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Impact of Water Projects on River Flow Regimes and Water Quality in Huai River Basin

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Abstract Research on the impact of water projects (dams or floodgates) on river hydrology and the surrounding environment is important in river basin management. However, it is a difficult scientific issue due to its complexity. Huai River Basin is a unique region in China with high densities in both population and water projects and is experiencing a serious pollution problem. Based on the extended SWAT model with consideration of dams & floodgates, this paper proposes a quantitative framework to assess the impact of dams & floodgates on the river flow regimes and water quality in the middle and upper reaches of Huai River Basin. The results show that: (1) The dams & floodgates reduced the basin's annual average flow by 2%, in comparison with the scenario of no water projects in the whole basin during 1991–2000, because of the regulation and storage of dams & floodgates. The flow in the non-flood season reduced 5% while the change of flow in the flood season was not acute. The impact of dams & floodgates on the annual flow are different in wet and dry years. In the wet year (1991), the impact of dams & floodgates is not obvious because the gates were opened to control the floods and their main functions are to change the temporal distribution in a year. In the dry year (1999), the flow reduced remarkably in comparison with the flow without dams & floodgates in the basin because the gates were closed in order to meet the water demand. The flow in the flood season increased by 8% whiles the flow in the non-flood season reduced

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by 12%. (2) There was a certain impact of dams & floodgates on water quality but they were quite different in the different area. It would be changed from the positive effect to the negative effect from the upriver to downstream. The dams & floodgates in the upper reaches played a positive role to improve water quality. But the ones in the middle and lower reaches played a negative role with contribution from 0 to 0.4. However, the contribution of exceeding pollutant discharge was more than 0.6. (3) The joint operation of dams & floodgates to control water quantity and quality will improve the water environment in Huai River Basin, but the key to improve the basin's water environment is pollution control. This research will guide the anti-pollution and the united water quantity and quality assessment of dams & floodgates in Huai River Basin. Moreover it will provide a foundation to achieve the integrated basin management and sustainability of Huai River Basin.

Keywords Water projects · Flow regimes · Water environment · SWAT · Huai River Basin

1 Introduction

Water project construction (dams and floodgates) is one of the major activities in basin development and utilization. Here the floodgates are usually located in the middle and lower streams with small storage capacity and main function of stopping water flow for flood control while the reservoirs are usually located in the headstream with large storage capacity main function of water storage, water supply and flood control. The impact of water projects on river hydrology, the surrounding environment and ecology is an important topic in river basin management and environmental protection. According to the statistics of The International Commission on Large Dams (ICOLD; http://www.icold-cigb.org/), to the end of year 1998, the number of completed large dams (more than 15 m height or 3 million m^3 storage capacity) is 49,248, approximately two-third of which are in the developing countries. Excessive dam and floodgate construction obstruct river flow, resulting in environmental degradation and biodiversity reduction (Berkamp et al. 2000). It was revealed that the Aswan Dam has seriously altered the ecological balance of the Nile River Basin and caused a series of environmental disasters such as soil salinity downstream of dam, the shrink of river mouth delta, the schistosomiasis endemic (Mohammed et al. 1989; Sadek et al. 1997; Selim et al. 2002; Stanley and Wingerath 1996). The similar problems also happened in other places such as Kenya (Bartholow et al. 2004).

China owns the most dams over the world, accounting about 50% of the world total (WCD 2000). According to a survey of 236 dams in China (Jiang and Fu 1997), the total amount of sediment deposition in dams has reached 115 billion m^3, which accounts for 14.2% of the total storage capacity. In Yellow River Basin, the upriver cascade reservoirs have caused frequent cease-to-flow and serious accumulation of sediment in the lower part of the river. In Huai River Basin, the excessive dam & floodgate construction and their unreasonable operation have leaded to serious water pollution. According to the Chinese Environment Bulletin in 2005, Huai River Basin, in which more than 83% rivers cannot reach to the national standard (GB3838-2002), has the worst water quality in the nation's top seven basins.

The current research on the impact of water projects on river flow and the surrounding environment is mainly restricted to a single water project and research on the impact of multiple dams & floodgates is rare. Karr (1991) systematically analyzed the impact of dam construction on river hydrology and related fields including physics, energy, chemistry, biology and ecology (species' structure, the habitat distribution and ecological function). Munoz et al. (2006) investigated the environmental role of the Santomera Dam in the river network which determines how to integrate water quality requirement with quantity requirement in the reservoir and downstream. Huang (2003) assessed the negative impact of Aswan Dam on the environment of Nile River by analyzing the monitoring data. Mao et al. (2005) reviewed the detail effect of the dams on the hydrological and hydrodynamic characteristics, the nutrients transportation, the structure and functions of the river ecosystem, and the corresponding measures for the ecological restoration. Albanakis et al. (2001) analyzed the reasons for anoxic conditions and sulphide formation in the newly-formed Thesaurus reservoir in Greece and indicated that sulphide formation was inevitable. Bednarek (2001) reviewed the possible ecological impacts of dam removal on sediment load, biotic diversity and aquaculture, and argued that dam removal, although still controversial, is an important alternative for river restoration. Moreover, mathematical modeling has been widely used in water quantity-quality assessment. Campbell et al. (2001) developed a computer model of water quantity (MODSIM) and quality (HEC-5Q) for the mainstream Klamath River, California, and evaluated the improvement of water quality conditions in potential scenarios for changing river system operations. By using 40-year post-dam data, Bartholow et al. (2004) combined a water quantity and quality model to predict how the removal of dams below Upper Klamath Lake might affect water temperatures and ultimately fish survival in the spawning and rearing portions of the mainstream Klamath. Horne et al. (2004) used the physical process models and empirical relationships to quantify the effect of temperature on young-of-year production and potential recruitment of Manistee River steelhead. Lowney (2000) derived an analytical model and illustrated the phenomenon of diurnal variation on steady flow and temperature over a 250 km regulated reach of the Sacramento River, located in the Central Valley of California. Lopes et al. (2003, 2004) studied the influence of reservoirs exploitation on hydrodynamics and water quality downstream of reservoirs. The case study was conducted on the river Lima, downstream of Touvedo dam and a Mondego river segment between the Aguieira and Raiva dams by ISIS programs (ISIS FLOW module and ISIS QUALITY).

This paper assesses the impact of dams & floodgates on river flow regime and water environment in Huai River Basin. The basin has the densest dams and floodgates and is experiencing severe eco-environmental deterioration and flood control challenge. The paper has three objectives: (1) By extension of SWAT model (Soil & Water Assessment Tool; see http://www.brc.tamus.edu/swat/), an assessment framework is developed by using physically-based distributed hydrological processes and simulation at the basin scale. The framework can handle the restriction of the lack of observations before the construction of water projects. (2) Applying the framework to assess the impact of dams & floodgates on river flow in the Shaying River, Hongru River, Guo River and the main stream of Huai River for 1991–2000 which include wet and dry years. (3) Quantifying the impact of dams & floodgates on river environment and identifying the major causes of river pollution, which is always the conflict point between the Chinese Environmental Protection Administration and the Chinese Water Resources Ministry. All the results can be used as a scientific basis of sustainable water resources use in the basin and action plan to improve water quality, and can provide a foundation for the cooperative dam & floodgate operation in the basin.

2 Study Area

Huai River basin (30°55′ ∼36°36′N, and 111°55′ ∼121°25′E) is located in eastern China (Fig. 1), between the Yangtze River Basin and the Yellow River Basin. It flows through five provinces of China, namely Hubei, Henan, Anhui, Shandong and Jiangsu. It is the seventh largest river basins in China, having the drainage area of 270,000 km^2. The population living in the basin is 165 million. Its average population density is approximately five times the nation's average. Although the annual mean precipitation and water resource of the basin are 888 mm and 83.5 billion m^3 respectively, water resources per capita and per unit area is less than one-fifth of the national average. Moreover, more than 50% of the water resources are overexploited, and is much higher than the recommended rate for international inland rivers (30%). The basin faces both flood and drought problems. According to the historical records, 42 floods and 12 droughts have occurred in the entire basin from 1901 to 1948.

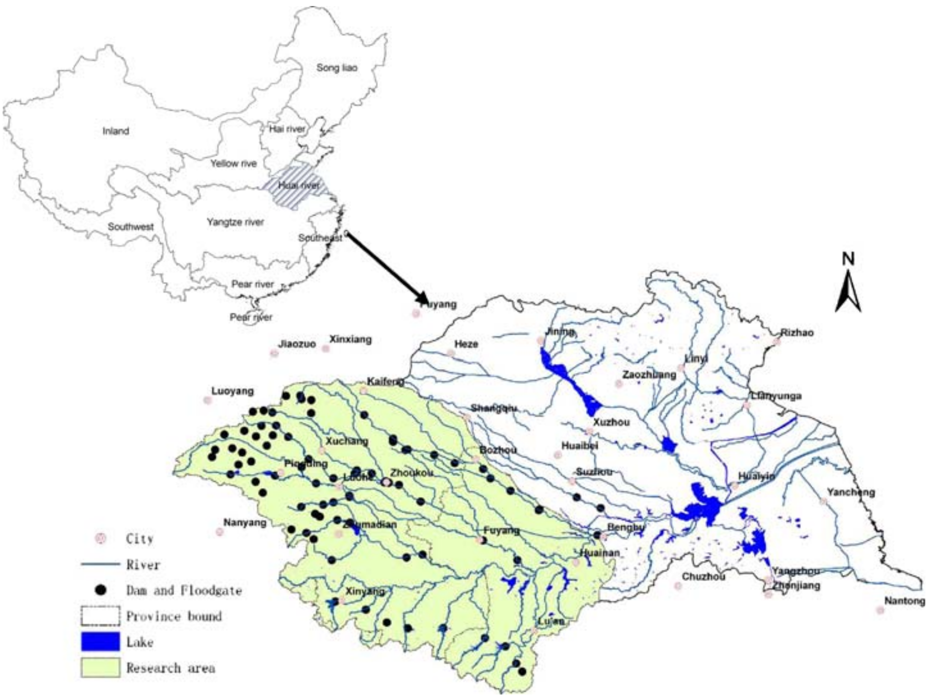

Fig. 1 Location of Huai River Basin in China

Since the establishment of the People's Republic of China in 1949, more than 5,700 dams and 5,000 floodgates have been constructed for the purpose of controlling the flood and relieving drought in the basin. The construction reached its peak during 1970 to 1980. At present, most rivers in Huai River Basin are regulated by dams or floodgates. There are 36 large dams, which control one-third of the entire drainage area. The number of large and middle scale dams is approximately 600. That is, there is one dam in every 50 km^2 and on average each branch has nearly ten floodgates or dams. The total storage capacity of dams & floodgates in the basin is 303 billion m^3 with active storage of 150 m^3, which account for 51% and 25% of the annual runoff, respectively. At the early stage, the dams and floodgates benefited the region in water supply, irrigation, flood control, electricity generation, etc., and thus enormously promoted the social and economic development.

However, along with the intensive human activity and the excessive dam and floodgate constructions, hydrological regimes in the basin have changed dramatically and the pollution load discharged to rivers rose year by year. In June 1994, most of the dams & floodgates surpassed the warning line by the sudden rainstorm and the gates were opened to discharge the flood simultaneously. The flood with the high concentration pollutants killed the fish and shrimp; and seriously destroyed the ecology and environment along the river. The drinking water of downstream residents was in danger, and the economic loss was hundreds of million dollars. This accidental water pollution event shocked the entire world. Since the first significant water pollution event in 1989, the Chinese government have invested 60 billion RMB (approximately $US 7.8 billion) to control and successively harness the river system. Unfortunately, the pollution problem has not been improved significantly, and the pollution events still occur regularly. So far, nearly 200 serious water pollution events have happened, and the situation of water pollution is still severe.

How to correctly understand the ecological and environmental problems affected by water projects in the Huai River Basin and to objectively assess the impact of water projects on hydrological regime and water environment are the essential questions needed to be answered urgently for the basin management. In 2005, General Offices of the State Council of China and the Ministry of Water Conservation emphasized on the necessity of re-assessing the existing and proposed dams and floodgates (Suo 2005).

3 Framework and Methodology

In order to assess the impact of dams & floodgates on river flow regime and water environment, it is necessary to know their process without interruption by dams and floodgates. Unfortunately, all the historical data were collected after the dam and floodgate constructions, that is, there is no information for non-dam scenario. Our research framework is that: Firstly, distributed hydrological and water quality model are developed and the model parameters are calibrated in order to well simulate the process under the current situation. Secondly, based on the calibrated model, the river flow regimes as well as the water quality process under non-dam scenario are simulated. Finally, the indictors of flow regimes and water quality for both with and without dams are calculated and the impact of dams and floodgates can then be assessed.

3.1 Data Collection

Historical data were collected from different sources. For the water quantity model, we collected 10 year (1991–2000) precipitations from 199 precipitation stations, and monthly flow data from 23 dams & floodgates and four important hydrological stations (Wangjiaba, Changtaiguan, Xixian and Lutaizi) in Shaying River, Hongru River, Guo River and Huai River. The first 8 year (1991–1998) data are used for hydrological parameter calibration and the last 2 year (1999–2000) data are used for validation. However, because of the difficulty of collecting water quality data, only 2-year (1999–2000) data are collected, including water quality monitoring data from 32 cross-sections and pollution discharge data from every county. Both ammonium (NH_3–N) and Chemical Oxygen Demand (COD_{Mn}), which are the main pollution indices used in China (GB3838-2002), are used in the water quality model. Moreover, the information on the basin's attributes including DEM, LUCC, dams & floodgates regulation were also collected. All the data used for this research were shown in Table 1.

3.2 Model Selection and Improvement

SWAT is a basin or watershed scale model with strong physical mechanism. It has been widely applied in Canada and North America (Fontaine et al. 2002). In China, SWAT has been applied to several important river basin with great successes (Wang et al. 2003 for Hei River Basin; Liu et al. 2003 for Hai River Basin and Liu et al. 2006 for Yellow River Basin). It is demonstrated and agreed that SWAT is well established because of its flexibility and suitability for hydrological simulation in complex basins and water resources management. SWAT has a reservoir module, in which the reservoir is treated as an independent unit to be added in the corresponding sub-basin. Therefore, it is appropriate for simulating the influence of the hydrological cycle in a region with reservoirs, such as our study basin.

Table 1 Basic data types for this research

Category	Data type	Usage
Hydrology	Runoff, precipitation, evaporation, water use, water level and runoff relationship	Basic hydrologic data
Dams & floodgates	Fundamental situation of dams & floodgates, regulation	Water cycle simulation
Basin attributes	DEM, water system, landuse, soil type	Water cycle simulation
River channel	Section information, landform, roughness	Water cycle simulation
Water environment	NH3-N, COD, water quality standard, water temperature, main drinking water supply sources, main pollution sources, pollutant discharge amount and its category, water function regionalization	Water environment assessment

However, there are some problems on direct application of SWAT to Huai River Basin. Firstly, we have four different types of reservoir outflow data, viz. measured daily outflow, measured monthly outflow, annual average release rate for uncontrolled reservoir and controlled outflow with target release (Neitsch et al. 2002). The first two are the directly measured data and the third one does not subject to the reservoir regulation. However, the last one needs the target reservoir volume for individual days and the number of days required for the reservoir to reach target storage. Therefore, the module of reservoir outflow needs to be extended to suit our data types. Secondly, Biochemical Oxygen Demand (BOD) is an important water quality index in China. However, in the water quality module of reservoir, BOD simulation is ignored and therefore its concentration is always treated as zero. Thirdly, in the water quality module, the nutrient (e.g. N and P) transport and transformation are considered but not COD. As a result, SWAT model must be modified before applying to the Huai River Basin.

According to the issues discussed above, we modify SWAT as follows. (1) The reservoir's outflow module is extended based on the relationship among storage capacity, outflow, water surface area, water level (see Fig. 2). The relationship of each dam or floodgate is written in an individual file and is read into SWAT model. For computing purpose, the codes in some files need to be modified (e.g. res.f, readres.f, allocate_parms.f). (2) BOD simulation function is added by considering the sedimentation and degradation based on zero dimension pollutant balance Eq. 3. From the oxidized mechanism analysis, both COD and BOD are the indexes that reflect the extent of water organic pollution. For a certain basin, the ratio of COD and BOD is quite stable because sewage, sediment and biological structure change only little. Such stable ratio is evidenced by the data collected in several rivers in the study basin (see Fig. 3). The codes in many files in SWAT (allocate_parms.f, bsbaa.f, bsbday.f, bsbmon.f, bsbyr.f, header.f, headout.f, rchaa.f, rchday.f, rchmon.f, rchyr.f, resnut.f, writea.f, writeaa.f, writed.f, etc.) were modified.

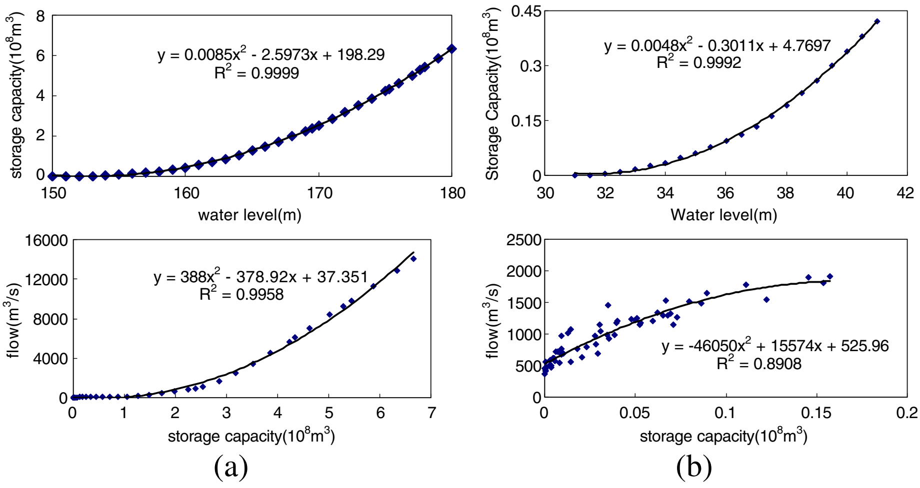

Fig. 2 Relationship of storage capacity with water level and the relationship of flow with storage capacity of dams & floodgates. **a** Baiguishan reservoir; **b** Huaidian floodgate

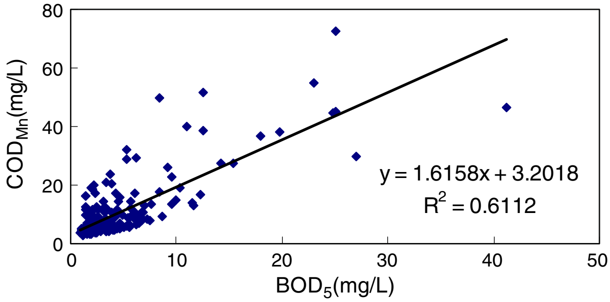

Fig. 3 Relationship of the observed of BOD_5 and COD_{Mn} concentration in 2000 in Hong River, Ying River, Guo River, Pi River and the main stream of Huai River

The extended SWAT model for the Huai River Basin is developed on the ARCVIEW SWAT2000 interface. Bengbu floodgate is selected as the outlet of the basin. All of the 29 targeted dams and floodgates (14 dams and 15 floodgates) are added into the model according to their positions (see Fig. 4). The study area is divided into 129 sub-basins and 468 hydrological response units (HRU) which is a unique combination of soil and land use overlay in the sub-basins and is the

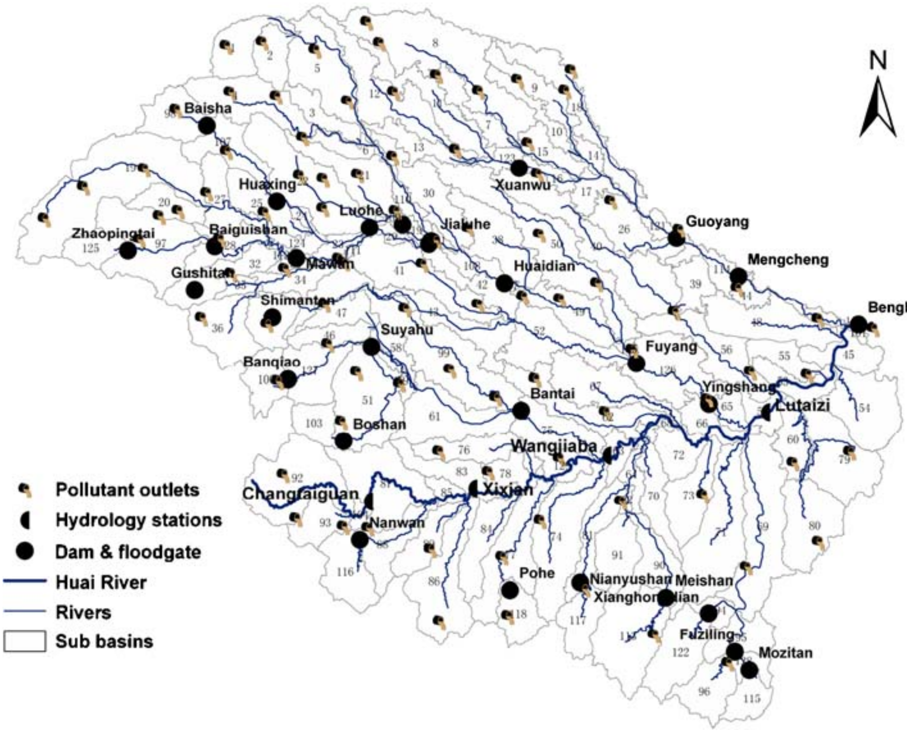

Fig. 4 Digitized streams, the position of pollutant outlets, dams & floodgates and the sub-basins delineation

minimum calculative unit of hydrological process (Neitsch et al. 2002). In this paper, the threshold value is 11% for land use and 10% for soil types, respectively.

3.3 Indices for Water Quality–Quantity Assessment

The indices used for assessing the water quantity and quality are described below. For water quantity, we use annual runoff (RVY), Runoff in the flood season (RVF) (Jun–Sept), Runoff in the non-flood season (RVNF) (Oct–May), and Peak value in the flood season (QP) to assess the impact of dams & floodgates on river flow regime; see Table 2.

The impact of dams and floodgates on water quality is evaluated by simulating the water quality process under three different scenarios: having dams and polluted (11), non-dam but polluted (01), and having dams but not polluted (10). For each cross section, the impact of dams & floodgates (η_{dam}) is defined as:

$$\eta_{dam} = \frac{\sum (C_{11} - C_{01})}{\sum C_{11}} \times 100\% \tag{1}$$

where the summations are taken over time (monthly), C_{11} and C_{01} are the pollutant concentrations under scenario (11) and scenario (01), respectively. If $\eta_{dam} < 0$, that is, $\sum C_{11} < \sum C_{01}$, meaning that the total concentration under scenario (11) is less than that under scenario (01), then the dams are helpful to reduce pollutant concentration. If $\eta_{dam} > 0$, that is, $\sum C_{11} > \sum C_{01}$, meaning that the water quality concentration under scenario (11) is larger than that under scenario (01), then the dams make water quality worsen. If $\eta_{dam} = 0$, that is, $\sum C_{11} = \sum C_{01}$, then the effect of dams on water quality is not obvious.

Similarly, we define the index to assess pollution control to water quality ($\eta_{pollution}$) as:

$$\eta_{pollution} = \frac{\sum (C_{11} - C_{10})}{\sum C_{11}} \times 100\% \tag{2}$$

where C_{10} and C_{11} are pollutant concentrations under scenario (10) and scenario (11). Normally, $\eta_{pollution} \geq 0$.

The contributions of dams and pollution control are then assessed by

$$\varepsilon_{dam} = \frac{\eta_{dam}}{\eta_{dam} + \eta_{pollution}} \quad \text{and} \quad \varepsilon_{pollution} = \frac{\eta_{pollution}}{\eta_{dam} + \eta_{pollution}} \tag{3}$$

Table 2 Indices for water quantity assessment

ID	Index name	Index	Unit	Remarks
1	Annual runoff	RVY	10^8 m^3	Non-dam/having dams
2	Runoff in the flood season	RVF	10^8 m^3	Non-dam/having dams
3	Runoff in the non flood season	RVNF	10^8 m^3	Non-dam/having dams
4	Peak value in the flood season	QP	m^3/s	Non-dam/having dams

where ε_{dam} and $\varepsilon_{pollution}$ are the contributions of dams & floodgates, and pollution control to water quality, respectively. If $\varepsilon_{dam} < \varepsilon_{pollutant}$, we know that the impact of dams & floodgates on water quality is less than that of pollution discharge and therefore the pollution discharge is the main reason of the river pollution. If $\varepsilon_{dam} > \varepsilon_{pollutant}$, we know that the impact of pollution discharge on water quality is less than that of dams and floodgates and therefore the dam is the main reason of the river pollution. If $\varepsilon_{dam} = \varepsilon_{pollution}$, we know that the impact of dams & floodgates on water quality is the same as that of pollution. In the case that $\eta_{dam} < 0$, we know that the dams and floodgates are helpful to reduce pollutant concentration and therefore the pollution discharge is the main reason for the river pollution.

If multiple water quality indices were selected, we assess the contributions by considering a linear combination of all individual contributions as:

$$\widehat{\varepsilon}_{\text{dams}} = \sum_{j=1}^{n} \omega_j \cdot \varepsilon_{\text{dams},j} \text{ and } \widehat{\varepsilon}_{\text{pollution}} = \sum_{j=1}^{n} \omega_j \cdot \varepsilon_{\text{pollution},j} \tag{4}$$

where j is a certain water quality index and n is the total number of the water quality indices. $\widehat{\varepsilon}_{\text{dams}}$ and $\widehat{\varepsilon}_{\text{pollution}}$ are the average contributions of dams & floodgates, and pollution control to multi-water quality indices, respectively. $\varepsilon_{\text{dams},j}$ and $\varepsilon_{\text{pollution},j}$ are the contributions of dams & floodgates, and pollution control to water quality index j, respectively. ω_j is the weight value of water quality index j.

4 Results

4.1 Calibration and Validation

In the simulation of hydrology and water quality, eighteen sensitive parameters listed in Table 3 are selected in the Huai River Basin's SWAT model, including six hydrological parameters and twelve water environment parameters (Arnold et al. 1998; Eckhardt and Arnold 2001; Lenhart et al. 2002; van Griensven et al. 2006; and Bärlund et al. 2006).

In the hydrological simulation, 18 out of 29 stations have volume errors within ± 0.15 accounting for 67% of all the simulated cross-sections. The average correlation coefficient is 0.75, and the average coefficient of efficiency is 0.41 in the calibration period (1991∼1998). For the validation period (1999–2000), 13 stations have volume errors are within ± 0.15 accounting for 48% of all stations. The average correlation coefficient is 0.82 and the average coefficient of efficiency is 0.53.

The results of water quality simulation are summarized as below. In NH_3–N simulation, there are 17 stations, whose average relative error is less than 0.45, account for 53% of all the cross-sections and 19 stations, whose correlation coefficient is more than 0.40, account for 59%. In COD_{Mn} simulation, 56% of cross-sections have less than 0.45 of average relative error and 47% have more than 0.40 of the correlation coefficient. The results for some important stations are summarized in Table 4 and demonstrated in Fig. 5 by a floodgate (Bengbu floodgate which is the outlet of the whole basin) and a dam (Zhaopingtai Reservoir located in upper reach) as examples (see Fig. 4).

Table 3 Selected hydrological and water quality parameters of SWAT in Huai River Basin

Parameters	Name	Definition	File name
Hydrology	CN2	Moisture condition II curve number	.mgt
	ESCO	Soil evaporation compensation coefficient	.hru
	EPCO	Plant uptake compensation factor	.hru
	SOL_AW	Available water capacity	.sol
	SOL_K	Saturated hydraulic conductivity of first layer	.sol
	SOL_Z	Depth from soil surface to bottom of layer	.sol
Water quality	BSETLR	COD settling rate in reservoir[a]	.lwq
	NSETLR	Nitrogen settling rate in reservoir	.lwq
	RK1	CBOD deoxygenation rate at 20°C	.swq
	RK3	Settling loss rate of CBOD at 20°C	.swq
	BC1	Rate constant for biological oxidation of ammonia nitrogen at 20°C	.swq
	BC2	Rate constant for biological oxidation of nitrite to nitrate at 20°C	.swq
	BC3	Local rate constant for hydrolysis of organic nitrogen to NH_4^+ at 20°C	.swq
	CtoB	The ration between BOD and COD[b]	.swq
	SOL_CBN	Amount of organic carbon in the layer	.sol
	USLE_K	USLE soil erodibility factor	.sol
	ERORGN	Organic nitrogen enrichment ratio	.hru
	ECBOD	cbod enrichment ratio[a]	.hru

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

4.2 The Impact of Dams & Floodgates on River Flow Regime

The impacts of dams & floodgates on river flow regime for all the stations are presented in Fig. 6 (a: RVY, b: RVNF; c: RVF and d: QP). The results are presented as the relative values of the non-dam scenario to the current situation.

The detailed results for Bengbu floodgate are shown in Fig. 7 and summarized in Table 5. It can be seen from the annual average flow regime from 1991 to 2000

Table 4 Simulation results of SWAT in some dams & floodgates

Dams & floodgates	Hydrology						Water environment			
	Calibration (1991~1998)			Validation (1999~2000)			NH_3–N		COD_{Mn}	
	rVol	*r*	NSEC	rVol	*r*	NSEC	RE	*r*	RE	*r*
Zhaopingtai	0.09	0.64	0.25	0.42	0.89	0.52	0.48	0.64	0.17	0.28
Baiguishan	−0.18	0.59	0.07	0.26	0.95	0.67	0.55	0.57	0.26	0.17
Mawan	−0.19	0.79	0.60	0.05	0.96	0.79	0.27	0.71	0.24	0.75
Zhoukou	0.00	0.97	0.94	0.02	1.00	0.97	0.39	0.69	0.30	0.77
Huaidian	−0.13	0.82	0.67	−0.05	0.69	0.48	0.38	0.82	0.28	0.81
Fuyang	−0.03	0.84	0.69	−0.19	0.83	0.67	0.15	0.51	0.56	0.52
Bengbu	−0.27	0.74	0.52	0.39	0.71	0.36	0.39	0.66	0.42	0.49
Fuziling	0.07	0.89	0.63	0.06	0.82	0.63	0.36	0.27	0.27	0.72
Wangjiaba	−0.03	0.94	0.86	0.00	0.99	0.97	0.57	0.21	0.67	−0.11

Appraisal Index: *r* correlation coefficient, *NSEC* efficiency coefficients, *rVol* volume error of the simulation runoff to the observed data, *RE* is the relative error

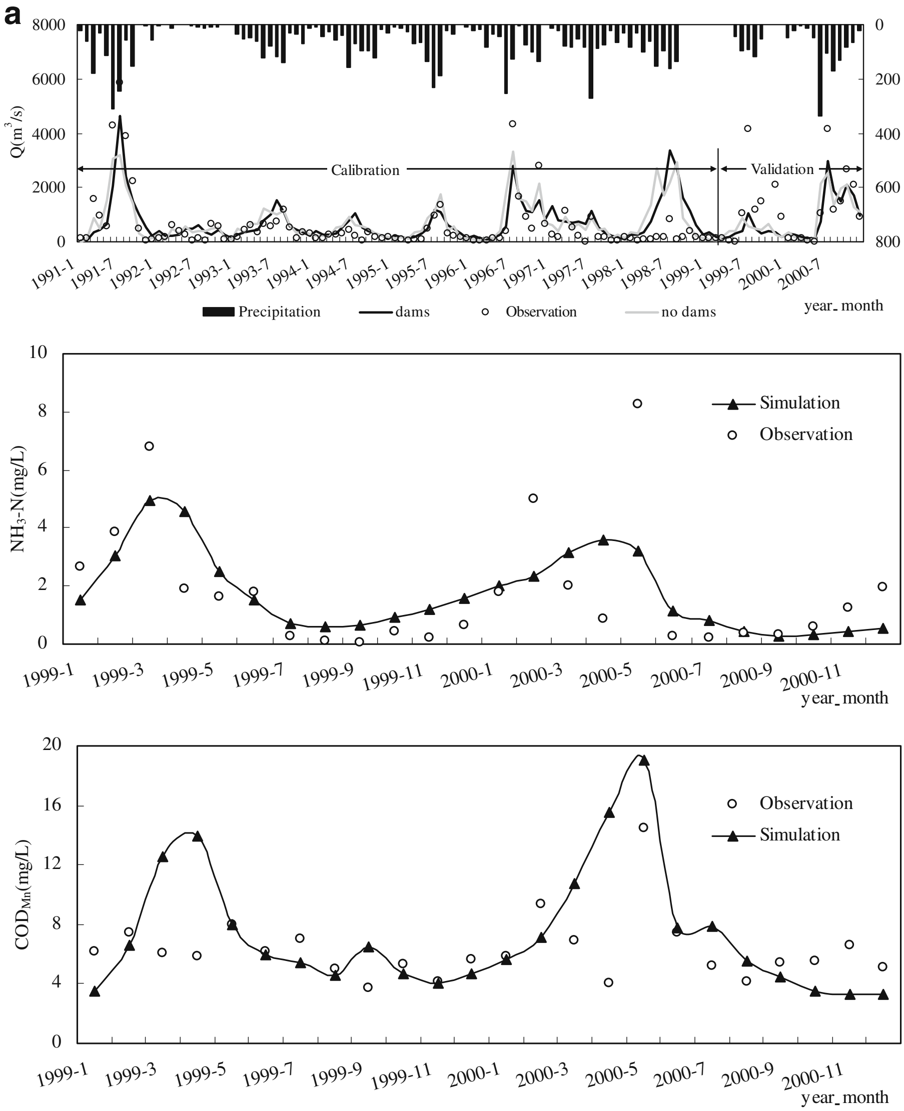

Fig. 5 **a** Simulation result of runoff and water quality in Bengbu floodgate. **b** Simulation result of runoff and water quality in Zhaopingtai reservoir

that RVY increased by 2% and RVNF increased by 11%. However, the RVF did not change obviously in no dams & floodgates scenario. In 1991 (a wet year), the impact of dams & floodgates on RVY was not obvious because the gates were open to control the floods and the main function of dams & floodgates was to change the temporal distribution in a year. RVF increased by 8% while RVNF reduced by 12%. In 1999 (a dry year), the flow reduced remarkably contrasting to the flow in no dams

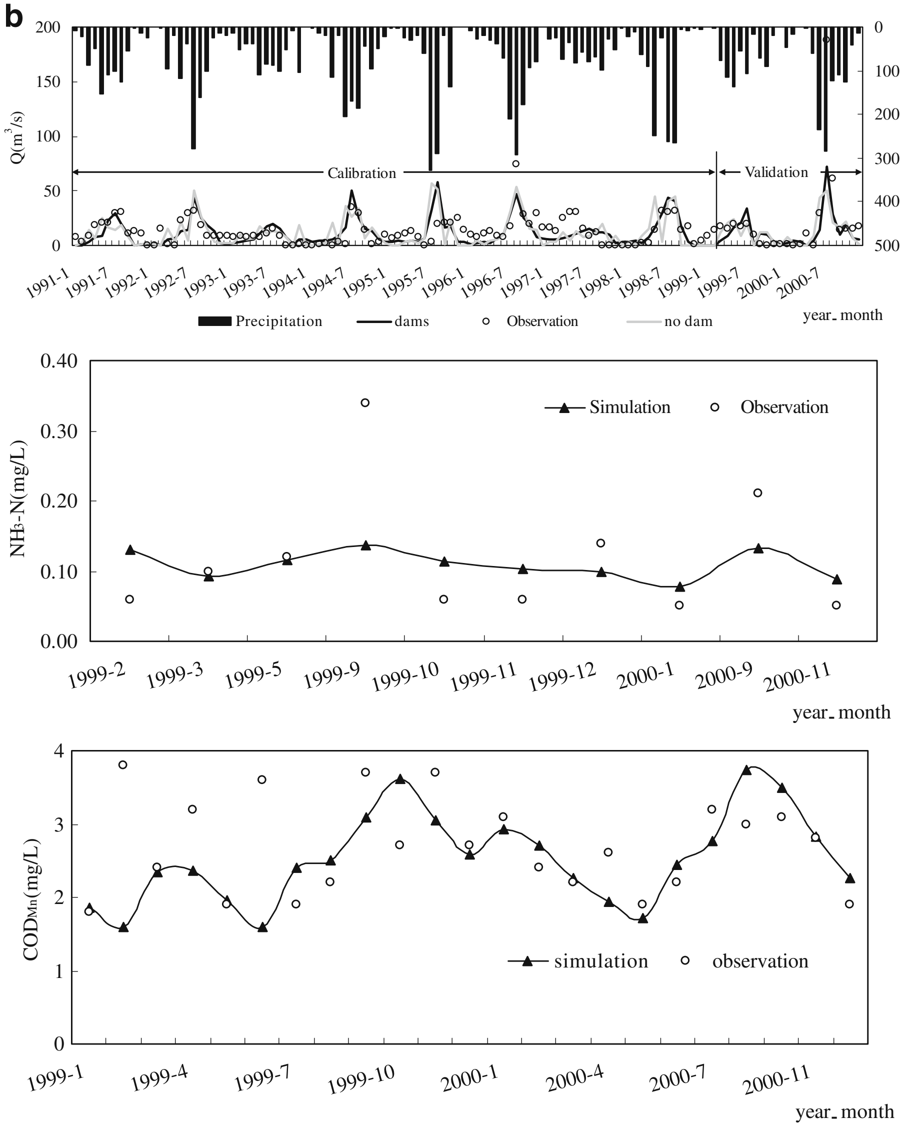

Fig. 5 (continued)

& floodgates scenario because the gates were closed for water storage in order to meet the water demand. However, QP increased by 17%.

4.3 The Impact of Dams & Floodgates on Water Quality

The impact of dams & floodgates and pollution discharge on water quality changed remarkably. As an example, the results for Shaying River, the biggest tributary of

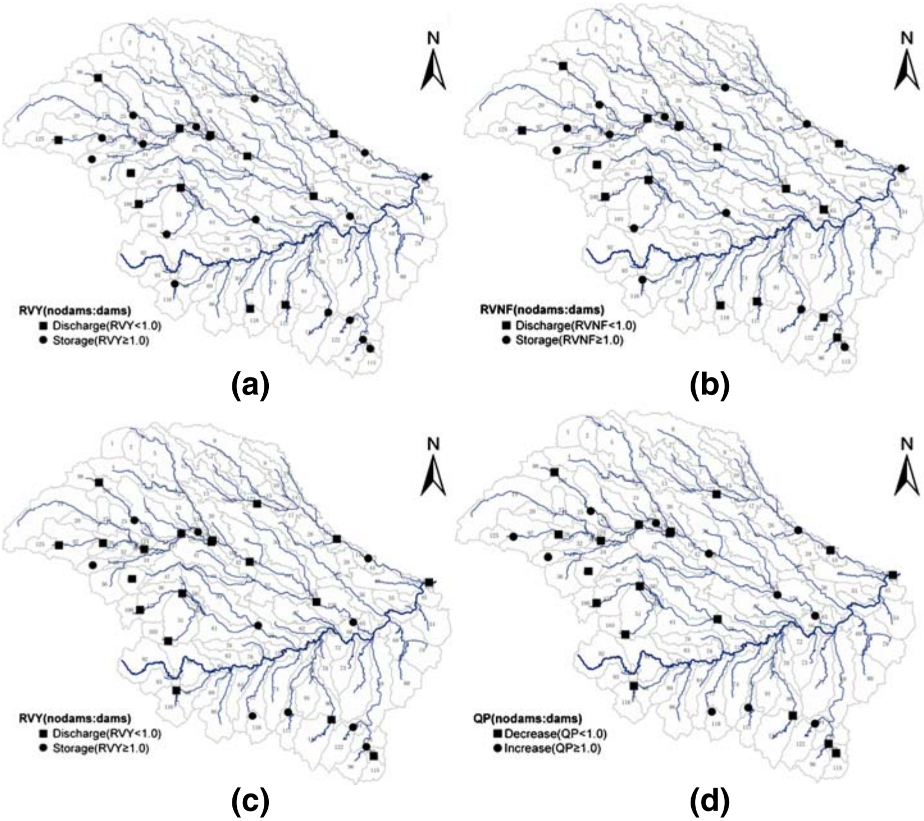

Fig. 6 Impact of dams & floodgates on river runoff in Huai River Basin. **a** Annual runoff, **b** runoff in the non flood season, **c** runoff in the flood season, **d** runoff peaking value in the flood season

Huai River, are presented in Figs. 8 and 9 and summarized in Table 6. In 1999 and 2000, the water qualities for all the dams & floodgates are polluted seriously except Baiguishan and Zhaopingtai reservoir. Scenario analysis indicates that the dams & floodgates in Shaying Rivers are closed in the non-flood season. Water discharge,

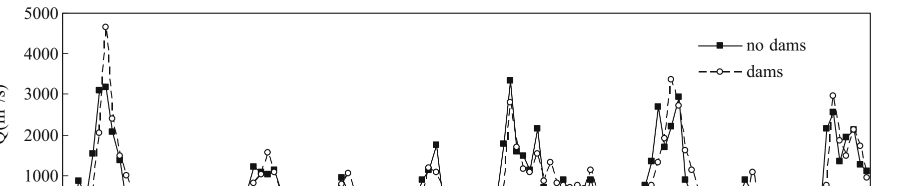

Fig. 7 Runoff process of Bengbu floodgate under the current situation and no dams & floodgates scenario

Table 5 Result of water quantity assessment in Bengbu floodgate

ID	Index	1991 (WET YEAR)			1999 (WET YEAR)			1991~2000 average annual		
		Dams	Non dams (2)	(1)/(2)	Dams (1)	Non dams (2)	(1)/(2)	Dams (1)	Non dams (2)	(1)/(2)
1	RVY ($10^8 m^3$)	357.21	344.81	0.97	109.53	117.66	1.07	2,218.72	2,266.10	1.02
2	RVF ($10^8 m^3$)	273.64	251.55	0.92	58.48	61.73	1.06	1,308.01	1,305.33	1.00
3	RVNF (10^8 m^3)	83.57	93.26	1.12	51.05	55.92	1.10	910.71	960.77	1.05
4	QP (m^3/s)	4,646.00	3,176.00	0.68	1,062.00	882.80	0.83	20,378.90	18,061.90	0.89

velocity and the degradation coefficient are all smaller than scenario (01). The water quality worsened. In the flood season when the dams & floodgates were opened, water qualities were not much different between scenario (11) and scenario (01) (see

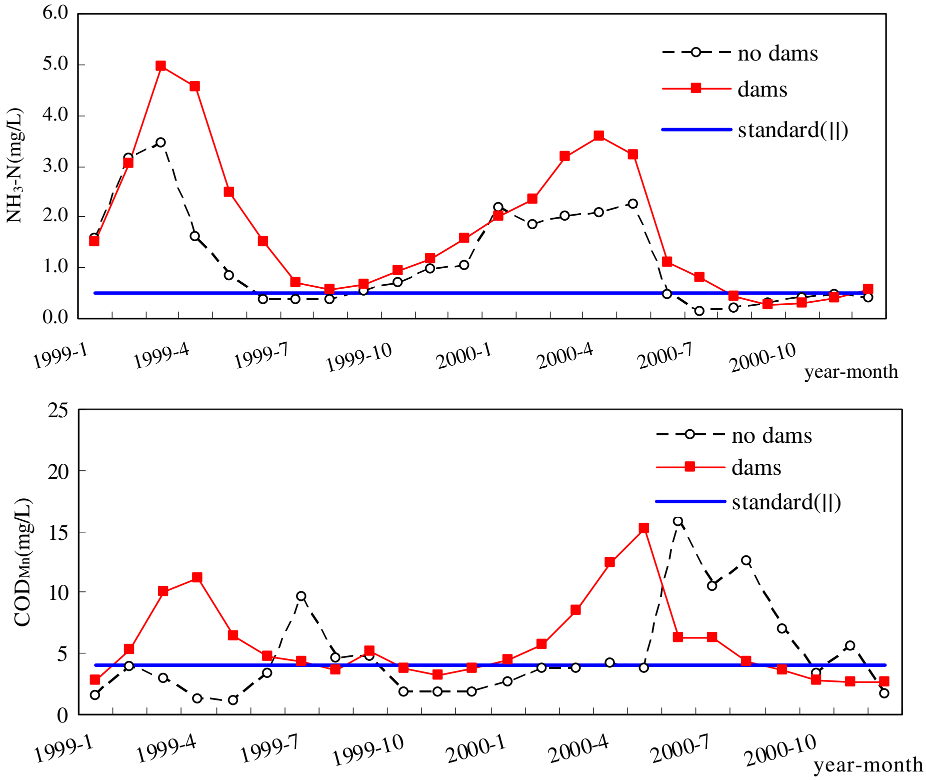

Fig. 8 NH_3–N and COD_{Mn} concentration of Bengbu floodgate in the having dams scenario (11) and non-dam scenario (01)

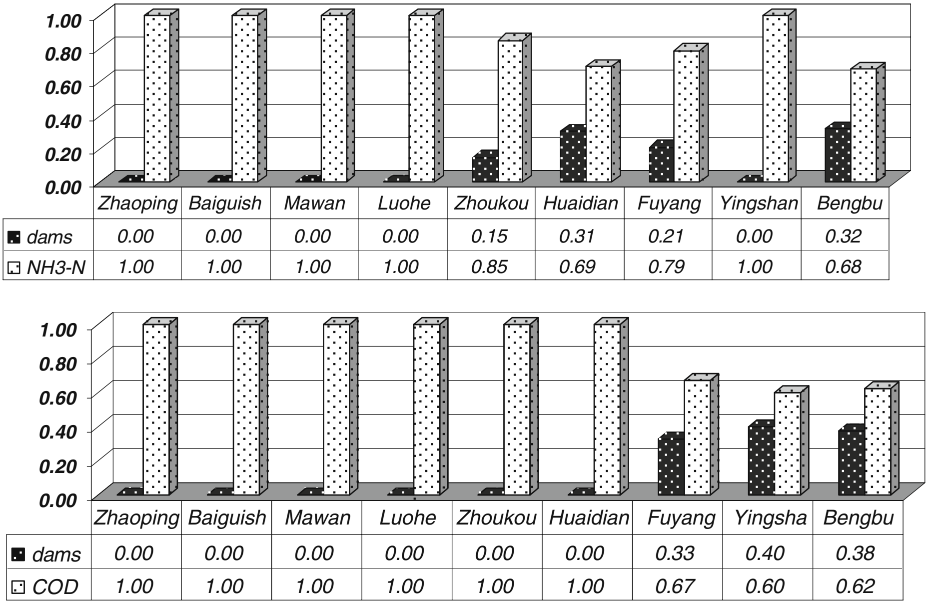

Fig. 9 Contribution of dams and pollution discharge to water quality in Shaying River and the main stream of Huai River

Fig. 8). From the upper reaches to the lower reaches, the impact of dam & floodgate changed from positive to negative and the contribution became gradually bigger. Generally speaking, the dams & floodgates in the upper reaches played a positive role to improve water quality. But in the middle and lower reaches, the dams & floodgates aggravated deterioration of water quality with the contribution from 0 to 0.4. However, the contribution of exceeding pollutant discharge was more than 0.6.

The results of the impact of twenty-nine dams & floodgates on water quality in the whole basin are shown in Fig. 10.

Table 6 Impact of Shaying River dams & floodgates on water quality

Dam & floodgate	NH_3–N (%)		COD_{Mn}(%)	
	η_{dam}	$\eta_{pollution}$	η_{dam}	$\eta_{pollution}$
Zhaopingtai	−0.01	0.00	−0.21	0.00
Baiguishan	−3.27	0.00	0.30	0.00
Mawan	−2.98	0.87	−5.24	0.09
Luohe	−4.75	0.44	−0.01	0.00
Shahe Zhoukou	0.16	0.88	−1.49	0.76
Huaidian	0.42	0.95	−0.57	0.66
Fuyang	0.30	0.94	0.14	0.29
Yingshang	−0.10	0.92	0.28	0.42
Bengbu	0.34	0.71	0.19	0.31

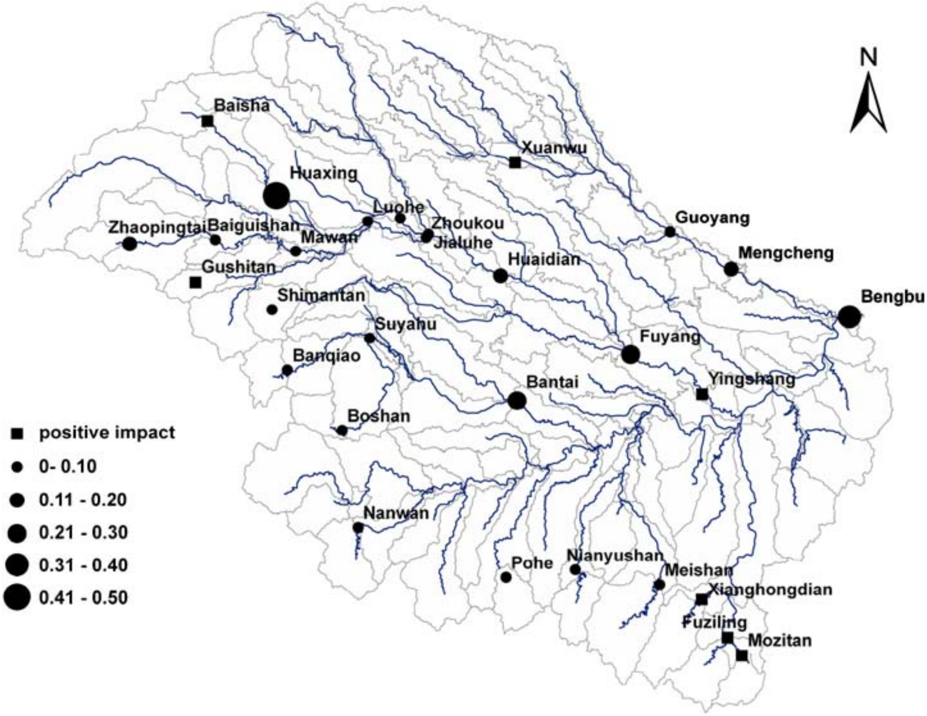

Fig. 10 Spatial distribution of the contribution of dams & floodgates on water quality in Huai River Basin

5 Discussion and Conclusions

Based on the analysis of water cycle and pollutant migration process in the river basin with multiple dams & floodgates, regulation and the effect of dams on the hydrological and water environment, our modified SWAT model provides a feasible method to assess the impact of dams & floodgates on flow regime and water quality, without suffering from the lack of data. The method is original and different from the former relative researches (Karr 1991; Lowney 2000; Albanakis et al. 2001; Bednarek 2001; Campbell et al. 2001; Lopes et al. 2003, 2004; Bartholow et al. 2004; Klamath. Horne et al. 2004; Mao 2005; Munoz et al. 2006; Wei et al. 2008).

By comparing the flow processes in different scenarios, the results showed that there were 17 dams & floodgates storing water, seven dams & floodgates discharging water and the other five dams & floodgates' impact were not obvious from annual average flow process (year 1991 to 2000). Except a few reservoirs (Baisha reservoir and Banqiao reservoir) in the north of Huai River, all other headstream reservoirs were in water storage condition in order to meet water demand. This result was consistent with the function of those reservoirs, viz., ensuring water supply, flood defense and storage. The floodgates in Shaying River were in water discharging condition while the others were in water storage condition. For the whole basin, if there were no dams & floodgates, the flow at outlet would increase for lack of dams' storage. In the wet year (1991), the impact of water projects was not obvious because the dams & floodgates were open for flood control, and the main function of dams & floodgates was to change the distribution of flow in a year. However, in the dry year (1999), the water projects were to store water to ensure the water use in the upper reaches. Thus the flow decreased remarkably compared with the flow without dams & floodgates in the basin.

The impacts of dams & floodgates on water quality varied considerably in the basin. Due to the significant change in flow regimes caused by the dams & floodgates, the pollutant transformation was superimposed by the flow process, resulting in the change of pollutants' spatial and temporal distribution. From the upper reaches to the lower reaches, the impact of dams & floodgates changed from positive effect to negative effect. The reservoirs and the floodgates located in the headstream were used for storing water, and the amount of water was much more. As a result, the water environment capacity was higher than natural rivers (Yuan 2004), and the dams played a positive role to improve water quality. The main functions of dams and floodgates in the middle and lower reaches were flood control by cutting off river flows and slowing down the flow velocity in the upper and downstream of dams & floodgates and, as a result, reduced river degradation ability which caused the water environment capacity decreased directly. Therefore, they played a negative role with contribution among 0.0 to 0.4, while the contribution of exceeding pollutant discharge was 0.60–1.00. Obviously, the pollutant discharge is the principal reason of water pollution in Huai River Basin at present. But the impact of water projects could not be ignored.

A joint water quality–quantity operation of water projects would be an important way to improve the water environment in the Huai River Basin (Zhang et al. 2007). However, in order to achieve the target of "clean Huai River" by 2010, pollution discharge along Huai River should be further reduced. At the same time, the dams & floodgates should be jointly controlled with consideration of the interests of economic and ecological environment in order to maintain a certain ecological base flow.

Research on the impact of water projects on hydrology, ecology, and environment is not only a new task in the basin management in China, but also one of the active international research areas and challenges. From modeling perspective, this paper analyzed the impact of dams & floodgates on river flow regime and water quality in the Huai River Basin and put forward the assess framework and the indices based on water cycle at a basin scale. All the results can be used as a scientific basis of sustainable water resources use and the water pollution improvement in the Huai River Basin, and provide a foundation for the water quantity–quality joint dams & floodgates' operation. However, in this paper we only analyzed the impact of dams & floodgates on water quantity and quality at the present situation. Further scenario analysis (such as considering the optimizing operation of dams & floodgates and reducing the pollutant amount in different areas) would also be very useful. We are conducting those analysis and the results is will be published elsewhere. Due to the limited observation, some issues cannot be addressed here such as intensive human activities on land use. Uncertainty analyses should be strengthened in the future research. Moreover, an optimal monitoring program needs to be developed in order to achieve a unified operation of dams & floodgates for joint water quantity and quality assessment, especially during water pollution events.

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