Comparative analysis of routed flood frequency for reservoirs in parallel incorporating bivariate flood frequency and reservoir operation

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Funding information
National Science and Technology Major Project of China, Grant/Award Number: 2017ZX07603-002; Natural Science Fund of Anhui Province, Grant/Award Numbers: 2008085ME158, 2008085ME159

Abstract
Flood frequency is commonly defined by natural flood characteristics such as flood peak, volume and duration. However, for floods at reservoir site, reservoir operation will significantly alter the natural flood process and flood frequency. This article presents a framework of routed flood frequency which incorporates multi-reservoir flood correlation and considers the effect of reservoir operation. Aggregated flood volume during reservoir operation has been adopted as indicator for the routed flood frequency curve (RFFC). A comparison has been made with a 62-year series of historic flood inflows observed at two parallel reservoirs in Eastern China. By comparing the derived RFFC with traditional univariate and bivariate flood frequency results, it can be seen that the RFFC results provide a reasonable estimation of flood frequency. A sensitivity analysis indicated that the reservoir maximum release allocation has significant impact on RFFC, and a balanced allocation of flood peak can greatly decrease the overtopping risk. The “peak–peak” contour lines of the RFFC show that there are different flood combination zones which need different operation strategies in real-time operation. Our findings improve the understanding of flood frequency concepts when considering the impact of reservoir operation and provide reference to manage real-time reservoir operation.

KEYWORDS
copula distribution, overtopping risk, parallel reservoirs, reservoir flood control operation, routed flood frequency curve

1 | INTRODUCTION

Flood frequency defines the one-to-one relationship between flood characteristic, that is, flood peak or volume, and its exceedance probability (Ahi1an, O’Sullivan, & Bruen, 2012; Raff, Pruitt, & Brekke, 2009), which has been widely applied in hydrologic planning and design (Eagleson, 1972; Xiong et al., 2019). However, it is controversial of traditional flood frequency that single indicator, flood peak, or volume, is not enough to reflect the severity of flood event (Fernandes & Noghettini, 2008; Olang & Furst, 2011; Papaioannou et al., 2016). For instance, a determined flood event might have different flood frequencies depending on which...
characteristic is adopted to calculate flood frequency. A flood event with high peak and low volume may have quite low frequency in peak but quite high frequency in volume. Moreover, there are additional factors that influence flood features such as hydrograph shape, duration, time to peak, and so forth (Shafaei, Fakheri-Fard, Dinpashoh, Mirabassi, & Michele, 2016). In summary, the limitation of univariate flood frequency was widely addressed in recent literatures.

To overcome the limitation of univariate flood frequency, the concept of multivariate flood frequency which incorporates more than one characteristic was proposed (Grimaldi & Serinaldi, 2006). As an effective method to describe multivariate distribution, Copula theory is widely used to construct the joint distribution of multiple flood characteristics (Chen, Singh, Shenglian, Hao, & Li, 2012; Fu & Butler, 2014; Guo, Muhammad, Liu, Xiong, & Yin, 2018; Li, Guo, Chen, & Guo, 2013; Shiau, Wang, & Tsai, 2006). Massive research results show that the multivariate flood frequency derived from copula function can simulate flood features precisely, meanwhile, it provides a reliable standard to evaluate whether the traditional univariate method over- or under-estimated the severity of flood events (Li et al., 2019; Sraj, Bezak, & Brilly, 2015; Xu, Ma, Lian, & Bin, 2014).

Another limitation of conventional flood frequency is the ignorance of reservoir operation effect. For reservoir planning stage, flood frequency is derived from historic natural flood records. However, it should be noted that once the reservoir was built and put into operation, natural flood process will be changed by reservoir operation (Gao et al., 2019; Goodarzi, Mirzaei, & Ziaei, 2012). Therefore, the “real” flood frequency after reservoir routing is different from the “natural” flood frequency in reservoir planning stage, which has been overlooked in various previous cases but highlighted in recent years.

Until now, a substantial progress has been obtained by introducing reservoir operation into flood frequency analysis. de Michele, Salvadori, Canossi, Petaccia, and Rosso (2005) were the first to construct flood frequency considering reservoir routing. In his work, the flood frequency variable is denoted by maximum water level after reservoir routing instead of traditional flood peak or volume, so that the effect of reservoir routing was incorporated into flood frequency. Salvadori, de Michele, and Durante (2011) further considered initial reservoir water level in reservoir routing process, forming a trivariate return period framework. Requena, Mediero, and Garrote (2013) defined the concept “routed return period” to measure the risk of dam overtopping by means of routing simulated inflow hydrographs. Volpi and Fiori (2014) proposed a similar concept “structure-based” routed return period framework, which also considered the effect of reservoir routing and bivariate flood characteristics in flood frequency.

The importance of routed flood frequency considering reservoir operation has been further highlighted in the latest studies. Serinaldi (2016) suggested that more emphasis should be focused on project failure or risk, rather than simply comparing flood frequency results of different methods. Guo, Liu, and Xiong (2016) reviewed research studies on reservoir flood control operation, and illustrated that comparing with natural flood characteristics, the maximum water level after reservoir routing should be taken as indicator of flood frequency in real-time reservoir operation stage. Michailidi and Bacchi (2017) proposed a structure-based flood frequency to estimate reservoir overtopping risk, where the “structure” denotes reservoir routing. Balistrocchi, Orlandini, Ranzi, and Bacchi (2017) proposed a new concept called “routed flood frequency curve” (RFFC). The RFFC describes flood frequency by considering the effect of reservoir routing as well as flood peak-volume bivariate characteristics, which reflects real-time flood risk under reservoir operation environment. Zhou, Liu, Jin, and Hu (2019) constructed a bivariate flood frequency definition that incorporating upstream and downstream flood risk on single reservoir, and comprehensively compared flood results of copula “Or” frequency and copula “And” frequency. Despite the abundance of literature available on flood frequency, a systematic analysis on routed flood frequency is still lacking. First, flood frequency for multiple reservoir system has not been comprehensively analysed, for instance, it remains a difficult problem on constructing flood frequency curve indicator for multiple reservoirs. Second, current research studies focus more on deriving new flood frequency definitions, but the comparisons of different flood frequency definitions and parameter sensitivity analysis are partly overlooked. In view of these existing limitations, a routed flood frequency considering both multivariate flood characteristics and reservoir routing is proposed. The proposed routed flood frequency is then comprehensively compared with traditional univariate and bivariate flood frequency results. The purpose of this study is not to directly reduce flood risks, but to objectively quantify what risk the reservoir system will face under various flood scenarios and reservoir routing schemes. Two reservoirs in parallel, the Mozitan and Bailianya reservoirs in mid-east China are applied as case study. This article is considered as a complete RFFC study including copula-based bivariate flood distribution, hydrograph simulation and reservoir routing, overtopping risk calculation, RFFC derivation, comparative discussion and sensitivity analysis.
The structure of this paper is the following: the study site and data are briefly introduced in Section 2. Section 3 describes the derivation of RFFC for parallel reservoirs. Section 4 presents case study and discussion. Conclusions are introduced in Section 5.

2 | STUDY SITE AND DATA

2.1 | Study site

This study is based on a real case study: the Mozitan reservoir and Bailianya reservoir in the Pi catchment—a tributary of the Huai river, China (Figure 1). The two reservoirs are located in the north–south climate boundary of China, leading to quite uneven rainfall distribution: 70% of annual precipitation concentrates in summer season (June–September). In order to diminish flood disaster, the Mozitan and Bailianya reservoirs were built at upstream tributaries of Pi river in 1956 and 2009, respectively, forming a parallel reservoir system. The maximum downstream safety flow at the stream gauge is 2,000 m³/s. The distance between the two reservoirs is about 32 miles, thus the rainfall and flood are basically synchronised at the two reservoirs. Specifications and flood characteristics of the two reservoirs are listed in Table 1.

2.2 | Data

A total of 62-year (1956–2017) historic flood records including annual maximum flood peak flow and 3-day flood volume of the Mozitan and Bailianya reservoir are used. Specific analysis of the flood characteristics is shown in Section 3.2.1.

Additional data include flood hydrographs with hourly time interval from 2002 to 2013, which provide reference for hydrograph simulation in this study. Typical flood hydrographs for each reservoir are also available, shown in Figure 2.

3 | METHODOLOGY

The analysis conducted in this article consists of two parts: RFFC derivation and sensitivity analysis. The framework of RFFC and univariate/bivariate flood frequency is presented in Figure 3. Based on comparative analysis of different flood frequency results, sensitivity analysis is carried out to examine how reservoir operating rule parameters influence routed flood frequency. Finally, some suggestions for real-time flood control reservoir operation are presented.

3.1 | Multivariate distribution of flood characteristics

3.1.1 | “Peak–peak” bivariate variables identification

Flood peak, volume, and hydrograph shape are the most critical flood characteristics for flood events. In this study, it is tested that there is no strong correlation between flood duration and peak or volume, so the duration is not included in the multivariate distribution variables. Meanwhile, historic flood hydrograph shape features such as peak time and peak duration are quite diverse, so the hydrograph shape feature is also not considered in multivariate flood frequency analysis. Flood
hydrograph shape selection will be further discussed in Section 3.2.

Therefore, for the two parallel reservoirs, there remain four variables of flood characteristics: (a) flood peak of Mozitan reservoir; (b) flood volume of Mozitan reservoir; (c) Bailianya reservoir flood peak of Bailianya reservoir; and (d) flood volume of Bailianya reservoir. It is large computing burden to construct a four-dimensional multivariate joint distribution, and the results would be complicated to describe. Herein, by analysing the correlation between peak and volume for each reservoir which is shown in Figure 4, it is indicated that there exist fine linear relationships between peak and volume for each reservoir, with $R^2$ value .9336 and .8162, respectively. For simplicity, we choose flood peaks of Mozitan and Bailianya reservoir as dependent variables for bivariate joint distribution (hereinafter referred to as “peak–peak” combinations). In this way,
the four-dimensional multivariate distribution was down-scaled to bivariate distribution, while flood volume corresponding to flood peak can be derived using the peak-volume regression functions in Figure 4.

3.1.2 Non-parametric marginal distribution

Marginal distribution for each dependent variable is the basis for multivariate distribution. Several parametric function types such as Pearson distribution (Kumar, 2019; Rao, 2009), generalised extreme value distributions (Salinas, Castellarin, Viglione, Kohnova, & Kjeldsen, 2014) and Gamma distribution (Chen, Singh, & Xiong, 2017; Nadarajah, 2007), performed well in fitting flood features. However, the parametric approach has its limitations, because the distribution type has to be pre-determined based on prior knowledge which brings uncertainty in distribution type estimation.

To overcome the limitation of parametric approach, a non-parametric method, kernel density estimation (KDE), is applied to estimate marginal distribution (Lux, Hardle, & Lessmann, 2019; Qiao, Escobar, Saupe, Ji, & Soberon, 2017; Sole-Mari, Fernandez-Garcia, Rodriguez-Escales, & Sanchez-Vila, 2017). The KDE method does not require a pre-determined function type, providing better adaptability in estimation of distribution. The KDE-based distribution function is expressed by:

$$\hat{f}_T(x) = \frac{1}{Th} \sum_{i=1}^{T} K\left(\frac{x - x_i}{h}\right)$$  \hspace{1cm} (1)

where $x_1, x_2, \ldots, x_n$ is a random sample with size $T$. $h$ is the bandwidth that determines the smoothness of the estimate. A higher bandwidth will smooth density estimate, which might mask some characteristics of the distribution; while a smaller bandwidth will smooth density estimate, which might exaggerates some characteristics of the sample. $K(.)$ is the kernel density estimator. Commonly used kernels include Gaussian kernel, uniform kernel, Tricube kernel, triangular kernel, and so forth (Matuszyk, Cardew-Hall, & Rolfe, 2010; Santhosh & Srinivas, 2013). For simplicity, a Gaussian kernel was applied in this study.

3.1.3 Copula-based bivariate distribution

Copula theory was introduced by Sklar (1959) to describe the joint distribution of multiple dependent variables. It can be understood as a multivariate cumulative distribution function among several uniform marginal distributions of variables. Taking bivariate copula as an example, given two dependent variables $X$ and $Y$, their joint distribution $C(u, v)$ can be described by a function of their own marginal distributions:

$$C(u, v) = P(X \leq x, Y \leq y)$$  \hspace{1cm} (2)

where

$$u = F_X(x) = P(X \leq x), v = F_Y(y) = P(Y \leq y)$$  \hspace{1cm} (3)

There are basically three types of copula functions that widely used in multivariate flood characteristics modelling: Gumbel, Clayton, and Frank copula type (Chowdhary, Escobar, & Singh, 2011; Ganguli & Reddy, 2013; Gargouri-Ellouze & Chebchoub, 2008). Table 2 presents the function and distribution feature of each copula type.

In this work, the three copulas were applied independently to fit the peak–peak joint distribution. Empirical copula, $\hat{C}(u, v)$, is introduced to evaluate the fitting performance of theoretical copula function:
that both variables exceed certain threshold, expressed as $P$.

Produced in the following sections.

univariate and bivariate flood frequency of natural flood

from the regression functions in Figure 4. In this way,

and their corresponding flood volumes can be derived

combinations with certain frequency can be obtained,

Based on the bivariate distribution of flood peaks, a num-

ber of (peak, peak) samples with this distribution can be

generated using Monte Carlo method, and then flood vol-

umes corresponding to each peak can be derived by the

linear regression function in Figure 4. Traditional hydro-

graph simulation for univariate flood frequency simply

scales typical hydrograph by a fixed ratio to meet the

peak or volume target. For bivariate target ($P_{\text{target}}, V_{\text{target}}$)
in this study, the fixed scale ratio method is unable to

meet both $P_{\text{target}}$ and $V_{\text{target}}$. Here, a variable-ratio scale

method is proposed to simulate hydrograph under fixed

peak and volume:

1. Select a typical hydrograph shape. Since the hydro-

graph shape features including flood duration and peak

time are not significant, in this study, we adopt the

hydrograph shapes used in reservoir planning stage

(Figure 2) to keep consistency and facilitate further result

comparison.

2. Scale flood peak to meet the peak target. Obviously,

the scale ratio at flood peak $\alpha = P_{\text{target}}/\text{peak of typical}

hydrograph}$. 

3. Scale flood inflows for the rest time periods. Denote

inflows for the rest $n$ time periods as $\text{inflow}_i$, the scale

method can be expressed as:

$$\sum_{i=1}^{n} \text{inflow}_i \ast \beta_i = V_{\text{target}}$$

(8)

where $\beta_i$ is the scale ratio for time period $i$, $V_{\text{target}}$ is $V_{\text{target}}$

subtract volume at the peak time step. $\beta_i$ can be either

fixed, or exponential to $x_i$:

$$\beta_i = x_i^k \quad k \geq 0$$

(9)

where $k$ is the exponential parameter that control the

slope of hydrograph. Greater $k$ will lead to a steeper sim-

ulated hydrograph curve, and vice versa. By setting the

exponential parameter $k$, the steepness of hydrograph

shape can be adjusted to better fit the actual hydrograph

of study site.

In this way, hydrographs can be simulated with both

flood peak and volume scaled to determined target,

meanwhile the overall shape of typical hydrograph can

be maintained.

### Table 2: Comparison of Clayton, Frank, and Gumbel copulas

| Copula type | Copula function $C(u,v)$ | Parameter $\theta$ | Feature |
|-------------|--------------------------|-------------------|---------|
| Clayton     | $\max\{u^{-\theta} + v^{-\theta} - 1; 0\}^{-1/\theta}$ | $\theta > 0$ | Sensitive to lower-tail sensitivity |
| Frank       | $-\frac{1}{\beta} \log\left(1 + \frac{(v^\theta - 1)(e^{\theta u\beta} - 1)}{e^{\theta u\beta} - 1}\right)$ | $R'[0]$ | Not sensitive to tail dependence |
| Gumbel      | $e^{-(-\log(u))^\theta + (-\log(v))^\theta}^{1/\theta}$ | $\theta > 1$ | Sensitive to upper-tail sensitivity |

\[
\hat{C}(u,v) = \frac{1}{n} \sum_{i=1}^{n} 1(u_{i1} \leq u_i, v_{i1} \leq v_i) \quad (4)
\]

where $n$ denotes the size of observed samples. $\hat{C}(u,v)$ can be obtained by counting the non-exceedance probability of each historic sample. By comparing the proximity of empirical copula value and theoretical copula value for the sample with length $n$, the best function can be determined. Root-mean-square error (RMSE) is adopted as an indicator to quantify the proximity:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( C(u_i,v_i) - \hat{C}(u_i,v_i) \right)^2} \quad (5)$$

Once the joint distribution is derived, some multivariate flood frequency definitions can be obtained, such as the copula “Or” (denoted as $FC_{or}(u,v)$) and “And” frequency (denoted as $FC_{and}(u,v)$). Since univariate flood frequency is described as $P(X \geq x)$, the copula “Or” frequency denotes the probability that either variable exceeds certain threshold, expressed as $P(X \geq x \lor Y \geq y)$, and the copula “And” frequency denotes the probability that both variables exceed certain threshold, expressed as $P(X \geq x \land Y \geq y)$ (Zhou et al., 2019). $FC_{or}(u,v)$ and $FC_{and}(u,v)$ can be derived from $C(u,v)$:

$$FC_{or}(u,v) = 1 - C(u,v) \quad (6)$$

$$FC_{and}(u,v) = 1 - u - v + C(u,v) \quad (7)$$

Once $FC_{or}(u,v)$ and $FC_{and}(u,v)$ are derived, peak–peak combinations with certain frequency can be obtained, and their corresponding flood volumes can be derived from the regression functions in Figure 4. In this way, univariate and bivariate flood frequency of natural flood can be derived. However, the peak-volume combinations under RFFC need more investigation, which is introduced in the following sections.

#### 3.2 Flood hydrograph simulation

Based on the bivariate distribution of flood peaks, a number of (peak, peak) samples with this distribution can be
3.3 Reservoir routing and risk indicator construction

A generally accepted simple routing strategy is applied here to implement flood routing, shown in Figure 5. Optimal operating rules such as incorporating inflow prediction may decrease overall flood risk, but they are difficult to implement in real-time operation due to lack of information or other realistic constraints, so that the flood risk may be underestimated. Therefore, in order to describe flood risk objectively, the simple but reliable operating rule shown in Figure 5 is adopted in reservoir routing.

For parallel reservoirs in this study, the allocation of peak outflow for each reservoir can be adjusted, as long as their total outflow does not exceed the downstream safety flow, 2,000 m$^3$/s.

The indicator of RFFC denotes the severity of flood risk for each frequency value, which plays an important role in flood frequency curve. In this study, the aggregated flood that stored in the two reservoirs during a flood event ($V_f$ in Figure 5) is taken as indicator of RFFC, as the overtopping risk is proportional to water volume that stored in reservoir during reservoir routing. For the parallel reservoir system, the indicator turns to be ($V_f$, Mozitan + $V_f$, Bailianya). Maximum reservoir water level and maximum flood volume can also describe flood risk during reservoir routing, but they are not the best indicators, because (a) it does not make sense to add up water level of different reservoirs; (b) reservoir flood risk exists in every time step in real-time operation due to inflow uncertainty, while maximum water level or volume is not comprehensive enough to reflect overall flood risk. Therefore, the indicator of RFFC turns to be ($V_f$, Mozitan + $V_f$, Bailianya) in this study.

By iterating the procedure from Sections 3.1 to 3.3, flood risk for each generated peak–peak sample can be derived, and the one-to-one relationship between flood scenario and risk indicator can be obtained.

3.4 Derivation of RFFC

The derivation of RFFC is similar with univariate flood frequency analysis (Eagleson, 1972): the frequency for a flood event is related to the annual exceedance recurrence interval of the given flood. Similarly, the vertical axis of RFFC is the overtopping risk of each calculated flood scenario, while the horizontal axis is the exceedance probability of each risk. Also, the routed flood return period $T_{routed}$ can be derived by means of RFFC:

$$T_{routed} = \frac{1}{\text{RFFC}}$$

4 RESULTS AND DISCUSSION

4.1 Marginal distribution and bivariate distribution

Theoretical marginal distributions for flood peaks of Mozitan and Bailianya reservoir are derived based on KDE. The bandwidth $h$ is defaulted as optimal for normal densities. In this case, the bandwidth for Mozitan peak and Bailianya peak is 280.80 and 394.17, respectively. Figure 6 shows theoretical and empirical marginal distribution for each reservoir.

Three copula function types, Gumbel, Clayton, and Frank were tested to fit the peak–peak samples, and the RMSE for each copula is 0.0575, 0.0187, and 0.0442. The Clayton function has the minimum RMSE, which is appropriate for peak–peak bivariate distribution. Moreover, as Table 2 shows, the Clayton copula is sensitive to lower-tail dependence, thus this is another reason for choosing the Clayton copula as the peak–peak samples concentrate in lower-tail zones.

Parameter $\theta$ in copula function determines the spread degree of copula function. In order to show the influence of $\theta$ on copula distribution, three sets of 10,000 synthetic samples of the “Mozitan peak ~ Bailianya peak” with $\theta$ value at 0.5, 5 and 50 are simulated respectively, which is shown in Figure 7. Obviously, with the increase of $\theta$, the synthetic samples tend to gather closer, and vice versa. In this study, the $\theta$ value is set as 5. To offset the uncertainty of $\theta$ value, a total of 10,000 samples are then generated to simulate flood hydrographs.

4.2 Hydrographs simulation with bivariate copula distribution

Based on the derived copula distribution, a total of 10,000 synthetic peak–peak pairs in Figure 7b are generated to
simulate flood scenarios. Flood volumes are derived from the peak-volume linear regression functions shown in Figure 4. Therefore, we totally simulate 10,000 pairs of flood hydrographs. As explained in Section 3.2, hydrograph shapes in reservoir planning stage (Figure 2) are adopted to simulate flood hydrographs. Parameter $k$ for flood hydrograph steepness is determined by iteration. The $k$ value for Mozitan reservoir and Bailianya reservoir is set as 1 and 1.2.

### 4.3 Reservoir routing and RFFC derivation

The 10,000 pairs of hydrographs were routed through the Mozitan and Bailianya reservoirs following the operating rules in Section 3.3. Here, the maximum release for Mozitan and Bailianya reservoir are set as 600 and 1,400 m$^3$/s, respectively. The RFFC is derived and shown in Figure 8.

### 4.4 RFFC result comparison and discussion

To better illustrate the result derived in this study, the RFFC result is compared with results from univariate and bivariate flood frequencies. Since the RFFC indicator for each synthetic sample in Figure 7b is obtained, flood peaks (X and Y axis) and their corresponding RFFC indicator (Z axis) constitute a three-dimensional surface. Contour lines with certain RFFC indicator can be derived on the surface using interpolation calculation. Similarly, the contour lines of bivariate flood frequency, the copula “Or” and copula “And” definition introduced in Section 3.1.3, can also be derived. Univariate flood frequency
result is a unique value for each reservoir, which is shown as a point in the figure. Results with return periods of 100, 50, and 20 years are taken for comparison. Figure 9 shows peak–peak combinations with four flood frequency definitions: RFFC, \(FC_{or}\), \(FC_{and}\), and univariate frequency. It can be observed that univariate peak values with return period 100 year (Figure 9a) and 50 year (Figure 9b) are mostly greater than the results from other definitions, while univariate result with return period 20 year (Figure 9c) is much less than the other three definitions. This indicates that the univariate flood frequency may probably overestimate flood risk at return period 100 and 50 year, while underestimate flood risk at return period 20 year. Although Figure 9c shows that the Mozitan reservoir peaks in left part of RFFC and copula “Or” contour lines are greater than the univariate results, but actually these combinations rarely happens because of the peak ratios are not proportional with historic records.

It is also indicated from Figure 9 that the RFFC line is always between copula “Or” and copula “And” lines. Since the copula “Or” concept was considered overestimate flood risk and the copula “And” concept was considered underestimate flood risk in previous studies (Requena et al., 2013; Salvadori & de Michele, 2004; Volpi & Fiori, 2014), it can be seen that the RFFC result is more objective in estimating real flood risk than the other results.

In summary, by comparing the four results of flood frequency under three return periods, it can be concluded that the result of flood frequency may vary a lot when adopting different frequency definitions, although this has been overlooked in many cases. For instance, the univariate flood frequency, as a popular flood frequency method, shows unstable estimation in different return periods. The result of RFFC definition proposed in this study is relatively neutral and stable. Therefore, it is
recommended that instead of single flood frequency definition, more comprehensive flood frequency results should be carried out and discussed for actual flood analysis, especially for study site influenced by multi-reservoir operation.

4.5 | Sensitivity analysis

4.5.1 | Response of RFFC to reservoir maximum release allocation

Maximum release allocation between parallel reservoirs plays an important role in overtopping risk. An optimal allocation of flood peak release can significantly decrease flood risk (Hui & Lund, 2015; Wang, Yoshitani, & Fukami, 2005). Here, a sensitivity analysis is carried out to illustrate the impact of maximum release allocation to RFFC.

Given the maximum total release of the two reservoirs 2,000 m$^3$/s, we set 10 maximum release allocation combinations of Mozitan and Bailianya reservoirs: (100 m$^3$/s, 1,900 m$^3$/s), (300 m$^3$/s, 1,700 m$^3$/s), (500 m$^3$/s, 1,500 m$^3$/s), (700 m$^3$/s, 1,300 m$^3$/s), (900 m$^3$/s, 1,100 m$^3$/s), (1,100 m$^3$/s, 900 m$^3$/s), (1,300 m$^3$/s, 700 m$^3$/s), (1,500 m$^3$/s, 500 m$^3$/s), (1,700 m$^3$/s, 300 m$^3$/s), (1,900 m$^3$/s, 100 m$^3$/s), and derive RFFC for each combination, shown in Figure 10. It is indicated from Figure 10a that the RFFC curve gradually falls down when the release allocation switches from (100 m$^3$/s, 1,900 m$^3$/s) to (900 m$^3$/s, 1100 m$^3$/s), illustrating an overall decrease in flood risk. On contrast, when release allocation switches from (1,100 m$^3$/s, 900 m$^3$/s) to (1,900 m$^3$/s, 100 m$^3$/s), the overall RFFC curve rises, indicating that overall flood risk increases, shown in Figure 10b. This trend reveals that a balanced flood release allocation between two reservoirs can decrease overall routed flood risk. This conclusion does not mean the optimal release allocation scheme is exactly at (1,000 m$^3$/s, 1,000 m$^3$/s), for the optimal allocation is dependent on multiple issues, such as hydrographs, flood storage capacity of each reservoir, and so forth, but it still provides some reference for water managers seeking for optimal maximum release allocation in a parallel structure reservoir system.

4.5.2 | Response of peak–peak contour lines to reservoir maximum release allocation

As introduced above, by adjusting maximum release allocation, the RFFC and peak–peak contour lines will change. To illustrate the changing trend of peak–peak contour lines, peak–peak contour lines with different maximum release allocations are drawn on the same coordinate. Results with return period 100, 50, and 20 years are shown, respectively, in Figure 11. It should be noted that the contour lines intersect with each other because their maximum release allocation schemes are different.

Figure 11 shows that the peak–peak contour lines with different maximum release allocations constitute a “bowtie-shaped zone.” By comparing the three figures with different return periods, it can be found that the bowtie shapes are partly overlapped in the edge zones. Since all the peak–peak combinations within the bowtie zone in each figure have the same routed flood frequency as long as they are operated at the given release allocation policies, we can deduce that the peak–peak combinations in the both edges of “bowtie edge zone” are relatively not sensitive to routed flood frequency, because their routed flood frequency can be equal by adjusting maximum release allocation schemes; however, the peak–peak combinations in the bowtie curve intersection zone are quite sensitive in routed flood frequency, because no matter how we adjust the maximum release allocation scheme, the contour lines still intersect with each other and concentrate in a very narrow range.

The above analysis provides some useful references for reservoirs real-time operation. First, if there happens...
flood coincidence with peak–peak combination at the bowtie intersection value, reservoir operation deciders should pay special attention to flood prediction—a tiny change in flood peak will cause different overtopping risk as well as routed flood frequency, whereas flood peak allocation adjusting will not be helpful. Second, if the peak–peak combination of coming flood event lies in the peaks in bowtie edge zone, one peak–peak combination may lead to different routed flood frequencies because these zones of different return periods are partly overlapped. In this circumstance, more attention should be paid to minimise flood overtopping risk by adjusting the maximum release allocation. In summary, the RFFC contour line sets provide real-time operation strategies on different flood characteristic coincidence scenarios.

The reason of the “bowtie-shaped zone” can be further explained. It can be found from Figure 11 that the slope of each contour line is negative, but the slopes of different contour lines are different. To illustrate the difference in slope, we take two contour lines with maximum release allocation (700, 1,300) and (1,500, 500), for instance, shown as green line and blue line in Figure 12. When the Mozitan reservoir flood peak increase from 3,000 to 4,000 m³/s, the vertical decrease of the (700, 1,300) contour line (denoted as Δ1) is greater than that of (1,500, 500) contour lines, which is denoted as Δ2.

5 | CONCLUSION

Flood frequency is an important foundation of flood severity evaluation and real-time reservoir operation. This article implemented a RFFC for parallel reservoirs, and compared it with other definitions in detail. The proposed RFFC presents actual flood risk with respect to multivariate flood characteristics, flood coincidence and reservoir operating rules. Comparisons of results from RFFC, traditional univariate flood frequency, bivariate copula “Or” and copula “And” flood frequency reveal that: (a) with each factor of flood frequency definition added, the flood frequency form increases by one more dimension: univariate flood frequency result is a fixed value (point), while bivariate “Or” and “And” frequency result is a set of combinations (line), and the RFFC result comprising reservoir routing is a zone (plane); (b) RFFC provides relatively objective estimation on flood frequency, while traditional univariate frequency may over- or under- estimate flood frequency in different return periods. Sensitivity analysis was carried out to test the
response of RFFC results to parallel reservoirs maximum release allocation schemes. It is indicated that a balanced release allocation can significantly decrease overall flood storage as well as overtopping risk; different operating strategies are recommended for different flood peak–peak combination scenarios in real-time operation to minimise overall flood overtopping risk. The findings of this article provide references for actual flood risk assessment and real-time reservoir flood operation from integrated flood frequency point of view.

The framework of RFFC proposed in this study is applicable to various reservoir structures that are not limited to parallel reservoir structure, while the RFFC indicator needs more exploration. For instance, only upstream risk is considered in this study, because the downstream is assumed safe all the time based on operating rules. Future research on RFFC indicator might address more issues considering reservoir structures and flood risk sources. This is a key component in future research to extend the RFFC methodology framework to various reservoir structures.

ACKNOWLEDGEMENTS

This work has been supported by the National Science and Technology Major Project of China (grant No. 2017ZX07603-002) and Natural Science Fund of Anhui Province (grant Nos. 2008085ME158, 2008085ME159).

DATA AVAILABILITY STATEMENT

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**How to cite this article:** Zhou, T., & Jin, J. (2021). Comparative analysis of routed flood frequency for reservoirs in parallel incorporating bivariate flood frequency and reservoir operation. *Journal of Flood Risk Management*, e12705. https://doi.org/10.1111/jfr3.12705