Flood season partition and flood limit water level determination for cascade reservoirs downstream Jinshajiang River

Bin Ju¹, Yucong Yu²³, Fahong Zhang¹, Xiaohui Lei⁴ and Fenghua You²³

¹Power China Huadong Engineering Corporation Limited; ²College of water resources and environment, Chang'an University, Xi’an, Shanxi 710054, China; ³Key Laboratory of Subsurface Hydrology and Ecological Effects in Arid Region of Ministry of Education, Chang’an University, Xi’an, Shanxi 710054, China; ⁴China Institute of Water Resources and Hydropower Research, 20 West Chegongzhuang Road, Haidian District, Beijing 100048, People’s Republic of China.

Abstract. The internal contradiction between flood risk and power generation benefit can be alleviated by studying the flood season and flood limit level of reservoir. It is of great significance to adjust the floodwater storage in flood season. In this paper, based on the normal distribution theory improved fuzzy set analysis method, according to the inflow flood of cascade reservoirs downstream Jinshajiang River, the flood season is divided into stages. The flood limit water level of cascade reservoir is determined by the mapping relationship between subordinate degree and flood control storage capacity. An intertemporal sampling method is proposed to correct the staging results and flood limit water level. The research results show that the end of the pre-flood season of cascade reservoirs downstream Jinshajiang River is July 15, and the beginning of the post-flood season is September 16, and the reasonable flood limit water levels of the four reservoirs from upstream to downstream are 962m, 800m, 575m and 374m respectively. The rationality of the stage flood limit water level is tested by the flood process with different typical flood magnification. The results of the lower stages of the Jinshajiang River and the stage water level of each reservoir can improve the economic benefits such as reservoir power generation and improve the utilization ratio of flood resources in flood season to a certain extent.

1. Introduction

The dynamic control of flood limit water level of reservoir not only conforms to the statistical law of flood change, but also can make use of flood resources as much as possible on the premise of ensuring flood control safety [1]. For a long time, many domestic and foreign scholars used different methods to carry out a lot of research on flood season and flood limit water level (the highest water level in a reservoir before a flood) of reservoirs [2-8]. The common methods of systematic clustering method [9], variable point analysis [10] and Fisher's optimal segmentation [11] etc. However, different methods may lead to inconsistent and even contradictory results, even great differences of flood season stages. Moreover, flood season is a "fuzzy phenomenon" [12], while flood season stages also have strong fuzzy attributes, and the single method has strong subjectivity and limitations.
Li studied flood season staging using an improved fuzzy set analysis [13]. He proposed a mean change point analysis method of flood season staging according to the change point to overcome the deficiency of subjective determination of threshold. Therefore, this paper use an improved fuzzy set analysis method based on normal distribution theory to stage the flood season of cascade reservoirs downstream Jinshajiang River. The mapping relation between membership degree and flood control reservoir capacity is used to determine the water level of fuzzy stage in flood season. Then, the intertemporal sampling method is adopted to improve the flood season staging results and the corresponding flood limit water level, so as to reduce the deficiency of the subjective determination threshold. Finally, the results are tested through the flood process amplified by different typical floods.

2. Methodology

2.1. Improved fuzzy set analysis method

The normal distribution function is adopted in this paper to fit the empirical membership function [14]. The membership function of itd from pre-flood season to main flood season is the left half of normal distribution, while the membership function of itd from main flood season to backward flood season is the right half of normal distribution. That is, equation (1).

\[
\mu_A(t) = \begin{cases} 
  \frac{1}{\sqrt{2\pi}b_1} e^{-\frac{(t-a_1)^2}{2b_1^2}}, & t < a_1, b_1 > 0 \\
  1, & a_1 \leq t \leq a_2 \\
  \frac{1}{\sqrt{2\pi}b_2} e^{-\frac{(t-a_2)^2}{2b_2^2}}, & t > a_2, b_2 > 0
\end{cases}
\] (1)

where \( a_1 \) and \( a_2 \) are the main start and end times of the flood season, and \( b_1 \) and \( b_2 \) are the parameters related to the flood control reservoir capacity at the earliest and latest time of the flood season. Through the mapping relation between membership degree and flood control storage, the fuzzy flood limit water level of the reservoir is determined.

\[
V_{ic} = \mu_A(t) \ast V_c
\] (2)

\[
V_{wc} = V_{min} + (1 - \mu_A(t)) \ast V_c
\] (3)

Where \( V_{ic} \) is the flood storage capacity required at different time periods, \( V_c \) is the flood control capacity of the reservoir, \( V_{min} \) corresponds to the reservoir capacity of the flood limit water level in the main flood season, \( V_{wc} \) represents the current storage capacity of the reservoir.

2.2. Intertemporal sampling method

As shown in Figure 1, the fuzzy flood limit water level is obtained based on the results of cascade reservoir flood season, forward and backward extension, get before the flood season and after the flood season staging time and flood limit water level. It is not only convenient for the practical operation of reservoir, but also can improve the flood control safety in flood season, and reduce the shortage of subjective threshold determined by fuzzy set analysis.

![Figure 1. Sample of cross-phase sampling method.](image)
3. Research area and data processing

3.1. Study area overview
Jinshajiang River basin is located in the upper reaches of the whole Yangtze river basin, covering 502,000 km². The Jinshajiang river basin spans the east longitude of 90° ~ 105° and the north latitude of 24° ~ 36°. On the main stream of downstream Jinshajiang River, the four reservoirs of Wudongde, Baihetan, Xiluodu, Xiangjiaba form cascade reservoirs. It has a planned total installed capacity of 41.16 million KW and an average annual generating capacity of 175.36 billion KWH for many years, which is equivalent to two Three Gorges reservoirs and site distribution are shown in Figure 2.

![Figure 2. Distribution diagram of cascade reservoirs and stations in the lower reaches of Jinsha river.](image)

3.2. Classification of cascade reservoir flood season
Analysis and calculation of flood season of Jinshajiang cascade reservoir take Wudongde reservoir as an example. The flow data of Panzhihua hydrological station, Ertan hydrological Station, Qiaojia hydrological Station and corresponding dam site in Jinshajiang River basin are sorted out. The time of the first flood and the end time of the last flood in Wudongde Reservoir and Baihetan Reservoir during the flood season of 54 years (June to October) from 1965 to 2018 is obtained. From this can roughly determine the flood season of Wudongde reservoir for June 24 solstice October 14. According to the traditional fuzzy set analysis method, the fuzzy set A of flood season is set as solstice of July 1, September 30. The empirical membership was calculated according to equation $P_A(t) = \frac{n_t}{n}$, where $n_t$ represents the number of times of fuzzy set A belonging to flood season, $n$ is n test results obtained from n years of flow data.

The empirical membership frequency is affected by the years of data and other subjective factors. The empirical membership frequency is generally not stable enough, so equation (1) can be used to deduce the fitting membership function value from the normal distribution theory. According to Figure 3, it can be seen that: $a_1$ = August 3, $a_2$ = August 6; Then equation (4) and equation (5) can be used to deduce the values of $b_1$ and $b_2$

$$b_1 = \frac{1}{n} \sum_{i=1}^{n} (a_i - \mu)^2 \ln[\mu(a_i)]$$

$$b_2 = \frac{1}{n} \sum_{i=1}^{n} (a_i - \mu)^2 \sum \ln[\mu(a_i)]$$

$P_A(t) = \frac{n_t}{n}$, where $n_t$ represents the number of times of fuzzy set A belonging to flood season, $n$ is n test results obtained from n years of flow data.

$P_A(t) = \frac{n_t}{n}$, where $n_t$ represents the number of times of fuzzy set A belonging to flood season, $n$ is n test results obtained from n years of flow data.
Table 1. Table of fitting membership degree and threshold correction results of fuzzy set A of Wudongde reservoir.

| Date                  | Fitting membership | Membership after the threshold is modified |
|-----------------------|--------------------|------------------------------------------|
| 07.01-08.02           | 0.231-0.999        | 0.231-0.897                              |
| 08.03-08.06           | 1                  | 1                                        |
| 08.07-09.30           | 0.999-0.393        | 0.895-0.393                              |

Using the method above, the Baihetan reservoir, Xiluodu reservoir and Xiangjiaba reservoir are divided into flood season stages. Due to the lack of data and the geographical location of cascade reservoir and storage capacity of the relationship, the stage results of Baihetan reservoir are used in Xiluodu reservoir and Xiangjiaba reservoir. In order to make the membership function value display more clearly, Figure 3 membership function curves of fuzzy set A of Wudongde reservoir flood season and Figure 4 membership function curves of fuzzy set A for Baihetan reservoir flood season are drawn.

![Figure 3](image1.png)  
![Figure 4](image2.png)

By comparing the flood season staging results of four reservoirs, that is, comparing the modified fitting membership function of four reservoirs and qualitative analysis, this paper unifies the flood season staging results of cascade reservoirs in Jinshajiang River basin. Pairs are shown in Table 2.

Table 2. Comparison of flood season results of cascade reservoirs.

| Cascade reservoirs | The results by installments |
|-------------------|-----------------------------|
|                   | pre-flood season | major flood period | later flood season |
| Wudongde reservoir| 06.24-07.26       | 07.27-08.24       | 08.25-10.14       |
| Baihetan reservoir| 06.01-07.25       | 07.26-08.27       | 08.28-10.14       |

Considering the flood control safety of reservoirs, the results of flood season staging should be more in the direction of safety. Therefore, the results of flood season staging of Baihetan reservoir are adopted as the results of flood season staging of cascade reservoirs. That is, June 1 to July 25 for the prior flood season, July 26 to August 27 main flood season, August 28 to October 24 for the later flood season.

4. Results and tests

4.1. Cascade reservoir flood limit water level

The results of flood season staging of cascade reservoir are not enough to determine the flood limit water level of cascade reservoir. Therefore, according to Equations (2) and (3), the flood control storage required for each period should be calculated, so as to calculate the reservoir capacity. According to the relationship between reservoir water level and reservoir capacity, the flood limit water level in different periods is calculated.
With the actual situation of reservoir operation, the inter-period sampling method is used to correct the flood limit water level and staging results of cascade reservoirs, as shown in Figure 5. Therefore, June 1 to July 14 is the pre-cascade reservoir flood season, September 17 to October 24 is the post-cascade reservoir flood season, and the reasonable flood limit water levels of the four reservoirs from upstream to downstream are 962m, 800m, 575m and 374m. July 15 to September 16 is the main flood season of cascade reservoir, the flood limit water level is 952m, 785m, 560m, 370m.

4.2. Results of inspection

Table 3. Typical flood simulation scheduling in 1966 and 1974.

| Staging period        | typical flood simulation scheduling in 1966 |                  | typical flood simulation scheduling in 1974 |                  |
|-----------------------|---------------------------------------------|------------------|---------------------------------------------|------------------|
|                       | recurrence interval | maximum discharge of cascade reservoir | Cascade flood reservoir capacity utilization rate | Maximum peak clipping of cascade | recurrence interval | maximum discharge of cascade reservoir | Cascade flood reservoir capacity utilization rate | Maximum peak clipping of cascade |
| Pre-flood and later flood seasons | 1% 20000 0.942 0.356 | 2% 20000 0.871 0.306 | 5% 20000 0.740 0.226 | 20% 15135 0.662 0.270 | 1% 20000 0.975 0.350 | 2% 20000 0.912 0.300 | 5% 17815 0.675 0.303 | 20% 14060 0.563 0.313 |
| Major flood period    | 1% 18399 0.705 0.407 | 2% 18319 0.605 0.365 | 5% 16120 0.547 0.376 | 20% 13245 0.393 0.361 | 1% 18311 0.697 0.405 | 2% 18101 0.496 0.366 | 5% 15670 0.409 0.387 | 20% 13245 0.257 0.353 |
In order to ensure that the results of flood season and flood limit water level meet the flood control safety and economic benefit of Jinshajiang cascade reservoir. Therefore, the flood process amplified by typical floods in the lower Jinshajiang River basin in 1966 and 1974 was used to conduct simulated dispatching [15]. As shown in Table 3, Cascade flood reservoir capacity utilization rate refers to the proportion of maximum occupancy of flood control storage capacity when flood comes. Maximum peak clipping of the cascade is the proportion of the maximum clipping peak to the original peak.

5. Conclusion
The results of this paper can meet the economic and safety benefits of Jinshajiang River cascade reservoir. It has ensured the flood control targets in the lower reaches of Jinshajiang River to control flood safely and allocate flood resources rationally, thus contributing to the flood control safety and rational allocation of water resources in the Yangtze river basin. The following conclusions are drawn:

(1) The flood season staging results of Jinshajiang cascade reservoir are as follows: June 1 to July 14 is the pre-flood season, July 15 to September 16 is the main flood season, September 16 to October 24 is the post-flood season.

(2) In the pre-flood season and post-flood season, the flood limit water level of cascade reservoirs is 962m, 800m, 575m and 374m, respectively; in the main flood season, the flood limit water level is 952m, 785m, 560m and 370m, respectively.

(3) The flood process amplified in typical years of 1966 and 1974 was used for testing. On the premise of meeting flood control requirements, the average utilization rate of flood storage capacity was increased by 25%. Under the circumstance that the flood occurs once every five years, the storage capacity of the reservoir in the former flood season and the later flood season has even increased by about 30%.

Acknowledgement
The authors acknowledge the financial supported by the key research and development project of Shanxi Province (No. 2019SF-237); the Fundamental Research Funds for the Central Universities, CHD (Program No. 300102299206, 300102269201), and the Xi’an Construction Science and Technology Planning Project (SJW2017-11).

References
[1] Xia Z, Penglin W, Xueping Z 2019 J. Yellow River in Chinese 41(02) 54-58+63
[2] Chongxun M, Dayang W, Xinrong Z, Yuli R, Guiyan M, Yitong L 2017 J. Hydraulic power in Chinese 43(06) 19-22+27
[3] Jiabiao W, Weihong L, Xiaojie F et al 2018 J. Water Resources and Hydropower Engineering in Chinese 49(1) 36-41
[4] Jiang H, Wang Z, Ye A, et al 2019 J. Environmental Earth Sciences 78(14) 399
[5] Lihua C, Zihao P, Weifu L, Xiang T 2019 J. Hydraulic power in Chineses 45(05) 17-21
[6] Mo C, Mo G, Liu P, et al 2018 J. Hydrological sciences journal 63(6) 926-937
[7] Mo C, Mo G, Yang Q, et al 2018 J. Water Science and Engineering 11(1) 81-87
[8] Rurui Z, Guohua L, Huicheng Z, Lin L, Min L, Bende W 2013 J. Journal of Water Resources & Water Engineering in Chinese 24(06) 145-148
[9] Shanshan L, Xingyuan S, Yanjun Z, Lin Y, Lu L, Di Y. 2012 J. Water Resources and Power in Chinese 30(02) 44-48
[10] Qian G, Pan LIU, Gaohong X, Honggang Z, Liping L 2012 J.JOURNAL OF HYDROELECTRIC ENGINEERING in Chinese 31(04) 39-43
[11] Xing T, Xiaobin W, Hui Y 2017 J.JIANGXI HYDRAULIC SCIENCE & TECHNOLOGY in Chinese 43(01) 23-26
[12] Zhangkang S, Ji L, Xiaohua D, Dan Y 2017 J. Journal of Hydroelectric Engineering in Chinese. 36, 7 55-64
[13] Jun L 2017 J. Journal of Yangtze River Scientific Research Institute in Chinese 34(12) 12-16
[14] Yujie L 2008 *Xi’an University of Technology in Chinese*

[15] Zhao L, Jiawei L, Zhifeng J, et al 2019 *J. Water*. **11**(6) 1134