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Water quantity and quality optimization modeling of dams operation based on SWAT in Wenyu River Catchment, China

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Abstract Water quantity and quality joint operation is a new mode in the present dams' operation research. It has become a hot topic in governmental efforts toward integrated basin improvement. This paper coupled a water quantity and quality joint operation model (QCmode) and genetic algorithm with Soil and Water Assessment Tool (SWAT). Together, these tools were used to explore a reasonable operation of dams and floodgates at the basin scale. Wenyu River Catchment, a key area in Beijing, was selected as the case study. Results showed that the coupled water quantity and quality model of Wenyu River Catchment more realistically simulates the process of water quantity and quality control by dams and floodgates. This integrated model provides the foundation for research of water quantity and quality optimization on dam operation in Wenyu River Catchment. The results of this modeling also suggest that current water quality of Wenyu River will improve following the implementation of the optimized operation of the main dams and floodgates. By pollution control and water quantity and quality joint operation of dams and floodgates, water quality of Wenyu river will change significantly, and the available water resources will increase by 134%, 32%, 17%, and 82% at the downstream sites of Sha River Reservoir, Lutong Floodgate, Xinpu Floodgate, and Weigou Floodgate, respectively. The water quantity and quality joint operation of dams will play an active role in improving water quality and water use efficiency in Wenyu River Basin. The research will provide the technical support for water pollution control and ecological restoration in Wenyu River Catchment and could be applied to other basins with large number of dams. Its application to the Wenyu River Catchment has a great significance for the sustainable economic development of Beijing City.

Keywords SWAT · Dams operation · Water quantity and quality · Wenyu River Catchment

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Introduction

Water quantity and quality joint operation of dams and floodgates is one of the effective approaches for water pollution control and ecological restoration in dam-crowded basins (Zhang et al. 2007). Currently, dams are an important means to meet water and energy needs and support economic development (Sule 1988; Mugabe et al. 2003; Feder 2004; Xie 2004; Wei et al. 2009). Nearly 50,000 large dams, defined as storage capacity of >1 million cubic meters, have been constructed all over the world by the end of year 1998, with nearly half (22,000) in China (WCD 2000). However, dam construction alters river flow and may increase pollution discharge into river systems. These changes often contribute to rivers running dry, sedimentation, the deterioration of environmental quality, and the decrease in biodiversity (Petts 1979; Topping et al. 2000; Kileshye et al. 2006; Ligon et al. 1995; Jansson et al. 2000; Ewa and Grazyna 2002). Research on new modes of dam and floodgate operation, which increase the positive effects while decreasing the negative effects, is a major goal of dam and floodgate management.

Dam design and operation typically focuses on its social functions, such as flood control, electricity generation, water supply, irrigation, and aquaculture (WCD 2000). The maximum social and economic benefits are usually selected as the optimization objective (Dong et al. 2007). Currently, the methods most widely used to optimize dam operation are dynamic programming method (Little 1955), multi-objects analysis (Yang and Liu 2001), decomposition and coordination of large scale systems (Turgeon 1981), genetic algorithms (Ahmed and Sarma 2005), and artificial neural networks (Karamouz and Houck 1982). Along with increased human activities in basins, the negative impacts of dams and floodgates on riverine ecology and environments have become more apparent in recent years. Some new operation modes, which address these issues more directly, are beginning to emerge, such as ecological water quantity and quality joint operation (Hayes et al. 1998; Shirangi et al. 2008), ecological operation (Symphorian 2002; Griphin et al. 2003), and water–sand joint operation (Deng et al. 2000). At present, such alternative remain at the stage of the theoretical research and preliminary attempts (Lv 2006).

Soil and Water Assessment Tool (SWAT) is a river basin, or watershed, scale model with strong physical mechanism developed by Jeff Arnold for the American Ministry of Agriculture Research Bureau (Arnold et al. 1998; Neitsch et al. 2002). There are some specific models that contributed significantly to the development of SWAT, such as CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al. 1987), EPIC (Erosion-Productivity Impact Calculator) (Williams et al. 1984), and QUAL2E (Enhanced Stream Water Quality Model) (Brown and Barnwell 1987). SWAT is easy to use and has been applied to watersheds in many countries and regions (Santhi et al. 2006) and the research areas include hydrologic assessment, pollutant migration and loss (e.g. N and P), climate change impact, sensitivity, and calibration and uncertainty analysis (Gassman et al. 2007). After more than 10 years of development and improvement, some modified SWAT models have emerged, with notable examples including SWAT-G (Lenhart et al. 2002), Extended SWAT (ESWAT) (van Griensven and Bauwens 2003, 2005), and Soil and Water Integrated Model (SWIM) (Krysanova et al. 1998, 2005). Wang et al. (2008) developed several auxiliary tools for SWAT, such as the water quantity analysis tool, parameter calibration tool, scenario analysis tool, and result display interface, which are very useful to overcome the limitation of AVSWAT2000. These tools are now widely used in the integrated water resources and environment management of Hai River Basin supported by the World Bank. Based on the specific characteristics of basins in China, Zhang et al. (2010) extended the water balance module of reservoir and the water quality module in the SWAT model by including dam and floodgate operation rules and chemical oxygen demand (COD) as an important water quality index. This extended model has been successfully applied to Huai River Basin. Sang et al. (2008) developed the agriculture management module and consumptive water use module of SWAT and applied the updated model to analyze the water resources in Tianjin City, China, a case where water cycling is strongly affected by human activities. Dai and Cui (2009) incorporated the irrigation water movement, paddy field water balance, and improved rice yield modules into SWAT model in order to account for both the effect of canal seepage on the supply of groundwater and the effect of ponds on irrigation. However, the unique problems associated with optimization of dam operation in dam-crowded basins remain as the most serious roadblock to the application of SWAT in China.

The purpose of this paper was to develop a water quantity and quality joint mode of dams and floodgates operation, at the basin scale, based on SWAT. Wenyu River, the mother river of Beijing City, China was selected as a study area for this new model. The first part describes the water quantity and quality joint mode of the dams and floodgates' operation mode (QCmode) and the hydrologic module of SWAT, especially as it relates to the water balance of dams. The method of linking QCmode to SWAT model and use of Genetic Algorithm (GA) to resolve the coupled model will also be discussed. The second part applies this QCmode-SWAT model to data from Wenyu River Catchment and explores the optimization of operation of the main dams or floodgates in different pollutant discharge scenarios. This research will provide the technical support for water pollution improvement and the ecological restoration for integrated basin management in Wenyu River Catchment. Moreover, it will be the foundation for the sustainable development of Beijing City in the future.

Materials and methods

The water quantity and quality optimal operation model of dams and floodgates based on SWAT will contain three parts. The first part is the distributed hydrology and water quality model (SWAT) coupling the operation of dams and floodgates. This part is the base of the whole model and is helpful to recognize hydrologic and pollutant variation at the basin scale and provide all the boundary conditions for dam operation. The second part is the optimal operation model of dams and floodgates, which will be developed to reach two objectives, viz. maximizing available water resources and minimizing water pollution. The third part is to couple and resolve distributed SWAT model and the optimal operation model of dams and floodgates. The framework is given in Fig. 1.

Model description

SWAT model

The hydrologic cycle of the SWAT model is based on the water balance equation, which considers the unsaturated zone and shallow aquifer above the impermeable layer as a unit.

$$\mathrm{SW}_t = \mathrm{SW}_0 + \sum_{i=1}^{t} \left(R_{\mathrm{day}} - Q_{\mathrm{surf}} - E_{\mathrm{a}} - w_{\mathrm{seep}} - Q_{\mathrm{gw}}\right) \tag{1}$$

where SW_t is the final soil water content, SW_0 is the initial soil water content, t is the time (days), R_{day} is the amount of precipitation on day i, Q_{surf} is the amount of surface runoff on day i, E_{a} is the amount of evapotranspiration on day i, w_{seep} is the amount of percolation and bypass flow exiting the soil profile bottom on day i, and Q_{gw} is the amount of return flow on day i.

The water balance for dam or floodgate considers the inflow, outflow, precipitation, evapotranspiration, and seepage. The equation is:

$$\begin{aligned} V = {} & V_{\mathrm{stored}} + V_{\mathrm{flow\,in}} - V_{\mathrm{flow\,out}} \\ & + V_{\mathrm{pcp}} - V_{\mathrm{evap}} - V_{\mathrm{seep}} \end{aligned} \tag{2}$$

where V is the water storage in the reservoir at the end of each day; V_{stored} is the water stored volume in the reservoir at the beginning of a day; $V_{\mathrm{flow\,in}}$ and $V_{\mathrm{flow\,out}}$ is the volume of water entering and flowing out of the reservoir during a day, respectively; and V_{pcp}, V_{evap}, and V_{seep} is the precipitation falling into the reservoir, the water removed by evaporation and the water lost volume by seepage, respectively. V_{pcp}, V_{evap}, and

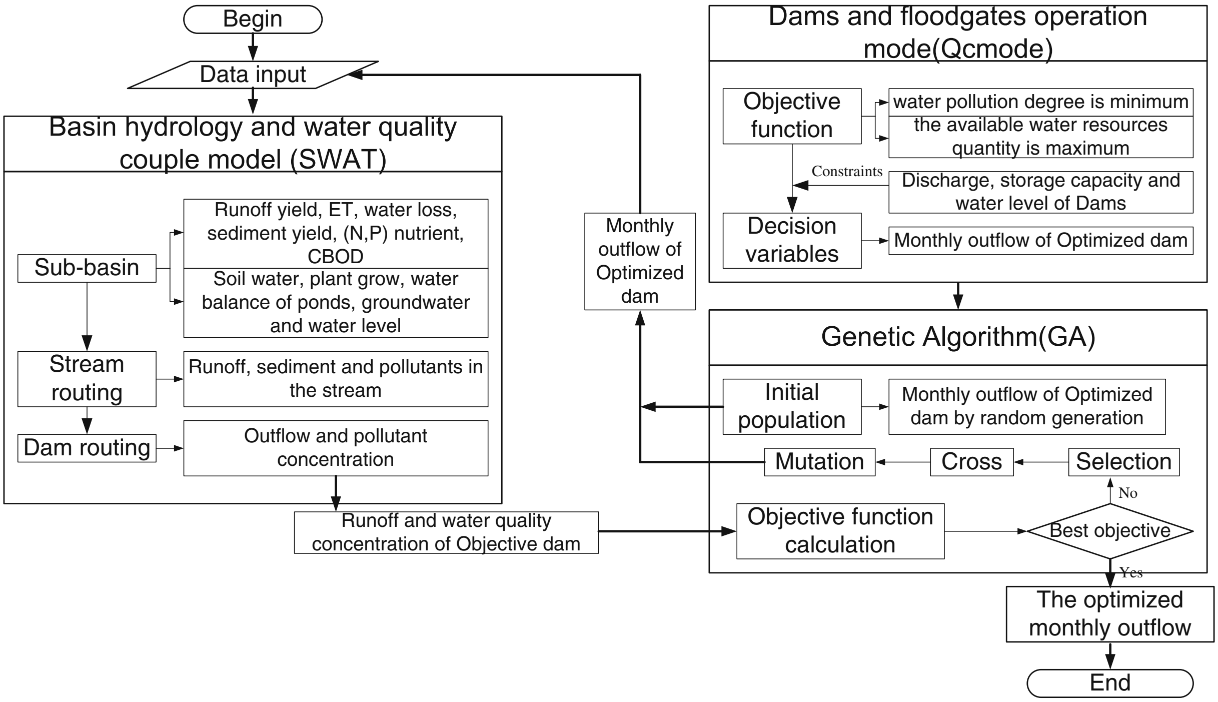

Fig. 1 SWAT-QCmode model flow chart

V_{seep} are functions of the water surface area (SA) of the reservoir:

$$V_{\text{pcp}} = 10 R_{\text{day}} \text{SA} \tag{3}$$

$$V_{\text{evap}} = 10 \eta E_0 \text{SA} \tag{4}$$

$$V_{\text{seep}} = 240 K_{\text{sat}} \text{SA} \tag{5}$$

where R_{day} is the same as in Eq. 1; η is an evaporation coefficient; E_0 is the potential evapotranspiration for a given day; and K_{sat} is the effective saturated hydraulic conductivity of the reservoir bottom. The area of water surface (SA) varies with the change of the water storage in the reservoir. The equation used to update surface area is

$$\text{SA} = \beta_{\text{sa}} V^{\exp \text{sa}} \tag{6}$$

where β_{sa} is a coefficient and expsa is an exponent.

In SWAT, there are four methods to calculate $V_{\text{flow out}}$, viz. measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release (Neitsch et al. 2002). In this study, the optimized outflow mode is the monthly outflow.

The water quality module of SWAT includes the non-point pollutant module (CREAMS), in-stream water quality module (QUAL2E) and the lake and water body water quality module (WASP). In the lake water quality module, SWAT assumes the system is completely mixed, and pollutants are instantaneously distributed throughout the volume as they enter the water body in a completely mixed system. The pollutant balance equation is

$$\begin{cases} V\frac{\mathrm{d}c}{\mathrm{d}t} = W(t) - Qc - vcA_i \\ M_{\text{settling}} = vcA_s dt \end{cases} \tag{7}$$

where V is the water volume in the dam; c is the concentration of a certain pollutant; $\mathrm{d}t$ is the length of the time step; $W(t)$ is the amount of pollutant entering the water body; Q is the rate of water flow exiting the water body; M_{settling} is the mass of pollutant lost by settling; v is the apparent settling velocity; and A_i is the area of the sediment–water interface.

Dams operation mode (QCmode)

The objective of this mode is to simulate and contrast the water quantity and quality processes in different scenarios of multi-dams' operation based on distributed SWAT to control the water pollution and increase the quantity of available water resources.

Objective function

The objective function is:

$$\mathrm{ob} = \max \sum_{i=1}^{T} \left(Q_i^j, - - \frac{C_{si,j}^j}{C_{st}^j} \right) \quad i = 1, 2, \cdots, T \tag{8}$$

where C_{st}^j is the water quality standard of the water function zone according to Chinese Environmental quality standards for surface water (GB 3838 2002); Q_i^j $C_{si,j}^j$ is the available water resources and water quality index concentration at the objective dam, respectively, which can be estimated by SWAT model. In this study, Q_i^j is considered as the total water resources, which reach the water quality standard. $\frac{C_{si,j}^j}{C_{st}^j}$ is the equivalent standard pollution index. An index value of less than or equal to 1.0 means that the water quality is good and meets the standard. An index value of greater than 1.0 means that water body is polluted and the pollution condition increase with the index value. T is the total times for optimizing, and j is the number of the objective dam or floodgate.

Constraints

(1) The minimum discharge of dams and the demand of flood control is:

$$Q_{i,\min}^k \le Q_i^k \le Q_{i,\min}^k, \quad i = 1, 2, \cdots, T \tag{9}$$

where $Q_{i,\min}^k$, $Q_{i,\max}^k$ is the minimum and the maximum discharge under the optimized dam operation at time i, respectively. Q_i^k is the discharge through optimized dams at time i. k is the number of the optimized dams. $Q_{i,\min}^k$ is determined by the environmental flow and water consumption at the downstream. $Q_{i,\max}^k$ is determined by the capacity of flood control at the downstream and the discharge capacity of the optimized dams.

(2) The storage capacity constraint is:

$$V_{i,\min}^k \le V_i^k \le V_{i,\max}^k, \quad i = 1, 2, \cdots, T \tag{10}$$

where $V_{i,\min}^k$, $V_{i,\max}^k$, V_i^k is the minimum, maximum, and actual discharge of the optimized dam operation at time i, respectively. $V_{i,\min}^k$ is determined by the environmental flow and water consumption at the upper stream. $V_{i,\max}^k$ is determined by the water storage capacity of optimized dams.

Coupling method

QCmode is compiled with FORTRAN and coupled in SWAT model. The coupling is flexible by reading in and reading out the txt files while at the same time some source codes and parameters files will be modified, including allocate_parms.f, main.f, rchmon(mdays).f, rchyr.f, rchinit.f, writem.f, writea.f, writeaa.f, modparm.f, etc. codes and the *.res parameters file. The output of QCmode is the monthly outflow of an optimized dam as txt file, which is an input file for SWAT. In addition, the outflow and water quality results (basins.rsv) of the objective dam calculated by SWAT are input file for QCmode as its input and selected the optimal monthly outflow.

Model solution

The solution of the QCmode-SWAT model is a complicated multi-constraints and nonlinear task. GA is employed to resolve this difficulty (Holland 1975). In the model, some key parameters have been set, including the maximum number of generations, the number of variables (monthly outflow), the probability of crossover, and the probability of mutation, for which values are 10, 12, 0.80, and 0.15, respectively.

Study area and data

Description of study area

Wenyu River Catchment is located in Beijing City, China and is the most intensive area of human activity in Hai River Basin (Fig. 2). Wenyu River, originates in the south of Yan Mountain and flows from north to south though Haidian, Changping, Shunyi, Chaoyang, and Tongzhou Districts, all of which are in the core area of Beijing City, and the main stream is 47.5 km. Of all the main streams of Beijing City, Wenyu River is the only river which originates in the border and it never runs dry. As a result, Wenyu River is usually called the mother river of Beijing.

The total area of Wenyu River Catchment is 2,478 km^2 and the main land uses are forest, agriculture, and urban, which represent 35.6%, 30.8%, and 25.7% of the total area, respectively. The predominant soil type is cinnamon (53.5% of the total area). The average annual temperature is 11.6°C. The average annual precipitation is 581.7 mm (for years 1956–2000), most of which (more than 80% the total precipitation) is concentrated in June to September (the flood season). The average annual

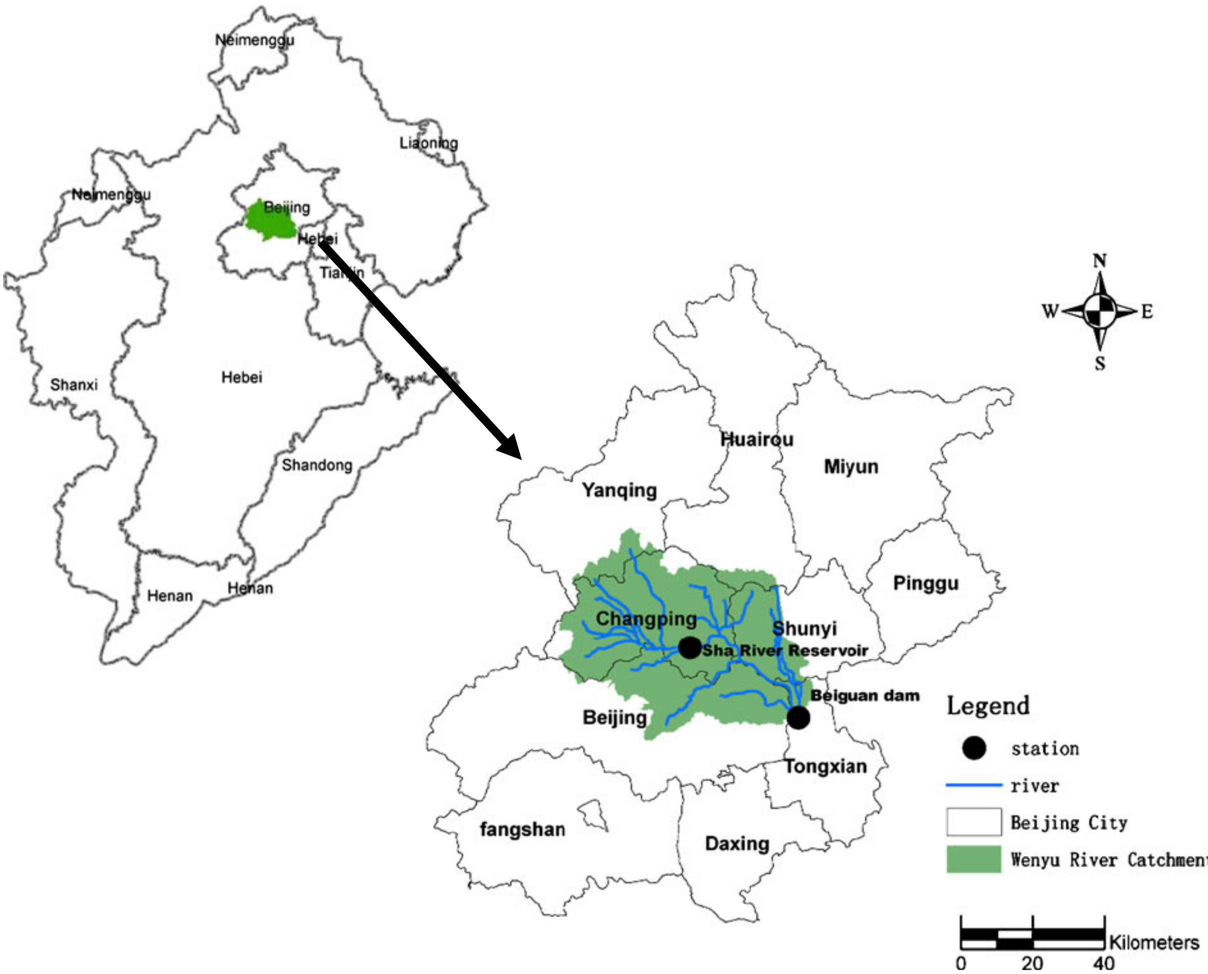

Fig. 2 Location of Wenyu River catchment in Beijing City, China and the corresponding monitoring sections

water surface evaporation is 1,175 mm, nearly twice the average annual precipitation. The average annual runoff is 0.450 billion cubic meters.

More than ten dams and floodgates have been constructed to control the water supply and flooding of Beijing City, and the operation of these dams and floodgates have changed the natural hydrologic characteristics dramatically. Moreover, there are only two water functions in Wenyu River Catchment divided by Lutong floodgates based on the quality standard of water supply. The upper stream of Lutong floodgates is entertainment water supply zone and the water quality standard is class four (NH_4–N, 1.5 mg/L; COD_{Mn}, 10 mg/L) of national standard (GB 3838 2002). The down stream of Lutong floodgates is agricultural and environmental water supply zone and the water quality standard is Class five (NH_4–N, 2 mg/L; COD_{Mn}, 15 mg/L). However, as the main pollutant discharge canal, the water quality in all the rivers exceeded the standard and their ecosystem has deteriorated. The ecology and environmental restoration of Wenyu River Catchment has become a very urgent task, and it will be restricted by the sustainable development of Beijing City.

Data collection

Historical data were collected from the meteorological, hydrologic, environment protection, urban development, economic, and agriculture departments in Beijing City. For the hydrologic simulation, we collected 2 years (2004 and 2005) of daily meteorological data (precipitation, wind speed, maximum and minimum temperature, relative humidity, and sunshine hours) from eight stations and monthly outflow data of Sha River Reservoir and Beiguan floodgate. We also collected the annual runoff with the different assurance rates (P = 50%, 75%, and 95%) for Sha River Reservoir, Lutong floodgate, and Beiguan floodgate. For the water quality simulation, we collected the annual treatment capacity of the main sewage treatment plants, the pollution discharge data from the outlets, and the water quality monitoring data in Sha River Reservoir and Beiguan floodgate in 2005. Moreover, the basin attributes information of DEM, land use map, soil map, dams, and floodgates regulation were also collected. All the data used for this research are shown in Table 1.

Table 1 Model input data sources

Data type	Scale	Source	Data discription
Topography	1:24,000 (grid, 90 m)	USGS	Elevation, Channel slopes, Lengths
Land use map	1:1,000,000	Institute of Geographic Science and Natural Resources Research	Land use classifications
Soil map	1:4,000,000	Institute of Geographic Science and Natural Resources Research	Soil physical properties such as bulk density, texture, saturated conductivity, etc.
Weather	8 stations	Beijing Weather Bureau	Daily precipitation, wind speed, maximum/minimum temperature relative humidity sunshine hours
Hydrology	2 stations	Beijing hydrologic station	Monthly outflow
Dams	10 dams	Beijing Hydraulic Research Institute	The reservoir's design data attribute parameters
Environment		Beijing Hydraulic Research Institute	Water quality standard
			The outlets and the discharge data
			Monthly water quality monitoring data

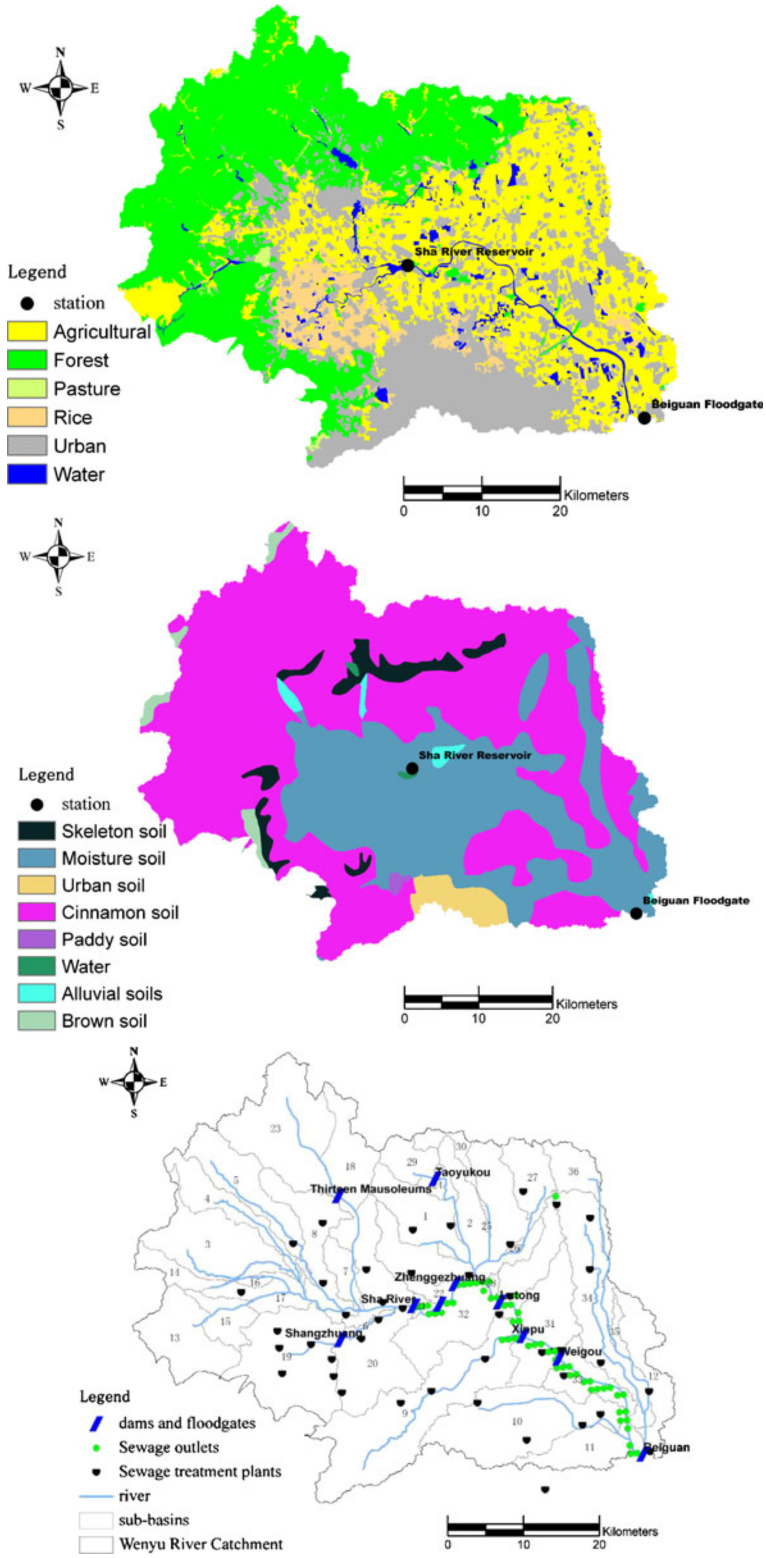

Fig. 3 Digitized land use, soil type and streams, the sub-basin delineation, and location of dams and floodgates, sewage outlets and sewage treatment plants

Model setup and evaluation

Model setup

The Arc View-Geographic Information System interface of the SWAT2000 version (Di Luzio and Arnold 2004) was used to develop the SWAT model of Wenyu River Catchment.

The catchment was divided into 36 sub-basins according to hydrologic stations, water quality stations, the position of dams and floodgates, the water function zones, and the discharge zones. The sub-basin threshold area was 2,000 ha. Beiguan floodgate was selected as the outlet of the whole basin. The hydrologic response unit (HRU), which is a unique combination of soil and land use overlay in the sub-basins (Neitsch et al. 2002), is the minimum calculative smallest unit of hydrologic process. With a threshold value of 10% for land use and soil types, the total number of HRUs was 126 (Fig. 3).

Moreover, 94 sewage outlets along the river and 55 sewage treatment plants in the catchment were added in the model as inlets. Beiguan Floodgate, Shangzhuang Floodgate, Sha River Reservoir, Shangxing Dam, Zhenggezhuang Dam, Thirteen Mausoleums Reservoir, Lutong Floodgate, Taoyukou Reservoir, Weigou Floodgate, and Xinpu Dam were added in the model as the outlets of sub-basins. Thirteen Mausoleums Reservoir and Taoyukou Reservoir were perennially closed, and the streams below the dams were dry. These two reservoirs cut off the water recharge from the upper stream. As a result, we set the outflow simulation code to the measured monthly outflow (IRESCO = 1) in their control files (*.res), and the monthly outflows are 0.0. The inflow and outflow data of Shangzhuang Floodgate, Shangxing Dam, Weigou Floodgate, and Xinpu Dam are deficient because they are too small and therefore have no monitoring data. We selected the average annual release rate for uncontrolled reservoir method (IRESCO = 0) and modified the reservoir's design data including reservoir surface area (RES_ESA) and volume of water (RES_EVOL) as the water level reaches the emergency spillway and surface area of reservoir (RES_PSA) and

Table 2 Hydrologic and water quality sensitive parameters of SWAT model of Wenyu River Catchment

Model processes	Name	Description	Range of values	Fil
Hydrology	CN2	SCS runoff curve number for moisture condition II	(43,96)	.mgt
	ESCO	Soil evaporation compensation factor	(0.005,0.845)	.hru
	EPCO	Plant evaporation compensation factor	(0.005,0.845)	.hru
	SOL_AW	Available water capacity of the soil layer (mm/mm soil)	(0.10,0.25)	.sol
	SOL_K	Soil conductivity (mm/h)	(0.05,1.68)	.sol
	SOL_Z	Soil depth	(96,1040)	.sol
Water quality	BSETLR	COD settling rate in reservoir[a]	(−100,100)	.lwq
	NSETLR	Nitrogen settling rate in reservoir	(−500,5.5)	.lwq
	RK1	CBOD deoxygenation rate at 20°C	(0.0,3.4)	.swq
	RK3	Settling loss rate of CBOD at 20°C	(−0.10,0.36)	.swq
	BC1	Rate constant for biological oxidation of ammonia nitrogen at 20°C	(0.05,0.10)	.swq
	BC3	Local rate constant for hydrolysis of organic nitrogen to NH_4^+ at 20°C	(0.20,0.40)	.swq
	CtoB	Biodegradability of river water[b]	(1.2,2.3)	.swq
	ERORGN	Organic nitrogen enrichment ratio	(1.8,3.5)	.hru
	ECBOD	cbod enrichment ratio*	(0.1,1.5)	.hru

[a,b]The added parameters in the improved SWAT

Table 3 The evaluation indices

Definition	Reference	Comments
$\mathrm{re}=\frac{\sum(O_i S_i)}{\sum O_i}$	Relative error	The optimal statistical value is close to 0
$\mathrm{r}=\frac{\sum\left(O_i-\overline{O}\right)\cdot\left(S_i-\overline{S}\right)}{\sqrt{\sum\left(O_i-\overline{O}\right)^2\cdot\sum\left(S_i-\overline{S}\right)^2}}$	Correlation coefficient	The optimal statistical value is close to 1
$\mathrm{NSEC}=\frac{\sum(O_i-S_i)^2}{\sum\left(O_i-\overline{O}\right)^2}$	Nash-Sutcliffe coefficient (Nash and Sutcliffe 1970)	The optimal statistical value occurs when the value does reach 1

O is the observed value; $\overline{O}$ is the average observed value; S is the simulated value; $\overline{S}$ is the average simulated value

volume of water (RES_PVOL) as the reservoir is filled to the principal spillway in their control files (*.res).

Model evaluation

Fifteen sensitive parameters (six hydrologic parameters and nine water quality parameters) that may have a potential influence on river flow and water quality were selected (Table 2) (Arnold et al. 1998; Eckhardt and Arnold 2001; Lenhart et al. 2002; van Griensven et al. 2006; Bärlund et al. 2007). The ranges of these parameters were obtained from the SWAT manual (Neitsch et al. 2002). The hydrologic parameters were calibrated to match the simulated and observed monthly flow data at Sha River Reservoir and Beiguan Floodgate from 2004 to 2005. Runoffs with different assure rates at Sha River Reservoir, Lutong Floodgate, and Beiguan Floodgate were used for validation. For the water quality parameters, the observed data of ammonia nitrogen (NH_4–N) and chemical oxygen demand (COD_{Mn}) at Sha River Reservoir and Beiguan Floodgate were used for calibration.

Several evaluation indices, including the relative error (re), correlation coefficient (r), and Nash–Sutcliffe coefficient (NSEC), were used to evaluate the model performance (Romanowicz et al. 2005) (Table 3). For the runoff simulation, if the correlation coefficient and NSEC coefficient are ≤ 0.0, and the relative error is >0.15 or <-0.15, the model prediction is considered "unacceptable or poor." If the correlation coefficient and NSEC coefficient are 1.0 and the relative error is 0.0, the model prediction is considered "perfect." If the relative error is >0.6, the NSEC coefficient is >0.5, and the relative error is between -0.15 and 0.15 the prediction was considered "acceptable." Each of these categories followed the criteria used by Santhi et al. (2001). Because the error of runoff simulation will affect the simulated results of water quality directly and the monitoring data is limited, if the relative error is between -30% and 30% and the correlation coefficient is greater than 0.40 for water quality, the prediction was considered "acceptable".

Results

Calibration and validation

At Sha River Reservoir, the observed monthly inflow is set as the objective for calibration and the observed outflow is an input of SWAT model as the reservoir's discharge, and the outflow simulation code is changed to the measured monthly outflow (IRESCO = 1) in the control file (.res) of Sha River Reservoir. This is a good way to avoid the simulated error's effect on runoff simulation at the downstream. For water quality simulation, the objective is the observed monthly value at upper stream of the reservoir. Sha River Reservoir is located at the upper stream of Weyu River, and its main function is to ensure the irrigation water demand. Unfortunately, there were no statistical data available for this area. As a result, the simulated peak flow is much less than the observed value, which causes the relative error and NSEC coefficient to be less precise, but the correlation between simulated runoff and observation is acceptable. If the flow peak is assumed to an outlier, and hence excluded from the statistical analyses, the relative error (−0.03) and NSEC coefficient (−0.91) will increase significantly. Due to the overestimate of runoff and the shortage of water quality observed data, both NH_4–N and COD_{Mn} simulated concentrations are underestimated, but the values of re and r are less than or very close to the acceptable standard.

For the "Sha River Reservoir-Beiguan Floodgate" region, the hydrologic and water quality parameters are calibrated based on the monthly outflow and water quality data observed at Beiguan Floodgate. The simulated runoff

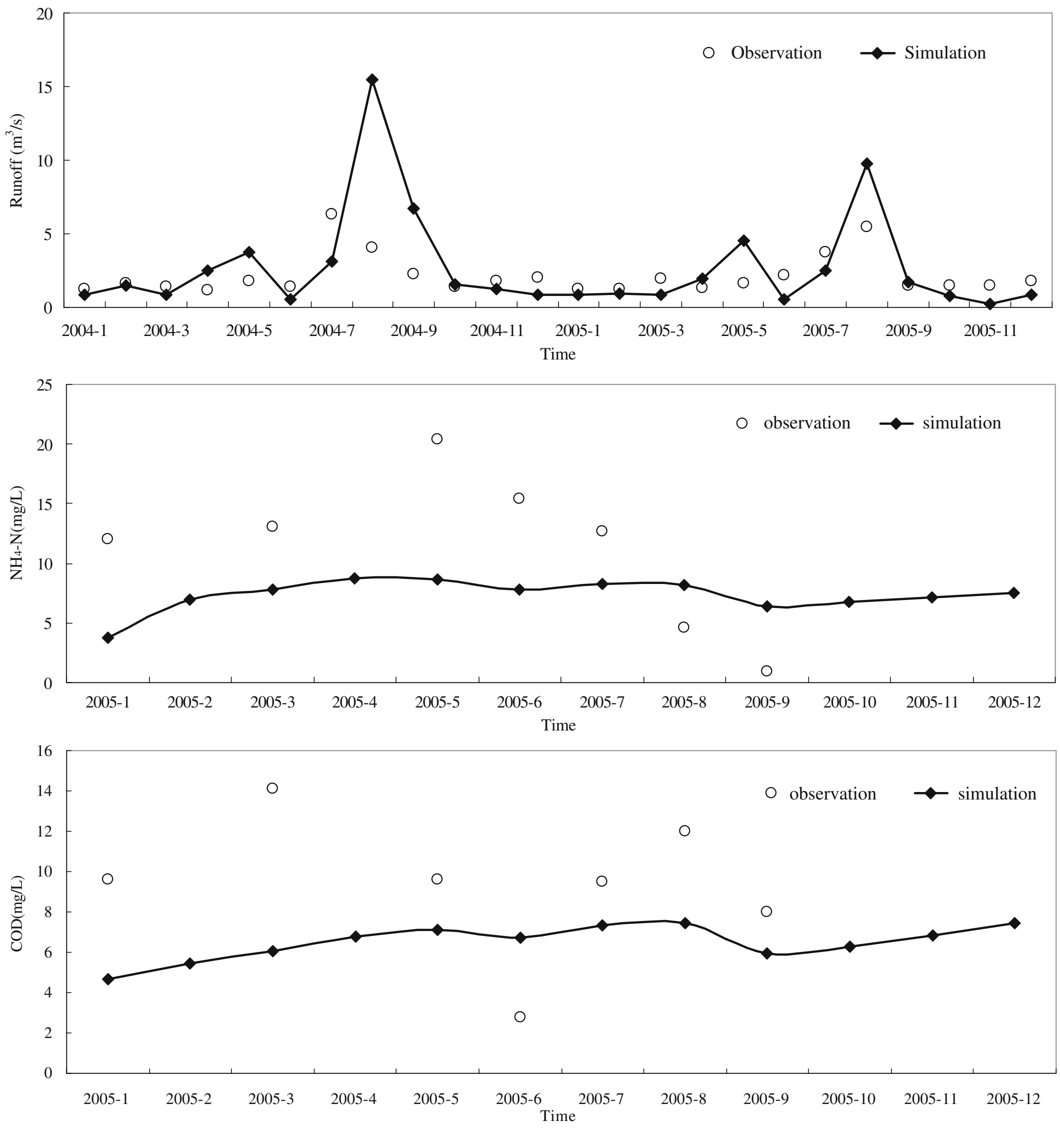

Fig. 4 Monthly observed and simulated runoff and NH_4–N and COD_{Mn} concentration at Sha River Reservoir

matched very well with the observations. Both the correlation coefficient and NSEC coefficient are more than 0.80, and the relative error is only −0.05. For NH_4–N simulation, the relative error is acceptable, and the trends of observation and simulation are consistent. For COD_{Mn} simulation, except for the obvious gap in January and August, the relative error of the other months is −0.08 and the correlation coefficient is 0.42. Given the fact that there were only six observations per year to calibrate the model, and matching the simulated values to those observed data alone is cumbersome, the results obtained seemed to be reasonable (Santhi et al. 2001).

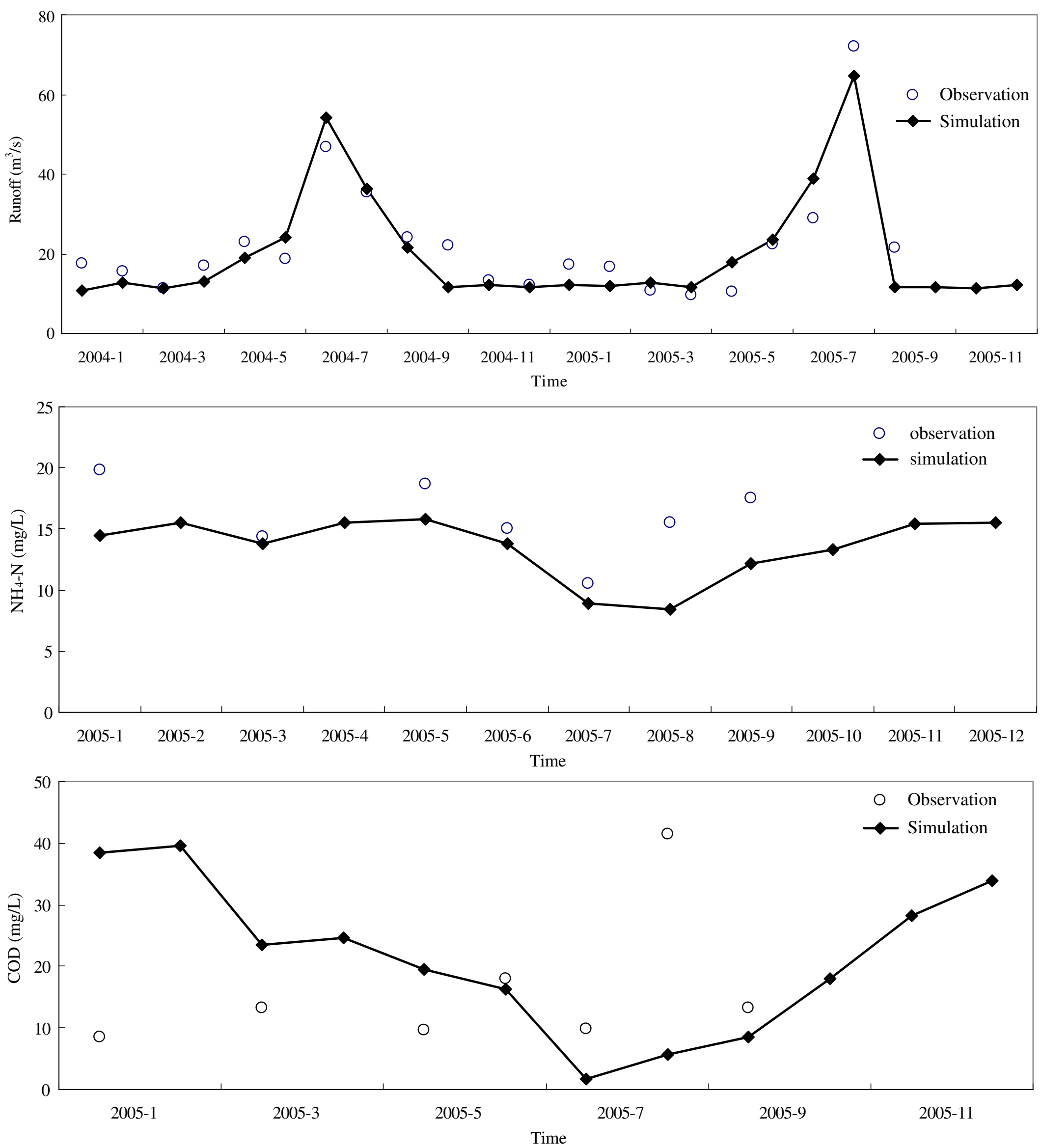

Fig. 5 Monthly observed and simulated runoff and NH_4–N and COD_{Mn} concentration at Beiguan Floodgate

Table 4 Simulated results of water quantity and quality in some main cross-sections

Section	Runoff			NH_4–N		COD_{Mn}	
	re	*r*	NSEC	re	*r*	re	*r*
Sha River Reservoir	−0.25	0.58	−3.83	0.33	0.39	0.25	0.35
Beiguan Floodgate	0.05	0.93	0.84	0.22	0.65	−0.08	0.42

The calibrated parameters' ranges are shown in Table 2, and the simulation results are shown in Figs. 4 and 5 and Table 4.

The average annual incoming runoff at Sha River Reservoir, Lutong Floodgate, and Beiguan Floodgate were then used to validate the hydrologic parameters. The relative errors of these three stations are 0.01, 0.08, and 0.21, respectively (Table 5). The average annual runoffs at Sha River Reservoir and Lutong Floodgate are close to the average annual values. Although the relative error of average annual incoming runoff at Baiguan Floodgate is a little greater, the monthly simulated runoff is very close to, and consistent with, the observed runoff. Thus, the model performance is appropriate to provide the basic foundation for the next steps considering the intensive human activities of Beijing City and the difficulties of data collection.

Optimal operation of dams and floodgates

Operation modes in the current pollution discharge scenario

Currently, all the rivers in the catchment are seriously polluted, and the available water quantity is nearly to 0.0. Year 2005 is selected to analyze the optimal operation of dams and floodgates, and year 2004 is the warm-up period of the QCmode-SWAT model. From the upper stream to the downstream, the operation rules of Sha River Reservoir, Lutong Floodgate, Xinpu Floodgate, and Weigou Floodgate have been optimized, and the results are shown in Fig. 6 and Tables 6 and 7.

The optimal rule of Sha River Reservoir is as follows: increasing the outflow by 720% before the flooding time, increasing outflow 48% in the flooding time, and decreasing outflow 58% after the flooding time. The total annual average outflow of Sha River Reservoir increased by 188%, and the equivalent standard pollution index decreased by 4%. The incoming runoff of the objective floodgate (Lutong Floodgate) increased by 162%, and the maximum extent of the equivalent standard pollution index decreased by 12%.

The optimal rule of Lutong Floodgate is as follows: increasing outflow by 341% before the flooding time, increasing outflow by 11% in the flooding time, and decreasing outflow by 42% after the flooding time. The total annual average outflow of Lutong Floodgate increased by 61%, and the equivalent standard pollution index decreased by 7%. The incoming runoff of the objective floodgate (Xinpu Floodgate) increased by 25%, and the maximum extent of the equivalent standard pollution index decreased by 7%.

The optimal rule of Xinpu Floodgate is as follows: increasing outflow by 97% before the flooding time, increasing outflow by 7% in the flooding time, and decreasing outflow by 35% after the flooding time. The total annual average outflow of Xinpu Floodgate increased by 24%, and the equivalent standard pollution index

Table 5 Contrasting the simulated results with the incoming water in the different assure rates in some main cross-sections unit: 10^4 m^3

Section	Average annual	Average annual from 2004 to 2005	re
Sha River Reservoir	7,830	8,482	0.08
Lutong Floodgate	13,160	13,244	0.01
Beiguan Floodgate	52,150	62,913	0.21

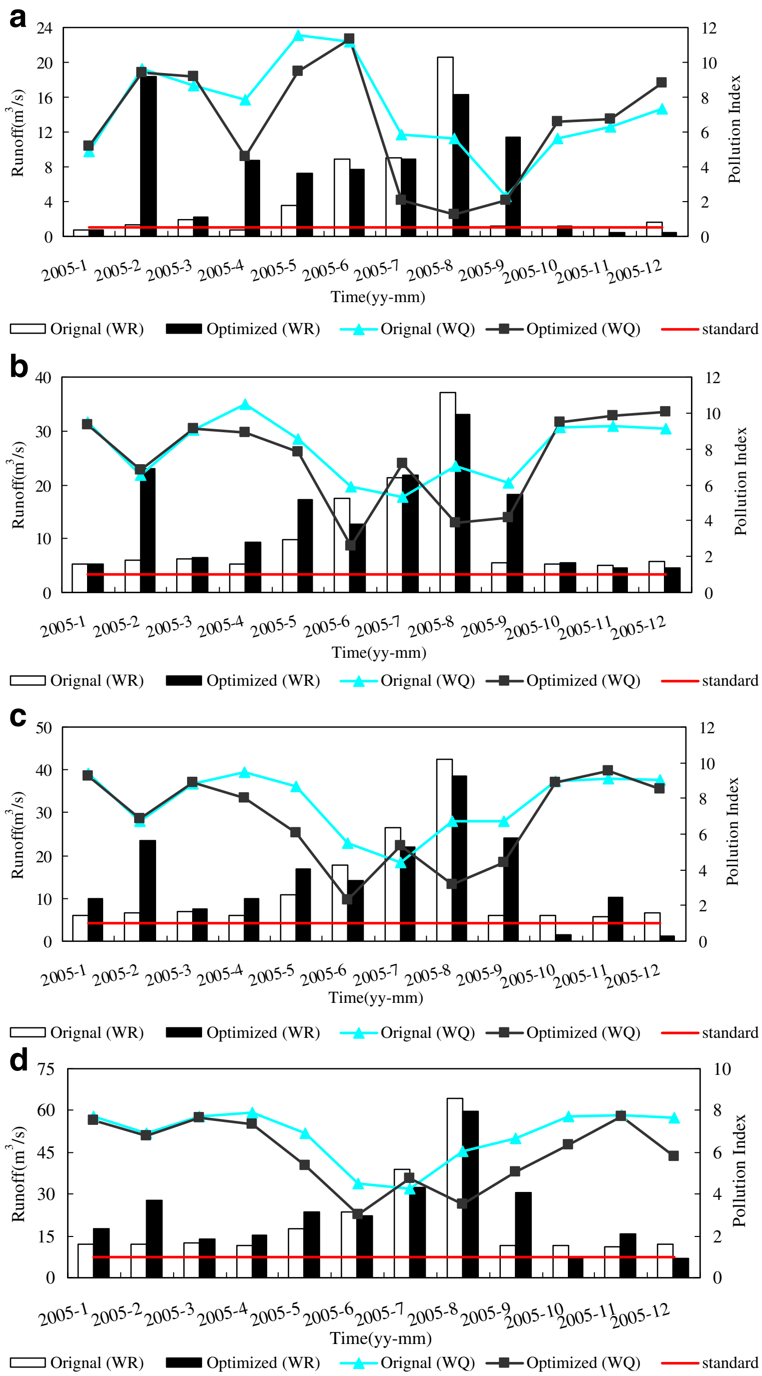

Fig. 6 Contrasting the optimized results with the original values of water quantity and quality at the upper stream of the main objective dams and floodgates in the current pollutant discharge scenario (**a** Lutong Floodgate, **b** Xinpu Floodgate, **c** Weigou Floodgate, **d** Beiguan Floodgate)

decreased by 3%. The incoming runoff of the objective floodgate (Weigou Floodgate) increased by 21%, and the maximum extent of the equivalent standard pollution index decreased by 13%.

The optimal rule of Weigou Floodgate is as follows: increasing outflow by 89% before the flooding time, increasing outflow by 6% in the flooding time, and decreasing outflow by 30%

Table 6 Monthly runoff distribution at the main dams and floodgates in the current pollutant discharge scenario unit (m^3/s)

Month	Dam and floodgate							
	Sha River Reservoir		Lutong Floodgate		Xinpu Floodgate		Weigou Floodgate	
	Original	Optimized	Original	Optimized	Original	Optimized	Original	Optimized
1	0.46	0.53	0.74	0.81	5.24	9.2	5.99	11.31
2	0.85	18.23	1.34	18.40	5.97	22.92	6.7	23.35
3	1.79	1.77	1.97	2.21	6.2	6.54	6.96	7.57
4	0.02	7.95	0.80	4.88	5.2	9.26	6.01	9.99
5	0.91	4.57	3.61	11.03	9.73	15.8	10.89	16.98
6	1.71	0.56	8.85	3.60	17.46	12.15	17.68	12.42
7	2.7	2.53	9.10	10.02	21.2	18.62	26.44	23.59
8	4.89	0.48	20.64	16.71	37.01	33.08	42.53	38.46
9	0.74	11.27	1.26	14.01	5.41	23.17	6.1	24.12
10	0.78	0.8	1.00	1.24	5.18	0.55	5.96	1.51
11	0.81	0.23	1.01	0.44	5.11	9.62	5.82	10.26
12	1.41	0.22	1.60	0.42	5.84	0.28	6.56	1.08
Average	1.42	4.1	4.33	6.98	10.8	13.43	12.3	15.05
Extent (%)	188		61		24		22	

after the flooding time. The total annual average outflow of Weigou Floodgate increased by 22%, and the equivalent standard pollution index decreased by 3%. The incoming runoff of the objective floodgate (Beiguan Floodgate) increased by 14%, and the maximum extent of the equivalent standard pollution index decreased by 13%.

Conclusively, increasing water discharge of dams before the flooding time enhanced the fluvial fluidity and was useful to prevent the accumulation of pollutant, which would have decreased the water quality (Fig. 6). Moreover, increasing water discharge before and during the flooding ensured the flood control safety during the flooding season. In the flooding season, the water quality concentration decreased ulterior. Although the pollutant concentrations increased slightly after the flooding time, the water quality improved appreciably in the whole year, and the average extent of the equivalent standard pollution index decreased 11.3%.This value is still more than 5.0, which is far greater than the standard and, therefore, the water pollution is still very serious. In order to increase the utilization efficiency of water resources and improve the water quality condition, pollution control should be strengthened.

Operation modes in the pollution discharge reduction scenario

To achieve the goals of improving both water quality in Wenyu River and water resources utilization from year 2006 to 2010, water environment capacities of NH_4–N and COD_{Mn} in Wenyu River and its tributaries are only 4.2–75.3% and

Table 7 The optimized results in the current pollutant discharge scenario

Dams and floodgates		The equivalent standard pollution index		
		Original	Optimized	Decrease extent(%)
Sha River Reservoir operation	Downstream of Sha River Reservoir	8	7.67	4
	Upper Stream of Lutong Floodgate	7.24	6.38	12
Lutong Floodgate operation	Downstream of Lutong Floodgate	5.39	5.01	7
	Upper Stream of Xinpu Floodgate	8	7.45	7
Xinpu Floodgate operation	Downstream of Xinpu Floodgate	7.83	7.57	3
	Upper Stream of Weigou Floodgate	7.8	6.77	13
Weigou Floodgate operation	Downstream of Weigou Floodgate	7.56	7.07	7
	Upper Stream of Beiguan Floodgate	6.81	5.91	13

21.4–51.1% of the amount of current pollutant discharge, respectively. In order to take full advantage of water quantity and quality operation of dams and floodgates, we set the discharge pollutant amount of the whole catchment to 5% of the current situation. By simulation, NH_4–N and COD_{Mn} concentration decreased remarkably in the hydrologic condition of year 2005, but in February, May, and June. NH_4–N concentration at Lutong Floodgate, Xinpu Floogate, Weigou Floodgate, and Beiguan Floodgate still do not reach the standard (Fig. 7).

The optimal rule of Sha River Reservoir is follows: increasing outflow by 674% before the flooding time, increasing outflow by 45% in the flooding time, and decreasing outflow by 36% after the flooding time. The total annual average outflow of Sha River Reservoir increased by 179%. The incoming runoff of the objective floodgate (Lutong Floodgate) increased by 59%, and the maximum available water resources quantity increased from 243.8 × 10^4m^3 to 570.7 × 10^4m^3, a 134% increase. The equivalent standard pollution index decreased by 4%. The effect of optimized Sha River Reservoir operation is very significant, and the amount of available water resources that reached the standard of water function zoning increased greatly.

The optimal rule of Lutong Floodgate is as follows: increasing outflow by 322% before the flooding time, increasing outflow by 10% in the flooding time, and decreasing outflow by 23% after the flooding time. The total annual average outflow of Lutong Floodgate increased by 59%, but the water quality concentration decreased by 24%. The incoming runoff of the objective floodgate (Xinpu Floodgate) increased by 24%, and the available water resources increased from 832.8 × 10^4m^3 to 1,102 × 10^4m^3, a 32% increase. The equivalent standard pollution index decreased by 12%.

The optimal rule of Xinpu Floodgate is follows: increasing outflow by 96% before the flooding time, increasing outflow by 5% in the flooding

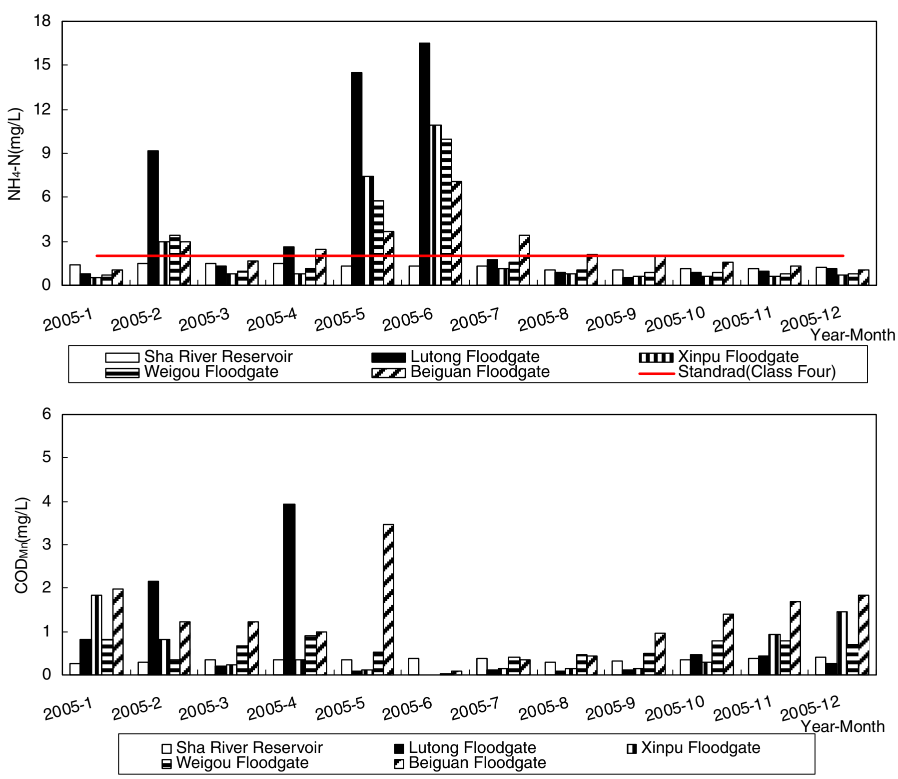

Fig. 7 NH_4–N and COD_{Mn} concentration in the main sections in the pollutant discharge reduction scenario

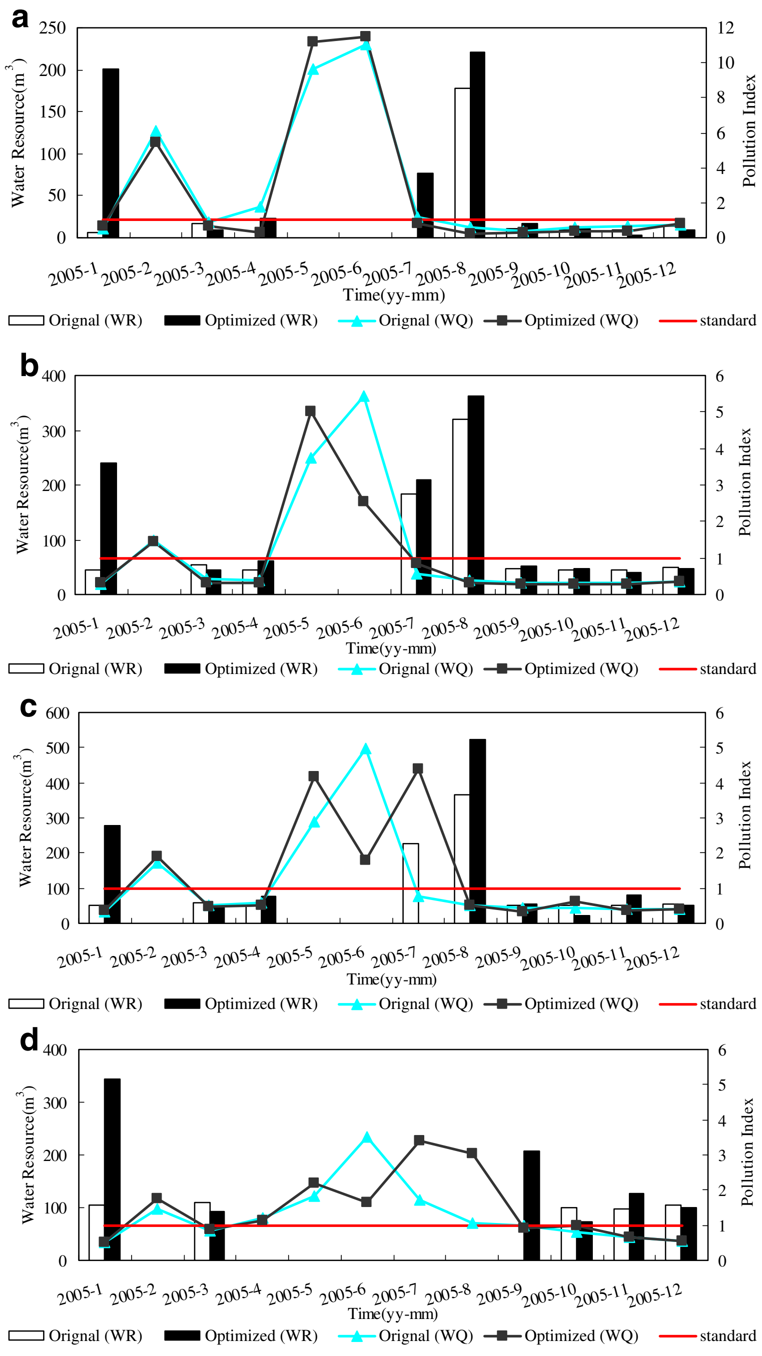

Fig. 8 Contrasting the optimized results with the original values of water quantity and quality at the upper stream of the main objective dams and floodgates in the pollutant discharge reduction scenario (**a** Lutong Floodgate, **b** Xinpu Floodgate, **c** Weigou Floodgate, **d** Beiguan Floodgate)

time, and decreasing outflow by 4% after the flooding time. The total annual average outflow of Xinpu Floodgate increased by 27%, and the equivalent standard pollution index decreased by 3%. The incoming runoff of the objective floodgate (Weigou Floodgate) increased by 23%, and the available water resources increased from 517.9 × 10^4m^3 to 944.2 × 10^4m^3, a 82% increase. The equivalent standard pollution index increased 14%.

Table 8 Monthly runoff distribution at the main dams and floodgates in the pollutant discharge reduction scenario unit (m^3/s)

Month	Dam and floodgate							
	Sha River Reservoir		Lutong Floodgate		Xinpu Floodgate		Weigou Floodgate	
	Original	Optimized	Original	Optimized	Original	Optimized	Original	Optimized
1	0.46	22.92	0.74	23.20	5.24	31.60	5.99	33.70
2	0.85	0.93	1.34	1.43	5.97	6.06	6.70	6.80
3	1.79	0.83	1.97	1.02	6.20	4.18	6.96	4.97
4	0.02	1.95	0.80	2.70	5.20	8.22	6.01	8.99
5	0.91	4.57	3.61	7.32	9.73	13.43	10.89	14.60
6	1.71	0.56	8.85	4.02	17.46	9.76	17.68	10.91
7	2.70	2.53	9.10	12.42	21.20	14.39	26.44	18.63
8	4.89	9.73	20.64	25.55	37.01	54.83	42.53	50.67
9	0.74	1.73	1.26	1.97	5.41	5.98	6.10	16.72
10	0.78	0.80	1.00	1.25	5.18	1.68	5.96	2.60
11	0.81	0.23	1.01	0.44	5.11	8.53	5.82	9.19
12	1.41	0.88	1.60	1.08	5.84	5.31	6.56	6.03
Average	1.42	3.97	4.33	6.87	10.80	13.66	12.30	15.32
Extent (%)	179		59		27		24	

The optimal rule of Weigou Floodgate is as follows: increasing outflow by 89% before the flooding time, increasing outflow by 5% in the flooding time, and decreasing outflow by 3% after the flooding time. The total annual average outflow of Weigou Floodgate increased by 24%, and the equivalent standard pollution index increased by 23%. The incoming runoff of the

Table 9 The optimized results in the different dams in the pollutant discharge reduction scenario

Dams and floodgates		The equivalent standard pollution index			Water resources quantity(104 m3)		
		Origin	Optimized	Decrease extent (%)	Original	Optimized	Increase extent (%)
Sha River Reservoir	Downstream of Sha River Reservoir	0.82	0.51	38			
	Upper Stream of Lutong Floodgate	2.83	2.71	4	243.8	570.7	134
Lutong Floodgate	Downstream of Lutong Floodgate	2.65	2.02	24	832.8	1102	32
	Upper Stream of Xinpu Floodgate	1.17	1.03	12			
Xinpu Floodgate	Downstream of Xinpu Floodgate	1.22	1.18	3	970.8	1133	17
	Upper Stream of Weigou Floodgate	1.16	1.32	−14			
Weigou Floodgate	Downstream of Weigou Floodgate	1.23	1.51	−23	517.9	944.2	82
	Upper Stream of Beiguan Floodgate	1.37	1.58	−16			
The whole basin		1.56	1.48	5	2565.3	3747.9	46

objective floodgate (Beiguan Floodgate) increased by 15%, and the available water resources increased from $970.8 \times 10^4 m^3$ to $1{,}133 \times 10^4 m^3$, a 17% increase. The equivalent standard pollution index increased 16%.

By optimizing the operation rules of the main dams and floodgates, the available water resources amount increases dramatically, with the average extent in the whole basin increasing by 46%. Overall, the water pollution in the whole basin decreases slightly (5%), although it increases slightly in some months at some cross-sections (Fig. 8, Tables 8 and 9).

Discussion

Hydrologic and water quality parameters in SWAT

In our study area, runoff is extremely sensitive to CN, ESCO, and SOL_AW, which are related to both soil and land use. The land use categories in the model are forest, agricultural land, rice land, and urban, but the soil variation is rather limited, including only cinnamon soil and moisture soil. Most runoff is generated on urban and agricultural land when compared to forest and rice land because the average CN values of urban and agricultural land are 92.51 and 89.36, while forest and rice land are only 52.78 and 47.00, respectively. The vegetation of forest land is in a good condition, and water is usually filled in rice land. Thus, the values of ESCO for forest (0.17) and rice (0.005) are lower than the values for agricultural (0.70) and urban (0.845) land, while the values of SOLAW for forest (0.21) and rice (0.25) are greater than those for agricultural (0.11) and urban land (0.11). The evapotransporation and water storage capacity of forest and rice land are larger than for agricultural and urban land. These results are similar to Eckhardt et al. (2003) and Gikasa et al. (2006).

The water quality module in SWAT does not account for the transport and degradation of COD_{Mn}, which is one of important indices in China. In this study, it was incorporated by the function developed by Zhang et al. (2010). The water quality concentrations of dams are more sensitive to BSETLR and NSETLR. At Sha River Reservoir, BSETLR and NSETLR are −250.5 and 0.0, while they are −550.0 and −100.0 at Beiguan Floodgate. Obviously, the sediment is also polluted seriously and releases pollutant in Wenyu River Catchment. The water storage volume is greater in the upper stream; thus, the values are less, and these parameters are reasonable in Wenyu River Catchment. With the exception of underestimated simulated concentrations of NH_4–N in May at Sha River Reservoir and COD_{Mn} in August at Beiguan Floodgate, the simulation results are acceptable considering the error of runoff simulation and the shortage of water quality observation data.

The optimal operation of dams and floodgates

The current operation of dams and floodgates involves always keeping them closed in the non-flood season to store water for irrigation. Thus, the water fluidity of the whole river system is compromised and still pools of polluted water are formed frequently in Wenyu River Catchment. The quantity of usable water resources is rare because of pollution. During the flood season, however, these dams and floodgates are usually open to discharge water for flood control. Thus, the runoff is larger, and water quality is better, but this less polluted water is not used effectively because it is simply discharged to prevent the flooding of Beijing City. By two scenario analysis from Sha River Reservoir, Lutong Floodgate, Xinpu Floodgate, and Weigou Floodgate, the water quality condition and the water resources quantity will be improved significantly after the implementation of water quantity and quality optimal operation of dams and floodgates (Tables 7 and 9). The runoff will be increased in the non-flood season to increase fluidity of rivers and improve water quality, while runoff will be decreased in flood season to store the less polluted water for utilization. The water quantity internal annual distribution will be more reasonable by the optimization operations.

Nevertheless, the operation will be restricted by the maximum storage capacity of dams and floodgates and the condition of pollution. The storage capacity of Sha River Reservoir is the largest; thus, the outcome is very encouraging, especially in the pollutant reduction scenario. The water resource quantity increased by 134% of the original condition, and the equivalent standard pollution index decreased by 38% at the down stream of Sha River Reservoir and by 4% at the upper stream of Lutong Floodgate. This outcome is not significant in the current pollutant discharge scenario, however, because of the serious pollution conditions. The storage capacities of Lutong Floodgate, Xipu Floodgate, and Weigou Floodgate are less, but the water resource quantity still increase 32%, 17%, and 82%, respectively, when compared to the original condition in the current pollutant discharge scenario. Although water quality decreases slightly in some months in Xinpu Floodgate and Weigou Floodgate, the total water resources quantity increases significantly during the whole year. The optimization operation is successful, given the restriction of storage capacity.

Conclusions

Water quantity and quality joint operation is a hot, new research topic in the integrated basin management and will provide a new approach to water environment improvement and ecological restoration. In this study, the water quantity and quality operation mode of dams and floodgates, and genetic algorithm were coupled with the SWAT model. The optimization of dam and floodgate operation at the basin scale overcame the limitation of the method of former reservoir operation and extended the reservoir operation module of SWAT model. It has been applied successfully in Wenyu River Catchment in Beijing City, China. Although this paper reports a preliminary study, and the results were not very satisfying due to limitations in available observation data, this model provides technical support and reference for water quantity and quality operation of dams and floodgates and will be a very useful method for future integrated basin improvement.

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