Towards sustainable water regulation based on a distributed hydrological model for a heavily polluted urban river, northwest China

Jiqiang Lyu, Pingping Luo, Shuhong Mo, Meimei Zhou, Bing Shen, Lei Fan and Daniel Nover

ABSTRACT

The Qinling Mountains are located in a transition zone between (semi)-arid regions in north China and humid regions in south China. The water resource and water ecology of regional rivers are strongly affected by climate change and human activity. In this paper, the stochastic simulation of river water regulation was performed and an optimal water regulation scheme of rubber dam projects was developed by establishing a multi-objective stochastic constraint water regulation model of rubber dam projects based on the coupling of a distributed hydrological model and a water balance model. Results show that a ~40% reduction of water occurred in the lower river channel due to the operation of water supply project in the upper reach and impoundment by rubber dam projects in the lower reaches. This water reduction was associated with decreased water environment self-purification capacity and serious deterioration of water quality for smaller ecological basic flow and mean flow velocity. By establishing a multi-objective stochastic constraint programming model, the average velocity and the ecological basic flow at different adjusting heights of rubber dams are determined. The regulation scheme of rubber dam projects we propose in this paper may optimize the current river water management strategies and help to improve the river water quality environment in urban rivers.

Key words | dam projects, distributed hydrological model, regulation scheme, urban river, water pollution

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INTRODUCTION

Global climate change and human activities have caused considerable changes in watershed hydrological cycles. Serious water problems such as floods, droughts, and environmental pollution are therefore encountered in many regions (Collier *et al.* 1996; Duan *et al.* 2013; Xu *et al.* 2013). The Qinling Mountains provide a natural boundary between north and south China. This mountain range is located in a transition zone between (semi)-arid regions in north China and humid regions in south China, with unique geographical locations and watersheds.

According to the evaluation results of regional water resources, the rivers at the northern foot of the Qinling Mountains provide ~92% of the main water source for urban agglomerations in the Guanzhong Plain in Shaanxi Province, China (Liu & Li 2016). Owing to the shortage of water resources in these watersheds, great effort has been made toward the development and use of water resources and hydro-ecological management in this area to reduce and prevent degradation of watersheds and solve conflicts between water supply and water demand

(Yang *et al.* 2004; Patro 2008; Xia *et al.* 2008; Duan *et al.* 2016).

Water supply reservoirs and rubber dam projects have been constructed over the last several years in urban rivers at the northern foot of the Qinling Mountains to address municipal water demand and water quality deterioration in the Guanzhong Plain. Consequently, watershed processes have been affected, including groundwater/surface water links. The changes in water resources are characterized by complex ranges and frequencies, and causes the forming of a versatile artificial–natural water cycle pattern (Xu *et al.* 2013). Water supply reservoirs and rubber dam projects increase the risks and uncertainties in the management of water resources and protection of the hydro-ecological environment.

Dam projects, important for developing and managing water resources, have enormous implications for mitigating energy shortages, especially in large energy consuming countries such as China. However, due to irrational development and use of water resources, the hydro-ecosystems of urban rivers continue to deteriorate in arid and semi-arid regions of China (Birhanu *et al.* 2014). It is important to investigate the impact of dam projects on rivers and propose countermeasures in order to reduce the degradation of river ecosystems. Numerous studies have investigated the impact of climate change and human activities on the hydrological regime (Collier *et al.* 1996; Church 2010; Xu *et al.* 2013) and water environment (Suchowolec & Gorniak 2006; Paul & Putz 2008) in rivers. Xia *et al.* (2008) analyzed the ecological water demand of rivers in arid and semi-arid regions of west China under the impact of human activities. Chisholm & Aadland (1994) and Gippel (1993) evaluated the impact of constructing and operating water conservancy projects on water ecosystems in the lower reaches of a watershed based on monitoring data of runoff and water quality. Yang *et al.* (2015) proposed a geomorphology-based hydrological model (GBHM) to investigate the mechanism by which climate change and human activities affect the hydrological situation and water environment of rivers in a semi-arid region of China. Other studies investigated the impact of dam projects on water quality and quantity in rivers and their regulation. For instance, Hayes *et al.* (1998) and Burke *et al.* (2009) analyzed the role of dam regulation in the evolution of river water quality and

quantity. Yeager (1994) and Wiatkowski & Paul (2009) quantitatively assessed the impact of dam projects on the river water environment. Birhanu *et al.* (2014) simulated the changes in the river water environment to optimize the integrated regulation and control rules of regional water quantity and quality. Additionally, Zuo & Li (2014) investigated the relationship between the discharge flow of dams in a heavily polluted river and the key indicators of a river water ecosystem through field experiments of dam regulation.

Previous studies have simulated the impact of dam projects on the river environment using qualitative analysis or numerical models (Xia *et al.* 2008; Zuo & Li (2014); Birhanu *et al.* 2014), with a lack of real experimental data. Meanwhile, most studies have evaluated the impact of dam projects on hydrological processes in the lower reaches on a macro scale. There is a lack of research on the impact of different types of dam projects on the hydrological process of downstream urban rivers under a changing environment. Moreover, owing to deficient hydrological observation data in west China, existing studies lack sufficient understanding about the interference of hydro-ecological environment by dam projects in the dry season. Therefore, studies are urgently needed to investigate the overall environmental change in watersheds based on the regulation of rubber dam projects and experiments in the field, in order to reveal the impact of rubber dams on water quality and ecology in the urban rivers of west China.

Here, the Bahe River, a heavily polluted urban river at the northern foot of the Qinling Mountains, was selected to undertake the following studies. (1) We adjusted the structure and calibrated the parameters of the GBHM and inversed the runoff generation and concentration processes in the upper and middle Bahe River watershed during different periods. This objective was achieved according to the changes in meteorological input, underlying surface conditions, and hydro-geological conditions caused by climate change and human disturbance (urbanization and water conservancy projects). (2) We also constructed a water regulation model of rubber dam projects in the lower urban reaches with the constraints of runoff process, water environment self-purification capacity, and ecological basic flow in the lower reaches. The model was used to determine the optimal hydro-ecological regulation scheme of rubber

dam projects in the lower urban reaches. This study may help improve the hydro-ecological environment in heavily polluted rivers. The results provide a reference for managing water resources and controlling hydro-ecology in heavily polluted urban rivers in semi-arid regions.

STUDY AREA AND DATA

Regional features and hydroecological status

The Bahe River is the largest first-class tributary of the Weihe River in eastern Xi'an city at the northern foot of the Qinling Mountains (109°00′–109°47′ E, 33°50′–34°27′ N), as shown in Figure 1. The river connects two major eco-regions, the Qinling Mountains and the Weihe River Watershed, and provides one of the main water sources for Xi'an city. The Bahe River is 104.1 km long, with a total watershed area of 2,581.0 km^2 and a mean riverbed slope of 6.0‰. The terrain is high in the south and low in the north, which can be roughly divided into four landform types from the source to the lower reaches: the Qinling Mountains, spurs and hills, loess tablelands, and river plains. The highest precipitation occurs in mountainous areas in the upper reaches, and the mean annual precipitation between 1956 and 2010 was greater than 830 mm, accounting for 65% of the total precipitation in the whole watershed (Liu & Li 2016; Miao *et al.* 2016). The lowest precipitation is found in the lower reaches, with a mean annual precipitation of less than 700 mm. The precipitation is concentrated in mountainous areas in the upper reaches, while there is a shortage of water resources in the lower, more developed, urban reaches. The condition of water resources restricts urban development in this region.

According to statistical data of annual precipitation and annual runoff from the Bahe River (1956–2010), the distribution of runoff is generally consistent with that of precipitation. Approximately 89% of the annual runoff is concentrated in May to November. The largest monthly precipitation occurs in September (~16.3% of the annual runoff), while the lowest monthly precipitation occurs in February (1.6–1.9% of the annual runoff). The runoff shows large intra- and inter-annual variability, so that runoff and water quality is poor in the urban reaches during the dry season.

In 2008, three rubber dams were constructed and operated in the river channel in plain areas of the lower Bahe River for regulating urban flood control and landscape impoundment. The long-term operation of rubber dams led to decreased flow velocity, increased river water

Figure 1 | The rubber dam project in Bahe River.

consumption (e.g. evaporation and infiltration), and lower water environment self-purification capacity. In June 2015, the Lijiahe Reservoir was constructed and operated in the upper Bahe River. This reservoir, one of the important domestic water supply reservoirs in Xi'an, Shaanxi Province, has a catchment area of 362 km^2 and a total storage capacity of 56.9 million m^3. After the construction and operation of the Lijiahe Reservoir, the water quantity in the lower Bahe River decreased sharply, leading to serious water shortages and pollution-induced water shortages in the lower urban reaches of the watershed.

Downstream water pollution is mainly derived from non-point source pollution of upstream farmland and the impacts of human activities (e.g. reservoir and dam construction), which, according to our discharge measurements (2016) and pollution surveys (2013–2016), may aggravate river water quality. Digital elevation model (DEM) data, river system, and station distribution in the Bahe River watershed are shown in Figure 2. The locations and image of rubber dam projects are shown in Figures 1 and 2. The 1# is a small overtopped cofferdam with little effect on local water resources, 2# and 3# are rubber dam projects. Mean chemical oxygen demand (COD) in 2# and 3# rubber dams is greater than 30 mg/L and the mean ammonia nitrogen (NH$_3$-N) concentration is greater than 1.5 mg/L. During the dry season (October–April), COD and NH$_3$-N concentrations are greater than 40 and 2.03 mg/L, respectively. The monitoring results of monthly maximum COD and NH$_3$-N in 2014 and 2016 are shown in Figures 3 and 4. After the operation of Lijiahe Reservoir in 2015, downstream water pollution became more serious. Along with population growth and rapid urban expansion in the middle and lower reaches of the watershed, there is an urgent need to solve water environmental problems such as the pollution of surface waters and the provision of ecological flows in the river channel.

Data and research approach

Meteorological and runoff data were obtained from 12 meteorological stations and one controlled hydrological station in the upper and middle reaches of the Bahe River watershed (Figure 2). Other data included DEM elevation, land use, and vegetation data in the watershed,

as well as channel water quality, monitoring and in-situ experimental data in the lower urban reaches. These data were used to construct the GBHM and a water regulation model in the lower river channel. Furthermore, we simulated runoff generation and concentration in the watershed, water quantity, water environment self-purification capacity, and ecological basic flow in the lower river reaches including regulation via rubber dam projects. The regulation scheme of rubber dam projects we propose after evaluating the impact of climate change and human activities on hydrological processes based on simulated outputs of hydrological models (GBHM) are different from previous studies (Xia *et al.* 2008; Zuo & Li 2014; Birhanu *et al.* 2014). The principles of optimal regulation under different scenarios are illustrated in Figure 5.

DISTRIBUTED HYDROLOGICAL MODEL AND WATER REGULATION MODEL

Brief description of the GBHM

The hydrological model that was used in this study is a distributed geomorphology-based hydrological model that was developed by Yang *et al.* (1998, 2015). The model is constructed based on DEM and geographic information system (GIS). The model structure is built on the catchment geomorphological properties, and the model represents the catchment's hydrological processes by using physically based equations. GBHM mainly consists of a hill slope hydrological module and a kinematic wave flow routing module (Yang *et al.* 2015). In the hill slope module, GBHM simulates the hydrological processes, including interception, evapotranspiration, infiltration, overland flow, unsaturated flow and groundwater flow (Yang *et al.* 1998). The model has four major parts, the spatial information database of watershed, the hydrological calculation module, the input module, and the output module. The structure of the GBHM is shown in Figure 6.

This model has been used frequently in humid regions and semi-arid regions of north China. The reliability and rationality of the model have been verified (Yang *et al.* 1998, 2015; Miao *et al.* 2016). The model clearly describes
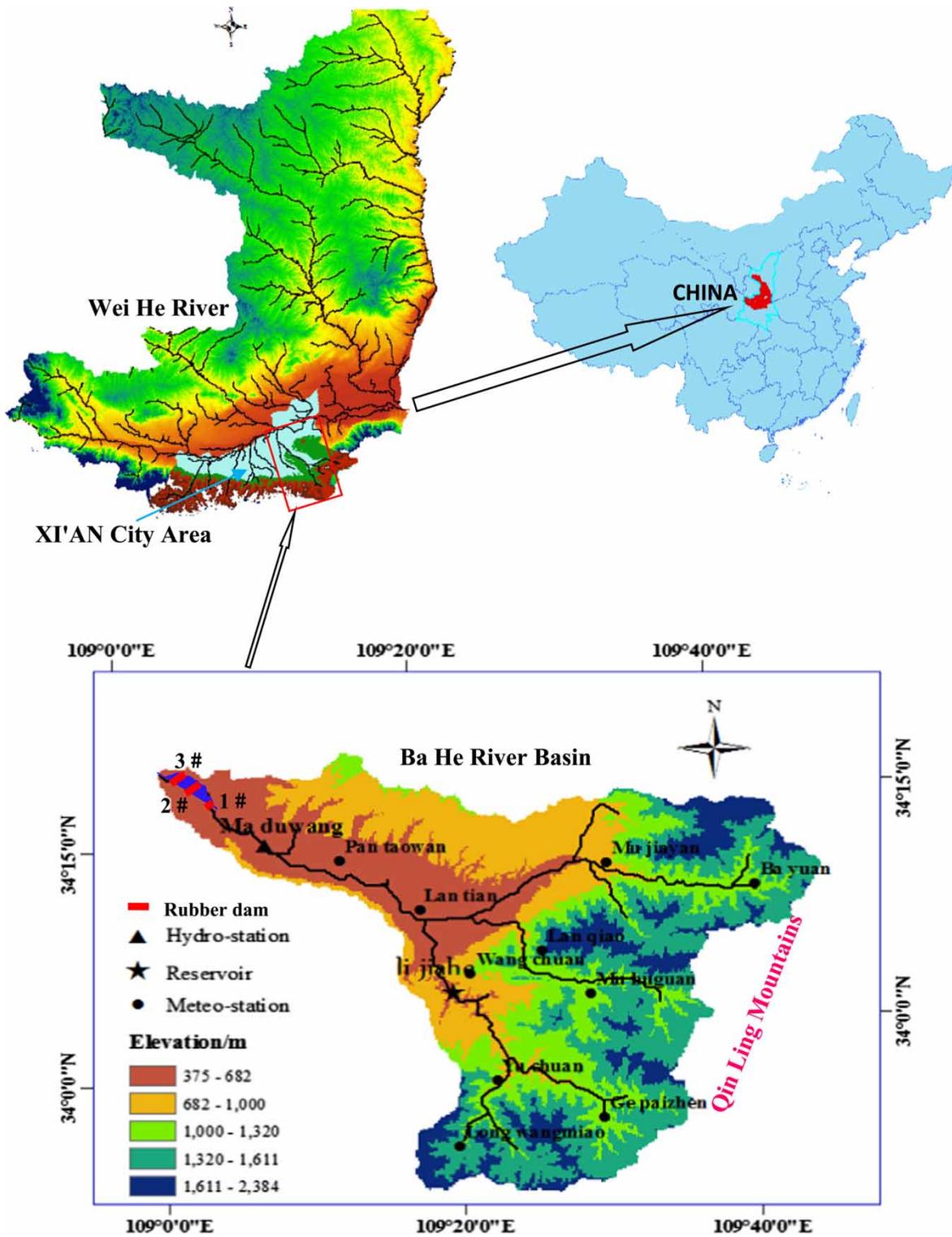
Figure 2 │ Locations of the Bahe River watershed, the hydrometeorological stations, dams and reservoirs used in this study.
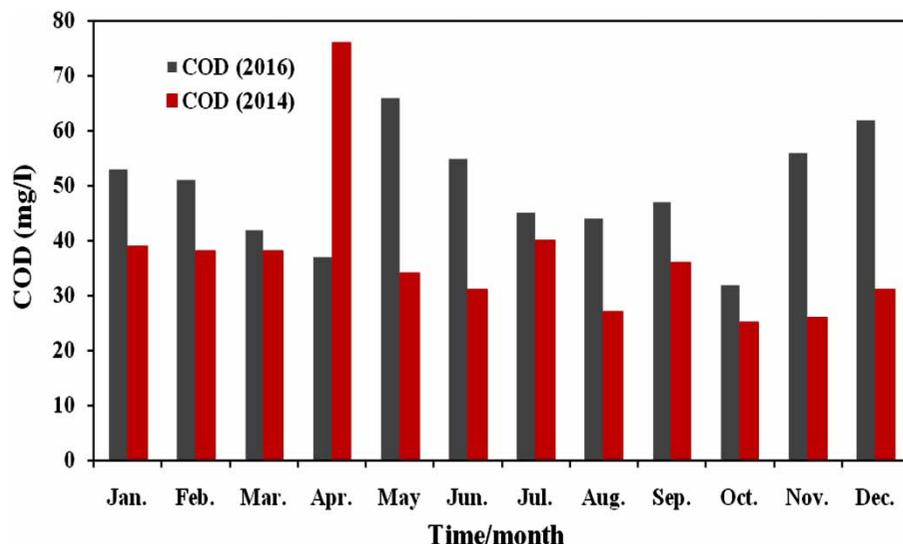
Figure 3 │ Monthly maximum chemical oxygen demand (COD) concentration in Bahe River in 2014 and 2016.
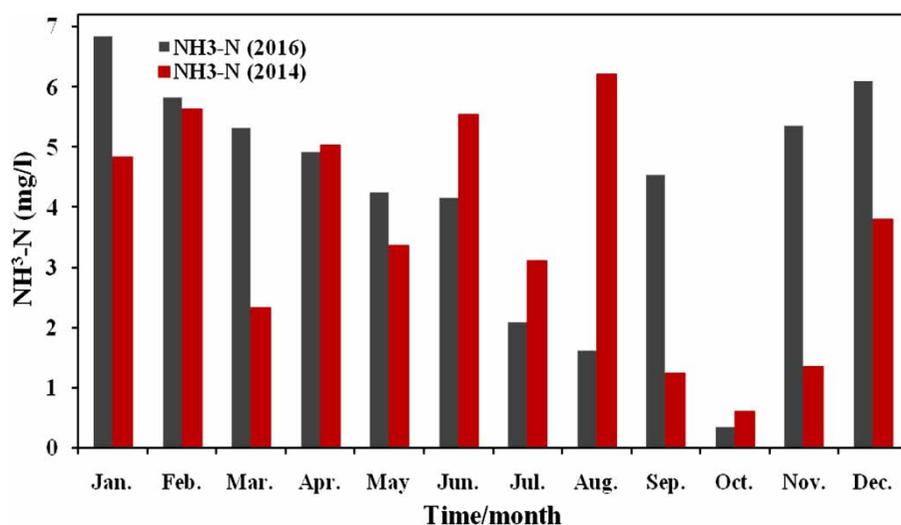

Figure 4 │ Monthly maximum ammonia nitrogen (NH₃-N) concentration in Bahe River in 2014 and 2016.

the physical mechanisms of hydrological processes. Modules can be added and the model structure and parameters can be adjusted according to specific conditions in the watershed. The model parameters include vegetation and land surface parameters, soil water parameters, and river parameters. Most model parameters are defined according to their physical meaning based on either *in situ* measurements or regional/global databases. Only a few parameters must be calibrated, such as the hydraulic conductivity of groundwater. A detailed description of the GBHM model

parameters is available elsewhere (Yang *et al.* 2015). In this study, we adjusted the subsystem modules and key parameters of the model for hydrological verification and simulation based on the spatial-temporal distribution of human activities in urban rivers. Consideration was given to the impact of changes in the underlying surface conditions, operation of water conservancy projects, and municipal water withdrawal and drainage in the upper reaches of the watershed and the middle and lower urban reaches on regional hydrological cycles.
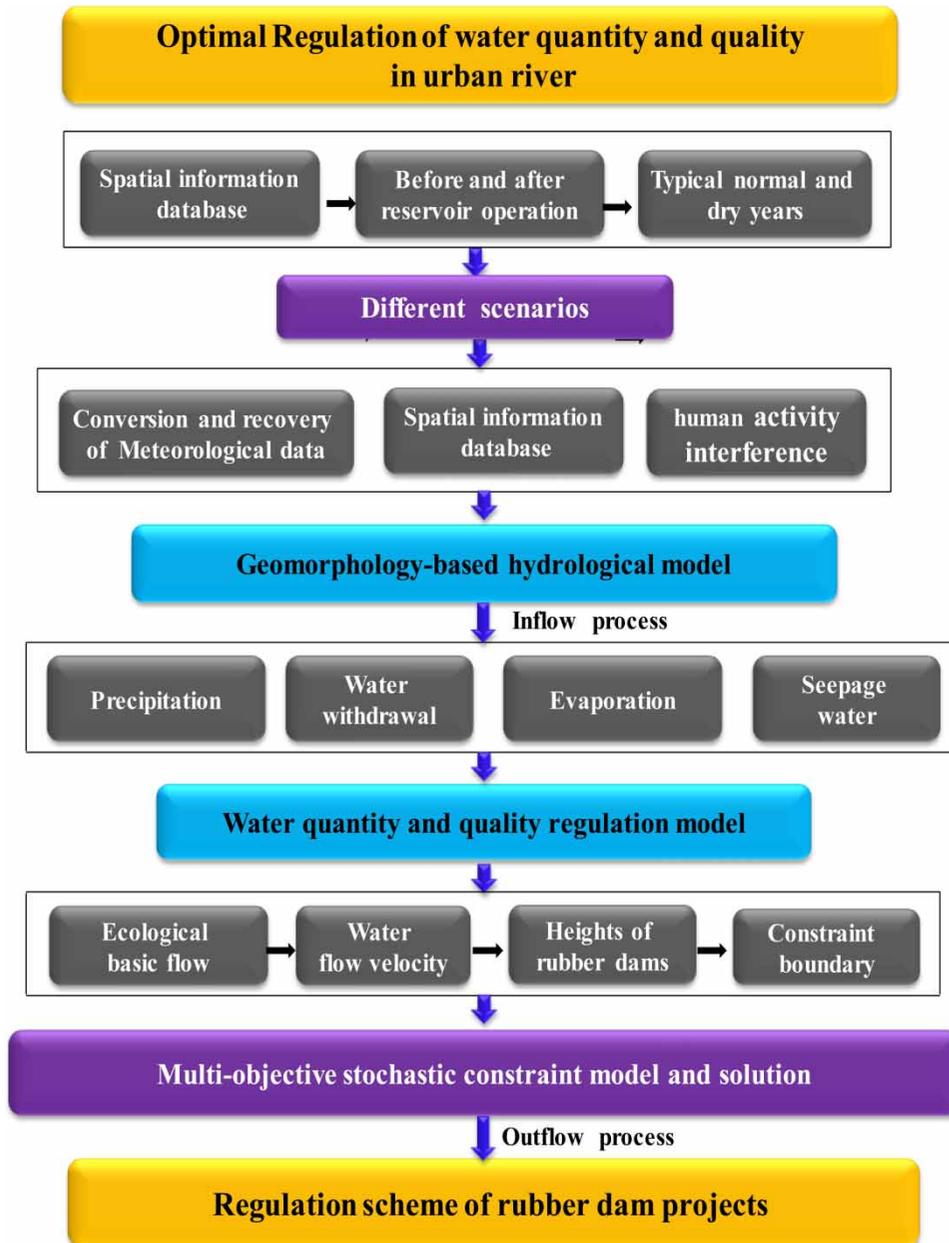
Figure 5 | Technical route for integrated regulation of water quantity and quality in an urban river.

Water regulation model and solution

We constructed the water regulation model of river reaches using two constraints based on the principle of water balance in river reaches, i.e. the inflow process from the upper river channel simulated by the GBHM and the mean critical flow velocity in the cross-section. The model was used to calculate the mean flow velocity in the cross-section, interval water consumption, and seepage in the rubber dam reservoir areas, with the rubber dam projects being elevated to different heights.

Water balance method

The water balance equation was established using the inflow, outflow, precipitation, infiltration and evaporation
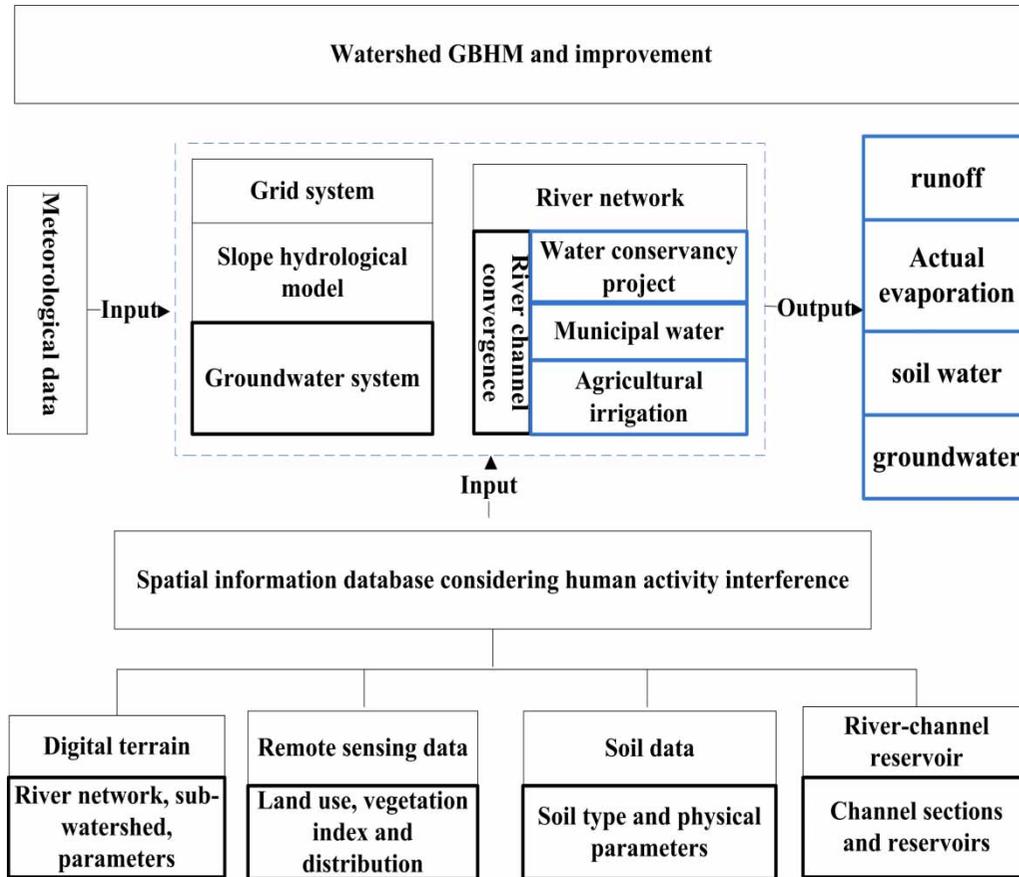
Figure 6 │ Structure of the geomorphology-based hydrological model (GBHM).

in the 3# and 2# rubber dam reservoir areas:

$$
\begin{aligned}
W_{\text{Outflow}} = W_{\text{Precipitation}} + W_{\text{Inflow}} + W_{\text{Evaporation}} \\
+ W_{\text{Leakage}} + W_{\text{Withdrawal}} \pm \Delta V
\end{aligned}
\tag{1}
$$

where $W_{\text{Precipitation}}$ is the precipitation during the study period; W_{Inflow} is calculated using the GBHM; W_{Outflow} is the outflow water of the rubber dam reservoir; $W_{\text{Evaporation}}$ is the water surface evaporation (calculated using monthly evaporation data) times the area, namely the total evaporation in the corresponding period; W_{Leakage} is the total of lateral seepage and bottom seepage in the river channel; $W_{\text{Withdrawal}}$ is the water storage and ΔV is the variation of water storage in the rubber dam reservoir areas.

Multi-objective stochastic constraint model and solution

We constructed the multi-objective stochastic constraint model based on water balance Equation (1). Constraint conditions of the multi-objective stochastic constraint model were as follows: mean flow velocity in the cross-section greater than critical flow velocity in the cross-section; water flow greater than ecological basic flow; and minimal seepage water loss. The water balance model of river reaches was used for simulation and calculation. Our experimental study showed that total phosphorus (TP), COD, and NH_3-N concentrations were lower in the river when the mean flow velocity was greater than 0.01 m/s. Therefore, we set the constraint of water flow in the rubber dam reservoir areas as mean flow velocity in the cross-section greater than 0.01 m/s to improve the water environment self-purification capacity. The mean flow rate, flow velocity, and water seepage at varying rubber dam heights (range, 0–3.0 m), and water surface evaporation were exported under the specific ensuring probability (greater than 90%). The ecological basic flow was estimated using the Tennant method (Burke *et al.* 2009).

The multi-objective stochastic constraint model and solution are described below. The main idea of multi-objective model is to minimize the deviation from the goals and obtain reasonable solutions at a given priority. The model obtains the solution using an intelligent optimization algorithm (Zuo & Li 2014; Birhanu *et al.* 2014). The basic framework of the multi-objective stochastic constraint model is:

$$\begin{cases} \text{MIN} \sum_{j=1}^{l} P_j \sum_{i=1}^{m} (u_{ij}d_i^+ + v_{ij}d_i^-) \\ s.t. \\ P_r \begin{Bmatrix} H_{ik}(y, \xi) \leq 0 \\ k = 1, 2, \ldots q_i \end{Bmatrix} + d_i^- - d_i^+ = w_i, \quad i = 1, 2, \ldots n \\ \qquad\qquad G_j(y, \xi) \leq 0, \qquad j = 1, 2, \ldots p \\ \qquad\qquad d_i^-, d_i^+ \geq 0, \qquad i = 1, 2, \ldots n \end{cases}$$
(2)

where P_j is the priority factor, which indicates the importance of the goals (P_j is far greater than P_{j+1} for all); u_{ij} is the weight factor of positive deviation for the ith goal of priority j; v_{ij} is the weight factor of negative deviation for the ith goal of priority j; d_i^- is the negative deviation of goal i from the target value; d_i^+ is the positive deviation of goal i from the target value; H_{ik} is the real-valued function in goal constraints; G_j is the real-valued function in uncertain environments; w_i is the target value of goal i; l is the number of priority levels; and n is the number of goal constraints.

RESULTS AND DISCUSSION

After the operation of Lijiahe Reservoir in May 2015, downstream water reduction and water pollution became more serious. Along with population growth and rapid urban expansion in the lower reaches of the watershed, it is urgently needed to solve practical problems such as the pollution of the surface water environment and ensure the ecological flow in the river channel. As there were no gauging stations in the lower urban reaches, we were unable to determine the inflow in the lower reaches of the Bahe River. Thus, we established the GBHM and inversed the inflow process in the lower reaches of the watershed during different periods according to the changes in meteorological input, underlying surface conditions, and hydrogeological conditions caused by urbanization and water conservancy project construction in the watershed. Furthermore, we constructed the water

regulation model of rubber dam projects with the constraints of runoff process, water self-purification capacity, and ecological basic flow in the lower reaches during different periods. The optimal water storage height of rubber dam projects in the lower urban reaches was finally determined using stochastic simulation and an intelligent optimization algorithm.

Water quantity in the lower reaches after reservoir operation

In order to construct a GBHM with better physical properties, we modified the sub-watershed units and added the reservoir operation modules according to the construction location, catchment area, and operating rules of reservoirs in the middle and upper reaches of the watershed (Figure 6). Then, we simulated the monthly runoff process into the lower reaches before and after reservoir operation according to the meteorology, hydrology, land use, vegetation cover, and terrain data during different periods of 1990–2010. The runoff process into the lower reaches was compared before and after reservoir operation to evaluate the impact of reservoir operation on water quantity in the river channel on a long time scale. Water quantity changes before and after reservoir operations are shown in Figure 7.

The results showed that the precipitation and runoff depth showed large spatial variations in the whole watershed. The reservoir was located in the middle Wangchuan River the largest upstream tributary and also the precipitation concentrated area of the Bahe River. The inverse calculation of watershed water quantity showed that after reservoir operation in the upper reach, the annual and monthly inflows into the lower river channel were reduced by ~30%. The proportional reduction of water flow was 36% compared with the annual and monthly water inflows in the dry years. After reservoir construction and operation in the upper reach, a significant reduction of water occurred during the flood season (July–September) in a year. The proportional reduction of mean monthly water flow was ~50%.

Optimal regulation scheme of rubber dams in the lower urban reaches in typical year

The runoff in the Bahe River watershed is mainly formed by precipitation. The precipitation in the mountain area is a
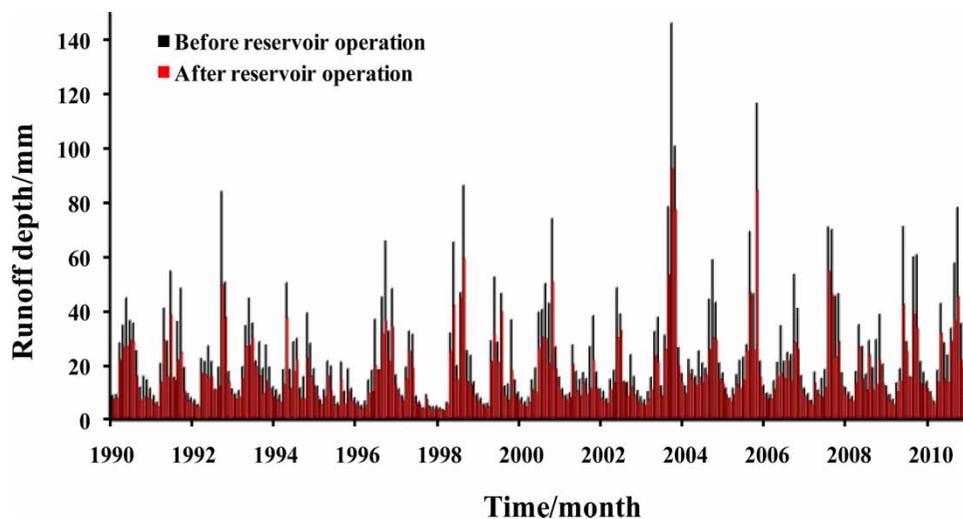
Figure 7 | Changes in the runoff depth before and after reservoir operation (1990–2010).

decisive factor for runoff change in lower reaches. In the Bahe River watershed, the runoff has large interannual variations, uneven intra-annual distribution, and significant seasonal changes. During the dry season, the channel inflow is low and water pollution occurs frequently, especially in normal and dry years. Therefore, we selected typical years for simulating hydro-ecological regulation in the lower urban reaches of the Bahe River, with a specific focus on the dry season in a year. The regulation scheme of rubber dams was developed for normal and dry years.

In accordance with the changes in the relationship between annual rainfall and runoff, we selected the normal year 2001 and the typical dry year 2005 for simulation and calculation based on the total annual runoff. A specific consideration was given to the inflow change during the dry season. The GBHM was used to inverse the downstream channel inflow process in the present conditions (land use change, operation of upstream water diversion project, and water withdrawal in river reaches). Water regulation of rubber dams in the lower urban reaches was simulated based on the water balance model. The calculation was conducted using the mean flow velocity of greater than 0.01 m/s and ecological basic flow greater than 10% of the inflow from the upper reach in order to improve the water environment self-purification capacity.

Tables 1 and 2 show the stochastic simulation and calculation results of water regulation in river reaches based on the GBHM coupled with the water balance model. There

Table 1 | Results of monthly water quantity regulation in a typical dry year (2001) based on the multi-objective stochastic constraint model

Month	Inflow runoff (m³/s)	Water storage height of 2# rubber dam (m)	Water storage height of 3# rubber dam (m)	Flow velocity in 2# dam reservoir area (m/s)	Flow velocity in 3# dam reservoir area (m/s)
1	4.82	1.13	0.82	0.011	0.010
2	4.82	1.13	0.82	0.011	0.010
3	3.64	0.60	0.50	0.015	0.013
4	19.13	3.00	2.15	0.016	0.016
5	3.77	0.90	0.60	0.011	0.011
6	3.76	0.90	0.60	0.011	0.011
7	5.00	1.13	0.82	0.011	0.011
8	2.74	0.66	0.38	0.010	0.012
9	8.72	1.13	1.26	0.019	0.012
10	16.81	3.00	2.86	0.013	0.010
11	4.47	1.09	0.60	0.010	0.013
12	4.18	1.04	0.67	0.010	0.011

was a ~40% reduction of water in the lower river reaches due to operation of water supply reservoirs in the upper reach and impoundment of rubber dam projects in the lower reaches. After reservoir operation in the upper reach, the annual and monthly inflows into the lower river channel were reduced by ~30%. Water surface area and surface evaporation also increased in the rubber dam reservoir areas. Evaporation increase accounted for ~6% of the water

Table 2 │ Results of monthly water quantity regulation in a typical normal year (2005) based on the multi-objective stochastic constraint model

Month	Inflow runoff (m³/s)	Water storage height in 2# rubber dam (m)	Water storage height in 3# rubber dam (m)	Flow velocity in 2# dam reservoir area (m/s)	Flow velocity in 3# dam reservoir area (m/s)
1	7.02	1.57	1.00	0.011	0.012
2	5.66	1.09	0.90	0.013	0.011
3	8.67	1.23	1.44	0.018	0.011
4	8.57	1.20	1.40	0.018	0.011
5	5.49	1.09	0.90	0.125	0.011
6	10.39	1.51	1.62	0.017	0.011
7	23.61	3.00	3.00	0.019	0.014
8	35.10	3.00	3.00	0.029	0.020
9	14.40	2.89	2.51	0.012	0.010
10	66.82	3.00	3.00	0.055	0.039
11	10.74	1.70	1.79	0.016	0.010
12	6.54	1.60	1.05	0.010	0.011

in the lower river channel. Meanwhile, the seepage of natural riverbed was increased by ~4% following the impoundment of rubber dam projects.

Both the monitoring data and water balance calculation results showed that the precipitation in 2016 was average, but the reduction of water in the lower river was more than 40%. The mean annual COD concentration was greater than 35 mg/L and the NH_3-N concentration was greater than 2.0 mg/L in the rubber dam reservoir area. During the dry season (October–April), the mean flow velocity was lower than 0.005 m/s in the reservoir area. Dam operation in the upper and lower reaches resulted in a reduction of water quantity and significant reduction in flow velocity in the lower reaches, leading to aggravated water pollution in 2016.

DISCUSSION

The past decade has seen declining water resources in the area of the Bahe River as populations have grown and industrial/agricultural development has progressed in Xi'an city. The shortage of water resources inevitably restricts urban development in this region. Due to irrational water

resources utilization and management, the hydro-ecosystems of the Bahe River continue to deteriorate, especially in the plain area of the river downstream, where the deterioration of the water environment is most obvious. The dam regulation influences the evolution of urban river water quality and quantity. We may improve the water environment self-purification capacity and water environmental condition by optimizing the relationship between the discharge flow of dams and the key indicators of river water quality in a heavily polluted river, as described in broad terms by Burke *et al.* (2009), Yeager (1994) and Hayes *et al.* (1998).

As there were no gauging stations in the lower reaches of the Bahe River (the lack of hydrological monitoring data is a common problem in the arid and semi-arid areas of urban rivers in western China), it was difficult to determine the inflow in the lower reaches of the Bahe River. Thus, we proposed a distributed hydrological model to investigate the mechanism by which climate change and dam projects affect the hydrological situation and water environment of urban rivers in the upper and middle Bahe River watershed. Based on the principle of water balance in river downstream and the experimental study in a regional water landscape, we constructed the multi-objective stochastic constraint water regulation model of dam projects and calculate the mean flow velocity in the cross-section, interval water consumption, and seepage in the rubber dam reservoir areas. We optimized the relationship between the discharge flow of dams and the key indicators of river water quality according to the hydrological regime in the urban river. The hydrological model and results presented in this paper contribute to the ongoing debate on the detection and modeling of hydrological response mechanism under a changing environment in semi-arid regions (Yeager 1994).

The proposed regulation scheme may effectively alleviate water pollution in heavily polluted rivers. However, a lack of hydro-ecological indicators and long-term monitoring water quality data, the accuracy of simulation results is low and is presently limiting the effect of the dam regulation scheme in improving the hydro-ecological conditions in urban rivers. With a shortage of water resources in semi-arid regions of China, increased construction of water conservancy projects and rapid urbanization have led to serious river water pollution. As living standards improve

in China, people expect higher requirements for the living environment. Artificial measures have been implemented for hydro-ecological restoration and protection and improvement of hydro-ecological conditions in urban areas. For example, artificial wetlands and lakes have been built and measures have been employed for controlling river water pollution. However, water consumption has increased. It remains difficult to resolve the fundamental contradiction between the water resources carrying capacity and continuously growing demand for water, a critical issue limiting hydro-ecological protection and water resource management in heavily polluted urban rivers in semi-arid areas, such as in northwest China.

SUMMARY AND CONCLUSIONS

Implementing optimal regulation of dams in the lower reaches of heavily polluted rivers is useful to ensure the environmental flow in river channels. Meanwhile, increasing flow velocity helps to improve the water environment self-purification capacity. These measures can effectively reduce the concentration of pollutants in heavily polluted urban rivers in semi-arid areas, with important implications for protecting the regional water resources. In this study, we proposed the optimal regulation scheme of rubber dams in order to improve the hydro-ecological conditions, especially in the plain area of the urban river downstream, where the deterioration of the water environment is most obvious. The main conclusions are as follows:

1. The operation of a water supply reservoir in the upper reach led to decreased channel inflow in the lower urban reach of the Bahe River. River impoundment by rubber dam projects in the lower reaches resulted in increased surface water area and strong water surface evaporation. Meanwhile, natural riverbed seepage increased. These were the main reasons for the decline of water quantity in the river channel and aggravation of water pollution in the lower Bahe River.

2. After the rubber dams impounds, lateral and bottom seepage in the river channel increased, contributing to shallow groundwater recharge. Groundwater reserves increased as a result, possibly alleviating the urban water shortages. With increasing groundwater exploitation, the groundwater level in the center of the funnel rises and tends to reach a dynamical equilibrium, potentially improving the groundwater environment in the riparian zone. These issues need to be studied further.

3. The performance of the models proposed in this paper was limited by the available data records. The proposed regulation scheme of rubber dam projects may help improve the river water quality. In order to improve the performance of the proposed regulation scheme, we suggest a reasonable water quality data length which exceeds the smallest cryptic period of the run-off time series.

4. In order to improve the hydro-ecological environment in urban rivers, one of the critical issues is to investigate and study the impact of dams on the distribution of 'runoff-evaporation-storage-seepage' in hydrological processes, as well as the water conversion and pollutant migration of groundwater and surface water.

Further research should focus on the influence of dams on the aquatic ecosystem.

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