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ORIGINAL PAPER

Integration of monthly water balance modeling and nutrient load estimation in an agricultural catchment

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Abstract Non-point sources pollution has become a serious environmental problem in the aquatic systems throughout the world. The Xitiaoxi catchment is located in the southwest of Taihu Basin, contributing large amounts of runoff and associated nutrients to Taihu Lake. Thus, identifying critical non-point sources pollution in this catchment is urgent and essential to control water pollution, improve the water quality, and reduce the pollutants drained into water bodies. The present study integrated a monthly water balance model with the export coefficient model for total nitrogen and total phosphorus loads estimation in the Xitiaoxi catchment in southeastern China. The simulated monthly runoff are in good agreement with the observed streamflow at both Hengtangcun and Fanjiancun stations with Nash–Sutcliffe coefficients higher than 0.80. The predictions showed reasonable ranges from 1687 to 2046 t/y (2002–2005) for total nitrogen loads, and from 106 to 157 t/y for total phosphorus loads (1999–2007), respectively, which are consistent with the observed values at Hengtangcun. Overall, the monthly export coefficient model coupling monthly water balance simulation to export coefficient model presented both the seasonal dynamics and magnitude for streamflow and nutrients loads, which generally match well with the observations. These findings demonstrate that the proposed model can provide encouraging results and can be used as an efficient tool to identify the pollution sources for planning and management of large-scale agricultural catchment.

Keywords Export coefficient model · Monthly water balance model · Nitrogen · PCRaster · Phosphorus · Xitiaoxi catchment

Introduction

Due to the developed industry and high speed of increasing population, the aquatic systems in some regions are degrading rapidly. Environment problems caused by point-sources (PS) and/or non-point sources (NPS) pollution have received much more attention throughout the world. Point sources are relatively easy to identify, quantify and control (Carpenter et al. 1998), while NPS pollution is much more complicated as it is driven by multiple factors and includes diffuse pollution (Novotny 1999). In recent decades, NPS pollution results in excessive loading of organic matter and nutrients into rivers, lakes, reservoirs and estuaries, and it has become an important issue for improving aquatic systems (Mahvi et al. 2005; Ding et al. 2010). Large amounts of nutrients, especially from agricultural activities, lead to variety of serious problems such as algal blooming, biodiversity decreasing, ecosystems degrading and shortage of drinking water. It is therefore

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essential and urgent to control water pollution, improve the water quality, and reduce the pollutants discharged into water bodies.

In order to improve the water quality and identify the pollution sources, numerous studies have focused on the loss and load estimation of pollutants from different pollution sources (Singh and Frevert 2002; Bowes et al. 2008; Zhao et al. 2011). Previous studies indicate that the NPS pollution is strongly associated with hydro-chemical processes, and thus hydrological models are commonly used to estimate the nutrient loadings, to quantify the effects of agricultural activities on water quality. A considerable number of water quality models have been developed and successfully applied to estimate the pollution loadings into the water bodies and evaluate the alternative management practices to reduce the point and NPS pollution (Shrestha et al. 2006). These models range from simple export coefficient models (Johnes 1996) to complex mechanistic models such as ANSWERS (Beasley et al. 1980), AGNPS (Young et al. 1989), SWAT (Arnold et al. 1993), and HSPF (Donigian et al. 1995), etc. Some of these models have been widely applied for catchment management and decisions making. However, a key constraint among the complex models is that numerous parameters cannot be obtained from field measurements and must instead be determined through model calibration. Furthermore, in many cases, water quality, hydrologic and ecological data are seldom collected simultaneously, which may limit the application of these models.

An alternative approach is to use an empirical export coefficient model to estimate nutrient transport in large catchments. With the advantage of requiring less data and having fewer parameters, the export coefficient model (ECM) has been recognized as a reliable tool for modeling NPS pollution (Bowes et al. 2008; Ding et al. 2010). Since the ECM was firstly proposed by Omernik (1976), it has been continuously improved and integrated different sources in order to obtain more accurate results. Currently, nutrients exported from various sources (i.e., land use, livestock, etc.) in the catchment have been taken into account. Although the ECM can provide acceptable precision, especially suitable for areas where little data are available, it should be noted that the ECM has some limitations. The ECM does not consider the heterogeneity of terrain and spatial–temporal distribution of precipitation, rather the same export coefficient is used for the same nutrient in different hydrologic years or various terrain regions (Ding et al. 2010). Moreover, export coefficients usually operate on an annual time step, while the NPS pollution is highly dependent on seasonal patterns of nutrients delivery, it is therefore necessary to increase the temporal resolution to capture the seasonal characters of nutrients loads (May et al. 2001).

The study area, Xitiaoxi River catchment, is one of the most important rivers drained into Taihu Lake. In the recent decades, large amounts of nutrients were discharged into rivers and transported to Taihu Lake, which lead to serious water pollution. Thus, considerable studies and efforts were conducted to improve the water quality since algal blooms in the lake occurred much more frequently, as well extending its coverage in summer. The ECM model has been applied to investigate the nutrients load in the Xitiaoxi catchment with long-term annual simulation by both Liang et al. (2008) and Li et al. (2009). Similarly, the annual nutrient loads' estimation was undertaken by Lai et al. (2006) and Yu et al. (2007) for the whole Taihu Basin using the SWAT model, which is a promising tool for long-term continuous simulations in predominantly agricultural watersheds. These studies provided good insights into the spatial and temporal characteristics of the nutrient loads and changes in the catchment. However, the nutrient simulation in annual scale cannot represent the seasonal changes of nutrient processes. Furthermore, the unavailable short-term measured nutrient data limit the existing model's application. Therefore, the objectives of this paper are to: (a) develop monthly export coefficient model (MECM) by integration of monthly water balance simulation and the ECM model to estimate the nutrient loading from individual sources and (b) Identify the spatial and temporal characters of nutrients losses in the Xitiaoxi catchment.

Materials and methods

Study area and data sources

The study area of the Xitiaoxi catchment, with the length of the river 157 km, covering more than 2,200 km^2, is located in the upstream of Taihu Lake in southeastern China (Fig. 1). The Xitiaoxi River is an important incoming branch in the Taihu Basin, supplying 27.7% of the water volume for Taihu Lake. The annual average rainfall is approximately 1,465 mm and strong spatial temporal variations are associated with various elevation. High mountainous and hilly areas are distributed in the southwest with maximum elevation of 1,585 m (above mean sea level), whereas low alluvial plains lie in northeastern parts with a well-developed drainage network.

The land use/cover information was extracted from Landsat 7 enhanced thematic mapper (ETM) images acquired on October 11, 2001, which was used for nutrients export coefficient determination. Figure 2 shows the land uses in the catchment, of which about 62.4% in the upper reaches are covered with forest. About 29.7% of the catchment is arable land, which is almost located in the low alluvial plains. Other land uses are minor with a residential

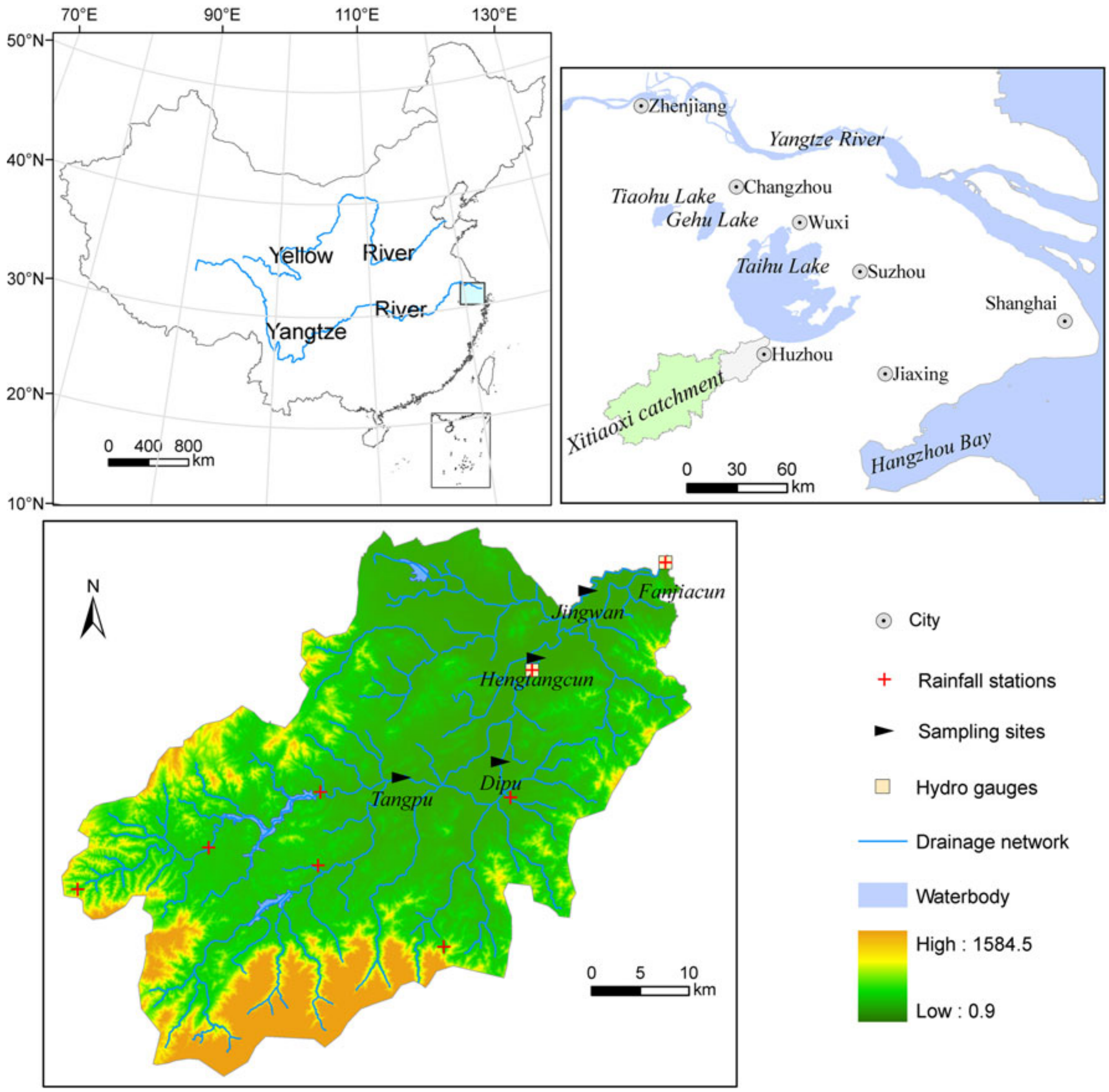

Fig. 1 Location of the study area and monitoring sites

area of 1.9%, grassland of 2.3%, and garden and water area of 3.7%. Among which, the paddy field accounted for 94.8% of the arable land, and bamboo forest accounted for 45.5% of the forest land. The above percentages indicated that forest and arable land were the main land use types in the study area (Fig. 2).

The Nanjing Institute of Geography and Limnology (NIGLAS), Chinese Academy of Sciences provided a digital elevation map (DEM) with a resolution of 25 m × 25 m (Fig. 1). The DEM was used to derive the hydrologic parameters of the catchment, i.e., slope, local drainage direction (LDD). Eight rainfall stations with daily precipitation over a period of 20 years (1988–2007) were provided by Anji Hydrology Bureau, as well as the pan evaporation at two stations (Anji and Fanjiacun). Data on total nitrogen (TN) and total phosphorus (TP) sources (human population and amount of livestock-poultry) in the Xitiaoxi catchment were collected from 1999 to 2005. The nutrient loads from the point sources were calculated according to the relationship between nutrient export rates and industrial productions in 1999 for the catchment (Li et al. 2004).

Model concepts

The MECM model integrates the water balance and nutrient simulation by using PCRaster, a dynamic environmental modeling system based on raster calculation (van Deursen 1995; Wesseling et al. 1996). PCRaster is a high-level computer language for construction of iterative spatial–temporal environmental models (http://pcraster.geo.uu.nl). It provides an efficient interactive raster GIS

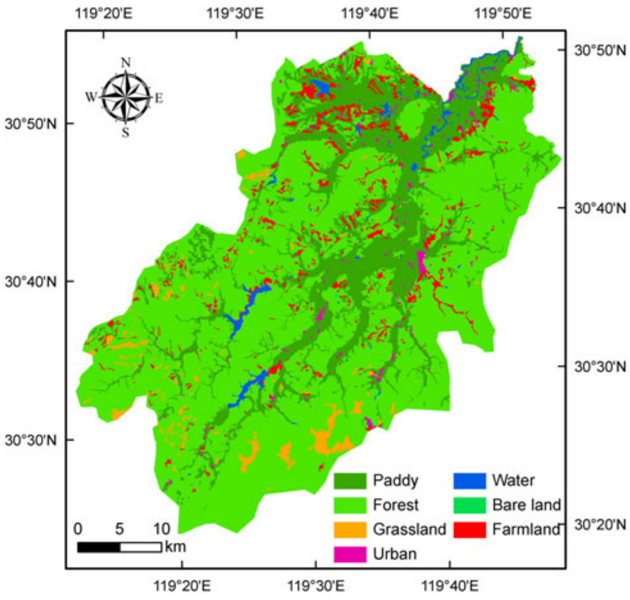

Fig. 2 Land use map in the Xitiaoxi catchment

environment for spatial data storage, manipulation and visualization, as well as an extendable library for creating users' costumed routines.

Water balance model

A two-parameter monthly water balance model proposed and developed by Xiong and Guo (1999) is implemented in PCRaster for monthly runoff estimation. The model has been tested in more than 100 small and medium size catchments in south China, which proved to be quite efficient in simulating the monthly runoff with the simple structure.

The actual monthly evapotranspiration is adapted from the Ol'dekop formula (1911, cited after Brutsaert 1992), which has been well established and used in calculating the long-term actual annual evapotranspiration of a catchment, as expressed below:

$$Ea = c \times Ep \times \tanh(\mathrm{Pr}/Ep) \tag{1}$$

where Ea represents the actual monthly evapotranspiration (mm), Ep (mm) is the monthly pan evaporation, Pr (mm) is the monthly rainfall, tanh() is the hyperbolic tangent function, and c is a model parameter.

For each grid, water enters the soil store S (mm) as rainfall Pr and leaves as evapotranspiration Ea or runoff R (mm). The monthly runoff R_t is a function of soil water content, calculated as follows:

$$R_t = S_t \tanh(S_t/S_c) \tag{2}$$

where S_t (mm) is the water content at time t month in soil, and S_c (mm) represents field capacity in the catchment.

Based on the above calculation, the soil water content S_t can be calculated according to the water conservation law:

$$S_t = S_{t+1} + \mathrm{Pr} - Ea - R_t \tag{3}$$

The model assumes that a fraction of the water surplus remains in the soil and recharges the groundwater storage. Thus, runoff is split into a direct fraction surface runoff QS (mm):

$$QS = k \times R_t \tag{4}$$

and a 'delayed' fraction, which is transferred to the groundwater storage Q_{recharge} (mm) as recharge:

$$Q_{\mathrm{recharge}} = (1-k)R_t \tag{5}$$

where k is the fractional parameter.

The groundwater storage S_{gw} (mm) is filled by recharge Q_{recharge} and drained by a groundwater discharge flux Q_{gw} (mm)

$$S_{\mathrm{gw},t} = S_{\mathrm{gw},t-1} + Q_{\mathrm{recharge}} - Q_{\mathrm{gw}} \tag{6}$$

It is assumed that the groundwater system behaves like a linear storage, which is estimated as:

$$Q_{\mathrm{gw}} = S_{\mathrm{gw}}/C \tag{7}$$

where C is the mean residence time of water in the groundwater system.

Total discharge is calculated as the sum of contributions by surface runoff and groundwater flow:

$$Q = QS + Q_{\mathrm{gw}} \tag{8}$$

Export coefficients model

On an annual basis, nutrients losses for each land-cover type were estimated using the export coefficient approach (Johnes 1996). Taking nitrogen as an example, TN loads from the field are expressed as:

$$\mathrm{TN} = \sum_{i}^{n} (A_i E_i) \tag{9}$$

where A_i is the area (ha) of the ith land-cover type, or number of animal types i, or number of people, E_i is the annual export coefficient for each source.

Assuming that the diffuse TN is contributed by two fractions from both surface water and groundwater flow, the TN loads from the catchment in month j can be estimated from the annual export coefficients for each land-cover class using the equation from May et al. (2001):

$$E_j = B_j c_b + QS_j \times \mathrm{Pr}_j \sum_i (E_i A_i) \Big/ (QS_a \times \mathrm{Pr}_a) \tag{10}$$

where E_j denotes the total nitrogen loads per month, Pr_j (mm) is the total rainfall for month j, QS_j (mm) is the fraction surface runoff drained into rivers from the catchment in the *j*th month, QS_a (mm) is the annual fractional runoff, and $\Pr_a$ is the annual rainfall (mm), B_j (mm) is the groundwater for month *j* (i.e., baseflow) to the river with a fixed concentration of c_b.

Model setup and calibration

All the spatial data (e.g., land use and DEM) are discretized to a grid size of 200 m × 200 m for model simulation to avoid large number of grid calculation and much more model running time. Continuously observed daily streamflow records at two gauge stations, (Fig. 1) Hengtangcun (1988–2007) and Fanjiacun (1988–2001), are converted to monthly streamflow (mm) for hydrological model calibration and validation. In addition, observed nutrient data at four sampling sites (Fig. 1) from 1999 to 2007 were used for nutrients model evaluation. The trial-and-error method was used to optimize the parameter values and calibrate the model. The model efficiencies according to the Nash–Sutcliffe efficiency (NE) (Nash and Sutcliffe 1970) and the correlation coefficient (R^2) were calculated at monthly resolution to evaluate the model performance.

The parameter values in the water balance simulation are derived from the similar catchments in the literature (Xiong and Guo 1999). The nutrient concentration in the groundwater was initialized by the observation (Chen et al. 2008b) in the Taihu Basin, and calibrated according to the measured nutrients concentrations afterwards.

Nutrients export coefficients for land use types in the Xitiaoxi catchment were firstly adopted from literatures (Johnes 1996; May et al. 2001; Li et al. 2004; Ding et al. 2010) regarding of similar catchment in south China (Table 1), and then all coefficients were determined after local validation using monthly streamflow and water quality data in the Xitiaoxi River from 1999 to 2007. Annual export coefficients were taken as constants for a particular land use based on agriculture practices shown in Table 1. Export coefficients for human and livestock–poultry are shown in Table 1 as well.

Table 1 Nutrients export coefficients from different sources in the Xitiaoxi catchment

Sources	TN (kg/(ha × yr))	TP (kg/(ha × yr))	References
Land use types			
Grassland	8	0.2	Liu et al. (2009)
Forest	2.38	0.15	Zhao et al. (2011)
Farmland	14.7	0.59	Yang et al. (2004)
Paddy land	19.4	1.16	Yang et al. (2004)
Villages/rural area	4.5	0.25/0.57	Drewry et al. (2006)
Continuous urban	11	0.91	Liu et al. (2009)
Bare land	9	0.2	Long et al. (2008)
Human and livestock (kg/(ca × yr))			
Human	2.14	0.18	Lai et al. (2006)
Big livestock	7.3	0.31	Liu et al. (2009)
Pig	0.74	0.15	Ding et al. (2010)
Sheep	0.4	0.45	Liu et al. (2009)
Poultry	0.06	0.006	Long et al. (2008)

Results and discussion

Water balance simulation

The water balance simulation was evaluated by comparing the corresponding measured data at Hengtangcun (1988–2007) and Fanjiacun (1988–2001) stations. Figure 3 shows the hydrographs of the measured and simulated monthly runoff at two stations. It can be clearly seen that the model presents reasonable and acceptable results during the periods for both calibration and validation. The simulated monthly discharge shows both the seasonal dynamics and magnitude, which generally match well with the observed values. A good correlation between observed and simulated monthly streamflow was detected with high efficiencies (NE and R^2) in range of 0.82 and 0.88 and from 0.80 to 0.88 for Hengtangcun and Fanjiacun stations, respectively.

Figure 4 illustrated a comparison of observed and simulated annual runoff at Hengtangcun and Fanjiacun stations in the Xitiaoxi catchment, which indicated that the simulated annual runoff were in agreement with the observations. However, it has to be noted that there are two reservoirs (Laoshikan and Fushi) located in the upstream of Xitiaoxi catchment. The gauging stations used in model performance evaluation are located downstream of the catchment and are far away from the reservoirs, therefore, the effects of the reservoirs on the measured runoff are considered to be limited (Zhao et al. 2011), especially for the annual water balance simulation. The current monthly water balance model has not considered the reservoirs operation for the runoff simulation.

Nutrients simulation

Figure 5 represents the comparison of the simulated and observed TN loads at Hengtangcun from July, 2002–2005. It clearly shows that the modeled TN loads fit generally well to the observed loads with NE equal to 0.84. Furthermore, the TN load simulation shows a pronounced seasonal dynamic with high loads in rainy season (Fig. 5). However, it should be mentioned that simulated TN loads

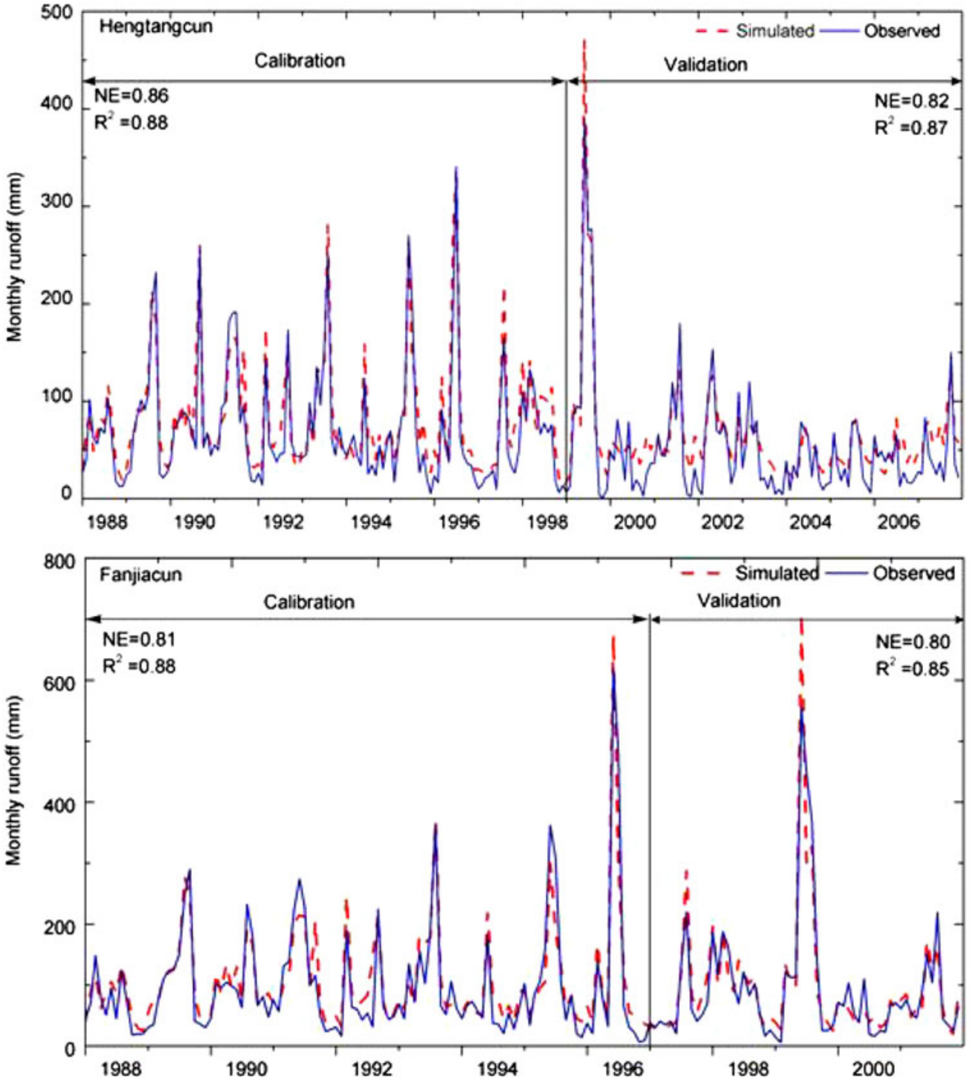

Fig. 3 Observed and simulated monthly runoff at Hengtangcun and Fanjiacun for water balance model calibration and validation

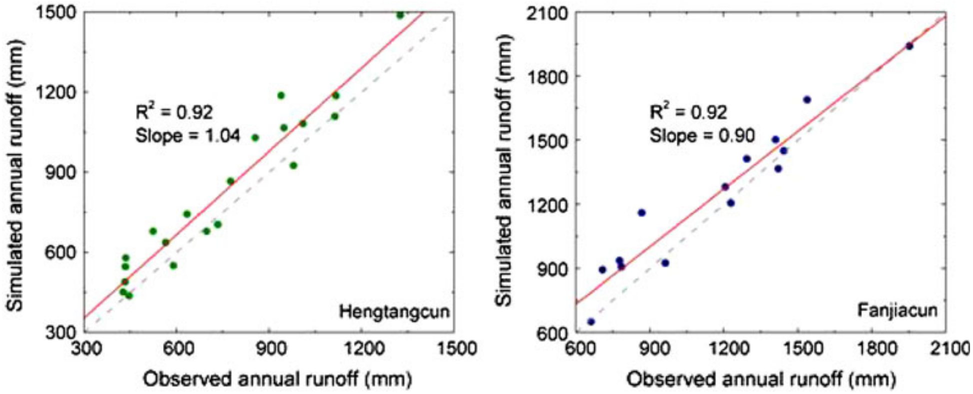

Fig. 4 Observed and simulated annual runoff at Hengtangcun and Fanjiacun in the Xitiaoxi catchment

are relatively higher than the observed values due to runoff overestimation in winter season (e.g., in 2003).

The simulation from the MECM in the present study is in the range of 1,687–2,046 t/y for total nitrogen export at Hengtangcun station during 2002–2005. This finding is consistent with the prediction by Li et al. (2004). They estimated the nutrient loads using ECM based on the relationship between land use types and nutrient concentration of the surface runoff, and found that annual nitrogen loads from diffuse sources was about 1,589 t/y and total

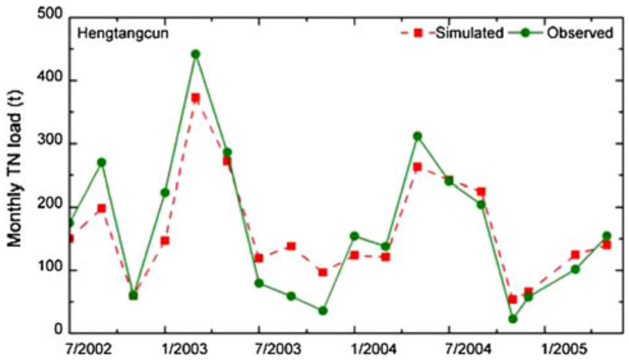

Fig. 5 Observed and simulated monthly TN loads at Hengtangcun station

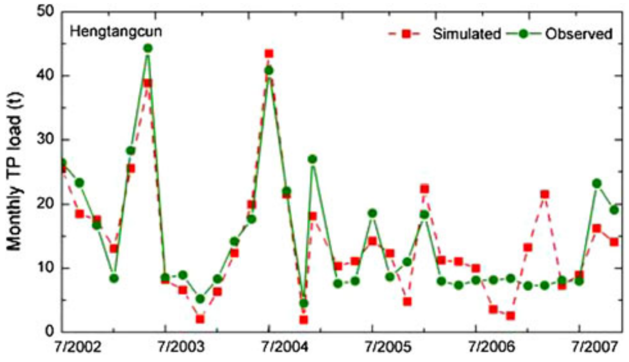

Fig. 6 Observed and simulated monthly TP loads at Hengtangcun station

nitrogen loss was approximately 2,031 t/y at Jingwan site in downstream of Hengtangcun (Fig. 1). In contrast, the simulation results have a broader range compared to their estimations, which may be attributed to the estimation based on the different annual precipitation during the studied period.

The simulated TP loads at Hengtangcun site match consistently well with the observed values from 2002 to 2007 (Fig. 6). The model generated the mean long-term TP loads as well as the seasonal variability, however, some years do not show a perfect match, which is partly attributed to the runoff simulation that indicates an over/under prediction in streamflow.

Li et al. (2009) estimated the TN and TP load in the catchment by using the improved export coefficient model, and the results showed that the export load for TP was 49.3 t, lower than the observed 137.53 t in 2004. In contrast, The TP loads estimation from the MECM are in a range of 106 to 157 t/y at Hengtangcun station from 1999 to 2007, which is consistent with the observed ranges between 99 and 161 t/y.

Figure 7 compared the observed TN and TP concentrations with the measurements at three different sites and plotted their distribution along with the 1:1 fit line. From Fig. 7, it can be seen that lower concentrations for both TN and TP are well simulated since most points lie across the 1:1 fit lines. However, high concentration of TN and TP are underestimated, especially at Dipu site. The observed values at Dipu have much wider range from 0.361 to 5.236 mg/L for TN and from 0.025 to 0.543 mg/L for TP, which was attributed by the point source pollution from Anji County. Although both the PS pollution and the excrement of human and livestock were taken into account in the current MECM model, the predictions for sewage from industrial point sources need to be improved with detailed dataset in the future.

Table 2 summarizes the simulation results for both monthly runoff and nutrients modeling in the Xitiaoxi catchment. Reasonably high coefficients of NE and R^2 (Table 2) indicated a positive relationship between the simulated and measured average values for both runoff and nutrients concentrations (from 0.80 to 0.88, and 0.56 to 0.82 for runoff and nutrients, respectively). The simulated nutrients concentrations show satisfactory match with the measured values for both TN and TP at four sites in the Xitiaoxi catchment.

Fig. 7 Observed and simulated nutrients concentration in the Xitiaoxi catchment

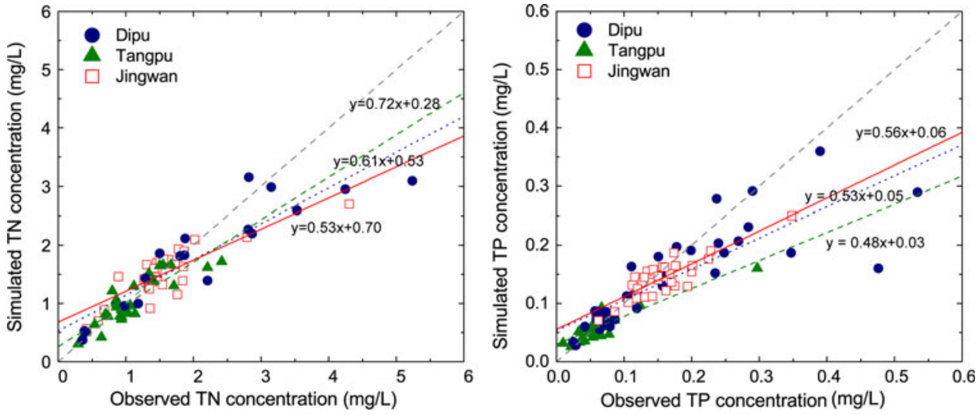

Table 2 Model performances for streamflow and nutrients in the Xitiaoxi catchment

Stations	Used for	Annual mean		Period	R^2	NE
		Observed	Simulated			
Runoff (mm)						
Hengtangcun	Cal	51.30	62.78	1988–1998	0.88	0.86
	Val	75.47	86.72	1999–2007	0.87	0.82
Fanjiacun	Cal	98.83	107.11	1988–1996	0.88	0.81
	Val	100.17	101.50	1997–2001	0.85	0.80
Total nitrogen (mg/L)						
Dipu	Cal	2.141	1.835	2002–2005	0.59	0.56
Tangpu	Cal	1.074	1.035	2000–2005	0.77	0.76
Jingwan	Val	1.562	1.507	2000–2005	0.70	0.65
Chaitanbu	Val	1.456	1.419	2002–2005	0.82	0.71
Total phosphorus (mg/L)						
Dipu	Cal	0.171	0.148	2002–2007	0.67	0.60
Tangpu	Cal	0.064	0.061	1999–2007	0.79	0.66
Jingwan	Val	0.155	0.143	1999–2007	0.73	0.63
Chaitanbu	Val	0.130	0.118	2002–2007	0.68	0.64

Cal calibration, *val* validation

Spatial distribution of nutrients loads

The simulated spatial distribution of TN and TP loadings in the catchment are shown in Fig. 8. It can be seen that the TN and TP loads vary significantly among land use types, especially among the forests, arable land and densely populated areas. As shown in Fig. 8, the highest TN export rate of 194 kg/ha/y occurs in the Anji County due to its large number of populations. The TN export of the dominated paddy land in the Xitiaoxi catchment within a range from 13.5 to 49.8 kg/ha/y is in response to the great N input, which is consistent with previous studies. A high riverine N export of 8.1–52.7 kg N/ha/y was found by Cao et al. (2006) under different land use regimes in an agricultural watershed of Jiulong River in southeastern China. The studies investigated by Guo et al. (2004) presented the high N losses were 34.1 kg for the Taihu region, and the export of TN varied according to land use and was

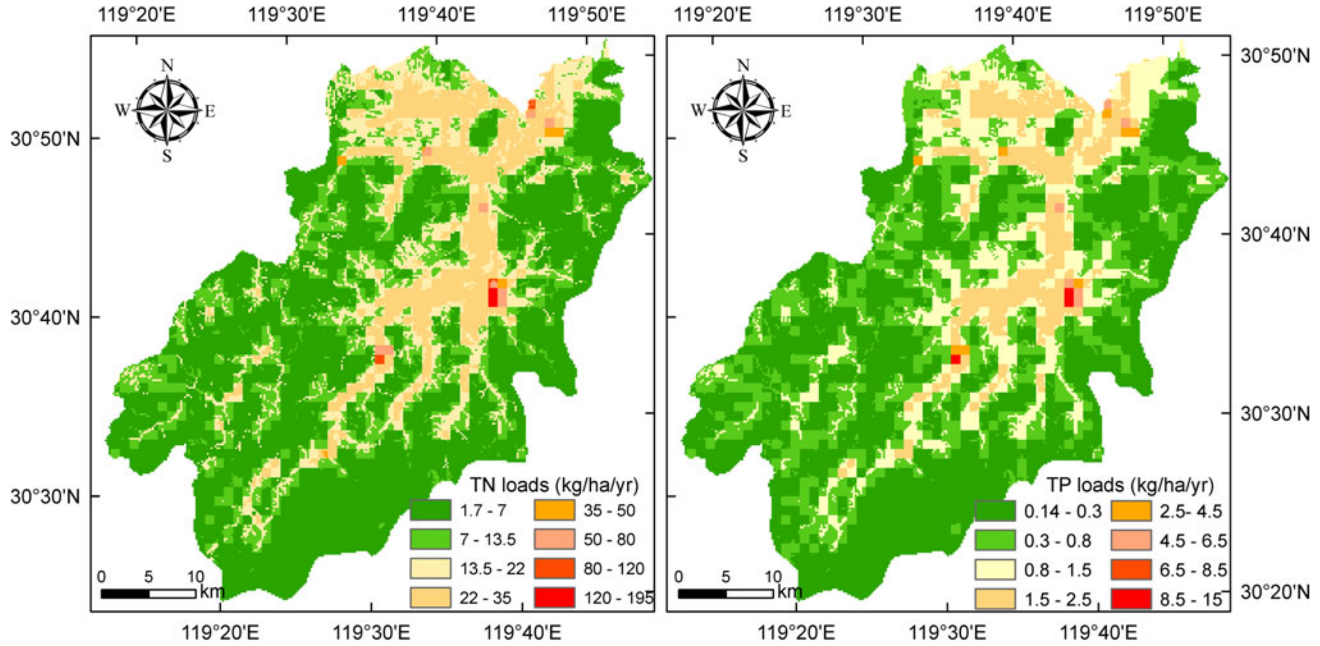

Fig. 8 Simulated spatial distribution of TN and TP loads in the Xitiaoxi catchment

significantly correlated to the net input of anthropogenic N (Filoso et al. 2003). In contrast, the lowest export rate lies in forest area with the values from 1.7 to 8.3 kg/ha/y. Similarly, study on TN losses and concentrations in Finland during the period 1981–1997 showed that TN loss in three agricultural catchment (average 15 kg N/ha/y) was higher than in nine forested catchment (average 2.5 kg N/ha/y) (Vuorenmaa et al. 2002). Meanwhile, the spatial distribution of the TP export rate is similar to TN with highest values occurring in the industrial region and lowest values in the forests. In the Taihu Basin, the results from Guo et al. (2004) indicated that TP load from agricultural land is 1.75 kg/ha/y. In contrast, the results show a broader range of TP loads between 1.34 and 4.8 kg/ha/y. In the Xitiaoxi catchment, the double-rotation of rice/wheat or rice/rapeseeds is the dominated agriculture practice in the broad alluvial plain, and the intensive agricultural practices raised the severe contamination. Overall, it can be found that the highest TN and TP loads mostly lie in the highly populated areas, which means large amount of domestic waste water drained into surface water bodies.

The TN losses from the catchment were mainly contributed by land use, which accounted for 47.2% of the total, followed by point sources (34.7%), livestock (10.6%) and domestic water from residents (7.5%). Among those seven land use types, paddy land made the largest contribution of the total. In the Xitiaoxi catchment, in order to obtain large crop yields, excessively fertilizers application in the arable land (especially in the dominated paddy land) has significantly increased the nutrients accumulation in the soil. It has been documented that the average total N input to the arable land was appropriately 500–600 kg N/ha/y, and 12.1–14% was export through runoff (Cao et al. 2006; Chen et al. 2008a).

The TP losses ranked differently from those of TN: with land use first (53.4%), followed by point sources (28.1%), rural residents (11.7%), and livestock (6.8%). Although land use accounted for a larger portion in TP simulation compared to TN, paddy land was still identified as the dominant contributor among those seven land use types, and the contribution from PS pollutions showed little differences between these two nutrients. However, domestic waste water from residents contributed a higher amount of TP (11.7%) than TN (7.5%).

Conclusion

In the current study, the MECM integrated a monthly water balance model with the export coefficients model to simulate and predict monthly runoff and nutrients loads in the Xitiaoxi catchment. The simulation results in this study provide a scientific basis for understanding nutrient losses in the catchment scale, as well as good knowledge for identifying the pollution sources.

The MECM took the basic climate, topography, land cover/use and agricultural data as input to simulate both monthly runoff and nutrients loads in the Xitiaoxi catchment in southeastern China. Monthly runoff simulation at two gauges (Hengtangcun and Fanjiacun) presented good agreement between simulated and observed monthly runoff with both NE and R^2 higher than 0.8. The MECM estimated the TN and TP loads according to different land use types, and the simulation results are acceptable and reliable for both the range and seasonal dynamic. Nitrogen concentrations at four different sites were also selected for model performance evaluation. The model efficiencies of NE in a range of 0.63–0.78 indicated that the model results were relatively reliable.

According to the spatial distribution of the nutrient loads in the Xitiaoxi catchment, paddy land was the dominant NPS of both TN and TP pollution. This was primarily because of the excessive fertilizer application. Several parts of the catchment were identified as the most serious polluted regions by TN and TP, which are all highly populated areas. Additionally, the spatial distribution of TN and TP were similar, which revealed consistency between these two pollutants.

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