Joint Operation of Reservoirs on Upper Yangtze River Facing new challenges

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Abstract. Suffering strong El Nino, the middle and lower reaches of the Yangtze River experienced extreme rainfall anomalies during the Bai-U rainy period (19th Jun. to 20th Jul.) in 2016. The 21 reservoirs including Three Gorges reservoir in upper Yangtze River were operated together to control flood. Most of these reservoirs are distributed on Jinsha River, Ya-lung River, Min River, Chia-ling River, and Wu River. They totally offered about 37.3 MAF available storage with 29.2 MAF for flood storage. This paper analysed the operation performance of the 21 reservoirs during the Bai-U rainy period. It evaluated the joint operation performance of 21 reservoirs, and proposed suggestions for multi-reservoir management of Yangtze River upstream in the future. The experience of operating multiple large reservoirs would inspire others to utilize reservoirs crossing multiple rivers solving flood problems in a better way, facing the new challenges from climate change.

1. Introduction

Last summer, a strong El Nino-fueled Bai-U rainy period (19th Jun. to 20th Jul.) generated unusually huge precipitation among Yangtze River Basin (YRB). The precipitation presented characteristics with long rainy period, huge rainfall, high intensity, concentrated raining locations. During the Bai-U rainy period, mostly rainfall struck the lower Yangtze River where accumulative precipitation (584.3 mm) is twice as much as the average precipitation of past 30 years (281.0 mm). The precipitation ranks 3rd among other historical precipitation during Bai-U rainy period, after CY1954 (811.5 mm) and CY1996 (695.7 mm) [1]. On 1st July 2016, the river inflow of Three Gorges Reservoir reached 50,000 m³/s, the flood was labelled as “the No.1 Flood 2016” of Yangtze River.

There were 21 reservoirs on upper Yangtze River participated in the joint operation for flood protection. The article presents the results of a comprehensive assessment of their operational performance during the Bai-U rainy period 2016. The assessment included an evaluation of unregulated flows without flood control by these 21 reservoirs. It also identified opportunities to better utilize the flood resource.

2. The Yangtze River Basin

The river above Yichang Station is called the upper Yangtze River and its watershed are 247 M acres. Generally, all running reservoirs in YRB whose maximum allowable storage is larger than 0.08 MAF should be included in the joint operation to control flood, i.e., 102 reservoirs with more than 64.9 MAF storage capacity and 32.1 MAF flood control pool. Based on comprehensive consideration of...
flood control ability and structural situations, 21 reservoirs were selected to be included in the joint operation. Their storage capacity is 37.2 MAF and flood control pool is 29.4 MAF. These reservoirs are Liyuan, Ahai, Jinanqiao, Longkaikou, Ludila, and Guanyinyan on the midstream of Jinsha River, Jinping I and Ertan on Ya-lung River, Pubugou and Zipingpu on Min River, Xiluodu and Xiangjiaba on the lower Jinsha River, Bikou, Baozhusi, Tingzikou and Caojie on Chia-ling River, Goupitan, Silin, Shatuo and Pengshui on Wu River, and Three Gorges, with details in Figure 1.

![Figure 1. The 21 reservoirs in YRB for joint operation to control flood in 2016.](image)

3. Unregulated flows

3.1. The model

The data covers inflows, outflows, and storage of 21 reservoirs and three hydrometrical stations (Cutan, Wulong, and Yichang) from 1st June to 19th July in 2016 with 6h as a time interval. There are two kinds of inflows to Three Gorges because of its huge channel-like reservoir zone. One is the total reservoir inflows at the ending points of its backwater zone. And another (the dam-site inflow) is the river runoff at the dam site of Three Gorges.

The stored water during a time interval by each reservoir was calculated respectively by water balance method and was turned into the stored flow. The travel time of outflows from one reservoir to another inside a cascaded-reservoir system were ignored, which means that one cascaded-reservoir system was considered as one virtual reservoir. There are two virtual reservoirs on Jinsha River, and one virtual reservoir on Ya-lung River, Min River, Chia-ling River, and Wu River respectively.

3.2. The methods

Hydrometrical stations Cutan and Wulong station were selected as the ending points of backwater zone of Three Gorges [2]. Cutan and Wulong represent the reservoir inflows of Three Gorges. 6 hydrometrical stations named Panzhihua, Xiaodeshi, Pingshan, Gaochang, Beibei, and Wulong were selected to represent the discharges of 6 virtual reservoirs on Jinsha River, Ya-lung River, Min River, Chia-ling River, and Wu River.

The stored flow routing from Pingshan station and Gaochang station to Cutan station utilized the Muskingum Method. And the stored flow routing in other parts of rivers utilized a linear time-delay method.

The unregulated reservoir inflow of Three Gorges without storage by other 20 reservoirs is calculated by:
\[ \Delta Q_c(t) = f_{p,c}\left(\sum_{i=1}^{8}\Delta Q_i(t - 8\Delta t) + \sum_{i=9}^{10}\Delta Q_i(t) + f_{g,c}\left(\Delta Q_{14}(t - 5\Delta t) + \Delta Q_{12}(t - 4\Delta t)\right) + \sum_{i=13}^{14}\Delta Q_i(t - 10\Delta t) + \Delta Q_{15}(t - 9\Delta t) + \Delta Q_{16}(t - \Delta t)\right) \]

\[ \Delta Q_w(t) = \sum_{i=1}^{\Delta t}\Delta Q_i(t) \]

\[ \Delta Q_i(t) = (V_i(t) - V_i(t - \Delta t))/\Delta t \]

Where \( Q_{221}(t) \) is the unregulated reservoir inflow of Three Gorges in cms, \( Q_c(t) \) and \( Q_w(t) \) are actual flows at Cutan station and Wulong station respectively, \( Q_{c,w,21}(t) \) is actual runoff of Three Gorges’ reservoir zone, \( \Delta Q_c(t) \) is the total stored flows of five virtual reservoirs on the upper river of Cutan station, \( Q_w(t) \) is the total stored flows of five virtual reservoirs on the upper river of Wulong station, \( f_{p,c}(\ast) \) and \( f_{g,c}(\ast) \) is the Muskingum function of flow routing from Pingshan to Cutan and from Gaochang to Cutan respectively, \( \Delta Q_i(t) \) is the average flow of reservoir i stored at time t, and \( \Delta t \) is the time interval (6 hours).

The unregulated flow at Yichang station without storage by 21 reservoirs is calculated by:

\[ Q'_y(t) = q_{221}(t) + \Delta Q_{221}(t) + \Delta Q_{c}(t - 10\Delta t) + \Delta Q_{w}(t - 9\Delta t) \]

Where \( Q'_y(t) \) is the unregulated flow at Yichang station in cms, and \( q_{221}(t) \) is the actual discharge of Three Gorges.

### 3.3. Result analysis

Bureau of Hydrology (BOH) of Changjiang Water Resources Commission (CWRC) utilized a similar way to calculate the reservoir inflow of Three Gorges [2]. As for the unregulated flow at Yichang station, BOH utilized hydrological models of MIKE 11 to calculate the flow routing of reservoir inflow from Cutan and Wulong to Three Gorges’ dam site and rainfall run-off model NAM to calculate the runoff of Three Gorges’ reservoir zone [3, 4]. The proposed method was testified by floods event in August 2009 and July 2010, and results were compared to reference [3] and [4], which is shown in Table 1.

| Flow at Yichang station (m³/s) | Flood event in August 2009 | Flood event in July 2010 | Unregulated max. flow without storage by Three Gorges | Unregulated max. flow without storage by Three Gorges |
|-------------------------------|---------------------------|--------------------------|-----------------------------------------------------|-----------------------------------------------|
| Actual max. flow              | Actual max. flow          |                          |                                                     |                                               |
| Reference [3]                 | 40200                     | 56100                    | -                                                   | -                                             |
| Reference [4]                 | -                         | -                        | 42000                                               | 65000                                         |
| Proposed method               | 39800                     | 56100                    | 41500                                               | 67200                                         |
| Deviation                     | 0.7%                      | 4.2%                     |                                                     |                                               |

The BOH method is complicated and requires lots of input data. The proposed method is relatively easy and needs less input data. The comparisons illustrate that proposed method is acceptable to calculate the unregulated flow at Yichang station for academic study. But the reservoir type and time interval length will affect the result reliability of the proposed method. If the reservoir inflow is low, the result will follow a sawtooth pattern. To the Three Gorges as a channel reservoir, its generated unregulated flow would be affected obviously by its backwater and show a sawtooth pattern (Figure 2, 3).
4. Joint operation of 21 reservoirs for flood control

4.1. Operation manual

CWRC has been in charge of operating reservoirs in YRB for flood control. At 30th June 2016, CWRC issued an annual operation manual (OM) about joint operation of 21 reservoirs on upper Yangtze River for flood control. The OM was drafted by the Changjiang Institute of Survey, Planning, Design and Research (CISPDR), which was made to offer suggestions to CWRC and other stakeholders for water management. It divided 21 reservoirs into 3 categories (one heart, two backbones, and five hands) according to their storage capacity and locations. According to the OM, Three Gorges as the heart should undertake most work for flood control to protect the middle and downstream of Yangtze River. Two backbones are Xiluodu reservoir and Xiangjiaba reservoir, which should be the backbone to help Three Gorges with reducing flood flowing to the downstream. Five hands are referring to five cascaded reservoir systems on Jinsha River, Ya-lung River, Min River, Chia-ling River, and Wu River respectively. These systems were supposed to help reduce reservoir inflow of Three Gorges, so the Three Gorges could store more flood for its downstream.

During the Bai-U rainy period 2016, the Three Gorges was operated by CWRC during four subperiods: 1) from 5th June to 25th June, the reservoir stage had been kept around 144.9 m to 146.5 m, 2) from 25th June to 3rd July, the first and strongest flood event in 2016 occurred and the Three Gorges had been kept a discharge at 31000 m$^3$/s, 3) from 3rd July to 16th July, Three Gorges released 1.12 MAF over three days and then kept its discharge around 20000 m$^3$/s during last days, and 4) from 16th July to 19th July, Three Gorges released water with rate around 25000 m$^3$/s but its outflows were made smaller than its inflows. Other reservoirs on Jinsha River, Min River and Ya-lung River had been operated to reduce inflows of Three Gorges from 25th June to 19th July.
4.2. Operation performance
From 5th June to 19th July 2016, 21 reservoirs on the upper Yangtze River accumulatively stored 11.30 MAF flood (as shown in Figure 4), of which the Three Gorges reduced 4.11 MAF flowing to its downstream. As the heart of flood control system in YRB, the Three Gorges stored 36% of totally reduced flood to lower Yangtze River from 5th June to 19th July. During the No.1 Flood 2016 event, Three Gorges decreased the peak value from 50000 m³/s to 31100 m³/s, once stored 2.4 MAF flood for 6 hours. Without Three Gorges, the river stage of Chenglingji station at the lower Yangtze River will be 34.5m exceeding its insuring stage with 0.1 m and the high stage may last for two days [5].
Other 20 reservoirs made the reservoir inflow of the Three Gorges kept as about 30000 m³/s from 3rd July to 19th July, with a maximum cut of inflows at 9860 m³/s, which let the Three Gorges could safely keep a low discharge to its downstream where the river stages had been higher than their warning stages for a long time.
- From 25th June to 10th July, reservoirs on the midstream of Jinsha River and Ya-lung River were the main force of storing runoff from the upper YRB.
- From 10th July to 19th July, reservoirs on the lower Jinsha River, Ya-lung River and Min River were the main force of storing runoff from the upper YRB. Reservoirs on Chia-ling River and Wu River also helped a little with reducing reservoir inflows of Three Gorges.

These 21 reservoirs together protected 9 provinces and about 100 million people in YRB. More than 82,000-acre farm lands were saved from flood.

4.3. Challenges and principles
- Dynamical allocation of cascaded flood control spaces
From 10th July to 19th July, the Three Gorges had been stored huge flood since 25th June and its reservoir stage was increasing rapidly. If the reservoir stage of Three Gorges is higher than 155m, it should stop store flood for the lower Yangtze River to leave enough flood control space for the midstream. However, the lower Yangtze River were still in need of help from Three Gorges. Since the river runoff in upper Yangtze River was low-risk, other 20 reservoirs on the upstream were supposed to store water that would reduce reservoir inflows of Three Gorges.
The OM suggested reservoirs on the midstream of Jinsha River and on the Ya-lung River should help Three Gorges store flood at first, then other 13 reservoirs would do a favor if necessary. So, during the beginning 10 days of July 2016 when heavy rainfall struck the upper Yangtze River, reservoirs on the midstream of Jinsha River and Ya-lung River had been storing flood water together with Three Gorges. The operation of cascaded reservoir systems should be dynamic and flexible, so flood control pools of reservoirs on different rivers could exchange with each other.
- Dynamical reservoir stage during flood season
Normally Xiluodu and Xiangjiaba should keep their stages not higher than their flood control pool level from 1st July to 10th September. So, reservoirs could leave enough space to fight against possible huge flood events. During last Bai-U rainy period, the peak values of Xiluodu and Xiangjiaba’s inflows were 10,500 m³/s and 12,500 m³/s respectively and both were smaller than the
peak values of their designed flood events with 5-year return period (28,200 m³/s). So, it is acceptable for these two reservoirs to keep their stages higher than their flood control pool levels.

The limiting stage of one reservoir during flood season normally was designed without considering help from other reservoirs’ flood control spaces. The truth is that keeping all reservoirs’ stages under the limiting stages may be not necessary, especially when the flood is not big. To a cascaded reservoir system on one river, let the upstream large reservoirs keep all flood control spaces of the system that other reservoirs could running with higher water stages. Optimize the order of storing and releasing water among these reservoirs could make it possible to reutilize the water from upstream to downstream for hydropower generation with higher average head water.

- Forecast informed reservoir operations under climate change

To insure enough flood control space, Tingzikou is supposed to keep its reservoir stage below 447m from 21th June to 31th August every year. Last April and May, the runoff in Chia-ling River was about 40% larger than its contemporaneous average runoff. So, it is understandable that Tingzikou released water earlier in May and its stage was about 5 meters lower than its flood control pool level (447 m) on 1st June. At the beginning of June, Tingzikou stored some water and released them immediately since 5th June because that its inflows were increasing obviously by then. It was supposed to release more space for possible big flood in June. But Chia-ling River’s runoff in last June and July was actually about 40% smaller than its contemporaneous runoff. If it had stored water in the beginning of last June, Tingzikou could have been operating safely with a higher stage which means more available water and better electricity generation efficiency.

The rainy patterns are changing under climate change. It is necessary to improve integration of weather forecast, hydrological forecast, and reservoir operation. Based on the study of dynamical reservoir stage during flood season, reservoir should learn to store, and release water smartly, even break the rule curve sometimes.

5. Conclusion

Anthropogenic influences are more apparent than ever. Climate change affects the rainfall patterns during the flood season. Recent flood events illustrated that storage abilities of rivers and lakes are weakening [6]. The river stage is higher in the same river during a same flood event with poorer storage capacity. Furthermore, there are numerous large reservoirs on the upstream and midstream of Yangtze River. They all need to release water to restore their full flood control spaces since April to July each year. Thus, huge water will flow to the downstream and rise downstream river stage. The long-term high river stage at the lower Yangtze River could be common in near future.

In comparison with single operation of Three Gorges, joint operation of cascaded reservoirs could reduce 5.3 MAF unsolvable flood [7]. So fewer residents around the downstream would be transferred in case of huge flood. The operation performance of 21 reservoirs in 2016 proved that joint operation could certainly reduce flood control pressure for the middle and lower reaches of the Yangtze River.

Dynamical allocation of cascaded flood control spaces makes it possible for Three Gorges to store water for its downstream without reducing its storage space for other cities around the midstream. Meanwhile, with numerous large reservoirs on the same river, the reservoir stage during flood season could be higher than its limiting level if the flood is not big. But threshold value of stage during flood season with acceptable risk should be studied further. To increase resiliency for droughts and floods, it is necessary to study forecast-informed reservoir operations. Just like what has been done for Lake Mendocino in California [8]. And the better utilization of water is, the more hydropower will be obtained, which also help keep the world be sustainable.

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References

[1] F. Zhang, L. Zi, H. Qiu. Climate characteristics analysis of rainstorm and flood in Changjiang River in 2016[J]. Yangtze River, 2017(04): 62-65.
[2] Y. Min, J. Wang, L. Chen. Discussion on calculation method of flood routing and inflow of Three Gorges Reservoir [J]. Yangtze River, 2011(06): 49-52.

[3] B. Feng, Y. Li, Y. Chen, et al. Influence of flood control regulation of Three Gorges Reservoir on flood of upper Yangtze River in August, 2009[J]. Yangtze River, 2011(06): 72-74,79.

[4] B. Zou, Y. Li, B. Feng. Analysis on dispatching influence of Three Gorges Reservoir on water level of main stream in mid-lower reaches of Yangtze River: a case study of flood in July, 2010 [J]. Yangtze River, 2011(06): 80-82,100.

[5] J. Zhang, L. Chen. Regulation effects of Three Gorges Reservoir and flood forecast for No.1 flood in 2016 of Changjiang River [J]. Yangtze River, 2017(04): 13-15,36.

[6] J. Wang. Characteristics and enlightenment of 2016 Changjiang River flood [J]. Yangtze River, 2017(04): 54-57,65.

[7] X. Jin. Study on co-regulation of reservoirs in upper reaches of Changjiang River in 2016 for flood control [J]. Yangtze River, 2017(04): 22-27.

[8] C. Talbot. Forecast informed reservoir operations: research on increasing resiliency for droughts and floods [J]. Flood Risk Management Newsletter, 2017.10(1):9-11.