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An integrated simulation-monitoring framework for nitrogen assessment: a case study in the Baixi watershed, China

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Abstract

As the deterioration of drinking water quality has become increasingly severe worldwide, there is a considerable need to accurately identify variable pollution sources. Currently, simulation programs have been shown to be less effective in short-term and detailed simulations. Therefore, this study advanced an integrated framework for simulation by combining the modelling and monitoring methods. A case study was conducted to identify the spatial and temporal distribution of nitrogen (N) in the upstream watershed of a typical drinking water reservoir, in the city of Ningbo, Zhejiang province, China. In this study, a watershed model, Soil and Water Assessment Tool (SWAT), was used to estimate N load for the 254 km^2 upper stream watershed; while storm runoff samples were also collected to illuminate more detailed processes in the storm event. Based on the model output, the critical N source in Baixi watershed was identified as the forest. The potential nonpoint source (NPS) pollution risk areas were also illustrated as Sub-basin 21, 20 and 26. In addition, the model simulation proved that the Qingshui River contributed more N load than the other two tributaries. Conversely, the short-term and detailed trends were obtained through storm sampling. By analyzing the storm samples, it was clear that the N load into the drinking water reservoir results from a combination of land-use, agricultural activities, as well as atmospheric deposition, especially in the acid rain control region. It could be further inferred that modelling and monitoring could serve as a framework to provide information for N load prediction and protection of drinking water. Using the integrated simulation-monitoring framework, the SWAT model could be used as an effective tool to foretell the potential risk of detrimental NPS conditions, while monitoring could provide an inventory and detailed means to further study short-term trends.

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1. Introduction

With continuous population and economic development, water scarcity and the deterioration of water quality have become increasingly severe in many river basins around the world, especially in drinking water sources [1,2]. As the quality of drinking water is threatened, the need for science-based protection and management decisions becomes urgent [3,4].

Sources of water contamination are widespread and include accidental spills, landfills, storage tanks, pipelines, and agricultural activities [5]. Of the sources, nonpoint source pollution (NPS) has been a major concern, particularly where intensive agricultural operations exist near environmentally sensitive waters. The growing number of NPS stresses on the drinking water has necessitated a more rapid conversion of basic studies into sound management practices. Many studies have focused on the fate and transport of NPS pollution located in the areas upstream of drinking water sources, which are often relatively poor and depend heavily on agriculture [6,7]. In previous studies, researches have been conducted experiments to solve problems as diverse as controlling eutrophication [8], protecting biota from the deleterious effects of land-use change [9], and preventing erosion-related disasters [6]. However, an important strategy for controlling NPS pollution is to minimize the pollutant load of in the critical source areas. Hence, there is considerable need to accurately identify these variable source areas.

Therefore, in regional scale analysis, it is essential to understand both the load and interaction factors to account for the spatially variable pollution leaching to the drinking water. Many researchers have provided the knowledge and techniques to quantify NPS pollution. Since the development of the Stanford Watershed Model [10], there has been a proliferation of watershed models. Specifically, watershed models combine the continuous simulation of pollutants from transportation, transformation and output, to determine the time of occurrence and the critical source areas. Many such models have been successfully developed for this purpose, such as Agricultural Nonpoint Source Model (AGNPS) [11], Soil and Water Assessment Tool (SWAT) [12], Simulation for Water Resources in Rural Basins (SWRRB) [13,14], Agricultural Nonpoint Source Watershed Response Simulation (ANSWERS) [15,16], Hydrological Simulation Program Fortran (HSPF) [17,18] and Better Assessment Science Integrating Point and Non-point Sources (BASINS) [19]. Currently, such simulation programs are coupled with GIS and integrated with biological and ecological sub-models. Therefore, these models can simulate processes such as the generation of runoff to the entry of nutrients to various water bodies, as well as predict flow volume, sediment levels, and the amounts of nutrients leaving the sub-basins of a watershed.

Among above models, AGNPS, SWAT and HPSF are most widely used tools worldwide, as well as a series of applications in China. Among these models, the AGNPS is a batch process, distributed parameter, continuous simulation model with a daily time scale [20, 21]. The model subdivides the watershed into suitably small cells of homogeneous land use, land management, and soil types. However, the studied areas of AGNPS are generally less than 200 km^2 and the pollutant cycle equation has not yet been combined into this model [20]. The HSPF model consists of a set of modules that can be applied either individually or in tandem, which increases its practicality for both simple and complicated watershed simulation projects [17, 18]. The disadvantage of HSPF is reported to be the highly complex model structure and a multitude of parameters, which may result in the increasing input data and computing time. In addition, the HSPF model has been proved to be less effective in N and P simulation than SWAT [22, 23]. The SWAT model is a physically based, continuously distributed model that operates on a daily time scale, which has been applied in many countries, including Finland [24], Germany [25], U.S. [16], India [26], France [27], and China [28]. In the SWAT model, a modification of

the SCS curve number method [29] and Green & Ampt infiltration method [30] are used to compute surface runoff volume for each Hydrologic Research Unit (HRU). The peak runoff rate is estimated using a modification of the Rational Method and daily or sub-daily rainfall data are used for calculations. River flow in the SWAT model is routed through the channel using a variable storage coefficient method developed by Williams [14] or the Muskingum routing method. However, SWAT is reported to be less effective in storm event simulations. This lower accuracy of runoff simulation can be attributed to the storm hydrographs prediction module in SWAT that is based on the theory of infiltration excess overland flow [31]. This theory assumes that flow production occurs when precipitation intensity is greater than the soil's infiltration capacity [32, 33]. Hortonian flow most commonly occurs during very high intensity rain storms and in areas where the ground's infiltration capacity is particularly low, which may be attributed to the soil's natural or modified structure, compaction processes, and/or surface sealing, especially where there is too little vegetation to protect the soil surface from raindrop impact [34, 35]. However, in humid, well-vegetated regions [36], the SWAT model is reported to be less effective [31, 37]. In general, NPS pollution from upstream in the watershed is not measurable due to the unknown spatial heterogeneity of the watershed as well as the high cost involved [38]. However, storm samples are often collected and analyzed by monitoring methods [39]. Thus, it could be inferred that modeling and monitoring NPS pollutants at multiple spatial and temporal scales could serve as an effective tool to protect soil and water resources.

The Baixi watershed is situated upstream of the Baixi reservoir, which is the largest hydropower dam and the main drinking water source of the city of Ningbo, which is in Zhejiang province, China. Despite the protective measures for the drinking water reservoir that have been taken since 2006, the concentration of nitrogen (N) still exceeds the permitted environmental standards at times, especially after heavy storms. The important role of drinking water reservoirs ensures that NPS-N is worth paying attention to. However, this watershed is described as a humid climate with stormy weather, limiting the application of the SWAT model in such areas. Thus, to identify the spatial and temporal distribution of N accurately, an integrated simulation-monitoring framework was introduced in this study.

The aim of this paper originated from the identification of the distribution of NPS-N in the upstream watershed for such a typical drinking water reservoir using an integrated simulation-monitoring framework. The framework combined: 1) A watershed mode that was used to estimate Total N (TN) for the 254 km^2 upstream watershed; 2) Samples that were collected to illuminate more detailed processes of the event rain. The paper was organized as follows: a description of the study area, the watershed model, and the sampling method; the spatial and temporal distribution of NPS-N was analyzed in the part of both results and discussion; followed by the conclusions section.

2. Study area and methodology

2.1 Study area

The Baixi reservoir is a major hydraulic facility in the city of Ningbo, in the east of the Zhejiang province, China (Fig. 1). The upstream watershed covers three main upstream rivers named as Dasong River, Hunshui River and Qingshui River, with a total upstream drain area of 254 km2. A humid north-subtropical-monsoon climate covers this area, featuring distinct seasons with adequate illumination and abundant precipitation: an annual mean temperature of 16.1^{o}C (from -9.6^{o}C to 39.7^{o}C) and an annual mean precipitation of 1091.2 mm. This region could be characterized as a mountainous area with agricultural vegetation, secondary forest and product forest. The main land uses in the watershed include 7% cropland, 91% forest, and 2% barren land (Fig. 2). In addition, zonal yellow soil (33%) and skeleton

soil (35%) are the dominant soil of the watershed, followed by 12% red soil, 19% yellow red soil and 0.2% paddy soil (Fig. 3).

Fig. 1.A map of the Baixi reservoir basin, indicating the major tributaries and reservoir site.

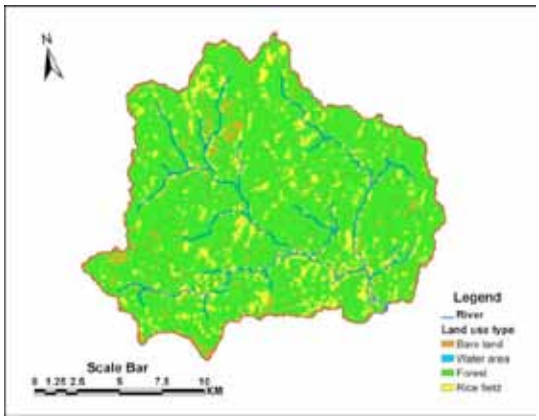

Fig.2 A map of land-use in the Baixi watershed.

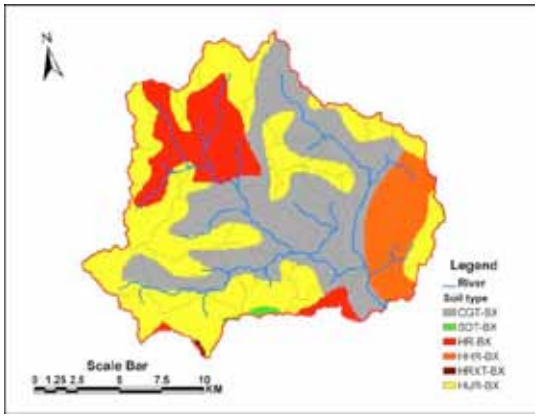

Fig.3 A map of the soil types in the Baixi watershed.

2.2 The SWAT model

The SWAT model is a hydrologic/water quality tool developed by the United States Department of Agriculture-Agriculture Research Service (USDAARS) [12]. The SWAT model is also available within the BASINS as one of the models that the US EPA supports and recommends for state and federal agencies to use to address point and nonpoint source pollution control. The hydrological processes are divided into two phases: the land phase and the channel/floodplain phase. Precipitation data could be daily if curve number (CN) method [29] is used or sub-daily if Green-Ampt [30] infiltration method is used to estimate surface runoff [40]. The SCS curve number equation is:

$$Q_{\text{surf}} = \frac{\left(R_{\text{day}} - I_{\text{a}}\right)^2}{\left(R_{\text{day}} - I_{\text{a}} + S\right)} \tag{1}$$

where Q_{surf} is the accumulated runoff or rainfall excess (mm H_2O); R_{day} is the rainfall depth for the day (mm H_2O); I_a is the initial abstractions, which includes surface storage, interception, and infiltration prior to runoff (mm H_2O); and S is the retention parameter (mm H_2O). The retention parameter varies spatially due to changes in soil, land use, management, and slope and temporally due to changes in soil water content. The retention parameter is defined as:

$$S = \frac{25400}{CN} - 254 \tag{2}$$

where CN is the curve number for the day.

The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) [14] to estimate sediment yield at the level of the Hydrological Response Unit (HRU). The loss of both N and P from the soil system of each HRU is accounted for by plant uptake, their transport via surface runoff, eroded sediment, lateral flow and percolation below the soil profile, and by volatilization to the atmosphere [40]. The MUSLE is defined as:

$$Q_{sed} = 11.8(Q_{surf} \cdot q_{peak} \cdot A_{hru})^{0.56} \cdot K_{usle} \cdot C_{usle} \cdot P_{usle} \cdot L_{usle} \cdot F_{CFRG} \tag{3}$$

where Q_{sed} is the sediment yield on a given day (metric tons); Q_{surf} is the surface runoff volume (mm H_2O/ha); q_{peak} is the peak runoff rate (m^3/s); A_{hru} is the area of the HRU (ha); K_{usle} is the USLE soil erodibility factor; C_{usle} is the Universal Soil Loss Equation (USLE) cover and management factor; P_{usle} is the USLE support practice factor; L_{usle} is the USLE topographic factor; and F_{CFEG} is the coarse fragment factor.

Flow, sediment and nutrient from all HRUs are added to the sub-watershed level and then routed through the channels, ponds, reservoirs, and wetlands to the watershed outlet. Flow is routed using either the variable-rate storage method [14] or the Muskingum method. Sediment and nutrients are introduced into the main channel through surface runoff and lateral subsurface flow, and transported downstream with channel flow. Sediment transport is simulated, using modified Bagnold's equation, as a function of peak channel velocity. Sediment is either deposited or re-entrained through channel erosion depending on the sediment load entering the channel. The QUAL2E model has been incorporated into SWAT to process in-stream nutrient dynamics. The detailed input information used in this study is shown in Table 1.

Table 1 The data sources for the SWAT model.

Data type	Scale	Sources
DEM map	1：50000	National Aeronautics and Space Administration (NASA)
Soil type map	1：1000000	Chinese Academy of Sciences
Land use map	1：100000	Remote sensing image interpretation

Meteorological	National Meteorological Center
Hydrological water	Baixi Reservoir Administration Bureau
Crop management practices	Field research
Socio-economic data	Yearbook of the regions

2.3 The sampling method

In this study, model prediction was used to provide the spatial distribution of NPS-N, while storm sampling offered an inventory method to determine the temporal trends during storm periods. In this study, storm and stream sampling was divided into two parts: 1) historical data was obtained from local government sources and analyzed to get the changes that have occurred from past activities and provide critical data for model validation; 2) storm water sampling provided glimpses into the detailed changes detected by a storm event. The historical trend was documented by analyzing the water quality report (from January 2005 to December 2008) provided by the local administration. The storm water samples were collected in April, 2010, after a major rainfall event in Baixi watershed. The sampling sites were set at Dasong River, Qingshui River, Hunshui River, as well as in the middle and in front of the reservoir. The runoff and TN was monitored both before and after the storm. Then water quality indexes were analyzed by state standard analyzing method: 1) pH: glass electrode method; 2) TN: alkaline potassium per sulfate oxidation-UV spectrophotometric method. The detailed sampling plan ss shown in Table 2.

Table 2. The sampling plan used in this study, including locations and methods of detection.

Time	Types	Location	Index	Method
April	Regular Sampling	Dasong River Qingshui River Hunshui River In the middle of the Reservoir In the front of the Reservoir	Runoff TN NH^{4+}	Runoff: Float Method; TN:alkaline potassium persulfate oxidation-UV spectrophotometric method; pH: glass electrode method
	Event rain Sampling	Dasong River Forest land In the front of the Reservoir	Runoff TN PH	

3. Results and discussion

3.1 The spatial distribution of TN

3.1.1 Calibration and validation

Many studies had shown that SWAT simulation in monthly steps provided generally better results than that in daily steps [41]. Thus in this work, stream flow was measured monthly, and TN was adopted for calibration and validation. Calibration of stream flow was performed from January 2005 to December

2006, and the period January 2007 to December 2008 was used for validation. Nash-Sutcliffe efficiency coefficient E_{NS} was set to assess the degree of fit between the observed data and SWAT results.

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{sim,i} - Q_{mea,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{mea,i} - \overline{Q}_{mea}\right)^2} \tag{4}$$

Where, $Q_{mea,i}$ is the observed data, $Q_{sim,i}$ is the simulated data, $\overline{Q}_{mea}$ is the mean value of the observed data, and n is the simulation time.

As shown in Fig. 3, for the runoff, the E_{NS} during calibration period and validation period was 0.79 and 0.84, respectively. The E_{NS} of ammonia was 0.66. Compared to other SWAT applications [42], the value of E_{NS} was judged to be quite acceptable. Thus, it could be concluded that the SWAT model was capable of modeling NPS-N in the Baixi Watershed.

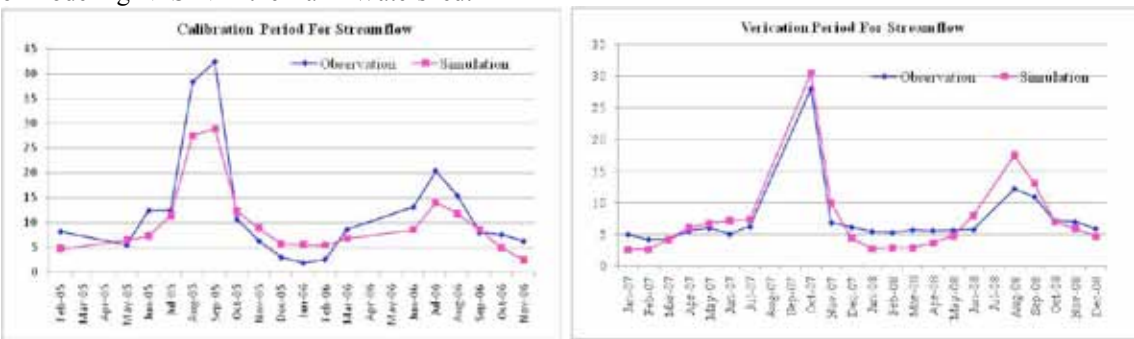

Fig. 4 Calibration and Validation results for stream flow.

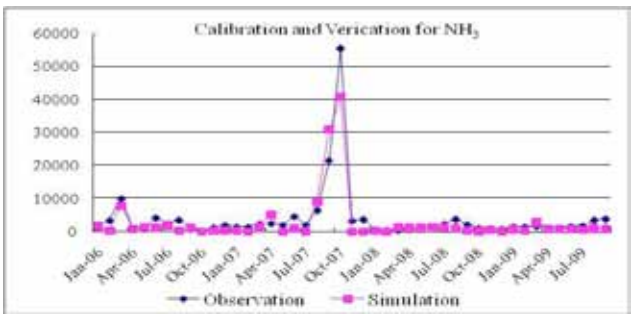

Fig. 5 Calibration and Validation results for TN.

3.1.2 Spatial distribution

As shown in Fig. 5, the sediment was not uniformly distributed through the Baixi watershed, while the largest amount of TN was concentrated in upstream of Dasong River and the downstream of Hunshui and Qingshui River, the least amount of TN was in the upstream of Qingshui River. However, the TN showed a different distribution from the sediment because the TN existed in the form of a solute, which was not attached to sediment [43, 44], showing a negative relationship with soil erosion.

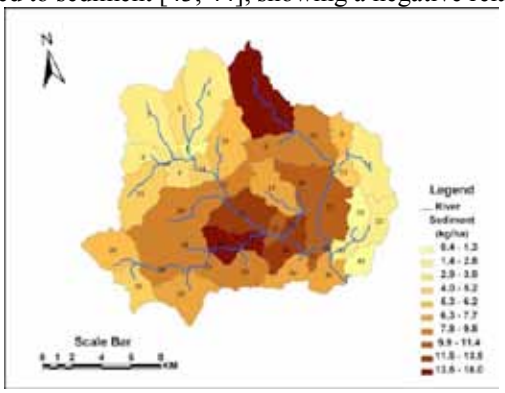

Fig. 6 The spatial distribution of Sediment.

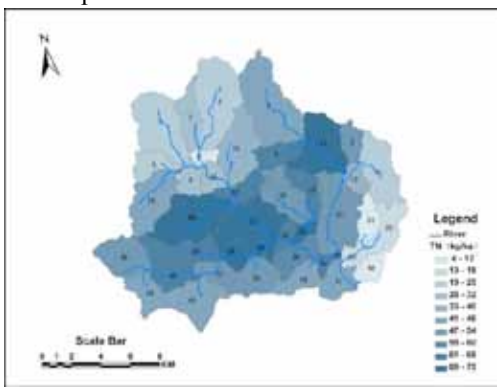

Fig. 7 The spatial distribution of TN.

Further studies were conducted by defining and adding TN from different land uses as well as soil types. As shown in Table 3, forest land contributed 91.41% of organic N and 88.80% of nitrate N; while cropland made up 6.67% of organic N and 9.94% of nitrate N; and bare land exported 1.92% of organic N and 1.26% of nitrate N. It could be inferred that the major NPS-N was from forest areas. This could be explained by the fact that the NPS from the forest were the decomposed products of decayed biomass and more importantly the solids from soil erosion and to some extent, atmosphericly dry/wet deposits [45].When storms happened in this area, the rapid runoff carried the NPS-N to the nearby receiving water bodies. In the Baixi watershed, the forest consisted of secondary forest and product forest, which would result in the lack of representation in plant residue [40]. Hence, the poor capacity of forest for water conservation in this area might be attributed to soil compaction and poor ground coverage under the trees.

As shown in Table 4, the skeleton soil and yellow soil accounted for 68.41% of the total basin, and the percentage of total pollution load originated was 70.13% of organic N, 31.52% of nitrate N, and 31.39% of organic P. The sequence of organic N per area ranked from high to low was: skeleton soil> yellow soil> red-yellow soil> red soil> paddy soil, compare to yellow soil > skeleton soil> red-yellow soil> red soil> paddy soil for nitrate N and organic P. The sequence of organic nitrogen per area ranked from high to low was: skeleton soil> yellow soil> red-yellow soil> red soil> paddy soil. This might be due to the application of N and P for planting crops, mainly in the upper 10 cm of soil, either remaining in soils or being exported to surface waters by erosion or leaching [7].

Table 3 The N and P production in different land use.

Land use	area（km^2）	Organic N（t）	Nitrate（t）	Organic P（t）
Forest	229.81	494.77	4.15	21.48
Paddy	16.76	55.38	0.37	2.76
Bare land	4.84	7.02	0.05	0.01
Total	251.40	557.17	4.57	24.25

Table 4 The N and P production in different soil types.

Soil type	area（km2）	Organic N（t）	Nitrate（t）	Organic P（t）
skeleton soil	87.768	36.881	0.278	1.625
red soil	30.694	2.753	0.016	0.077
red-yellow soil	48.797	5.891	0.036	0.150
yellow soil	83.608	39.746	0.547	2.291
Paddy soil	0.626	0.015	0.001	0.006
total	251.494	284.065	2.617	12.479

Table 5 gives a specific description of the NPS-N distribution in each sub-basin and tributaries. It was clear that the Sub-basin 21 produced highest load per area (7.498 kg/ha), followed by Sub-basin 20 (6.984 kg/ha) and Sub-basin 26 (7.42 kg/ha), while Sub-basin 6 contributed the least load (0.4334 kg/ha). However, the total load of Sub-basin 1 (7.65 t), Sub-basin 12 (7.87 t), Sub-basin 27 (7.26 t) were higher than other sub-basins due to larger areas. Table 5 also illustrated the total load from different tributary rivers. It is obvious that the Qingshui River contributed more NPS load than the other two tributary rivers. This might be due to the higher flow amount in the Qingshui River (stream flow from high to low was as follows: Qingshui River > Dasong River > Hunshui River). In addition, though the average TN load per area of Qingshui River was smaller than the other two rivers, there were more sub-basins along the

Qingshui River, resulting in a higher load from the entire Qingshui watershed. In sum, the model predictions provided potential risks of NPS occurrence and developed appropriate management measures under the spatial distribution of NPS pollution and foretell the effect of measures under different detrimental conditions.

Table 5 TN load from the Sub-basin and tributaries

River	Sub-basin	Area (km^2)	TN（kg/ha）	TN (t)
Dasong river	1	16.7	4.578	7.65
	4	4.45	6.233	2.77
	5	3.33	4.733	1.58
	11	9.55	2.124	2.03
	12	11.51	6.834	7.87
	13	2.69	3.591	0.97
	27	13.55	5.355	7.26
Qingshui river	2	5.42	2.7	1.46
	3	14.75	2.432	3.59
	6	1.56	0.433	0.07
	7	12.59	1.93	2.43
	8	3.03	2.813	0.85
	9	3.91	2.228	0.87
	10	1.02	1.87	0.19
	14	3	3.137	0.94
	15	10.23	3.959	4.05
	16	9.61	4.259	4.09
	17	4.13	6.44	2.66
	20	13.91	6.984	9.71
	21	9.55	7.498	7.16
Hunshui river	26	2.65	7.42	1.97
	28	4.27	7.293	3.11
	29	5.1	6.348	3.24
	30	5.03	5.926	2.98
	35	6.31	5.312	3.35
	36	7.78	4.969	3.87
	37	3.75	5.256	1.97
	38	7.06	6.041	4.26
	39	4.99	4.054	2.02
	42	8.56	4.473	3.83

3.2 Sampling results

Fig. 8 illustrates the long trend (from 2005 to 2008) of the water quality. It was clear that N stayed stable in the recent years. However, there has been further development of local forest planting in the Baixi watershed and more strict rural management since 2006. Thus, it could be inferred that the upper stream watershed management showed little effect on TN. In addition, it could be observed that the N concentration increased significantly in the rainy season, indicating that heavy storms might be a major source of NPS-N into the drinking water reservoir. The N exceeded the permitted environment standard at times of stormy weather, which might be due to both atmospheric deposition and storm runoff.

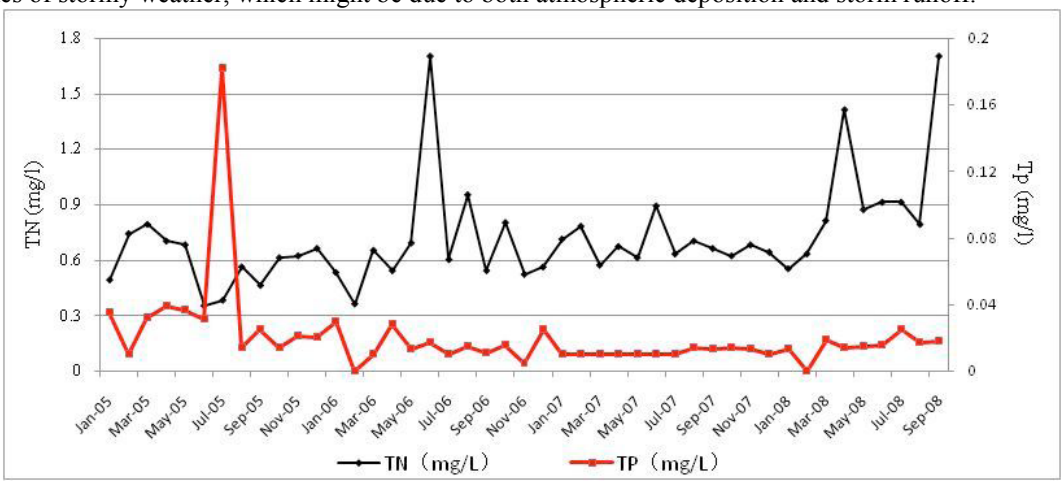

Fig. 8 The monthly nitrogen and phosphorus (2005.1- 2008.12).

To further illustrate the trend in storm events, the runoff and rain samples of a major storm (April 10th, 2010) was collected and analyzed. In this study, the sampling sites were set at the inlet of tributaries, such as Dasong River, Qingshui River, and Hunshui River, as well as in front and in the middle of the reservoir. In addition, the runoff and rain samples were collected from the corresponding hilly forest land, which were selected by orienting to the critical areas identified by the SWAT model.

As seen in Fig. 9, the blue line demonstrated the N concentration sampled before the storm. The diverse trend was illustrated between the storm event sampling and the SWAT simulation. It was clear that although the upper stream watershed of Dasong and Hunshui River produced more TN per area, there was no big difference between the various tributaries. This might be due to the dilution and degradation in the process of river transferring. However, the N concentration was slightly higher in the front of the dam, mainly due to more soil erosion and TN directly leaching from the nearby sub-basin, which agreed well with the SWAT output (Fig. 6 and Fig. 7). In addition, the TN in the middle of the reservoir was lower than that in front of the dam. This could be explained by that Baixi reservoir was a typical kind of river-type reservoir, therefore, the N showed a degree of degradation over the process of migration.

Samples from storm events were described by the black line in Fig. 9. It could be observed that water quality deteriorated immediately during the storm. These could be explained by storm transporting more N via the catchment, such as the forest land, leading to the eventual entry of N into stream channels. By compareing the blue line and red line, it was obvious that the enhanced N from forest land was carried and flushed by storm runoff into the tributaries. This might be due to the fact that forest produced more decomposed products of decay biomass and the solids from soil erosion and to some extent, atmospheric dry/wet deposit [46-48]. Thus, forest land might be a critical source of NPS-N in the Baixi watershed.

The biggest change of N concentration happened in Hunshui River, which could be explained by Table 5 that Hunshui watershed contributed the most amount of N per area. Conversely, the N concentration was much higher there than in front of the dam, indicating the atmospheric N deposition direct into the surface of the Baixi reservoir might be an important cause of the drinking water deterioration. It could be further interpreted by analyzing the value of pH and N concentration of the rain sample. Based on the rain sample in April 10th, the pH value was 5.43, showing the obvious characteristic of acid-rain (acid rain was defined as precipitation which has a pH was less than 5.6). Furthermore, the background concentration of TN in the rain sample was as high as 1.10 mg/L, indicating that acidic N deposition should be considered as a major N input in the Baixi watershed. According to studies by Chen [38], this watershed is in the major region for acid rain deposition in China. Thus, it was clear that the NPS-N load into the drinking water reservoir, especially in the acid rain control region, results from a combination of land-use, agricultural activities, as well as atmospheric deposition.

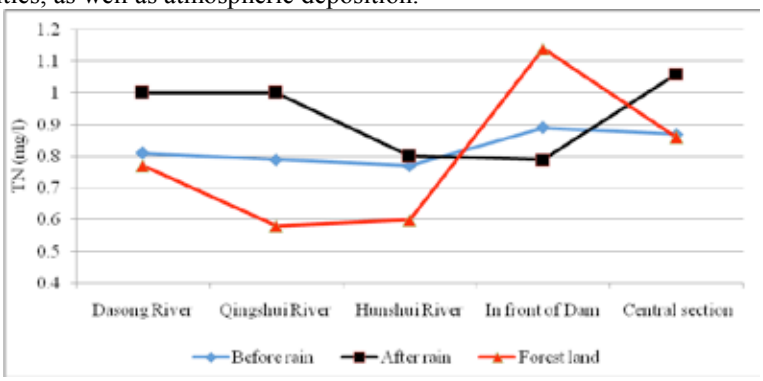

Fig. 9 The TN determined from storm sampling at indicated locations during 2010.

Based on this study, the modeling and monitoring method could serve as a framework to predict the TN load and protect the source of drinking water by providing information to assess the trends and event status. As the key processes, SWAT model prediction provides glimpses into the spatial distribution of NPS, providing insight into the causes of NPS pollution and the long-term trend. The model output could also provide a reference for the selection of monitoring sites. Conversely, historical monitoring data documented the change that had occurred from past activities and provided critical data for model validation, while storm monitoring offered the inventory temporal trend during storm rains. By storm sampling, a more precise description of NPS-N sources could be obtained. Thus, both the monitoring and modeling methods proved to be valuable and when carefully coordinated could enhance and supplement one another. It could be inferred that the SWAT model could be used as an effective tool to foretell the potential risk of detrimental NPS conditions as well as determining spatial and temporal distribution of NPS pollution. While monitoring could provide an inventory and detailed mean to further study short-term and critical-site trend.

3. Conclusion

In this study, an integrated simulation-monitoring framework was advanced to identify the spatial and temporal distribution of NPS-N in the upstream watershed of a typical drinking water reservoir, in the city of Ningbo, Zhejiang Province, China. Based on the model simulation, the major TN distribution was identified as the forest and Sub-basin 21, Sub-basin 20 and Sub-basin 26 were implicated as the critical risk areas. In addition, the SWAT simulation proved that Qingshui River contributed more TN load than

the other two tributaries. Conversely, a more detailed trend was obtained by storm sampling. By analyzing the storm samples, it was clear that the NPS-N load into the drinking water reservoir, especially in the acid rain control region, results from a combination of land-use, agricultural activities, as well as atmospheric deposition. It could be further inferred that modeling and monitoring NPS at multiple temporal scales served as a tool to protect soil and water resources by providing information to assess trends and the status of NPS both long-term and short-term trends. This framework would be helpful to take sound actions for water quality management in such regions.

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