Study on the Staged Operation of a Multi-Purpose Reservoir in Flood Season and its Effect Evaluation

Chongxun Mo
Guangxi University
Can Zhu
Guangxi University
yuli ruan (yuliruan777@163.com)
College of architecture and civil engineering Guangxi university https://orcid.org/0000-0003-2715-1952
Juan Deng
Guangxi University
Juliang Jin
Hefei University of Technology

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Study on the staged operation of a multi-purpose reservoir in flood season and its effect evaluation

Chongxun Mo[1], Can Zhu[2], Yuli Ruan[3], Juan Deng[4], Juliang Jin[5]

[1]College of Civil Engineering and Architecture, Key Laboratory of Disaster Prevention and Structural Safety of the Ministry of Education, Guangxi Key Laboratories of Disaster Prevention and Engineering Safety, Guangxi University, Nanning, 530004, PR China (Email: mo_209@163.com)

[2]College of Civil Engineering and Architecture, Key Laboratory of Disaster Prevention and Structural Safety of the Ministry of Education, Guangxi Key Laboratories of Disaster Prevention and Engineering Safety, Guangxi University, Nanning, 530004, PR China (Email: 1569051733@qq.com)

[3]College of Civil Engineering and Architecture, Key Laboratory of Disaster Prevention and Structural Safety of the Ministry of Education, Guangxi Key Laboratories of Disaster Prevention and Engineering Safety, Guangxi University, Nanning, 530004, PR China (Email: yuliruan777@163.com)

[4]College of Civil Engineering and Architecture, Key Laboratory of Disaster Prevention and Structural Safety of the Ministry of Education,

Guangxi Key Laboratories of Disaster Prevention and Engineering Safety, Guangxi University, Nanning, 530004, PR China (Email: Email: 1361039545@qq.com)

[5]*School of Civil Engineering, Hefei University of Technology Hefei 230009, PR China (674319486@qq.com)*

Corresponding author: Yuli Ruan Email address: yuliruan777@163.com

Abstract: A reasonable analysis of flood season staging is significant to the utilization of flood and the alleviation of water shortage. For a case study of the Chengbi River reservoir in China. Based on fractal theory, the flood season is divided into several sub-seasons by using four indexes (multi-year average daily rainfall, multi-year maximum rainfall, multi-year average daily runoff, and multi-year maximum daily runoff) in this study. The Cubic spline interpolation function is then used to determine the flood limit water levels of each sub-season. And the Benefit-Risk theory is applied to evaluate the effects of staged dispatching. The results show that the flood season of Chengbi River basin should be divided into the pre-flood season (13 April-6 June), the main flood season (7 June-9 September) and the post-flood season (10 September-31 October). Adjustment of flood limit water level for sub-season and benefit evaluation. When the risk rate after reservoir flood season operation increases by 0.13×10^{-5}, the average annual expected risk is 0.2264 million RMB, and the average annual benefit increases by 0.88-1.62 million RMB. The benefits obtained far outweigh the risks, indicating the importance of staging the flood season.

Key words: effect evaluation, fractal method, flood season staging, multi-purpose reservoir, risk rate, staged operation

1 Introduction

According to the statistics of the United Nations Environment Programme, compared to the past 100 years, the global annual per capita water resources have reduced from 40,000 m^3 to 6,840 m^3. Besides, it is expected that by 2030, nearly 50% of the world population will have less than 1,000 m^3 of annual per capita water resources and will be in a state of severe water shortage (Eckstein et al. 2010). With the development of society and the growing population, water shortages are becoming more and more prominent, however, large amounts of water have been discharged during the flood season, resulting in a huge waste of water resources. Nowadays, the use of flood has become more and more important in most areas (Chang et al. 2017). Reservoir scheduling is an effective way to utilize flood resources and has been studied by a large number of scholars(Chao et al. 2020; Feng et al. 2020; Lu et al. 2020; Rani et al. 2020). In most of the countries, floods have seasonal patterns of change, it is necessary to study the flood season and stage it rationally to raise the FLWL (flood limit water level) of the reservoir appropriately. In this way, flood resources can be fully utilized, which is one of the important issues that need to be studied and solved today.

There have been many studies on the seasonal patterns and staging of floods during the flood season (Chen et al. 2010; Collins 2018; Hall and Blöschl 2017; Jiang and Li

2012; Li and Zhang 2018; Mukherjee et al. 2018). Different staging methods have been used to segment the flood season, such as the Probabilistic change-point analysis technique (Liu et al. 2010a), the Vector statistic and Relative frequency method (Bo et al. 2011; Campos-Aranda 2017; Chen et al. 2019; Cunderlik et al. 2004), and the Fuzzy set method (Beurton and Thieken 2009; Jia and Mu 2015; Li et al. 2019; Ma et al. 2017; Shu et al. 2017). As for the selection of indicator factors for staging, most previous studies have used a single factor to stage the flood season. For example, peak flow (Ma et al. 2017) or average daily maximum flow (Zhang et al. 2019) are used as a single indicator factor for flood staging studies, causing the staging results cannot be mutually verified. A reasonable determination of the FLWL is the key to coordinate flood risk and reservoir benefit (Eum et al. 2010). Therefore, many scholars have carried out extensive research on the optimization of FLWL. An FLWL model dynamic control was applied to reservoirs with indeterminate flood process lines, which effectively improved hydropower generation and flood utilization (Xiang et al. 2010), Liu et al. (2015) optimized the design of staged flood limit levels; a framework for optimal reservoir scheduling based on flood staging results was proposed (Jiang et al. 2014).

In summary, most previous studies have used a single indicator factor for flood staging leading to uncertainty in the results. In addition, there is less involvement in the calculation of FLWLs for each phase and the evaluation of the benefits of the flood staging. Therefore, the objective of this study is to stage the flood season by selecting multiple indicator factors and then evaluate the benefits of the staging results. The Chengbi River reservoir is selected as the object of this study, multi-year average daily rainfall time series, multi-year maximum rainfall time series, multi-year average daily runoff time series and multi-year maximum daily runoff time series are used as index factors to divide flood season by fractal method. The Cubic spline interpolation function is then used to determine the FLWLs of each sub-season, and the Benefit-Risk theory is applied to evaluate the effects of staged dispatching.

2 Analytical Methods

2.1 Fractal Method

According to the knowledge of fractal theory, hydrological processes that exhibit periodic changes over a certain period of time influenced by deterministic factors can be considered to be self-similar (Tian et al. 2018). The occurrence of seasonality and timing of floods can be considered to have similar mechanisms, so the fractal theory has been used in flood staging (Ductien 2010; Li et al. 2018). The fractal feature is described by capacity dimension. Assuming F is a bounded subset of the d-dimensional Euclid space and $N(\varepsilon)$ is the least number of closures covering F of radius ε, then the capacity dimension D_b is defined as follows.

$$D_b = \lim_{\varepsilon \to 0} \left(\log N(\varepsilon) / \log (1/\varepsilon) \right) \tag{1}$$

The capacity dimension is calculated as follows:

1). Take the sample point series $x_1, x_2, \cdots, x_n$ in the flood season, and determine the period length T according to the start length and step span of the sample period, then select the flood season segmentation level Y in period T to reflect its sample.

2). Take the time scale $\varepsilon = \{1\mathrm{d}, 2\mathrm{d}, \ldots, 10\mathrm{d}\}$ and count the number of periods $N(\varepsilon)$ in which the sample x_i exceeds the segmentation level Y. Calculate the corresponding relative time scales $NT(\varepsilon)$ and relative measures $NN(\varepsilon)$ from equation (2) and equation (3) based on T and ε, and a linear fit to $\ln(\varepsilon)$ and $\ln NN(\varepsilon)$ to find the slope of the correlation b. The capacity dimension D_b is obtained from equation (4).

$$NT(\varepsilon) = T / \varepsilon \qquad (2)$$

$$NN(\varepsilon) = N(\varepsilon) / NT(\varepsilon) \qquad (3)$$

$$D_b = 2 - b \qquad (4)$$

3). Change the period length T and repeat the above steps. If the D_b obtained is basically equal, then T at this time is the same stage.

2.2 Cubic Spline Interpolation Function of Reservoir Characteristic Curve

2.2.1 Water level and Reservoir Capacity Relation Curve

For the relation curve of water level and storage capacity, Consider the dead water level and the dam crest elevation as the two endpoints of the interpolation region. The relation curve of water level and storage capacity is expressed as equation (5) by Cubic spline interpolation function.

$$V(Z) = M_{V\,j-1}\frac{(Z_j - Z)^3}{6h_j} + M_{V\,j}\frac{(Z - Z_{j-1})^3}{6h_j} + (V_{j-1} - \frac{M_{V\,j-1}h_j^2}{6})\frac{Z_j - Z}{h_j} + (V_j - \frac{M_{V\,j}h_j^2}{6})\frac{Z - Z_{j-1}}{h_j}$$

$$(Z_{j-1} \le Z \le Z_j) \qquad (5)$$

where $h_j = Z_j - Z_{j-i}$ is the water level difference of the sample section; Z_{j-1} and Z_j are the water level at the beginning and end of the corresponding sample section; M_{Vj}

is the second derivative of the storage capacity with respect to the water level, that is, $V''(Z_j)$.

2.2.2 Relation Curve Between Water Level and Discharge

The water level when the gate is fully open and the water level when the maximum discharge capacity is reached are regarded as the endpoints of the interpolation region. The relation curve of water level and discharge is expressed as equation (6).

$$q(Z) = M_{qj-1}\frac{(Z_j - Z)^3}{6h_j} + M_{qj}\frac{(Z - Z_{j-1})^3}{6h_j} + (q_{j-1} - \frac{M_{qj-1}h_j^2}{6})\frac{Z_j - Z}{h_j} + (q_j - \frac{M_{qj}h_j^2}{6})\frac{Z - Z_{j-1}}{h_j}$$

$$(Z_{j-1} \le Z \le Z_j) \qquad (6)$$

where Z_{j-1} for the water level at the beginning and Z_j for the water level at the end of the corresponding sample segment; and M_{qj} for the second derivative of the discharge flow with respect to the water level, that is, $q''(Z_j)$.

2.3 Risk and Benefit Analysis Methodology

2.3.1 Risk Rate

Considering only the effect of flooding factors, the reservoir staging dispatch risk rate calculation model is as follows.

$$P = P(q \ge Q) \qquad (7)$$

Where q represents a random variable. P- III (Pearson type III) curve is generally used in flood peak discharge frequency curve. Then its density function can be expressed as

$$f(q) = \frac{\beta^\alpha}{\Gamma(\alpha)}(q - a_0)^{\alpha-1}e^{-\beta(q-a_0)} \qquad (8)$$

$\Gamma(\alpha)$ ——The gamma function of α

α、β、a_0——Three parameters characterizing the shape, scale and location of P-III distribution. $\alpha > 0$, $\beta > 0$.

The risk rate integral can be expressed as

$$P = P(q \geq Q) = \int_Q^{\infty} f(q)\mathrm{d}q \tag{9}$$

2.3.2 Benefit Analysis

In the benefit analysis, the reservoir capacity should be calculated according to the actual situation. The increased capacity will not only bring direct benefits in terms of power generation and water supply, but also generate indirect economic benefits such as irrigation, farming, tourism, etc. Water supply and power generation benefits are calculated using the following formula.

$$W_i = V_i \times \eta_i \tag{10}$$

where W is the economic benefit from water supply or electricity generation, V is the additional storage capacity after adjusting the FLWL, and η_i is the efficiency for one cubic meter of water.

3 Study Area and Data

Chengbi River Reservoir is located in Baise City, Guangxi Province, downstream of Chengbi River, (106°21'E-106°48'E, and 23°50'N-24°45'N) (Fig 1). It is the second-largest earth-rock dam reservoir project in China, with a total storage capacity of 1.15 billion m³ and a normal storage level of 185 m. But it operates under the rule of a single FLWL for the entire flood season, resulting in a low storage rate after floods and a large waste of flood resources. The average precipitation of the watershed over the years is

1560 mm, and the rainfall is unevenly distributed during the year, mostly concentrated in April to September, accounting for more than 85% of the annual rainfall. The flood season of the Chengbi River is from April 13 to October 31 with a low storage rate after flood season. Since the flood of Chengbi River mainly comes from precipitation, the data selected in this paper is the daily precipitation and daily measured runoff from Ba Shou Station (BBS) from 1963 to 2016, and the four index factors of average daily rainfall, maximum daily rainfall, average daily runoff and maximum daily runoff, which reflect the characteristics of the flooding period are used as the basic data of staging.

4 Results

4.1 Flood Staging Results

The fractal calculation is carried out based on the runoff and rainfall data of the Chengbi River Reservoir from 1963 to 2016. When calculating the capacity dimension D_b, taking into account the seasonal characteristics of the flood change pattern and its causes, the staging is generally not shorter than 30 days(MWR 2006). According to scholars (Liu et al. 2010b; Qian and Zheng 2012), the maximum deviation of the capacity dimension of a fractal is less than 5% classified as a class. The initial length of the study is 30d, then 10d as a step to calculate the D_b, and finally shortened to 5d for the calculation. The results are shown in Table 1 to Table 4.

From Table 1, it can be seen that the maximum deviation of the D_b at $T = 30d \sim 55d$ is 1.96% （<5%) of the minimum capacity dimension, so it is in the same stage. When $T=60d$, it is not considered to be in the same stage as the previous time period, because the value of D_b is mutated and the maximum deviation is 10.8% (>5%). Therefore, the pre-flood season can be identified as 13 April to 6 June. A sudden change in the value of the D_b at time period $T=85d$, with a maximum relative error of 1.74% in the preceding time period, which can be classified as the second stage. Accordingly, the main flood season can be identified as 7 June to 25 August, and the duration of the post-flood season is from August 26 to October 31.

Using a relative error equal to 5% as the threshold for whether or not it is the same stage, it is clear from Tables 2 and Tables 3 that the flood season can be divided into three phases. The flood segmentation results by using average daily maximum rainfall as an indicator factor is as follows: the pre-flood season (13 April to 6 June), the main flood season (7 June to 30 August), the post-flood season (31 August to 31 October). The flood segmentation results by using average daily maximum rainfall as an index factor is as follows: the pre-flood season (13 April to 11 June), the main flood season (12 June to 30 August), and the post-flood season (31 August to 31 October). As shown in Table 4, the flood segmentation using multi-year average daily maximum runoff can be divided into four phases, but according to the *Code for Hydraulic Calculations for Water Projects*, a flood should not be divided into more than three sub-flood seasons. Therefore, based on the multi-year runoff characteristics of the Chengbi River basin, combining the first and second phases into one as the pre-flood season. Then the pre-flood season is 13 April to 16 June, the main flood season is 17 June to 9 September and the post-flood season is 10 September to 31 October.

The results of the above calculations are summarized in the table 5. Taking into consideration and based on the principle of extending the main flood season as much as possible, the results of the phasing were revised as follows: the pre-flood season is from 13 April to 6 June, the main flood season is from 7 June to 9 September, and the post-flood season is from 10 September to 31 October.

4.2 Results of Flood Diversion Calculation

4.2.1 Control water level

The maximum water level obtained from the flood regulation calculation in the main flood season is used as the control water level to raise the FLWL in other stages, and the flood hydrograph of 1,000 years flood and 10,000 years flood in the main flood season is calculated by 185m. The rule of flood regulation is that when the reservoir inflow is less than the storage outflow at the FLWL, gates are used to control the underflow is equal to the incoming flow. So that the water level in the reservoir to maintain the FLWL. When the reservoir inflow is greater than the corresponding discharge flow of the FLWL, the gates are fully open to discharge flow. When the reservoir water level falls back to the FLWL, the discharge is controlled by the gates to keep the water level unchanged. The change of water level in the flood regulation calculation is shown in Fig 2, then the highest water level in the 1,000 years flood regulation calculation in the Chengbi River reservoir during the main flood season is 187.85m, and the highest water level in the 10,000 years flood is 189.13m, which are used as the control levels in the flood regulation calculation during the pre-flood season and post-flood season.

4.2.2. Flood limit water level

Because raising the FLWL during the main flood season is not considered, only the different starting levels for the pre-flood season and the post-flood season are trialed. The initial water level is adjusted from 185m and trialed in steps of 0.5m. The results are summarized in Table 6. It can be seen that the maximum water level will not exceed the control level of 187.85m when the FLWL is between 185.0 and 187.5 during the flood regulating calculation at the 1,000 years flood process line in the pre-flood season. In the 10,000 years flood process line flood adjustment calculation, when the FLWL is 185.0 to 188.0m, the maximum water level will not exceed the control level of 189.13m. Therefore, the FLWL of the pre-flood season is set between 185.0 and 187.5m without reducing the flood control standard of the reservoir. Correspondingly, the FLWL in the post-flood season is set between 185.0 and 187.5m.

To sum up, the FLWL of Chengbi River reservoir in the pre-flood season and the post-flood season can be increased to some extent. But for the pre-flood season in April and May, it makes little sense to raise the FLWL. Firstly, it is the time when agriculture in Baise City needs a lot of water, so it becomes impractical to raise the FLWL of the reservoir by reducing the water supply. Secondly, the interval between the beginning and end of the pre-flood season is only 54 days, and the main flood season still maintains the FLWL unchanged. Based on the above considerations, only the FLWL of the post-flood season is raised.

4.3 Risks and Benefits

The paper calculates the FLWL for the post-flood season in 0.5m increments to obtain risk rates and risk rates increases for different starting water levels (Fig 3), and the expected risk and expected risk increases (Fig 4). When the FLWL is set at 187.5m in the post-flood season, the maximum risk rate is 2.52×10^{-5}, which is less than the risk rate of the reservoir calibration flood of 1×10^{-4}. Compared to the original flood level, the risk rate increases by 2.34×10^{-5}. From Figure 3, it can be seen that when the FLWL is 185m~186m, the risk rate changes very little and the trend of increasing risk rate is also moderate. However, when the FLWL is 186-187.5m, the risk rate tends to increase abruptly. The risk rate of the average FLWL of 186m in the post-flood season is 0.31×10^{-5}, which is increasing of 0.13×10^{-5} compared to the risk rate of the original level. From Figure 4, it can be seen that when the FLWL is set at 185-186m, there is little trend in the expected risk of flood protection. However, when the FLWL is set at 186-187.5m, the expected risk increases steeply.

The risk-benefit analysis was carried out by setting the flood level of the Chengbi River Reservoir at 186m in the post-flood season, the average increase of beneficial capacity is 0.04 billion m^3. With the information about water supply and power generation from 2019 to 2020, it is calculated that the increase of beneficial capacity is used for power generation or water supply, then the average annual increase in benefits is between 0.88 and 1.62 million RMB. The increase in expected risk of 0.0093 million RMB relative to the original level when the FLWL during the post-flood season of the reservoir is 186m. And after taking into account the increased inundation losses of

0.2171 million RMB at that level, the sum of the average annual expected increase in risk is 0.2264 million RMB, which is much less than the expected benefit.

5 Conclusions and Discusssion

Research on reservoir flood staging and FLWL is significant to improve the utilization of water resources. The study selects multi-year average daily rainfall time series, multi-year maximum rainfall time series, multi-year average daily runoff volume time series and multi-year maximum daily runoff volume time series as index factors, and uses the fractal method to stage flood season. On this basis, the flood regulation calculation is carried out by using the Cubic spline interpolation function to determine the FLWLs of each stages. Finally, the effect of phased dispatching is evaluated in relation to the Benefit-risk theory. The results are as follows:

The pre-flood season of Chengbi River Reservoir is from 13 April to 6 June, the main flood season is from 7 June to 9 September, and the post-flood season is from 10 September to 31 October. Considering the irrigation water demand and flood control risk around the reservoir area, the FLWLs in each stages was finally determined to be 185m in the pre-flood season, 185m in the main flood season and 185~187.5m in the post-flood season. It is found that when the FLWL in the post-flood season is set at 186m, the risk rate after reservoir operation by stages in the flood season increases by 0.13×10^{-5}, the average annual expected risk is 0.2264 million RMB. However, the average annual increase in benefits is 0.88 to 1.62 million RMB.

Compared with the research results of existing scholars (Huang et al. 2013; Jiang and Li 2012; Ma 2004; Wei et al. 2014), the present study classifies the flood season to the daily scale with improved accuracy. When the average daily rainfall was used to stage the flooding of the Chengbi River reservoir, the multi-year average series differed from the multi-year maximum series by about 5 days. Using daily runoff for flood staging, the maximum deviation of the multi-year average series and multi-year maximum series results is about 10 days. The difference between the calculated results of the average daily rainfall time series and the average daily runoff time series is 5 to10 days. It suggests that the selection of different factor indicators can have an impact on flood staging.

In this study, the staging and scheduling of reservoir floods and the determination of FLWL are investigated. The innovations of the paper are as follows: (1) the fractal methods and multiple index factors are used to divide the flood season into daily scales, which improves the staging accuracy; (2) the cubic spline interpolation function is used to solve the FLWLs, which avoids the Runge phenomenon caused by the traditional linear interpolation method and the large errors and calculations with the Newton iterative method. However, there are still some shortcomings in the study. Improvements are needed in the following areas. Firstly, in terms of flood staging, it is recommended that multiple methods of staging should be used and then mutually validated because of the uncertainty and complexity of hydrology. Secondly, the indirect benefits of tourism and aquaculture due to increased storage capacity have not been calculated because of limited information. Finally, this study is based on long-term rainfall and runoff data, but one direction of research on reservoir scheduling is to forecast the future based on short-term data(Ramaswamy and Saleh 2020), and how to combine long-term and short-term data needs to be studied further in the future.

Declarations:

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Conflicts of interest/Competing interests (Not application)

Availability of data and material

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions. We will conduct further research on this aspect in the future. The existing research data will be gradually developed in the subsequent papers, and it is only temporarily confidential at present.

Code availability (Not application)

Authors' contributions

Chongxun Mo, Juan Deng and Juliang Jin contributed to the conception of the study;

Chongxun Mo, Can Zhu and Yuli Ruan contributed significantly to analysis and manuscript preparation; Chongxun Mo, Can Zhu, Yuli Ruan performed the data analyses and wrote the manuscript; Juan Deng and Juliang Jin helped perform the analysis with constructive discussions.

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Figures

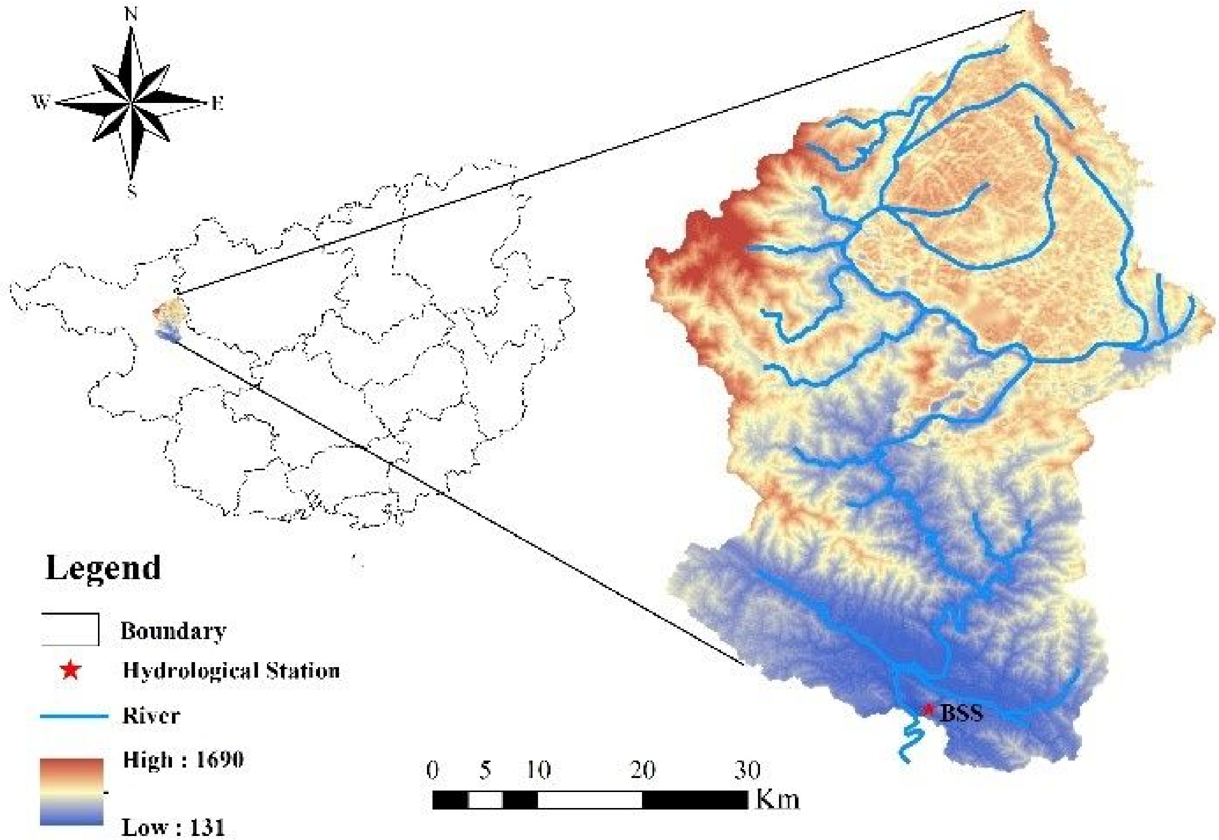

Figure 1

Location of the Chengbi River Reservoir Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

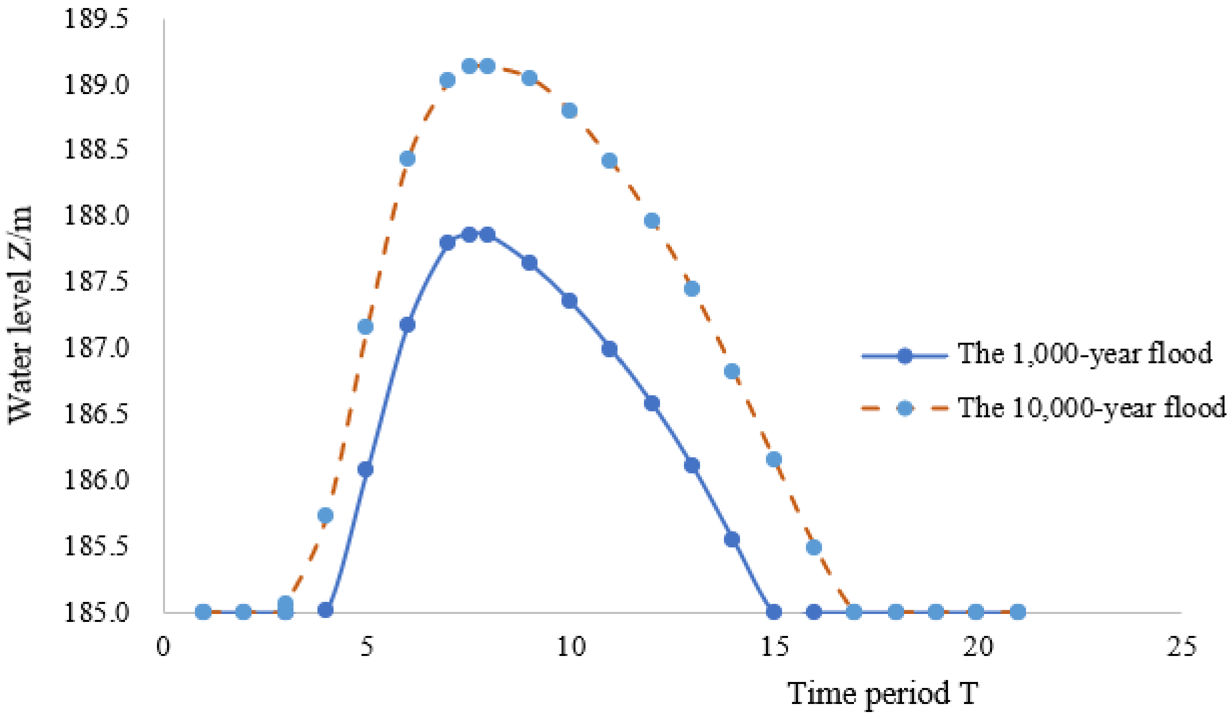

Figure 2

Variation of water level in flood regulation calculation of characteristic floods

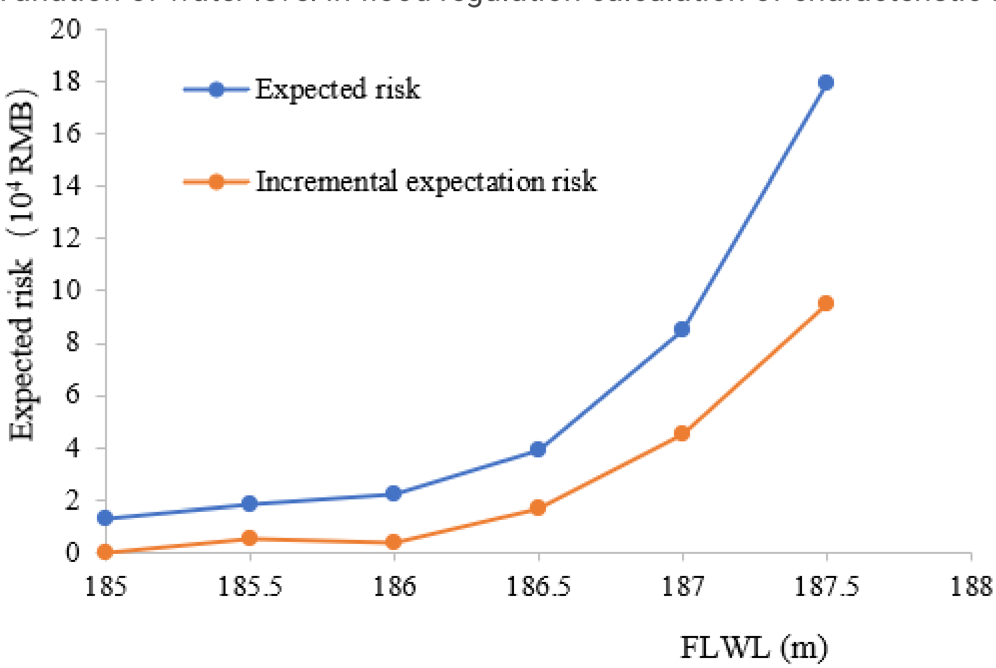

Figure 3

Risk rates and risk rates increases in the post-flood season

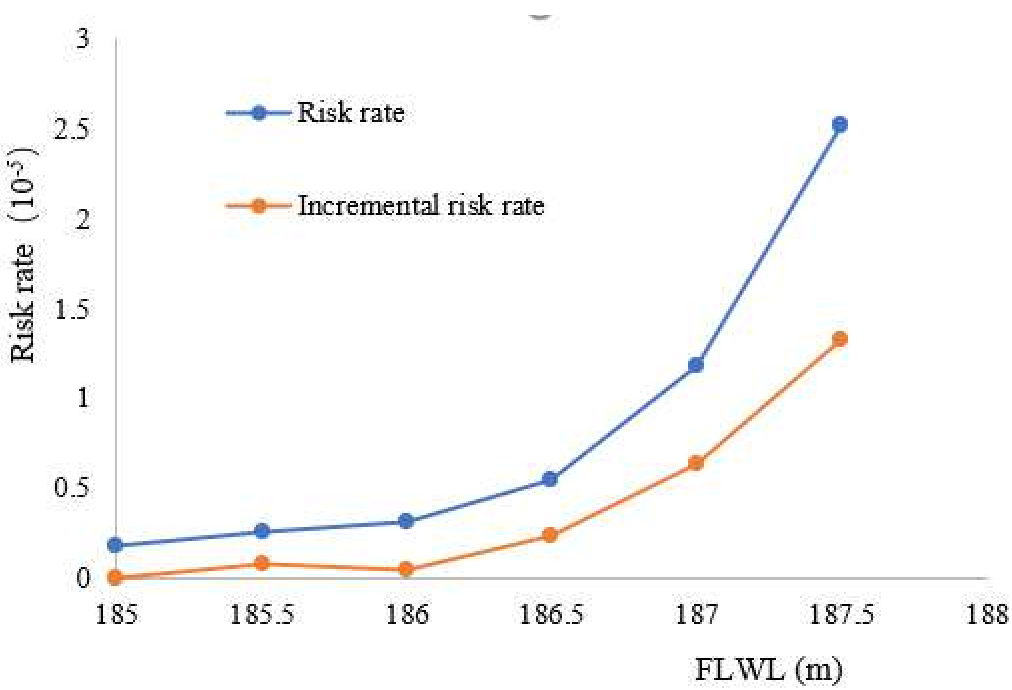

Figure 4

Expected risk and expected risk increases at different water levels