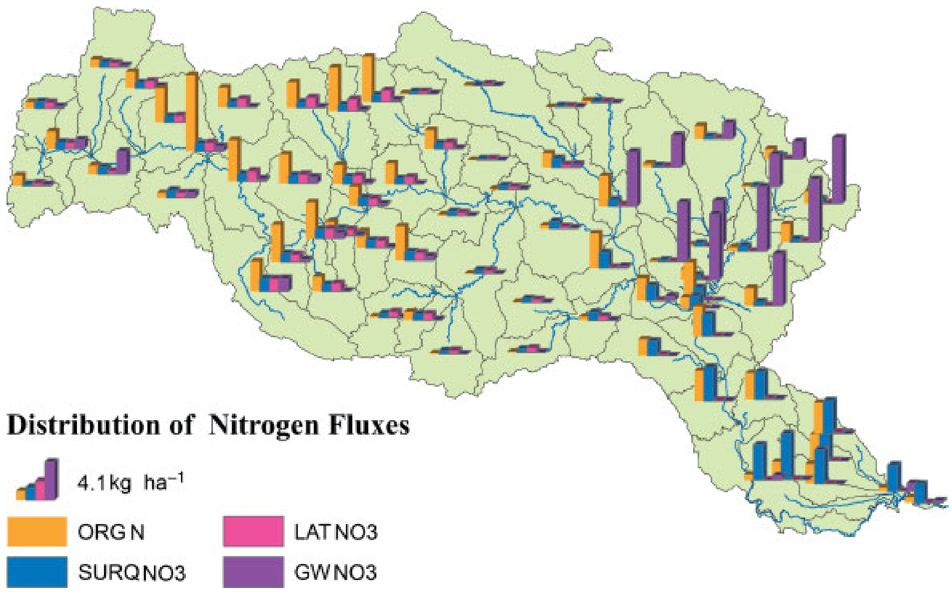

Figure 7. Distribution of simulated nitrates, such as organic nitrogen (ORG N), NO_3 in surface flow (SURQ NO3), lateral flow (LAT NO3), and groundwater (GW NO3), in 2008.

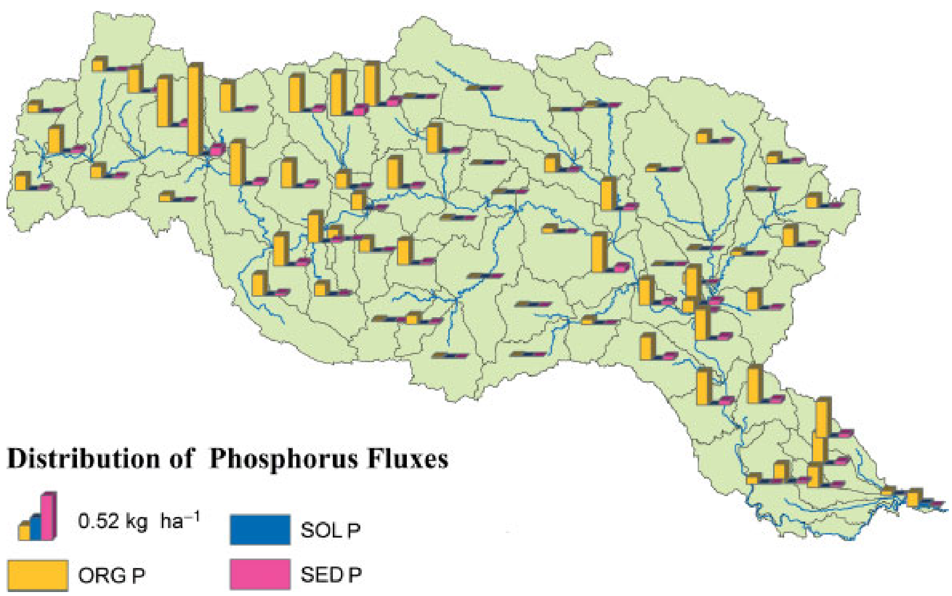

Figure 8. Distribution of simulated phosphorus loads, such as organic phosphorus (ORG P), soluble phosphorus (SOL P), and sediment phosphorus yield (SED P), in 2008.

Evaluation of the effects RCFF on both water resources and the water environment is important for integrated watershed management. For this purpose, we simulated a scenario of RFCL for which cultivated lands with a slope $>15^\circ$ were reforested according to the RCFF, and we then compared the results with actual conditions during 1998–2008. Figure 9 provides the simulation results, showing the effect of RFCL on river discharge, sediment loads, and water quality (NH_4-N, T-P) at the Xiandao Station in the lower reaches of the Hanjiang River. The numerical simulation indicated that RFCL would have a relatively small effect on river discharge but that the effects on the water quality in the river would be remarkable. Table 4 provides details of the effects of RFCL on both hydrological factors and nutrients. It is apparent that reforestation would cause an obvious decrease in surface runoff (−23.6%, $P < 0.01$) but an increase in groundwater (71.8%, $P < 0.01$) and percolation out of the soil (24.7%, $P < 0.01$). The total water yield does not change significantly (−4.4%), but the decrease in total sediment loading is substantial (−56.2%, $P < 0.01$). The simulation results also show that RFCL would greatly decrease the organic N (−42.6%, $P < 0.01$), NO_3 yield in surface flow (−37.1%, $P < 0.01$), and the NO_3 yield in sub-surface flow (−25.5%, $P < 0.01$), whereas the NO_3 yield in groundwater flow would increase (107%, $P < 0.01$). As a result, the NO_3 leaching would increase (19.7%, $P < 0.01$), and the final NO_3 in the soil would decrease (−29.8%, $P < 0.01$). In terms of phosphorus, RFCL would cause both organic phosphorus (−38.2%, $P < 0.01$) and the phosphorus yield from the soil (−33.3%, $P < 0.01$) to decrease.

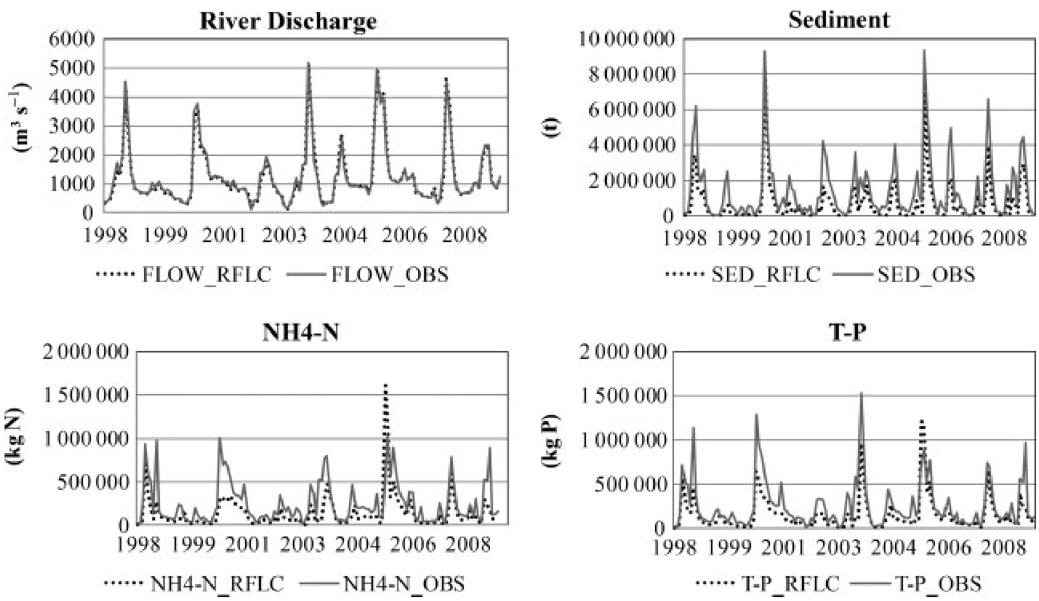

Figure 9. Simulation of the effects of RFCL on river discharge, sediment, and water quality (NH_4-N, T-P) at the Xiandao Station on the lower reaches of the Hanjiang River.

Table 4. Simulated effects of RFCL on hydrological factors and nutrients

Hydrological factors	Control case (mm)	RFCL case (mm)	Effects (%)
SURQ	149.23	114.02	−23.6
LAT Q	110.75	115.77	4.5
GW Q (Shallow)	24.14	41.48	71.8
GW Q (Deep)	5.80	7.14	23.1
WATER YIELD	278.51	266.25	−4.4
PERCO LATE	110.74	138.11	24.7
ET	457.80	460.10	0.5
Sediment	Control case (t ha^{-1})	RFCL case (t ha^{-1})	Effects (%)
SED YIELD	4.79	2.10	−56.2
Nutrients	Control case (kg ha^{-1})	RFCL case (kg ha^{-1})	Effects (%)
ORG N	1.41	0.81	−42.6
SURQ NO3	0.74	0.47	−37.1
LATQ NO3	0.57	0.43	−25.5
GWQ NO3	0.55	1.13	107.0
LEACHED NO3	16.19	19.38	19.7
SOIL NO3	8.84	6.20	−29.8
UPTAKE N	26.07	24.47	−6.2
ORG P	0.17	0.11	−38.2
SOL P	0.00	0.00	−33.3
UPTAKE P	3.17	3.11	−1.9

CONCLUSIONS

This study presents a simulation and scenario prediction for water and nutrient dynamics using the SWAT model. The model successfully integrated the effects of dams, soil properties and land use/cover, as well as management factors. As a case study, the nitrogen and phosphorus dynamics in the Hanjiang River basin, the largest sub-catchment of the Changjiang (Yangtze River) in subtropical China, were modeled. The accuracy of the model was validated by water quality monitoring data at several hydrological stations above the Hanjiang River. The calibration process was based on a comparison of measured hydrodynamic and water quality variables against model estimates for 1998–2003. This comparison shows that the actual river discharge values agree with the simulated values very well, with high regression coefficients in the sub-watershed, upper reaches, and even the lower reaches. During the validation period from 2004 to 2008, the measured and simulated monthly flows also were also in agreement, as they were for the calibration period. The results of both the calibration and validation revealed a realistic model.

By using the validated model, we evaluated the effects of the RFCL initiative on both water resources and water quality in a catchment ecosystem. The numerical simulation suggested that RFCL would have a relatively small effect on the river discharge, while having substantial purification effects on the water quality in the river. Specifically, RFCL will dramatically decrease the surface runoff while greatly increasing the groundwater and percolation out of the soil. The total water yield will change only slightly, but the total sediment loads will decrease greatly. The simulation results also showed that RFCL will drastically decrease the organic nitrogen, NO_3 yield in both surface and sub-surface flow, but will increase the NO_3 yield in groundwater flow. As a result, NO_3 leaching will increase, and the final NO_3 in soil will decrease. For phosphorus, RFCL will cause the organic phosphorus to decrease, while increasing the phosphorus yield from the soil.

This study suggested that RFCL is an effective policy for watershed environment management, which might have a relatively small effect on the river discharge but that the purification effects on the water quality in the river would be remarkable. We are now continuing our research to modify this model to be able to evaluate the influences of water transfer projects between large river basins, such as the Yangtze (Changjiang) and Yellow (Huanghe) River basins.

Finally, we would like to point out that a major limitation of this simulation is the lack of actual spatial detail, such as high-resolution topography, land use and soil maps required to correctly simulate environmental processes. Also, owing to the sparse observation data, it is difficult for us to capture the spatial variability associated with precipitation within a watershed. Another limitation is the shortage of data including landscape management and conservation practices, such as riparian buffers and vegetative filter strips. To overcome these limitations, we need to obtain data of field experiment for fitting parameters for landscape management and conservation practices in the future.

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