RESEARCH ARTICLE

# Simulation of runoff and nutrient export from a typical small watershed in China using the Hydrological Simulation Program–Fortran

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**Abstract** The Hydrological Simulation Program-Fortran (HSPF), which is a hydrological and water-quality computer model that was developed by the United States Environmental Protection Agency, was employed to simulate runoff and nutrient export from a typical small watershed in a hilly eastern monsoon region of China. First, a parameter sensitivity analysis was performed to assess how changes in the model parameters affect runoff and nutrient export. Next, the model was calibrated and validated using measured runoff and nutrient concentration data. The Nash–Sutcliffe efficiency ($E_{NS}$) values of the yearly runoff were 0.87 and 0.69 for the calibration and validation periods, respectively. For storms runoff events, the $E_{NS}$ values were 0.93 for the calibration period and 0.47 for the validation period. Antecedent precipitation and soil moisture conditions can affect the simulation accuracy of storm event flow. The $E_{NS}$ values for the total nitrogen (TN) export were 0.58 for the calibration period and 0.51 for the validation period. In addition, the correlation coefficients between the observed and simulated TN concentrations were 0.84 for the calibration period and 0.74 for the validation period. For phosphorus export, the $E_{NS}$ values were 0.89 for the calibration period and 0.88 for the validation period. In addition, the correlation coefficients between the observed and simulated orthophosphate concentrations were 0.96 and 0.94 for the calibration and validation periods, respectively. The nutrient simulation results are generally satisfactory even though the parameter-lumped HSPF model cannot represent the effects of the spatial pattern of land cover on nutrient export. The model parameters obtained in this study could serve as reference values for applying the model to similar regions. In addition, HSPF can properly describe the characteristics of water quantity and quality processes in this area. After adjustment, calibration, and validation of the parameters, the HSPF model is suitable for hydrological and water-quality simulations in watershed planning and management and for designing best management practices.

**Keywords** HSPF · Watershed · Runoff · Nutrient · Parameter sensitivity analysis · Drinking water source · China

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## Introduction

Excessive nutrient loading is a major threat to aquatic ecosystems around the world and leads to profound changes in aquatic biodiversity and biogeochemical processes (Woodward et al. 2012). Most streams and lakes in the USA are affected by nonpoint source (NPS) pollution, such as nutrients, pesticides, and sediments from farms and urban areas (Mitsch et al. 2001). NPS pollution is recognized as a major threat to water quality and is the most important water pollution problem in many countries (Yang and Wang 2010). Intensive agriculture practices increase soil erosion and sediment load and result in the leaching of nutrients and agricultural chemicals into the groundwater, streams, and rivers (Foley et al. 2005). Agriculture has become the largest source of excess nitrogen and phosphorus in waterways (Bennett

et al. 2001). The need to reduce anthropogenic nutrient inputs to aquatic ecosystems to protect drinking water supplies and to reduce eutrophication has been widely recognized (Conley et al. 2009). Information regarding the distribution of nutrient outputs across a watershed is critical to the design of regional development policies because NPS pollution has become a serious environmental concern in watershed management (Zhang 2010).

Advances in understanding the hydrological and water-quality processes in watersheds, the accumulation of information from observations and measurements, the increased ability to express physical processes by mathematical formulae, and developments in computer and software technology have resulted in the widespread use of comprehensive and complex watershed models (Albek et al. 2004). A distributed-parameter continuous-time model that is supported by remote sensing (RS) and geographical information system (GIS) databases can assist management agencies in identifying the most critical erosion-prone areas and in selecting appropriate management practices. The Hydrologic Simulation Program-Fortran (HSPF) is one such model. HSPF is a comprehensive model that was developed by the United States Environmental Protection Agency (USEPA) to simulate many processes related to water quantity and quality in watersheds of almost any size and complexity (Albek et al. 2004). HSPF has the ability to simulate watershed hydrology under various land use and climatic conditions and to simulate the hydraulics of dams and reservoirs (Mishra et al. 2007). In addition, HSPF has been widely used in the USA (Praskievicz and Chang 2011; Tong et al. 2012), Europe (Yang and Wang 2010), and other countries (Akter and Babel 2012, Goncu and Albek 2010; Lee et al. 2010) and has experienced limited use in China (Li et al. 2012).

Water problems are particularly challenging in China, and water crises have prompted the Chinese government to develop an ambitious water conservation plan (Liu and Yang 2012). Two thirds of China's 669 cities have experienced water shortages, more than 40 % of China's rivers are severely polluted, and 80 % of China's lakes suffer from eutrophication (Chinese Academy of Sciences Sustainable Development Strategy Study Group 2007). Located in the Yangtze River delta in eastern China, the Taihu Lake is the third largest freshwater lake in China. Its area is also one of the most highly developed economic zones in China. Water-quality deterioration of the lake has been a national concern since the early 1980s because the lake has become increasingly eutrophic. Drinking water is scarce due to pollution in the Taihu Lake basin, which has reached 2–3.5 billion m$^3$ annually and has become the main limiting factor that impacts regional socio-economic development and people's lives (Yang et al. 2004). Water pollution will become a greater problem in the next few decades and may affect drinking water quality and sustainable socioeconomic development. To solve this problem and supply sufficient amounts of high-quality water, reservoirs in the upper reaches of the mountainous areas have been chosen as drinking water sources (Zhu 2003). Lakes and reservoirs are major drinking water sources in many regions of China (Jin 2001), and many lakes and reservoirs that were originally used for flood prevention, agricultural irrigation, and aquaculture have become regional drinking water sources. Thus, it is important to protect water quality in lakes and reservoirs and watersheds because this quality will directly affect the regional security of the water supply. It is important to understand the dynamics of watershed nutrient export to formulate measures that minimize adverse effects in downstream environments.

In this study, a typical small watershed in the Taihu Basin was studied and modeled using HSPF. This study is the first to apply the HSPF model to a drinking water source watershed in China to understand the hydrological and nutrient export processes that occur in the watershed and to observe the adaptability of the HSPF model for this type of watershed. The results of this study have implications for watershed management by decision makers and in the design of best management practices.

## Data and methods

### Study area

The Tianmu Lake (119°24 4 E, 31°15 26 N) is located at the intersection of Jiangsu, Anhui and Zhejiang Provinces and is a typical national level reservoir (also called the Shahe Reservoir) in the Taihu Lake basin. It is a drinking water source for Liyang City, which has a population of 0.6 million. Several studies have shown that the water quality in Tianmu Lake has decreased in recent years due to intensive agricultural activities. The lake has experienced meso-eutrophication, and the conditions of lake may become worse in the future without the implementation of effective protection measures (Gao et al. 2009). Surface runoff is the main source of nutrient input into the reservoir.

Located in the southern part of the Tianmu Lake watershed, the Zhongtianhe River is the largest tributary of Tianmu Lake and drains a watershed area of 45.8 km$^2$, which accounts for one third of the watershed (Fig. 1). This region has a subtropical monsoon climate and an average annual precipitation of approximately 1,170 mm according to daily rainfall data from Liyang's national meteorological station for the period of 1971 to 2010. The soils in the watershed are predominantly classified as yellow soils. The local economy is mainly based on agriculture, and the principal crops are rice, wheat, and rapeseed. The land use and land cover of the Zhongtianhe watershed are relatively simple. Forests and grasslands, cultivated and garden lands, residential areas, and other types of land make up 66.8, 24.0, 3.5, and 5.7 % of the watershed,

**Fig. 1** Location map of the Zhongtianhe watershed showing sampling points, digitized stream and sub-watershed boundaries, and land cover data
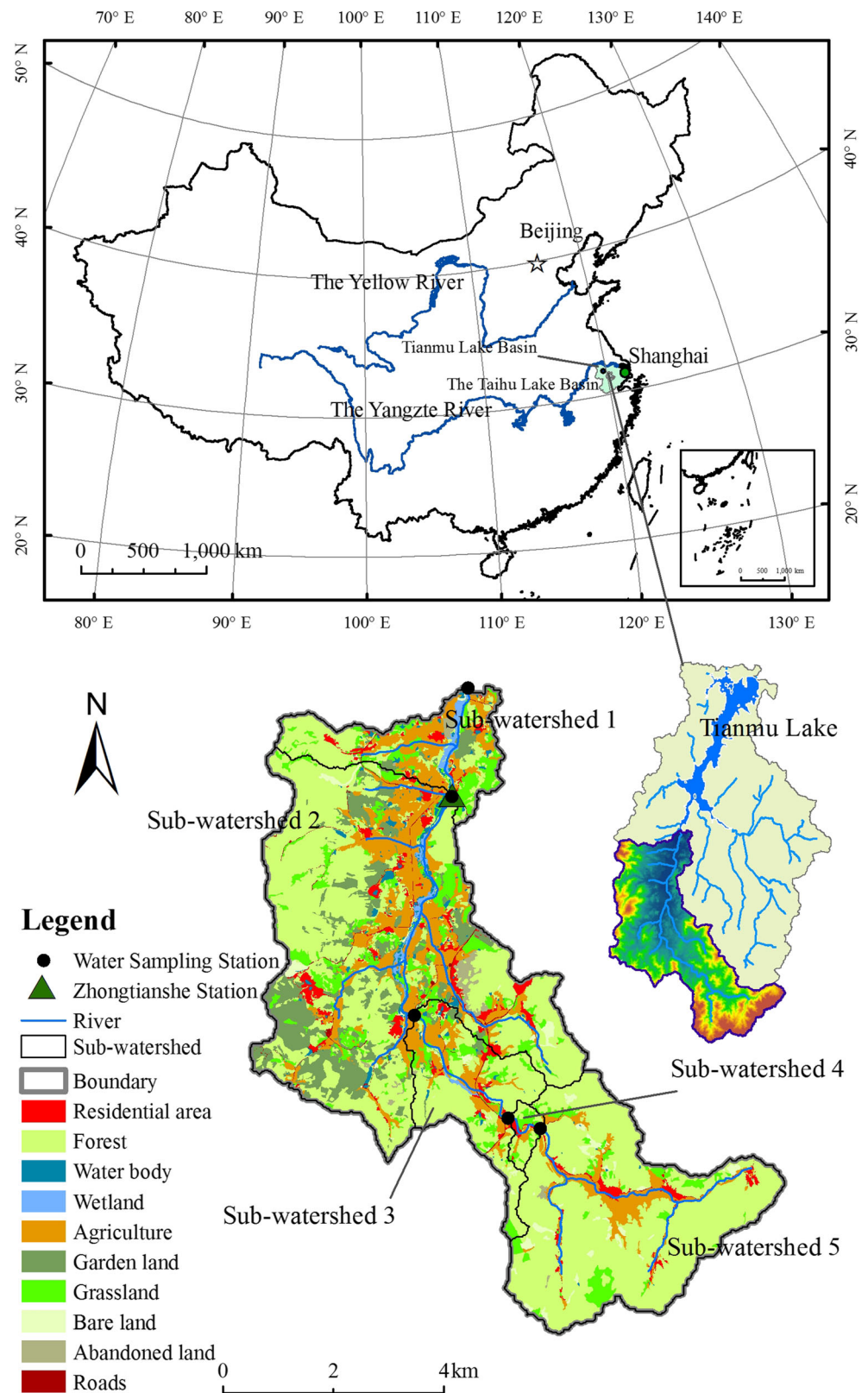


respectively (Fig. 1). The watershed has hilly relief, the elevation decreases from south to north, and the elevation ranges from 516.1 to 17.8 m. The flow of the Zhongtianhe River is

monitored at the Zhongtianshe Station, which is located along the lower Zhongtianhe River and is shown by the green triangle in Fig. 1. Runoff was monitored daily from January

to December in 2010. Five sampling points, which are shown as black circles in Fig. 1, were used to monitor the monthly water quality from June 2008 to September 2009.

### Application of the HSPF model to the Zhongtianhe river watershed

The HSPF model was developed by the USEPA to continuously simulate water quantity and quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments (Bicknell et al. 2005). The WinHSPF model was designed as an interactive Windows interface to improve the efficiency of using HSPF. In addition, the WinHSPF model has been fully integrated into a multipurpose environmental analysis system, the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) system, which was developed by the USEPA based on a Geographic Information System (GIS) foundation to perform watershed and water-quality-based studies (Battin et al. 1998).

The HSPF modeling process consists of building a BASINS project, delineating the watershed, setting up a WinHSPF environment, preparing the time series data, and simulating, calibrating, and validating the surface water quantity and quality. As shown in Fig. 2, the spatial and attribute databases were constructed in the HSPF model preparation phase using the MapWindows GIS and Watershed Data Management Utility (WDMUtil) tools in BASINS. A digital elevation model (1:50,000), the land use/land cover data, soil

maps, drainage maps, meteorological data, flow data, and other relevant data of the Zhongtianhe River watershed were collected. Watershed delineation was performed using the GIS extensions provided by BASINS to automatically divide the study area into hydrologically connected segments or sub-watersheds for detailed watershed characterization and modeling. The watershed outlets were selected based on the locations of the water gauge stations and river quality monitoring stations. Based on the topographical characteristics and the digital elevation model, the watershed can be divided into five sub-watersheds. These five approximately homogenous segments in the study area were defined so that lumped parameters could be assigned to each segment to represent its characteristics.

The meteorological and flow time series data were managed using the WDMUtil tools of BASINS. HSPF requires eight meteorological time series to simulate the hydrological cycle in a watershed, the air temperature, dew-point temperature, cloudiness, wind velocity, atmospheric pressure, solar radiation, potential evapotranspiration, and precipitation. The meteorological data were obtained from the Liyang national meteorological station (no. 58345, 31°26′ N, 119°29′ E), which is located in the nearby city of Liyang. This station is the closest station to the watershed and is located approximately 7 km from the center of the watershed.

In addition to the meteorological time series, HSPF also requires hydrological and water-quality time series data. Daily runoff data were collected from the Zhongtianshe Station,

**Fig. 2** HSPF model application framework
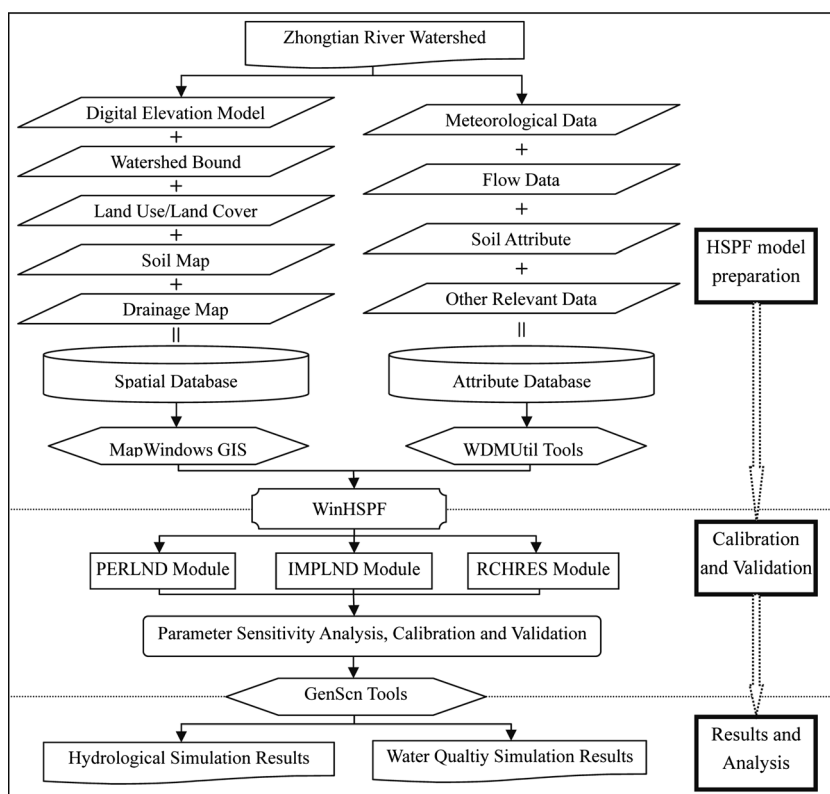
which is located at the outlet of sub-watershed 2. Monthly water-quality data were collected at the outlets of the five sub-watersheds. All of these time series data were integrated in WDM files using WDMUtil.

When the HSPF project was created from BASINS, a UCI file is created to hold and supply the parameters to WinHSPF. Three basic application modules comprise WinHSPF, PERLND (Pervious Land Segment), IMPLND (Impervious Land Segment), and RCHRES (free-flowing reach or mixed reservoirs). A water balance for selected points can be calculated based on precipitation inputs with hydrological parameters for different land cover classes. The parameter sensitivity analysis began by performing a baseline model run. Sensitivity analysis can test the overall responsiveness of the model to changes in certain input parameters and identify critical parameters that need to be carefully calibrated. The HSPF calibration is an iterative process that is used to establish the most suitable values for process-related parameters. The important parameters for the hydrological and water-quality simulations were calibrated and validated using the observed data. After calibration and validation, the GenScn tool was used to present and analyze the hydrological and water-quality results.

Parameter estimation and sensitivity analysis

Parameter sensitivity analysis is necessary to make the calibration and validation more efficient and can be used to test the overall responsiveness of the model to changes in certain input parameters (Oyarzun et al. 2007) and to identify critical parameters that need to be carefully investigated by gathering data and conducting field studies to obtain reliable model outputs. Additionally, sensitivity analysis during the calibration phase can be used to understand the general behavior of a model and to evaluate its accuracy and interpret the results (Kleijnen 2005).

In general, the parameters in HSPF fall into two categories, fixed parameters and process-related parameters (Al-Abed and Whiteley 2002). The fixed parameter values remain constant throughout the simulation period. In this study, the fixed parameter values (including the soil type, model manipulation switches, and the hydraulic characteristics of the drainage network) were mainly established from field measurements. These parameters did not require a sensitivity analysis and were not involved in the calibration process. For example, the geometrical properties of the river, such as the depth, width, and fluvial cross section at the sampling sites, were measured in the field and subsequently used to establish the hydraulic behavior in the HSPF model. Except for the initial conditions at the beginning of the simulation, such as the temperature and soil moisture determined from observation data, numerous other process-related parameters could be adjusted.

In this study, the perturbation analysis method was used to calculate the sensitivity of the parameters. The following equation was used to calculate the sensitivity:

$$S = \frac{\sum_{i=1}^{n-1} \dfrac{(Q_{i+1} - Q_i)\big/ Q_b}{(P_{i+1} - P_i)\big/ 100}}{n-1} \tag{1}$$

where $S$ represents the relative sensitivity, $P_i$ and $P_{i+1}$ are the adjusted percentages at times $i$ and $i+1$, respectively, $Q_b$ is the output result after validation, $Q_i$ and $Q_{i+1}$ are the output results of the modeling at times $i$ and $i+1$, respectively, and $n$ is the modeling time. Based on the range of $S$ values, the sensitivities are classified into 4 categories: I, $0 \leq |S| < 0.05$, insensitive; II: $0.05 \leq |S| < 0.2$, ordinary sensitivity; III: $0.2 \leq |S| < 1.0$, more sensitive; and IV: $|S| \geq 1.0$, extremely sensitive.

The sensitivity analysis highlighted the 21 most important parameters in the hydrological and nutrient simulations. Detailed explanations, the sensitivity values, and the levels of these parameters are shown in Table 1. The subsequent calibration and validation of this study was performed based on these parameters.

Parameter calibration and validation

*Calibration and validation of hydrological parameters*

Calibration of the HSPF model is an iterative process that is used to establish the most suitable values for process-related parameters. As shown in Table 1, AGWRC, UZSN, INFILT, DEEPFR, and LZSN are sensitive parameters of hydrological processes. These important water flow parameters were calibrated and validated using the monitored flow data at the Zhongtianshe Station, which is at the outlet of sub-watershed 2. Of the runoff simulation parameters, INTFW, IRC, and LZETP had clear effects on the simulated flow of the storm events even though they were not sensitive to the annual flow. Here, INTFW is the interflow inflow parameter; IRC is the interflow recession parameter (for zero inflow, the IRC value is the ratio of a day's interflow outflow rate to the previous day's rate); and LZETP is the lower zone evapotranspiration parameter, which is an index of the density of deep-rooted vegetation (Bicknell et al. 2005). The calibrated results of these parameters for rainstorm events are shown in Table 1.

Meteorological data from January 1, 2005, to December 31, 2010, were used for the river flow and water-quality simulations. Three hydrological years (October 1, 2005, to September 30, 2008) were used for the calibration period for the annual flow. The other two hydrological years (October 1, 2008, to September 30, 2010) were used as the validation period. The daily observed river flow data from January 1,

**Table 1** Important hydrology and water quality parameters in the Zhongtianhe Watershed

| Category | Parameter | Explanation | Unit | Sensitivity(S) | S level | Calibrated value |
|---|---|---|---|---|---|---|
| Hydrological parameters | LZSN | Lower zone nominal soil moisture storage | in. | −0.07 | II | 12–15 |
| | INFILT | Index to infiltration capacity | in.h$^{-1}$ | 0.23 | III | 0.09–0.14 |
| | AGWRC | Base groundwater recession | day$^{-1}$ | 0.69 | III | 0.35–0.88 |
| | DEEPFR | Fraction of GW inflow to deep recharge | – | −0.1 | II | 0.09–0.11 |
| | UZSN | Upper zone nominal soil moisture sotrage | in. | −0.54 | III | 0.96–2.1 |
| | LZETP | Lower zone ET parameter | – | 0 | I | 0.4–0.7 |
| | INTFW | Interflow inflow parameter | – | 0.003 | I | 3–7.5 |
| | IRC | Interflow recession parameter | day$^{-1}$ | 0 | I | 0.60 |
| Nitrogen parameters | WSQOP | Rate of surface runoff that results in 90 percent washoff in one hour | in./h | 1.52 | IV | 0.2–0.7 |
| | SQOLIM | Asymptotic limit for SQO as time approaches infinity | qty/ac | 1.34 | IV | 0 |
| | MON-IFLW-CONC | Monthly concentration of QUAL in interflow | qty/ft$^3$ | 0.22 | III | 0.03–0.2 |
| | MON-GRND-CONC | Monthly concentration of QUAL in active groundwater | qty/ft$^3$ | 4.9 | IV | 0.025–0.15 |
| | KTAM20 | The unit oxidation rate of total ammonia at 20 C | 1/h | 0.3 | III | 0.15 |
| | TCNIT | The temperature correction coefficient for the nitrogen oxidation rates | – | 0.18 | II | 1.07 |
| | PHYSET | The rate of phytoplankton settling | ft/h | 0.06 | II | 0.02 |
| | MALGR | The maximum unit algal growth rate for phytoplankton | 1/h | 0.07 | II | 0.085 |
| Phosphorus parameters | MON-POTFW | Monthly washoff potency factor | lb/ton | 0.08 | II | 0 |
| | MON-IFLW-CONC | Monthly concentration of QUAL in interflow | qty/ft$^3$ | 0.11 | II | 0.009–0.1 |
| | MON-GRND-CONC | Monthly concentration of QUAL in active groundwater | qty/ft$^3$ | 0.51 | III | 0.005–0.05 |
| | MALGR | The maximum unit algal growth rate for phytoplankton | 1/h | 0.11 | II | 0.085 |
| | PHYSET | The rate of phytoplankton settling | ft/h | 0.15 | II | 0.02 |

2010, to December 31, 2010, were used to calibrate and validate the river storm event runoff processes.

During the calibration process, the HSPF parameters were adjusted by comparing the differences between the simulated and observed river flow data using the GenScn module in BASINS. To reduce the parameter uncertainty, only one parameter was adjusted at a time. More than 60 runs were carried out before achieving satisfactory simulation results. Table 1 shows the calibrated values with physical explanations of the important hydrological parameters in HSPF.

*Calibration and validation of the water-quality parameters*

After the hydrological processes were calibrated, the water-quality parameters were calibrated and validated using the limited water-quality data that were collected monthly from July 2008 to September 2009. The water-quality data from July 2008 to April 2009 were used for the model calibration, and the data from May to September 2009 were used for model validation. The most sensitive parameters of TN export were WSQOP, SQOLIM, MON-IFLW-CONC, MON-

GRND-CONC, KTAM20, TCNIT, PHYSET, and MALGR, and the most sensitive parameters for $PO_4^{3-}$–P were MON-POTFW, MON-IFLW-CONC, MON-GRND-CONC, MALGR, and PHYSET. The calibrated parameters included nitrogen and phosphorus, and the interpretations and calibrated values of these parameters are shown in Table 1.

## Results and discussion

Hydrological simulation results and analysis

*Annual river flow simulation*

Hydrological and water-quality simulation results were obtained by applying the HSPF model to the Zhongtianhe River watershed. The hydrological simulation includes both the calibration (October 1, 2005–September 30, 2008) and validation (October 1, 2005–September 30, 2008) periods. Figure 3 shows the total yearly flows at the Zhongtianshe
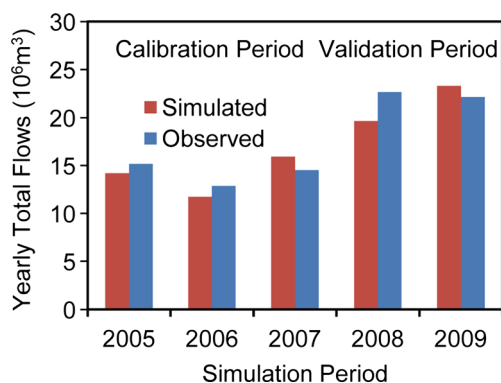
**Fig. 3** Comparison of the simulated and observed annual flows

Station based on the observations and simulations. A comparison of the simulated and observed annual flows indicated good agreement for the entire simulation period. The relative errors between the simulated and observed total yearly flows were −6.39, −8.7, 9.66, −13.31, and 5.22 % for the 2006 to 2010 hydrological years, respectively. The average simulated and observed annual flows were $13.95 \times 10^6$ and $14.18 \times 10^6$ m$^3$, respectively, for the calibration period and $21.46 \times 10^6$3 and $22.39 \times 10^6$ m$^3$, respectively, for the validation period. Thus, the relative errors between the simulated and observed average annual runoffs were 1.65 and 4.15 % for the calibration and validation periods, respectively. The relatively small errors showed that the model accurately represented the watershed hydrological processes. The Nash–Sutcliffe efficiencies ($E_{NS}$) were 0.87 for the annual flow calibration and 0.69 for the validation. These results indicated that the hydrologic model accurately simulated the annual flow, which was categorized as "very good" in terms of the HSPF model efficiency targets (Donigian 2000).

*Event-runoff simulation*

Figure 4 shows the daily precipitation and simulated daily runoff at the Zhongtianshe Station in 2010. Rainfall mainly occurred from February to July, with two heavy rainfall events between February and March and in July. Because we only had one year of daily runoff data for 2010, the first storm event of 2.24–3.15 was used as a calibration period for the event-based runoff simulation, and the second storm event of 7.3–
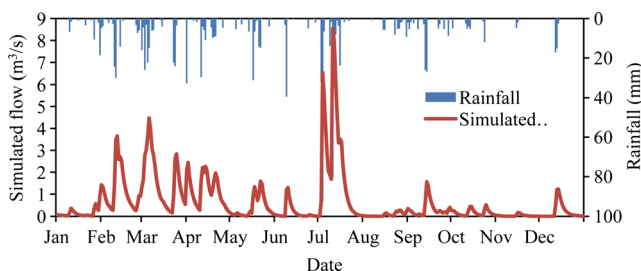


**Fig. 4** Daily precipitation and daily mean runoff at the Zhongtianshe Station in 2010

7.10 was regarded as the validation period. As shown in Fig. 4, the trends of the simulated runoff and precipitation are consistent. The runoff peak occurred in July when the most precipitation occurred, and the second runoff peak occurred in March, which corresponded to the rainy period. The amount of precipitation was lower in the autumn and winter, which corresponded to lower runoff.

Figures 5 and 6 show the calibration and validation results for the two rainstorm events. The results showed good agreement between the simulated and observed flows. The correlation coefficients were 0.965 for the calibration period and 0.848 for the validation period (Fig. 6). The values of $E_{NS}$ were 0.93 and 0.47 for the calibration and validation periods, respectively. Generally, these results indicated that the hydrologic model captured most of the peak river flows and that the simulation performance was good. The simulation accuracy was very high for the first storm event, but the model underestimated the second storm event in July. The main reason for this underestimate may be the difference in the antecedent precipitation and the soil moisture conditions between these two storm events. One small rainfall event occurred before the first storm in March, which replenished the soil moisture. In contrast, the 15 days before the second storm event in July were dry. The hydrologic module potentially overemphasized the effects of the antecedent soil moisture conditions on the runoff yield. Additional detailed research should be conducted to explore the effects of soil conditions and precipitation on the model equations.

*Assessment of the applicability of HSPF for hydrological simulations*

In this study, the most sensitive hydrological parameters for simulating the annual flows are LZSN, UZSN, INFILT, AGWRC, and DEEPFR. This result is similar to the results of previous studies in other regions (Chung et al. 2011; Kim et al. 2007). Using a sensitivity analysis, (Chung et al. 2011) identified six key parameters that affected runoff in the Anyangcheon watershed, including LZSN, UZSN, INFILT, INTFW, IRC, and AGWRC. Lee et al. (2010) used HSPF to simulate the Nogok stream watershed (51 km$^2$) in the Han River region of Korea and found that the simulation results were similar to the observed values, which indicated the suitability of the HSPF model in this area. In addition, this study showed satisfactory simulation results. HSPF can provide good accuracy for hydrological simulations after calibration and validation. For the annual flow simulation, the values of $E_{NS}$ were 0.87 for the calibration period and 0.69 for the validation period, and the relative errors were 1.63 % for the calibration period and 4.14 % for the validation period. The correlation coefficients between the simulated and observed data for the daily flow during storm events were 0.965 for the calibration period and 0.848 for the validation period, and the
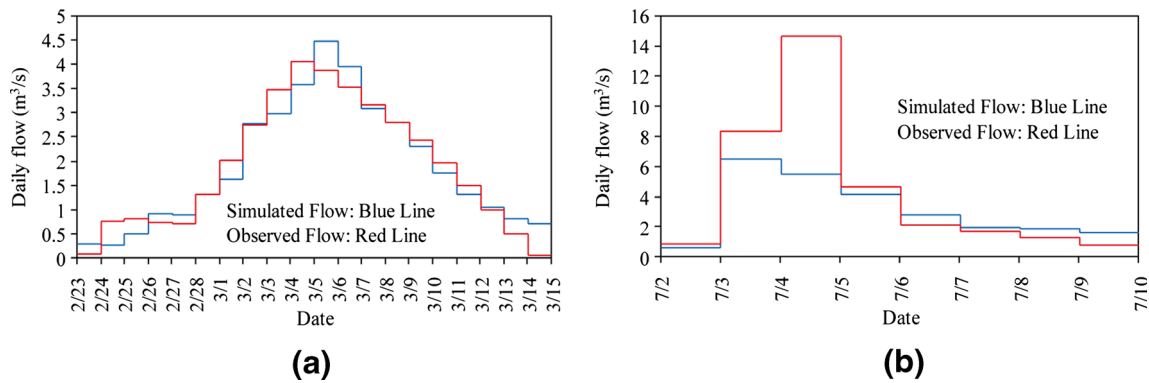
**Fig. 5** Comparisons between the observed and simulated daily flows for event-based rainfall processes: **a** calibration and **b** validation

values of $E_{NS}$ were 0.93 and 0.47 for the storm event simulations of the calibration and validation periods, respectively. These results indicate that the sensitive hydrological parameters observed for this area are similar to those observed in other areas and that the HSPF model can properly describe the characteristics of hydrological processes in this area when it is calibrated and validated using monitored flow data.

Nutrient export simulation results and analysis

*Total nitrogen simulation*

Figure 7 shows the results of the total nitrogen (TN) simulation for all five sub-watersheds. The simulated and observed TN concentrations exhibited similar trends during the entire monitoring period from July 2008 to September 2009. However, there were minor differences between the simulated results of the five sub-watersheds. The simulations generally underestimated the TN concentrations in the upper sub-watersheds (sub-watersheds 3, 4, and 5) and overestimated them in the downstream sub-watersheds (sub-watersheds 1 and 2). Human activities potentially caused these differences. Land use and land cover differences are major reasons for underestimations in the upstream sub-watersheds and overestimations in the downstream sub-watersheds. As shown in Fig. 1, residential areas are located near the river in the upstream sub-watersheds, which results in greater nutrient

concentrations. This is particularly true in sub-watershed 4, whose outlet is located at a village. The nutrient concentrations increase after the river passes through the village. In the downstream sub-watersheds, the residential areas are located far from the main river, the terrain slopes gently, and the wetlands and abandoned lands are distributed on both sides of the river. All of these factors will cause nutrient retention and decrease the nutrient concentrations. However, the HSPF model cannot accurately represent the effects of nutrient export that are caused by differences in the spatial patterns of land cover. Furthermore, domestic fowl, such as ducks and geese, were raised near the upstream part of the river during the period of water-quality monitoring. The TN concentrations in the river increased due to greater nitrogen inputs into the river by domestic waterfowl. The models cannot reproduce these conditions. In addition, the simulated TN concentrations in the downstream sub-watersheds were lower than the observed concentrations, especially during the wet season, because the runoff from storm events was underestimated (as described in Event-runoff simulation section). The lower simulated runoff resulted in less soil erosion and nitrogen export.

The simulation results provided satisfactory TN concentrations. A limited monitoring period from July 2008 to April 2009 was used as the calibration period for the nutrient simulations, and the period from May to September 2009 was used as the validation period. Figure 8 shows the correlation between the simulated and observed TN concentrations for the

**Fig. 6** Scatter plots and fitting curve of the observed and simulated daily streamflows: **a** calibration and **b** validation
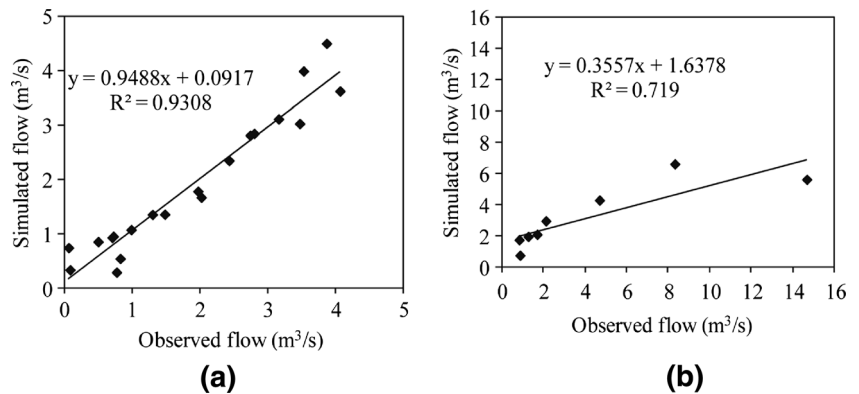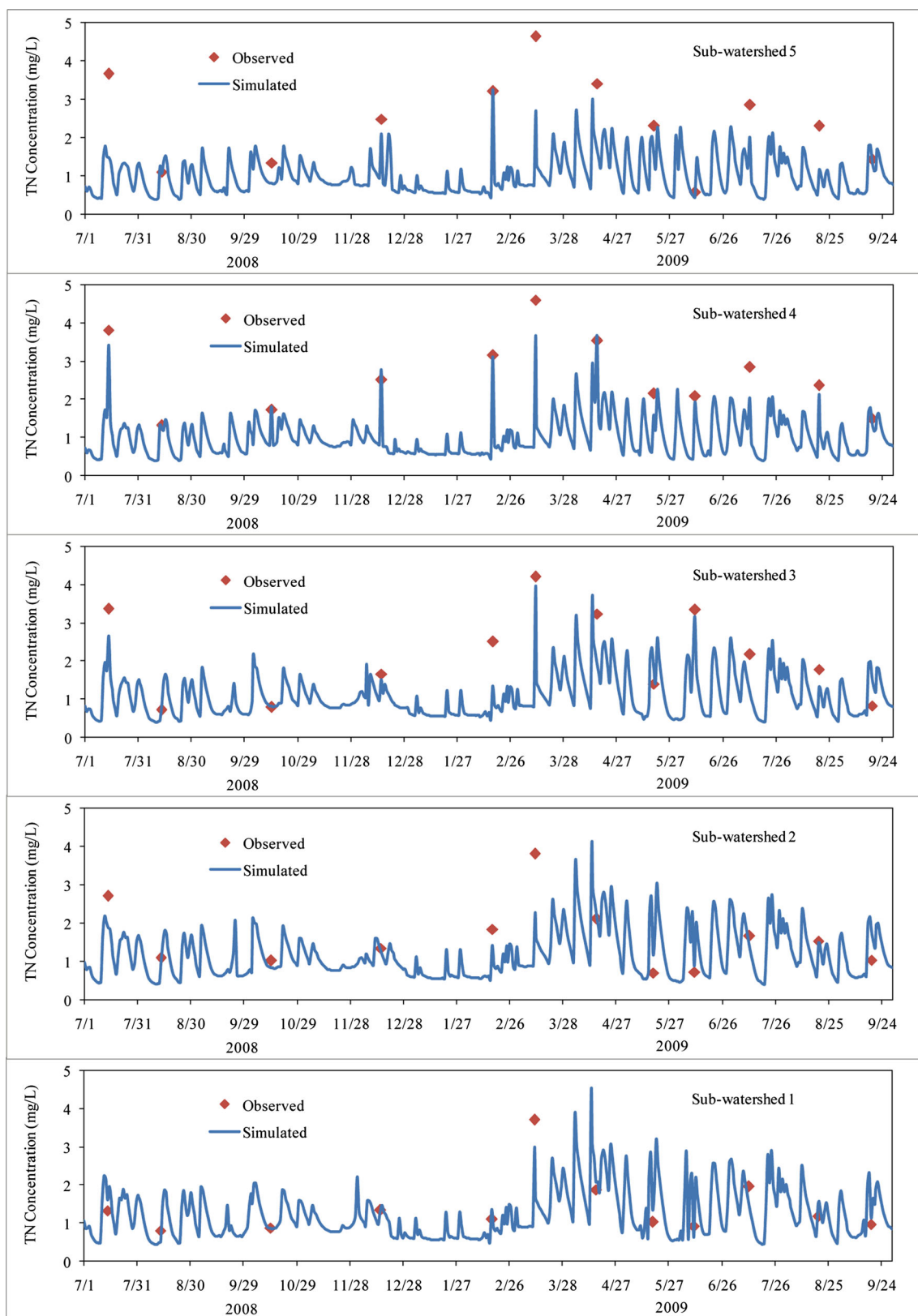
**Fig. 7** Comparison of the simulated and observed total nitrogen concentrations in the Zhongtianhe River

calibration and validation periods. The results show high correlation coefficients of 0.839 and 0.740 for the calibration and validation periods, respectively. The Nash–Sutcliffe efficiency was 0.58 for the TN calibration and 0.51 for the

**Fig. 8** Correlations between simulated and observed TN concentrations



**(a)** Calibration
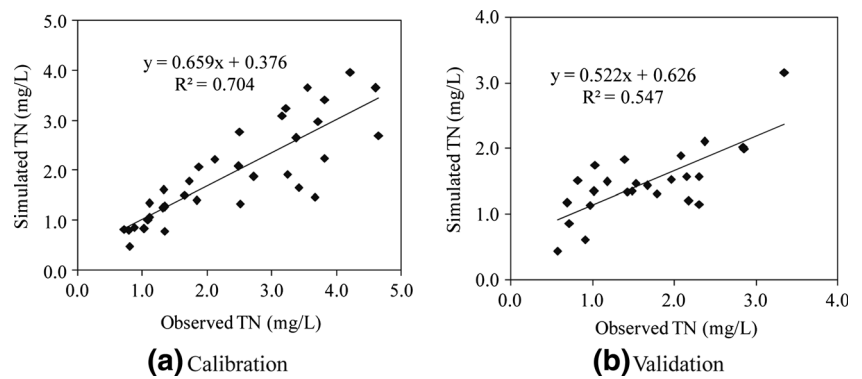
**(b)** Validation

validation, which are acceptable for nutrient simulations using HSPF.

### $PO_4^{3-}–P$ simulation results and analysis

Figure 9 shows the simulation results of the $PO_4^{3-}–P$ concentrations and the observed values at each sub-watershed outlet. The simulated and measured $PO_4^{3-}–P$ values agree well from July 2008 to September 2009. The observed $PO_4^{3-}–P$ concentrations ranged from 0.001 to 0.073 mg/L, and the simulated $PO_4^{3-}–P$ concentrations ranged from 0.001 to 0.067 mg/L. Furthermore, the $PO_4^{3-}–P$ concentrations are lower than in other areas, primarily because of the small amount of agricultural and residential land in the region and because laundry detergent that contains phosphorus is prohibited by the local government in the Taihu Lake watershed.

As in the TN simulation, the period of July 2008 to April 2009 was used as the calibration period, and the period of May to September 2009 was used as the validation period. The correlation between the simulated and observed $PO_4^{3-}–P$ concentrations is shown in Fig. 10. The simulation results are consistent with the observations for most months, although there are several small departures from the regression line. In addition, Fig. 10 shows high correlation coefficients of 0.963 and 0.941 for the calibration and validation, respectively. The calculated Nash–Sutcliffe efficiencies were 0.89 and 0.88 for the $PO_4^{3-}–P$ calibration and validation, respectively. These results indicate that the HSPF model can be applied for simulating phosphorus export processes in the watershed.

### Evaluation of HSPF for the nutrient export simulations

In summary, the HSPF simulations of nutrient export in the Zhongtianhe watershed resulted in $E_{NS}$ values of 0.58 for the TN calibration period and 0.51 for the validation period. In addition, the correlation coefficients between the simulated and observed TN concentrations were 0.839 for the calibration and 0.740 for the validation. The $E_{NS}$ values for the $PO_4^{3-}–P$ simulations were 0.89 for the calibration period and 0.88 for the validation period. Furthermore, the correlation coefficients

between the simulated and observed data were 0.963 and 0.941 for the calibration and validation periods, respectively. Compared with applications of HSPF in other areas, these simulation results are satisfactory. For example, Liu et al. used HSPF to model the Little Miami River in southwest Ohio, USA, and found $E_{NS}$ values of 0.66 and 0.35 for the flow calibration and validation, 0.52 and 0.45 for the nitrogen calibration and validation, and 0.59 and 0.14 for the phosphorus calibration and validation (Liu and Tong 2011). Yang and Wang (2010) showed that HSPF is suitable for modeling water pollution from diffuse sources and can be included in the Program of Measures in River Basin Management Plans to improve the implementation of the EU Water Framework Directive.

Compared with the hydrological simulation results, which consisted of daily time series data, the water-quality monitoring data were limited and were collected at monthly intervals. Nonetheless, this study obtained satisfactory simulation results for nitrogen and phosphorus export from this typical drinking water source watershed. The simulated nitrogen and phosphorus concentrations were consistent with the observations. Thus, the HSPF model can provide satisfactory simulation results of nutrients after calibration and validation. The HSPF model is one of a few watershed models that can simultaneously simulate land and water processes and can be used for water quantity and quality simulations at the watershed scale.

### Conclusions

The results of the HSPF evaluation in this study show that the calibrated HSPF model can simulate hydrological and water-quality processes in this type of drinking water source watershed in the eastern monsoon area of China. For the hydrological simulations, the yearly calibrated runoff had $E_{NS}$ values of 0.87 and 0.69 for the calibration and validation periods, respectively. For storm event runoff, the correlation coefficients between the simulated and observed daily flows were 0.98 for
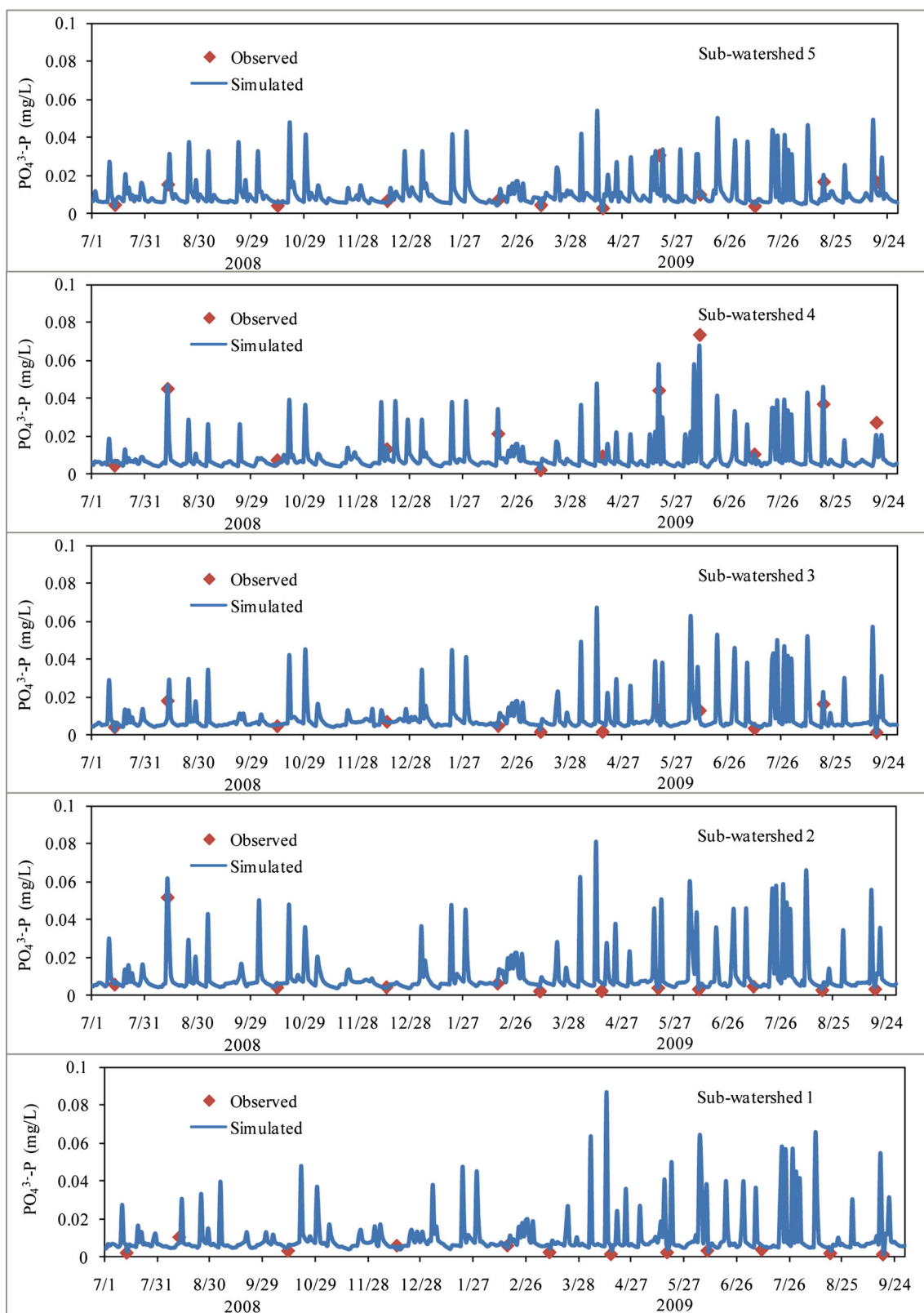
**Fig. 9** Comparison of the simulated and observed $PO_4^{3-}$–P concentrations in the Zhongtianhe River

the calibration and 0.92 for the validation, and the $E_{NS}$ values were 0.93 for the calibration and 0.47 for the validation. The

storm event flows in the wet season were underestimated. The $E_{NS}$ values for nitrogen export were 0.58 and 0.51 for the

**Fig. 10** Correlations between simulated and observed $PO_4^{3-}$–P concentrations



(a) Calibration
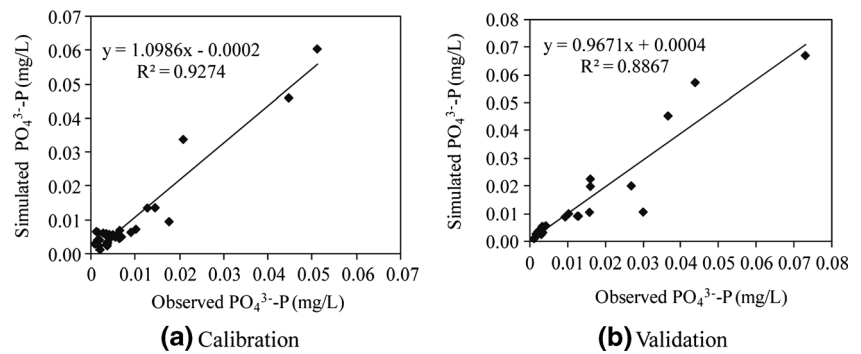
(b) Validation

calibration and validation periods, respectively. The correlation coefficients between the observed and simulated TN concentrations were 0.839 for the calibration and 0.740 for the validation. For $PO_4^{3-}$–P export, the $E_{NS}$ values were 0.89 for the calibration and 0.88 for the validation. The correlation coefficients between the observed and simulated $PO_4^{3-}$–P concentrations were 0.963 for the calibration and 0.941 for the validation. The results of the simulations of the nutrient export processes are relatively satisfactory.

The results indicated that when the HSPF model is well calibrated and validated using observed data, it is capable of describing the characteristics of water quantity and quality processes in this area. BASINS provides a sound data management component with MapWindows GIS and WDMUtil tools that help users easily manipulate large amounts of time series data and spatial data and improves the efficiency of the modeling process. It is a suitable surface water model for supporting the management of nonpoint sources at the watershed scale. However, because HSPF and BASINS were specifically designed for water resource studies in the USA, several manual tasks (such as projection, data collection, and data format conversion) are required to use these models in other countries. Because of the lack of fundamental precipitation, runoff, and water-quality data, further studies are needed to assess the suitability of applying HSPF in other areas of China.

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