International Journal of Chemical Engineering and Applications, Vol. 1, No. 4, December 2010
ISSN: 2010-0221

Water Quality Response to Different Defarming Scenarios in Bai River Basin

Jiangkun Zheng, Xinxiao Yu

***Abstract*—In order to estimate non-point source pollution under different defarming scenarios in Bai River Basin. Geographic informational system (GIS) and the Soil and Water Assessment Tool (SWAT) was used to simulate the transport of runoff, sediment, total nitrogen and total phosphorus into the Zhangjiafen stations. The results showed: The SWAT generally performs well and could accurately simulate monthly runoff, sediment, total nitrogen and total phosphorus yield with a Nash-Sutcliffe coefficient and a coefficient of determination of greater than 0.7 during calibration and validation. Three kinds of measures were obvious with reducing sediment, total nitrogen and total phosphorus in effect, conversion of farmland back to forests in whole watershed had the most effect on it.**

***Index Terms*—water quality, SWAT, conversion of farmland, Bai River Basin.**

I. Introduction

Compared to the simulation for streamflow, simulation of sediment erosion and transport throughout a catchment is a challenging task. It is difficult to capture all erosion and transport processes that occur on the land surface and the river reach. However, model performance in relation to sediment simulation is very important when trying to quantify non-point source pollution [1]. During the past two decades there has been a dramatic increase in the development and uses of physically based distributed hydrological models to simulate complex hydrological processes and to estimate soil erosion and non-point source pollution [2]. The ability of a model to simulate hydrological processes depends on how well the hydrological processes are represented and how well the catchment is described by the model. A spatially explicit hydrological model (Thales) was used to simulate a variety of theoretical catchments with soils dominated by combinations of infiltration excess, saturation excess, and subsurface stormflow processes and different soil constituent concentrations that were spatially interacting[3]. Runoff prediction of two models (ADAPT and SWAT) were calibrated for individual field plots having one till and two no-till management practices [4]. Average annual sediment load to streams simulated by SWAT using hydrologic cataloguing units (HCUs) show the highest sediment loads in the mid-west and Pacific coast [5].

To evaluate the impact of management decisions on water quality, The Pasture Phosphorus Management (PPM) Calculator was developed to predict average annual phosphorus (P) losses from pastures under a variety of field conditions and management options [6]. The tillage practice with mould board plough has been found to have a more appreciable impact on the sediment and nutrient losses than conventional tillage practices for the existing level of fertilizer [7]. A stepwise procedure was presented for the representation and evaluation of hydrologic and water quality impacts of several agricultural conservation practices with the SWAT2005 model [8]. Decrease in excessive use of N and P fertilizers and their synergism with organic manures is recommended that would significantly reduce nutrient pollution in the lake ecosystem [9]. Many erosion models divide the river basin into smaller areas or sub-basins. Each sub-basin is assumed to be homogeneous in hydrological features, with parameters representative of the entire sub-basin [10]. The size, scale, and number of sub-basins can affect a watershed modeling process and subsequent results [11]. Spatial resolution effects resulting from watershed subdivision also have a strong influence on model-based evaluation of long term impacts of best management practices (BMPs) on fate and transport of sediments and nutrients within watersheds [12].

In recent years, non-point source pollution from agriculture is increasingly responsible for the degradation of surface water quality. This, in turn, increases the need of integral water-quality management with enhanced hydrologic models [13]. Furthermore, quantifying relationships between stream water quality and catchment land uses is a major goal of many water quality monitoring programs. In this study, SWAT model was applied to runoff, sediment, water quality in calibration and validation, and then simulated sediment and water quality with the change of land use under different measures of farmland conservation in Bai River Basin. The scientific basis was to provide for water conservation, watershed management measures and policy formulation in this area.

II. Study Area and Data Description

Bai River derives from Guyuan Country of Hebei province,

This work was supported in part by the National Natural Science Foundation of China(Grant No. 40871136) and State Forestry Administration, People's Republic of China for Special Funding Projects of Forestry Nonprofit Industry Research (Grant No. 200804022).

Jiangkun Zheng is with the School of Soil and Water Conservation, Beijing Forestry University, 86-01082380418, e-mail: zhengjiangkun999@163.com.

Xinxiao Yu. was with the School of Soil and Water Conservation, Beijing Forestry University, e-mail: yuxinxiao111@126.com.

runs through Chicheng country and flows into Miyun reservoir around Zhangjiafen station via Yanqing, Huairou, Miyun Country respectly. As a part of Chaobai River system, its area is 8827km2. The characteristic of the climate is temperate continental and semi-arid. During the past 50 years, average annual air temperature ranges from 9 to 10°C and the annual rainfall varies between 300 and 700 mm. The catchment receives an average annual rainfall of 489 mm, of which the monsoon season (June to September) contributes more than 80% rainfall. The elevation varies from 160 m at the basin outlet to 2290 m at the highest point in the catchment. The topography of the watershed is undulating. It is characterized by mountain ranges, steep slopes and deep valleys.

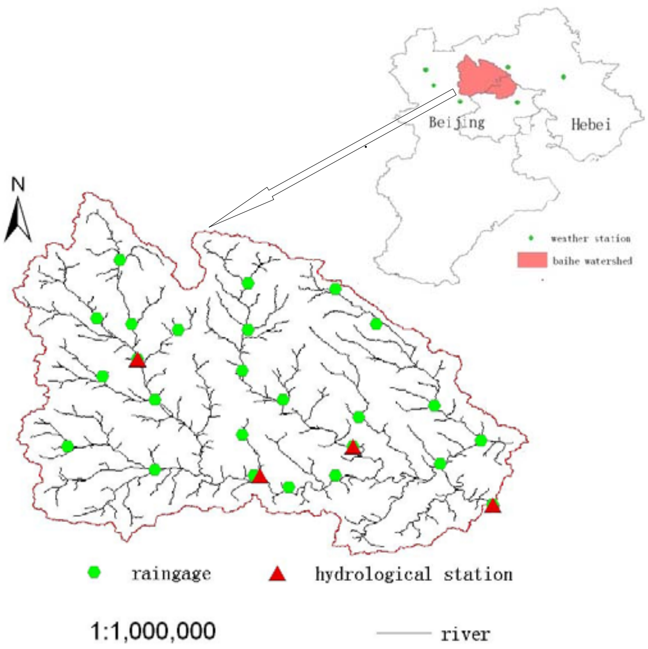


Figure 1. Map showing location, 6 meteorological stations, 4 hydrological stations and 25 rain gauging Stations of Bai river basin.

As a major drinking water source in Beijing, both water quality and water quantity are important concerns in the reservoir watershed. However, due to the decrease in incoming water from the upstream, the water level has been declining continuously [14]. The restriction on nutrients into the river significantly restricts the development of economics when the growth directly or indirectly increases phosphorus and nitrogen delivery to surface water.

The key steps in the application of the SWAT model are the mathematical representation of the catchment, arranging meteorological and hydrological input, estimation of model parameters, as well as model calibration and validation. The SWAT model requires input on soils, land use, weather, channels, shallow aquifer and management.

1. A digital elevation map (DEM) at the scale of 1 : 50 000 with a resolution of 100m×100m, a soil map at the scale of 1 : 600 000, and a land use map at the scale of 1 : 1 00 000 in 2000 were obtained from the Data Center for Resources and Environmental Sciences (RESDC), Chinese Academy of Sciences, as shown in Figure 2. Among 13 types of soil, the predominant soil of the basin is Neutral rhogosol and Fluvent soil . The dominant land uses in the Bai River Basin are forest (63.5%), grassland (19.0%) and agricultural land (16.6%), while urban areas comprise less than 0.6% of the watershed.

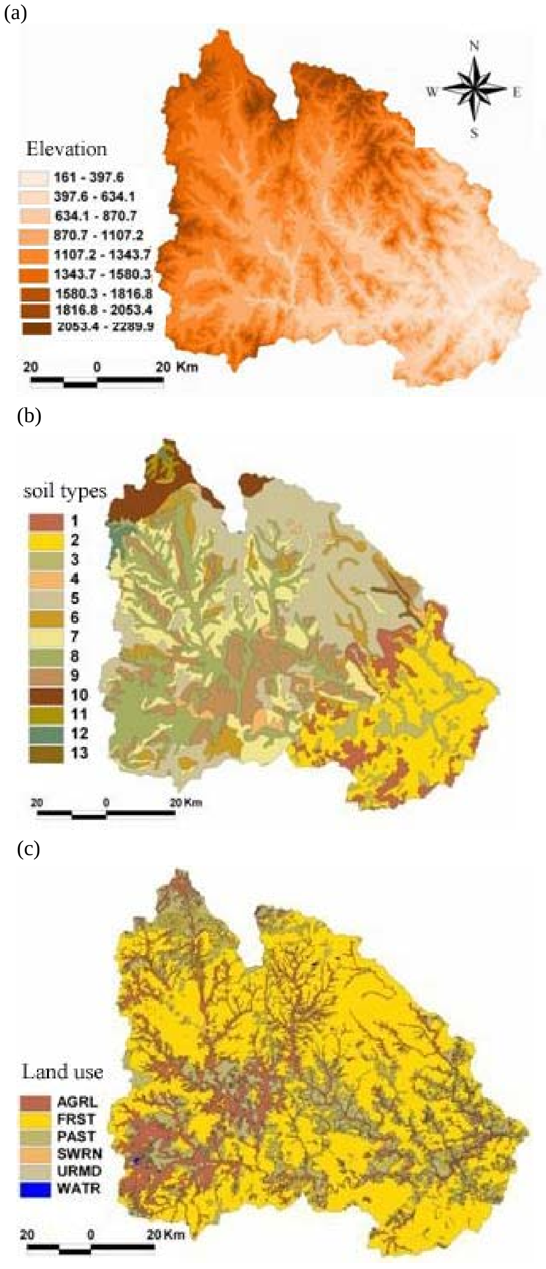


Figure 2. (a) Digital map of the study area (b) Soil map of the study area (c) Land use map of the study area.

In soil types, 1,rhogosol; 2, Neutral rhogosol; 3, calcareous Drab; 4, lithosol; 5, Fluvent soil; 6, grayish brown soil; 7, gray cinnamonic soil; 8, Drab; 9, chestnut soil; 10, Dark chestnut soil; 11, gray forest soil; 12, Castano-cinnamon soils; 13, calcareous meadow soil;

In land use, AGRL, Agricultural Land; FRST, Forestland; PAST, Pasture; WATR, Water; URMD, Residential-Medium; SWRN, Unused land.

2. Daily precipitation, maximum and minimum air temperature data from 6 meteorological stations and 25-rain gauging stations over a period of 18 years (1990–2007) were collected. Daily climate inputs used in SWAT model were precipitation, minimum and maximum air temperature, and wind speed. These inputs were based completely on measured data within or close to the study area, as shown in Figure 1. Additional climate variables such as solar radiation and dew-point temperature were generated from weather generator using monthly values from the nearest standardized weather station.

3. Owing to data limitation, the daily discharge data collected for this study were from Zhangjiafen station at the Bai River Basin for 18 years from 1990 to 2007. Sediment

yield was measured continuously at Zhangjiafen station for 7 years from 2000 to 2006. Owing to no water quality monitoring data in Zhangjiafen hydrological station, Date of total N and total P yield in Daguan bridge site near the hydrological station was used for 6 years from 2001 to 2006. Model calibration was runoff in the first order, and then sediment, the water quality in the final.

4. Because Total N and Total P are not directly given in Model output file, it based on the following formula:

$$TN\_OUT = ORGN\_OUT + NO3\_OUT + NH4\_OUT + NO2\_OUT \quad (1)$$

$$TP\_OUT = ORGP\_OUT + MINP\_OUT \quad (2)$$

TN _OUT, watershed nitrogen export load (kg); ORGN _OUT, watershed export of organic nitrogen (kg); NO3_OUT, watershed exports of nitrate (kg); NO2_OUT, watershed nitrite export (kg). TP_OUT, export of total phosphorus load for the watershed (kg); ORGP_OUT, watershed export of organic phosphorus load (kg); MINP _OUT, watershed export of mineral phosphorus load (kg).

Relative error Re, coefficient of determination R2 and Nash-Suttcliffe efficiency coefficient Ens was chosen to evaluate model. Formula is as follows:

$$\mathrm{Re} = \frac{P_t - O_t}{O_t} \times 100\% \quad (3)$$

$$R^2 = SSR/SSTO \quad (4)$$

$$Ens = 1 - \frac{\sum_{i=1}^{n}(Q_o - Q_p)^2}{\sum_{i=1}^{n}(Q_o - Q_{avg})^2} \quad (5)$$

Re, relative error for the model simulation; P_t, the simulated value; O_t the measured value. R^2, coefficient of determination; *SSR*, total variation explained by *X*; *SSTO*, total variation. *Ens*, Nash-Suttcliffe coefficient; Q_o, the observed value; Q_p, the measured value; Q_{avg} ,the average for the observed value; *n* is the number of observations.

III. Result Analysis and Discussion

A river basin can be divided into sub-basins by discretization schemes. In the present study, the study area was subdivided into natural sub-watersheds to preserve the natural flow paths, boundaries and channels for realistic routing of water and sediment. According to the natural river network, the topography of the basin and the distribution of rainfall stations, taken 18000ha as river threshold area, the study area was divided into 29 sub-basins, as shown in Figure 3. In order to get a reasonable resolution of soil properties, land use and management practices, with 10% of land use and 10% of soil type as the threshold value, these sub-basins were further divided into a total of 198 hydrological response units(HRUs). The watershed parameterization and the model input were obtained using the ArcView interface to SWAT, which provides a graphical support for the disaggregation scheme and allows the construction of the model input from digital maps. The initial values of model parameters are either directly obtained from the database (e.g. parameters concerning soil property, crop property, rainfall, etc.) or estimated by AVSWAT based on input maps and database (e.g. curve number, manning roughness coefficients). In this study, the SWAT model was calibrated based on monthly measured discharge, sediment total N and total P at Zhangjiafen station at the catchment outlet from the Bai River catchment. A split sample procedure was used for calibration and validation. Since SWAT has a large number of parameters, a sensitivity analysis was first conducted to identify the set of parameters that have the most influence on simulated streamflow, sediment total N and total P yield. The results are presented therefore in three sections. First, the sensitivity of model performance to some of the alternative parameters is outlined in the Section on Sensitivity Analysis. Then, section on calibration compares simulated results and measured discharge, sediment total N and total P yield over the calibration period by adjusting the sensitive parameters. Finally, simulated results and measured yield are compared and analysed in the Section on Validation.

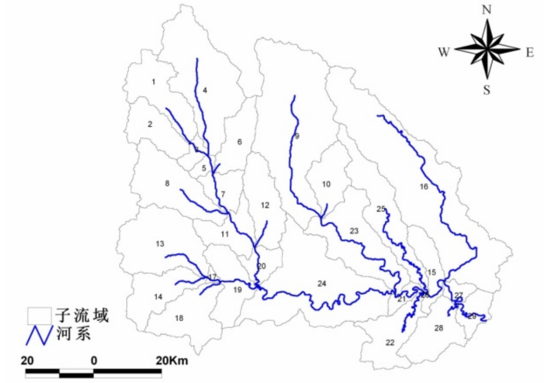
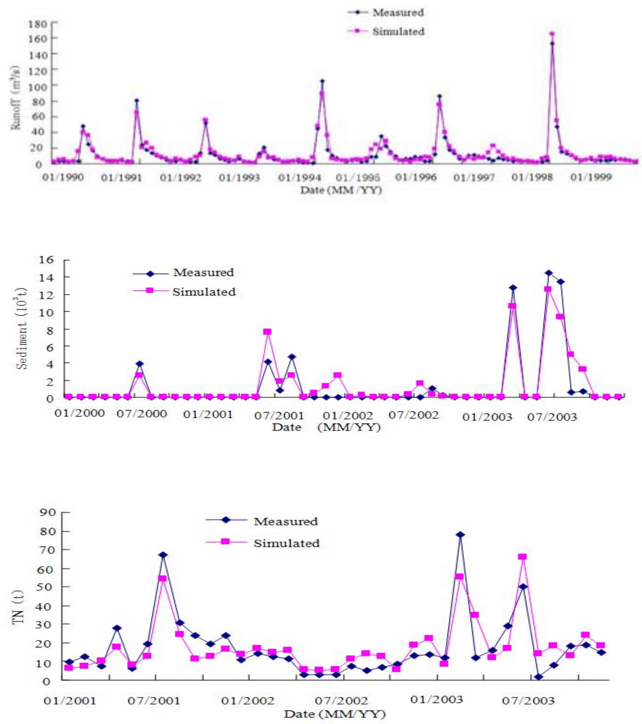


Figure 3. Sub basin and river net divide in the Bai River Basin

Sensitivity analysis



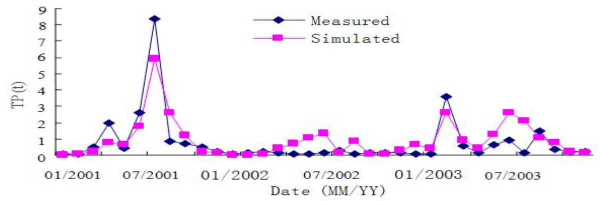
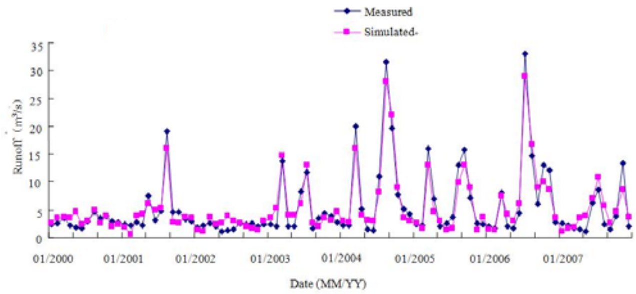
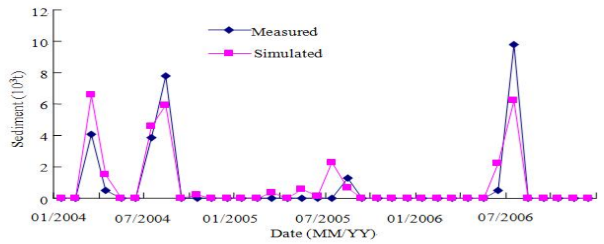
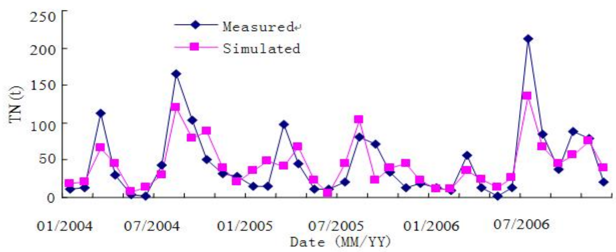


Figure 4. Monthly simulation curve of runoff, sediment, total nitrogen(TN) and total phosphorus(TP) yield at calibration period

In this paper, Latin Hypercube One-factor-At-a-Time (LH-OAT) was adopted to sensitivity analysis that combined advantages of LH sampling and OAT sensitivity. Sensitivity analysis was performed to evaluate the effect of parameters on the performance of the SWAT model in simulating. On the basis of sensitivity analysis performed, it was concluded that the runoff was highly sensitive to CN, CH_K2. Sediment to SPCON and ADJ_PKR, Total N to BIOMIX and N_UPDIS, total P to ERORGP and PPERCO. These parameters were modified during the model calibration. After sensitivity analysis, both calibration and validation were done at monthly time steps.







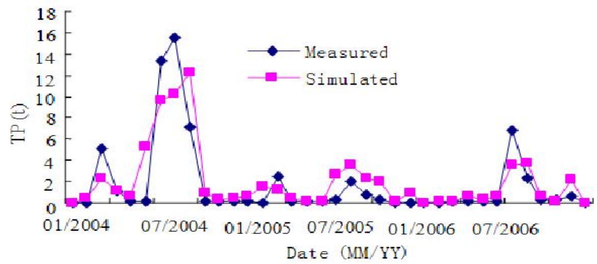


Figure 5. Monthly simulation curve of runoff, sediment, total nitrogen(TN) and total phosphorus(TP) yield at validation period

Model calibration

In this study, calibration efforts focused on improving model performance at main gauging stations. Although daily load estimation may be available, their uncertainty was higher than the measured flow uncertainty due to reduced sampling frequency. Therefore, calibration focused mainly on monthly simulation rather than daily simulation. The calibration objective for each constituent of interest was to maximize the coefficients R2 and Ens. The model was calibrated first for runoff , then for sediment, total N and total P yield at monthly scale. The baseflow separation technique and HYSEP developed by USGS [15] was used to estimate the baseflow component of measured and calibrated model flows. The capability of a hydrological model to adequately simulate process typically depends on the accurate calibration of parameters. Although automatic parameter estimation procedure in SWAT model is available presently, a trial-and-error method is used in this study. Continuous runoff, sediment, total N and total P yield are used to estimate parameter values .The observed values for each measured time were compared with the simulated values for that time.

Figure 4 compares graphically measured and simulated monthly runoff，sediment，total N and total P values at Zhangjiafen station for the calibration period. Monthly estimation by the model at Zhangjiafen station showed that although the trends of simulated and measured were similar during most months of the calibration period, the runoff was a little underestimated whereas sediment, total N and total P were a little overestimated. High sediment discharge total N and total P events were not well matched and were mostly underestimated. This underestimation could be due to rainfall characteristics. For example, in practice, high-intensity and even short duration rainfall can generate more sediment than did the model based on daily rainfall. The poor performance for the simulation of runoff is another possible reason for the underestimation of sediment, especially for the initial period of simulation due to the lack of ‘warm-up’ implementation. Model validation

TABLE I. LIST OF MAIN SENSITIVE PAREMETER CALIBRATED

Order	Runoff	Sediment	Total N	Total P
1	CN	SPCON	BIOMIX	ERORGP
2	CH_K2	ADJ_PKR	N_UPDIS	PPERCO
3	CH_N2	PRF	ERORGN	P_UPDIS
4	ESCO	SPEXP	NPERCO	PHOSKD

CN ,curve number; CH_K2, effective hydraulic conductivity in main channel (mm/h); CH_N2, main channel Manning coefficient ; ESCO, soil evaporation compensation coefficient; SPCON, linear parameter for calculating maximum amount of sediment;

ADJ_PKR, adjusted peak rate based on sediment calculations; PRF, peak rate adjustment for main channel; SPEXP, exponent parameter for calculating sediment; BIOMIX , biological mixing efficiency; N_UPDIS , distribution coefficient of nitrogen absorption; ERORGN, the enrichment ratio coefficient of organic nitrogen in the sediment; NPERCO, Nitrogen permeability coefficient; ERORGP, the enrichment ratio coefficient of organic phosphorus in the sediment; PPERCO, phosphorus permeability coefficient; P_UPDIS, distribution coefficient of phosphorus absorption; PHOSKD, coefficient of separation phosphorus from soil.

TABLE.III EVALUATION RESULT OF RUNOFF, SEDIMENT, TOTAL N AND TOTAL P MONTHLY SIMULATION

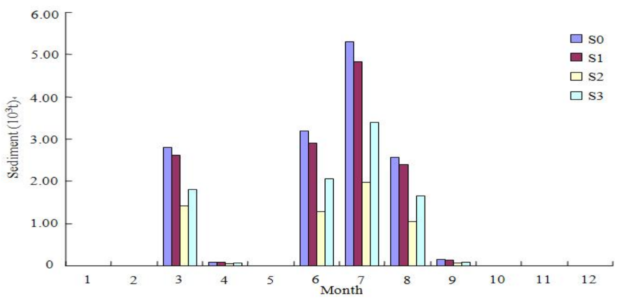
Item	Period	Re	R2	Ens
Runoff	Calibration (1990–1999)	-0.06	0.93	0.87
	Validation (2000–2007)	-0.09	0.91	0.85
sediment	Calibration (2000–2003)	0.16	0.84	0.86
	Validation (2004–2006)	0.13	0.80	0.88
Total N	Calibration (2001–2003)	0.26	0.71	0.79
	Validation (2004–2006)	0.33	0.72	0.76
Total P	Calibration (2001–2003)	0.23	0.71	0.77
	Validation (2004–2006)	0.28	0.71	0.73

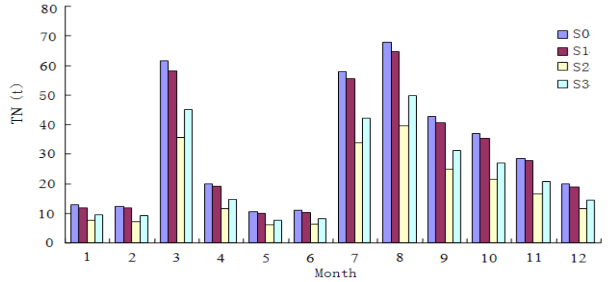
TABLE IV. AREA OF DIFFERENT LAND USE TYPES UNDER 4 KINDS OF SCENARIOS(KM^2)

Land use type	S0	S1	S2	S3
Agricultural Land	1460.55	1392.7	0	0
Forestland	5602.56	5670.41	7063.11	5602.56
Pasture	1676.48	1676.48	1676.48	3137.03
Water	33.75	33.75	33.75	33.75
Residential-Medium	42.85	42.85	42.85	42.85
Unused land	6.46	6.46	6.46	6.46

An attempt has been made to validate the model performance of runoff for 8 years from 2000 to 2007，sediment, total N and total P for 3 years from 2004 to 2006. A close relationship between simulated and observed monthly indicates a good performance of the model, as shown in Figure 5. The Relative error, coefficient of determination and Nash-Sutcliffe efficiency of -0.06～0.33, 0.71～0.93 and 0.73 ～ 0.88 at Zhangjiafen station appeared a good agreement between the monthly observed and simulated (Table III). Although an underestimation of monthly runoff and overestimation of monthly sediment, total N and total P by the model, considering the overall statistics it can be said that model simulations were relatively satisfactory.

Considering the goodness-of-fit statistics and the summary statistics discussed above, it is generally reasonable to conclude that the SWAT simulations calibrated and validation at a monthly time steps are reasonably good, and the calibrated model may be employed for further analysis.





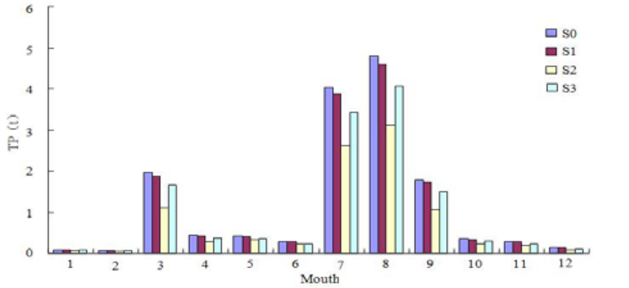


Figure 6. Monthly mean sediment, total nitrogen(TN) and total phosphorus(TP) yield under 4 kinds of scenarios

Change of sediment and water quality under different farmland conversions

Since the implementation of Beijing and Tianjin sandstorm source control projects in 2001, land use has changed greatly owing to conversion measures of farmland, thereby the transport of sediment, Nitrogen and Phosphorus were affected. The type of land use in 2000 is set as the base (S0), three kinds of scenarios were established as follow.

S1: cropland is converted to forest land on slope of 25 °or more of the basin;

S2: all cropland within the watershed is converted to forest land;

S3: all cropland within the watershed is converted to grassland;

Four kinds of land-use scenarios could be gotten through superposition of the slope extracted from DEM and cropland (Table IV). Average monthly and annual sediment, total nitrogen and total phosphorus values was simulated respectively under real climate data from 2001 to 2006, and then it was analyzed that the measures affectted on sediment, total nitrogen and total phosphorus .

Figure 6. shows that the amount of sediment, total nitrogen and total phosphorus in three kinds of measure was consistent with the baseline scenario S0. That were relatively large value of rainy season (July to September) and relatively small value of the dry season. Compared with the baseline scenario, the amount of sediment, total nitrogen and total phosphorus of three kinds of measures were significantly reduced, and it reduce obvious in the rainy season. Compared through the corresponding month found that, S2 measured the smallest amount, followed by the S3 and S1. Table 8.2 shows that the percentage reduction in sediment loads are all the largest, followed by total nitrogen and total phosphorus. It indicated that influence of measures to sediment was large. By comparison of various measures, reduction benefits of Sediment, nitrogen and phosphorus were the strongest among the conversion of farmland to forest in the whole basin. However, It would affect economic development and

livelihood issues of the local residents, which require state subsidies and industrial transfer under guidement.

IV. Conclusion

Calibration and validation results of the SWAT model show that the simulated were in reasonable agreement with measured values. It showed that the SWAT model could be used successfully to accurately simulate runoff，sediment，total N and total P yield in the study area. From this study, the following conclusions are drawn: (1) A set of model parameters are gotten within physically realistic ranges and acceptable approximations. (2) Sensitivity analysis of the SWAT parameters indicates that hydrological process is most sensitive to the 16 parameter. This will help reduce the calibration time for future applications of the model under similar studies. (3) Although the model underestimates monthly runoff yield and overestimates sediment，total N and total P yield. simulation is within the acceptable limits of accuracy. (4) Three kinds of measures were obvious with reducing sediment, total nitrogen and total phosphorus in effect, conversion of farmland back to forests in whole watershed had the most effect on it.

Acknowledgment

This work was supported by the National Natural Science Foundation of China(Grant No. 40871136) and State Forestry Administration, People’s Republic of China for Special Funding Projects of Forestry Nonprofit Industry Research (Grant No. 200804022). The authors are grateful to Xie Hefang for assistance in experimentation and data collection.

References

[1] J Benaman and CA Shoemaker, “An analysis of high-flow sediment event data for evaluating model performance,” Hydrological Processes, vol.19, 2005, pp. 605–620.

[2] MP Tripathi, RK Panda, NS Raghuwanshi and R Singh, “Hydrological modeling of a small watershed using generated rainfall in the soil and water assessment tool model,” Hydrological Processes, vol. 18, 2004, pp.1811–1821.

[3] L. N. Neumann, A. W. Western and R. M. Argent, “The sensitivity of simulated flow and water quality response to spatial heterogeneity on a hillslope in the Tarrawarra catchment, Australia,” Hydrological Processes, 2009, doi: 10.1002/hyp.7486

[4] Anand, Shilpa, Kyle R. Mankin, Kent A. McVay, Keith A. Janssen, Philip L. Barnes and Gary M. Pierzynski. “Calibration and Validation of ADAPT and SWAT for Field-Scale Runoff Prediction,” Journal of the American Water Resources Association (JAWRA), vol.43, No.4, 2007, pp. 899-910, doi: 10.1111／j.1752-1688.2007.00061.x.

[5] R. Jayakrishnan, R. Srinivasan,* C. Santhi and J. G. Arnold, “Advances in the application of the SWAT model for water resources management,” Hydrological Processes, vol.19, 2005, pp. 749–762, doi: 10.1002/hyp.5624.

[6] White, J. Michael, Daniel E. Storm, Michael D. Smolen and Hailin Zhang,“Development of a Quantitative Pasture Phosphorus Management Tool Using the SWAT Model,” Journal of the American Water Resources Association (JAWRA), vol.45, No. 2, 2009, pp.397-406, doi: 10.1111/j.1752-1688.2008.00295.x.

[7] M. P. Tripathi, R. K. Panda and N. S. Raghuwanshi, “Development of effective management plan for critical subwatersheds using SWAT model,”Hydrological Processes, vol. 19, 2005, pp.809–826, doi: 10.1002/hyp.5618.

[8] Mazdak Arabi, Jane R. Frankenberger, Bernie A. Engel and Jeff G. Arnold, “Representation of agricultural conservation practices with SWAT,” Hydrological Processes, vol. 22, 2008, pp.3042–3055, doi: 10.1002/hyp.6890.

[9] Qiuling Zhang, Yingxu Chen, Ghulam Jilani, Imran Haider Shamsi and Qiaogang Yu, “Model AVSWAT apropos of simulating non-point source pollution in Taihu lake basin”. Journal of Hazardous Materials, vol.174, 2010, pp.824－830.

[10] MP Tripathi, NS Raghuwanshi, GP Rao, “Effect of watershed subdivision on simulation of water balance components,” Hydrological Processes, vol.20, 2006, pp.1137–1156.

[11] Jha, Manoj, Philip W. Gassman, Silvia Secchi, Roy Gu and Jeff Arnold, “Effect of Watershed Subdivision on SWAT Flow, Sediment, and Nutrient Predictions,” Journal of the American Water Resources Association (JAWRA), vol.40, No. 3, 2004, pp.811-825.

[12] Arabi, Mazdak, Rao S. Govindaraju, Mohamed M. Hantush and Bernard A. Engel, “Role of Watershed Subdivision on Modeling the Effectiveness of Best Management Practices With SWAT,” Journal of the American Water Resources Association (JAWRA), vol. 42 No.2, 2006, pp.513-528.

[13] Yuzhou Luo and Minghua Zhang, “Management-oriented sensitivity analysis for pesticide transport in watershed-scale water quality modeling using SWAT” Environmental Pollution, vol.157, 2009, pp. 3370－3378.

[14] XY Wang, XF Wang, QP Wang, “Estimation of nonpoint source pollution load in the Miyun Reservoir catchment,” Journal of Geographical Sciences, vol.24, No. 2, 2004, pp.227–231. (in Chinese).

[15] RA Sloto and MY Crouse, HYSEP: “A Computer Program for Streamflow Hydrograph Separation and Analysis. Lemoyne: U.S. Geological Survey,”Water Resources Investigations Report, 1996, pp.96–4040. ..