



# A Forecast-Based Operation(FBO) Mode for Reservoir Flood Control Using Forecast Cumulative Net Rainfall

Xiao Wang<sup>1</sup> · Zhao Liu<sup>1,2</sup> · Weibo Zhou<sup>3</sup> · Zhifeng Jia<sup>1,2</sup> · Qiyong You<sup>4</sup>

Received: 12 December 2018 / Accepted: 15 April 2019 /

Published online: 6 May 2019

© Springer Nature B.V. 2019

## Abstract

With advance of up-to-date hydrology measuring and forecasting system, reservoir operations are no longer required to be as conservative as they once were. The incorporation of flood inflow and weather forecasts allows for greater flexibility in the management of reservoir space and inherently increases opportunities for acquiring additional water supply and reducing flood risks effectively advance. In this paper, taking Ankang Reservoir as an example, a forecast-based operation (FBO) mode for flood control is developed with cumulative net rainfall in the real-time rolling prediction as the primary indicator and the water level in the reservoir as the auxiliary indicator. Based on the accuracy of flood forecasting data, FBO rules for reservoir flood control are formulated by using the stepwise regulation method considering the actual situation of Ankang Reservoir. For verification, a flood routing simulation is conducted for designed and typical flood processes with different recurrence intervals using the formulated rules. The results show that the maximum flood level is lower than for conventional regulation and that the duration of the maximum discharge under the forecast operation mode is slightly shorter than the conventional discharge, which indicates that the flood risk is reduced to some extent by applying the formulated FBO rules and, correspondingly, demonstrates the merits and applicability of implementing FBO mode for Ankang reservoir.

**Keywords** Flood control · Reservoir · Forecast-based operation · Cumulative net rainfall · Water level

## 1 Introduction

Climate change significantly impacts global water resource distribution (Ahmad et al. 2014). As a result, droughts and floods occur alternately and more frequently around the world, and they have led to massive economic losses (Min 2013). Reservoir operation plays a very important role in water resource regulation and reallocation as well as flood control. In view of hydrological uncertainty (Uysal et al. 2018), the traditional reservoir operation mode didn't

---

✉ Zhao Liu  
lz975315@yahoo.com

depend on forecasted information, which could ensure that no uncertainty accompanying this information was introduced. However, thanks to rapid development of forecast system hardware and hydrometeorological forecast theories in the past decades, many researchers have focused on a new reservoir operation mode that involves the varied forecast information available in the past few years (Bowles et al. 2004; Chen et al. 2018; Dong et al. 2013; Liu et al. 2015; Kozel and Starý 2015), such as the forecast flood inflow, or forecast runoff. Herman (2017) introduced the forecast operation rules combining state-of-the-art weather forecasts with a novel tree-based policy optimization framework. Liang et al. (2009) studied the decision-making rule for the inter-basin water transfer operation according to the forecasted runoff and the relationship between irrigation-water and inflow of Dahuafang reservoir. It is the so called forecast-based operation (FBO). FBO may improve the performance of reservoirs in many aspects, including water supply, flood hazard reduction and ecosystem protection and restoration. In a word, it's believed that with higher requirements for water resource shortage mitigation and flood disaster reduction under climate change, there must be an inevitable trend for the development of an FBO mode for reservoir flood control and flood forecasting theories and techniques.

Traditionally, reservoir flood control took “the water level” or the actual “flood inflow rate” as primary indicators, usually in the course of flood routing, to determine the discharge flow rate (Feldman 1994). When FBO is performed, the predicted rainfall, or net rain yield, or even flood inflow within the forecast lead time is chosen as indicator to determine the outflow, water level and storage before the dam are regulated to minimize potential risk and maximize benefits (Chang et al. 2019). There are two basic purposes for reservoirs to conduct FBO: 1. Enhancement of flood protection provided for each reservoir. (For example, pre-releasing reservoir storage in the valid forecast period before a flood comes. Furthermore, the storage can be released in advance by means of power generation with enhanced flow rate before the flood wave comes. The initial flood control level or limit water level is usually decreased before the surge of a big flood to reduce the risks of reservoir flood routing); 2. FBO allows additional water to be stored in the reservoir temporarily, so it can enhance the water supply or acquire other benefits through the relaxation of conventional reservoir flood control rules. For example, by elevating the limit water level in flood season appropriately when there is no effective precipitation on the upstream watershed according to forecast, higher electrical generation can be acquired for the hydropower station at the dam-toe. As a result, reservoir flood control flexibility is substantially promoted with forecast information of definite accuracy in FBO mode.

As a matter of fact, the rapid development of forecast theories and techniques, and modern observation and monitoring system engineering have laid a solid foundation for reservoirs to put FBO mode into practice in most watersheds. As the main distinction from its conventional counterpart, forecast factor indicators play a vital role in the whole period of real-time operation for a given prediction system precision.

However, in the past research on forecast flood control, forecast information was only used as indicators, and problems such as reservoir regulation and design flood, as well as upstream and downstream flood control capabilities were ignored. Later, as the research progressed, some scholars (Sun et al. 2015; Yang et al. 2015) used precipitation and flood forecast information to formulate flood control rules, to solve the problems such as the flood resources utilization and power plant efficiency. But affected by the floods characteristics in the upper reaches of the reservoir and the runoff confluence characters, the forecast flood control has

great differences for specific projects, there is no unified mode. Hence, it is necessary to formulate rules according to local conditions.

Duo to the above problems, this paper proposes a FBO mode based on the forecasted accumulated net rainfall within 3 h. In case study, we analyze the feasibility of implementing forecast flood control of Ankang Reservoir, and discuss the distribution of net rainfall error. And we formulate FBO rules with different spatial patterns to regulate design and actual floods. The FBO mode can provide a theoretical basis for improving the dispatching mode of Ankang Reservoir.

## 2 FBO Rules and Formulation

As the indicators of FBO rules, the success of forecast-based reservoir flood control depends heavily on the precision of forecasted elements such as forthcoming inflow, net rainfall or even precipitation. Fortunately, meteorological and hydrological forecast information with higher precision has been achieved in most large or middle sized watersheds (Krstanovic and Singh 1991a, b). Currently, most of the flood control agencies or watershed authorities in China are equipped with satellite cloud image access systems, sophisticated synchronized satellite cloud maps, meteorological facsimiles, advanced weather monitors and forecast systems. However, the meteorological changes are complex and it is impossible to avoid quantitative forecasting error completely (Mukherjee and Mansour 1996; Koussis et al. 2003; Young 2002; Li et al. 2006). Even if there were practicable rainfall or flood forecasting models and schemes, forecasting errors would still exist due to complex runoff generation mechanisms and incomplete prediction methods (Zhou et al. 2005). In fact, the accuracy of the forecasting level is not always satisfactory because it depends on only limited available data. Therefore, as an important precondition, it is indispensable to carry out evaluation and analysis on the availability of forecast information and its error.

### 2.1 Forecast Error Distribution and Test

In mathematical statistics, one of the basic problems extracts samples from the overall population to be studied for observation or experiment to obtain information, and then infer the whole based on the limited information. Each inference must be accompanied by a certain probability showing the inference reliability degree. A major aspect of the inference process is the hypothesis test.

Generally, the errors of flood inflow forecast were thought to comply with a normal, lognormal or gamma distribution, etc. according to previous work (Engeland et al. 2010; Diao et al. 2007). To understand the characteristics of forecast inflow error for a given reservoir or flux error at a cross section somewhere on the mainstream, hypothesis testing is conducted to determine the possible probability distribution function according to the error data series. The  $\chi^2$  testing is a kind of hypothesis test that reflects the difference between forecasted inflow and observed data. It means that if  $X_1, X_2, \dots, X_n$  are independent random variables and all obey a standard normal distribution, then the sum of the squares of random variables  $\sum_{i=1}^n x_i^2$  obeying the standard normal distribution would constitute a new random variable called the  $\chi^2$  distribution. The general two steps here for hypothesis testing are: first, making an assumption

on the overall distribution for the sample series, and second, testing whether the assumptions hold for the sample.

Suppose  $X_1, X_2, \dots, X_n$  are given samples, for instance, the flood inflow error series, assume that  $H_0: f(x)$  is the density function of the overall population  $X$ , and  $F(x)$  is the corresponding distribution function.

Taking a normal distribution  $N(\mu, \sigma^2)$  for example here,  $\mu = \bar{x}$ ,  $\sigma^2 = M = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2$ ,

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}, F(x) = \int_{-\infty}^x f(x)dx.$$

Select  $k-1$  points on the real axis and let  $t_1 < t_2 < \dots < t_{k-1}$ , and then the real axis is divided into  $k$  intervals  $(-\infty, t_1], (t_1, t_2], \dots, (t_{k-1}, +\infty)$ . If the sample number falling into the  $i^{\text{th}}$  interval is  $f_i$ , the corresponding frequency is  $f_i/n$ , here  $i = 1, 2, \dots, k$ . Then, if the original assumption  $H_0$  holds, the probability of  $X$  falling into the certain interval is  $p_i = F(t_i) - F(t_{i-1})$ ,  $i = 1, 2, \dots, k$ . Here, let's write  $t_0$  as  $-\infty$ ,  $t_k$  as  $+\infty$ .

When  $H_0$  is true and the test is conducted a large number of times,  $|\frac{f_i}{n} - p_i|$  should not be large according to the Law of Large Numbers, accordingly,  $\sum_{i=1}^k \left(\frac{f_i}{n} - p_i\right)^2 \frac{n}{p_i} = \sum_{i=1}^k \frac{(f_i - np_i)^2}{np_i}$  should also not be large when more trials are conducted. Therefore,  $\chi^2$  can be used as a statistic for testing the  $H_0$  hypothesis as shown in Eq. (1).

$$\chi^2 = \sum_{i=1}^k \frac{(f_i - np_i)^2}{np_i} \tag{1}$$

If  $n$  is large enough ( $n \geq 50$ ) and  $H_0$  is true, the statistic always follows the  $\chi^2$  distribution approximately with the degree of freedom  $k-r-1$ , here,  $r$  is the number of parameters to be estimated.

For a given significance level  $\alpha$ , the critical value of  $\chi^2$  and  $\chi_{1-\alpha}^2(k-r-1)$  can be calculated based on the samples. If  $\chi^2 \geq \chi_{1-\alpha}^2(k-r-1)$ , then  $H_0$  is rejected, otherwise,  $H_0$  is accepted.

### 2.2 FBO Rule Formulation Principles

The principles of FBO rule formulation for reservoirs require that all of the following preconditions should be unchanged: the design standards of reservoirs, the flood control standards both upstream and downstream, the relations between the primary and secondary protecting objects, and the limited discharge or water levels with different conditions. To make the FBO rules more effective and reasonable in guiding the actual operation, the following principles should be followed in the indicator selection and FBO rule formulation (Vol 2004; Zhou et al. 2006; Akbari et al. 2014; Aboutalebi et al. 2015):

#### (1) Flood control principle

The selected indicators should be the key factors for the safety of reservoir flood control. For example, for reservoirs with large flood regulation storage, the flood volume may play a critical part in terms of flood control safety. On the contrary, reservoirs with small flood control storage may be more sensitive to inflow rate than flood volume. If the cumulative net rain is used as an indicator, an inverse calculation is necessary to convert the flood volume into corresponding net rainfall when the FBO rules are formulated. In addition, net rainfall should

not be larger than the design flood total runoff with same the frequency, otherwise, the outflow should be controlled in accordance with a higher return period design flood.

(2) Nonsingle value control principle

Considering the uncertainties of flood inflow and the differences of various typical flood processes, the outflow should be determined when the selected cumulative net rainfall or other indicators vary in a specific range instead of a fixed value according to the formulated rules.

(3) Representation and inclusionary principle

The representation referring to the selected indicators and rules can be derived by reservoir flood routing simulation with the design floods or typical flood processes, whereas the formulated rules should also have an inclusionary characteristic to be verified and work well for other typical flood processes. Therefore, it is preferred to derive the rules by simulating various typical floods as well as design floods.

### 2.3 Selection of FBO Indicators

In real-time reservoir operation, certain indicators are required as references to determine the reservoir outflow at any moment, so flood control security both upstream and downstream is guaranteed. Generally, these indicators include: water level, flood inflow, pre-peak storage, cumulative net rainfall, etc. (Kozel and Starý 2015; Pereira et al. 2018).

For the decision-maker in real-time FBO, the available information that could be potential indicators, appears in chronological order due to the process of runoff yield and concentration: the forecast precipitation is available earlier than the actual rainfall, the actual rainfall is available earlier than the net rain forecasted inflow, as well as flood peak information, etc. However, for reservoir flood control, the potential risks could be raised if earlier information was adopted as indicators instead of later information, because there is less uncertainty for actual rainfall than forecasted precipitation. Similarly, there is less uncertainty for forecasted net rain than forecasted inflow, which involves various errors. For instance, the systematic and computation error of runoff yield, concentration and flood routing. Actually, this is an art of balance, not only between lead time and uncertainty but also between profit and risk. The cumulative net rainfall is one such appropriate quantity weighing both aspects (Cheng and Chau 2004; Wasimi and Kitanidis 1983).

Overall, cumulative net rainfall(CNR) reflects the flood volume. It can be used as an excellent indicator to determine the evolving flood magnitude and subsequently determine the appropriate discharge. On the one hand, cumulative net rainfall has less uncertainty than forecasted rainfall because it is derived only when the actual rainfall occurs. On the other hand, compared with taking the flood inflow of the reservoir as the indicator, which is applied for a number of reservoirs with conventional operation mode, taking the cumulative net rainfall allows the operator to confirm the outflow as early as possible because it is not necessary to consider the time consuming process of flow confluence and flood routing. Therefore, FBO mode with CNR as indicator would ensure flexible or even uniform discharge of the reservoir storage before the flood wave arrives. As a result, flood storage capacity is relatively increased and the flood risk reduce through changing the discharge flow at the corresponding magnitude of the net rainfall in advance considering the forecast information, meanwhile, the water level

behind the dam can be controlled within a certain ideal range to meet the maximum requirement of profit on power generation or water supply, and the utilization efficiency of floodwater can be improved.

## 2.4 FBO Rule Formulation Methods

The FBO rules that determine real time outflow are critical to reservoir operation. They demand that all relative requirements for flood safety be met when different typical floods and designed floods are regulated based on the formulated rules. Additionally, definitely on the condition that the limit water level is given and there are no floods exceeding the design standard. The following methods can be used in formulating the rules:

### (1) Stepwise regulation method(SR)

Based on the “principle of total runoff volume control”, if the cumulative net rainfall is selected as the indicator, a so-called stepwise regulation method is applied to determine each stage and the corresponding threshold. The procedures for FBO rule formulation are shown in Fig. 1.

### (2) Stepwise regulation with hysteretic discharge (SRHD)

The difference between this method and the former one is that the outflow is lagged on purpose by considering the errors and time-lag of runoff yield and flood routing in the river, which is designed to leave some leeway for flood inflow calculation, negotiation, and operation of the sluice gate. In most cases, the discharge lags behind a time step.

### (3) Envelope method(EM)

Based on the SRHD method multiple typical floods with inverse-calculated cumulative net rainfall are regulated successively by flood routing simulation, and the threshold for each stage is actually determined by the upper and lower envelopes.

### (4) Primary and auxiliary index method

Based on the SRHD method, considering the intensity differences of different storms or fluctuation ratio of flood waves, some other factors, for example, net rainfall intensity or the actual flood inflow could be selected as the auxiliary indicator.

## 3 Case Study

### 3.1 Ankang Reservoir

Ankang Reservoir, located in the upper reaches of the Han River, is a large-scale comprehensive hydro project with upstream catchment area of 35,700 km<sup>2</sup>, and its main functions include hydroelectric power generation, flood control and shipping. The total reservoir storage capacity is approximately 3.2 billion m<sup>3</sup>, in which 980 million m<sup>3</sup> is flood regulation storage. The

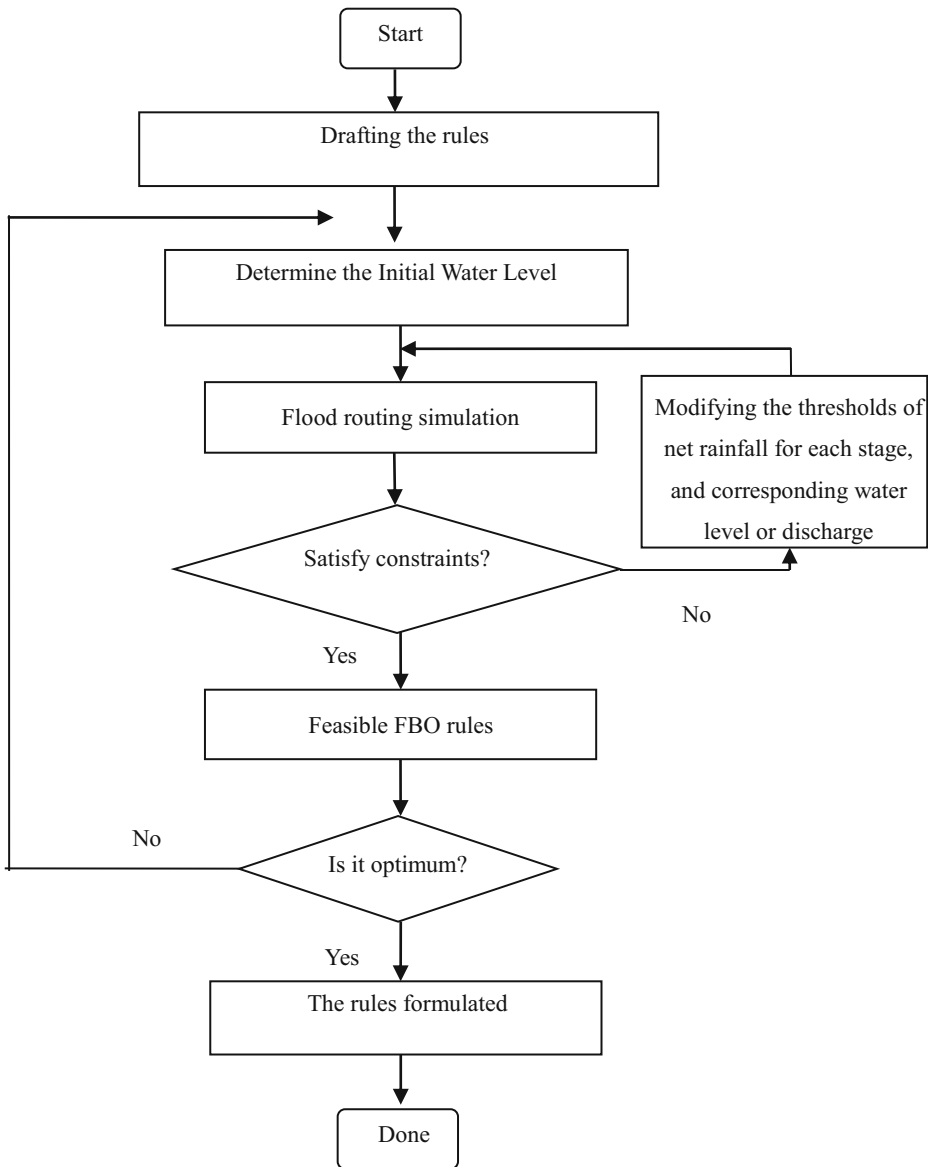


Fig. 1 The flow chart for FBO rules formulation

dead water, normal water, limited water, designed flood and checked flood levels of the reservoir are 305 m, 330 m, 325 m, 333 m and 337.33 m respectively. The climate in the upper reaches of the Han River is subtropical humid with relatively abundant precipitation. July, August and September are the main flood seasons in the basin. The rainfall in these 3 months accounts for approximately 50% of the annual precipitation. The average annual runoff is approximately 26 billion m<sup>3</sup> with as much as 75–80% in summer and autumn, 10–15% in spring, and only 5% in winter. The largest peak flow very likely appears in July or September.

The Ankang hydropower plant is one of the backbone suppliers of the Shaanxi power grid, and the reservoir also undertakes flood control for Ankang city downstream. At present, Ankang Reservoir still adopts the conventional flood control mode in which the indicator operation rules are the inflow rate and water level. The conventional mode copes with shifting flood events by sticking to a fundamental principle. It not only lacks flexibility but also may lead to potential loss or even risk. Although flood forecast information was referenced in the real-time control of the Ankang reservoir, it's still not FBO mode because there are no FBO rules and no decision making depends on this forecast information. The conventional flood control rules for Ankang reservoir are shown in Table 1.

### 3.2 Distribution of Net Rain Forecast Error

The Ankang hydrological monitoring and forecasting system has 38 stations integrating 25 rain gauging stations, 8 water level rain gauging stations and 5 relay stations. The system is in good condition with the following functions: real-time data acquisition and processing, equipment monitoring and reporting, voice query and alarm systems, data management, hydrological forecasting, flood process analysis and calculation, etc.

Based on the rolling flood forecast information and the actual flood process, the actual net rain data are obtained by inversion analysis according to the unit hydrograph, and the corresponding forecasted net rain can be acquired according to the system. A total of 149 Ankang Reservoir samples are selected for analysis,  $\mu=0.019$ , and  $\sigma^2=0.1882$ . The actual error-frequency histogram and the corresponding normal function curve are derived as shown in Fig. 2.

It can be seen from Fig. 2 that the sample error obeys an approximate normal distribution and hypothesis testing is performed below. Suppose X is a random variable that obeys a normal distribution (2).

$$F(x) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^x e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \tag{2}$$

Here,  $\mu=\bar{X}=0.019$ ,  $\sigma=S^*=0.188$ . Divide X into 5 intervals for calculation, so k = 5, then:

$$\chi^2 = \sum_{i=1}^5 \frac{(f_i - n \cdot p_i)^2}{n \cdot p_i} = 4.1926. \tag{3}$$

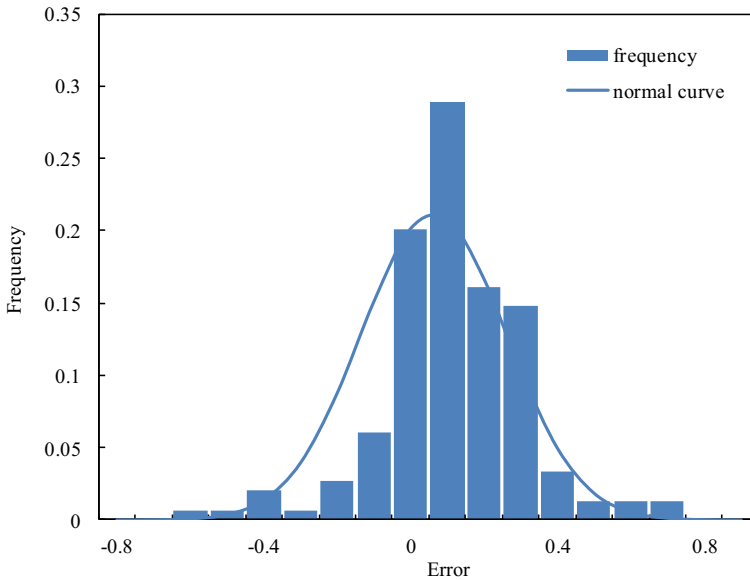
Here,  $\alpha = 0.05$ ,  $k - r - 1 = 5 - 2 - 1 = 2$ . Due to  $\chi^2 = 4.1926 < \chi_{0.05}^2(2) = 5.9915$ , the forecasted net rain error can be considered as complying with  $N(\mu, \sigma^2)$ ,  $\mu=\bar{X}=0.019, \sigma=S^*=0.188$ .

**Table 1** The conventional flood routing rules for Ankang reservoir

Number	Inflow (m <sup>3</sup> /s)	Water level Z(m)	Discharge (m <sup>3</sup> /s)	Notes
1	12000 < Q <sub>in</sub> ≤ 15100	Z ≤ 326 Z > 326	Q <sub>out</sub> = 12000 Q <sub>out</sub> = Q <sub>in</sub>	Q <sub>in</sub> and Q <sub>out</sub> represent inflow and discharge
2	15100 < Q <sub>in</sub> ≤ 17000	Z > 326	Q <sub>out</sub> = Q <sub>in</sub>	P = 10%, flood rising flood rising
3	17000 < Q <sub>in</sub> ≤ 21500	326 < Z ≤ 328 Z > 328	Q <sub>out</sub> = 17000 Q <sub>out</sub> = Q <sub>in</sub>	
4	21500 < Q <sub>in</sub> ≤ 24200	Z > 328	Q <sub>out</sub> = Q <sub>in</sub>	P = 1%, flood process, discharge if inflow has the discharge capacity
5	Q <sub>in</sub> > 24200	Z > 328	discharge	

The initial water level is kept at 325.0 m





**Fig. 2** The actual error-frequency histogram and corresponding normal function curve

Combined with analysis of flood forecasting information over the years, especially the relative error of flood peak, peak time and certainty coefficient, the conclusion is drawn that the Ankang hydrological monitoring and forecasting system can generate high-precision net rain forecasts. The reservoir operation is in good condition and has gained wider flood regulation experience in past decades, laying a solid foundation to implement FBO rules.

### 3.3 Selection of Flood Control Forecast Operation Indicators

At present, Ankang Reservoir adopts the real time flood inflow and water level as indicators, and implements graded gate opening to control outflow. From a global viewpoint, flood inflow is a flow rate that cannot reflect the overall flood process, and this could lead to disadvantages and uncertainty in the complete flood regulation for reservoirs. The accumulated net rainfall is one such effective indicator that can reflect not only the possible inflow but also the whole flood volume in a certain interval. Meanwhile, as its forecasted counterpart, the forecasted accumulated net rainfall could be a good FBO indicator due to higher accuracy because it is derived from the actual precipitation. Considering both the flow rate and flood volume, the time interval should not be too long. In this research, “the forecasted accumulated net rainfall within 3 h” was chosen as the key indicator, and the water level was used as an auxiliary indicator to formulate the FBO rules for Ankang Reservoir.

### 3.4 Formulation of FBO Rules

To formulate the flood regulation rules, flood No. 19830730 is selected as a typical flood process. Correspondingly, the possible net rainfall process is derived inversely using a unit hydrograph. Based on the stepwise regulation method and Fig. 1, several key net rainfall amounts corresponding to the key inflow rate for Ankang reservoir, such as 12,000 m<sup>3</sup>/s,

15,100 m<sup>3</sup>/s, 17,000 m<sup>3</sup>/s..., are estimated as preliminary regulatory thresholds. These inflow rates are actually the peak flow of the return periods of two-year, five-year, ten-year floods and so on. Keeping the 325.0 m limit water level during flood season as the initial water level for the flood routing simulation, the simulations of the check flood, designed flood and other typical flood hydrographs are conducted, respectively, while investigating all of the flood control targets and the constraint conditions. Appropriate modifications could be necessary when some requirements cannot be met. The feasible operation rules are formulated until all of the simulations were done.

As shown in Table 2, the FBO rules for Ankang Reservoir are formulated finally by repeated regulation and multischeme simulation analyses. In the Table,  $\sum R_i$  is the accumulated net rain in the past 72 h. Furthermore, it should be pointed out that rules No.1 to 6 listed in Table 2 are applicable only for the rising stage of a flood.

### 3.5 Verification of the Formulated FBO Rules

To verify the formulated FBO schemes, actual flood routing simulations are carried out for different flood types such as original design floods, typical floods, and the real-time flood hydrograph.

#### (1) Design flood regulation

For the design flood process with different return periods as seen in Table 3, the simulations are conducted for conventional operation and FBO, respectively, taking the 325.0 m cautionary water level in flood season as the initial water level for operation. The simulation results are shown in Table 3. The flood inflow, discharge hydrographs and water level of the simulations are shown in Figs. 3, 4, 5, 6, 7, 8, 9, and 10, respectively.

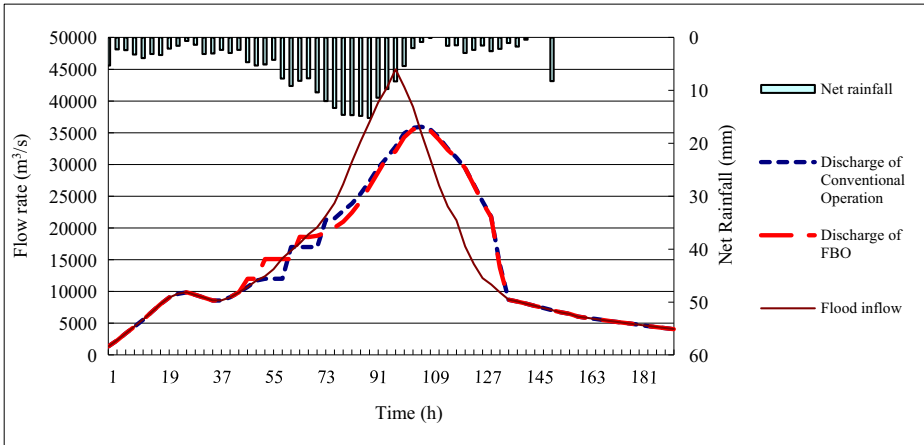
The flood operation results show that, for 20-year floods, both FBO and Conventional Operation have the same discharge process under the premise of the same design flood process and the same initial water level, whereas the highest water level for FBO is lower than its

**Table 2** The formulated FBO rules for Ankang reservoir (only for flood rising stage)

Number	Net rainfall (mm)	Water level Z (m)	Discharge (m <sup>3</sup> /s)	Notes
1	$\sum R_i \leq 43$		$Q_{out} = Q_{in}$	(1) $Q_{in}$ , $Q_{out}$ and $Q_t$ represent inflow, discharge and the corresponding discharge of the last time step.
2	$43 < \sum R_i < 55$	$Z \leq 326$ $Z > 326$	$Q_{out} = 12000$ $Q_{out} = Q_{in}$	
3	$55 < \sum R_i < 62$	$Z \leq 326$ $Z > 326$	$Q_{out} = 15100$ $Q_{out} = Q_{in}$	(2) The rules with serial No.1–6 for flood rising only, i.e., $\sum R_i \leq \sum R_{i-1}$ .
4	$62 < \sum R_i < 79$	$Z \leq 326$ $326 < Z \leq 328$ $Z > 328$	$Q_{out} = 15100$ $Q_{out} = 17000$ $Q_{out} = Q_{in}$	
5	$79 < \sum R_i < 90$	$Z \leq 328$	$Q_{out} = 21500$ $Q_t > 21500$ , $Q_{out} = 21500$ $Q_t \leq 21500$ , $Q_{out} = Q_t$	(3) The rules with serial No.7 for flood fall.
6	$\sum R_i > 90$	$Z > 328$	$Q_{out} = Q_{in}$ Free overflow	
7	$\sum R_i \leq \sum R_{i-1}$	$Z \geq 325$ $Z = 325$	$Q_{out} = Q_t$ $Q_{out} = Q_{in}$	

**Table 3** The contrast of conventional operation and FBO for the Ankang designed floods reservoir

Return period	10,000			1000			100			20			5		
	highest water level (m)	maximum discharge (m <sup>3</sup> /s)	highest water level (m)	maximum discharge (m <sup>3</sup> /s)	highest water level (m)	maximum discharge (m <sup>3</sup> /s)	highest water level (m)	maximum discharge (m <sup>3</sup> /s)	highest water level (m)	maximum discharge (m <sup>3</sup> /s)	highest water level (m)	maximum discharge (m <sup>3</sup> /s)	highest water level (m)	maximum discharge (m <sup>3</sup> /s)	
Conventional operation	336.91	35,923	332.92	30,934	328.76	24,823	328.29	17,000	326.62	12,000					
Forecast operation	336.76	35,690	332.44	29,892	327.62	23,239	327.77	17,000	326.47	12,000					

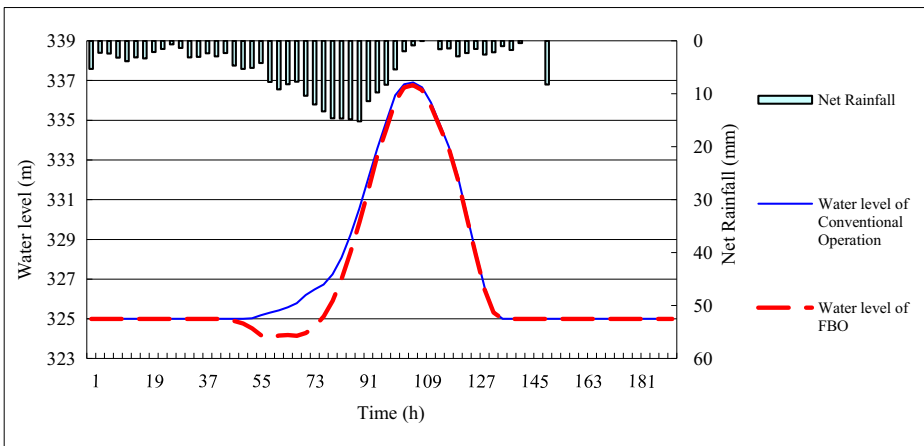


**Fig. 3** Comparison of the discharge process for conventional operation and FBO for a 10,000-year return period flood (check flood)

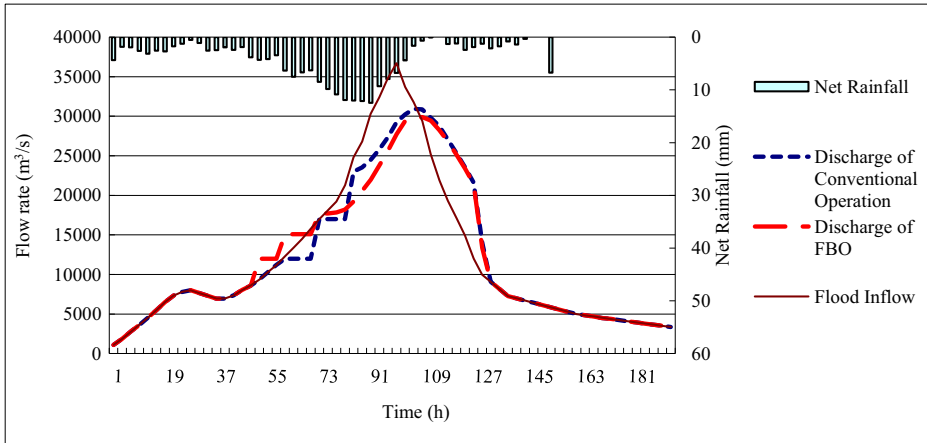
conventional counterpart, by 0.52 m. For the 100-year, 1000-year and 10,000-year floods, both the discharge and highest water level are lower than conventional operation. The discharges for FBO are reduced by 1584 m<sup>3</sup>/s, 1042 m<sup>3</sup>/s and 233 m<sup>3</sup>/s, and the highest water levels are lower by 1.14 m, 0.48 m, and 0.15 m, respectively, which are favorable for reservoir safety and protection of downstream areas.

(2) Regulation of the typical flood “19680910”

Flood “19680910” is a typical flood on the whole basin in terms of its spatial pattern with the peak flow of 19,700m<sup>3</sup>/s on September 10, 1968. The peak time appears a little bit retarded and the shape of the flood hydrographs is relatively flat as shown in Fig. 11, all thought to be unfavorable for reservoir operation. Comparisons of discharge and water level for two different operation modes are shown in Figs. 11, and Fig. 12, respectively.

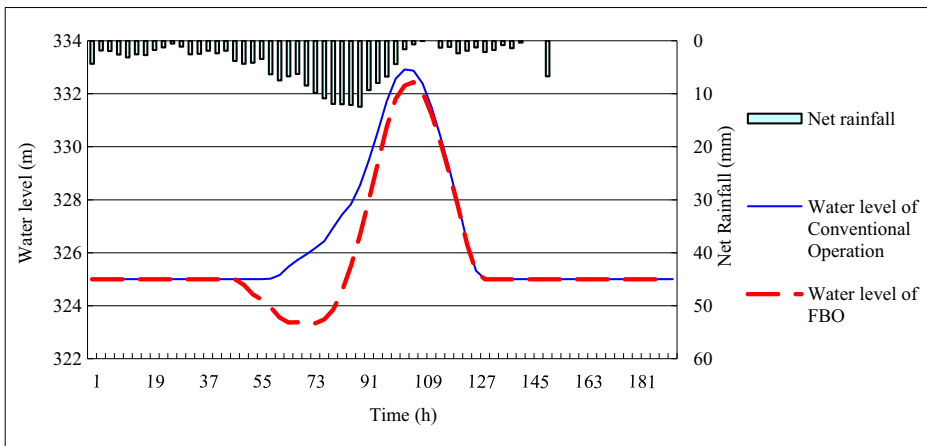


**Fig. 4** Comparison of the water level from conventional operation and FBO for a 10,000-year return period flood (check flood)



**Fig. 5** Comparison of the discharge process for conventional operation and FBO for a 1000-year return period flood (design flood)

According to Figs. 11 and 12, the net rain peak appears approximately 9 h ahead of the inflow peak. The water level for both operation modes reaches the maximum 9 h later than the peak inflow. With intensified discharge 12 h in advance, in contrast with conventional operation, FBO mode reduces the water level to 323.6 m for a time before the peak flow and this is below the Ankang Reservoir limit water level. Apparently, this pre-discharge makes room and flexibility for regulating the upcoming peak flood inflow. Consequently, more than 112.5 million m<sup>3</sup> of extra water resources can be used by enhancing the water supply or increasing the hydro power plant output by implementing FBO mode. Moreover, the maximum reservoir discharge is the same as the conventional operation. Both the highest water level and the maximum discharge duration are lower than conventional operation. The duration of maximum discharge is reduced from 30 to 21 h, and the highest water level is reduced by 0.14 m, manifesting lower risk in the course of flood regulation.



**Fig. 6** Comparison of the water level from conventional operation and FBO for a 1000-year return period flood (design flood)

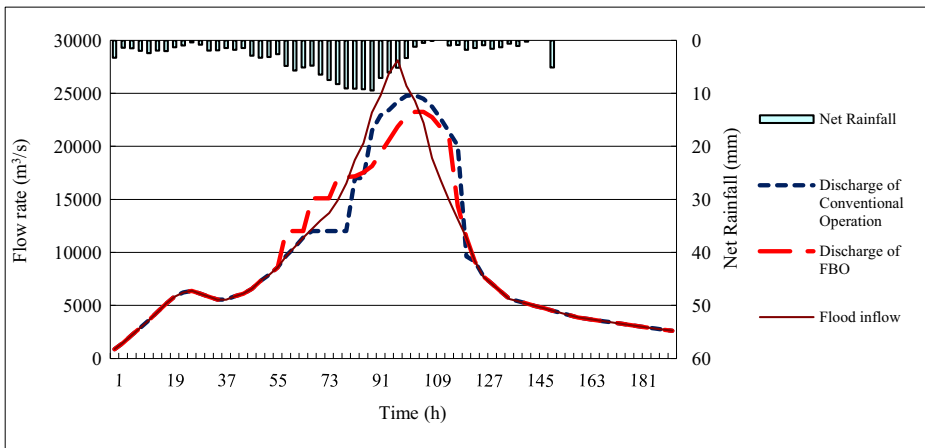


Fig. 7 Comparison of the discharge process for conventional operation and FBO for a 100-year return period flood

(3) Regulation of flood “20110918”

Because there is actually no effective precipitation monitoring and available flood forecast system back to the 1970s in China, the net rainfall processes adopted in the verification of FBO mode on the design flood and the typical flood “19680910” above are derived according to the flood hydrograph and the corresponding unit hydrograph based on inversion analysis. Whereas, with the construction and completion of sophisticated precipitation and flood monitoring systems, Ankang Reservoir has met all the software and hardware requirements for implementing FBO mode in reservoir operation since the beginning of this century.

As far as magnitude is concerned, flood “20110918”, with peak flow 18,500 m<sup>3</sup>/s on September 18, 2011, approximately falls between the 10-year and 20-year return period floods. The flood regulations based on the formulated FBO rules are conducted to simulate real time forecast operation. Comparisons of the two operation modes on the discharge and the water level are shown in Figs. 13 and 14, respectively.

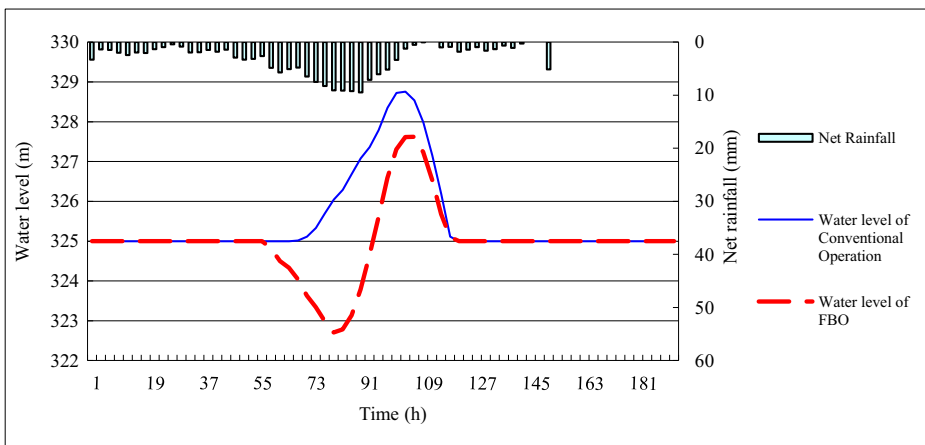
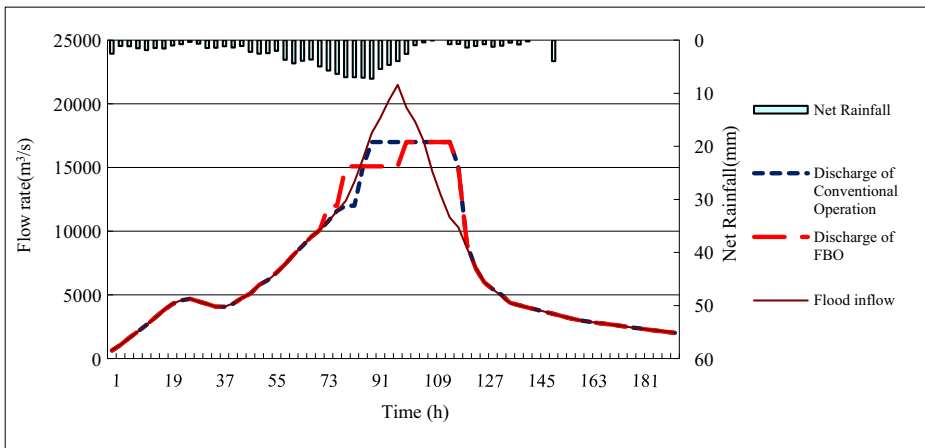
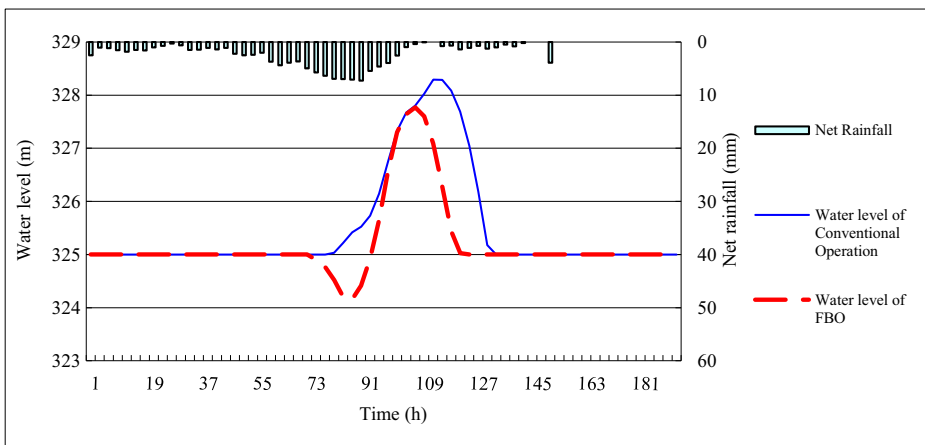


Fig. 8 Comparison of the water level for conventional operation and FBO for a 100-year return period flood



**Fig. 9** Comparison of the discharge process for conventional operation and FBO for a 20-year return period flood

As seen in Fig. 13, the net rain peak of 5.5 mm appears 8 h earlier than the peak inflow. There is no difference between the two operation modes before the former 12 h. For conventional operation, there is no pre-discharge which means the outflow is always less than the inflow, whereas there is an evident pre-discharge in FBO mode starting from the 13th hour, and the water level descends correspondingly below the 325.0 m limit water level. It reaches the maximum discharge at the 29th hour and lasts for 8 h for FBO. For its conventional counterpart, the maximum discharge appears at the 22nd hour and lasts for 19 h. It is clear that more than 16.2 million m<sup>3</sup> of extra water resources can be used by enhancing the water supply or increasing hydro power plant output by implementing FBO mode. Moreover, the maximum reservoir discharge for FBO is the same as for conventional operation, and its duration is shorter. Maximum discharge is reduced from 60 to 27 h. Correspondingly, the water maintains a higher level in conventional operation as seen in Fig. 14. The highest water level is reduced by 0.31 m in FBO mode in contrast with conventional mode, which also suggests less risk by implementing FBO mode for reservoir flood regulation.



**Fig. 10** Comparison of the water level for conventional operation and FBO for a 20-year return period flood

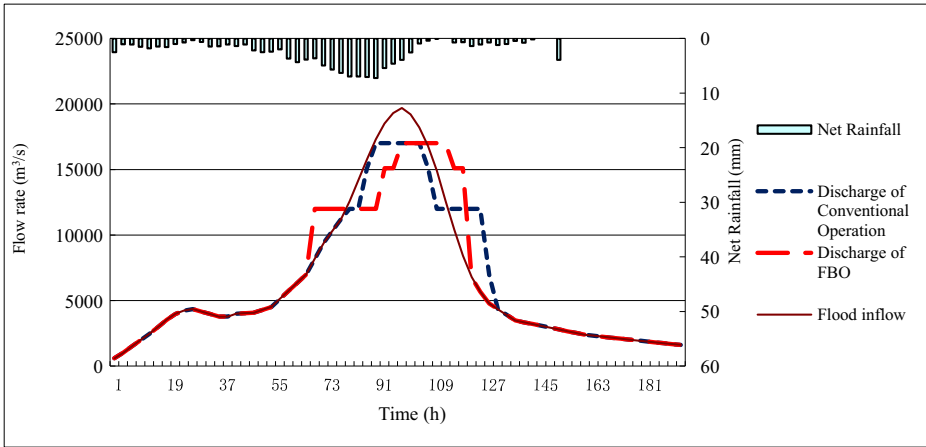


Fig. 11 Comparison of discharge between FBO and conventional operation for flood “19680910”

### 4 Discussion

According to the instance analysis and verification above, it is not difficult to find several advantages to adopting FBO mode for reservoir flood control. With ideal net rainfall forecast information accuracy for the Ankang Reservoir watershed, the application of FBO has great advantages. Sun et al. (2015) put forward a pre-storage and pre-discharge operation model and the real-time dynamic control scheme for Mianhuatan Reservoir based on the limited water level in 2010. Yang et al. (2015) proposed the dispatching rules of Huanren reservoir coupling of flood and 24 h precipitation forecasting information. It indicates that the FBO rules formulation is crucial for forecast flood control and the key is the indicators selection. However, there is no fixed model for the floods characteristics in the upper reaches of the reservoir and hydrological forecasting system.

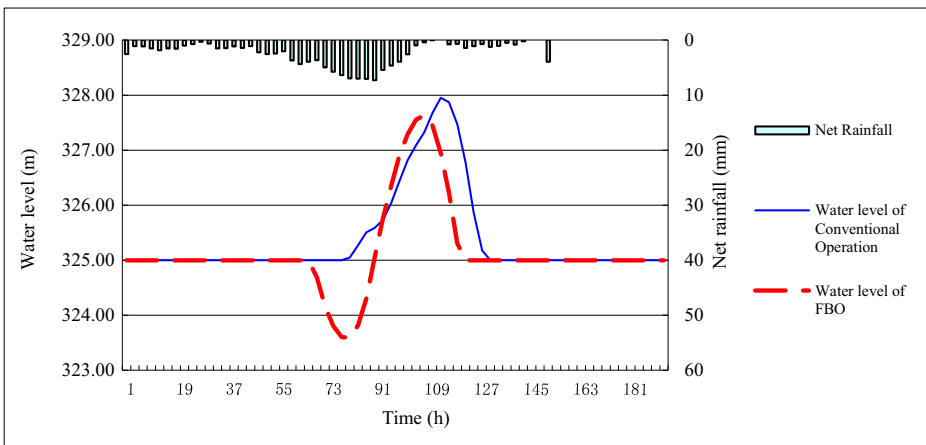


Fig. 12 Comparison of water level between FBO and conventional operation for flood “19680910”



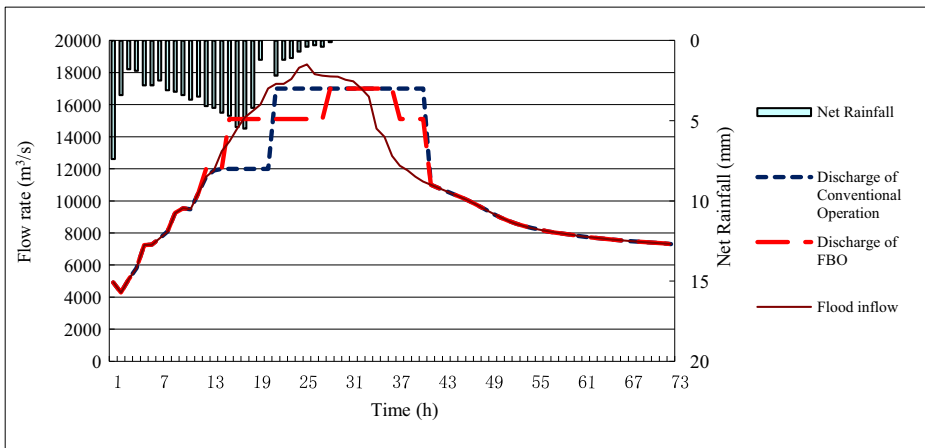


Fig. 13 Comparison of discharge between FBO and conventional operation for flood “20110918”

Hence, it is necessary to clarify that the FBO rules formulated above are based on rainfall and net rainfall derived here, which are assumed to be distributed evenly on the whole watershed. The spatial pattern of rainfall and flood distribution have only a little impact on the reservoir flood regulation in this case for a middle or small catchment. However, for a larger catchment, the spatial pattern of floods or rainfall distribution should not be neglected. This is especially true when partial rainfall and a resulting regional flood happen on a partial catchment. In fact, from the viewpoint of forecast-based flood regulation, the key problem is the difference of the lead time for forecast regional and whole-valley floods.

The lead time refers to the time interval between the publication of a valid forecast and the occurrence of the event. Net rainfall is a quantity of water in a time interval that translates into runoff in the form of reservoir inflow in the forthcoming time interval. Therefore, the flood inflow lead time for Ankang Reservoir is actually the time needed for runoff yield and concentration. As one of important lead time factors, the flood concentration time in a river

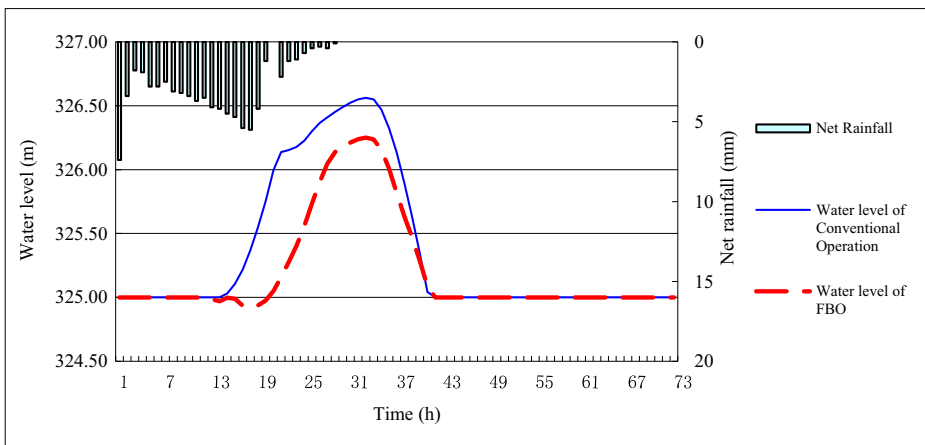


Fig. 14 Comparison of water level between FBO and conventional operation for flood “20110918”

might have some impact on forecast based flood regulation considering the regional pattern of rainstorms. According to the analysis of flood spatial patterns, the runoff concentration time is definitely influenced by the distribution of regional rainfall patterns. The flood concentration time is approximately the time lag of the peak flood inflow with respect to the corresponding peak rainfall. As the most common pattern, the concentration for a whole-valley flood is relative slow. The time needed for concentration ranges from 5 to 8 h when the flood flow rate is in the range of 5000 m<sup>3</sup>/s to 20,000 m<sup>3</sup>/s, and it fluctuates a little bit widely. Flood “19680910” is a typical whole-valley flood that grew on September 9th, 1968 for example.

In addition to the whole-valley flood, there are still two other patterns of regional floods for the Ankang Reservoir catchment: the upstream and interval floods. The upstream flood pattern refers mainly to a flood caused by a rainstorm on the upstream catchment of the Shiquan hydropower station. For instance, flood “19,830,731” starting on July 31, 1983, and took a little bit longer for concentration. Based on the analysis of historical floods and the corresponding inflow forecast, it takes approximately 5–6.5 h for a flood wave to propagate from the upstream Shiquan Reservoir to Ankang Reservoir. The interval flood pattern refers to flood inflow caused mainly by a storm on the interval catchment between Shiquan and Ankang Reservoirs. For instance, flood “19,740,911” starting on September 11, 1974, took less time for flood concentration than the upstream pattern flood. Generally, approximately 2.6–6.5 h are needed for an interval flood peak to reach Ankang Reservoir after the peak rainfall emergence.

Generally, duo to the concentration time difference, the lead time between different flood patterns is not so remarkable. It has been demonstrated that the rules formulated in this paper still work for upstream and interval pattern floods, although they were derived by simulation according to regulation of a whole-valley flood.

## 5 Conclusions

On the premise of available precipitation and flood forecasting information with enough accuracy, forecast-based reservoir flood operation presents obvious advantages not only for flood control but also flood water utilization. There are two expected potential benefits: 1. The flood control risks could be reduced by pre-releasing storage or decreasing the maximum water level during flood regulation; 2. Extra water resources can be used or acquired by enhancing the water supply before flood peak arrival, or increasing hydro power plant output in advance.

Based on the forecast information precision, statistical regularity and distribution, and appropriate indicators for the operation rules, etc., the FBO rules were formulated by trial simulation and corrected repeatedly according to “the stepwise regulation method” for Ankang Reservoir forecast-based flood regulation, in which “the cumulative net rainfall” was the primary indicator and the water level was the auxiliary indicator. According to the rules, the designed floods with different return periods and several typical flood processes were regulated for verification. The results show that FBO mode performs better for both water resource utilization and flood control. The main results are as follows:

- (1) For investigating the precision and availability of forecast indicators, a hypothesis test was conducted using  $\chi^2$  testing based on the actual flood processes and forecasted net rain of Ankang Reservoir. The results show that the flood forecasting system is reliable and the net rain forecast error in 3 h complies with the normal distribution of  $N(0.019,$

- 0.188<sup>2</sup>). The Ankang Reservoir hydrological monitoring and forecasting system is proven in good condition with higher precision for the net rain forecast.
- (2) According to Ankang Reservoir conditions, the FBO rules with dual indicators were formulated in which cumulative net rainfall was the main indicator and water level was the auxiliary indicator. The application of the rules demonstrates their feasibility and superiority: for the typical flood “19680910”, more than 112.5 million m<sup>3</sup> of extra water resources can be used by enhancing water supply or increasing hydro power plant output by implementing FBO mode. Moreover, the maximum reservoir discharge is the same as for conventional operation. The maximum discharge duration is reduced from 30 to 21 h. The maximum reservoir water level can be cut down 0.14 mm more than for the conventional operation. For the actual flood “20110918”, more than 16.2 million m<sup>3</sup> of extra water resources can be used with FBO mode by enhancing the water supply or increasing hydro power plant output. Moreover, the maximum reservoir discharge is the same as for conventional operation, and the duration is reduced from 60 to 27 h. The maximum reservoir water level can be cut down 0.31 m more than the conventional operation level.
  - (3) Considering the time differences of runoff yield and concentration, which are thought to be important factors influencing forecast lead time, the different spatial patterns of flood and rainfall distribution were discussed for the Ankang Reservoir drainage area. The results show that there are only limited effects on reservoir flood control, and the formulated FBO rules are practicable for floods with different spatial patterns.

**Acknowledgements** The authors acknowledge the financial supported by the Fundamental Research Funds for the Central Universities, CHD (Program No. 300102299206, 300102269201), the Shaanxi Provincial Department of Water Resources Technology Planning Project (2018SLKJ-10) and the Xi’an Construction Science and Technology Planning Project (SJW2017–11).

## Compliance with Ethical Standards

**Conflict of Interest** None.

## References

- Aboutalebi M, Olea BH, Loaiciga HA (2015) Optimal monthly reservoir operation rules for hydropower generation derived with SVR-NSGAI. *J Water Resour Plan Manag*:04015029. [https://doi.org/10.1061/\(asce\)wr.1943-5452.0000553](https://doi.org/10.1061/(asce)wr.1943-5452.0000553)
- Ahmad A, El-Shafie A, Razali SFM et al (2014) Reservoir optimization in water resources: a review. *Water Resour Manag* 28(11):3391–3405. <https://doi.org/10.1007/s11269-014-0700-5>
- Akbari M, Afshar A, Mousavi SJ (2014) Multi-objective reservoir operation under emergency condition: Abbaspour reservoir case study with non-functional spillways. *J Flood Risk Manag* 7(4):374–384. <https://doi.org/10.1111/jfr3.12061>
- Bowles DS, Mathias JD, Chauhan SS et al (2004) Reservoir release forecast model for flood operation of the folsom project including pre-releases. Proceedings of the 2004 USSD Annual Lecture, St. Louis
- Chang JX, GUO AJ, WANG YM, HA YP et al (2019) Reservoir operations to mitigate drought effects with a hedging policy triggered by the drought prevention limiting water level. *Water Resour Res* 55(2):904–922. <https://doi.org/10.1029/2017WR022090>
- Chen J, Zhong PA, Wang ML et al (2018) A risk-based model for real-time flood control operation of a cascade reservoir system under emergency conditions. *Water* 10(2):167. <https://doi.org/10.3390/w10020167>

- Cheng CT, Chau KW (2004) Flood control management system for reservoirs. *Environ Model Softw* 19(12): 1141–1150. <https://doi.org/10.1016/j.envsoft.2003.12.004>
- Diao YF, Wang BD, Liu J (2007) Study on distribution of flood forecasting errors by the method based on maximum entropy. *J Hydraul Eng* 38(5):591–595. [https://doi.org/10.1016/S1872-2032\(07\)60018-3](https://doi.org/10.1016/S1872-2032(07)60018-3)
- Dong SH, Zhao YK, Lin YH (2013) Risk analysis on downstream of a reservoir when the flood control forecast operation method is used - an example of Shenwo reservoir. *Appl Mech Mater* 368-370:261–264. <https://doi.org/10.4028/www.scientific.net/AMM.368-370.261>
- Engeland K, Renard B, Steinsland I et al (2010) Evaluation of statistical models for forecast errors from the HBV model. *J Hydrol* 384(1):142–155. <https://doi.org/10.1016/j.jhydrol.2010.01.018>
- Feldman AD (1994) Assessment of forecast technology for flood control operation. *Coping with floods*. [https://doi.org/10.1007/978-94-011-1098-3\\_26](https://doi.org/10.1007/978-94-011-1098-3_26)
- Herman JD (2017) Balancing flood risk and water supply in California: policy search combining short-term forecast ensembles and groundwater recharge. *Agu Fall Meeting*
- Koussis AD, Lagouvardos K, Mazi K, Kotroni V, Sitzmann D, Lang J et al (2003) Flood forecasts for urban basin with integrated hydrometeorological model. *J Hydrol Eng* 8(8):1–11. [https://doi.org/10.1061/\(ASCE\)1084-0699\(2003\)8:1\(1\)](https://doi.org/10.1061/(ASCE)1084-0699(2003)8:1(1))
- Kozel T, Starý M (2015) Stochastic forecast of flow reservoir behavior. *Proc Earth Planet Sci* 15:940–944. <https://doi.org/10.1016/j.proeps.2015.08.150>
- Krstanovic PF, Singh VP (1991a) Univariate model for long-term stream flow forecasting: I. development of. *Stoch Hydrol Hydraul* 5:173–188
- Krstanovic PF, Singh VP (1991b) Univariate model for long-term stream flow forecasting: II. Develop *Stoch Hydrol Hydraul* 5:189–205. <https://doi.org/10.1007/BF01544057>
- Li W, Guo SL, Liu P et al (2006) A reservoir dynamic flood limited water level control method based on real-time forecasting information. *Water Power* (03):8–12
- Liang G, Wang G, Wang B et al (2009) Study on forecast-based operation mode for Dahuofang inter-basin water transfer project. *J Hydroelect Eng* 28(3):32–34. <https://doi.org/10.1016/j.jacepubpol.2008.11.004>
- Liu Z, Guo Y, Wang L et al (2015) Streamflow forecast errors and their impacts on forecast-based reservoir flood control. *Water Resour Manag* 29(12):4557–4572. <https://doi.org/10.1007/s11269-015-1080-1>
- Min Y (2013) Spatiotemporal evolution of the droughts and floods over China. *Acta Phys Sin* 62(13):139203–139203. <https://doi.org/10.7498/aps.62.139203>
- Mukherjee D, Mansour N (1996) Estimation of flood forecasting errors and flow-duration joint probabilities of exceedance. *J Hydraul Eng* 122(3):130–140
- Pereira R, Batista AL, Neves LC (2018) Probabilistic model for the representation of the reservoir water level of concrete dams during normal operation periods. *Water Resour Manag* (7):1–12. <https://doi.org/10.1007/s11269-018-1973-x>
- Sun T, Dong ZC, Zhu Z et al (2015) Rainfall forecast information based-dynamic control model of flood limited water level for Mianhuatan reservoir. *Water Resour Hydropower Eng* 46(4):114–118
- Uysal G, Alvaradomontero R, Schwanenber D, Sensoy A (2018) Real-time flood control by tree-based model predictive control including forecast uncertainty: a case study reservoir in Turkey. *Water* 10(3):340. <https://doi.org/10.3390/w10030340>
- Vol N (2004) Computer simulation of flood operation in multireservoir systems. *Simul Trans Soc Model Simul Int* 80(2):101–116. <https://doi.org/10.1177/0037549704042730>
- Wasimi, Kitanidis (1983) Real-time forecasting and daily operation of a multi-reservoir system during floods by linear quadratic gaussian control. *Water Resour Res* 19(6):1511–1522. <https://doi.org/10.1029/WR019i006p01511>
- Yang JQ, Yuan JX, Peng AB (2015) Flood control forecast operation and dispatching rule establishment for Huanren reservoir in later flood season II. *Water Resour Power* 33(11):29–33
- Young PC (2002) Advances in real-time flood forecasting. *Philos Trans R Soc A Math Phys Eng Sci* 360(1796): 1433–1450. <https://doi.org/10.1098/rsta.2002.1008>
- Zhou HC, Yan JX, Wang BD (2005) Influence of flood forecast error to flood control forecast operation. *Water Resour Hydropower Northeast Chin* 23(9):30–33 (in Chinese)
- Zhou HC, Wang BD, Wang GL et al (2006) Study on a reservoir dynamic flood limited water level control method. *Dalian university of technology press* 12:118 (in Chinese)

**Affiliations**

**Xiao Wang**<sup>1</sup> · **Zhao Liu**<sup>1,2</sup> · **Weibo Zhou**<sup>3</sup> · **Zhifeng Jia**<sup>1,2</sup> · **Qiyong You**<sup>4</sup>

<sup>1</sup> School of Environmental Science and Engineering, Chang'an University, 126 Yanta Road, Xi'an 710054, People's Republic of China

<sup>2</sup> Key Laboratory of Subsurface Hydrology and Ecological Effects in Arid Region of the Ministry of Education, Chang'an University, 126 Yanta Road, Xi'an 710054, People's Republic of China

<sup>3</sup> School of Earth Science and Resources, Chang'an University, 126 Yanta Road, Xi'an 710054, People's Republic of China

<sup>4</sup> School of Science, Chang'an University, Xi'an 710064, China