Analysis of reservoir flood control risk considering forecast uncertainty

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Abstract. The reservoir flood control risk is closely related to the accuracy of hydrological forecasting. High-accuracy hydrological forecasting technology can greatly reduce the reservoir flood control risk. Based on the definition of reservoir flood control risk, the risk exceeding the check water level of the reservoir and the risk exceeding safe flow of downstream flood control object are selected as the risk index of reservoir flood control in this paper. The relationship between the standard deviation of the relative error and the certainty coefficient of the flood process is analyzed. According to the distribution law of the flood forecast error, the Monte Carlo method is used to generate multiple inflow scenarios to simulate the flood control operation of reservoirs and analyze the risk rate of reservoir flood control operation. Taking Xiluodu and Xiangjiaba cascade reservoirs as an example, the risk rate of exceeding the check water level of the reservoir and exceeding safe flow of downstream flood control object under different flood forecasting accuracy are calculated. It provides a scientific basis for flood forecasting and operation of Xiluodu and Xiangjiaba cascade reservoirs.

1. Introduction

Flood disasters occur frequently and are highly destructive. They are one of the most harmful natural disasters to humans [1]. As an important flood control project, the reservoir plays a prominent role in preventing floods [2]. How to make full use of existing reservoirs and scientifically apply flood control theories to optimal operation and management of cascade reservoirs are of great concern to both academic and engineering circles [3-6]. Due to the randomness and uncertainty of rainfall and flood in the river basin and various human uncertainties, there are inevitable overtopping, dam breaks and protection area flooded [7]. The flood control operation of reservoir needs to consider the dam's own safety, downstream flood control safety and numerous complex constraints. Therefore, it has important practical significance on how to analyze and evaluate the risk brought by the uncertain factors and determine the optimal operation scheme to meet the dam and downstream flood control requirements.

Risk is a concept complementary to reliability. It was first proposed by the military industry. After decades of development, the concept of risk and its related research and application have penetrated into various fields, and the theoretical system has gradually improved that forms a more perfect theoretical science [8,9]. The concept of risk was introduced into the field of water resources in the
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1950s and has been widely developed and applied. The research scope includes a series of risk issues such as hydrology, hydraulics, economy, society and environment. The concept of risk appeared in the reservoir schedule in the late 1980s, and the risk analysis method on reservoir schedule has achieved many research results. Yazicigil et al [10] believe that the highest flood control level of the reservoir calculated according to the typical year design flood may cause relatively large risk that the water level exceeding the check water level. Karlsson et al [11] conducted a risk analysis of the dam safety problem by the so-called “blocking multi-target risk method”, and used five types of probability distribution functions to compare the results. Salmon et al [12,13] introduced the “allowable risk analysis method”, which can directly link the risk of dam breaks loss with the risk rate of dams’ operation.

In this paper, the forecast uncertainty is considered in the analysis of reservoir flood control risk. In Section 2, the definition of reservoir flood control risk is presented. In Section 3, a method for flood risk rate calculation considering forecast uncertainty is introduced. In Section 4, the flood control research of Xiluodu and Xiangjiaba cascade reservoirs on Yibin city is taken as an example, and the simulation results are discussed.

2. Definition of reservoir flood control risk

There is no unified definition of risk in the academic interests. When the awareness of risk is different, or the perspective of research on risk is different, the concept of risk has different interpretations. In risk analysis, for the specific risk event (or destruction event), its risk is usually defined and a corresponding risk indicator is proposed. In the reservoir flood risk analysis, possible risk events include the maximum water level in front of the dam exceeding the dam crest elevation or the check water level, and the maximum discharge flow exceeding the downstream safety discharge. The dam crest elevation, check water level and safe discharge flow can be used as protection targets or risk control indicators. Therefore, the risk of reservoir flood control can be defined as the probability that the protection target will be destroyed. For a flood with a frequency of \( P(A) \), the random event in which the protection target is destroyed at this frequency is \( B \), and the probability of occurrence of the event is \( P(B) \), then the probability of the flood target being destroyed can be calculated as follows:

\[
P = P(AB) = P(A)P(B/A)
\]

where \( P(B/A) \) denotes the conditional probability of occurrence of random event \( B \) when event \( A \) occurs.

According to the definition of reservoir flood risk, the reservoir flood risk rate is essentially a conditional probability, that is, the probability that the reservoir flood control target will be destroyed under a certain frequency flood. In this paper, the check water level is selected as the characteristic water level for the safety of reservoir. The flow corresponding to the downstream flood control standard is used as the safety discharge flow of the flood protection object. The risk rate exceeding the check water level of the reservoir is marked as \( R_1 \), and the risk rate exceeding safe flow of downstream flood control object is marked as \( R_2 \). These two indicators are used as the risk indicators for safety evaluation of reservoir operation.

3. Method for flood risk rate calculation considering forecast uncertainty

There is a close relationship between the risk analysis target and the risk factor. The relationship can be represented by some mathematical form. The main risk factors are the uncertain factors with known probability distribution. In practical problems, the relationship between risk factors and risk accidents occurrence probabilities is complex, and simple mathematical functions cannot characterize this relationship. The Monte Carlo simulation method is a commonly used method in risk estimation which extracts a set of random variable factors by the random number generator and obtains a set of risk estimates through multiple simulated sampling. In this paper, the Monte Carlo method is adopted for risk estimation of flood control operation objectives. The steps are as follows (figure 1):
Figure 1. Risk estimation of flood control operation based on Monte Carlo method.

**Step 1:** Determine the risk factors and their probability distribution.

**Step 2:** Randomly extract values that are inconsistent with the distribution of risk factors by the Monte Carlo method.

**Step 3:** Select the typical flood process and perform a simulation considering multiple distributions of risk factors under the typical flood process.

**Step 4:** The reservoir is operated according to the forecast pre-discharge mode to obtain multiple samples, and the risk rates $R_1$ and $R_2$ are calculated by statistical analysis.

The error of flood forecasting always exists. The flooding process predicted by different hydrologic model is different. The certainty coefficient is generally used to measure the quality of the forecasting results to characterize the coincidence degree between the flood forecasting process and the measured process. Yan [14] studied the relationship between the certainty coefficient and the forecast error, and tried to use the certainty coefficient to reverse the distribution law of flood forecasting error. The research results show that the distribution law of flood forecasting error is determined by the certainty coefficient of forecasting scheme. The certainty coefficient is expressed as:

$$R^2 = 1 - \frac{\sum_{t=1}^{n}(Q'_t - Q_t)^2}{\sum_{t=1}^{n}(Q_t - \bar{Q})^2}$$

(2)

where $Q'_t$ denotes the value of forecasting flood flow at $t$ time, $Q_t$ denotes the value of observed flood flow at $t$ time, $\bar{Q}$ denotes the average value of observed flooding process, $n$ denotes the length of flood.

By equation transformation, it’s shown as follows:
\[ \sum_{i=1}^{n}(Q'_i - Q_i)^2 = (1-R^2) \sum_{i=1}^{n}(Q_i - \bar{Q})^2 \]  

(3)

The relative forecast error is expressed as:

\[ \varepsilon_i = \frac{Q'_i - Q_i}{Q_i} \]  

(4)

The equation (3) can be expressed as:

\[ \sum_{i=1}^{n} \varepsilon_i^2 Q_i^2 = (1-R^2) \sum_{i=1}^{n}(Q_i - \bar{Q})^2 \]  

(5)

Both sides of the equation take the expectation, it’s shown as:

\[ \sum_{i=1}^{n} Q_i^2 E(\varepsilon_i^2) = E(1-R^2) \sum_{i=1}^{n}(Q_i - \bar{Q})^2 \]  

(6)

The relative forecast error can be approximated as a normal distribution with a mean of 0 and a mean square error \( \sigma^2 \), that is, \( \varepsilon_i \sim N(0, \sigma^2) \). Then

\[ E(\varepsilon_i^2) = D(\varepsilon_i) + [E(\varepsilon_i)]^2 = \sigma^2 \]  

(7)

The equation (6) can be expressed as:

\[ \sigma^2 \sum_{i=1}^{n} Q_i^2 = (1-R^2) \sum_{i=1}^{n}(Q_i - \bar{Q})^2 \]  

(8)

The mean square error of flood forecasting process can be expressed as:

\[ \sigma = \sqrt{(1-R^2) \sum_{i=1}^{n}(Q_i - \bar{Q})^2 / \sum_{i=1}^{n}Q_i^2} \]  

(9)

Since the mean square error of flood forecasting process \( \varepsilon_i \sim N(0, \sigma^2) \), the forecast value of the flooding process \( Q'_i \) is also subject to a normal distribution at any time. Equation (9) shows that the distribution law of the forecast error depends on the certainty coefficient of the forecasting scheme. Therefore, the certainty coefficient of flood forecasting is used as a risk factor to analyze the flood control risk considering the forecast uncertainty.

4. Case study

4.1. Study area

The Xiluodu and Xiangjiaba cascade reservoirs are located in the lower reaches of Jinsha river (figure 2). The Xiluodu and Xiangjiaba reservoirs are designed for flood control, power generation, sand interception and improving downstream shipping condition. On the one hand, the projects are designed to meet the electricity demand of regional economic development in East China, Central China and South China. On the other hand, it’s designed to solve the flood control problem of the downstream river, so that the flood control standards of cities such as Yibin, Luzhou and Chongqing will be significantly improved. The main parameters of the cascade reservoirs are shown in table 1.
4.2. Result and discussion
The flood control research of Xiluodu and Xiangjiaba cascade reservoirs on Yibin city is taken as an example. The design flood level of Xiluodu reservoir is based on the 0.1% frequency of flood, and the check flood level of Xiluodu reservoir is based on the 0.01% frequency of flood. The design flood calculation of Xiluodu and Xiangjiaba reservoirs is mainly based on the flood series of Pingshan station. It is calculated from the 1939~1998 measured series of Pingshan station and the 1924, 1860, 1892, 1905, 1928, and 1966 historical floods during the feasibility study stage of Xiluodu and Xiangjiaba reservoirs (table 2).

Table 2. The design flood of Xiluodu and Xiangjiaba reservoirs.

| Item                  | Parameters | Frequency (%) |
|-----------------------|------------|---------------|
|                       |            | Average      | Cv  | Cs/Cv  | 0.1 | 0.5 | 1   | 2   | 5   |
| Peak flow (m$^3$/s)   | 17900     | 0.3          | 4.0 | 43800  | 37600| 34800| 32000| 28200|
| 3 days flood volume (10$^8$m$^3$) | 43.9       | 0.3          | 4.0 | 107    | 92.1 | 85.4 | 78.5 | 69.1 |
| 7 days flood volume (10$^8$m$^3$) | 97.0       | 0.3          | 4.0 | 237    | 204  | 189  | 173  | 153  |
| 15 days flood volume (10$^8$m$^3$) | 186.0      | 0.29         | 4.0 | 443    | 382  | 355  | 327  | 289  |

According to the same frequency amplification method, the 1966 typical flood is amplified to obtain the check flood process of 0.01% frequency which is taken as the actual inflow process of the Xiluodu reservoir. The forecasting pre-discharge method is used for the flood control operation of Xiluodu and Xiangjiaba cascade reservoirs. The flood forecast period is set as 24 h.

The forecasting result can be used to official forecasting only if the forecasting accuracy reaches two levels, namely A and B. Therefore, only these two kinds of forecasting result are considered in the risk analysis of reservoir flood control operation. The certainty coefficient corresponding to the level A accuracy is 0.90~1.00, and the certainty coefficient corresponding to the level B accuracy is 0.70~0.90. The certainty coefficient of forecasting result $R^2$=0.95, 0.90 and $R^2$=0.80, 0.70 are selected to represent the accuracy level of A and B, respectively. The impacts of different certainty coefficient values on the risk of flood control operation of Xiangjiaba and Xiluodu cascade reservoirs are
analyzed. Table 3 shows the flood control risk rate of reservoirs with different forecasting accuracy.

| $R^2$ | $\sigma$ | $R_1$ | $R_2$ |
|-------|----------|-------|-------|
| 1     | 0        | 0     | 0     |
| 0.95  | 0.152    | 1.2*10^{-6} | 0     |
| 0.90  | 0.215    | 5.8*10^{-5} | 0     |
| 0.80  | 0.305    | 3.1*10^{-5} | 5.1*10^{-6} |
| 0.70  | 0.373    | 1.2*10^{-5} | 3.7*10^{-6} |

It can be seen from table 3 that with the decrease of forecast accuracy, the risk rate of reservoir flood control operation will increase. In order to reduce the flood control risk of reservoir operation, it’s needed to improve the accuracy of hydrological forecasting and prolong the forecasting period. What’s more, the management level of flood control operation of reservoirs needs to be improved, so that it can reduce the flood control risk of reservoirs through scientific and effective schedule methods.

5. Conclusions
The certainty coefficient is an important indicator reflecting the degree of agreement between the forecasting flood process and the observed flood process. It reflects the discretization degree of flood forecasting error to some extent. Based on this, this paper proposes a method to reverse the distribution law of flood forecasting error by certainty coefficient. The Monte Carlo method is used to generate multiple inflow scenarios to simulate the flood control operation of reservoirs and analyze the risk rate of reservoir flood control operation of Xiluodu and Xiangjiaba cascade reservoirs. The results show that with the decrease of forecast accuracy, the risk rate of exceeding the check water level of the reservoir and exceeding safe flow of downstream flood control object will increase. It’s suggested that the accuracy of hydrological forecasting and the management level of flood control operation of reservoirs needs to be improved. The research results enrich and develop the existing reservoir flood risk analysis method, and provide a scientific basis for flood forecasting and operation of Xiluodu and Xiangjiaba cascade reservoirs.

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