

Optimal Design of Seasonal Flood Limited Water Levels by Jointing Operation of the Reservoir and Floodplains

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Abstract Reservoirs play an important role in the exploitation and utilization of water resources, and the flood limited water level (FLWL) is a key parameter to balance flood control and conservation in reservoir operation. This study is aimed at joint operation of the reservoir and floodplains to improve floodwater utilization and enhance economic benefits. The net profits, namely the benefits from power generation and water supply minus the losses from the flood volume diverted to floodplains, are set as the objective function. To maximize the net profits, an optimization model is then proposed. Finally, a nonlinear optimization technique, the complex method, is used to find the optimal seasonal FLWL. The China's Danjiangkou Reservoir (DR) is selected as a case study. The results show that the joint use of floodplains enables 2.0 m and 0.5 m increment of FLWLs in summer and autumn, respectively, compared to the conventional FLWLs. Since the increment of the FLWL decreases the reservoir flood storage by 0.44 billion m³, the flood volume need to be diverted to floodplains is increased by 0.54 billion m³ per year. Meanwhile, the power generation and water diversion are increased by 0.59% and 2.99%, respectively. The assurance probabilities of power generation, water diversion and minimum flow are also increased by 1.1%, 0.96% and 0.70%, respectively. As a result, the economic benefits can be increased by 0.037 billion USD per year. It is concluded that the reservoir seasonal FLWL can be improved by joint operation of reservoirs and floodplains, which is able to enhance economic benefits without increasing flood risks. Moreover, the increment of economic benefits could be shared by reservoir managers and residents that live in floodplains. This novel operating approach is helpful to the integrated water resources management.

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1 Introduction

With the growth of population and rapid development of social economy, the tradeoff between flood control and water supply is increasingly crucial (Cheng 2005; Guo et al. 2011; Yeh 1985). Structural options, including reservoirs, levees and channel improvement, and non-structural options, including flood warning and evacuation systems, can be used as measurements for flood damage reduction (Lind 1967; Lund 2002; Wood et al. 1985). Specifically, as a part of flood control system components, joint operation of reservoirs, floodplains and dikes are strongly recommended (Aparicio et al. 2009).

The role of the reservoirs is therefore very important, whose functions are exerted both in flood control and integrated water resources development (Deng et al. 2015; Guo et al. 2011; Ming et al. 2017; Zhou and Guo 2014). To meet society's energy and water requirements, various purposes served by the reservoirs should be optimized to improve the efficiency of available water resources, and then maximize the comprehensive benefits (Yang et al. 2015; Zhou and Guo 2013; Zhu et al. 2014).

The flood limited water level (FLWL), the most significant parameter of tradeoff between flood control and conservation, should not be exceeded during the flood season in order to offer adequate storages for flood prevention (Li et al. 2010; Liu et al. 2015; Yun and Singh 2008). However, the conventional FLWL is mostly determined according to design flood estimation from annual maximum flood series, while neglecting seasonal flood information and hydrologic forecasting (Chen et al. 2010). To tackle this issue, seasonal and dynamic FLWLs were proposed to optimize the flood control of reservoir operation. Using flood seasonality, varied seasonal FLWLs could be developed to obtain more economic benefits, using the Copula function to consider the joint distribution of seasonal floods (Liu et al. 2011). Using hydrologic forecasting, Chen et al. (2013) proposed a simulation-based optimization model for dynamic control of FLWL that made an effective tradeoff between the flood control and hydropower generation for the Qingjiang River cascade reservoirs. Zhou et al. (2014) extended the dynamic control models of FLWL for a mixed multi-reservoir system. Ouyang et al. (2015) proposed an optimal design for FLWL of cascade reservoirs to consider flood control risk and economic benefits simultaneously.

However, floodplains are seldom considered in reservoir operation. As an effective method for flood risk reduction, floodplains allow a portion of the flood volume to be temporarily stored, thus reduce and delay the flood peak discharge (De Martino et al. 2012; Topa et al. 2014). Investigators have been trying to optimize the management of floodplains considering the combination of land use due to urban encroachment (Correia et al. 1999; Karamouz et al. 2008). However, few cases were reported to enhance economic benefits by integrating floodplains with reservoir operation.

The aim of this study is to derive an optimal seasonal FLWL, with the objective to maximize comprehensive benefits, by considering the joint operation of reservoirs and floodplains. The optimized reservoir FLWL is tested whether it is feasible to exchange flood storages between reservoir and downstream floodplains without increasing flood risks. The China's Danjiangkou Reservoir (DR) is selected for case study to maximize economic benefits by using the joint operation with downstream floodplains.

2 Methodology

The following steps are used to optimize the reservoir seasonal FLWL (Fig. 1).

- (1) Based on the historical streamflow, the benefits, including annual average power generation and annual average water supply, are assessed by using the reservoir operating rule curves with varied seasonal FLWLs.
- (2) The annual average flood losses of downstream floodplains are estimated by flood routing based on design flood hydrographs.
- (3) With the objective of maximizing the net profits (reservoir benefits minus flood losses) through joint operation of the reservoir and floodplains, the optimal seasonal FLWL is obtained by using the complex method without increasing the flood risk.

2.1 Objective Function

A reservoir generally pursues multiple functions in water resources development, such as flood control, water supply and power generation (Liu et al. 2015; Yang et al. 2015; Zhou and Guo 2013). Using different weights, this multi-objective problem can be integrated into a single objective (Li et al. 2009; Raje and Mujumdar 2010; Zhou and Guo 2013). To maximize the net profits, the objective function is established as follows:

$$Max \quad B = \alpha E + \beta S - \gamma L \tag{1}$$

where B are the annual average net profits; E is the annual average power generation (kWh); S is the annual average water supply (m^3); L is the annual average volume of flood diversion (m^3); α, β, γ are the unit price of three objectives, respectively.

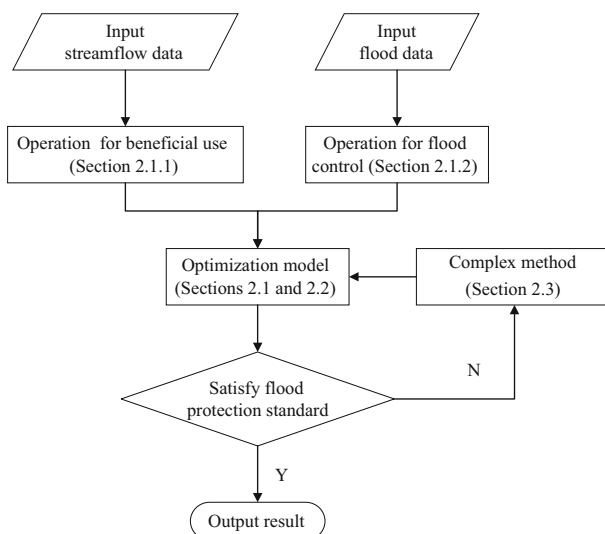


Fig. 1 Flowchart of the method for the optimal design of reservoir seasonal flood limited water levels

2.1.1 Benefits

The benefits consist of two parts, namely the benefits from power generation and water supply (Yang et al. 2015), which can be estimated from the reservoir simulation.

Power Generation

$$E = \sum_{t=1}^T (N_{(t)} \times \Delta t) / Y, \tag{2}$$

$$N_{(t)} = K \times Q_{pg(t)} \times H_{(t)}$$

where t is the number of operational period; T is the total number of operational periods; $N_{(t)}$ is the output in period t (kW); Δt is the time interval (s); Y is the total number of years for the operational periods; K is the hydropower generation efficiency; $Q_{pg(t)}$ is the flow for power generation in period t (m³/s); $H_{(t)}$ is the average hydropower head in period t (m).

Water Supply

$$S = \sum_{t=1}^T (Q_{d(t)} \times \Delta t) / Y \tag{3}$$

where $Q_{d(t)}$ is the diversion water from reservoir in period t (m³/s).

2.1.2 Flood Losses

With the seasonal FLWL altered, the flood diversion to floodplains would change. Due to the inflow uncertainty, a series of design flood hydrographs for different frequencies are chosen as the inflow, then the flood diversion can be derived using flood routing. Based on different flood frequencies, the annual average flood volume diverted to floodplains is estimated as follows:

$$L = \frac{\sum_{i=1}^{n-1} \int_{p_i}^{p_{i+1}} f(z, p) \times dp}{\sum_{i=1}^{n-1} \int_{p_i}^{p_{i+1}} dp} \tag{4}$$

where n is the total number of flood frequency; z is the predetermined seasonal FLWL (m); p is the exceeding probability of the flood i ; $f(\cdot)$ is the flood diversion that relates to the FLWL and flood probability (m³).

2.2 Constraints

Constraints of the reservoir operation are as follows (Lian et al. 2016; Yang et al. 2015; Zhang et al. 2016):

- (1) The reservoir water balance equation:

$$V_{(t+1)} = V_{(t)} + (Q_{in(t)} - Q_{out(t)} - Q_{d(t)}) \times \Delta t \tag{5}$$

where $V_{(t)}$ and $V_{(t+1)}$ are the reservoir storages in period t and $t + 1$ (m^3), respectively; $Q_{in(t)}$ is the reservoir inflow in period t (m^3/s); $Q_{out(t)}$ is the reservoir release to downstream in period t (m^3/s), which is consist of the hydropower discharge $Q_{pg(t)}$ and the spilled discharge.

(2) Reservoir water level limits:

$$Z_{(t)}^L \leq Z_{(t)}^S \leq Z_{(t)}^U \tag{6}$$

where $Z_{(t)}^S$ is upstream water level in period t (m); $Z_{(t)}^L$ and $Z_{(t)}^U$ are the minimum and maximum reservoir water levels in period t (m), respectively.

(3) Reservoir outflow limits:

$$Q_{out(t)}^L \leq Q_{out(t)} \leq Q_{out(t)}^U \tag{7}$$

where $Q_{out(t)}^L$ and $Q_{out(t)}^U$ are the minimum and maximum discharges from reservoir in period t (m^3/s).

(4) Power generation limits:

$$N_{(t)}^L \leq N_{(t)} \leq N_{(t)}^U \tag{8}$$

where N_t is the output in period t (kW); $N_{(t)}^L$ and $N_{(t)}^U$ are minimum and maximum outputs in period t (kW), respectively.

(5) The Muskingum equation of downstream channel flood routing:

$$\begin{aligned} Q_{(t+1)} &= C_0 \times I_{(t+1)} + C_1 \times I_{(t)} + C_2 \times Q_{(t)} \\ C_0 + C_1 + C_2 &= 1 \end{aligned} \tag{9}$$

where C_0 , C_1 and C_2 are the coefficients in the Muskingum flood routing, $Q_{(t)}$ and $I_{(t)}$ are streamflow of the downstream flood control point and reservoir outflow in period t (m^3/s).

2.3 Optimization Method

The above objective function and constraints are used to build a simulation-based optimization model (Chang et al. 2005; Liu et al. 2015), with decision variables of FLWL. The proposed optimization model is nonlinear, because the hydropower generation is included in the objective function (Fayaed et al. 2013; Gu et al. 2012; Hossain and El-shafie 2013).

A nonlinear optimization technique, namely complex method (Wang et al. 1997; Zhang et al. 2015a; Zhang et al. 2015b; Zhang et al. 2016), is used to maximize the objective function, i.e., net profits. The complex method is based on the comparison of function values at the vertices, followed by the replacement of the worst point by another point. This method can converge towards the final maximum with given constraints (Huang and Mccoll 2002; Nelder and Mead 1965; Santos et al. 2010; Wang et al. 2005).

An initial value is randomly set, which lies between the lower and upper boundaries, then their local optima are produced by using the complex optimization many times (Liu et al. 2006). Finally, the optimal solution is obtained by selecting the best one among the local optima.

3 Case Study

3.1 The HanJiang River Basin

As shown in Fig. 2, the Hanjiang River Basin, with an area of 159,000 km², is the largest tributary of the Yangtze River in China. The basin has sub-tropical monsoon climate and the annual precipitation varies from 700 to 1100 mm, in which 70–80% of the total amount occurs in the flood seasons from May to October. Due to the flood seasonality, the flood season has been segmented into two sub-seasons, the pre-flood season (namely summer, from June 21st to August 31th) and post-flood season (namely autumn, from September 1st to October 10th).

3.1.1 The Danjiangkou Reservoir

The Danjiangkou Reservoir (DR) (32°36′–33°48′N, 110°59′–111°49′E) was firstly completed in 1973. It lies middle reach of the Hanjiang River Basin at the junction between the Hanjiang River and Danjiang River.

Since the DR is used as the water source for middle route of the South-to-North Water Diversion Project in China, the height of the Danjiangkou Dam was increased from 162.0 m to

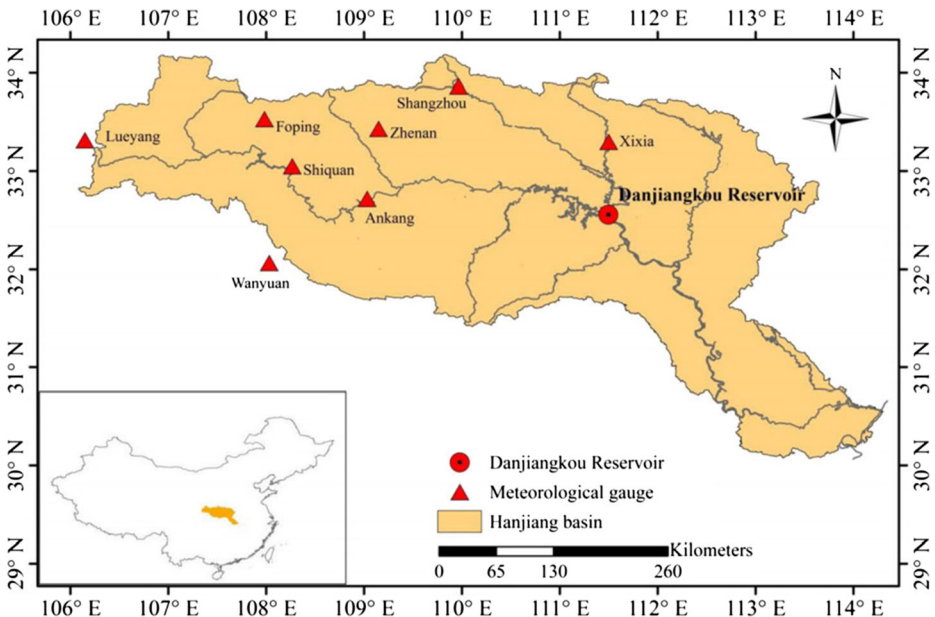


Fig. 2 Location of the DR and the Hanjiang River Basin in China

176.7 m above mean sea level between September 2005 and September 2013. After this increase of height, the normal water level and storage capacity of the DR increased from 157 m to 170 m and from 17.45×10^9 to 29.05×10^9 m³, respectively (Li et al. 2015). And the main functions of reservoir have been adjusted to flood control, water supply, hydropower generation, irrigation, etc. The characteristic parameter values of the DR are listed in Table 1.

The daily inflow data of the DR from 1954 to 2010, where the streamflow from 1954 to 1973 are restored, is used for the benefit simulation, while the design flood with varied return periods, which was derived by the Changjiang Water Resources Commission, is used for flood losses analysis.

3.1.2 The Floodplains

The generalized layout of the downstream of the Hanjiang River Basin is presented in Fig. 3. The floodplains of Hanjiang River Basin can be divided into two parts. One is the Dujiatai floodplain, with an available flood control storage of 2.29 billion m³. The other are the floodplains with an available flood control storage of 3.51 billion m³.

3.2 Conventional Operating Rule Curves

The conventional operating rules of the DR are shown in Fig. 4. From June 21st to August 20th, the reservoir FLWL is fixed at 160 m, and then it is increased to 163.5 m from August 21th to 31th. The FLWL is kept at 163.5 m from September 1st to October 10th to allow for the possible flood in autumn. Once the flood season ends, the reservoir water level should return to normal pool level 170 m as far as possible, aiming at meeting to water demand in the dry season. During flood seasons in summer and autumn, the flood peak must be reduced when the inflow exceeds the downstream safety discharge, and the redundant floodwater should be released through the spillways when the hydropower generation reaches its maximum capacity.

Although the conventional operating rules are easy to implement, the spilled water during the pre-flood and the post-flood seasons leads to the low floodwater utilization rate. Thus, it is possible to re-design the seasonal FLWL of the DR by joint operation of the reservoir and the downstream floodplains to take full advantage of the floodwater without reducing the flood prevention standard.

Table 1 The characteristic parameter values of the DR

Parameter	Value	Unit
Total storage	33.91	billion m ³
Flood control storage in summer	14.1	billion m ³
Flood control storage in autumn	11.1	billion m ³
Crest elevation	176.6	m
Normal pool water level	170	m
Flood limited water level in summer	160	m
Flood limited water level in autumn	163.5	m
Dead water level	150	m
Install capability	900	million W

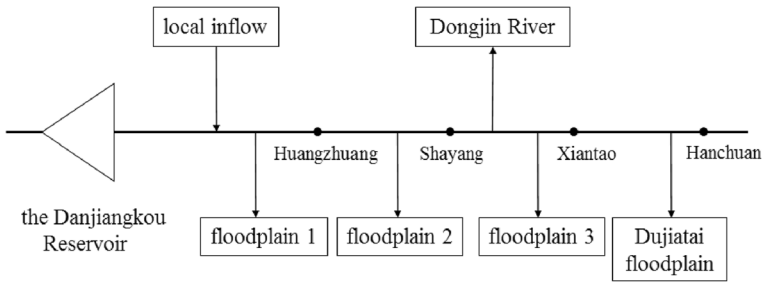


Fig. 3 Sketch of downstream floodplains

4 Results and Discussion

4.1 Benefits and Losses Estimation Based on Simulation

The daily streamflow from 1954 to 2010 is used for the simulation, with the conventional seasonal FLWLs (saying 160.0 m and 163.5 m for summer and autumn, respectively). As shown in Table 2, the annual average power generation, water diversion and flood diversion yield are 3.57 billion kWh, 9.40 billion m³ and 1.22 billion m³, respectively. According to Wang and OuYang (2016), the annual average power generation and water diversion are 3.844 billion kWh and 9.249 billion m³, respectively, indicating that the obtained simulation results are reasonable.

Three typical years are chosen for further analysis, and the results are shown in Fig. 5. It is shown that the flood flow peak has been decreased significantly in the wet year, while the reservoir outflow of normal and dry years is steady. Finally, the conclusion can be drawn that the regulating capacity of the DR is remarkable.

The design flood hydrographs with varied return periods are used to calculate the volume of floodwater need diverting by using Eq. (4). Results are showed in Figs. 6 and 7. It is indicated

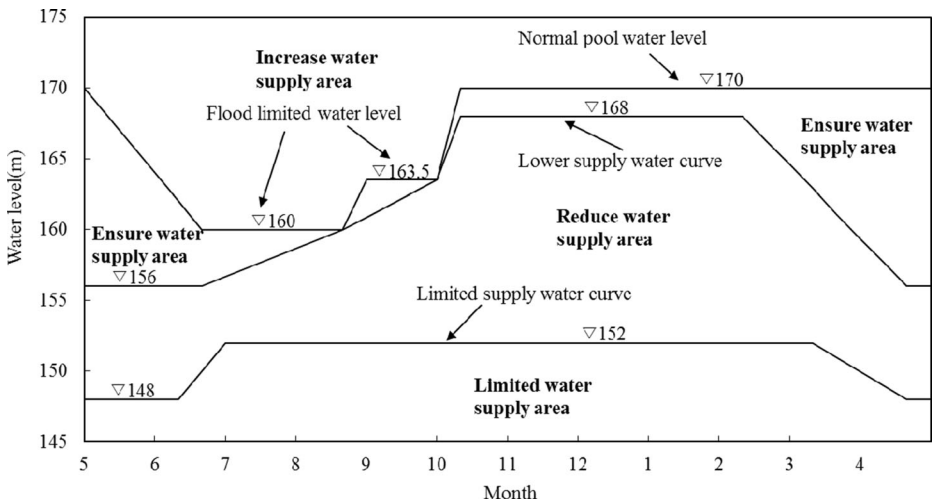


Fig. 4 Designed operating rule curves of the DR

Table 2 Comparison of the conventional and optimal schemes

Content	Unit	Conventional scheme	Optimal scheme	Change in value
FLWL in summer	m	160.00	162.00	2.00
FLWL in autumn	m	163.50	164.00	0.50
Annual average power generation	billion kWh	3.57	3.59	0.02
Annual average water diversion	billion m ³	9.40	9.68	0.28
Annual average spilled water	billion m ³	7.44	7.35	-0.09
Assurance probability of power generation	%	95.48	96.53	1.06
Assurance probability of water diversion	%	95.86	96.78	0.92
Assurance probability of minimum flow	%	96.53	97.20	0.67
Annual average flood diversion	billion m ³	1.22	1.76	0.54
Annual average net profits	billion USD	2.76	2.80	0.037

that the diverted floodwater is monotonously increased with the increase of the FLWL when the return period is fixed, and the diverted floodwater is increased with the increase of the return period when the FLWL is fixed. Specially, when the return period is less than 20 years, it is possible to heighten the FLWL without increasing the volume of floodwater need diverting.

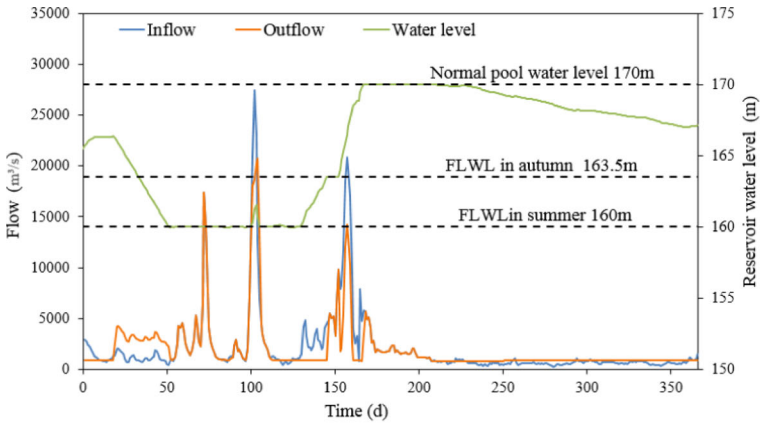
The net profits under different FLWLs can be obtained by using Eq. (1) with the reservoir simulation of the operating rule curves, when the α , β and γ are set as 0.03, 0.3 and 0.088 USD per m³, respectively. It should be noted that the values of the α , β and γ have an effect on the final optimal scheme.

4.2 Seasonal FLWL Derivation Based on Optimization

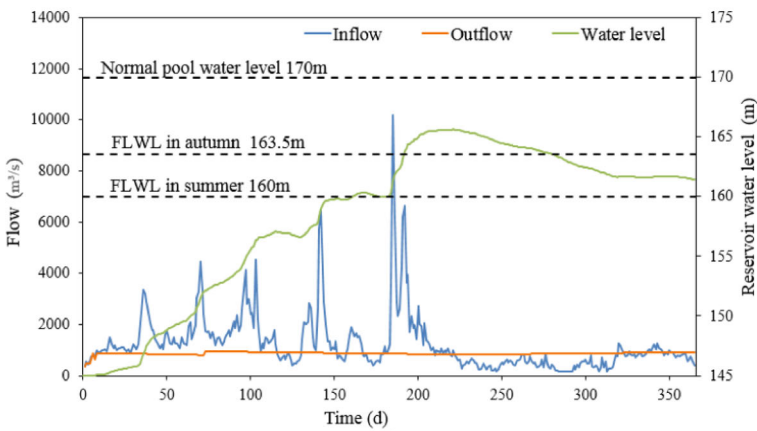
The above simulation model is used to evaluate net profits, and then the simulation-based optimization model can be built. Only two variables, i.e., the FLWLs in the summer and autumn, are optimized by using the complex method. It should be noted that the proposed model take full advantages of exchanging flood storages among different sub-seasons (Liu et al. 2015). Floodwater utilization rate has been improved among cascade reservoirs by considering exchanging the flood storages (Chang et al. 2017; Chen et al. 2013; Ouyang et al. 2015; Zhou et al. 2014). Thus, the exchange of the flood storages of reservoirs and floodplains is implemented to take full use of the flood storages, which improves the floodwater utilization and economic benefits. Finally, the optimal FLWLs in summer and autumn are 162.0 m and 164.0 m, respectively.

4.3 Comparison of Conventional and Optimal Schemes

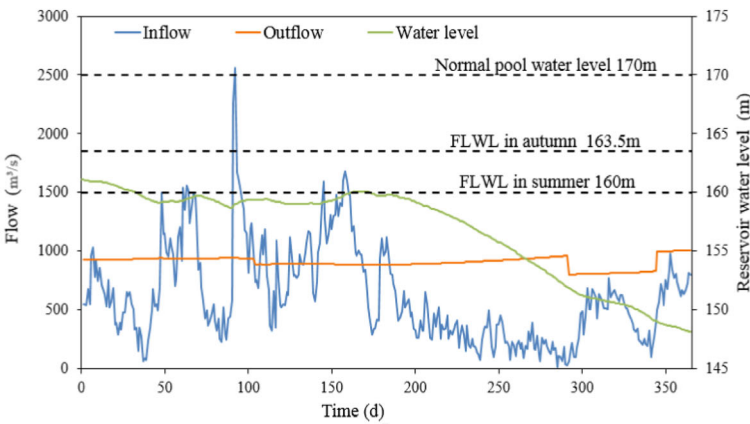
Comparing between the conventional and optimal schemes in Table 2, we can find that the power generation, water supply have been increased in the optimal FLWL, with a relative increase of 0.6% and 3%, respectively. And the result indicates that the optimal FLWL has a remarkable improvement in water supply, which is the most important task of the DR besides flood control. For flood control, the FLWL increment of 0.5 m and 2 m during summer and autumn indicates that reservoir flood storage has been decreased about 0.44 billion m³, while the annual average flood diversion of downstream floodplains is increased 0.54 billion m³. It is shown that flood risk does not increase by exchanging storages between the reservoir and



(a) Wet year (1976)



(b) Normal year (1997)



(c) Dry year (2002)

Fig. 5 Reservoir operation of the conventional FLWL

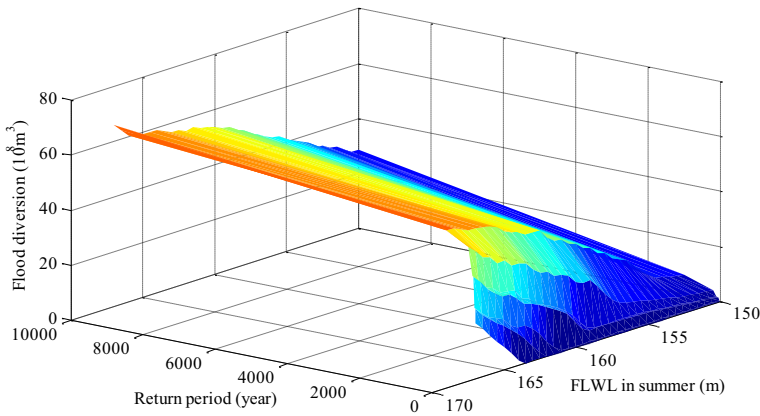


Fig. 6 The relationship among flood diversion, return period and FLWL in summer

downstream floodplains. It should be noted that optimal scheme is unable to tackle an extreme flood (saying the flood with a return period of 1000-year), while the conventional one can deal with (Zhao et al. 2017). However, this part has been considered in the flood losses estimation. Finally, net profits increase 1.3% compared to conventional FLWL, which means the optimal scheme could produce more benefits without increasing flood risks.

Figure 8 shows the power generation and its assurance probability to valid the optimal scheme, from which we could be informed that the power generation may increase or decrease among different years, but the assurance probability of power generation is increased as a whole, especially obvious in dry years. It is therefore shown that the optimal scheme can also improve the assurance probability of power generation.

Figure 9 indicates the water diversion and its assurance probability for valid schemes. As mentioned above, the volume of water diversion influences the effectiveness of the middle route of the South-to-North Water Diversion Project, and the figure shows the optimal scheme

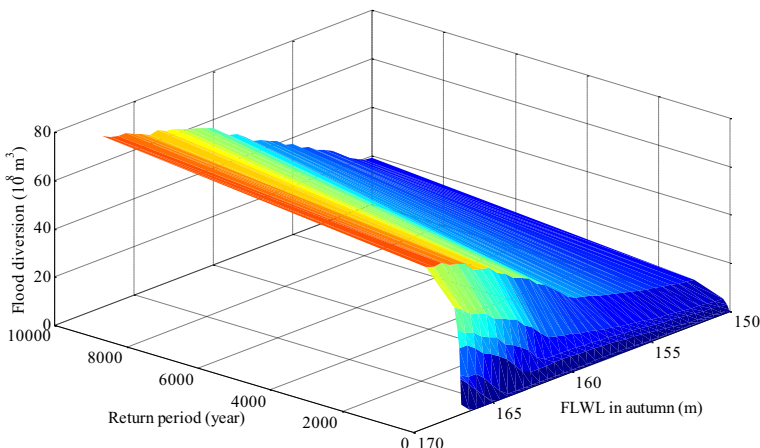


Fig. 7 The relationship among flood diversion, return period and FLWL in autumn

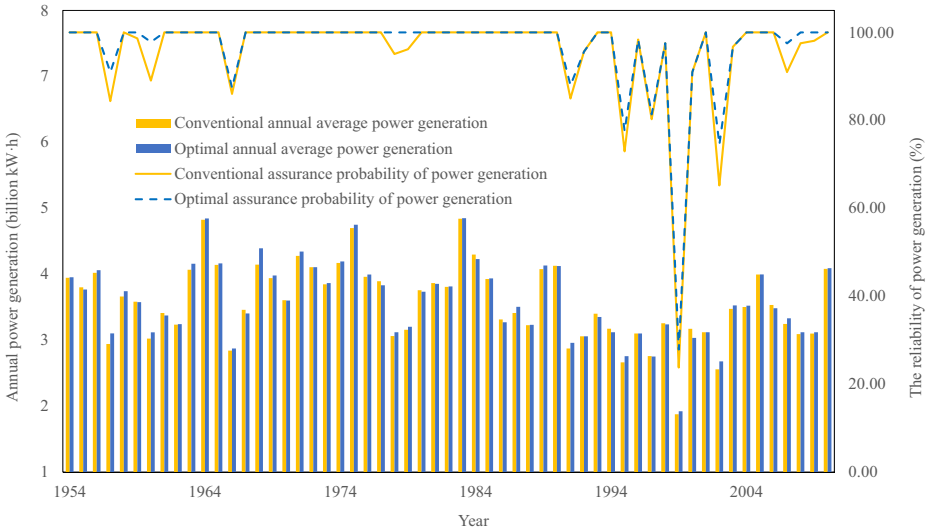


Fig. 8 Comparison of power generation and its assurance probability in the optimal and conventional schemes

can enhance the volume of water diversion greatly, which contributes a lot to alleviating the status quo of the north water shortage. The increment not only in the volume of water diversion but also its assurance probability is of great importance in the optimal scheme.

As shown in Fig. 10, the volume of the spilled water is reduced in most years, especially in dry years, which states that the optimal scheme can take full advantage of the water resources. Similarly, the assurance probability of the minimum flow in the optimal scheme is improved every year, which indicates a better balance between the development of economy and environmental protection.

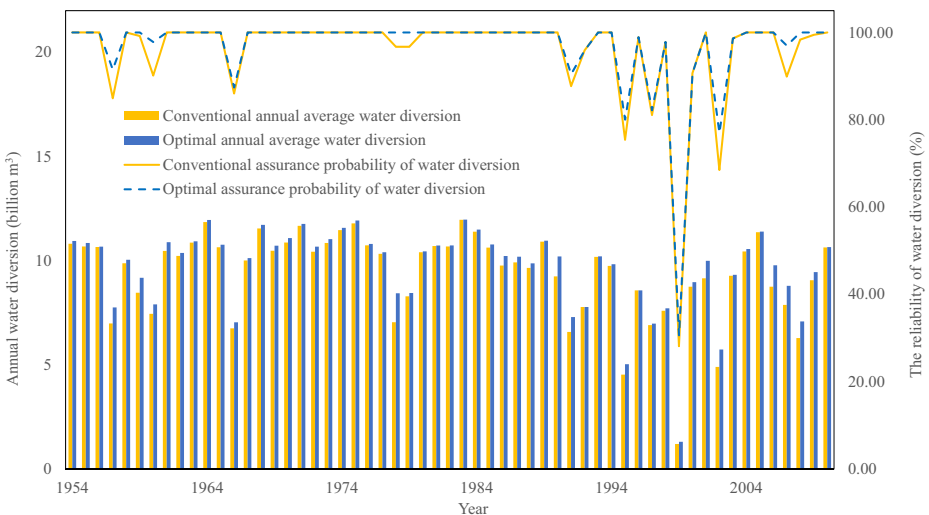


Fig. 9 Comparison of water diversion and its assurance probability in the optimal and conventional schemes

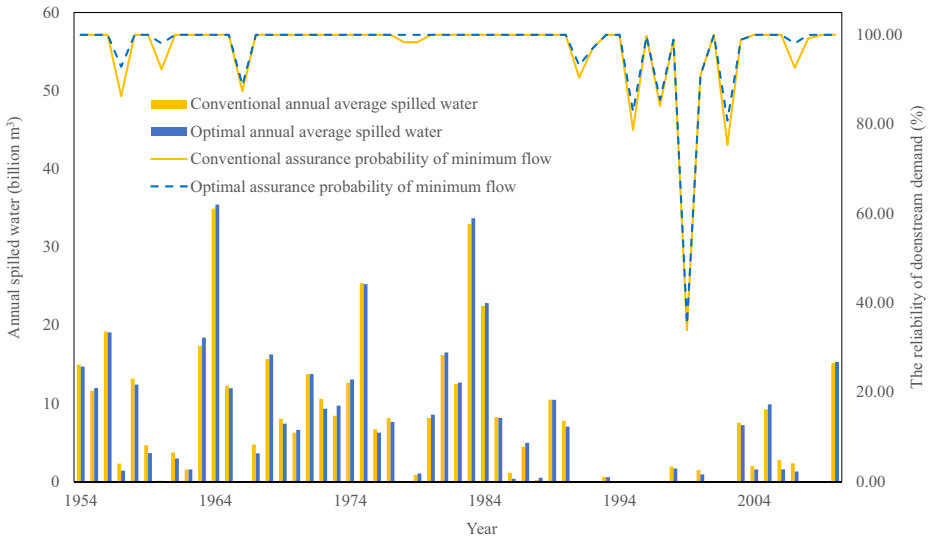


Fig. 10 Comparison of spilled water and minimum flow assurance probability in the optimal and conventional schemes

5 Conclusions

This study is aimed at optimizing the reservoir FLWL by the joint operation of the reservoir and floodplains. An objective function is established considering comprehensive benefits, and the complex method is used to find the optimal FLWL. Based on the results of a case study of the DR, conclusions are summarized as follows:

- (1) It is feasible to exchange flood storages between reservoir and downstream floodplains without increasing flood risks. That is, the flood volume need to be diverted in downstream floodplains is increased by 0.54 billion m^3 per year because the increment of FLWL decreases the reservoir flood storage by 0.44 billion m^3 . By joint operation of the reservoir and downstream floodplains, the optimal seasonal FLWLs of the DR are 162.0 m in summer and 164.0 m in autumn, respectively.
- (2) The optimal design of the seasonal FLWL can effectively balance various benefits, including flood control, power generation and water supply. When the flood volume need diverting is increased at 0.54 billion m^3 per year, the relative increments of annual average power generation and water diversion are 0.59% and 2.99%, as well as the assurance probabilities of power generation, water diversion and minimum flow are 1.1%, 0.96% and 0.70% respectively. As a whole, the economic benefits can be increased by 0.037 billion USD per year. The optimal design of the seasonal FLWL can enhance the utilization rate of water resources during the flood season without reducing the original flood prevention standards.

Although an optimization model has been established and the optimal seasonal FLWL has been obtained, there are still a number of issues, such as the flood volume need to be diverted, the institute to build, and the optimal seasonal FLWL's sensitivity to the unit price, which require further research.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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