Investigation of point source and non-point source pollution for Panjiakou Reservoir in North China by modelling approach

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ABSTRACT
Panjiakou Reservoir is the main water supply source for Tianjin City, which has a population of over 14 million. In order to develop a watershed management strategic plan for source water protection, it is necessary to have reliable information on point source (PS) and non-point source pollution (NPS). The modelling approach has been frequently used in the study of partitioning of PS and NPS pollution on a basin scale. This study employed the Loading Simulation Program in C++ (LSPC) model to investigate the PS and NPS source pollution loadings to Panjiakou Reservoir. The hydrological model and the water quality model were developed and validated using field data from 2006 to 2010. It has been found that the PS pollution is still the major source for chemical oxygen demand (COD) loadings, accounting for about three-quarters of the total annual loadings to the reservoir; while near half of the total nitrogen (TN) and total phosphorus (TP) total annual loadings are from NPS pollution. There is a large seasonal variation for TN and TP loadings from NPS pollution. The contribution of TN and TP from NPS in the flooding seasons can reach 70%, whereas the contribution can also be as low as 4% during the dry season in the winter.

Key words | Hai River Basin, LSPC, non-point source pollution, point source pollution

INTRODUCTION

Pollution for a watershed mainly includes two parts: point source (PS) pollution and non-point source (NPS) pollution. PS pollution is mainly from factories, municipal discharge, etc. NPS pollution is mainly brought on by the surface runoff from rain events to water bodies. With the economy booming in China, water pollution has become increasingly critical, and it has become more detrimental to human health and to the national economy. Compared with PS pollution, NPS pollution is more diffuse and harder to identify, isolate, and control (Lai et al. 2011; Tang et al. 2011). Partitioning PS and NPS pollution would help decision-makers gain better management and control of water resources.

Hai River Basin (HRB), managed by the Hai River Water Resource Conservancy Commission (HWCC), is one of China’s seven major river systems. Most of the basin is located in Hebei Province. Two major metropolitan areas, Beijing and Tianjin, are also located inside the basin. HRB is about 318,000 km² in area, which makes up 3.3% of the national territory area. Agriculture activities are intensified in this basin. There are about 10,000 km² of farmland, which accounts for 10% of that of the whole country. The average annual water resource in HRB only accounts for 1.5% of the national total, but the basin supplies water to 10% of the country’s population (Liu et al. 2013). The water resource per capita is 270 m³, less than 1/7 of the national average and only 1/24 of the world average. Due to the limited assimilative capacity of water and intensified agriculture development, the NPS pollution is especially severe in this area. According to the survey documented in China’s environmental bulletin of 2008, the water resource in HRB is severely contaminated, about 50.8% is worse
than the lowest water quality standard, class V (Zhu et al. 2010). Panjiakou Reservoir is one of the large-scale reservoirs in HRB, which provides the water supply of the city of Tianjin, the third largest metropolitan area in China. As the ecosystem deteriorates, it is important to investigate the PS and NPS pollution for environmental management. A number of research studies have demonstrated that NPS pollution is highly correlated with the soil type, land use, rainfall intensity or runoff (Lindenschmidt et al. 2007; Gunes 2008). Some studies have focused on the water quality in flush and flood events (Warrick et al. 2004; Boldrin et al. 2005; Ribarova et al. 2008), and have shown that the flooding events have a significant influence on pollutant transmission. The loadings could be much higher than those in a dry season. In China, due to the excessive use of fertilizers and pesticides, agriculture has become a major source for NPS pollution and has raised wide concerns. Additionally, in rural areas, livestock and domestic wastes as well as other wastewaters are not well managed, and can therefore become large NPS pollution sources (Soller et al. 2010; Lee et al. 2014). Guo et al. (2014) studied agriculture NPS pollution in the upstream of Yongding River and assessed the environmental sustainability index. This study indicated that agriculture activities in the study area were unsustainable, and control measures of NPS pollution for farmland should be in place. Recently, in developed countries like America, Canada, or some European countries, most PS pollution is under control and NPS is the major concern for receiving water bodies. Researchers and government agencies therefore have started to pay more attention to NPS pollution investigation and control, the pathway of pollutants (Lee et al. 2014), NPS pollution exposure to human health (Vinten et al. 2008), etc. In China, due to the limited monitoring data available, water quality studies at the watershed level are sufficient, especially the studies for NPS pollution. In this study, the land surface NPS pollution loading, primarily estimated from the data of yearbooks and the observed PS monitoring data given by HWCC, were applied in a watershed model to study the transmission and contribution for NPS and PS pollution.

Mathematical methods such as Bayesian (Alameddine et al. 2011; Patil & Deng 2011; Chen et al. 2012) or watershed-quality integrated models are implemented in the NPS pollution study. These models which integrate hydrological cycles and water quality components have been widely used worldwide, and include for instance, Loading Simulation Program in C++ (LSPC), Hydrological Simulation Program-Fortran (HSPF), Soil and Water Assessment Tool (SWAT) and Integrated Watershed Management Model (IWMM). LSPC or HSPF have been widely implemented for watershed pollutant load estimation (Nasr et al. 2007) or total maximum daily load (TMDL) assessments (Benham et al. 2006; Petersen et al. 2013; Narayana & Pandrakoulis 2011; Zhang 2012). SWAT developed by the United States Environmental Protection Agency (US EPA) is also a widely used model for simulation and assessment of diffuse pollution from agriculture areas. Nasr et al. (2007) conducted a comparison among SWAT, HSPF and SHETRAN in a case study in Ireland. The study revealed that HSPF was best in the simulation of mean daily discharge. Lai et al. (2011) did a study that combined watershed model IWMM and water quality model Water Quality Analysis Simulation Program in Taiwan Kaoping River Basin. The results demonstrated that the integrated two-model system improved the accuracy in estimating the water quality.

The aim of this study is to investigate the PS and NPS pollution in Panjiakou Reservoir Basin. Tianjin is one of the largest cities in China with a population over 14 million. Due to severe water shortage in Tianjin, Panjiakou Reservoir has become the major water supply source for Tianjin since the 1980s; hence, pollution prevention and watershed management to ensure safe source water for the portable water supply is very important. In this paper, LSPC model was employed as the hydrological and water quality model for the partition of the PS and NPS pollutions. This study is part of the development of the watershed management strategic planning for source water protection. It provides valuable information about the design of pollution control strategies for the basin.

**METHODOLOGY AND MATERIALS**

**Model description**

Many mathematical models used to assess NPS pollution load have been developed since the 1960s (Shen et al. 2012). LSPC is a conceptual lumped hydrological modelling system developed by US EPA. It consists of a set of modules
arranged in a hierarchical structure, which permit the continuous simulation of a comprehensive range of hydrological processes, e.g., rainfall–runoff, infiltration, ET, interflow, groundwater and water quality process (Bicknell et al. 2001). The LSPC model includes a hydrological module, hydraulic module, sedimentation module and general water quality module as well as a simplified fate and transport module for stream flow. LSPC has been widely used for water, sediment and pollutant yields like mining applications and TMDL controls (US EPA) to assess the effects of land-use changes, reservoir operations, etc., on the runoff process and the flow routing in the stream. It is designed to handle large-scale watershed modelling applications for continuance modelling with time steps from 1 min to 1 day. The model has been successfully used to simulate watershed systems composed of over 1,000 sub-watersheds. It supports data processing and post-processing for statistical and graphical analysis of data through Water Resource Database. The latest version LSPC2011 is used in this study. A road map to develop an LSPC model is described in Figure 1.

Water quality module

The water quality module simulates water quality constituents/pollutants in the outflows using flow rate and/or sediment yield (Bicknell et al. 2001). The pollutant constituents can be simulated in surface and subsurface outflow; its behaviour in surface outflow is more complicated due to many more factors influencing the processes. The water quality processes can be simulated through two approaches. One approach is associated with sediment removal, and the other is associated with atmospheric deposition and/or basic accumulation and depletion rates by wash-off (HSPF User’s Manual; Bicknell et al. 2001). In the present study, the second method with accumulation and depletion by wash-off was utilized. The schematic for water quality module is shown in Figure 2.

The pollutant wash-off simulated through accumulation and removal rates can be monthly variables considering seasonal fluctuations, and it is simulated through the relationships as shown in Equations (1) and (2) below:

\[
SOQO = SQO \times (1.0 - \exp (-SURO \times WSFAC))
\]

(1)

\[
SQO = ACQOP + SQOS \times (1.0 - REMQOP)
\]

(2)

where \(SOQO\) is the wash-off of the constituent of concern from the land surface (quantity/ac per interval); \(SQO\) is the storage of constituent of concern on the surface (quantity/ac); \(SURO\) is the surface outflow of water (inches/interval); \(WSFAC\) is the susceptibility of the constituent of concern to wash-off (unitless); \(ACQOP\) is the accumulation rate of the constituent of concern (quantity/ac per day); \(SQOS\) is the \(SQO\) at the start of the interval; \(REMOP\) is the unit removal rate of the stored constituent of concern (per day).

Study area

The study was carried out in the Panjiakou Reservoir Basin, as shown in Figure 3. The basin lies in the middle of the Luan River Basin in the east of the Northern Plain of China between 39°40’–42°35’N and 115°40’–119°20’N. Some small areas of land in the Inner Mongolia Autonomous Region, Shanxi, Henan, Liaoning and Shandong Provinces, are also within this basin. The total area of Panjiakou Reservoir Basin from upstream to the downstream end of the river is 42,443 km², while the upstream area of Panjiakou Reservoir is about 33,292 km². The river is 888 km in length. The elevations for the extreme upstream area within Inner Mongolia vary from about 1,300 m to
Panjikou Reservoir Basin has a variety of landforms including plateaus, mountains, hills and plains, etc. The mountainous area in the middle part of the basin occupies most of the area. The terrain gradually slopes down from the northwest to the southeast. Most of the study region is covered by forests, grassland and crops; the dominant soil types are loam and sand clay. The upstream area of Panjikou Reservoir Basin is typically well covered with vegetation, while the soil type for the middle part of the Panjikou Reservoir Basin is dominated by loam and sandy clay with relatively less vegetation cover. These areas are thus more prone to soil erosion.

The watershed typically follows a marked subtropical monsoon climate with distinct seasons and fairly unevenly distributed rainfall, spatially and temporally, with high temperatures and abundant rainfall in the summer, while it is cold, dry and with almost no rainfall in the long winter. The annual average rainfall is about 390–800 mm, with about 70% of the rainfall occurring in summer and in the downstream part of the area. Due to intensive rainfall in summer and the steep slopes in the middle part of the area, floods with high peaks and large quantities of flow can occur, and thus may result in disasters such as mud-rock flows. The potential evapotranspiration (PET) of water surface in the region can be as high as 950–1,150 mm. This leads to the severe water shortage in this area. The average temperature is between −0.3 and 11 °C, and the annual average solar radiation is 2,800 hours.

**Dataset and model setup**

In this study, LSPC model input requires meteorological data, digital elevation model (DEM) map, land use and soil map, while the validation requires the observed flow data and water quality data. In Panjikou Reservoir Basin, there are four national meteorological stations, namely Duolun, Weichang, Chengde and Qinglong, providing daily data between 1951 and 2013, including precipitation, air temperature, wind speed and solar radiation. The locations of the four meteorological stations are shown in Figure 3. Since the rainfall is significantly correlated with the surface runoff and the pollutants washing off on land.
surfaces (Huang et al. 2014), precipitation data from 25 local rain gauge stations which could take the spatial variety into consideration were utilized in this study. These rainfall stations are also shown in Figure 3. In addition, data on the dew point, PET and cloud cover are also required. As we could not obtain the cloud cover information, it was assumed that the cloud cover is 0 and the total solar radiation is used as input meteorological data in this study. There is one major hydrological station, Wulongji, in the mainstream of Luan River, which has both daily flow records and monthly water quality records (winter time not included) from 2006 to 2010.

A DEM map (Figure 4) of 30 m resolution was obtained from the international scientific data sharing platform. A land use map (Figure 5) with a resolution of 500 m for the year 2008 was taken from the land cover product of MOD12 (MODIS product). The land cover product originally had 12 categories, and was reclassified to six categories, including water (0.02%), forest (24.65%), shrub (0.75%), grassland (28.45%), agriculture and rural area (45.34%) and urban area (0.79%), shown in Figure 6(a). The soil map (Figure 6(a)) (1:1,000,000,000) was obtained from the Harmonized World Soil Database (HWSD, version 1.1), and was provided by the Institute of Soil Science, Chinese Academy of Science. The soil types primarily include loam, loamy sand, sand, sandy clay loam and sandy loam. It is first classified to be SCS (Soil Conservation Society) hydrological soil group A, B, C and D. Due to the parameter setup of LSPC, the soil hydrological group is represented by the one which has the highest percentage of coverage with the boundaries of one sub-basin. From this point of view, the soil
hydrological group ID is assumed to be 1, 3, 5, 7 and an area-weighting calculation was conducted for every single sub-basin. The soil hydrological group for sub-basins is shown in Figure 6(b), and the sub-basins are dominant by group A-B (ID 2) and B (ID 3). Group A soils have the best drainage capacities among the four soil groups and therefore usually generate least runoff (USDA 1972), while group B soils have relatively moderate drainage capacities and generate moderate runoff. The infiltration rate for group A could be more than 0.3 inches/hr (1 inch = 25.4 mm), while for group B it could be 0.15–0.3 inches/hr (USDA 1986).

When modelling a watershed, it is necessary to delineate the entire watershed into some small-scale sub-basins in order to provide a more detailed, higher resolution representation for the watershed. In this study, BASINS4.0 was utilized to conduct the watershed delineation with a proper DEM map. Watershed delineation is automatically done by BASINS with reference to DEM. Through defining the threshold, the minimum and maximum sub-basin area can be determined. It is extremely important to determine the details of the stream network and the sub-basin where the observed flow data are available to evaluate the performance of the model (Ryu 2009). For the middle part of Panjiakou Reservoir Basin, 145 sub-basins with a corresponding 145 reaches were identified by the delineation, as shown in Figure 7. The locations of the three flow stations used for model validation are also shown in Figure 7. For sub-basins, the average area is 34,194.5 acres (1 acre = 4046.856 m²) and the average slope is 22.3%. For reaches, the average length is 15,133 m and the average slope is 0.66%.

In the upstream area of Panjiakou Reservoir Basin, the PS pollution discharge data were from observed records with 62 monitoring points. Discharge volume, concentrations for chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) were provided by Hai River Water Conservancy Commission (HWCC). The
PS data were arranged in time series files in the access database for model input. The loads for NPS pollutants were estimated by referencing to the yearbooks and some were provided by HWCC. The estimated loads of NPS were then applied through accumulation rate in the quality module. The NPS pollution investigation was conducted for four categories, namely, the pollutions from urban surface runoff, from fertilization and pesticide application in agriculture, from domestic sewage and solid waste in rural areas, and from livestock waste in free-range farming. The accumulation rates for water quality input for COD, TN and TP are shown in Table 1.

The LSPC model was run in daily time steps with spin-up periods from 2001 to 2005. The model was also validated in daily scale for hydrological module and monthly scale for water quality module for the period between 2006 and 2010.

**Model performance evaluation**

The coefficient of determination ($R^2$), Nash-Sutcliffe efficiency (NSE) and the index of agreement (IA) were used as evaluation indexes for the observed and simulated flow. $R^2$, NSE and IA were calculated with Equations (3)–(5) shown below. $R^2$ is the square of correlation coefficient (CC) which indicates stronger correlation between observed and simulated flow when it is closer to 1. The NSE is considered to be the most appropriate relative error or goodness-of-fit measure available due to its straightforward physical interpretation (Legates & McCabe 1999), as well as the IA. Moreover, the frequency analysis was conducted as another evaluation index.

$$R^2 = \frac{\left[ \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y}) \right]^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}$$

(3)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Urban</th>
<th>Pasture</th>
<th>Agriculture</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>0.09506</td>
<td>0.42148</td>
<td>0.60578</td>
</tr>
<tr>
<td>TN</td>
<td>0.02990</td>
<td>0.10758</td>
<td>0.63597</td>
</tr>
<tr>
<td>TP</td>
<td>0.00369</td>
<td>0.02388</td>
<td>0.14625</td>
</tr>
</tbody>
</table>

$1\text{lb} = 0.453592\text{kg}$.

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n} [(x_i - y_i)^2]}{\sum_{i=1}^{n} [(x_i - \bar{x})^2]}$$

(4)

$$\text{IA} = 1 - \frac{\sum_{i=1}^{n} [(x_i - y_i)^2]}{\sum_{i=1}^{n} [(x_i - \bar{x})^2 + (y_i - \bar{y})^2]}$$

(5)

**RESULTS AND DISCUSSION**

**Hydrological simulation**

Figure 8 shows the comparison of simulated flow with the observed data at three hydrological stations, namely, Sandaohezi, Wulongji and Panjiakou Inlet. The locations of these three hydrological stations are shown in Figure 7. The black dots represent the observed flow and the thin lines represent the simulated flow. The comparison at Sandaohezi station indicates good agreement for both the base flow during the dry season and the peak flow during the flooding season, while for the comparison at Wulongji and Panjiakou inlet, the base flows during the dry season are simulated fairly well and the simulated peak flow during the flooding season for the years 2007 and 2009 are somewhat less than the observed flows. The comparison of frequency analysis for simulated flow and observed flow are shown in Figure 9. For Wulongji station, the frequency curves for simulated flow (thin line) and observed flow (black dot) almost line up together. There are small discrepancies when the frequency exceeds 85%. Similar to Wulongji’s upstream and downstream stations, for Sandaohezi and Panjiakou inlet the simulated flow and observed flow are in the same regime. As for water quality modelling, especially for NPS pollution, we are concerned about the more frequent events rather than the extreme events. In these cases, the hydrological model could well represent the hydrological characteristics for the sub-basins in the upstream of Panjiakou Reservoir and it is satisfactory for water quality modelling. The evaluation index is shown in Table 2, and the values for $R^2$, NSE and IA are 0.78, 0.77 and 0.94, respectively. They show excellent goodness of fit between simulated and observed flow for daily scale.
Figure 8  |  Validation for hydrological model at three hydrological stations.
Figure 9 | Comparison of frequency analysis for flows at three hydrological stations.
The simulated results indicated that modelling of the hydrological process by LSPC for the study area was valid (Table 3).

### NPS and PS pollution loadings

Based on the well-performing hydrological model, the water quality module was then developed for the identification of NPS pollutions. The PS data in the access database were used as input data for the water quality model. The accumulated rate for NPS pollution on land surface for different land use type was estimated through the yearbook. Due to the coarse water quality monitoring data, the quality module was validated on a monthly scale. Figures 10(a)–10(c) present the comparisons of observed COD, TN and TP concentrations and the simulated results. Due to the uncertainty of monitoring, Figure 11 compares the observed and simulated monthly mean value within the simulation period for COD, TN and TP concentrations. The simulation basically captured the general characteristics of the concentrations for COD, TN and TP.

It was observed that the pollutant concentrations were very high in the winter due to the lack of precipitation and rather low flow. In the winter time in north China, the temperature can be as low as −30 °C, and the water in stream is frozen. The water velocity is slowed down, and hence the process of pollutant degradations are also slowed down. Due to the monthly scale resolution for the observed water quality data, the uncertainty of the data made the validation quite challenging. Therefore, the validation and evaluation for annual monthly average concentration were carried out. Results of the comparison are shown in Figure 12. For November and December, only one or two observed data were available for the simulation period (2006–2010). The limited number of data sets in the winter is not sufficient for validation purposes. Thus, the evaluation index for the annual monthly average was computed for the period from April to October. The performance of the simulation is shown in Table 4. All the evaluation indexes were beyond 0.5 and thus the result is still quite acceptable. Moreover, all the values of IA for the three parameters (COD, TN and TP) are above 0.95. It is concluded that the water quality module performs well and it is valid for future investigation of PS and NPS pollution.

Based on the well-performing hydrology and quality modules, the investigation of the total loads for PS and NPS pollution into Panjiakou Reservoir was conducted. The results of the analysis are shown in Figures 12(a)–12(c). Most of the NPS pollution occurred in the summer time, from June to September. The contribution of NPS could reach 50% or more, while from November to February, PS pollution was the dominant source, and the contribution for

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**Table 2 | Evaluation index for Wulongji Gauging Station**

<table>
<thead>
<tr>
<th>Evaluation Index</th>
<th>Sandaohezi</th>
<th>Wulongji</th>
<th>Panjiakou Reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.77</td>
<td>0.78</td>
<td>0.66</td>
</tr>
<tr>
<td>NSE</td>
<td>0.88</td>
<td>0.77</td>
<td>0.65</td>
</tr>
<tr>
<td>IA</td>
<td>0.93</td>
<td>0.94</td>
<td>0.89</td>
</tr>
</tbody>
</table>

**Table 3 | Hydrological parameters used in literature and their validated values in this study**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bounds $^a$</th>
<th>Value in literature</th>
<th>Validated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGWRC</td>
<td>0.001–0.99</td>
<td>0.95$^{II}$, 0.98$^{III}$ $^V$, 0.99$^{IV}$, 0.92–0.98$^{VII}$</td>
<td>0.975</td>
</tr>
<tr>
<td>INFILT</td>
<td>0.001–100</td>
<td>20.3$^{II}$, 1.78–15.49$^{III}$, 1.78$^{IV}$, 0.027–0.33$^{V}$, 4.06$^{VI}$, 0.05–0.18$^{VII}$</td>
<td>0.2–0.7</td>
</tr>
<tr>
<td>IRC</td>
<td>0.1–0.9</td>
<td>0.4$^{II}$, 0.6$^{III}$, 0.5$^{IV}$, 0.5–0.7$^{VII}$</td>
<td>0.5</td>
</tr>
<tr>
<td>LZSN</td>
<td>0.01–0.01</td>
<td>5$^{II}$, 4.5$^{III}$, 1.3–2.91$^{IV}$, 6$^{VI}$, 3.8–5$^{VII}$</td>
<td>6.0–9.0</td>
</tr>
<tr>
<td>UZSN</td>
<td>0.01–10</td>
<td>0.5$^{II}$, 0.5–1.22$^{III}$, 1.13$^{IV}$, 0.43–0.72$^{VII}$</td>
<td>0.2</td>
</tr>
<tr>
<td>LZETP</td>
<td>0–2</td>
<td>0.5$^{II}$, 0.1–0.8$^{III}$, 0.5$^{IV}$, 0.2$^{VI}$, 0.27–0.8$^{VII}$</td>
<td>0.2</td>
</tr>
<tr>
<td>DEEPFR</td>
<td>0–1.0</td>
<td>0.1$^{II}$, 0.0$^{III}$</td>
<td>0.05</td>
</tr>
</tbody>
</table>

*Parameter definitions (Bicknell et al. 2001): AGWRC, groundwater recession rate, day$^{-1}$; INFILT, index to soil infiltration capacity, inch/h; IRC, interflow recession rate, none; LZSN, lower zone nominal soil moisture storage, inch; UZSN, upper zone nominal soil moisture storage, inch; LZETP, index to lower zone evapotranspiration, none; DEEPFR, fraction of groundwater inflow that will enter deep groundwater, none.

$^a$Bicknell et al. (2001); $^b$Doherty et al. (2003); $^c$Kim et al. (2007); $^d$Im et al. (2003); $^e$Al-Abed et al. (2002); $^f$Ryu (2009); $^{VII}$Xu (2007).
Figure 10 | Monthly validation for pollutant concentration in stream.

Figure 11 | Comparison of monthly average constituent concentration at Wulongji station.
Figure 12 | The annual monthly percentage for NPS and PS contribution to reservoir.
PS pollution could be more than 80% for TN and TP, and more than 90% for COD. This is mainly because in the winter the rainfall is too little to transport NPS pollution into the reservoir, while in the summer the intensive rainfall could wash off the contaminants accumulated on the land surface and transport them into the rivers and reservoirs. The annual average contributions for PS and NPS are shown in Figure 13. The PS pollution is the major source for COD contribution in the river and reservoir. It accounts for about three-quarters of the total COD loadings to the water body. The NPS pollution loadings are slightly less than the PS pollution for TN and TP in this watershed. The higher PS contributions, especially the extremely high COD contributions from the PS source, imply that the intensified industrial development with insufficient control is still the major problem in the basin. To ensure a healthy water supply source for Tianjin City, mitigation measures for COD loadings from the industrial sector is very important for reducing the COD levels in Panjiakou Reservoir. For TN and TP loadings, nearly half of the loadings are from the agriculture sector. Therefore, effective management measures like BMP should be taken into consideration to reduce the pollution loadings from agriculture and free-range farming.

### DISCUSSION AND CONCLUSIONS

The LSPC model was applied for a watershed in the northeast of China. The hydrological model was developed and validated using observed data from 2006 to 2010. The evaluation index for the performance of the hydrological model, namely, $R^2$, NSE and IA are all above 0.7 for daily scale modelling. It indicates that the hydrological model has sufficient accuracy to represent the characteristics of the watershed. Based on the validated hydrological model, the water quality model was developed based on the PS data provided by HWCC and the NPS pollution loadings estimated based on land use characteristics. The validation of the water quality model was conducted on a monthly basis. The indices of $R^2$, NSE and IA for the evaluation of the performance of the water quality modelling are 0.689, 0.641 and 0.979, respectively, which indicate a sufficient accuracy for the partitioning of PS and NPS pollutions. From this study, the following conclusions have been obtained:

1. More than three-quarters of COD of the annual loadings are from the PS, mainly from the industrial sector in the basin.
REFERENCES


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