Application of GWLF model in the Baohe River Watershed: Analysis of the source composition of nitrogen and phosphorus in the region

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Abstract. The Luan River is one of the main rivers entering the Bohai Sea, and the Baohe River is a major tributary of the Luan River. Determining the contribution of pollution sources in the watershed where the upstream river enters the sea is a prerequisite for formulating environmental management measures in the sea area. Facts have proved that the model is an effective tool to determine the main environmental targets, especially in the analysis of pollution sources in the watershed. This paper uses the General Watershed Load Function (GWLF) model to simulate the monthly streamflow, dissolved nitrogen (DisN) load and dissolved phosphorus (DisP) load in the Baohe River Watershed from 2006 to 2014, and the contribution ratio of each pollution source in the source allocation of nitrogen and phosphorus load is emphasized. The application of the model shows the effectiveness of planning nitrogen and phosphorus management strategies for decision-makers, and provides a certain decision-making reference for pollution control in the watershed into the sea.

1. Introduction

In recent years, with the development of economy, environmental problems have become increasingly prominent. The interaction between land and ocean is a key issue in the study of global environmental change, which is increasingly receiving widespread attention[1].

The Luan River in the Haihe River Watershed is one of the main rivers entering the Bohai Bay. It is also the most water-scarce and polluted river Watershed in China. As a result, the pollutants entering the sea often exceed the standard [2]. Therefore, the pollutant contribution composition of the tributaries of the Luan River Watershed is studied[3]. Proportion and clear governance priorities play a vital role in the environmental governance of Bohai Sea. The Baohe River is an important tributary of the Luanhe River, which has a remarkable impact on the overall water quality of the Luanhe River. Pollution analysis and targeted treatment of this watershed are of great significance to the overall water quality of the Luanhe River.

Pollution sources in the watershed are diverse, with complex pollution composition, and obvious changes over time. They are extremely closely related to the hydrological process in the watershed. Many unfavorable factors make it difficult to assess the pollution sources in the watershed. In order to
meet the needs of scientific research and management, an important decision-making support tool which is able to utilize existing monitoring data in various river watersheds, comprehensively consider meteorological, geographical conditions, human interference, hydrological cycle processes and pollutant transformation mechanisms--watershed model technology is created[4]. General Watershed Pollution Load (GWLF) Model is one of the 65 models of the TMDL plan in the United States, and has been widely used all over the world[5]. The data requirements match the standards of my country's monitoring system[6].

Based on the above conditions, this paper chooses the GWLF model to simulate the streamflow of the Baohe River Watershed and the load of soluble nitrogen and phosphorus, and analyze the source of nitrogen and phosphorus.

2. Materials and Methods

2.1. Study Area
The Puhe watershed, which is located in north China (figure 1a and figure 1b). The whole watershed covers an area of 1885.14 km². The highest and lowest elevation are 1557 and 231 meters above the sea level respectively. The climate is dominated by a temperate semi-arid monsoon climate, with a mean annual temperature of 6.2 °C and a mean annual precipitation of 431 mm during the period from 2006 to 2014. Most of the precipitation is concentrated from April to August. Figure 1c and figure 1d respectively show the digital elevation map and land use distribution of the study area.

![Figure 1](image1.png)

Figure 1. Location (a, b), elevation (c) and landuse (d) of the Puhe watersheds.

2.2. Watershed Models description
The GWLF model is a semi-distributed and semi-empirical watershed hydrological model algorithm proposed by Professor Haith of Cornell University in 1987[7]. It can be used to simulate the streamflow and nutrient load in a mesoscale watershed. It can provide monthly simulation results and quantitative analysis of pollution source composition. The GWLF model calculates the hydrological process on a daily basis, ignoring the spatial transmission time of the water body. The surface runoff is simulated by the SCS-CN runoff curve equation based on different land use types. Assuming that the groundwater is
a one-dimensional linear reservoir; the lumped parameter method is used to simulate the nitrogen and phosphorus nutrients of surface runoff and groundwater; the daily source nutrients are calculated based on the per capita discharge and plant absorption. Table 1 summarizes the data used for the model setup in this study.

| Type        | Description                                    | Source                                      | Time         |
|-------------|------------------------------------------------|---------------------------------------------|--------------|
| Weather     | Rainfall stations with the daily precipitation; | Annual Hydrological Report P.R. China       | 2006–2014    |
|             | Temperature stations with the daily average temperature | China Meteorological Data Service Center (http://cdc.cma.gov.cn/en) | 2006–2014    |
| DEM         | Digital elevation model (30 m * 30 m)          | Geospatial Data Cloud (http://www.gscloud.cn/) | 2009         |
| Land-use    | Raster Format                                  | Institute of Geographic Sciences and Natural Resources Research, CAS | 2010         |
| Hydrology   | Streamflow/ Monthly                            | Annual Hydrological Report P.R. China       | 2006–2014    |
| Water Quality | DisN and DisP/ Monthly                        | Chinese Academy of Environmental Planning   | 2006–2014    |
| Point source | Annual discharge                              | Chinese Academy of Environmental Planning   | 2006–2014    |

3. Results and Discussion

3.1. Objective function and calibration method

A well-calibrated and validated model can help managers clarify the impact of various nutrients, and then evaluate and formulate an effective water quality management plan. The simulation duration of this study is 9 years, from January 2006 to December 2014. In order to make the initial value of the model closer to the real situation, the data of the first year (2006) is repeatedly used as the warm-up period. By comparing the time series of simulated and observed water flow, dissolved nitrogen (DisN) load and dissolved phosphorus (DisP) load, monthly aggregated data from 2006 to 2011 was used for calibration, and data from 2012 to 2014 was used for verification. The parameters are calibrated in the order of flow rate, soluble nitrogen load, and soluble phosphorus load. Nash–Sutcliff coefficient (NSE) [8] was chosen to evaluate the parameter sets’ goodness of fit as the most frequently used likelihood measure for Generalized Likelihood Uncertainty Estimation (GLUE) method[9]. The formulas is as follows:

\[
\text{NSE} = 1 - \frac{\sum_{i=1}^{n} (Y_{\text{sim},i} - Y_{\text{obs},i})^2}{\sum_{i=1}^{n} (Y_{\text{obs},i} - \bar{Y}_{\text{obs}})^2}
\]

where, \(Y_{\text{obs},i}\), \(Y_{\text{sim},i}\) and \(\bar{Y}_{\text{obs}}\) are the observed values, simulated values and average observed values.

3.2. Simulation results of flow and nutrients

Figure 2 a–c illustrate the observed and simulated monthly mean streamflow, DisN and DisP series of GWLF model in Puhe watershed; the numerical criteria of model performance are summarized in Table 2.

On the monthly time scale of streamflow, the performance of the model indicates its excellent predictive ability. The GWLF model replicated the entire trend of the streamflow hydrograph with the simulated peak values and low flows consistently and perfectly matching the observed data throughout all years (Figure 2a). It can also be clearly seen from the statistical indicator Nash coefficient that the streamflow simulation is very good, with 0.79 for the calibration period and 0.64 for the validation period, respectively.
Table 2. The Nash coefficients of the models in different periods.

|               | Entire period | Calibration | Validation |
|---------------|---------------|-------------|------------|
| Flow          | 0.76          | 0.79        | 0.64       |
| DisN          | 0.61          | 0.73        | 0.38       |
| DisP          | 0.52          | 0.57        | 0.41       |

Figure 2. Simulated and observed monthly streamflow (a), DisN (b) and DisP (c) for Puhe watershed.

The DisN simulated results performed worse than streamflow in tracking peak timing (Figure 2b). The model adequately simulated the trend of monthly DisN load, but tended to underestimate extremely a few very high values. Meanwhile the DisN load simulation performed fairly well in tracking lower-value timing. It is clear predicted fairly acceptable as reflected by the ENS values, with 0.73 for the calibration period, 0.38 for the validation period and 0.61 for the entire period respectively.

Similar to the simulation result of the DisN load result, the simulation result of the DisP is also worse than the simulation result of the streamflow and also underestimated some peaks values. The trend shape of the monthly DisP was roughly represented and there were large fluctuations for the simulation of peak and low values compared to the measured data (Figure 2c). However, in general, the model predicted monthly DisP loads with reasonable accuracy during the entire simulation time based on the passable values of ENS, which are 0.57 for the calibration period, 0.41 for the validation period and 0.52 for the entire period respectively.

In summary, all streamflow, DisN and DisP simulations by the GWLF model had a satisfactory performance on a monthly time scale, which indicates robustness of the RGWLF model, according to previous research[10].

3.3. Source apportionment analysis of DisN and DisP loads

The source apportionments of each year and average annual DisN are shown in figure 3a and figure 3b and the same results of DisP are shown in figure 4a and figure 4b. In the entire DisN load, agricultural source load is the main pollution source, accounting for 73%, followed by point sources, accounting for 36%, and the rest are living sources, accounting for 20%, and forest land sources and grassland sources combined are less than 1%. As shown in Figure 3a, the minimum annual load of DisN is 370 tons and the maximum is 1003 tons. For soluble phosphorus, point sources are the largest contributor, accounting for up to 73%. The remaining sources account for a relatively low proportion, including 6% of agricultural sources, 3% of forest land sources, 12% of grassland sources, and 6% of domestic sources. As shown in Figure 4a, the minimum annual load of DisP is 7.75 tons and the maximum is 26.44 tons.
Figure 3. Source apportionment of each year (a) and average annual (b) DisN loads.

Figure 4. Source apportionment of each year (a) and average annual (b) DisP loads.

4. Conclusion
The GWLF model has been successfully applied to the Baohe River Watershed in northern China. As shown in the model calibration and result verification, the model provides reasonable estimates of the monthly flow, DisN load and DisP load of the watershed. For decision makers, a simple, reliable and mature model can more quickly identify pollution problems in a watershed, and then clarify the source and composition of pollutants entering the sea, and provide certain help for the coordination and effectiveness of the watershed water environmental governance and marine environmental management policy formulation.

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