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Risks Analysis and Response of Forecast-Based Operation for Ankang Reservoir Flood Control

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Abstract: With the improvement of short-term flood forecasting and short-term rainfall forecast accuracy, as well as the advance of hydrological and meteorological information collection and collation methods, the reservoir flood regulation method taking rainfall or inflow forecast into consideration is gaining more and more attention. As the index of Forecast-Based Operation (FBO), the forecasted factor plays an important part in determining success or failure of FBO due to its uncertainty and accuracy. In this study, possible risk sources were analyzed considering the process and the characteristics of reservoir flood regulation firstly, and the uncertainty of the forecast information and the FBO risks were discussed based on hypothesis testing. Then, combined with the case study of applying FBO on Ankang Reservoir, in which the forecasted net rainfall was selected as the index of the FBO rules, the probability distribution of the forecasted net rainfall errors was derived as the basis of risk analysis. Finally, FBO risk analysis was conducted based on Monte Carlo method for several real flood processes, while a simulation was also carried out with the Conventional Operation (CO) for contrast. The results indicate that the maximum risk was reduced more than half when FBO was adopted. Consequently, the possible remedial measures were put forward in the case of invalid forecast happened based on simulation and the analysis of the principle of flood regulation. The conclusions and methods in this research provide ideas for real-time flood regulation and risk management of reservoirs.

Keywords: reservoir operation; reservoir flood regulation; uncertainty analysis; risk analysis; remedies

1. Introduction

As many researchers have pointed out, climate change impacts pattern and distribution of precipitation not only regionally but also worldwide [1]. As one of the possible characteristics of climate change, the tendency of intensified variation of spatial or temporal distribution of precipitation could have a significant impact on regional hydrological system. Changes in hydrological systems associated with climate change may threaten the reliability of water resources management systems [2]. It is reported that some regions in south China could face potential long-term water scarcity threat, while both meteorological drought and heavy rainfall in a short time will tend to be aggravated and appear alternately in some areas of north China. Consequently, the surface runoff with uneven spatial or temporal distribution also poses a big challenge on water resources management [3]. Therefore, it is vital to study and formulate more adaptable operations or management methods for reservoirs and other water projects on rivers in response to the variation of water resources condition [4–6]. With an important function of regulating river flow, e.g., storing in the wet season and supplying in the dry season, reservoirs also play a crucial role in flood prevention and disaster relief [7]. Ankang Reservoir is located on the upper reaches of the Han River, the largest tributary of the Yangtze River. Generally, with a large peak flow and huge volume, the floods in the Han River present great interannual variation, and they concentrate mainly in the flood season from June to October. Modeling flood susceptibility in watersheds and reducing the damages caused by flooding is an important component of environmental and water management [8]. Traditionally, the primary targets of reservoir flood control are to cut down the flood inflow peak and guarantee the safety of downstream objectives when the flood is rising, while little consideration is given to utilization of flood water. The traditional operation rules determining how the reservoir store the flood inflow or release the storage are formulated based only on historical flood hydrographs in the planning stage of the engineering. They do not forecasted inflow or the possible flood process in the future; forecasted information is only used for reference sometimes in real-time operation, instead of included as a part of the rules. In the last decades, theories and methods related reservoir operation and flood regulation have been developed greatly. Researchers discussed global problems from different perspectives such as reservoir flood routing and corresponding risks, optimal operation and its application, etc., [9–11]. An effective reservoir optimization operation strategy should focus on the critical period when rainfall is lacking and the demand of water is not reduced [12]. Some researches pointed out that more attention should be focused on improving the operational effectiveness and efficiency of the reservoir systems for maximizing benefits on aspects of both flood control and water resources utilization [13,14]. With tangible improvement of the precipitation and inflow forecast in the past decades [15–21], more and more reservoirs tend to include hydrological forecasts in the real-time operation combined in accordance with the specific conditions of the reservoirs [22]. Reservoir flood control considering rainfall information tends to prevail for its advantages in meeting sudden increases in water requirements. In addition, machine learning (ML) methods contribute highly in the advancement of prediction systems providing better performance and cost-effective solutions [23]. However, because of the inherent uncertainty with forecast information, the risk of reservoir flood routing incorporating forecast information is bound to be discussed cautiously [24–26].

Risk theory was introduced into water resources research field in the late 1970s [27,28]. As an interdisciplinary subject with rich content, diverse approaches and complete theoretical systems, it was gradually developed [29] in the following years. As an important impact factor, the level of the risk determines the feasibility of reservoir flood regulating scheme directly. Risk measurement in the course of reservoir flood regulation is concerned all over the world in view of the possible disastrous consequences [30,31].

Because of the involving of introduced forecast uncertainties, the risk issues are of particular concern for the reservoir owner or water conservancy authority in practicing of the FBO mode; risk analyses are usually prerequisite in this case. Some scholars discussed the risks or uncertainties in reservoir flood routing in terms of risk factors, evaluation methods and so on. However, the relative problems are still far from being solved due to their complicated mechanisms; especially, the risk measurement and crisis response on forecast-based reservoir flood regulation is still subject to intensive research.

2. Materials and Methods

2.1. The Contrast of Risk Factors for Two Operation Modes

To understand the inducements of risk in reservoir flood control, it is necessary to analyze all of potential risk factors in the process of flood regulation for two different modes, CO and FBO, as shown in Figure 1 [31,32].

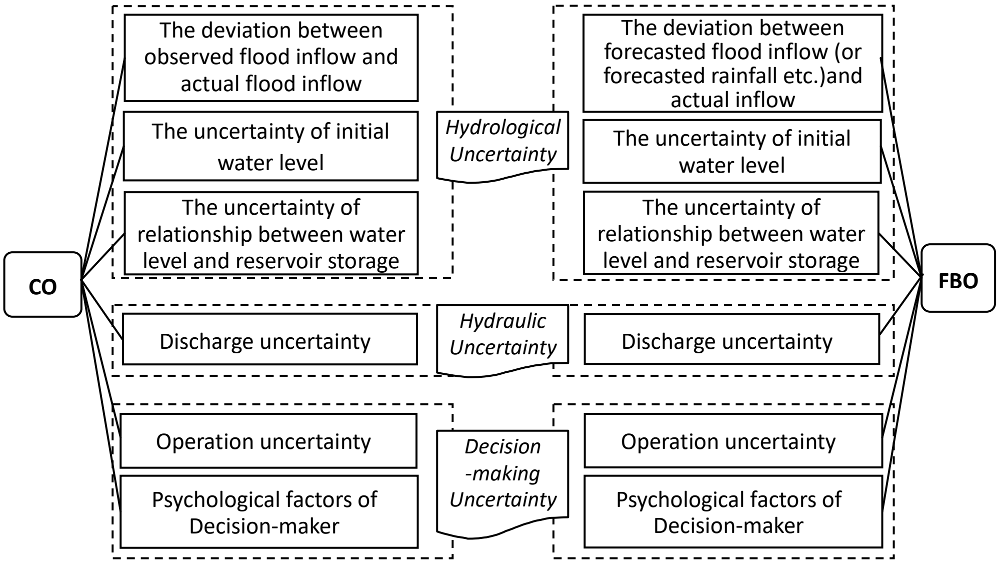

Figure 1. The potential risk factors for two flood regulation modes.

As a contrast for the two modes, it is clear that all other risk factors are the same except the first item listed in hydrological uncertainty category, as shown in Figure 1. The only difference in uncertainty, e.g., the source of the risk, determines how different the risk will be for the two operation modes. The biggest difference for the two operation modes is undoubtedly that there are no forecasting errors for CO because no forecast information is involved, while the FBO is based on the forecast flood inflow or other forecasted factors in a certain period of the future. However, the risk of FBO does not necessarily exceed the risk of CO. We first performed a qualitative analysis. The uncertainty in the forecasted information actually refers to the errors of the forecasted series, which can be defined as the deviation of the forecasted value to the actual value. Although there are no forecasting errors in CO, it cannot be ignored that the observed flood inflow is not completely accurate yet; there are still errors between the observed or measured inflow and its actual value. This mainly lies in:

- The flood inflow is actually an instantaneous value, which changes from time to time, thus it is difficult to measure along with the rise and the drop of the flood wave. Even if it can be calculated as the average inflow in a certain period of time, there are still deviations. In practice, the flood inflow is usually estimated according to the observation of the adjacent upstream hydrometric station, or the change of water level in the period by back calculation. Therefore, the so-called "observed inflow" is actually an estimated value, which largely based on the upstream river flow and the experience of dispatcher; the value, in fact, has a large deviation sometimes from "the true inflow".
- What is "inflow"? Where is the cross section once the stream flow passes? Can it be thought of as in the reservoir? All these concepts are actually vague. In view of dynamic change of the water surface curve under different storage conditions of reservoirs and the impact of different flood waves, there is no a constant cross section to define "inflow" and the inflow itself is a concept with fuzzy characteristics, which cannot be accurately determined.
- The flood wave and real-time inflow are under the effects of boundary conditions. Even if the dynamic change of storage capacity is considered, it is not possible to fully describe the inflow process and its effects. Although they theoretically comply with the Saint-Venant equations for the unsteady flow, they are difficult to solve due to various complicated conditions. Conversely, even if the flood flow is the same, for different water levels or different operation stages of the reservoir, the evolution and the hydraulic effects of the flood wave in the reservoir are different.

From the analysis above, we can conclude that the so-called "observed inflow" is actually not perfect, and the error which refers to its deviation to the "real inflow" is inevitable and could be significant.

2.2. The Main Risk Sources and Factors

As shown in Figure 1, the many factors fal into three categories in the real-time flood regulation. It is practically impossible to carry out the risk analysis including all of those factors with different nature at the same time. In fact, there is compatibility to some extent between different risk factors; some factors influence decisions making only indirectly, they are not the main aspects and may be related to or implicated in other main risk factors [32]. Some studies have pointed out that the uncertainty of the flood inflow is the most significant uncertainty, as is the forecasted inflow, while the other uncertain factors are relatively stable [33–35]. For instance, hydraulic uncertainty is basically determined by the hydraulic principles of the orifice outflow or weir flow; although there is definitely a difference between the calculated value and the actual value, the difference is relatively stable under a certain head. Therefore, as the most significant risk source, the hydrological uncertainty should be considered as the significant risk source; consequently, the uncertainty of flood inflow or its forecasted value were considered as the main risk factors in this study.

2.3. Forecasted Accuracy and Flood Regulation Risk

As analyzed above, the inflow uncertainty is the most important risk factor for reservoir flood routing, no matter what mode is adopted. Therefore, for assessing the flood regulation risk, to figure out the cognitive deviation toward the flood inflow could be the primary task for reservoir operator.

2.3.1. The Distribution and Evaluation of Forecast Error

There are many kinds of distribution laws for describing the errors of forecasted flood flow, such as normal distribution, log-normal distribution, logarithmic distribution, Pearson distribution, etc. Hypothesis testing is usually adopted to determine the distribution of the error for given forecasted series, and the error of the forecasted series is from the historical forecast results. Assuming the kind of overall distribution, then the hypothesis is established as true or false according to the sample test. This study used the χ^2 method to test.

Let X_1, X_2, ..., X_n be the given sample, assuming:

H_0: The density function of overall X is $f(x)$, the corresponding distribution function is $F(x)$.

For example, for a normal distribution $N(\mu, \sigma^2)$, use the following formulas:

$$\mu = \overline{x} \tag{1}$$

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n} (x_i - \overline{x})^2 \tag{2}$$

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \tag{3}$$

$$F(x) = \int_{-\infty}^{x} f(x)dx \tag{4}$$

Take $k-1$ points $t_1 < t_2 < \ldots < t_{k-1}$ on the real axis and divide the real axis into k intervals $(-\infty, t_1]$, $(t_1, t_2] \ldots (t_{k-1}, +\infty)$.

Suppose the number of samples in the first interval is $f_i (1 \le i \le k)$, the frequency is f_i/n, i = 1,2, ..., k.

Note t_0 is $-\infty$, t_k is $+\infty$.

If the null hypothesis holds, then the probability of X falling into the first interval can be calculated by the formula:

$$p_i = F(t_i) - F(t_{i-1}), i = 1, 2, \ldots, k. \quad (5)$$

When the null hypothesis is true and the number of tests is very large, according to law of large numbers, $\left|\frac{f_i}{n} - p_i\right|$ should not be very large, so that

$$\sum_{i=1}^{k} \left(\frac{f_i}{n} - p_i\right)^2 \frac{n}{p_i} = \sum_{i=1}^{k} \frac{(f_i - np_i)^2}{np_i} \quad (6)$$

should also be relatively small. Based on this, Pearson used

$$\chi^2 = \sum_{i=1}^{k} \frac{(f_i - np_i)^2}{np_i} \quad (7)$$

as a statistic to test H_0.

If n is sufficiently large ($n \geq 50$) and the null hypothesis H_0 is true, the statistics always approximately obey the χ^2 distribution, and the degree of freedom is $k-r-1$, r is the number of parameters to be estimated.

For a given significance level α, the critical value $\chi^2_{1-\alpha}(k-r-1)$ can be found from the schedule, and the specific value of χ^2 can be calculated from the sample. When $\chi^2 \geq \chi^2_{1-\alpha}(k-r-1)$, the hypothesis H_0 is rejected, otherwise H_0 is accepted.

2.3.2. Flood Regulation Risk Based on Monte-Carlo

There are some traditional methods in assessing the risks in reservoir flood routing such as typical probability distribution function method, limit state method, first-order second-moment method, JC method (Equivalent Normalization method, a method used by the Joint Commission on International Structural Safety (JCSS) to convert non-normal random variables into normal variables, also called JC method.), Markov process method, etc. Some of these methods require strict mathematical derivation or model, while others need to determine some sensitive parameters, hence the reliability and rationality are restricted to some extent. Due to the complicated influence mechanism in the forecast-based flood regulation, objectively, it is not easy to accurately estimate and determine the distribution patterns and parameters of all the risk factors. Stochastic simulation risk analysis method presents its unique advantages in dealing with complicated multi-factors risk analysis problems such as the forecast-based reservoir flood regulation, one of the most common methods, Monte Carlo simulation is extensively used for its clear conception and ease of use. Monte Carlo simulation was applied in this study to determine the risk of FBO mode. Firstly, an error series was produced with a random number generator based on the probability distribution of the forecast information error, and then a forecast series was constructed to later input into the simulation model. The error series was superimposed to the historical observed series, the FBO simulation model was built and the risk event was defined according to the condition of the reservoir. Inputting all the required data and simulating the historical floods in sequence, the simulation could be conducted repeatedly because the generated error sample series were different every time despite identical distribution. Finally, the risk could be figured out based on statistical analysis according to the frequency of risk events and the simulation times. The main steps for Monte-Carlo simulation are shown in Figure 2. Next, taking Ankang Reservoir as an example, based on the historical data, the Monte Carlo simulation method was mainly used to study and compare the uncertainties and risks of the two operation methods: FBO and CO.

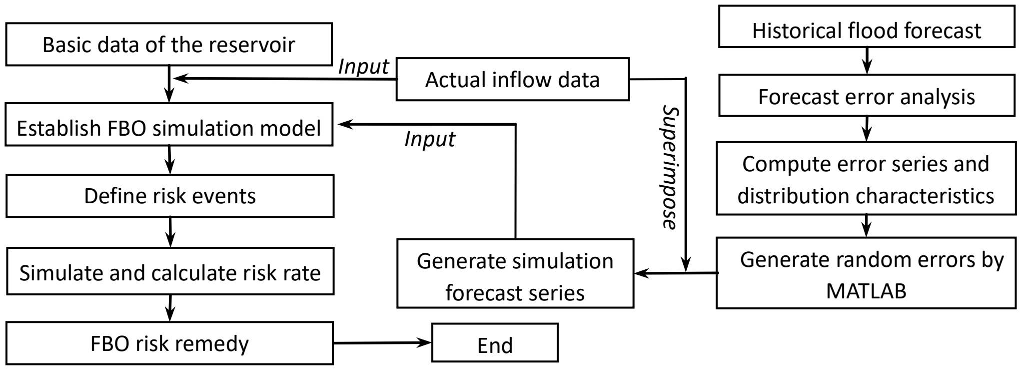

Figure 2. The risk analysis of FBO based on Monte Carlo simulation.

3. Case Study

3.1. Overview of Ankang Reservoir

Ankang Reservoir is located in the upper reaches of the Han River as shown in Figure 3, and the control catchment area is 35,700 km^2. Ankang Reservoir is a large-scale water project with multiple purposes such as electricity generation, flood control, water supply, shipping and other comprehensive utilization. The reservoir is an incomplete annual regulation reservoir with a total capacity of 3.2 billion m^3 and a maximum flood storage capacity of 980 million m^3. The dead water level of the reservoir is 305 m, the normal water level is 330 m, the limit water level in flood season is 325 m, the design flood level is 333 m and the maximum flood level is 337.33 m. The climate in the upper reaches of the Han River is a subtropical humid climate with relatively abundant water resources. The rainfall in the flood season, i.e., July, August and September, accounts for about 50% of the yearly total in the basin. The average annual runoff is approximately 26 billion m^3. The annual runoff distribution is 75–80% in summer and autumn, 10–15% in spring and only about 5% in winter. The largest flood peak usually appears in July or September.

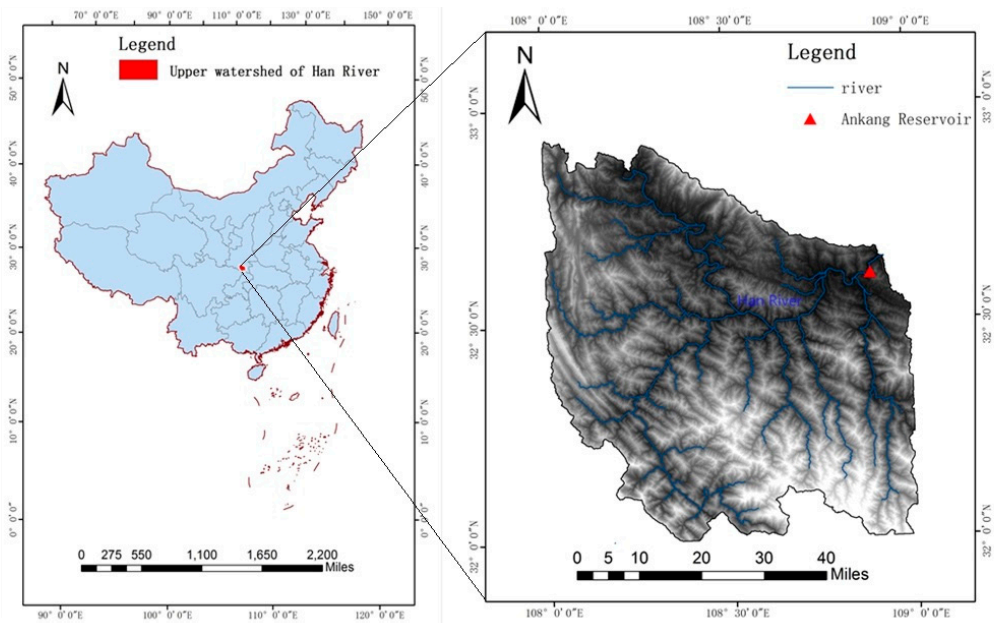

Figure 3. The location of Ankang Reservoir.

3.2. The Formulated FBO Rules for Ankang Reservoir

For a rainfall–runoff process, the net rainfall during a given period of time over the drainage area is consequently transformed into flood inflow of the downstream reservoir in the corresponding time;

the overall net rainfall is thought of quantitatively equivalent to the runoff depth on the drainage basin. As a critical factor for carrying out FBO, the net rainfall was adopted as the indicator of the operation rules for Ankang Reservoir in this research.

Currently, Ankang Reservoir employs routine operation rules in regulating flood, which were formulated in the design phase of the reservoir and take the real-time water level and flood inflow as indicators of rules to determine the discharge; no forecasted indicator is involved, as shown in Table 1. The flood regulation starts when the water level is beyond the limit water level (325.0 m). The conventional operation rules lack flexibility for regulating different types of floods under unpredictable weather and changing flood patterns. Although the flood forecast information is referenced in the real-time operation, it is used only qualitatively and empirically, lacking a theoretical basis. This is still not FBO because no forecasted indicators are involved in the operation rules. With the improvement of flood forecast system of the reservoir, it is high time to push reservoir operation and flood management forward.

Table 1. The Routine Operation Rules of Ankang Reservoir for CO.

Number	Inflow (m^3/s)	Water Level Z (m)	Release (m^3/s)	Notes
1	$12{,}000 < Q_{in} \leq 15{,}100$	$Z \leq 326$ $Z > 326$	$Q_{out} = 12{,}000$ $Q_{out} = Q_{in}$	Q_{in} and Q_{out} represent flood inflow and discharge
2	$15{,}100 < Q_{in} \leq 17{,}000$	$Z > 326$	$Q_{out} = Q_{in}$	$P = 10\%$, flood rising
3	$17{,}000 < Q_{in} \leq 21{,}500$	$326 < Z \leq 328$ $Z > 328$	$Q_{out} = 17{,}000$ $Q_{out} = Q_{in}$	
4	$21{,}500 < Q_{in} \leq 24{,}200$	$Z > 328$	$Q_{out} = Q_{in}$	$P = 1\%$
5	$Q_{in} > 24{,}200$		Free overflow	

Based on the accuracy of flood forecasting data, FBO rules for Ankang Reservoir flood control were formulated by using the stepwise regulation method considering the actual situation of the reservoir, as shown in Table 2.

The initial regulating water level for the FBO rules is also 325.0 m, which is the same as it for CO rules. $\sum R$ in Table 2 represents the accumulated net rainfall in the computational period, i.e. 72 h. In addition, it should be pointed out that the formulated FBO rules are only for flood in rising stage.

Table 2. Formulated FBO Rules for Ankang Reservoir.

No.	Cumulative Net Rainfall (mm)	Water Level Z (m)	Release (m^3/s)	Remarks
1	$\sum R \leq 43$		$Q_{out} = Q_{in}$	Q_{in} and Q_{out} represent flood inflow and discharge
2	$43 < \sum R \leq 55$	$Z \leq 326$ $Z > 326$	$Q_{out} = 12{,}000$ $Q_{out} = Q_{in}$	
3	$55 < \sum R \leq 62$	$Z \leq 326$ $Z > 326$	$Q_{out} = 15{,}100$ $Q_{out} = Q_{in}$	
4	$62 < \sum R \leq 79$	$Z \leq 326$ $326 < Z \leq 328$ $Z > 328$	$Q_{out} = 15{,}100$ $Q_{out} = 17{,}000$ $Q_{out} = Q_{in}$	
5	$79 < \sum R \leq 90$	$Z \leq 328$ $Z > 328$	$Q_{out} = Q_c$ $Q_{out} = Q_{in}$	
6	$\sum R > 90$		Free overflow	

3.3. Error Analysis on Forecasted Net Rainfall

There are 38 hydrological stations in the hydrological forecasting system of Ankang Reservoir, including 25 rainfall stations, 8 water level monitoring and rainfall quantity stations, and 5 repeater stations. The main functions of the system are real-time data acquisition and processing, equipment condition monitoring, voice query and alarm, data management, hydrology forecast, simulation and analysis of reservoir flood routing, etc. The system is in good condition. For understanding the forecast error and its statistic characteristics, the forecast error series were acquired according to the forecast net rain and corresponding actual runoff depth based on more than ten real flood processes in past several years. In total, 149 sample points were selected for analysis. The mean value of the calculated net rain forecast error $\overline{\Delta R_i}$= 0.019 and variance S^2= 0.187^2. Letting the random variable of the net rainfall forecast error be X, the absolute error-frequency histogram and the corresponding normal function curve were drawn (Figure 4).

It can be observed visually in Figure 4, the sample error obeyed normal distribution approximately; however, the hypothesis test was necessary to prove it.

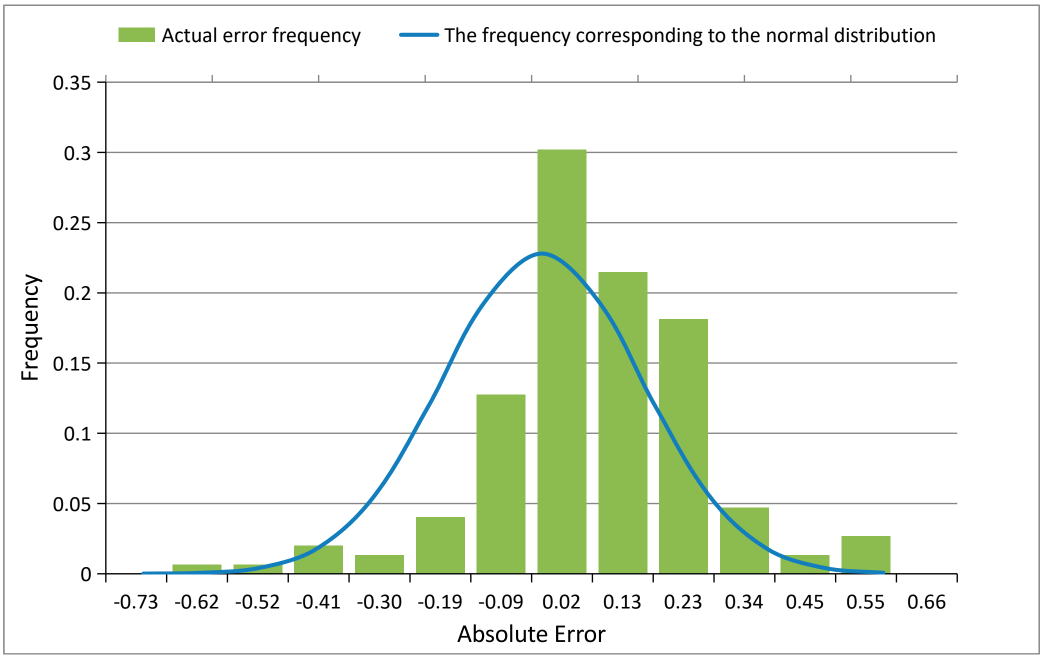

Figure 4. The absolute error frequency histogram and the corresponding normal function curve.

Hypothesis H_0: the population X obeys normal distribution $N(0.019, 0.188^2)$, the distribution function is:

$$F(x) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{x} e^{-\frac{(x-\mu)^2}{2\sigma^3}}dx \tag{8}$$

where $\mu = \overline{X} = 0.019$, $\sigma = S^* = 0.188$.

Based on statistics, χ^2 distribution can be applied for hypothesis test. If the X is divided into five intervals, then use the equation

$$\chi^2 = \sum_{i=1}^{5}\frac{(f_i - n\cdot p_i)^2}{n\cdot p_i} \tag{9}$$

to calculate the value of χ^2 is 4.1926.

Take $\alpha = 0.05$, then the degree of freedom is: $k - r - 1 = 5 - 2 - 1 = 2$.

The critical value $\chi^2 = 4.1926$ is less than $\chi_{1-\alpha}{}^2(2) = 5.9915$, so the hypothesis H_0 is accepted, the forecast error of the net rainfall obeys $N(\mu, \sigma^2)$, where $\mu = \overline{X} = 0.019$, $\sigma = S^* = 0.188$.

Based on the distribution of the absolute error of forecasted net rainfall derived above, $X \sim N(0.019, 0.188^2)$, the specific value of the forecast net rain at different frequencies can be calculated in term of the formula

$$P(\Delta R > \Delta R_i) = 1 - \Phi(\frac{\Delta R - \mu}{\sigma}) \tag{10}$$

which could be achieved using the function X = NORMINV (P, MU, SIGMA) in MATLAB software, as shown in Table 3.

Table 3. Absolute error and corresponding frequency of the forecasted net rain.

Frequency *P* (%)	0.01	0.1	1	5	10	20
The Absolute Error of the Net Rain Δ*R* (mm)	0.7182	0.6	0.4564	0.3282	0.2599	0.1772

3.4. Risk Analysis of Ankang Reservoir Forecast-Based Operation

Before carrying out the risk analysis on FBO, the risk of the conventional operation could also be estimated. Because there is actually no way to determine the authentic error of observed inflow, the error can be approximated as the difference between the average inflow in a time interval and the instantaneous observed value. The errors series could be obtained according to the great number of real operation processes in the past. When the inflow rate was higher than 3000 m^3/s, the distribution of the error was estimated and complied with the normal distribution: $Y \sim N(189.32, 775.81^2)$.

For risk analysis with Monte Carlo method, firstly, a series of random numbers are generated according to the distribution Y, which is considered the error series of the flood inflow. Then, the series are superposed on the typical flood hydrograph with a specific return periods, for example 20-year flood, so that a new flood hydrograph is generated. Thousands of floods for flood routing simulating can be generated in this way, as can floods with different return periods. During simulations, the generated flood hydrograph was used only for decision making, i.e., determining the discharge according to the rules of CO; it did not participate in the calculation. The storage was determined by the typical flood process in each simulation. The initial water level was set as 325 m, and, for a given return period of flood, the number of simulations was set as 10,000 times. Investigating the maximum water level $Z_{a\text{-}max}$ and the maximum discharge $Q_{a\text{-}max}$ in the simulations, if any of them went beyond the corresponding permissible value $Z_{a\text{-}max}$ and $Q_{a\text{-}max}$ as shown in Table 4, then the risk events were triggered.

Table 4. The risk estimation results on CO for floods with different return periods.

Return Period (year)	**Z_{a_max}(m)**	**Q_{a_max} (m^3/s)**	**Simulation Times**	**Counts (Z > Z_{a_max} or Q > Q_{a_max})**	**Frequency *P* (%)**	**Risk Rate Ψ (%)**
10,000	337.05	——	10,000	0	0	0
1000	333.1	——	10,000	0	0	0
100	330.0	——	10,000	0	0	0
20	328.6	17,000	10,000	5	0.05	0.0025
5	326.7	12,000	10,000	54	0.54	0.108

According to the results in Table 4, there was no operation risk for the floods with return period more than 100 years in consideration of inflow uncertainty. This indicates that the maximum water level and discharge were more sensitive to frequent flood. The risk for 20-year flood was about 0.0025%, while for five-year flood was the highest (0.108%). Actually, the maximum water level and discharge should not go beyond 326.7 m and 12,000 m^3/s, respectively, according to flood control requirements. Figure 5 shows that, for maximum discharges in the 10,000 simulations for five-year flood, 46 points in the graph exceed the permissible value 12,000 m^3/s, and eight overtop the permissible water level Z_{a_max}, totaling 54 risk events out of 10,000 simulations, as shown in Table 4.

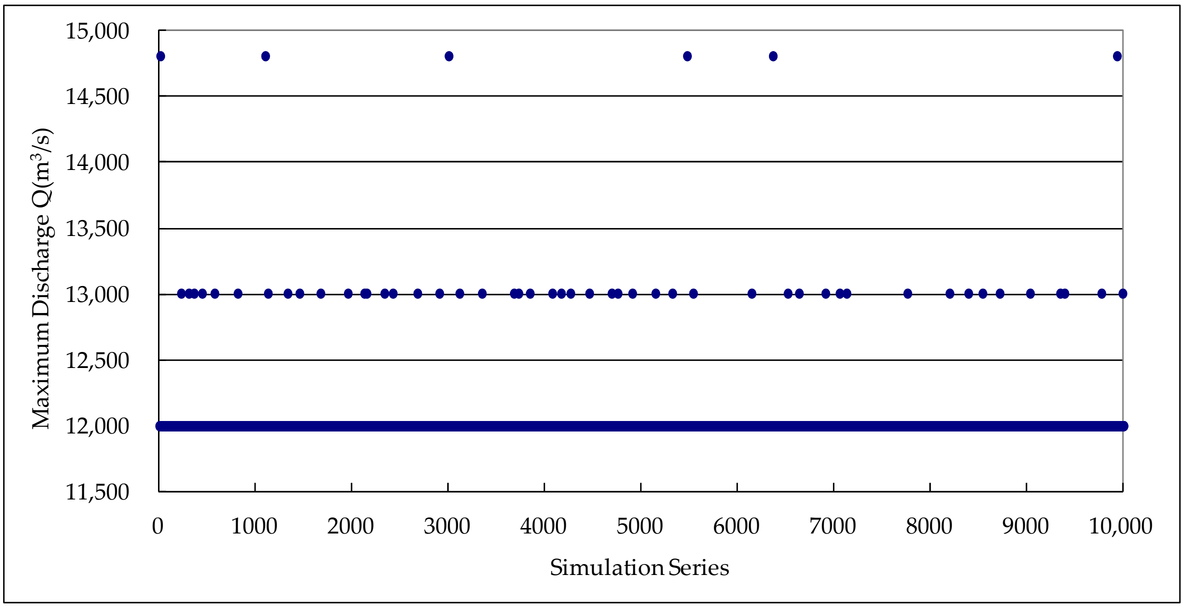

Figure 5. Maximum discharge distribution in 10,000 simulations for five-year flood based on CO.

For the operation risk of FBO, the analysis method is similar. The error series were generated according to the distribution $X \sim N(0.019, 0.188^2)$. Then, they were superposed on the net rainfall series, which was inversely derived from the flood inflow series, to create a forecasted net rainfall series. This procedure was performed 10,000 times. In the flood routing simulations of FBO, the release of the reservoir was determined according to FBO rules, while the reservoir storage and corresponding water level were still computed using the actual flood inflow based on the balance equation of water quantity. The definition of risk event and the initial water level, Z_{a_max} and Q_{a_max}, were the same as CO while conducting simulations for floods with different return periods. The results are listed in Table 5.

Table 5. The risk estimation results for FBO for floods with different return periods.

Return Period (year)	Z_{a_max}(m)	Q_{a_max} (m^3/s)	Simulation Times	Counts ($Z > Z_{a\_max}$ or $Q > Q_{a\_max}$)	Frequency P (%)	Risk Rate Ψ (%)
10,000	337.05	——	10,000	0	0	0
1000	333.1	——	10,000	0	0	0
100	330.0	——	10,000	0	0	0
20	328.6	17,000	10,000	1	0.01	0.0005
5	326.7	12,000	10,000	22	0.22	0.044

As shown in Table 5, there was still no risk for 100-year, 1000-year and 10,000-year floods, while the risk of five-year flood was the highest (0.044%) and the risk of 20-year flood was 0.0005%. This indicates that the flood forecast system has enough accuracy for flood regulation in practice. Under the current accuracy situation, the forecasted net rainfall error has limited effects on reservoir flood routing; FBO could be better than CO for lowering flood regulation risk.

Taking the five-year flood as an example, the simulation results show that the water level does not exceed the maximum allowable water level Z_{a_max} at all, and in only 22 out of 10,000 does the maximum discharge overtop the permissible value of 12,000 m^3/s, as shown in Figure 6.

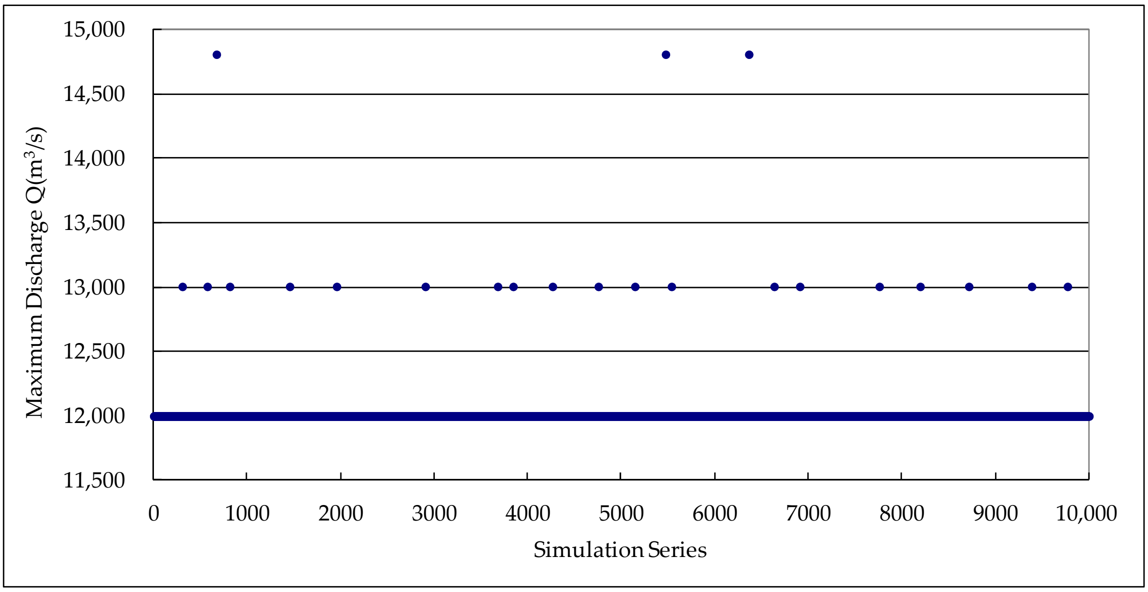

Figure 6. Maximum release in 10,000 simulations for five-year flood (P = 20%) based on FBO.

It is apparent that the operational uncertainties of small floods are higher than those of big floods according to Table 5. There are two reasons to explain this. On the one hand, the release of the reservoir would reach the stage of free overflow for big floods, which could counteract the uncertainty caused by the forecasted errors to some extent, while the uncertainty for small flood easily emerges because it is more sensitive to inflow or forecast errors in the confined stage of release rules, as shown for Nos. 1–5 in Table 2. On the other hand, as FBO takes the forecasted net rainfall as the indicator, the forecast errors are corrected continually in the later operation process, and the impact of the forecasted net rainfall errors are more evident on small floods than big floods.

According to the Monte Carlo simulation on the two operation modes, for the 20-year flood, the possible risk rate is 0.0025% when CO is adopted, while it is 0.0005% when FBO is adopted. For the five-year flood, the possible risk rate for CO is 0.108%, and 0.044% for FBO. These indicate that the possible maximum risk of FBO reduces by more than half the maximum risk of CO.

3.5. Preliminary Probing on the Remedies of Significant Forecast Error

Although the risk of FBO is preferable, it is necessary to make emergency plans to respond to the significant forecast error events. It is believed that there is no unified model or remedial measure for various situations because of the complexity and uncertainty of the hydrological process. Here, some basic ideas are put forward conceptually for discussion.

The basic ideas on remedies of significant forecast bias in FBO are adjusting discharge in time according to error pattern. The relative errors of forecasted net rainfall can be classified into two categories generally: false-negative (insufficient) and false-positive (excessive). Negative forecast errors mean that the forecasted value is less than the actual value and positive forecast errors imply that the forecasted value is larger than the actual value.

Figure 7 shows the process of the discharge changing with time and compares the single-step operation and multi-step operation. Figure 7 illustrates a remedial measure for risk reduction in the case of negative forecast error occurrence in FBO. The situation could be analogized for the positive forecast error. Suppose that the negative forecast error occurred at Point A in Figure 7 at 63 h. Because the release determined by the FBO rules is relatively low, the water level would rise unreasonably in subsequent flood routing as Point B presents potential risk occurrence point. Therefore, some remedial measures must be taken immediately. The risk can be reduced by discharge adjustment according to the error categories. Generally, an enlarged discharge is expected for adjusting the negative forecast errors. Theoretically, there are two types of risk reduction techniques: single-step operation and multi-step operation. The single-step risk reduction operation refers to the discharge adjustment being adopted all at once and instantly after the forecast error occurred (at Point C in Figure 7), and then flood regulation mode will return to CO mode (at Point D in Figure 7). The strategy for the single-step operation can be formulated beforehand for the false forecast with specific frequency (which can be set to 5%, 1%, 0.5%, etc.) under premise of different flood magnitude. Single-step operation cannot suffice because the outflow can sometimes have a great jump. The multi-step risk reduction technique is preferred in this case, which adjusts the outflow gradually based on the correctional forecast and allows FBO mode to be maintained, as shown in Figure 7, where the gray shaded area indicates the lead time of the rolling forecast in the real-time flood control.

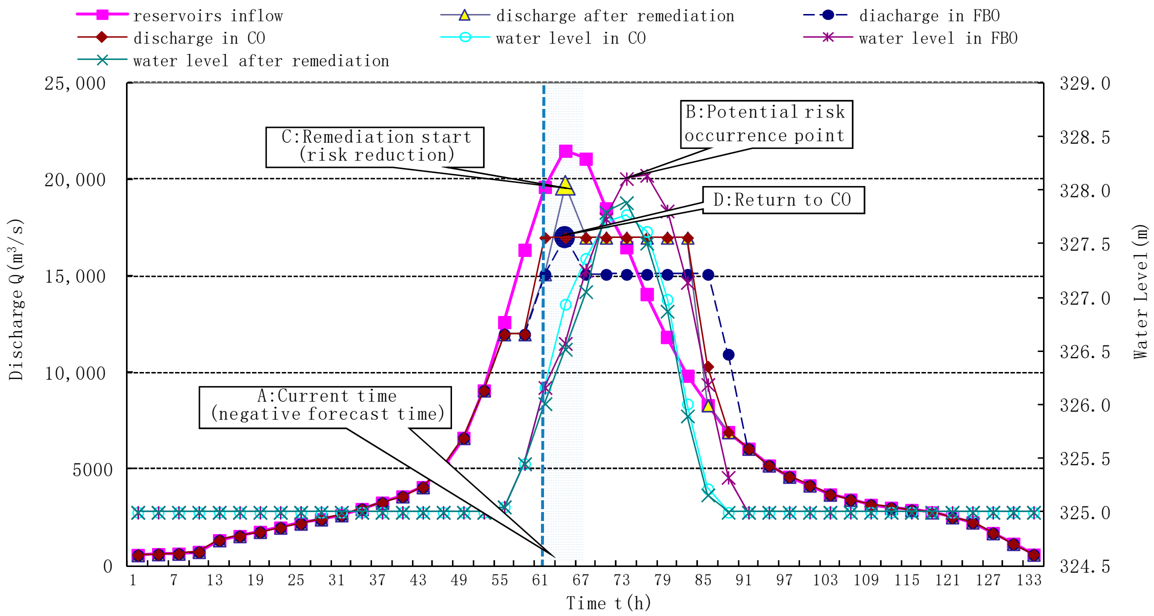

Figure 7. Schematic diagram of flood regulation risk reduction for significant forecast error in FBO.

4. Conclusions

Based on the flood forecasting information with preferable accuracy, reservoirs would benefit more from FBO mode by both obtaining more water resources for irrigation, water supply and hydropower, and reducing the flood risks in the flood regulation. Thanks to the reliable flood inflow forecast information, all of these merits could be achieved by storing or releasing in advance. A case study of FBO on Ankang Reservoir was carried out to illustrate the accuracy of the forecasted net rainfall and its application in FBO. The risk levels of FBO and CO were analyzed and compared in terms of flood with different return periods. The main conclusions of this research are as follows:

(1) Qualitative analysis showed that, among different types of uncertainties, the hydrological uncertainty should be considered as the significant risk source in reservoir flood control. Therefore, the forecast factor accuracy and its availability are crucial to determine the feasibility of FBO. As an illustration, the distribution of forecasted net rainfall errors for the Ankang hydrological monitoring and forecasting system obeyed approximately normal distribution $N(0.019, 0.188^2)$ based on the hypothesis test.

(2) The Monte Carlo simulation is more appropriate for risk evaluation of FBO in view of its multiple factors and complexity. In contrast to CO, there are obvious advantages for FBO in risk control during real time flood regulation: for 20-year floods, the possible risk rate was reduced to approximately a quarter of CO. For five-year floods, the possible risk rate was reduced by more than half of CO.

(3) The risk remedial measures for FBO were discussed conceptually. The basic assumption on remedies of significant forecast bias in FBO was put forward according to the different

classifications of the forecast errors, false-negative and false-positive. Theoretically, there are two types of risk reduction techniques: single-step operation and multi-step operation. Taking the single-step risk reduction as an example, the main idea of the technique is presented with a schematic diagram, while, in view of the complexity of this problem, especially the intrinsic uncertainties in hydrologic process and forecast products, we believe that it is hard to find a quantitative and fixed model for various situations. All of these issues are subject to further study.

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References

1. Vechpanich, E.; Ruangrassamee, P.; Putthividhya, A.; Tanaka, K. Applications of Land Surface Model to Assess Impacts of Climate Change of Rainfall Pattern and Surface Runoff in the Chao Phraya River Basin of Thailand. In Proceedings of the World Environmental & Water Resources Congress, Austin, TX, USA, 17 May 2015.
2. Etkin, D. Utilizing Seasonal Forecasts to Improve Reservoir Operations in the Comoe River Basin. Ph.D. Thesis, Tufts University, Medford, MA, USA, 2009.
3. Mo, C.; Mo, G.; Peng, L.; Zhong, H.; Wang, D.; Huang, Y.; Jin, J. Reservoir operation by staging due to climate variability. *Hydrol. Sci. J./J. Des. Sci. Hydrol.* **2018**, *63*, 1–12. [CrossRef]
4. Karami, H.; Mousavi, S.F.; Farzin, S.; Ehteram, M.; Singh, V.P.; Kisi, O. Improved Krill Algorithm for Reservoir Operation. *Water Resour. Manag.* **2018**, *32*, 3353–3372. [CrossRef]
5. Ehteram, M.; Mousavi, S.F.; Karami, H.; Farzin, S.; Singh, V.P.; Chau, K.W.; El-Shafie, A. Reservoir operation based on evolutionary algorithms and multi-criteria decision-making under climate change and uncertainty. *J. Hydroinform.* **2018**, *20*, jh2018094. [CrossRef]
6. Nohara, D.; Hori, T.; Sato, Y. Real-Time Reservoir Operation for Drought Management Considering Operational Ensemble Predictions of Precipitation in Japan. *Adv. Hydroinform.* **2018**. [CrossRef]
7. Guo, S.; Zhang, H.; Chen, H.; Peng, D.; Liu, P.; Pang, B.O. A reservoir flood forecasting and control system for China. *Hydrol. Sci. J.* **2004**, *49*, 972. [CrossRef]
8. Choubin, B.; Moradi, E.; Golshan, M.; Adamowski, J.; Sajedi-Hosseini, F.; Mosavi, A. An ensemble prediction of flood susceptibility using multivariate discriminant analysis, classification and regression trees, and support vector machines. *Sci. Total Environ.* **2019**, *651*, 2087–2096. [CrossRef]
9. Arunkumar, R.; Jothiprakash, V. Optimal Reservoir Operation for Hydropower Generation using Non-linear Programming Model. *J. Inst. Eng.* **2012**, *93*, 111–120. [CrossRef]
10. Reznicek, K.; Cheng, T.C.E. Stochastic modelling of reservoir operations. *Eur. J. Oper. Res.* **1991**, *50*, 235–248. [CrossRef]
11. Tao, B.; Kan, Y.B.; Chang, J.X.; Qiang, H.; Chang, F.J. Fusing feasible search space into PSO for multi-objective cascade reservoir optimization. *Appl. Soft Comput.* **2017**, *51*, 328–340.
12. Haddad, O.B.; Afshar, A.; Mariño, M.A. Honey-Bees Mating Optimization (HBMO) Algorithm: A New Heuristic Approach for Water Resources Optimization. *Water Resour. Manag.* **2006**, *20*, 661–680. [CrossRef]
13. Yeh, W.W.G. Reservoir Management and Operations Models: A State-of-the-Art Review. *Water Resour. Res.* **1985**, *21*, 1797–1818. [CrossRef]
14. Labadie, J.W. Optimal operation of multi-reservoir systems: State-of-the-art review. J Water Resour Plan Manage ASCE. *J. Water Resour. Plan. Manag.* **2004**, *130*, 93–111. [CrossRef]

15. LINDASEE; STANOPENSHAW. Applying soft computing approaches to river level forecasting. *Int. Assoc. Sci. Hydrol. Bull.* **1999**, *44*, 16.
16. Young, P.C. Advances in real-time flood forecasting. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2002**, *360*, 1433–1450. [CrossRef]
17. Koussis, A.D.; Lagouvardos, K.; Mazi, K.; Kotroni, V.; Sitzmann, D.; Lang, J.R.; Zaiss, H.; Buzzi, A.; Malguzzi, P. Flood Forecasts for Urban Basin with Integrated HydroMeteorological Model. *J. Hydrol. Eng.* **2003**, *8*, 1–11. [CrossRef]
18. Krstanovic, P.F.; Singh, V.P. A univariate model for long-term streamflow forecasting. *Stoch. Hydrol. Hydraul.* **1991**, *5*, 189–205. [CrossRef]
19. Thornes, J.E.; Stephenson, D.B. How to judge the quality and value of weather forecast products. *Meteorol. Appl.* **2010**, *8*, 307–314. [CrossRef]
20. Dalezios, N.R.; Tyraskis, P.A. Maximum entropy spectra for regional precipitation analysis and forecasting. *J. Hydrol.* **1989**, *109*, 25–42. [CrossRef]
21. Bai, T.; Wei, J.; Yang, W.; Huang, Q. Multi-Objective Parameter Estimation of Improved Muskingum Model by Wolf Pack Algorithm and Its Application in Upper Hanjiang River, China. *Water* **2018**, *10*, 1415. [CrossRef]
22. Bolouri-Yazdeli, Y.; Haddad, O.B.; Fallah-Mehdipour, E.; Mariño, M.A. Evaluation of real-time operation rules in reservoir systems operation. *Water Resour. Manag.* **2014**, *28*, 715–729. [CrossRef]
23. Mosavi, A.; Ozturk, P.; Chau, K.W. Flood Prediction Using Machine Learning Models: Literature Review. *Water* **2018**, *10*, 1536. [CrossRef]
24. Apel, H.; Thieken, A.H.; Merz, B.; Blöschl, G. A Probabilistic Modelling System for Assessing Flood Risks. *Nat. Hazards* **2006**, *38*, 79–100. [CrossRef]
25. Xu, Z.X.; Ito, K.; Liao, S.; Wang, L. Incorporating inflow uncertainty into risk assessment for reservoir operation. *Stoch. Hydrol. Hydraul.* **1997**, *11*, 433–448. [CrossRef]
26. Yazicigil, H.; Houck, M.H. The effects of risk and reliability on optimal reservoir design1. *Jawra J. Am. Water Resour. Assoc.* **2010**, *20*, 417–424. [CrossRef]
27. Paik, K. Analytical derivation of reservoir routing and hydrological risk evaluation of detention basins. *J. Hydrol.* **2008**, *352*, 191–201. [CrossRef]
28. Plate, E.J. Flood risk and flood management. *J. Hydrol.* **2005**, *267*, 2–11. [CrossRef]
29. Zhang, Y.K. Theories and Methods of Risk Analysis for Multipurpose Reservoir Operation. Ph.D. Thesis, North China Electric Power University, Beijing, China, 2012.
30. Burn, D.H.; Venema, H.D.; Simonovic, S.P. Risk-based performance criteria for real-time reservoir operation. *Can. J. Civ. Eng.* **1991**, *18*, 36–42. [CrossRef]
31. Pan, L.; Lin, K.; Wei, X. A two-stage method of quantitative flood risk analysis for reservoir real-time operation using ensemble-based hydrologic forecasts. *Stoch. Environ. Res. Risk Assess.* **2015**, *29*, 803–813.
32. Zhong, P.; Zeng, J. Research on Risk Analysis of Reservoir Real- time Flood Control Operation. *Water Power* **2008**, *34*, 8–9.
33. Apel, H.; Thieken, A.H.; Merz, B.; Blöschl, G. Flood risk assessment and associated uncertainty. *Nat. Hazards Earth Syst. Sci.* **2004**, *4*, 295–308. [CrossRef]
34. Cheng, C.T.; Chau, K.W. Flood control management system for reservoirs. *Environ. Model. Softw.* **2004**, *19*, 1141–1150. [CrossRef]
35. Liu, Z.; Huang, Q.; Yan, A.; Lin, L. Reduction of Risks in Hydro Engineering Stage Construction Using Discharge Control of Upriver Reservoir. In Proceedings of the International Conference on Risk Analysis & Crisis Response, Shanghai, China, 25 September 2007.