# Hydrology simulation and water resource management selections for Beiyun River basin, Beijing

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Beijing, capital of China, is a typical city short of water resources. Beiyun River, as the most important drainage basin of Beijing, flows over the east of Beijing city. Rainfall in this watershed is remarkably uneven in temporal distribution. Most of the rainfalls concentrate in several storms in the flood season, causing flood rising sharply and dropping steeply. To manage water resources requires mastering the characteristics of hydrology processes of this catchment. In the study, the distributed hydrological model DWSM is applied to simulate the hydrological processes in storm events. It is proved to simulate hydrological processes reasonably well by calibration and verification. From the simulation results for rainfall of different frequencies, we find that flood peak appear earlier when the rainfall intensity is greater. The peak flow discharge, as well as runoff coefficient increases synchronously with rainfall intensity. The regime for the operation of reservoir dams and floodgates are applied in this model to change hydrological processes and store flood water. The regulation of reservoirs not only increase the amount of available water resources but also effectively reduce the peak flow at the outlet of Beijing area and lighten the risk of flooding in lower reach.

**Keywords**: Beiyun River; water resources; hydrological processes; DWSM model; rainfall

## Introduction

Beijing is a typical city short of water resources in China. Annual average rainfall here is about 643mm deep, of which accounting for about 85% concentrated in the flood season from June to September. The rainfall is so uneven in temporal distribution that it is easier to be flooding in flood season and short of water in non-flood season. How to manage water resources is an urgent task to meet water demand of Beijing city. Beiyun River, as the most important drainage basin, flows over the east of Beijing city. The rational utilization of water resources of Beiyun River is a key point to solve the water shortage problem of Beijing city. To reach this goal, we need to know the characteristics of hydrological processes in Beiyun River, and then decide when and how to store water, and how much water can be stored when a storm comes up. The development of hydrological model provides an efficient tool to predict hydrological processes of runoff and master their characteristics.

Hydrological model was developed in about 1950s (Rui, 1997, Hu and Zhang, 2004)，since then models spring up more and more. According to the uniformity of parameters, they can be classified as lumped and distributed models (Yuan, 1990). Lumped model regards the watershed as a whole basin without considering the spatial distribution of rainfall and hydrological underlying surface, so the parameters within the whole basin are considered homogeneous. On the contrary, the distributed hydrologic model overcomes this disadvantage, considering the impact of spatial distribution of rainfall and surface conditions. The watershed is divided into various subwatersheds, with each subwatershed having its own representative parameter. At present, the typical distributed hydrological models are HSPF, Xin'anjiang, SWAT, AnnAGNPS and DWSM (Dynamic Watershed Simulation Model) . As Chen et al., (1995) has proposed that HSPF is a long-term model which could handle long-term water balance quite well in watershed. AnnAGNPS, developed from AGNPS, integrates AGNPS with GIS and topographic analysis tools (Binger et al., 1997). Then the watershed can be divided into subwatersheds with different parameters. A more recent study (Yuan et al., 2001) has presented AnnAGNPS a daily time step, the simulated runoff is an daily average value. Continuous for large basin, SWAT is an improvement version of SWRRB model (Arnold et al., 1995). It is a semi-empirical model, not capable of single-event simulation. It can simulate daily or monthly runoff reasonably well (Wang et al., 2003). Among these popular distributed hydrological models, HSPF, AnnAGNPS and SWAT are long-term simulation models. The rest are capable of storm events simulation models. Xin’anjiang can both simulate long-term condition and storm events condition. For Xin’anjiang model, rainfall excess appears only after the soil porosity being saturated, not suitable for the heavy rainfall intensity (Zou et al., 2000). It is worth mentioning that DWSM is short-term simulation model, which could simulate the runoff process dynamically. The simulating time interval ranges from several minutes to hours, so the results present the runoff of each time interval better. Thus we could get the accurate characteristic of runoff.

Based on the above analysis of models, DWSM is selected to model the hydrological processes in Beiyun River watershed. The DWSM model was developed by Borah to simulate the hydrology processes of rural area in a storm event. It has been calibrated and verified in small watersheds and performs reasonably well, such as Big Ditch watershed in Illinois (Borah et al., 2001), watershed W5 in Mississippi and watershed P4 in Georgia (Borah et al., 2002).To meet the challenge of water resource management, we take into account the regime for the operation of reservoir dams and sluices and improve the corresponding module of this model.

## Methods and procedures

### *Research area description*

The whole watershed of Beiyun River covers an area about 6266km$^2$. From the north to the south of the watershed, main creeks are Sha creek, Lin creek, Qing creek, Ba creek, Xiaozhong creek, Tonghui creek, Liangshui creek. The upper reach of Beiyun River locates in Beijing while the middle and lower reach in Hebei province and Tianjin city. Figure 1 shows the upper reach in Beijing, on which we mainly focus in this study. The main channel of Beiyun in Beijing is 89.4 km long and the total area in Beijing is 4300 km$^2$.

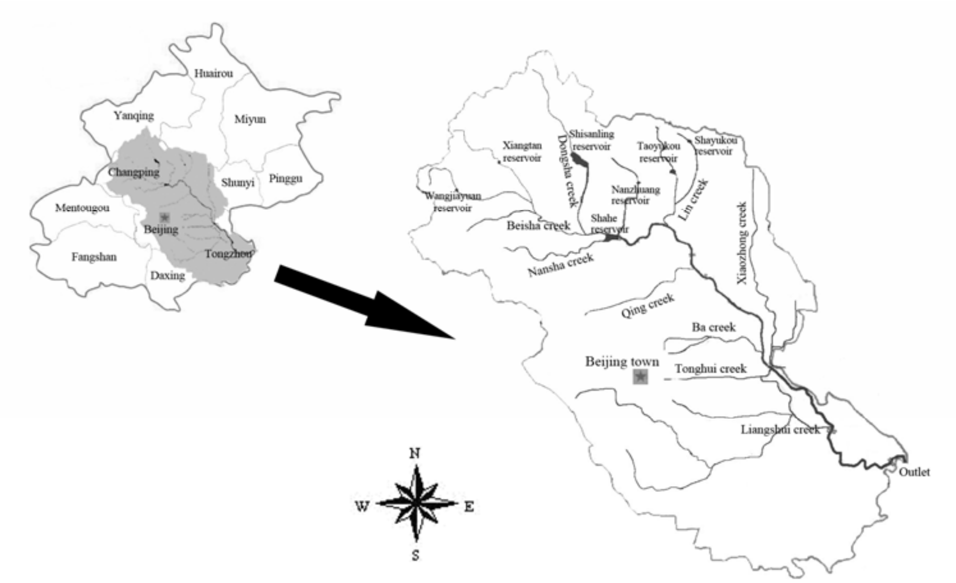


Figure 1. The sketch of Beiyun River drainage basin in Beijing

According to the uniformities of topographic, soil, and land-use features, the whole watershed is divided into 317 subwatersheds. This means that each subwatershed has its own representative topography, slope length, slope gradient, roughness and soil property. Every subwatershed contains two overlands and one channel, with overlands on both sides of the channel. There are 13 reservoirs scatted in main creeks.

The range of the gradient is about 0.01 percent to 0.38 percent. Main part of land use here is cultivated fields, about 56.85%. Residential housings and industrial fields occupy more than 26.43%. Forest area covers about 14.44% of the watershed. The remaining land uses are grass land, wetland, lakes and unused area, less than 2.28% of the land in the watershed, shown in Figure2 (b). Soils here are predominantly fluvo-aquic soil and cinnamonic soil, covering about 69.67%, 26.49% respectively. The rest is loess.

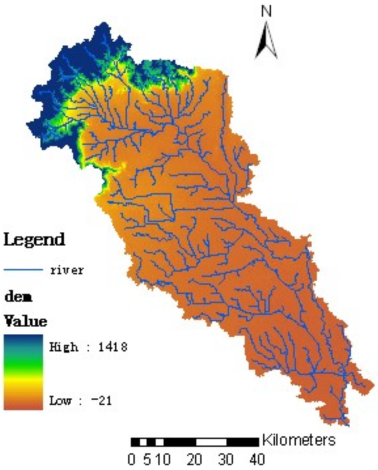


Figure 2(a). DEM and digital river of the watershed

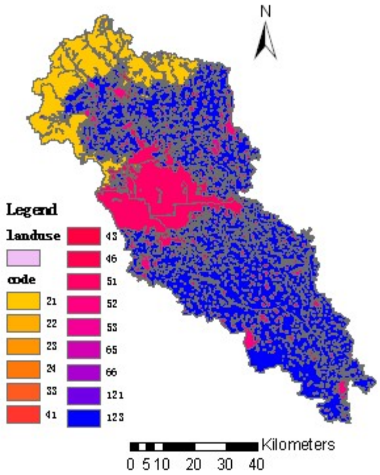


Figure 2(b). Land use of the watershed

***DWSM Model description***

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. It has three major components: hydrology, soil erosion and sediment transport, and nutrient and pesticide transport. Each component has routing schemes based on approximate analytical solutions of physically based equation preserving the dynamic behaviors of water, sediment, and the accompanying chemical movements within a watershed. The hydrology component is used and improved in this study.

*Rainfall excess*

There are two methods provided for users to choose. One is Soil Conservation Service (SCS, 1972), using only one parameter, the runoff curve number (*CN*), to estimate the rainfall excess. This method may be expressed as,

$$Q = (P - 0.2S)^2 / (P + 0.8S) \qquad (1)$$

$$S = 25400/CN - 254 \qquad (2)$$

where $Q$ is the direct runoff or rainfall excess; $P$ is the accumulated rainfall; $S$ is the potential difference between rainfall and direct runoff; $CN$ is the curve number representing runoff potential of a surface.

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. The daily interception is computed in Eq. (3).

$$C_d = C_m * \frac{LAI}{LAI_m} \quad (3)$$

where $C_d$ is the maximum daily interception caused by plants; $C_m$ is the maximum daily interception ability supposing the trees and ground covers grow sufficiently; $LAI$ is the daily leaf area index of the plants; $LAI_m$ is the maximum leaf area index of the plants including trees and ground covers.

When the rainfall intensity is less than or equal to the maximum interception deducting the initial interception, no rain reach to the ground. If the rain goes through the ground surface, infiltration occurs. The infiltration can be calculated by Eq. (4).

$$f = K_h * (1 + H_c * (1 - S_c) * \theta_c / F) \quad (4)$$

where $f$ is the infiltration; $K_h$ is the effective hydraulic conductivity; $H_c$ is the capillary suction at the wetting front; $S_c$ is the effective water saturation; $\theta_c$ is the effective soil porosity which equals to soil porosity minus water content; and *F* is accumulated infiltration.

*Reservoir regulation*

Many watersheds have reservoirs to store water, which can increase the available amount of water resources. Reservoir regulation should be considered in the simulation model. Sluices are used to control the outflow rate of reservoir. The operation of reservoirs (sluices) can be automatical control or artificial control. Based on the regulation, when the initial simulated water level is lower than normal water level, gate is closed to store water. When the simulated water level starts to exceed normal water level, outflow occurs. If automatical outflow is chosen, we use stage-capacity method (Borah et al., 2002) to calculate the reservoir's water level, storage and outflow. It is described as,

$$\frac{2S_{t+\Delta t}}{\Delta t} + O_{t+\Delta t} = (I_t + I_{t+\Delta t}) + (\frac{2S_t}{\Delta t} - O_t) \quad (5)$$

where *S* is the reservoir storage; *O* is the outflow rate; *I* is the inflow rate; *t* is time; and $\Delta t$ is the time interval.

On the contrary, if artificial control is chosen, new method must be presented. The outflow is calculated as follows.

$$Q_o = \begin{cases} O_t & O_t \le I_t, O_t < O_{mx} \\ O_{mx} & O_t \le I_t, O_t > O_{mx} \\ I_t & O_t > I_t \end{cases} \quad (6)$$

where $Q_o$ is the outflow rate of reservoir; $Q_t$ is the outflow rate calculated by Eq. (5); $I_t$ is the inflow rate; and $O_{mx}$ is the maximum control outflow rate. We called this method a modified stage-capacity method.

**Model calibration and verification**

There are 29 rain gage stations distributed in the whole watershed, which monitor rainfall intensity continuously. The rainfall data are collected by the rain gage stations as input condition to start the simulation. In the study, it is calibrated with the 5$^{th}$ to 6$^{th}$ July 1998 storm, and verified with the 30$^{th}$ to 31$^{st}$ July 2008 storm and the 3$^{rd}$ to 6$^{th}$ July 1998 storm. All the rainfall dropped in a short period with high intensity and covered almost the whole watershed.

10 crosses were observed for their flood peak discharge in the 5$^{th}$ to 6$^{th}$ July 1998 storm, while 5

crosses for their flood peak discharge or daily average flow discharge in July 2008 storm. The observed crosses and reservoirs distribute in main stream or branches and cover almost the whole watershed.

Table 1 shows the comparisons between the observed and the predicted flood peak discharge in July 1998 storm. Table 2 shows the observed and predicted flood peak discharge in July 2008 storm. Figure 3 presents the calibrated discharge hydrograph with the $5^{th}$ to $6^{th}$ July 1998 storm, and figure 4 presents the verified stage hydrograph with the $3^{rd}$ to $6^{th}$ July 1998 storm.

Table 1. Comparisons between observed and predicted peak flood discharge at each cross section (flood peak discharge calibration with the $5^{th}$ to $6^{th}$ 1998 July storm).

| Cross name | Catchment area ($km^2$) | Peak flow discharge ($m^3$/s) | | Relative Error (%) |
|---|---|---|---|---|
| | | predicted | observed | |
| 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 |

Table 2. Comparisons between observed and predicted peak flood discharge at each cross section (verification with the $30^{th}$ to $31^{st}$ July 2008 storm).

| Cross name | Catchment area ($km^2$) | Peak Flood discharge ($m^3$/s) | | Relative Error (%) |
|---|---|---|---|---|
| | | predicted | observed | |
| Zhuishikou ditch | 67.34 | 113.37 | 92.8 | 18.14 |
| 7-hole Bridge | 29.08 | 29.61 | 28 | 5.44 |
| Cross name | Catchment area ($km^2$) | Daily average water discharge ($m^3$/s) ($1^{st}$ Aug., 2008) | | Relative Error (%) |
| | | predicted | observed | |
| Tumenlou | 3811.05 | 52.35 | 54.40 | -3.77 |
| Tong county | 2571.96 | 89.95 | 88.40 | 1.75 |
| Niumutun | 20.61 | 6.80 | 7.88 | -13.71 |

As shown in tables 1 and 2, the relative errors in these simulation results are less than 19%. The model simulates reasonably well on peak flood discharge. Seen from the figures 3 and 4, it is clear that the model predicts the time well when the flood peak appeared. The model performs well in the propagation of flood waves.

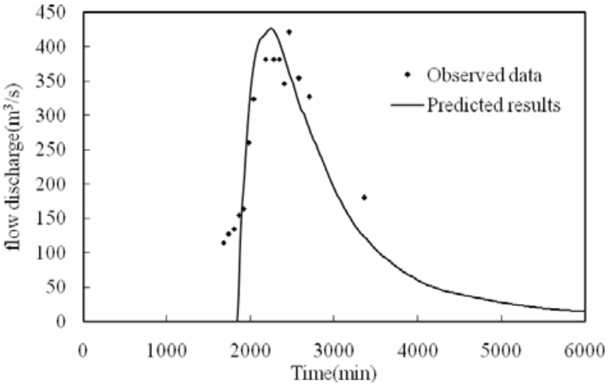


Figure 3. Observed and predicted discharge hydrograph resulting from the $5^{th}$ to $6^{th}$ 1998 July storm at Beguan floodgate

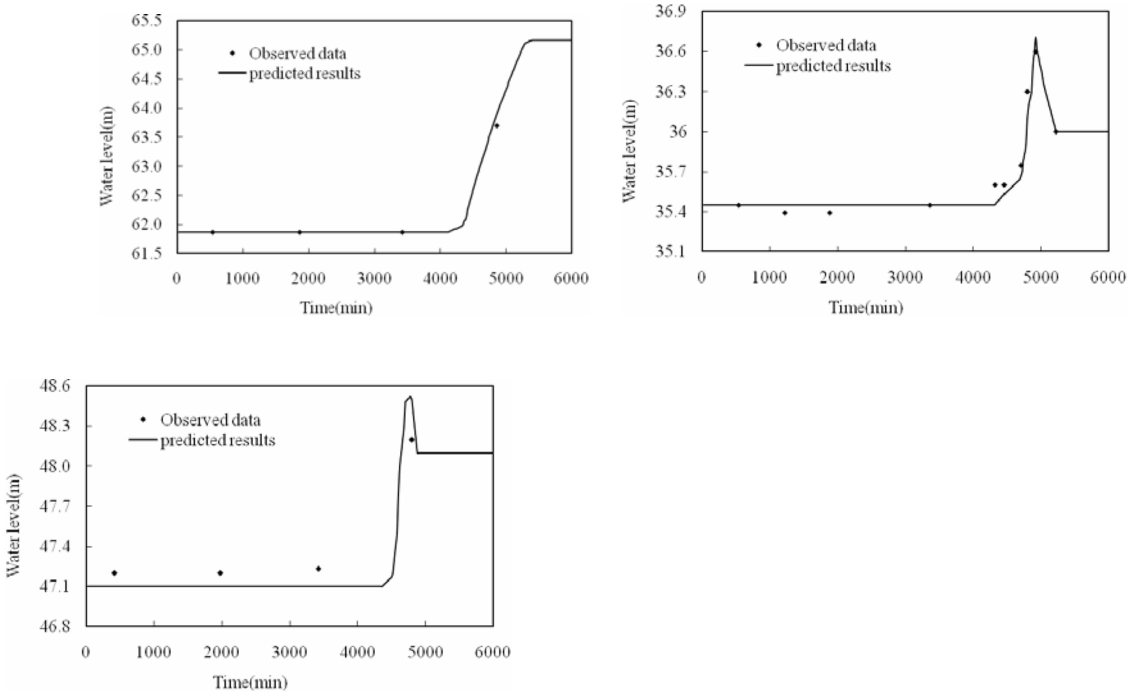


Figure 4. Observed and predicted water level of Taoyukou, Shahe and Nanzhuang reservoirs resulting from the 3rd to 6th 1998 July storm

## Results and Analysis

### *Analysis on water resources of Beiyun River, Beijing*

In order to describe the characteristic of hydrological process in Beiyun River and find out how much runoff water resource we can get when a storm comes, we should select typical rain storms as basic input data of model. Rainfall storms of different frequencies are calculated with rainfall data in history from Beijing Hydrology Manual – Rainstorm Atlas. The rainfall process of rainfall stations in mountain area is computed from 24-hour-rain pattern list for Beijing mountain area and hilly area, while that in plain area is computed from 24-hour-rain pattern list for Beijing urban area and plain area. The runoff processes under conditions of 5-year, 10-year, 20-year and 50-year frequency rain storm are simulated with DWSM in this paper. Table 3 lists the result of some characteristic quantities for runoff in main creeks.

Table 3. Results of main creeks under different rainfall conditions

| | | 5-year | 10-year | 20-year | 50-year |
|---|---|---|---|---|---|
| Sha creek | AR (mm) | 116.56 | 180.67 | 212.56 | 310.11 |

| | | | | | |
|---|---|---|---|---|---|
| | RV (×$10^4$$m^3$) | 2121 | 5770 | 13244 | 28750 |
| | RC | 0.16 | 0.28 | 0.55 | 0.65 |
| | TPF (h) | 35 | 56 | 46 | 39 |
| | PFD ($m^3$/s) | 0.39 | 297.10 | 838.53 | 2636.30 |
| Lin creek | AR (mm) | 148 | 206 | 269 | 352 |
| | RV (×$10^4$$m^3$) | 708 | 1928 | 4426 | 9606 |
| | RC | 0.13 | 0.25 | 0.43 | 0.71 |
| | TPF (h) | 81 | 46 | 38 | 33 |
| | PFD ($m^3$/s) | 9.45 | 247.78 | 679.64 | 1837.28 |
| Qing creek | AR (mm) | 150.5 | 209 | 271 | 353 |
| | RV (×$10^4$$m^3$) | 358 | 975 | 2239 | 4862 |
| | RC | 0.12 | 0.24 | 0.43 | 0.71 |
| | TPF (h) | 35 | 29 | 30 | 26 |
| | PFD ($m^3$/s) | 19.61 | 161.24 | 495.38 | 1501.84 |
| Ba creek | AR (mm) | 147.5 | 205.5 | 265.5 | 346 |
| | RV (×$10^4$$m^3$) | 278 | 762 | 1738 | 3772 |
| | RC | 0.13 | 0.25 | 0.44 | 0.73 |
| | TPF (h) | 33 | 28 | 26 | 26 |
| | PFD ($m^3$/s) | 11.90 | 106.62 | 374.15 | 1060.15 |
| Xiaozhong creek | AR (mm) | 149.3 | 206.6 | 268.5 | 350.3 |
| | RV (×$10^4$$m^3$) | 530 | 1443. | 3314 | 7194 |
| | RC | 0.12 | 0.24 | 0.43 | 0.72 |
| | TPF (h) | 82 | 68 | 52 | 44 |
| | PFD ($m^3$/s) | 4.57 | 66.19 | 249.18 | 726.84 |
| Tonghui creek | AR (mm) | 148.83 | 204.67 | 262.5 | 340.33 |
| | RV (×$10^4$$m^3$) | 493 | 1343 | 3082 | 6690 |
| | RC | 0.13 | 0.25 | 0.44 | 0.74 |
| | TPF (h) | 81 | 52 | 37 | 33 |
| | PFD ($m^3$/s) | 25.68 | 233.43 | 837.70 | 2364.03 |
| Liangshui creek | AR (mm) | 140 | 185 | 232 | 293 |
| | RV (×$10^4$$m^3$) | 1171 | 3186 | 6131 | 12360 |
| | RC | 0.13 | 0.27 | 0.42 | 0.67 |
| | TPF (h) | 43 | 35 | 31 | 28 |
| | PFD ($m^3$/s) | 67.21 | 377.04 | 1059.99 | 2768.56 |
| Outlet of Beijing area | AR (mm) | 140 | 195 | 238 | 324 |
| | RV (×$10^4$$m^3$) | 6797 | 18483 | 41268 | 88634 |
| | RC | 0.13 | 0.26 | 0.48 | 0.75 |
| | TPF (h) | 44 | 37 | 39 | 34 |
| | PFD ($m^3$/s) | 146 | 1296.50 | 4114 | 10101 |

NOTE：AR: 24-hour accumulated rainfall; RV: Runoff volume; RC: Runoff coefficient; TPF: time to peak flow; PFD: Peak flow discharge.

For the rainfall frequency of 5-year, we could seen from Table 3 that there is about 3.5million $m^3$ runoff yield in Qing creek, 7.1million in Lin creek, 2.8million in Ba creek, 21 million in Sha creek, 4.9million in Tonghui creek, and 12million in Liangshui creek. Consequently, there is about 68million $m^3$ runoff yield at the outlet of Beijing area. For the rainfall frequency of 10-year, there is about 7.5million $m^3$ runoff yield in Qing creek, 15million in Lin creek, 2.8million in Ba creek, 44million in Sha creek, 10million in Tonghui creek, and 24million in Liangshui creek. Consequently, there is about 138.75million $m^3$ runoff yield at the outlet of Beijing area. The runoff yield under the rainfall frenquency of 20-year and 50-year increses sharply, even though the 24-hour accumulated rainfall does not multiply correspondingly. That’s why it is easier to be flooding when heavier storm comes.

Runoff volume, runoff coefficient, time to peak water and peak flow 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. It costs less time to pond water and exceed. The runoff coefficient increases with the rainfall intensity increasing.

***Analysis on reservoir regulation***

Reservoir regulation is one of the important efficient tools to manage water resources. There are 7 reservoirs locating in Dongsha creek, Nansha creek, Beisha creek, Lin creek of Beiyun River drainage basin (see Figure 1), as well as 6 gravel pits which are used to temporarily store flood water if Extraordinary flood occurs. Dongsha creek, Nansha creek and Beisha creek are the upstream of Sha creek. Each reservoir can be put into use or not. When the reservoirs are put into work, there are two methods described in Eq. (5) and Eq. (6). Stage-capacity method is used in Eq. (5) to calculate the reservoir's water level, storage and outflow discharge. Eq. (6) is a modified method of Eq. (5). In this method, we define a maximum control outflow rate before the peak flow appears. If the outflow rate calculated by Eq. (5) is greater than the defined maximum control outflow rate, the maximum control outflow rate is applied. Thus, the reservoir may work at the maximum control outflow rate for a long time after the peak time until the calculated outflow rate return below the maximum control outflow rate. Of course, all these methods must guarantee the reservoirs' safety. The maximum control outflow rate should be reasonably determined with the predicted inflow process and the storage capability of water.

The operation of reservoir influences not only the stored water volume of reservoir but also the outflow process of reservoir and hydrological process at outlet of drainage basin. Figure 5 shows the outflow hydrograph of Shisanling reservoir, the largest of Beiyun River basin, under different operations in the 10-year rainfall storm. If the reservoir is not put into use, the water level remains the minimum water level and water volume stored is 7.78million $m^3$. If the reservoir is on operation, the water volume can reach to 30million $m^3$ at the end of calculation. That is to say, there are 22 million $m^3$ more water resources which can be used for enterprises and villages due to operation of Shisanling reservoir.

According to the equation of modified stage-capacity method, this kind of method will work only when the rainfall is heavy enough for the water level exceeding the normal water level. If a heavy storm comes, the water level of reservoir is easier to exceed the normal water level. At that time, reducing the peak flow is more important than storing water for the reservoirs. It is more effective to use the modified stage-capacy method in reducing the peak flow. Considering the safety of reservoir, we define different maximum control outflow rates in different frequency rain storms. We define 75 $m^3/s$ as the maximum control outflow rate for a 10-year rain storm. It can be clearly seen from figure 5 that the modified stage-capacity method reduced the peak flow from 180$m^3/s$ to 75 $m^3/s$.

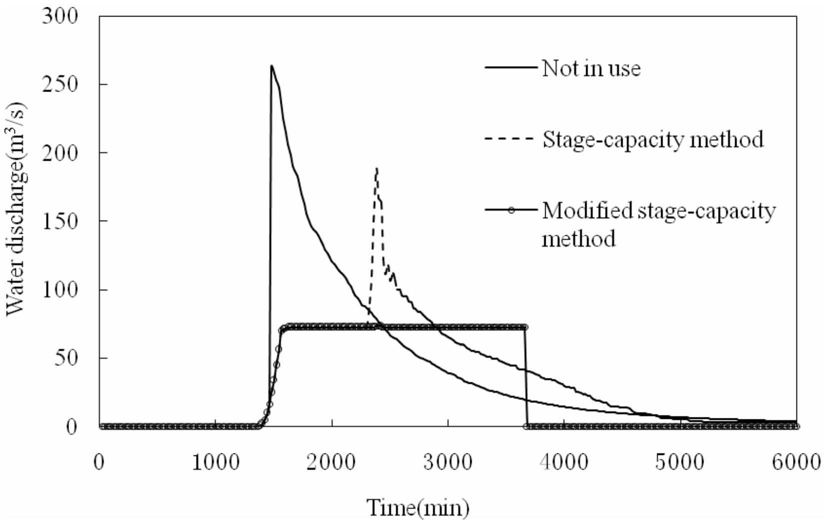


Figure 5. Outflow hydrograph of Shisanling reservoir under different operations

All other reservoirs and gravel pits can also be operated in this way to regulate the flood routing and store water of this drainage basin. Table 4 shows the stored water volume in reservoirs and pits under different operations in different rain storms. As all the reservoirs and pits are scatted in Sha creek and Lin creek, water saving efficiency in these two creeks is obvious. We could see from the table that it will store 25.89 million $m^3$, 31.16 million $m^3$, 51.95 million $m^3$ and 101.14 million $m^3$ water in 5-year, 10-year, 20-year and 50-year rain storm using reservoirs only, respectively. It will store 2.3 million $m^3$, 4.4 million $m^3$, 5.6 million $m^3$ and 10.2 million $m^3$ more water in 5-year, 10-year, 20-year and 50-year rain storm using both reservoirs and pits, respectively. Reservoirs and gravel pits can be selectively used according to the size of rainfall or flood. They are best not to use in a 5-year rain storm to ensure a certain amount of water for the protection of downstream river health. But they should be all put into use in a large flood to save more available water resources and control flood. These reservoirs and gravel pits can intercept about 30% of the water volume yield in Sha creek and Lin creek in 20-year and 50-year rain storm, greatly reducing the flood pressure downstream.

Table 4. Stored water volume in reservoirs and pits in different rain storms

| Rain storm | Runoff yield in Sha and Lin creek (million $m^3$) | Not in use | | Using reservoirs only | | Using both reservoirs and pits | |
|---|---|---|---|---|---|---|---|
| | | stored water volume (million $m^3$) | Storage percent % | stored water volume (million $m^3$) | Storage percent % | stored water volume (million $m^3$) | Storage percent % |
| 5-year | 28.29 | 22.03 | 0.78 | 25.89 | 0.92 | 28.22 | 1.00 |
| 10-year | 76.89 | 22.03 | 0.29 | 31.16 | 0.41 | 35.57 | 0.46 |
| 20-year | 176.70 | 22.03 | 0.12 | 51.95 | 0.29 | 57.56 | 0.33 |
| 50-year | 383.56 | 22.03 | 0.06 | 101.14 | 0.26 | 111.33 | 0.29 |

However, reservoirs cooperated with the floodgates on creeks and main channel may give more choices to manage water resources. That needs a hydrodynamic model to cooperate with our hydrological model, which we will describe in other reasearch.

**Conclusions**

The study presents hydrology simulation and water resources management for watershed of Beiyun River in Beijing, China. The DWSM model has been used and improved. A new treatment for the reservoir operation has been further discussed to meet the new demand of human being. The calibration and certification results show good capability of DWSM model for simulation in this watershed.

By the calculation, we can see that there are about 68, 185, 413 and 886 million $m^3$ runoff water resources yield in Beiyun River basin of Beijing area in 5-year, 10-year, 20-year and 50-year rain storm, respectively. The runoff yield under the rainfall frenquency of 20-year and 50-year increses sharply compared to 5-year and 10-year, even though the 24-hour accumulated rainfall does not multiply correspondingly. That's why it is easier to be flooding when heavier storm comes. Reservoirs and gravel pits can be selectively used according to the size of rainfall or flood. They are best not to use in a 5-year rain storm to ensure a certain amount of water for the protection of downstream river health. But they should be all put into use in a large flood to save more available water resources and control flood.

Furthermore, the regulations of reservoir effectively reduce the peak flow at the outlet of Beijing area and lighten the risk of flooding in lower reach.

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