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SIMULATION OF THE PEAK FLOW REDUCTION OF SMALL RESERVOIRS. A CASE STUDY OF THE BROWN BRIDGE POND, MICHIGAN, USA

Due to the high frequency and great damage of flood disasters, it is important to reduce the flood peak when it goes through the reservoir. A hydraulic model which integrates the implicit equation of water balance, water head-discharge carves, and water head-storage carves together, is proposed to simulate the flood peak reduction of a small reservoir. The proposed method was employed to simulate the flood peak reduction in the Brown Bridge Reservoir, Michigan, US. The results show that the proposed method can simulate the flood peak reduction in a small reservoir, and the Brown Bridge Dam can reduce the flood peak when hundred-year floods go through. When all gates or spillways are fully opened, the initial water head of the reservoir significantly influences the capacity of flood peak reduction. When the initial water head of the Brown Bridge Reservoir is 240.18 and 241.40 m, the hundred-year flood peak would be reduced to 23.11 m^3/s and 25.85 m^3/s, respectively. By optimizing the gates or spillways, the hundred-year flood peak could be reduced. When the initial water head of the reservoir is 241.40 and 240.18 m, the hundred-year flood peak would be reduced to 17.98 and 16.54 m^3/s, respectively.

1. INTRODUCTION

Due to the high frequency and great damage of flood disasters, it was regarded as of natural disaster, which had been one of the most influential and resulting largest loss in the world [1]. The sluice gate control of the reservoir was proposed to reduce the flood peak when the floods happened. It was a flood regulation process, which was to balance the relation between the outflow and storage capacity of the reservoir [2]. The potential capacity of reservoirs to control floods would be determined by many factors such as the maximum storage capacity of reservoirs, the lasting time and flood peak, the outflow-water head carve of reservoirs, and the initial water head of the reservoir [3, 4].

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By managing the sluice gates, one part of the flood remained in the reservoirs, and the other part flowed downstream. In the downstream area, the peak of the flood would be reduced, and its damage would lessen or disappear.

Many optimization models were proposed to manage the reservoirs' flood control operations. For the dynamic reservoir flood control operation limited water level would solve the contradictions between reservoir flood control and beneficial operation [5]. For a single reservoir, the contribution of pre-release operation would significantly reduce the potential flood peak downstream [6]. In northeastern Brazil, the reservoir network model was proposed to investigate the connectivity properties of the reservoir group; the results showed that the thousands of small and middle-sized reservoirs had tremendous potential ability to reduce the flood peak [3]. The reservoir regulation was a dynamic system with complexity, which was always a combination of inflow, outflow, hydraulic pressures, and sluice gate switches [7].

The simulation of flood events which were the input conditions of reservoir regulation played an important role in reducing flood peaks by reservoir best dispatching [8]. Both hydraulic and hydrologic approaches used the principle of water balance, which was usually employed to simulate flood events. The hydraulic approach based on the momentum equation, considered the dynamic effects of flood flow, while the hydrological approach simply regarded the volume of water in the river channel as a single-valued function of discharge with the storage-continuity equation [9–11]. Almost all the small reservoir regulations depended on the experience or judgment of the decision-maker to make the scheduling scheme. The scheduling schemes were not always the best solutions; thus, it was hard to reduce the flood peak [12]. Hence, hydraulic routing was one of the most challenging and important tasks for the hydrologists.

After the Brown Bridge Dam was removed to return to its historic channel and status in 2012, some inhabitants in the low-lying downstream of the dam suffered from floods. It is meaningful to simulate the peak flow reduction of the dam to supply a reference for controlling floods in downstream areas. A dynamic routing model was proposed to analyze the potential ability to reduce flood peaks in the Brown Bridge Reservoir. The rest of the article is organized as follows. In Section 2, the methods of the water balance equation, water head-discharge relation, water head-storage relation, and flooding process were introduced. Section 3 describes the information on the Brown Bridge Dam. Section 4 shows the results of the water head-outflow curve of Brown Bridge Dam, and its potential capacity of reducing flood peak for different situations.

2. METHOD

Water balance equation. For the conservation of mass and a given time interval, the continuity equation used in reservoir routing methods is that the volume of inflow minus the volume of outflow equals the change in volume of storage. Thus, the control equation managing the water balance can be obtained

$$\Delta t\left(\bar{I}-\bar{O}\right)=\Delta S \tag{1}$$

where $\Delta t = t_2 - t_1$ is the time interval, s. $\bar{I}$ and $\bar{O}$ are the average rates of inflow (1) and outflow (2) during the time interval, respectively, m^3/s. ΔS is the change in storage volume during the time interval, m^3, where

$$\bar{I}=\frac{I_1+I_2}{2} \tag{2}$$

$$\bar{O}=\frac{O_1+O_2}{2} \tag{3}$$

$$\Delta S = S_2 - S_1 \tag{4}$$

After simple transformations of the equations (1)–(4), we obtain [13]

$$\frac{S_2}{\Delta t}+\frac{O_2}{2}=\frac{I_1+I_2}{2}+\frac{S_1}{\Delta t_1}+\frac{O_1}{2} \tag{5}$$

The time intervals for outflow and inflow in Eq. (5) are equal. Thus, the method takes no account of the effects of the length or size of reservoirs [14–16].

Water head-discharge relations for reservoirs. Not only the design parameters of sluice gates and water turbine but also its operational state would codetermine the water head–discharge relations for reservoirs [17]. The relation between the water head of the reservoir and the bottom of sluice gate or spillway usually determines the flow mechanism such as underflow or overflow. When the water head of the reservoir is above the bottom of sluice gates or spillway, their outflowmay be calculated as [18, 19]

$$Q_1=\Delta t C_1 B\left(h-h_0\right)\left(2g\left(h-h_0\right)\right)^{1/2} \tag{6}$$

where Q_1, m^3/s, is the outflow of sluice gates or spillway in Δt. C_1 is the coefficient of sluice gates or spillways at underflow; the values of C_1 for lower gates, upper gates, and spillways are 0.38, 0.54, and 0.61, respectively. B, m, is the width of sluice gates or spillway. h, m, is the water head of the reservoir, h_0, m, is the dead water head of sluice gates or spillway, g, m/s^2, is the gravitational acceleration.

When the water head of the reservoir is between dead water head of sluice gates or spillway and a corresponding bottom head, the outflow could be calculated from

$$Q_2 = \Delta t C_2 B\left(h_1 - h_0\right)\left(2g\left(h_1 - h_0\right)\right)^{1/2} \tag{7}$$

where Q_2, m^3/s, is the outflow of sluice gates or spillway in Δt, C_2 is the coefficient of sluice gates or spillway at overflow, the values of C_2 for lower gates, upper gates, and spillways are 0.38, 0.43, and 0.46, respectively, h_1 is the bottom head of sluice gates or spillway.

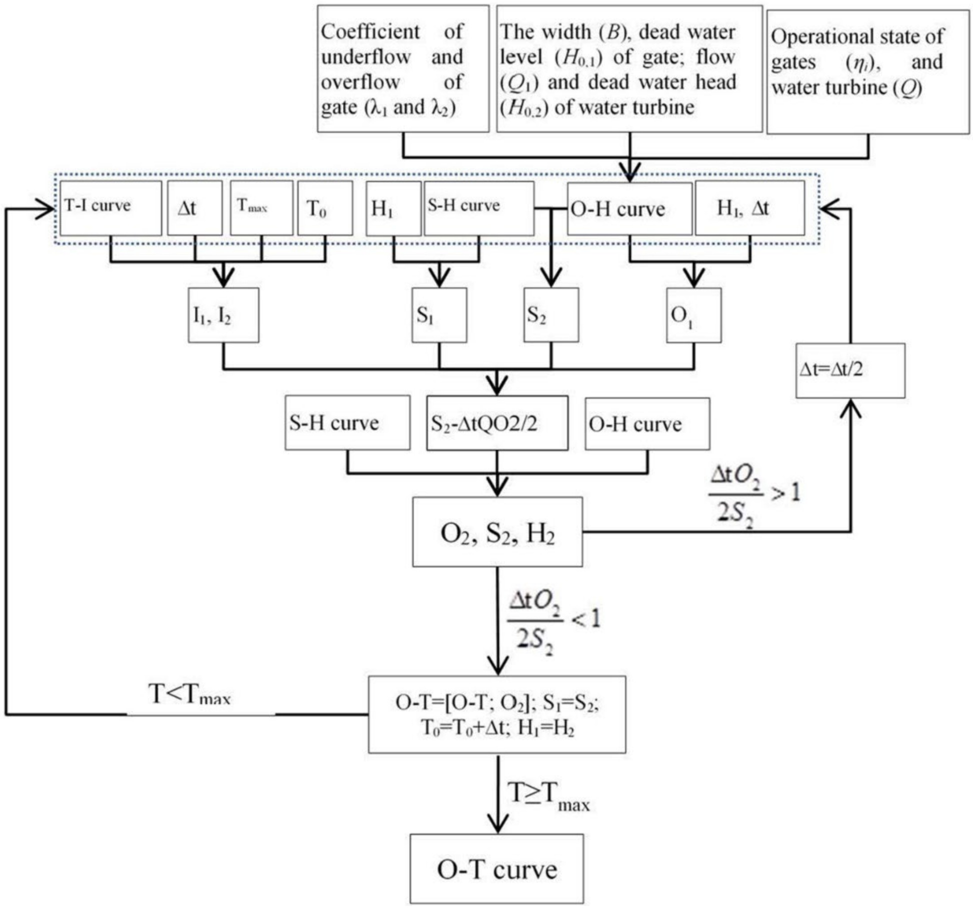

Fig. 1. The framework of the programing flowchart

The total discharge capacity in some operational states is the sum of outflow for each sluice gate and spillway.

$$Q = \sum_{i=1}^{n} Q_i \tag{8}$$

where Q, m^3/s, is the total potential discharge capacity of the dam in some operational states, n is the number of sluice gates and spillways, Q_i, m^3/s, is the potential discharge capacity of the ith sluice gates and spillway.

Water head–storage curve of reservoirs. The relations between the water head and the storage of reservoirs are usually described by the water head-storage curve. Before the dam was constructed, water head-storage information was usually calculated, by gradually increasing the water head from the lowest elevation at the centerline of the dam to an elevation slightly higher than the expected top of the dam. The water head-storage curve would be developed from contour plots of the reservoir area.

Calculation. The research can be divided into the following steps (Fig. 1).

Step 1. Data referred to the properties and operation ways of each sluice gate, spillways, and turbine, and corresponding coefficients of underflow and overflow should be chosen. The properties of sluice gates and spillways include their widths and dead water heads.

Step 2. The inflow–time, outflow head, and water head–storage curves should be loaded or calculated. In the study, the inflow–time curve is the hundred-year flood which is obtained from USGS. Based on the operation of sluice gates, spillways, and turbine, the outflow head curve is calculated according to Eqs. (6) and (7). The water head–storage curve is the previously measured data.

Step 3. $(S_2/\Delta t + Q_2/2)$ according to S_1, O_1, H_1, I_1, and I_2. S_2, H_2, and O_2 could be obtained based on the water head–storage curve, outflow–head curve, and the value of $(S_2/\Delta t + Q_2/2)$. Then, one should calculate and judge whether $\Delta t O_2/2S_2 > 1$ [20]. If so, the value of Δt is smaller than half, then turn to step 1. If not, save the results and stop calculation.

3. STUDY AREA

The Brown Bridge Reservoir which was formed by the construction of the Brown Bridge Dam in 1922, is located 11 miles southeast of Traverse City with coordinates W85°30′34″, N44°38′36″. The temperature typically varied from –9 to 27 °C. The precipitation included rainfall and snowfall, with 589.8 mm and 580.5 mm, respectively. In 2006, the Brown Bridge Dam was slated for removal as it was no longer economically feasible to produce hydroelectric power on the Boardman River. In 2012, the removal of Brown Bridge Dam eliminated the reservoir and allowed the Boardman River to return to its historic channel and status as a high-quality free-flowing river. There are some inhabitants in the low-lying downstream of the dam. Thus, it is significant to simulate the peak flow reduction.

The Brown Bridge Dam consisted of an approximately 488 m long earthen embankment and a combined powerhouse/spillway structure. The dam had a structural height of approximately 14 m. Its surface area is about 0.768 km^2, and its storage volume is

234 3615 m^3. According to USGS, the flood peak of 10-year, 100-year, and 500-year floods in the Boardman River are 21.24, 28.32, and 36.82 m^3/s, respectively. The Brown Bridge Reservoir contains two upper Tainter gates 3.66 m wide, 1.68 m high, two lower Tainter gates 3.66 m wide, 1.68 m high, a log chute 1.83 m wide, 1.83 m high, and turbines with maximum discharge of 5.67 m^3/s. The dead water head of two upper and log chutes are 240.80 m and 241.55 m, while that of two lower Tainter gates is 239.83 m. The two lower Tainter gates cannot be opened if the water level is above an elevation 241.10 m.

4. RESULTS AND DISCUSSION

4.1. WATER HEAD-OUTFLOW CURVE

Besides the turbine, a sluice gate, a discharge gate and two spillways could be operated to regulate the outflow of the Brown Bridge Reservoir. Figure 2 shows the relationships between outflow and water head when all gates and spillways are fully opened. When the water head is greater than 239.83 m and 240.80 m, the sluice gates, and discharge gates could regulate the outflow, respectively. While the water head is greater than 241.55 m, both spillways could adjust the outflow. When the water head equals to the maximum value (which is the height of Brown Bridge Dam, 243.83 m), the maximum discharge of gates and spillways are 10.17 m^3/s (one sluice gate), 14.15 m^3/s (one discharge gate) and 25.0 m^3/s (both spillway), respectively. The maximum flood discharge capacity of the Brown Bridge Reservoir is 48.83 m^3/s, when all gates are opened fully, with its water head equaling its height.

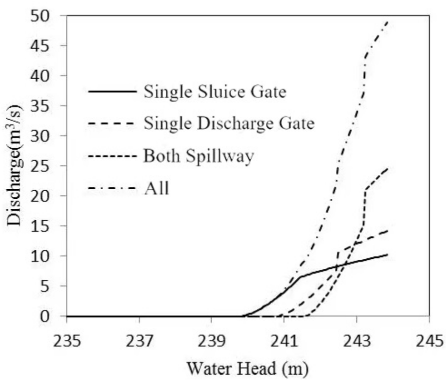

Fig. 2. The dependences of discharges on water head

Figure 2 shows that the sluice gate is the sole discharge channel when the water head is lower than 240.80 m. The dead water heads of the discharge gate and spillway are 240.80 m and 241.55 m, respectively. When the water head is higher than 242.6 m, the outflow of the discharge gate would be greater than that of the sluice gate and become the major discharge channel. Similarly, when the water head is higher than 243 m, the outflow of spillways would be greater than that of the discharge gate and become the major discharge channel.

For the sole reservoir, both the initial water head and flood discharge capacities would directly affect the capacity of flood peak reduction [21]. The lower the initial water head, the stronger the capacity of flood peak reduction is [22]. The sluice gates, discharge gates, and spillway of Brown Bridge Dam play the major roles of discharge channels in low, middle, and high water levels, respectively. Thus, the remaining capacity of the Brown Bridge Reservoir could be managed by operating the sluice gate before the flood goes into it. Operating the discharge gate could be an effective way to modulate flood peak while operating the spillways is an effective way to control the water level of the Brown Bridge Reservoir lower than its maximum water level.

4.2. PEAK FLOW REDUCTION FOR ALL GATES FULLY OPENED

Not only the water head discharge but also the initial water head could influence the outflow peak, water head, and storage of reservoirs.

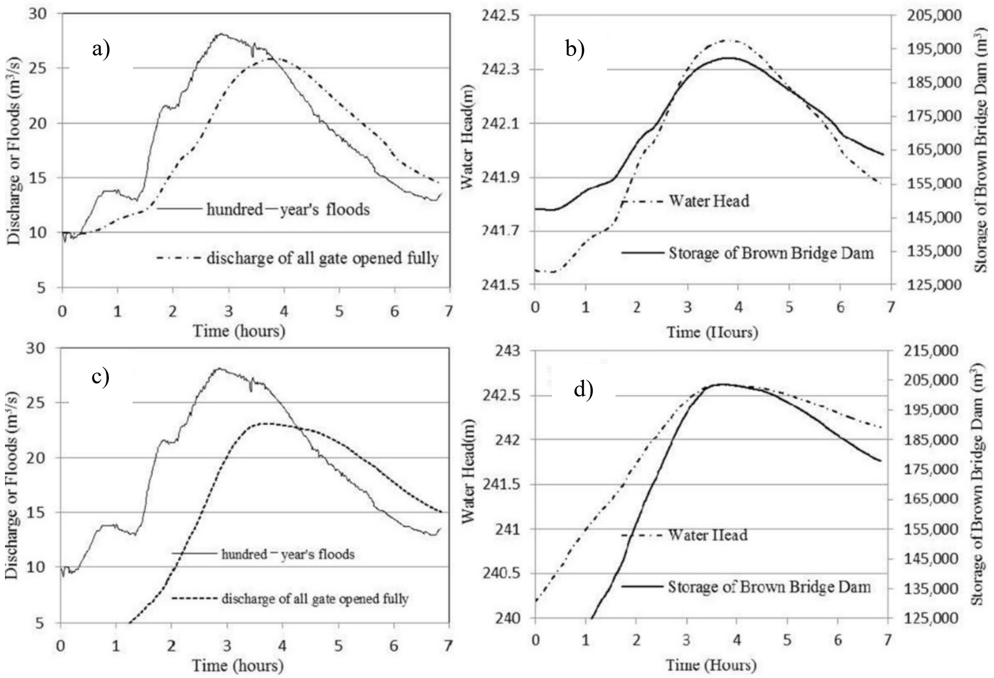

Fig. 3. Simultaneous outflow for hundred-year's flood (28.14 m^3/s) with all gates fully opened; a), b) initial water head of 241.55 m, c), d) initial water head of 240.18 m

All gates are fully opened; the water head-discharge carve is immobile as Fig. 2 shows. When the hundred year's floods with perk flood 28.14 m^3/s go through the Brawn Bridge Reservoir, the capacity of reducing flood peak with initial water head 240.18 m and 241.40 m are shown in Fig. 3.

When the initial water heads are 240.18 and 241.40 m, the hundred-year flood peak with 28.14 m^3/s would be reduced to 23.11 m^3/s and 25.85 m^3/s, respectively. The initial water head of reservoirs would significantly influence the capacity of flood peak reduction. The Brown Bridge Reservoir with an initial water head 240.18 m could reduce the hundred-year flood peak from 28.14 to 23.11 m^3/s, almost 17.87% of the flood peak would be reduced. Whereas, when its initial water head is 241.40 m, the Brown Bridge Reservoir can only reduce 8.14% of the hundred-year flood peak.

Generally, the water head of the reservoir would change with the flood process. When the flood flow equals to the discharge flow, the reservoir would reach a balanced state. Then, the water head would decline with the flooding process until the discharge flow is smaller than the flood flow. Similarly, the storage of reservoirs would have the same process as the water head. When the hundred-year flood goes through the Brown Bridge Reservoir with an initial water head 240.18 m, the maximum water head and storage of the reservoir are 242.41 m and 192 296.5 m^3, respectively. While the initial water head is 241.40 m, the maximum water head and storage of the reservoir are 242.62 m and 203 616.4 m^3, respectively. The maximum water head of the Brown Bridge Reservoir in the flooding process is lower than the elevation level of the Brown Bridge Dam, thus it is possible to operate the gates or spillways to reduce the flood peak.

4.3. PEAK FLOW REDUCTION UNDER ALL GATES PARTLY OPENED

The turbine would be considered as a discharge channel when the reservoir regulation is applied to reduce the flood peak. The operation of gated spillways during floods is a complex issue in dams, and the availability of a comprehensive operational rule would help the operation effectively [23]. When the hundred-year floods go through the Brown Bridge Reservoir, it is possible to reduce the flood peak and avoid the water head exceeding the maximum water head of the Brown Bridge Dam by managing the gates or spillways. As the reservoir regulation progresses, the relationship between water head and discharge flow is shown in Fig. 4.

When the water head is lower than 241.73 m, the discharge flow with the initial water head 240.18 m is the same as that with the initial water head 241.40 m. According to the water head-storage capacity curve, the higher water head is always associated with less remaining storage capacity. Thus, the remaining storage capacity with an initial water head 240.18 m is more than that with an initial water head 241.40 m. The discharge flow with an initial water head 241.40 m should be larger than that with an initial water head 240.18 m.

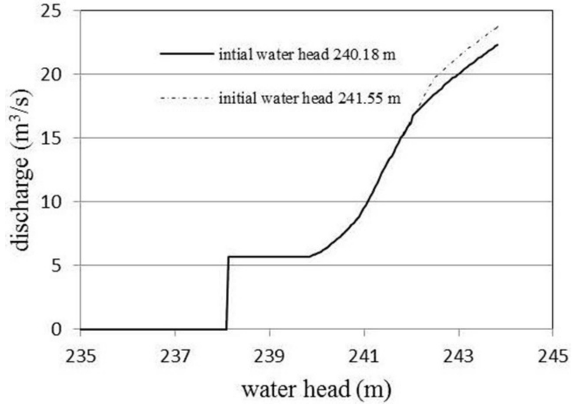

Fig. 4. The dependences of discharges on water head for optimized operation

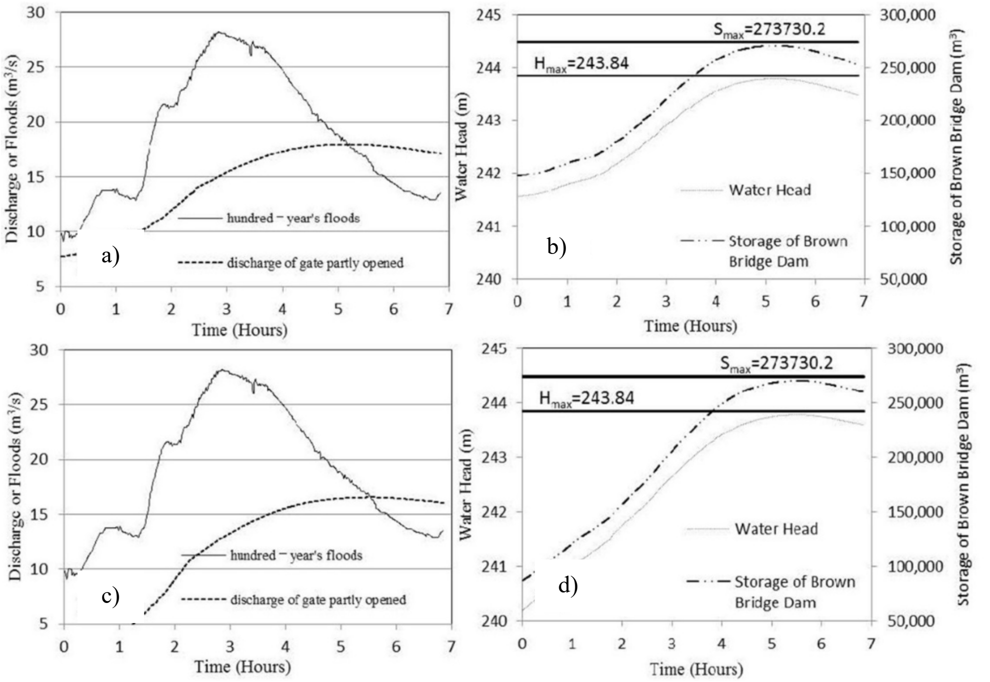

Fig. 5. Simultaneous outflow for hundred-year's flood (28.14 m^3/s) with all gates partly opened: a), b) initial water head of 241.55 m, c), d) initial water head of 240.18 m

During the flood flowing through the reservoirs, the operation of gates or spillways could not be changed. In other words, reducing the flood peak by optimizing gates or spillways is a static process. The processes of a hundred-year flood going through the Brown Bridge Reservoir are shown in Fig. 5. When the initial water head of the Brown

Bridge Reservoir is 241.40 m, the hundred-years flood with peak-flow 28.14 m^3/s would be reduced to 17.98 m^3/s by optimizing the gates or spillways. Meanwhile, the water head and storage of the reservoir would be close to its maximum water head (243.84 m) and reservoir storage (273 730.2 m^3), respectively. Compared with all gates or spillways fully opened (with a peak flow 25.85 m^3/s), 7.87 m^3/s of a peak flow would be reduced.

When the initial water head of the Brown Bridge Reservoir is 240.18 m, the hundred-year flood with a peak flow of 28.14 m^3/s would be reduced to 16.54 m^3/s by optimizing the gates or spillways. Meanwhile, its water head and storage would be also close to its maximum water head (243.84 m) and reservoir storage (273 730.2 m^3). Compared with all gates or spillways fully opened (with a peak flow 23.11 m^3/s), 6.57 m^3/s of peak-flow would be reduced.

5. CONCLUSIONS

The reservoir usually plays an important role in flood prevention; especially it could reduce the flood peak downstream. The classic flood controlling method which integrated with the implicit equation of water balance, water head-discharge carve, and water head-storage carve together was employed to investigate the capacity of flood peak reduction of the Brown Bridge Reservoir.

Even all gates or spillways of the Brown Bridge Reservoir are fully opened; the reservoir has some flood-controlling capacity. The initial water head could influence the capacity of flood peak reduction. Under the initial water head with 240.17 m and 241.40 m, the reservoir could reduce the hundred-year floods (28.14 m^3/s) by about 17.87% (23.11 m^3/s) and 8.14% (25.85 m^3/s), respectively. The maximum water head in the flooding process is lower than the elevation level of a reservoir (design flood level), thus it is possible to operate the gates or spillways to reduce the flood peak.

By optimizing the gates or spillways of the Brown Bridge Reservoir, the reservoir could significantly reduce the flood peak. Under the initial water head with 240.14 m and 241.40 m, the reservoir could reduce the hundred-year floods (28.14 m^3/s) by about 41.22% (16.54 m^3/s) and 36.11% (17.98 m^3/s), respectively.

Flood controlling is a complicated process, but the discharge capacity of the dam, and the flood characteristic is also decisive factor in reducing the flood peak. During the flood controlling process, the flood waters and flood duration are usually unknown, thus the short-term flood prediction plays the most important role.

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