SWAT Model Simulation of Non-Point Source Pollution in the Miyun Reservoir Watershed

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Abstract. Non-point source pollution is becoming an important factor affecting water environment in China. The Soil and Water Assessment Tool (SWAT) model, the most powerful tool in measuring NPS, has played a significant role in NPS research across China. The suitability and calibration of the SWAT model is of primary importance. This study evaluated the effectiveness and applicability of SWAT model in runoff and nutrient load in Miyun Reservoir watershed. The SWAT model was also calibrated and validated using parameter sensitivity analysis, which showed that ALPHA_BF, SOL_AWC, CN2, NPERCO, PHOSKD and PPERCO were the most sensitive parameters, resulting in large variations in hydrological and nutrient loads. SWAT calibration and verification suggested it is a reliable method of measuring the NPS pollution in Miyun Reservoir watershed. This study estimated and analyzed spatial and temporal variations in NPS pollution loads in Miyun Reservoir watershed from 2005 and 2010. Significant variations in NPS pollution loads were found in different simulation periods. There were noticeable differences and an uneven distribution between high- and low-flow years. Nutrient loss occurred most frequently during high-flow years and wet seasons, the crucial period for pollution prevention. The results show that the total nitrogen loads is much higher than the total phosphorus loads. The pollution loads resulting from various land use types showed significant spatial differences: agricultural land had the most TN and TP load per unit area, followed by grassland. Forest land had the least pollution load per unit area. NPS load has a remarkable association with the spatial distribution of precipitation across the entire watershed.

1. Introduction
In recent years, with the effective control of point source pollution, the influence of non-point source pollution on water environment has attracted more and more attention. Non-point source pollution is increasingly recognized as a particularly serious water management problem in China [1]. NPS pollution is a complex watershed process involving agriculture, forestry, meteorology, hydrology, and many other aspects. Due to the complex mechanism and uncertain characteristics of non-point source pollution, evaluation of non-point source pollution poses challenges to decision makers and planners. Computer modelling has become increasingly useful and popular in the regular monitoring of NPS pollution, because field experiments tend to be laborious, time-consuming, and expensive. In the past few decades, a variety of models, such as SWAT, AnnAGNPS, and HSPF, have been developed to assess and predict the effects of NPS pollution on watersheds.

Swat model is a distributed parametric watershed scale model based on physical processes that can simulate the long-term effects of runoff, sediment, nutrients, and pesticides. This model has been...
tested and validated worldwide [2, 3], and applied to several research areas for use in hydrologic assessment and pollution load prediction, parameter sensitivity analysis, and assessment various types of land use management [4, 5, 6].

The basic problem that must be considered when applying the SWAT model is scale. Based on the reviews mentioned above and for further evaluation of the model, several studies have been carried out in many different locations with varying scales (from 21.3 km$^2$ to 491,700 km$^2$). However, only few of these studies take the scale effect into consideration, and hardly any researcher had extended their evaluation from a small scale to a large scale within the same watershed.

The water environment quality of miyun reservoir directly affects the life of people in Beijing, the capital of China, because miyun reservoir is the only surface drinking water source in Beijing. Since secondary reserves have recently banned the discharge of plant wastewater to control point source pollution, nitrogen and phosphorus loads now come mainly from non-point sources [7, 8]. As a result, water pollution and eutrophication have become serious problems in the region. It is imperative that a detailed, quantitatively study evaluating stream flow, sediment, and nutrient loads resulting from NPS pollution be carried out. The purpose of this study is as follows: (1) to assess the applicability and predictive capability of SWAT in the Miyun Reservoir watershed by using two different scales to estimate their effects on the model evaluation; (2) to identify the key parameters of SWAT model in Miyun reservoir watershed based on sensitivity analysis; (3) to analyze spatial and temporal variations in NPS pollution loads during different hydrological years, based on the estimation and validation of the model.

2. Materials and Methods

2.1. Study Area

Miyun reservoir is located in the mountainous area of northeast of Beijing. Miyun is the largest reservoir in northern China, with a surface area of 224 km$^2$ and a storage capacity of 43.75 billion m$^3$ [9]. The two major tributaries of the Miyun Reservoir watershed are the Chao and Bai Rivers, whose annual stream flow discharge are about 60% and 40%, respectively. They function as the major surface water suppliers for Beijing City, and are the most important groundwater recharge sources for the plain areas.

Two watershed areas are determined in this study (see figure 1): The basin covers 4,888 km$^2$ of Chao river watershed and 8,826 km$^2$ of Bai river watershed. The study area has a temperate semi-arid and semi-humid continental monsoon climate with an average annual precipitation of 600 mm. The influence of topography and climate cause spatial variations in precipitation, significantly changing the amount of precipitation within a single inter-annual distribution and hydrology period. The precipitation from July to September accounts for 76.5% of the total annual precipitation [10]. High-intensity, short-duration summer storms cause serious soil and water loss.

The soil in the study area is divided into four major categories: cinnamon soil, brown soil, meadows soil, and chestnut soil. Cinnamon soil is found to be the most dominant soil type in the watershed, covering over 60% of the study area, followed by brown soil, which covers 30% of the total area. Based on satellite images taken in 2000, the study area is divided into six land use types: agricultural land, forest land, grassland, water, urban land, and unused land. The principal land types in Hebei province are as follows: forest land (45%), grassland (30%), and agricultural land (25%). In Beijing City, forestland (65%) is the most common land type in the watershed area. Grassland and agricultural land cover 20% and 12% of the area, respectively [11].
2.2. Model Description
SWAT model is a widely used tool for the simulation of streamflow and pollutant loads over long time periods [12, 13]. The hydrological and pollutants processes that can be simulated in SWAT include rainfall, streamflow, sediments, and nitrogen and phosphorus loads [14, 15].

2.3. Data Preparation
The source and resolution of the data needed to construct the SWAT model are showed in table 1 and figure 2. A digital elevation model was established with 30m×30m grid data of 1:50,000 topographic map. Land use maps were represented using Landsat-TM/ETM (2000/2005) satellite imagery and digitized soil maps with a scale of 1:100,000. The daily weather parameters required for SWAT were obtained from four weather stations located within and near the study area. Runoff and sediment data for model calibration and validation were obtained from hydrological monitoring stations located at the outlet of the basin. An investigation of NPS pollution was applied to the watershed socioeconomic information and other databases, such as water conservation measures, to improve modeling accuracy.
Table 1. Data Preparation

| Data                        | Description                                      | Data source                                      | Year    | Scale         |
|-----------------------------|--------------------------------------------------|--------------------------------------------------|---------|---------------|
| Hydrological data           | Flow, sediment load data                         | Hydrological monitoring station                  | 2000-2010 | daily         |
| Meteorological data         | Precipitation, evaporation, temperature          | 4 meteorological stations                        | 1961-2010 | daily         |
| Slope surface observation   | Validated data                                   | Slope surface observation from Shixia experimental plot | 2000-2005 | Plot          |
| Other data                  | Database of hydraulic engineering, water conservation measures, and investigation of NPS pollution | Topographic map 1:50,000                          | 1980    | 30 m          |
| DEM                         | For delineation of cells and generation of stream network | Landsat-TM/ETM data by unsupervised classification | 2000-2005 | 1:100,000    |
| Land use map                | Land use types                                   |                                                  | 1980    | 1:100,000    |
| Soil data                   | Soil types                                      |                                                  | 1980    | 1:4,000       |
| Administrative region       | County and province boundary                     |                                                  | 1980    | 1:250,000     |
|                             | Town boundary of Hebei province                  |                                                  |         |               |

Figure 2. Study Area Maps a) DEM, b) Soil map, c) Land use map (2000-2005)
3. Results and Discussion

3.1. Sensitivity Analysis
Sensitivity analysis is generally an important step in the simulation processes. After identifying important parameters, the sensitivity analysis can be used to optimize the model calibration process and minimize the uncertainty of the model output [16]. In this study, the SUFI-2 algorithm was used as the basis for global sensitivity analysis, and the SWAT-CUP was used to identify the most sensitive parameters [17]. Nine sensitive parameters were selected to reflect the characteristics of runoff and nutrient loss respectively (see table 2). The sensitivity analysis revealed that streamflow is most sensitive to ALPHA_BF, followed by SOL_AWC and SCS_CN2, whereas nutrient is most sensitive to NPERCO, followed by PHOSKD and PPERCO.

| Parameter         | Rank | Parameter         | Rank |
|-------------------|------|-------------------|------|
| Alpha_Bf.gw       | 1    | Nperco.bsn        | 1    |
| Sol_Awc.sol       | 2    | Phoskd.bsn        | 2    |
| SCS_Cn2.mgt       | 3    | Pperco.bsn        | 3    |
| Canmx.hru         | 4    |                   |      |
| Esco.hru          | 5    |                   |      |
| Sol_K.sol         | 6    |                   |      |

3.2. Calibration and Validation of the SWAT
On the basis of sensitivity analysis, monthly runoff and nutrient load during 2000-2010 were calibrated and verified. The SWAT model performed well above the satisfactory criteria as recommended by Moriasi et al. (2007) [18] during the calibration and validation periods of monthly runoff, TN and TP loads (see table 3).

In the process of runoff calibration and verification, the SWAT model performed better at Xiahui gage station (NSE = 0.82–0.86, PBIAS = 10.5%–14.5%), compared to the Zhangjiafeng gage station (NSE = 0.81–0.84, PBIAS = 11.2%–18.3%).

| Parameter | Gage station | NSE Cal. | NSE Val. | PBIAS Cal. | PBIAS Val. |
|-----------|--------------|----------|----------|------------|------------|
| Streamflow| Xiahui       | 0.86     | 0.82     | 10.6%      | 14.5%      |
|           | Zhangjiafeng | 0.84     | 0.81     | 11.2%      | 18.3%      |
| TN        | Xiahui       | 0.55     | 0.53     | 21.5%      | 25.3%      |
|           | Zhangjiafeng | 0.56     | 0.52     | 23.0%      | 27.4%      |
| TP        | Xiahui       | 0.55     | 0.52     | 23.0%      | 27.6%      |
|           | Zhangjiafeng | 0.54     | 0.52     | 22.3%      | 25.0%      |
Figure 3. Monthly Runoff Simulation Results

Figure 3 shows that the occurrence time of runoff peak is consistent with that of the maximum rainfall intensity. This suggests that the model can sufficiently reflect the hydrological characteristics in the Miyun Reservoir watershed.

However, the SWAT model showed slightly lower performance in simulating monthly TN and TP loads at the outlet (see table 3). The model underestimated the TN and TP loads during high flow years, particularly in the Bai River watershed (see figure 4). The unsatisfactory result for peak loadings may have been caused by the overestimated peak flows. Meanwhile, the influence of the reservoir may be another reason for the inaccurate estimation. Water conservancy facilities found in the reservoirs on the upper basin of the Bai River can intercept nutrient efficiently.

Figure 4. Monthly TN and TP Loads Simulation Results

4. Spatial and Temporal Variations of NPS Pollution
Through the calibration and verification of the above parameters, the SWAT model was applied to the simulation of TN and TP loads in Miyun reservoir watershed. According to the characteristics of land use, the simulation period is divided into two stages: 2000-2005 and 2005-2010.
4.1. Temporal Variation
The occurrence and transmission of non-point source pollution had a direct relation to the rainfall distribution and the amount of runoff during the years covered by study. With the increase of rainfall, the runoff increased, and the loss of TN and TP also increased.

During the period of 2000 to 2010, the NPS pollution varied over time during the wet and dry seasons. During the wet season, the runoff for the Chao River and Bai River watersheds was 96.02% and 97.02%, respectively. TN and TP loads during the wet season were more than 90% of the total annual loads.

In this study, NPS pollution loads in the Chao River and Bai River watersheds was found to occur mostly during the wet season. Therefore, the wet season can be regarded as the pivotal period for the prevention of nutrient loss. TN loads was found to exceed TP loads: the TN loads were 103 times greater than the TP loads in the Chao River watershed, and 41 times greater in the Bai River watershed.

4.2. Spatial Variation
The spatial distribution of non-point source pollution loads from 2000 to 2010 was shown in figure 5 and figure 6.

Higher TN loads occurred primarily in the upstream areas of the Bai River watersheds (see figure 6). In addition, the central zone of the Chao River watershed was identified as the major source area of TN loads owing to the larger volume of rainfall experienced by that area.

Figure 5. Spatial Distribution of TN Loads in Miyun Reservoir Watershed (2000–2010)

The spatial distribution of TP load (see figure 7) showed a pattern similar to that of TN loads. Higher TP loads were observed downstream of the study area. By comparing the land use map with the areas occupied by intensive agricultural land, the index values were found to be higher.

Figure 6. Spatial Distribution of TP Loads in Miyun Reservoir Watershed (2000–2010)

NPS pollution and load per unit area were calculated based on the simulated time period. Land use type has a significant impact on streamflow and NPS pollution loads. The greatest contributor to streamflow was found to be forest land, followed by grassland and agricultural land. Forest land contributed the least pollution load per unit area, whereas agricultural contributed the highest (twice that of forest land).
From highest to lowest, the TN load contributions were: forest land (786.29 t·a⁻¹), grassland (355.13 t·a⁻¹), and agricultural land (249.49 t·a⁻¹). Agricultural land contributed the most pollution load per unit area (345.35 kg·ha⁻¹·a⁻¹), followed by forest land and grassland.

There were subtle differences among the three land use types in terms of TP load. Forest land contributed slightly more than the others. However, agricultural land contributed more per unit area (6.10 kg·ha⁻¹·a⁻¹), compared with forest land and grassland. These results may be attributed to differences in fertilizer application among the land use types.

The results show that the spatial distribution of TN and TP load is mainly related to the distribution of farmland and soil type. Therefore, water environment management should focus on management measures and rational development of land use.

5. Conclusion
The NPS pollution loads in the Chao River and Bai River watersheds exhibited significant temporal differences. The nutrient loads changed significantly based from the inter-annual rainfall amount and the hydrology period. The high-flow year and wet season were found to be the pivotal periods for the prevention of nutrient loss.

The TP loads were mainly distributed spatially in the downstream areas of the Chao and Bai Rivers. The critical TN loading sub-basins were distributed between the source area of the Bai River watershed and the central zone of the Chao River watershed. For the watersheds as a whole, the spatial distribution of NPS load was remarkably associated with precipitation.

Different land use types exhibited significant spatial differences in terms of NPS pollution loads. Agricultural land had the greatest TN, and TP loads, followed by grassland. Forest land had the least pollution load per unit area.

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