The Optimal Utilization of Flood in Small and Medium magnitude for Cascade Reservoirs in Jinsha River

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Abstract. The large reservoirs generally undertake flood control, power generation, navigation and many other scheduling tasks. In flood season, flood control is the primary task for reservoirs. Then, how to realize effective utilization of the flood control capacity for flood interception and take into account other comprehensive benefits simultaneously, has become an urgent problem to be solved. In order to solve the problem, a multi-objective optimization model which can give full play to the comprehensive benefits under the premise of guaranteeing the safety of flood control is proposed. With the case study of Xiluodu and Xiangjiaba cascade reservoirs (XXCR), a practical scheme of small and medium-sized floods’ utilization (SMFU) is presented. Finally, the SMFU scheme is applied to the operation in comparison with the original design scheme to verify its effectiveness. The results indicate that the SMFU scheme can improve power generation and navigation guaranteed rate while ensuring flood control safety, which adequately indicates that SMFU is an effective approach to make full use the flood resources in flood season.

1. Introduction

With the growing energy demand, more and more key reservoirs are being built in the world, especially in developing countries. These reservoirs not only contribute to flood control, but also play important roles in power generation, water supply and navigation, etc. Some researchers have devoted themselves to the economic dispatching of cascade reservoirs[1]-[4], and some have spent lots of time on flood control which is extremely important for the safety of people's life and property[5]-[8]. Besides, lots of attentions have been paid to water supply, navigation and ecological environment[9]-[12].

Most of key reservoirs generally undertake all the tasks above. In the design schemes of the reservoirs, the highest priority is assigned to flood control for safety, while power generation and navigation comes after. Their operation water levels can't exceed flood limited water level (FLWL) unless devastating flood happens, and they must be reduced to FLWL as soon as possible once the flood peak passed. The design scheme pays too much attention to flood control, reserving too much storage for rare devastating flood. The flood control storage can't be utilized effectively.

In order to manage flood reasonably, the flood is generally classified by flood peak or flood volume. According to the Chinese Standard GB/T 22482-2008 (AQSIQ and SAC 2008), the flood whose return period is less than 5 years is defined as small flood. The flood whose return period is in the range of 5 years to 20 years is defined as medium flood. The flood whose return period is more
than 20 years is defined as extreme flood. When dealing with a flood, different measures will be adopted according to the magnitude of the flood.

Considering flood seasonal variation, a seasonal FLWL method giving multiple FLWLs in periods has been proposed to supply more storage for beneficial utilization[13]-[14]. For making full use of limited flood control storage, some operation strategies[15]-[17] as well as optimization models[18]-[20] have also been developed. These researches have already received various degrees of success. However, they mainly focused on flood control for devastating flood, not suitable for daily operation when small and medium-sized floods happen.

As 3~7 days runoff forecasting technology matures, its application on reservoir operation becomes more and more meaningful[21]-[23]. Instead of the traditional fixed FLWL, some dynamic control of FLWL methods have been studied and proposed[24]-[26]. The operation water level of reservoir changes real-time with the current inflow and forecasting inflow. The operation process of reservoir will be optimized with more time and information provided by 3~7 days runoff forecasting.

Xiluodu and Xiangjiaba cascade reservoirs (XXCR), located in the lower reaches of the Jinsha River, constitute one of the largest cascade systems. As the main power sources of "West Power to East” project, XXCR supply plenty of electricity for many provinces such as Hubei, Guangdong and Shanghai. Meanwhile, they also have to reserve enough storage for the safety of projects and downstream large cities in flood season. Moreover, the downstream navigation requires that Xiangjiaba should have a reasonable water discharge. Though XXCR undertake these tasks at the same time, the current design scheme mainly focuses on flood control without considering beneficial utilization in flood season.

Compared with rare devastating flood, small and medium-sized floods frequently happen in flood season. If part of flood control storage is supplied for beneficial utilization in normal flood, the integrated benefits will be sharply increased while flood control safety is insured. Therefore, a multi-objective optimization model is proposed in this paper to balance flood control and beneficial utilization. With Xiluodu and Xiangjiaba cascade reservoirs (XXCR), a practical scheme of small and medium-sized floods' utilization (SMFU) is presented. Finally, the proposed SMFU scheme is applied to the operation in comparison with the design scheme to verify its feasibility and effectiveness.

2. Problem formulation

SMFU is an effective approach to realize the tradeoff between flood control and beneficial utilization in flood season. Because of multiple objectives and various constraints, SMFU is a complex multi-objective optimization problem which can be formulated as follows:

2.1 Objective function

Most of key reservoirs generally undertake the tasks of comprehensive utilization such as flood control, power generation and navigation. The objective of flood control is to determine water level and water discharge for the safety of the project and protective zones. The runoff in flood season is often much bigger than annual runoff, which can be utilized fully for power generation. Moreover, navigation should be taken into account if the downstream reach plays an important role in transportation. The objectives are described as follows:

(1) Upstream flood control safety. The water level of reservoir should be kept as low as possible to ensure the safety of project and upstream areas.

\[
\min F_1 = \max \{ Z_t \} \quad t \in [1,T]
\]

where \( F_1 \) denotes the maximum water level over all periods, the minimum of \( F_1 \) is to ensure upstream safety; \( Z_t \) denotes the water level in the t-th period; \( T \) is the number of periods.

(2) Downstream flood control safety. The water discharge of reservoir should be kept as small as possible to prevent downstream protective zones from drowning.

\[
\min F_2 = \max \{ Q_t \} \quad t \in [1,T]
\]
where $F_2$ denotes the maximum water discharge over all periods, and the minimum of $F_2$ is to ensure downstream safety; $Q_t$ denotes the water discharge in the $t$-th period.

(3) Maximize total power generation. With plenty of flood resources in flood season, the reservoir can store certain flood to raise its water level for more power generation.

$$\max F_3 = \sum_{t=1}^T N_t \Delta t = \sum_{t=1}^T A H_t q_t \Delta t$$

(3)

where $F_3$ denotes the total power generation over all periods; $A$ denotes output coefficient; $\Delta t$ is the interval of scheduling; $N_t$, $H_t$ and $q_t$ denote the output, water head and power discharge in the $t$-th period, respectively.

(4) Maximize navigation guaranteed rate. Downstream navigation requires an appropriate range of water discharge. If the water discharge is outside the range, the reach will be not suitable for navigation. So it should be kept in the range as far as possible.

$$\max F_4 = \frac{1}{T} \sum_{t=1}^T K_t$$

and

$$K_t = \begin{cases} 1 & Q_t \in [Q_{\text{nav},\min}^\text{nav}, Q_{\text{nav},\max}^\text{nav}] \\ 0 & Q_t \not\in [Q_{\text{nav},\min}^\text{nav}, Q_{\text{nav},\max}^\text{nav}] \end{cases}$$

(4)

where $F_4$ denotes the guaranteed rate over all periods; $K_t$ is an intermediate variable; $Q_{\text{nav},\min}^\text{nav}$ and $Q_{\text{nav},\max}^\text{nav}$ denote the minimum and maximum water discharges for navigation, respectively.

2.2 Constraints

There are kinds of equality and inequality constraints to insure the feasibility of results during the optimization process. These constraints are presented as follows:

(1) Water level constraints

$$Z_{t,\min} \leq Z_t \leq Z_{t,\max}$$

(5)

where $Z_{t,\min}$ and $Z_{t,\max}$ denote the lower and upper water level limits, respectively.

(2) Water discharge constraints

$$Q_{t,\min} \leq Q_t \leq Q_{t,\max}$$

(6)

where $Q_{t,\min}$ and $Q_{t,\max}$ denote the minimum and maximum water discharge limits, respectively.

(3) Output constraints

$$N_{t,\min} \leq N_t \leq N_{t,\max}$$

(7)

where $N_{t,\min}$ and $N_{t,\max}$ denote the minimum and maximum output limits, respectively.

(4) Water balance equation

$$V_{t+1} = V_t + [I_t - Q_t] \Delta t$$

(8)

where $I_t$ and $V_t$ denote inflow and water storage, respectively.

(5) Water head equation

$$H_t = (Z_t + Z_{\text{ds}})/2 - f_{\text{ds}}(Q_t)$$

(9)

where $f_{\text{ds}}$ denotes the relation function between water discharge and downstream water level.

(6) Water spillage equation

$$\begin{cases} q_t = \min\{Q_t, q_{\text{max}}\} \\ S_t = \max\{Q_t - q_{\text{max}}, 0\} \end{cases}$$

(10)

where $S_t$ denotes the water spillage in the $t$-th period; $q_{\text{max}}$ denotes power discharge capacity.

(7) Initial water level

$$Z_0 = Z_{\text{again}}$$

(11)

3. Operation demands of XXCR

Located in the lower reaches of Jinsha River, Xiluodu is an important reservoir with annual regulation ability. Xiangjiaba located downstream from Xiluodu about 150km is another key project. Considering the closely hydraulic connection, XXCR will obtain more benefits if the two reservoirs operate as a complex by joint dispatching. Moreover, some large cities such as Yibin and Luzhou are located in the downstream reaches of XXCR. For the safety of these cities, the safe water discharges of XXCR are
required in flood season. The basic parameters and topological structure of XXCR are shown as Table 1 and Fig. 1.

| Reservoir   | Normal water level (m) | Dead water level (m) | Flood limited water level (m) | Regulation storage (m$^3$) | Flood control storage (m$^3$) | Installed capacity  |
|-------------|------------------------|----------------------|--------------------------------|----------------------------|-------------------------------|---------------------|
| Xiluodu     | 600                    | 540                  | 560                            | 46.6×10$^8$               | 46.5×10$^8$                    | 13500 MW            |
| Xiangjiaba  | 380                    | 370                  | 370                            | 9.03×10$^8$               | 9.03×10$^8$                    | 6400               |

3.1 Operation rules of XXCR

Xiluodu is a key project privileged to power generation, incorporating with flood control and navigation. Xiangjiaba is a project with undertaking the tasks of power generation, navigation and flood control. As the re-regulation reservoir of Xiluodu, it should cooperate with Xiluodu during operation. According to the "Reservoir Dispatching Rules of Xiluodu" and "Reservoir Dispatching Rules of Xiangjiaba" approved by government departments, XXCR must follow some basic rules during normal operation.

(1) Flood control rules

From July 1 to September 10, XXCR undertake flood control task to ensure the safety of Chuanjiang Reach, and cooperate with the Three Gorges for the safety of Jingjiang Reach. XXCR have to supply 10×10$^8$m$^3$ as reserved storage for devastating flood although they have 55.53×10$^8$m$^3$ flood control storage in flood season. In general, XXCR keep their water levels under 560/370m unless they execute flood control task to reduce flood. Considering the actual operation factors, their water levels can rise to 561/372.5m within a short time, but they must be reduced to FLWL as soon as possible before flood comes. Once the flood peak passed, XXCR have to reduce their water levels timely while not increasing flood control pressure. These flood control rules can be considered when the SMFU scheme is drafted.

(2) Power generation rules

XXCR also undertake power generation and peaking modulation besides flood control. Considering the safety of projects and protective zones, power generation has lower priority than flood control in flood season. The water levels of XXCR are determined by flood control rules rather than power generation rules in flood season. However, they can vary from their dead water levels 540/370m to their normal water levels 600/380m in other seasons. XXCR start to impound water in early September, and their water levels will reach to 600/380m in late September. Because of water supply, their water levels gradually drop to 540/370m in dry season, and they will rise to FLWL 560/370m again in late June as flood season comes.

(3) Navigation rules

The Jinsha River is an important water corridor to transport regional resources. As the key projects on the river, XXCR have the responsibility to meet the navigation requirements of the Lower Jinsha River. According to the dispatching rules, navigation also submits to flood control in flood season, and it should be coordinated with power generation. Therefore, the rules for flood control and power
generation can't be neglected when the navigation scheme is drafted. For the navigation safety of Lower Jinsha River, the tail water level of Xiangjiaba should be kept in the range of 265.8–277.25m relating to the water discharge of 1200–12000 m$^3$/s. Moreover, the daily variation of the tail water level is required less than 4.5m/d for avoiding strong fluctuation, and the hourly change should be less than 1.5m/h.

3.2 Operation constraints of XXCR
Because of different requirements of water level, flood control and beneficial utilization are conflicting in flood season. Therefore, XXCR have to satisfy various constraints for normal operation. With the above operation rules, some important constraints are summarized.

(1) Upstream flood control constraints
According to the flood control rules, XXCR must supply $10 \times 10^8$ m$^3$ as reserved storage for devastating flood. Considering their different flood control storages, Xiluodu is suitable to supply the whole reserved storage for maximizing the total power generation. Therefore, the operation water level of Xiluodu can't exceed 593m in normal flood, and the storage between 593m and 600m is reserved for devastating flood. Meanwhile, the operation water level of Xiangjiaba is kept in the range of 370m to 380m.

(2) Downstream flood control constraints
Some large cities such as Yibin and Luzhou are located in Chuanjiang Reach. Their flood control safety requires the reasonable water discharges of XXCR. The warning water level of these cities is 300m, and the corresponding runoff is 24500m$^3$/s. The safe water level of these cities is 303m, and the corresponding runoff is 29000m$^3$/s. Thus, the final water discharge of XXCR (that is, the water discharge of Xiangjiaba) can't exceed 24500m$^3$/s in normal flood, and it can't exceed 29000m$^3$/s in devastating flood.

(3) Power generation constraint
Most of the inflows exceed the power discharge capacities of XXCR in flood season. The water discharge makes little sense to the improvement of power generation. In other words, the power generation can't be increased unless the operation water level is raised. However, upstream flood control requires low operation water level for safety. To balance flood control and power generation, the SMFU scheme won't be taken unless the current inflow exceeds power discharge capacity. The power discharge capacity of Xiluodu is 7500 m$^3$/s. The power discharge capacity of Xiangjiaba is 6500m$^3$/s.

(4) Navigation constraints
Besides flood control and power generation, XXCR also have to ensure the navigation safety of Chuanjiang Reach (that is, Lower Jinsha River). Therefore, they have to keep the final water discharge in the range of 1200m$^3$/s to 12000m$^3$/s. Moreover, the daily variation of the tail water level of Xiangjiaba can't exceed 4.5m/d, which requires that the daily variation of the final water discharge should be kept under 4500m$^3$/s.

4. The SMFU scheme for XXCR
Because of practical demands and limited leading time, the SMFU model in Section 2 can't be optimized effectively during actual operation. Compared to an unpractical optimal scheme, a reasonable scheme which takes all objectives and various constraints into account is more meaningful. Here, a practical SMFU scheme for XXCR is presented.

4.1 Inflow characteristics of XXCR
The flood of Jinsha River not only happens frequently, but also lasts for a long time with huge volume. SMFU is an effective approach to make full use of flood resources, but it is relative to flood characteristics closely. We can't draft the SMFU scheme for XXCR without the detailed analysis of flood characteristics. According to the historical runoff data in flood season from 1940 to 2010, the probabilities of different inflows are listed in Table 2:
Table 2. The interval and cumulative probabilities of different inflows in flood season

| Inflow range (m³/s) | Probability | Cumulative | Inflow range (m³/s) | Probability | Cumulative |
|---------------------|-------------|------------|---------------------|-------------|------------|
| 0~6500              | 18.76%      | 18.76%     | 16000~17000         | 1.82%       | 94.60%     |
| 6500~7500           | 12.52%      | 31.28%     | 17000~18000         | 1.76%       | 96.36%     |
| 7500~9000           | 17.62%      | 48.90%     | 18000~19000         | 1.25%       | 97.61%     |
| 9000~10000          | 9.84%       | 58.74%     | 19000~20000         | 0.96%       | 98.57%     |
| 10000~11000         | 8.96%       | 67.70%     | 20000~21000         | 0.49%       | 99.06%     |
| 11000~12000         | 7.03%       | 74.73%     | 21000~22000         | 0.41%       | 99.47%     |
| 12000~13000         | 6.31%       | 81.04%     | 22000~23000         | 0.24%       | 99.71%     |
| 13000~14000         | 5.54%       | 86.58%     | 23000~24500         | 0.13%       | 99.84%     |
| 14000~15000         | 3.72%       | 90.30%     | 24500~29000         | 0.16%       | 100.00%    |
| 15000~16000         | 2.48%       | 92.78%     | >29000              | 0%          | 100.00%    |

As the results listed in Table 2, 81.24% of the inflows exceed 6500m³/s, and 68.72% of the inflows exceed 7500m³/s. Most of the inflows can meet the requirements for the expected outputs of XXCR. In other words, power generation is mainly affected by water level instead of water discharge in flood season. Thus, the SMFU scheme can improve power generation by raising water level. Moreover, 74.73% of the inflows are smaller than 12000m³/s, which indicates that the navigation requirements can be met most of the time.

With 3~7 days runoff forecasting, a pre-impound & pre-release scheme can be taken to balance power generation and flood control in small flood. XXCR will pre-impound water to raise their water levels when the inflow is smaller than 12000m³/s. On the contrary, they will pre-release stored water for flood control when the forecasting inflows exceed 12000m³/s. For further analysis, the durations of the floods exceeding 12000m³/s are listed in Table 3:

Table 3. The durations of different historical floods in flood season

| Flood peak discharge (m³/s) | <10 days | 10~20 days | 20~30 days | >30 days |
|-----------------------------|---------|------------|------------|---------|
| 12000~15000                 | 6       | 28         | 16         | 13      |
| 15000~18000                 | 1       | 14         | 10         | 5       |
| 18000~21000                 | 0       | 8          | 6          | 4       |
| 21000~24500                 | 1       | 0          | 2          | 7       |
| >24500                      | 0       | 1          | 1          | 0       |
| Total times                 | 8       | 51         | 35         | 29      |

As it can be seen from the results in Table 3, 51 floods last about 10~20 days, and 64 floods last more than 20 days. The flood duration of XXCR is very long, and it will be longer as the flood peak flow increases. However, the available storage of XXCR is limited in flood season, which prevents from reducing flood peak adequately. The SMFU scheme for XXCR has to balance the current utilization and later operation during flood control stage.

4.2 Availability of inflow forecasting

Inflow forecasting is an important factor for the pre-impound & pre-release scheme. Xiluodu started the first impounding in May 2013. Xiangjiaba started the first impounding in October 2012. XXCR have been in normal operation for a short time, few researches on the inflow forecasting were presented. The leading time of the inflow forecasting for XXCR is 12~48h instead of 3~7 days at present. According to the 12~48h forecasting results from May 2013, the accuracies of the forecasting inflows for XXCR in flood season are listed in Table 4.
As Table 4 shows, XXCR have excellent 12–48h inflow forecasting results. The average accuracy of the 48h forecasting inflows reaches to 95.12%, which can satisfy the accuracy demand of inflow forecasting for the SMFU scheme completely. As the owner of XXCR, the China Three Gorges Corporation has been trying to prolong leading time although 3~7 days inflow forecasting for XXCR hasn't been done at present. The SMFU scheme for XXCR will be more reasonable and effective with 3~7 days forecasting inflows.

The accurate 3~7 days inflow forecasting is a hotspot issue, which has attracted lots of researchers in recent years. Bao[22] have coupled ensemble weather predictions with Grid-Xinanjiang model for the flood forecasting of Xixian catchment, obtaining excellent 6-day flood forecasting results. Webster[27] have proposed a new ensemble flood prediction scheme to realize 10-day forecasting floods in Ganges and Brahmaputra. Bürger[21] and Gouweleeuw[23] have obtained perfect forecasting results within 5-day leading time by ECMWF Ensemble Prediction System. According to these researches, ensemble prediction is an effective approach to realize the 3~7 days inflow forecasting for XXCR. Therefore, the SMFU scheme for XXCR will be reasonable and effective.

4.3 Pre-impound & pre-release scheme

The pre-impound & pre-release scheme will be taken when the current inflow is smaller than 12000m$^3$/s. The upper water level limits of XXCR are key factors to balance flood control and power generation in the scheme. If they are too high, the operation water levels won't be reduced timely without affecting navigation. On the contrary, the benefits of power generation won't be realized adequately. For determining the upper water level limits, three schemes 565/375m, 570/375m and 575/375m are selected as candidates. Based on 3~7 days leading time, the extra water discharges of XXCR in the three schemes are listed in Table 5:

As Table 5 shows, if the upper water level limits are set to 575/375m, the total extra water discharge of XXCR will reach to 3350m$^3$/s within 7 days leading time, and it will increase to 7800m$^3$/s within 3 days leading time. The extra water discharges are so large that the water levels can't be reduced timely. The extra water discharges are small within all leading times in 565/375m scheme, but low water levels are inefficient for power generation. Compared to other schemes, the extra water discharges and operation water levels of XXCR are acceptable in 570/375m scheme. The scheme can balance power generation and flood control, thus the upper water level limits of XXCR are selected to 570/375m.

Analyzing the above description, XXCR won't impound water unless their power discharge capacities are satisfied, and they will release stored water if any forecasting inflow exceeds 12000m$^3$/s. The inflow is classified by the grades of 6500, 7500 and 12000 in pre-impound & pre-release scheme. Besides, a grade of 10000 is added to satisfy the daily variation of water discharge. The detailed pre-impound & pre-release scheme is summarized as follows:
a) When the current inflow \( I < 6500 \text{m}^3/\text{s} \), XXCR keep their water levels 560/370m, and their water discharges equal the inflow; b) When \( 6500 \leq I < 7500 \text{m}^3/\text{s} \), XXCR keep their water levels under 570/375m, and their water discharges equal \( I/6500 \text{m}^3/\text{s} \); c) When \( 7500 \leq I < 10000 \text{m}^3/\text{s} \), XXCR keep their water levels under 570/375m, and their final water discharge equals \( 7500/6500 \text{m}^3/\text{s} \); d) When \( 10000 \leq I < 12000 \text{m}^3/\text{s} \), XXCR keep their water levels under 570/375m, and their final water discharge equals \( 10000 \text{m}^3/\text{s} \); e) When the forecasting inflow within leading time \( I_{\text{fore}} \geq 12000 \text{m}^3/\text{s} \), XXCR reduce their water levels to FLWL 560/370m as soon as possible while keeping their final water discharge under 12000m³/s.

4.4 Detailed flood control scheme

According to the design schemes of XXCR, they will not impound flood unless the current flood exceeds 24500m³/s. In such a way, the flood control storage can’t be utilized adequately. Their water levels are kept FLWL 560/370m most of the time, which leads to poor power generation. Their water discharges are very big in most floods, the flood control safety of downstream protective zones can’t be ensured effectively. Therefore, a detailed flood control scheme is proposed to realize the trade off among different demands.

In this flood control scheme, XXCR not only prevent the flood exceeding 24500 m³/s, but also utilize the flood in the range of 12000–24500m³/s. With limited flood control storage, XXCR can’t reduce all floods to 12000m³/s for navigation, but reduce flood peak moderately. So the range of 12000–24500 is divided into several small ranges by the grades of 15000, 18000 and 21000. According to these small ranges, XXCR will impound flood by the lower limit of range, and release flood by the upper limit of range.

XXCR can’t supply all storage for the current flood during the impounding stage. They have to reserve enough storage for later more serious flood. Their operation water levels must be limited to balance the current utilization and later operation. With the historical data and the impounding rules above, the required storage for each flood in the range of \([12000, 24500]\) is calculated to determine the upper water level limits of XXCR. These required storages are classified by the small ranges and presented as Fig.2.

![Figure 2. The cumulative probability curve of required storage for different floods in the range of [12000, 24500] m³/s](image)

As Fig.2 shows, some of the required storages are too big to be met with limited flood control storage. Especially, the maximum required storage for the floods in \([12000, 15000]\) is nearly \(30 \times 10^8 \text{m}^3\), and that for the floods in \([15000, 18000]\) exceeds \(20 \times 10^8 \text{m}^3\). The floods in the two ranges require about \(50 \times 10^8 \text{m}^3\) storage, while the total available storage of XXCR is \(55.53 \times 10^8 \text{m}^3\) in flood season. Moreover, part of the available storage must be supplied for the flood exceeding \(24500 \text{m}^3/\text{s}\). Thus, the available storage of XXCR must be divided into several parts to reduce the floods in different ranges reasonably.

Besides the required storages above, the maximum required storage for the floods in the range of \([24500, 29000]\) is \(15.3 \times 10^8 \text{m}^3\), which must be supplied fully for downstream flood control safety. The
available storage for small and medium-sized floods will be only $30.23 \times 10^8 \text{m}^3$ if the reserved storage for devastating floods is deducted. Considering the navigation demands, more storage will be supplied for the floods in [12000, 15000]. Here, an allocation scheme of water level and available storage is presented as Table 6.

Table 6. The practical allocation scheme of water level and useable storage of XXCR for different floods

| Flood grade (m$^3$/s) | Storage allocation (10$^8$ m$^3$) | Cumulative storage (10$^8$ m$^3$) | Upper water level limits (m) | Useable storage (10$^8$ m$^3$) | Total useable storage (10$^8$ m$^3$) |
|-----------------------|----------------------------------|----------------------------------|-------------------------------|-------------------------------|----------------------------------|
| [12000, 15000]        | 14                               | 14                               | 570                           | 375                           | 10.30                            | 4.38                            | 14.68                          |
| [15000, 18000]        | 7                                | 21                               | 575                           | 375                           | 15.91                            | 4.38                            | 20.29                          |
| [18000, 21000]        | 5                                | 26                               | 580                           | 375                           | 21.52                            | 4.38                            | 25.90                          |
| [21000, 24500]        | 4                                | 30                               | 583                           | 375                           | 25.14                            | 4.38                            | 29.52                          |
| [24500, 29000]        | 15.3                             | 45.3                             | 593                           | 380                           | 36.50                            | 9.03                            | 45.53                          |
| >29000               | –                                | –                                | 600                           | 380                           | 46.50                            | 9.03                            | 55.53                          |

As Table 6 shows, the required storages for the floods in [24500, 29000] are both satisfied, about 75% of the required storages for the floods in [12000, 15000] are satisfied, and more than 60% of the required storages for the floods in other ranges are satisfied. The scheme can satisfy most of the required storages for the floods in other ranges, and supply enough storage for devastating flood. In such a way, XXCR will impound flood under the maximum water level limits while reserving adequate storage for later more serious flood.

4.5 The SMFU scheme for XXCR

In the above sections, the pre-impound & pre-release scheme and the detailed flood control scheme are proposed for different floods. They can be summarized as the SMFU scheme for XXCR, which considers flood control, power generation and navigation simultaneously. The SMFU scheme is presented as Table 7 (When the flood exceeds 10000 m$^3$/s, XXCR impound or release flood by determining the final water discharge.).

Table 7. The SMFU scheme for XXCR in flood season which contains the water discharges and upper water level limits of XXCR corresponding to different floods

| Flood grade (m$^3$/s) | The water discharges of XXCR (m$^3$/s) | Upper water level limits (m) | Notes |
|-----------------------|--------------------------------------|-------------------------------|-------|
|                       | Xiluodu                               | Xiangjiaba                    |       |
| <6500                 | Inflow                                | Inflow                        | 560   | 370 | Pre-impound |
| [6500, 7500]          | 6500                                 | 6500                          | 560   | 375 | Pre-impound |
| [7500, 10000]         | 7500                                 | 6500                          | 570   | 375 | Pre-impound |
| [10000, 12000]        | 10000                                | 10000                         | 570   | 375 | Pre-impound |
| [12000, 15000]        | 12000                                | 12000                         | 570   | 375 | Navigation |
| [15000, 18000]        | 12000-15000-12000                    | 575                           | 375   |      | Flood control |
| [18000, 21000]        | 12000-15000-18000-15000-12000        | 580                           | 375   |      | Flood control |
| [21000, 24500]        | 12000-15000-18000-21000-18000-15000-12000 | 583                           | 375   |      | Flood control |
| [24500, 29000]        | 12000-15000-18000-21000-24500-21000-18000-15000-12000 | 593                           | 380   |      | Flood control |
| >29000                | 12000-15000-18000-21000-24500-29000-24500-21000-18000-15000-12000 | 600                           | 380   |      | Devastating flood |

The following notes can’t be neglected during the practical dispatching of SMFU:
a) XXCR impound flood based on their usable storages, and release flood based on their stored water volumes; b) XXCR pre-impound water to raise the water levels when the current inflow and forecasting inflows are smaller than 12000m\(^3\)/s; c) XXCR pre-release the stored water to reduce their water levels when any forecasting inflow exceeds 12000m\(^3\)/s; d) When the current flood exceeds 12000m\(^3\)/s, XXCR impound flood by the lower limit of flood range during rising stage while keeping their water levels under the limits, release the stored flood by the upper limit of flood range during falling stage while keeping their water levels above 570/375m; e) The water discharges will be reduced if the flood peak lasts less than 3 days.

5. Application benefits analysis
The proposed SMFU scheme is applied to the dispatching of XXCR in comparison with the design scheme to verify its effectiveness. With the current runoff forecasting technology, the inflows in the next 7 days are supposed as forecasting inflows during simulation.

5.1 Risk and benefits of flood control
The safety of projects and protective zones must be ensured during SMFU. Otherwise, no matter how much the benefits of power generation and navigation will make no sense. To verify the risk and benefits of flood control, the typical adverse floods in 1966 and 1998 are selected. Considering all of the historical floods are normal floods, 1% design floods are also obtained to verify flood control risk further. According to the flood characteristics, the 1% design flood of 1966 is obtained by Peak and Volume-Amplitude Method, but the 1% design flood of 1998 is obtained by Volume-Amplitude Method with 30 days flood volume. With these floods, the simulation results are presented as Fig.3 and Fig.4.

Figure 3. The operational processes (inflow, water discharge and water level) of XXCR in different historical floods in design scheme and SMFU scheme; (a) Xiluodu in 1966 historical flood, (b) Xiangjiaba in 1966 historical flood, (c) Xiluodu in 1998 historical flood, (d) Xiangjiaba in 1998 historical flood.
The operational processes (inflow, water discharge and water level) of XXCR in different design floods in design scheme and SMFU scheme; (a) Xiluodu in 1% design flood of 1966, (b) Xiangjiaba in 1% design flood of 1966, (c) Xiluodu in 1% design flood of 1998, (d) Xiangjiaba in 1% design flood of 1998.

As it can be seen from Fig.3 and Fig.4, the proposed SMFU scheme can ensure the safety of projects and protective zones in normal and devastating floods, which indicates that the scheme is feasible. In the 1966 historical flood, XXCR can reduce the water levels to FLWL 560/370m timely before serious flood comes while keeping their final water discharge under 12000m$^3$/s. All the inflows of Xiangjiaba exceed 12000m$^3$/s during the whole season of other floods. According to the detailed flood control scheme, Xiangjiaba will impound flood during the rising stage and release flood during the falling stage. Thus, its water levels rise with the increasing of flood peak before serious flood comes.

As the figures show, Xiluodu plays the main role in runoff regulation during SMFU. With different flood characteristics, the benefits of flood control are different in the floods of 1966 and 1998. XXCR can reduce each flood peak effectively in the floods of 1966, obtaining perfect effects of flood control. However, they can't reduce later flood peaks in the floods of 1998. Due to the long durations of these floods, they have to reserve enough storage for more serious flood. Moreover, their water discharges increase or decrease step by step during the flood control stage. The water levels of XXCR can be reduced to 570/375m quickly after the peak flood passed.

Compared with the design scheme, the SMFU scheme can obtain higher water levels and smaller water discharges while subjecting to kinds of constraints. In such a way, upstream projects may take certain flood control pressure, but the flood control pressure of downstream protective zones is sharply reduced. In other words, upstream safety and downstream safety are considered and balanced. Moreover, the smaller water discharges bring better navigation guaranteed rate, the higher water levels bring more power generation.

The inflow forecasting is a vital important factor for pre-impound & pre-release scheme. The accuracy will be decreased with the increasing of leading time. Therefore, the forecasting schemes with different leading times are applied to the SMFU for XXCR. The processes of Xiluodu in the 1966
The water discharge and water level processes of Xiluodu in 1996 historical flood with 1-day, 3-day, 4-day, 5-day and 7-day inflow forecasting.

As Fig.5 shows, the water levels of Xiluodu can be reduced to FLWL 560m timely within 4~7 days, and they are also sharply reduced within 3 days. However, the reduction of water level is very small within 1 day. The water discharges of Xiluodu are smaller than 12000m$^3$/s during pre-release stage with different leading times, and they will be decreased as leading time increases. In a word, the SMFU scheme can reduce the water levels of XXCR within 3~7 days while not affecting navigation safety.

5.2 Benefits of power generation and navigation

The SMFU scheme also considers power generation and navigation besides flood control. It can improve the benefits of power generation and navigation by the analysis above. In order to further quantify the benefits, the total power generation and navigation guaranteed rate of XXCR are obtained with the historical floods. The results are shown as Fig.6 (The navigation guaranteed rate is calculated by judging the water discharge of Xiangjiaba.):

Figure 6. The results of XXCR in design scheme and SMFU scheme in the historical floods from 1940 to 2010; (a) The annual total power generation of XXCR; (b) The annual navigation guaranteed rate of XXCR.

Compared to the design scheme, the proposed SMFU scheme can improve the total power generation and navigation guaranteed rate of XXCR. According to the detailed results from 1940 to 2010, the average power generation is 276.96×10$^8$kwh in the design scheme, while that is 292.54×10$^8$
kwh in the SMFU scheme. The power generation is improved by 15.58×10^8 kwh on average, which takes about 5.62% of that in design scheme.

Because of different inflow characteristics, the navigation guaranteed rate varies from rear to year. All the inflows are less than 12000m^3/s during the whole flood season in some years, the rate can reach to 100%. On the contrary, the rate is very small in other years due to devastating flood. The SMFU scheme can improve navigation guaranteed rate no matter how the rate varies every year. Compared with 75.33% in the design scheme, the mean navigation guaranteed rate is 86.38% in the SMFU scheme, which is improved by 11.05%. In a word, the SMFU scheme is benefit for the power generation and navigation of XXCR.

6. Conclusions

In order to make full use of flood resources, a multi-objective optimization model which takes flood control, power generation and navigation into account is proposed in this paper. A pre-impound & pre-release module is proposed to balance power generation and flood control. A detailed flood control module is proposed for flood control and navigation. With the model and two modules, a practical scheme of small and medium-sized floods' utilization (SMFU) for cascade reservoirs is presented.

Focusing on Xiluodu and Xiangjiaba cascade reservoirs (XXCR), the practical demands of comprehensive utilization are summarized according their dispatching rules. Based on the detailed analysis of inflow characteristics and inflow forecasting, the flood is classified by several ranges, the available storage of XXCR is divided to several parts. The parameters of pre-impound & pre-release module and the detailed flood control module are determined. The SMFU scheme for XXCR is drafted and applied to the operation.

According to the simulation results, XXCR pre-impound water to raise their water levels in small flood, and lower their water levels to FLWL 560/370m timely before serious flood comes while keeping the final water discharge under 12000m^3/s. When facing medium flood or devastating flood, XXCR raise their water levels and increase their water discharges step by step, upstream safety and downstream safety are both ensured effectively. The total power generation is improved by 5.62%. The navigation guaranteed rate is improved by 11.05%.

The SMFU scheme can improve power generation and navigation guaranteed rate while ensuring the safety of upstream projects and downstream zones. SMFU which can realize the tradeoff among different tasks is an excellent approach to make full use flood resources.

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