Assessment of water quality under changing climate conditions in the Haihe River Basin, China

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Abstract For the purpose of underpinning the technical requirements of saving energy and reducing emissions, this study attempts to construct a model, which aims to demonstrate the process of “pollutant production–discharge into rivers–transformation–discharge into seas” by choosing regular pollution indices as a research objective on a macroscale for a long period. This study focuses on the construction, calibration and verification of an integrated simulation model on water quantity and water quality for the Haihe River Basin, China, which has serious water shortages and pollution. The basin is divided into smaller units, including 3067 sub-basins and 11 752 contours, and in each unit pollutant loads are evaluated. The model has sufficiently high precision that it can be used to support water resources protection and water environment management. The study reported herein produced initial outcomes of the water pollution equilibrium status and made a preliminary exploration into integrated management of water resources and pollutant balance. The results indicated that the water quality has been degrading since the 1980s and is projected to continue to degrade in the context of climate change. The underlying reason behind the current situation is the continued pollutant discharge into the river, particularly during dry seasons when the low flow is insufficient to dilute the pollution. Concurrent with the river water quality degradation, groundwater and soil pollution further deteriorated. Therefore, it is advisable for the relevant departments (soil or land management and groundwater) to focus on controlling pollutant sources and remediation of contaminated areas.

Key words water quantity; water quality; assessment; China

1 INTRODUCTION

Water shortage is a major concern in North China. Some notable observations include the discontinuous flow of some rivers and the continuous discharge of wastewater from cities and industry into rivers, lakes and wetlands, resulting in serious pollution and water-quality degradation of surface water, soil water and groundwater. Pollutants in soils and groundwater are difficult to evaluate and they are a long-term threat to basin water resources, the water environment and water ecology. It is difficult to determine how rapidly pollutant transport will occur and what the factors are that will affect the transport from macroscopic scale studies. Modelling is needed to extrapolate groundwater pollutant transport.

Many water-quality models have been developed during the last 20 years, including Qual2e (Brown & Barnwell, 1987), MIKE11 (DHI, 2001; Kojiri & Ikebuchi, 1998), SHETRAN (Ewen et al., 2000) and SWAT (Arnold, 1995), which provide a good basis for the integrated assessment of water quantity and water quality. However, these models have been developed for specific purposes with limitations with respect to the functionality required for a holistic integrated water resources assessment and management, e.g. some models like Qual2e and MIKE11 consider many pollutant issues but are only suitable for water-quality problems in freshwater river systems.

Natural hydrological cycle simulation is simpler and more precise compared with that in areas strongly influenced by human activities. Also, water pollution process simulation tends to be more complicated when accounting for human activities. Moreover, water-quality simulation in river courses is easier than that within the whole river basin. In order to support energy-saving targets and environmental protection, this study evaluates COD and NH3-N in a water-quality simulation on medium to long timescales (monthly, yearly). A model was developed to describe the pollutant process and to meet the planning requirements for water pollution protection and treatment.
2 MODEL AND APPROACH

Numerical models are needed to evaluate pollutant transfer in river basins with support field investigations. A framework of a newly developed water-quality model is shown in Fig. 1. The water-quality model is based on a distributed hydrological model and includes three modules, i.e. pollutant production, pollutant transport into the river, and pollutant transformation in the river.

2.1 Distributed hydrological model

The boundary condition of water flow for the water-quality model is provided by WEP-L (Water and Energy transfer Processes for Large basins), a distributed hydrological model. The water-quality module of WEP-L simulates processes of point sources, non-point sources, and pollutant advection and transfer in river channels.

The distributed hydrological model WEP-L is used to simulate the hydrological processes. It is based on the WEP model (Jia et al., 1998, 2001). The model includes a vertical component with an interception layer of vegetation and buildings, storage layer in ground depressions, topsoil, a transition layer, and shallow and deep groundwater from top to bottom. A “mosaic” method is applied to incorporate land-use heterogeneity by classifying land use into bare land, vegetation, irrigated farmland, non-irrigated farmland, open water, and impervious areas for calculation of water and heat fluxes across and through the land surface.

WEP-L takes “contour strips within sub-basins” as simulation units in its horizontal structure. Runoff routings on slopes and in streams are carried out based on the elevation, gradient and the Manning roughness by applying a 1-D kinematic wave approach or dynamic wave approach. Numerical analysis is made for groundwater flow in the mountains and plains, separately, considering exchange of groundwater with surface water, soil moisture and streamflow. For more details about WEP-L see Jia et al. (2010).

2.2 Pollutant production

Pollutant sources can be divided into point and non-point. Point sources include industry and human. Point source loads are estimated using the quota method; the industrial point source load is determined by GDP and human point source load is determined by population density.

Non-point pollution includes: (a) runoff from urban; (b) farmland with fertilizer and pesticide application; (c) rural domestic sewage and solid waste; (d) soil erosion; and (e) waste sewage of livestock and poultry. Soil and sediment can absorb and carry many pollutants, such as phosphorus, nitrogen and metals. Consequently, soil erosion and sediment transport, which are important for water-quality modelling, were also simulated. This study adopts the US Department of Agriculture (USDA) Universal Soil Loss Equation (USLE) to calculate soil loss from each of the 29 types of land cover (Fernandez et al., 2003).
2.3 Pollutant transport into the river
Untreated point source pollution is discharged into rivers. Non-point pollution discharged into rivers was generalized as local runoff into rivers based on results of the water cycle model. Pollutant load into a river reach was computed as the point source load multiplied by a coefficient. The transfer coefficient into a river reach was estimated using data and results from scientific investigations in various districts.

2.4 Pollutant transformation in the river
Because of the long temporal and large spatial scales addressed in this study, a 1-D river channel water-quality model was used. In this model, the following were considered: point and non-point source pollution; the advection of pollutants in the river without considering the discrete processes; sediment transport and deposition and the release of sediment-bound pollutants in a tank model; and the self-purification of the river as described by a comprehensive attenuation coefficient.

3 APPLICATION IN STUDY AREA
The Haihe River Basin is one of the river basins with the most serious water shortage in China. The basin has a per capita quantity of water resources of 293 m³, ranking last of the 10 major river basins in China. Subject to extreme pressure from social and economic water demand, water users in the Haihe River Basin have excessively developed water resources and discharged extremely large quantities of wastewater, causing major environmental problems. Among the 55 major rivers in the Haihe River Basin, 49 are seriously polluted, and the river length having the poorest rating (Grade V) accounts for 58.7% of the total river length, ranking the worst in the country. The situation in the Haihe River Basin is severe: “All rivers are dried up, all waters are polluted and overdraft depression cones prevail in the whole area”. Both water shortage and water-quality deterioration have constrained the socio-economic development in the basin. Integrated water resources and water environment management is needed in the basin, and this would be best served by a comprehensive integrated assessment of water quantity and water quality.

3.1 Study area introduction
The Haihe River Basin is located at 112°E–120°E longitude and 35°N–43°N latitude. Its total area is 318 000 km², and it is subdivided into 170 000 km² of mountainous area and 150 000 km² of lower relief plains. In 2005, the population, GDP and food products in the basin accounted for 10.2%, 14.1% and 9.9% of the respective totals for China (Ren, 2007).

The Haihe River Basin is shown in Fig. 2, in which WRA2 and WRA3 denote the 2nd-level national water resources assessment sub-basin and the 3rd-level in China, respectively. There are four 2nd-level sub-basins and 15 3rd-level sub-basins. The Haihe River originates in the western Taihang Mountains and traverses to the eastern Bohai Sea, running through Beijing City, Tianjin City, Hebei Province, Shanxi Province, Shandong Province, Henan Province, Liaoning Province and the Inner Mongolia Autonomous Region. The basin contains 35 municipalities and 26 large cities (>0.5 million people each).

3.2 Model calibration
On the basis of a 1-km DEM (digital elevation model) and the digitized hydrography, 3067 sub-basins were plotted for the Haihe River Basin. Then 1–10 contour belts were carved in every sub-basin, giving 11 752 contour belts subdividing the whole basin.

A comparison of simulated and observed annual runoff by the WEP-L hydrological model indicate that average errors are <10%, Nash-Sutcliffe efficiency of monthly runoff at the main gauge stations is >60%, and the correlation coefficient of monthly runoff at the various gauging stations is >80%. A comparison of results for the monthly runoff at Huangbizhuang station is shown in Fig. 3. For additional details, see Jia et al. (2010).
The pollutant source investigation is based on the results of the Comprehensive Water Resources Planning of China carried out from 2002 to 2006. It includes both point and non-point source investigations. The remaining contributions to the COD and NH₃-N loads are from non-point sources.

Generally, COD₉₅ was selected as the pollutant source evaluation index, whereas COD_Mn concentration was monitored at the water-quality stations. The relationship between COD_Mn and COD₉₅ is evaluated in this paper. The results indicate that COD₉₅ is about four times COD_Mn. This relationship is the basis for the water-quality model calibration. The validation of water-quality simulation is carried out in this study. Figures 4 and 5 show an example of simulated and observed concentrations of COD and NH₃-N at stations in the Haihe River Basin. They indicate that the simulated concentration is close to the observed value when the values are low, but they are not similar for the extreme values. The concentration extremes occur concurrently with pollution accidents/spills or when the river dries up, and these processes are extremely difficult to simulate with the limited available data.

3.3 Assessment of water quality in the Haihe River Basin

Because the water-quality model is based on distributed spatial regions, pollution loading in the Haihe River Basin can be simulated and evaluated according to a spatial classification. The pollution loading amount classification for 2000 is listed in Table 1.
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Fig. 4 Simulated and observed COD$_{Me}$ at the Huangbizhuang station in the Haihe River Basin.

Fig. 5 Simulated and observed NH$_3$-N at the Guojiatun station in the Haihe River Basin.

Table 1 COD pollution loading amount classification in the Haihe River Basin during 2000 (unit: 10 000 t).

<table>
<thead>
<tr>
<th>Classification</th>
<th>Items</th>
<th>COD</th>
<th>NH$_3$-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources</td>
<td>Point</td>
<td>224.5</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>Non-Point</td>
<td>719.8</td>
<td>76.2</td>
</tr>
<tr>
<td>Urban / rural area</td>
<td>Urban</td>
<td>232.2</td>
<td>22.4</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>712.1</td>
<td>75.5</td>
</tr>
<tr>
<td>Topography</td>
<td>Mountains</td>
<td>221.7</td>
<td>31.8</td>
</tr>
<tr>
<td></td>
<td>Plains</td>
<td>722.6</td>
<td>66.1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>944.3</td>
<td>97.9</td>
</tr>
</tbody>
</table>

For those pollutants discharged by the river, the model incorporates pollutant mass balance as follows:

\[
W_{sea} = W_{in} - W_{d1} - W_{d2} + W_{out} - W_{k} - W_{u}
\]

Where $W_{sea}$ is the pollutant load discharged into sea, $W_{in}$ is the pollutant load discharged into river, $W_{d1}$ is the pollutant load deposited in the channel, $W_{d2}$ is the pollutant load deposit due to a decrease in streamflow, $W_{out}$ is the pollutant load released from suspended sediment, $W_{k}$ is the pollutant load degraded along the channel, and $W_{u}$ is the pollutant load removed by humans. The equilibrium of the pollution loading of the Haihe River Basin in 2000 is shown in Fig 6.
In 2000, the COD discharged into the Haihe River Basin was 1.7 Mt (Fig. 6). The amount of the COD deposited due to the decrease in river flow was 0.3 Mt and release of sediment-bound COD was 0.21 Mt. Therefore, the total COD associated with sediment is 0.51 Mt, which is 30% of the river pollution load. The self-purification load is 0.53 Mt, which is 31% of the river pollution load. The COD discharged by agriculture and industry was 0.5 Mt, which is 29% of the river pollution load. Pollutant discharged into sea accounts for 29% of the river pollution load or 0.34 Mt. By the end of 2000, the amount of COD stored in the sediment was 2.27 Mt.

4 CONCLUSIONS

On the basis of the distributed hydrological model WEP-L and a water-quality module for large basins, an integrated model of water quantity and quality was developed. The model incorporates estimates of point and non-point sources of pollutants discharged into the Haihe River. The aim of the modelling effort is to use the model for pollution prediction and management. The model may be used to support integrated water and environment planning, though the model and application need further improvement.

The integrated model of water quality and quantity of the Haihe River Basin was calibrated and verified. The water quality status was evaluated based on the water-quality model. The results of applying the model in the Haihe River Basin show that the actual water quality status is worse than has been suggested from traditional investigations, and water quality in sub-basins is better than that of the main channel. The results also provide a pollutant balance for water resources development and management in the basin.

However, research is needed to improve the model, including additional data collection to properly calibrate model parameters, to enhance the model with respect to the migration and transformation of pollutants, to evaluate the impact of groundwater quantity and quality on the river, to evaluate the impacts of reservoir operation and to evaluate impacts of sewage treatment and discharge.

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REFERENCES


