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Integrated flood management for Beiyun River, China

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Abstract: Beiyun River Basin is holistically suffering a water shortage and relatively concentrated flood risk. The current operation (level-control) of dams and floodgates, which is in passive defense mode, cannot meet the demands of both flood control and storm water resources. An integrated flood forecasting and management system is developed by the connecting of the hydrological model and hydrodynamic model and coupling of the hydrodynamic model and hydraulic model for dams and floodgates. Based upon the forecasted runoff processes, a discharge-control operation mode of dams and floodgates is proposed to be utilized in order to well regulate the flood routing in channels. The simulated water level, discharge, and water storage volume under different design conditions of rainfall return periods and floodgates operation modes are compared. The results show that: (1) for small floods, current operation modes can satisfy the objectives, but discharge-control operation can do better; (2) for medium size floods, since pre-storing of the floods affects the discharge of follow-up floods by floodgates, the requirement of flood control cannot be satisfied under current operations, but the discharge-control operation can; (3) for large floods, neither operation can meet the requirement because of the limited storage of these dams. Then, the gravel pits, wetlands, ecological lakes and flood detention basins around the river must be used for excess flood waters. Using the flood forecasting and management system can change passive defense to active defense mode, solving the water resources problem of Beijing city and Beiyun River Basin to a certain extent.

Keywords: Rainstorm; Hydrological model; Hydrodynamic model; Hydraulic model; Water resources; Dams and floodgates.

INTRODUCTION

Extreme water shortage has seriously hampered the economic development of Beijing. Beiyun River is an important river system of Beijing and the full use of its water resources could alleviate the water shortage in the city. Meanwhile, Beiyun River is the main drainage channel for the city of Beijing thus flood safety is significant. The reservoirs play a limited role in flood control in this area because most of the channels are located in the plains and the source of the Beiyun River found in mountainous area is minimal. Dams and floodgates are used to control flood and manage water resources. Previous research has focused on the reservoir operation for controlling flood (Cheng and Chau, 2004; Li et al., 2010), and less on the operation of dams and floodgates. Obviously there is a great difference between these.

The Beiyun River has a large number of floodgates and dams on the channel, which change the course of natural river flow. The current operation mode of these floodgates and dams uses the design flood water level as a control indicator (Zhang et al., 2007). Namely, water level is controlled in order to store water if no flooding occurs, and all the floodgates are fully opened in the event of a flood, and later flood waters are blocked when flood waters recede. The disadvantages of this operation mode are: (1) storm water resources of the Beiyun River Basin are not fully utilized because much water is discarded during peak flood periods; (2) as a result of the short source path, steep slope, flash flood and the increase of urban road hardening, significantly increasing the flood risk, flood waters converge in a very short period of time (Fu, 2006a; Zhang et al., 2007). The use of this mode is due to the lack of a flood management system and the unknowns of the upstream runoff process. Therefore, this mode is a defensive mode. To fundamentally change the operation mode, a flood management system must first be established.

A flood forecasting and management system needs to predict upstream runoff based on the rainfall and then determine rational operations of dams and floodgates based on the predicted runoff. Constructed wetlands and other low-lying areas are considered for use as storage for excess flood waters. A combination of the hydrological model and hydrodynamic model, coupled with a hydraulic model for dams and floodgates, could better represent the physical mechanisms of flood forecasting and floodgate operation, but such combinations are rare. Zhang et al. (2010, 2011) tried to use the SWAT model to simulate flood routing and floodgate operation in the Wenyu and Huai Rivers at the one month time scale, simplifying both the flow dynamics in channel and the hydraulics for dams and floodgates. This study attempts to research flood control and water resources management under the condition of rain storms in the Beiyun River Basin, using a distribution hydrological model DWSM (Dynamic Watershed Simulation Model) and a hydrodynamic model CREST-1D (Code of Coastal, River, Environmental and Sediment Transport-one dimensional). DWSM, developed by Borah in 1979, can simulate the hydrological processes of river basins in suburban areas under the condition of a single rain storm. It has been applied and tested in small watersheds, such as Big Ditch watershed in Illinois (Borah et al., 2001), watershed W5 in Mississippi and watershed P4 in Georgia (Borah et al., 2002), among others. Preliminary results indicated that the model performs reasonably well in simulating hydrology in small watershed. The hydrological model was first developed in the 1950s (Hu and Zhang, 2004; Rui, 1997)，and since then, such models spring up more and more. At present, the more widely used theoretical hydrological models are distributed hydrological models. The typical distributed hydrological models include HSPF (Chen et al., 1995), SWAT (Arnold et al., 1995; Wang et al., 2003), MIKE-SHE model (Refsgaard et al., 1995), AnnAGNPS (Bingner et al., 1997), STORM and SWMM (Novotny, 1981). Among these models, HSPF, SWAT, MIKE-SHE and AnnAGNPS are long-term and basin scale models, incapable of simulating single storm floods. STORM and SWMM can simulate rain storms, but can only be used for urban areas. CREST-1D, developed by Fang et al. (2008), was coupled with a hydraulic model for dams and floodgates. This model can simulate one-dimensional flood routing, sediment and contaminant transport in open channels under unsteady flow conditions, as well as complex conditions of forked rivers, dam water discharge and flood diversion area storage. The principle and method are similar to MIKE11 and HEC-RAS, not mentioned here.

The Beiyun River Basin has the densest dams and floodgates and is experiencing severe eco-environmental deterioration and flood control challenges. This study has two objectives: (1) to integrate the hydrologic model, hydrodynamic model and hydraulic model for floodgates and dams with a GIS-based platform, forming a flood forecasting and management system for the simulation of runoff yield, flood wave propagation and the floodgate scheduling process, and (2) to analyze and assess the impact of a new floodgate operation on flood control and storm water resources. All results can be used to guide the utilization of storm water resources in the Beiyun River Basin, addressing the prominent contradictions between flood control and water resources management.

STUDY AREA

The Beiyun River Basin, lying in the northern tip of the North China Plain, originates in the south of Yanshan territory. From northwest to southeast, the Beiyun River flows through the Changping, Haidian, Shunyi, Chaoyang and Tongzhou Districts of Beijing, and through Hebei and Tianjin into the Haihe River, with a total drainage area of 6166 km^2, seen in Fig. 1. The Beijing Beiyun River is 90.3 km long with a drainage area of 4293 km^2. Mountainous areas in this watershed are small, of about 1000 km^2 including the hilly areas. The Beiyun River Basin has a continental monsoon climate with annual precipitation of 600 mm. The precipitation is unevenly distributed during the year and mostly concentrated into several heavy rains in July and August. Thus the peak flood waters can form easily. Water collection time becomes shorter and the peak flow becomes higher as a result of the increase of impervious urban areas. The characteristics of such flood are much higher at their highest point, great amount of waters, rapid, all of which create increasing pressure on Beiyun River floodgates. The Beiyun River is the main drainage channel of Beijing city, bearing 90% of the city's drainage tasks. The floods from Qing creek, Ba creek, Xiaozhong creek, Tonghui creek and Liangshui creek are all discharged by the Beiyun River. According to the analysis of outflow water from the Beiyun River from 1961 to 1998, the amount of annual average outflow is 931 million m^3. Although continuous drought occurred from 1999, the amount of average annual outflow still reaches 487 million m^3. The distribution of outflow is also uneven that the amount of outflow during flood season accounts for two-thirds of the total for the year.

There are six floodgates (Shahe, Lutuan, Xinpu, Weigou, Beiguan, Yulin and Yangwa) and five rubber dams (Shangxin, Zhenggezhuang, Caonian, Tugou, Luwan) built on the main channel of the Beiyun River. The Beiguan floodgates include two parts, Lanhe Gate on the main channel of the Beiyun River and Fenhong Gate on the channel of the river's outflow branch. Lanhe Gate, together with Fenhong Gate form a small reservoir. The maximum water storage of all these dams and floodgates is about 54.29 million m^3. Table 1 shows the important dams and floodgates on Beiyun River channel. Overall, the storage capacity of the Beiyun River dams is limited.

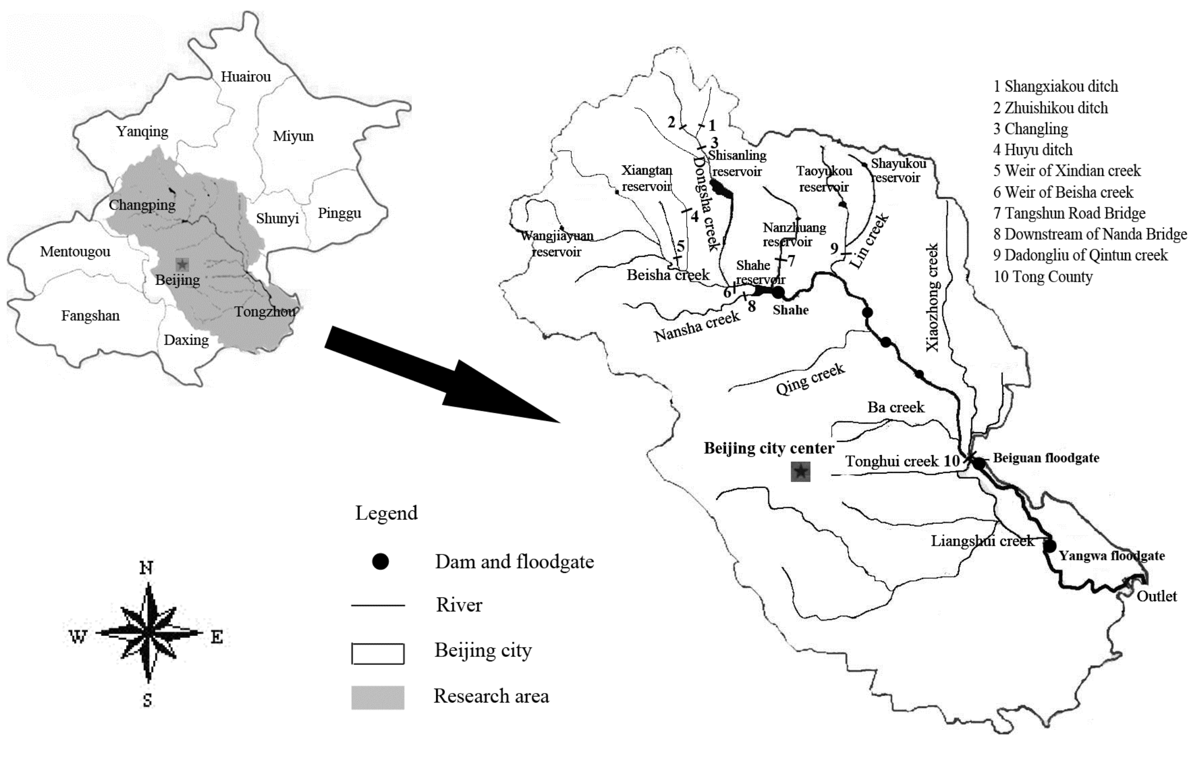


Fig. 1. Location of Beiyun River Basin in Beijing City.

Table 1. Important dams and floodgates on Beiyun River channel.

Name		Size (holes/width×height)	Bottom elevation (m)	High water level (m)	Water storage (million m^3)
Shahe floodgate		13/8.5×3.0	34.1	37.1	15.89
Beiguan floodgates	Lanhe Gate	7/12×5.0	15.77	20.5	7.86
	Fenhong Gate	9/10×4.0	16.86		
Luwan dams		3/60×4.0	14.0	18.0	8.51
Yulin floodgate		15/6×5.0	11.7	16.5	6.96
Yangwa floodgate		15/8.0×5.0	9.4	14.0	6.99

FRAMEWORK AND METHODOLOGY

To study the Beiyun River Basin flood control and storm water resources management approach, the rainfall and runoff characteristics should firstly be understood, and then dam and floodgate operation for floods under different rainfall conditions should be determined. The aim is to develop an appropriate method to maximize the flood safety and take full advantage of water resources. The flood forecasting and management system in the Beiyun River Basin, however, is currently less than perfect. The quantitative impact of dams and floodgates on floods and water storage capacity is unclear. Our research framework is as follows: First, distributed hydrological and hydrodynamic models are developed and the model parameters are calibrated in order to best simulate the runoff and flood routing processes under the current situation. Secondly, based on the calibrated model, the flow routing processes under new operations of dams and floodgates are simulated. Finally, the impact of new operations on flood control and storm water resources can then be assessed and compared with the results of old operations.

Data collection

First of all, the basin's DEM, land use map, soil map were collected, which are shown in Fig. 2(a), (b) and (c). There are 28 rain stations in and around the Beiyun River Basin, controlling the rainfall measurement in the entire basin. The location of rain stations and their controlling areas are demonstrated in Fig. 2(d). For calibration, a heavy monsoon rain which occurred in July, 1998 was selected. Rainfall data from these 28 rain stations and peak flow discharges at 23 controlling cross sections were collected. These sections were found scattered mostly in small tributaries, controlling the runoff yield in overland segments and upper streams. Moreover, the regulation of dams and floodgates both during the July, 1998 monsoon rain and in normal operating mode were also collected. Furthermore, the rainfall gathered in real time by automatic rain stations can also be used as the input of hydrological model. The integrated system has an interface to connect with the real-time database and download the data at a certain time interval.

Model selection and integration

DWSM model

The DWSM model simulates surface and subsurface storm water runoff, propagation of flood waves, soil erosion, and transport of sediment, nutrients, and pesticides in agricultural and rural watersheds. These processes are simulated by dividing the watershed into subwatersheds. These divisions take into account the nonuniformities in topography, soil, and land-use characteristics, which are treated as being uniform with representative characteristics within each of the segments. Each subwatershed is a combination of a channel and two overland segments. The overland segments are represented as rectangular areas with representative length, slope, width, soil, cover and roughness. The channels are described with representative cross-sectional shape, slope, length and roughness. The reservoir is treated as an individual computational node, put at the outlet of a channel.

There are two methods provided for users to choose in DWSM. Soil Conservation Service or SCS (1972) runoff curve number method is the simpler of the two alternative methods used to compute rainfall excess. This method uses only one parameter, the runoff curve number (*CN*), to estimate the excess. This method may be expressed as,

$$Q_r = (P - I_a)^2 \big/ (P - I_a + S), \tag{1}$$

$$S = 25400 \big/ CN - 254, \tag{2}$$

where Q_r is the direct runoff or rainfall excess (mm), P is the accumulated rainfall (mm), I_a is initial loss of rainfall which includes surface storage, interception and infiltration prior to runoff (mm), S is the potential difference between rainfall and direct runoff (mm), CN is the curve number representing the runoff potential of a surface. Suggested values of CN with respect to soil cover complex factors are given by SCS (1972). Accumulated rainfall exceed at each breakpoint time interval is calculated by using the Eqs (1) and (2), CN values and the accumulated rainfall at the breakpoint. The rainfall intensities are computed by dividing the rainfall increments by the corresponding time intervals. The initial loss of rainfall is affected by the state of the basin before the precipitation. As we suggest, $I_a = 0.26S$ when there is no antecedent precipitation before the precipitation, while $I_a = 0.20S$ when there is antecedent precipitation.

The other method is interception-infiltration method. The rainfall losses caused by tree canopies and ground covers is considered. Another part of rainfall losses is infiltration, computed by Green-Ampt method (Green and Ampt, 1911) which is newly added into the model. This method is more complicated and needs more supported data, which therefore is not used in this paper.

The surface water routing algorithm for both overland and channel flow segments is based on kinematic wave approximations (Lighthill and Whitham, 1955) of the Saint-Venant, or shallow water wave equations governing unsteady free surface flows.

CREST-1D model

The unsteady one-dimensional free surface flow in an open channel can be described by the Saint-Venant equations as follows (Chaudhry, 1993):

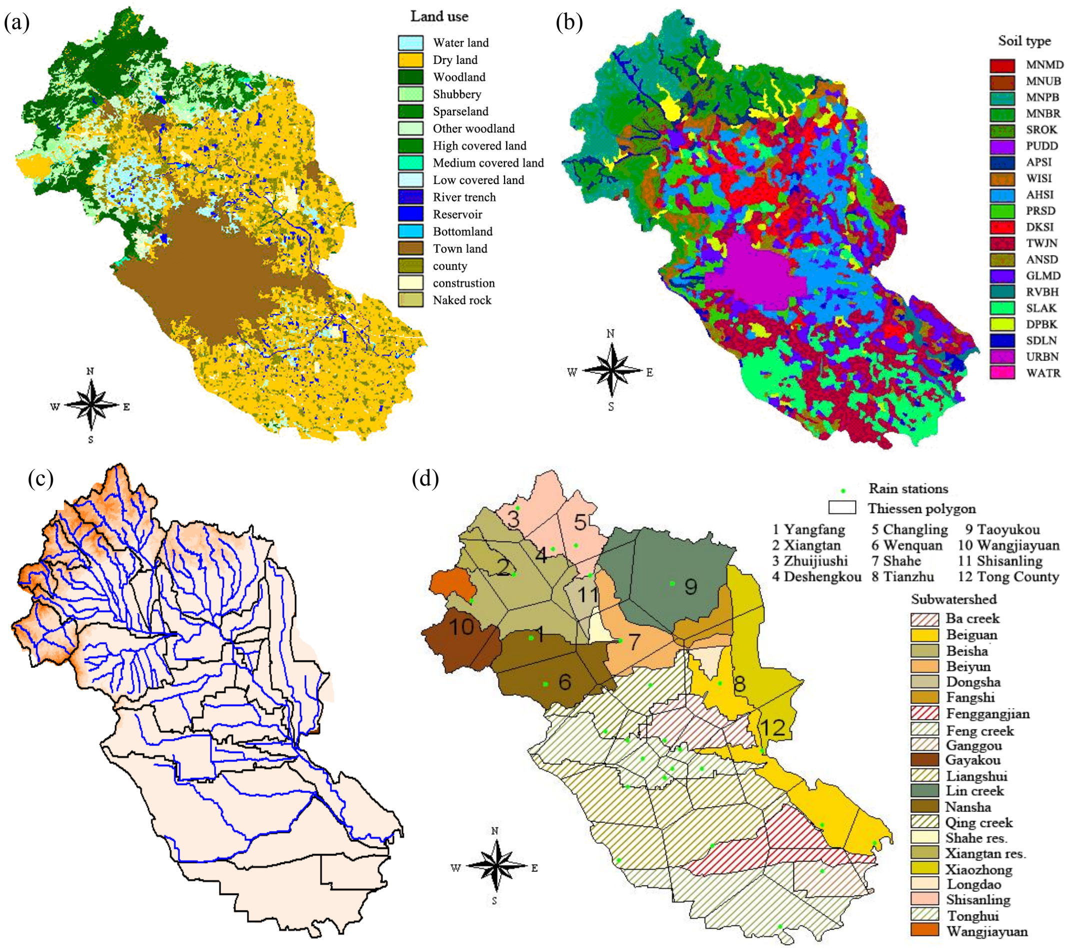


Fig. 2. Basic information of the basin: (a) land use, (b) soil type, (c) streams and sub-basin delineation, (d) controlling area of rain stations.

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_l, \tag{3}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+gA\frac{\partial Z}{\partial x}+g\frac{Q|Q|}{C^2AR}=\frac{Q}{A}q_l, \tag{4}$$

where x and t are spatial (m) and temporal (s) axes, Q is flow discharge ($m^3\ s^{-1}$), A is flow area (m^2), q_l is the lateral discharge per unit channel length ($m^2\ s^{-1}$), g is gravitational acceleration ($m\ s^{-2}$), C is the Chezy resistance coefficient, defined as $C=\frac{1}{n}R^{1/6}$, with n being the Manning coefficient of roughness, R is the hydraulic radius (m), and Z is water stage (m).

The Preissmann implicit four-point finite difference method is used to discretize the governing equations (Fang et al., 2008). During the iteration process, one may assume $A_j^{n+1}=A_j^*+\Delta A_j$ and $Q_j^{n+1}=Q_j^*+\Delta Q_j$, in which the symbol * denotes variable values at the last iteration step, and ΔA and ΔQ are the increments of flow area and discharge, respectively. By substituting the above relations into Eqs (3) and (4), and linearizing the nonlinear terms, the following iteration equations are obtained after simplification and rearrangement:

$$a_{1j}\Delta Q_j+b_{1j}\Delta Z_j+c_{1j}\Delta Q_{j+1}+d_{1j}\Delta Z_{j+1}=e_{1j}, \tag{5}$$

$$a_{2j}\Delta Q_j+b_{2j}\Delta Z_j+c_{2j}\Delta Q_{j+1}+d_{2j}\Delta Z_{j+1}=e_{2j}, \tag{6}$$

where a_{1j} to e_{1j} and a_{2j} to e_{2j} are coefficients and may be computed with known values of hydraulic parameters, geometry at time t^n.

Two additional equations are supplied by the specified upstream and downstream boundary conditions to enclose this homogeneous algebraic equation system. These equations are then solved by successively applying the double sweep Thomas algorithm (Cunge et al., 1980).

Hydraulic model for dams and floodgates

In a practical project, floodgates and dams are often built to control water discharge or water stage. According to the design manual of US Army Corps of Engineers, the patterns of outflow through the gate are divided into 4 classes: 1) full opening free flow, 2) full opening submerged flow, 3) partial opening free flow, and 4) partial opening submerged flow. In class 1) and 2), the gate has no control of flow and the flow equation is the same as that of weir flow. The criteria of these flow patterns and flow equations are as follows.

1) Full opening free flow

$$Q=mB\sqrt{2g}H_0^{3/2}\quad\left(\frac{e}{H_0}\ge 0.65,\frac{h_s}{H_0}\le 0.72\right), \tag{7}$$

where m is the discharge coefficient for free weir flow, B is the width of the gate (m), H_0 is upstream energy head above crest including velocity energy head (m), e is gate opening (m), and h_s is downstream water depth above crest (m).

2) Full opening submerged flow

$$Q = \varphi_m B h_s \sqrt{2g\left(H_0 - h_s\right)} \quad \left(\frac{e}{H_0} \geq 0.65, \frac{h_s}{H_0} > 0.72\right), \tag{8}$$

where φ_m is the discharge coefficient for the submerged weir flow.

3) Partial opening free flow

$$Q = \mu B e \sqrt{2gH_0} \quad \left(0 < \frac{e}{H_0} < 0.65,\ h_s \leq h_c''\right), \tag{9}$$

where μ is discharge coefficient for free gate flow, h_c'' is downstream water depth after water jump (m), computed as

$$h_c'' = \frac{h_c'}{2}\left(\sqrt{1 + 8\frac{q_c^2}{g h_c'^3}} - 1\right) \tag{10}$$

where h_c' is downstream water depth before water jump (m), i.e. water depth at contracted section, and q_c is unit flow discharge through gate ($m^2\ s^{-1}$).

4) Partial opening submerged flow

$$Q = \mu_0 B e \sqrt{2g\left(H_0 - h_s\right)} \quad \left(0 < \frac{e}{H_0} < 0.65\ \ h_s > h_c''\right), \tag{11}$$

where μ_0 is the discharge coefficient for submerged gate flow.

All the discharge coefficients in the above equations, m, φ_m, μ and μ_0, are determined by referring to the industrial standard SL265-2001-design specification for sluice (MWRPRC, 2001) or calibrated by model experiment. This model automatically determines the form of over-current based on water level, flow discharge and the operation of floodgates and selects the appropriate hydraulic formulas. At each iteration step of flow calculation, weir flow or gate flow is firstly determined by giving the opening of floodgate and the upstream energy head calculated at last iteration step. Free flow or submerged flow is then fixed with the second criteria of each flow pattern. It is worth mentioning that the criteria are based on the values of last iteration step in order to avoid trial calculation. Therefore the time interval cannot be too large.

Connecting and coupling method

The Beiyun River flood forecasting and management system is integrated by jointing and coupling the hydrological model, hydrodynamic model and hydraulic model for dams and floodgates. The coupling is flexible by reading and outputting text or binary files for data exchange. The hydrological processes at the outlet sections of each tributary are simulated by the hydrological model, and are set as the boundary input conditions of the hydrodynamic model. The flood routing in the channel is simulated by the hydrodynamic model based on the setup of dams and floodgates operation. New results feed back to the floodgates operation setup by considering the regulation objectives and constraints.

CALIBRATION AND VALIDATION

A flood caused by a monsoon rain from the 3rd to the 6th of July, 1998 was used to calibrate the hydrological model and hydrodynamic model. Corresponding peak flood discharges at ten cross sections were observed in the storm. During calibration, sensitive model input parameters, i.e., runoff curve number CN, overland and channel Manning's roughness coefficients, were varied, starting with literature values, until the best comparisons of the simulated and observed results were found. The final estimated CN values ranged from 42 to 50. If there was antecedent precipitation, the CN values would increase by 10% to 20%. The roughness coefficients ranged from 0.04 to 0.20 for overland planes and from 0.025 to 0.04 for channel segments. The validation runs were made with the same parameters used in the calibration runs. Table 2 shows the comparisons between the observed and the predicted peak flood discharge. The observed cross sections and reservoirs distribute into main streams or branches and cover almost the entire watershed. The model performed reasonably well in predicting the peak flood discharge. Although peak flow at some cross-sections were overpredicted (e.g. Huyu ditch) and some were underpredicted (e.g. Zhuishikou ditch), the relative errors of these results were all less than 12% which could be accepted in predicting runoff discharge (Borah et al., 2004). Fig. 3 demonstrates the comparison between observed data and predicted results of discharge hydrograph at the Beiguan floodgate from the hydrodynamic model. It is clear that the model accurately predicted when the peak flood appears and the peak discharge as well.

Physical model experiments on the Beiguan floodgates were conducted by Beijing Hydraulic Research Institute to check the relationship between discharge rates and different gate openings. Since the Beiguan floodgates include two separate parts and flow is divided into two branches, the upstream water level and flow split ratio was selected to validate the model's performance. Fig. 4 shows the validation results, where the simulated and experimental water level and flow split ratio were compared. All the points in this figure are scattered closely around the line showing their well matches. Clearly, the condition of inflow discharge and gate opening at each point were set the same.

RESULTS AND DISCUSSION

Design rainfall and hydrology simulation

In order to simulate the hydrological processes in the Beiyun River Basin and the regulating processes on dams and floodgates under different rainfall conditions, rainfall processes of different return periods for 28 rain stations are designed. These rainfall processes describe the rainfall characteristics of the entire basin over the past decades. But, for the purpose of floodgates operation, only 10-year, 20-year and 50-year storm flood processes are selected in this study. The design rainfall amounts of different return periods are determined according to the 1999 "Beijing Hydrology Manual – Rain Atlas", presented in Fig. 5. The rainfall processes for different rain stations are calculated based on the 24 hours rainfall distribution table for the city of Beijing, for both mountainous and plains areas, depending on the location of the station.

Table 2. Comparisons between observed and predicted peak flood discharge at each cross section in the July, 1998 storm by DWSM.

Cross name	Catchment area (km^2)	Peak flow discharge ($m^3\ s^{-1}$) predicted	Peak flow discharge ($m^3\ s^{-1}$) observed	Relative error (%)
Shangxiakou ditch	34.45	53.13	55.60	–4.48
Zhuishikou ditch	67.34	191.68	204.00	–6.43
Changling	106.84	227.85	254.00	–11.48
Huyu ditch	26.62	35.22	33.40	5.18
Weir of Xindian creek	94.24	93.30	88.50	5.14
Weir of Beisha creek	1182.47	141.39	149.00	–5.38
Tangshun Road Bridge	75.00	36.34	35.00	3.69
Downstream of Nanda Bridge	250.41	330.80	328.00	0.85
Dadongliu of Qintun creek	121.18	94.02	96.20	–2.32
Tong County	2571.96	446.28	421.00	5.66

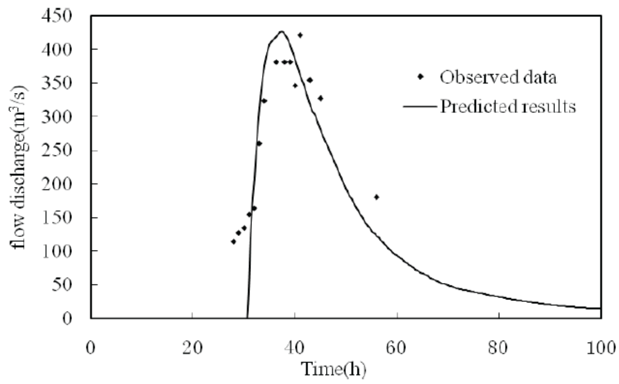


Fig. 3. Comparison of the inflow discharge hydrograph at Beiguan floodgate in July 1998 storm.

The runoff processes in all the main tributaries under different rain conditions can then be simulated by DWSM. As an example, the results for the Shahe Reservoir, Lin creek, Qing creek and Liangshui creek, four typical tributaries of the Beiyun River, are presented in Fig. 6 and summarized in Table 3. Runoff coefficient, time to peak water and peak flow discharge are strongly affected by the topography, the catchment area and the rainfall intensity. For the same creek, peak flow discharge appears earlier if the rainfall intensity is greater. The runoff coefficient increases with increasing rainfall intensity.

Regulation of flood

Currently, the main dams and floodgates of the Beiyun River use design flood water level as a control index called level-control mode. This operation mode is characterized by the regulation of gate holes and gate openings based on the upstream discharge in order to maintain the water level on the gate. If there is a large flood follow up which exceeds the discharge capacity of the floodgate, a flood disaster takes place. The distributed hydrological model developed in this study can forecast the upstream river flow processes, peak flow, and time to peak flow several hours in advance. Floodgates can be correspondingly operated to guarantee the pass-through of peak flow and interception of good quality tail water during the process as the flood subsides based on the forecasted flow process, called discharge-control mode. For comparison, the condition of no dam and floodgate in the Beiyun River is also considered as another scenario.

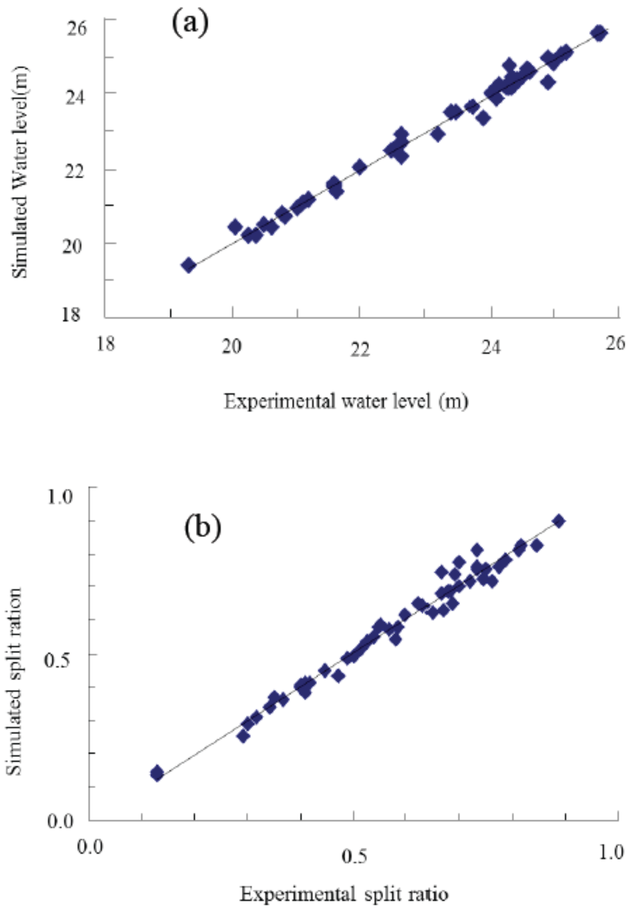


Fig. 4. Comparison of results of Beiguan floodgates: (a) upstream water level, (b) flow split ratio.

Take the Beiguan floodgate as an example. Water level processes and discharge processes at the floodgate under the conditions of 10-year, 20-year and 50-year design rainfall are simulated. Three modes (non-floodgate, level-control and discharge control) of floodgate operation are considered and compared, represented in Figure 7(a), (b) and (c), respectively. The following can be seen from the figures: 1) For small floods, such as those less than 10-year, the water level at the Beiguan floodgate

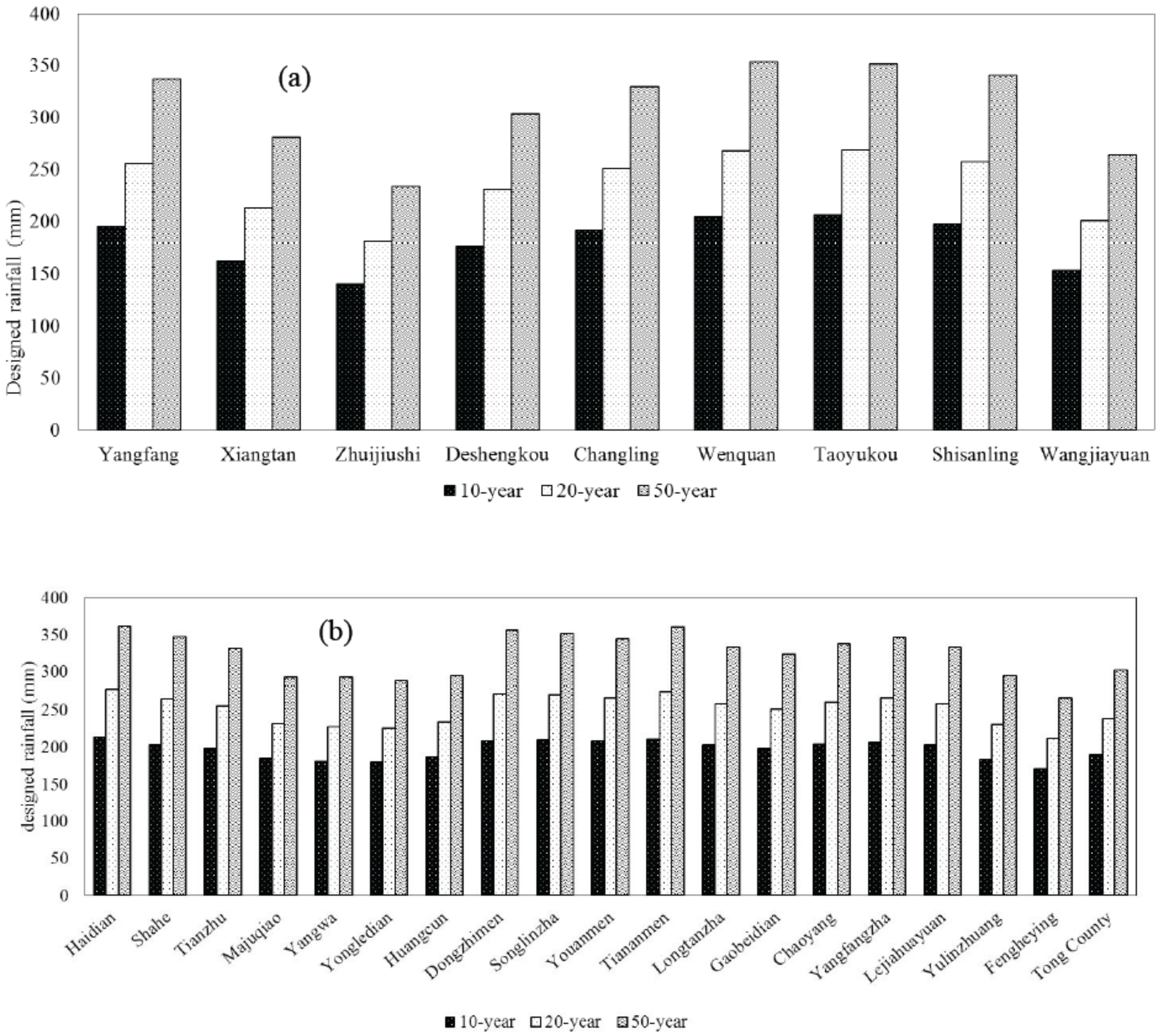


Fig. 5. Design rainfall amounts of different return periods: (a) stations in mountainous areas, (b) stations in plains areas.

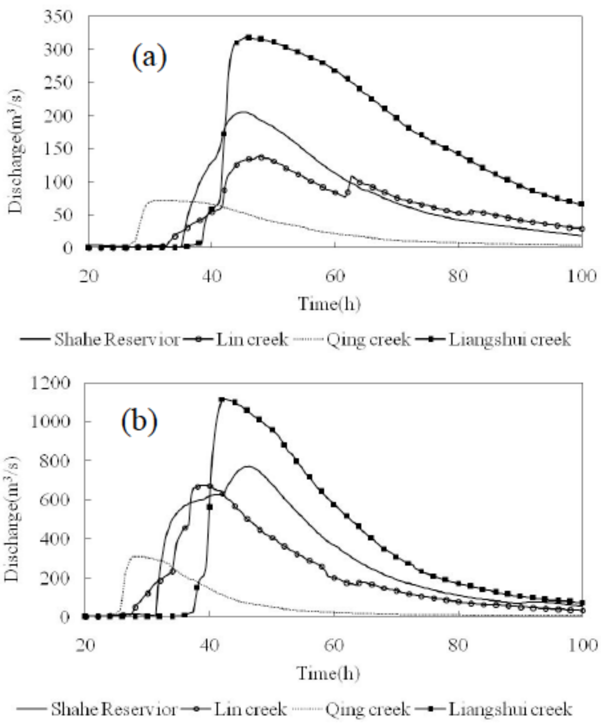
Table 3. Results of main creeks under different rainfall conditions.

Creeks	10-year			20-year			50-year		
	RC	TPF (h)	PFD ($m^3 s^{-1}$)	RC	TPF (h)	PFD ($m^3 s^{-1}$)	RC	TPF (h)	PFD ($m^3 s^{-1}$)
Shahe Reservoir	0.28	47	297.1	0.55	45	838.53	0.65	36	2636.3
Lin creek	0.25	46	247.78	0.43	38	679.64	0.71	33	1837.28
Qing creek	0.24	30	161.24	0.43	29	495.38	0.71	26	1501.84
Liangshui creek	0.27	46	377.04	0.42	41	1059.99	0.67	38	2768.56

Note: RC is Runoff coefficient, TPF is time to peak flow, PFD is peak flow discharge.

is low if no dam exists. The water level is near death water level after a flood passes. Gate opening regulations can almost maintain the water level at the floodgate at a normal pool level of 19.5m under the operation mode of level-control. Since the peak flood is less than the maximum flow discharge capacity of the floodgate at this water level, flood control is safe and the operation mode is feasible. The process of discharge-control mode is different. The water previously stored and that from flood in an early period are discharged from the floodgate at full opening. Gate opening is dynamically regulated to make the water level reach normal pool level and remain unchanged. 2) For a 20-year rainfall flood, the high water level on the Beiguan floodgate reaches to 22.47 m under the level-control operation mode, exceeding the design flood water level of 22.4 m. There is the risk of overflowing the dam. The high water level, however, is 22.14 m under the discharge-control operation mode because the storage is emptied before peak flood comes. The flood control is safe in this scenario. 3) For a 50-

year rainfall flood, the flood controls under three operation modes are all unsafe. This is mainly due to the low design flood standard of the Beiguan floodgate which cannot successfully withstand the 50-year rainfall flood. The simulated water level exceeds design flood water level for about 22 hours. In this situation, low-lying areas around the Beiyun River need to be utilized to share the excess flood waters (Fu, 2006b). In this study, Baigezhuang Lake, Zhenggezhuang Lake and the Qing estuarine wetlands are considered having a maximum storage of 90.5 million m^3. The water level at the Beiguan floodgate and discharge process in this scenario is demonstrated in Fig. 7(c).



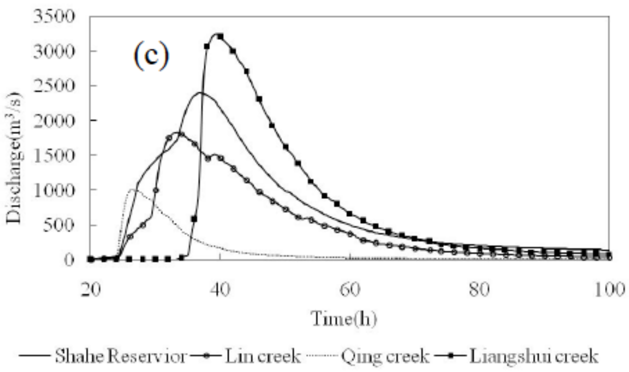
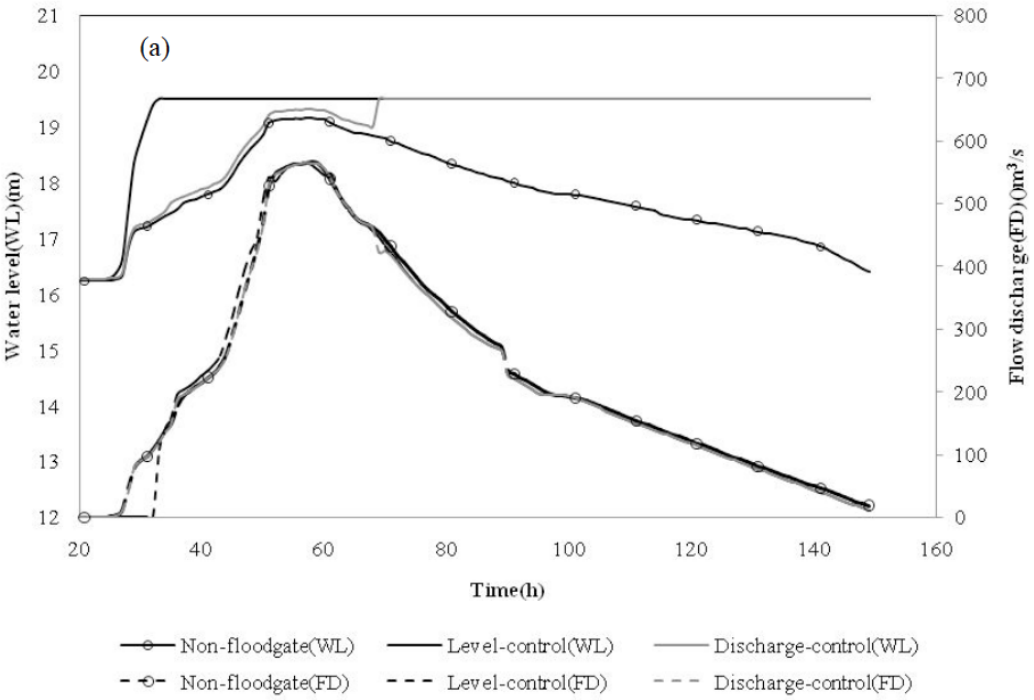


Fig. 6. The runoff processes in all the main tributaries under different rain conditions: (a) 10-year rainfall, (b) 20-year rainfall, (c) 50-year rainfall.

Discussion on flood control and water use

Dam design and operation typically focuses on its social functions, such as flood control, electricity generation, water supply, irrigation, and aquaculture (WCD, 2000). For the Beiyun River Basin, flood control and water use (including water supply and irrigation) are the most important objectives of these dams and floodgates though they fundamentally conflict. During the flood season, the water level cannot always be kept high because of the possible incidences of large floods. On the other hand, the dam cannot be kept completely empty during this period because subsequent inflows may be too meager to satisfy the remaining conservation needs (Jain et al., 1992). Dams operation must consider both flood control and water use, and find a balance between these two objectives. The current operation mode, however, does not perform well in this respect. Because the follow-up runoff process is unknown, only passive defensive mode can be adopted. Water is stored in the early



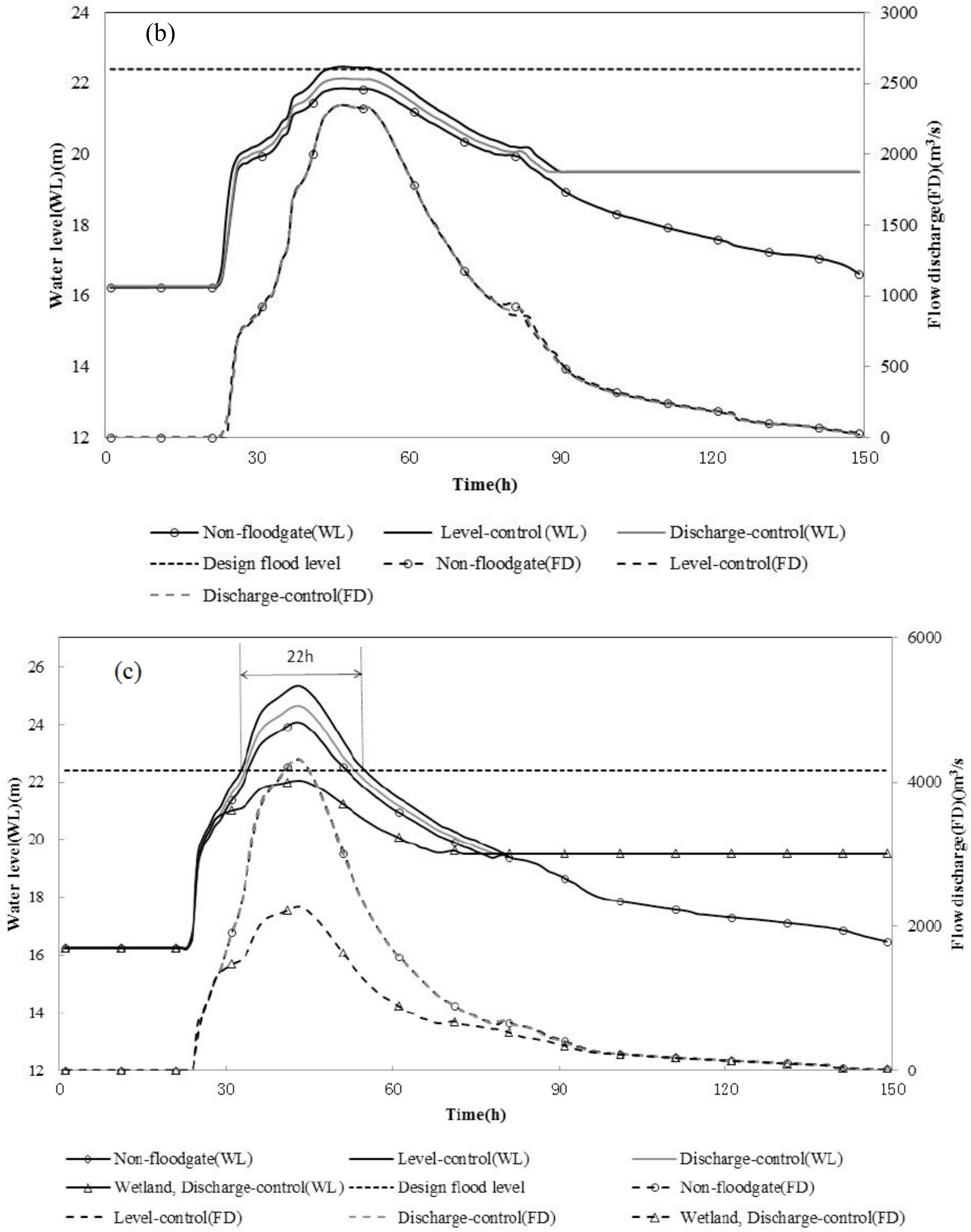


Fig. 7. Simulated upstream water level and discharge at Beiguan floodgate: (a) 10-year rain storm, (b) 20-year rain storm, (c) 50-year rain storm.

period of floods for protection of water resources. Consequently, the floodgate can only be passively regulated according to follow-up flood. After the runoff processes are forecasted by the hydrological model, discharge-control mode can be adopted and the operation of dams can be arranged in advance. Thus, both flood control and water use should be considered. For small floods, the current operation can satisfy the needs. But discharge-control is more reasonable because the poor quality flood water in the first flooding caused by non-point source pollution is discarded. For medium size floods, since pre-storing of the flood waters affects the discharge of follow-up floods, the requirement of flood control cannot be satisfied under the current operation but the discharge-control operation can. For large floods, neither operation can meet the requirement because of the limited storage of these dams. Then, the gravel pits, wetlands, ecological lakes and flood detention basins around the river must be used to share excess flood waters. The flood control and water storage results under different conditions are summarized in Table 4.

CONCLUSIONS

The main problem of flood control and storm water resources management in the Beiyun River Basin is the lack of an effective flood forecasting system. In the past, the design flood water level could only be used as a control index. This passive

Table 4. The flood control and water storage results under different conditions.

Design rainfall return period		Non-floodgate	Level-control	Discharge-control	
				No wetland	Use wetland
10-year	Flood protection	Safe	Safe	Safe	
	Water storage (million m^3)	0.04	3.87	3.87	
20-year	Flood protection	Safe	Not safe	Safe	
	Water storage (million m^3)	0.06	3.87	3.87	
50-year	Flood protection	Not safe	Not safe	Not safe	Safe
	Water storage (million m^3)	0.04	3.87	3.87	94.41

operation mode magnifies the floods' risk of catchment and cannot fully use the storm water resources. Using the flood forecasting and management system established in this study, passive defense can be changed to active defense mode, solving the water resources problem of the city of Beijing and the Beiyun River Basin to a certain extent. The DWSM model can forecast the floods several hours ahead of their manifestation. This period of time is precious for both water control and water use. Discharge-control mode can then be applied which has more advantages compared with the current operation mode: (1) the stored water before the arrival of flood and flood water in the first flooding which is often heavily polluted is discharged and more storage volume is freed up for good quality water in the later flood period; (2) for larger floods, the flood water in the rising period is discharged as soon as possible, avoiding the risk that follow-up flood waters exceed the discharge capacity of the floodgate; (3) for extreme floods, the low-lying areas along the Beiyun River can be utilized to store more flood water ahead of time. Thus, the flood risk is reduced and more available water resources are saved for use by the city.

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