Adaptive Regulation of Cascade Reservoirs System Under Non-stationary Runoff

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Abstract. Under the influence of climate change and human activities, the spatial and temporal distribution of river runoff has changed. The statistical characteristics of runoff such as mean, variance and extreme values have changed significantly. Hydrological stationarity has been broken, deepening the uncertainty of water resources and their utilization. Hydrological stationarity is a fundamental assumption of traditional water resources planning and management. The occurrence of non-stationarity will undoubtedly have an impact on the operation and overall benefits of reservoirs, and may even threaten the safety of reservoirs and water resources. There is uncertainty as to whether reservoirs can operate safely and still achieve their design benefits under the new runoff conditions. Therefore, it is important to carry out adaptive regulation of reservoirs in response to non-stationary runoff. Based on the multi-objective theory of large system, a multi-objective joint scheduling model of the terrace reservoir group is constructed for adaptive regulation simulation. A set of combination schemes based on optimal scheduling, flood resource utilization, water saving is constructed. The adaptive regulation is validated using a real-world example of the Xiluodu cascade and Three Gorges cascade reservoirs system in Yangtze River, China. The adaptive regulation processes are analyzed by simulation and the adaptive regulation effects are evaluated. The results show that the non-stationary runoff in upper Yangtze River has had an impact on the comprehensive benefits of large hydropower projects. The use of non-engineering measures to improve flood resource utilization, adjust upstream water use behavior and optimize reservoir scheduling are effective means to reduce the negative impact of non-stationary runoff on cascade reservoirs system.

Keywords: Adaptive regulation · Cascade reservoirs system · Non-stationary runoff · Optimization and control · Hydropower system

1 Introduction

Climate change and human activities have led to significant changes in the global hydrological cycle, directly affecting precipitation, evapotranspiration, land use and land cover in watersheds, resulting in varying degrees of change in the spatial and temporal distribution of river runoff (Ye et al. 2020; Zhang et al. (2021a); Zhang et al.

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(2021b); Wang et al. 2021). The statistical characteristics of runoff such as mean, variance and extreme values have changed significantly. Hydrological stationarity, a fundamental assumption of traditional water resources planning and management, has been broken. This has increased the uncertainty in water resources development and use and has brought new challenges to water resources management (Dau et al. 2020).

Reservoirs usually have some storage capacity and play a key role in water resources management (Ahmad et al. 2014; Turner et al. 2020). The occurrence of non-stationarity will undoubtedly have an impact on reservoir operations and overall benefits, especially in large reservoir complexes (Qin et al. 2020). There is uncertainty as to whether the reservoir system can operate safely and achieve the design benefits under the new runoff conditions (Zhang et al. 2017; Chang et al. 2018). Therefore, how to mitigate the negative impacts of non-stationary runoff on reservoirs is a new challenge for water resources management under the current climate change and anthropogenic impacts (Alimohammadi et al. 2020).

There are two different ways to deal with this issue: one is to develop hydrological forecasting technologies that reduce the uncertainty of incoming water; the other is to develop theories and methods of adaptive operation under changing conditions (Liu et al. 2020). At present, under the first way, the effective period of the short-term hydrological forecast is extended, which improves the efficiency of reservoir operation (Stringer et al. 2020; Sun et al. 2020). The second idea is to adopt a dynamic learning method to propose control measures to guide the operation and management of the reservoir group based on the assessment of the impact of runoff change on the reservoir group, to overcome the design limitations under changing conditions.

In recent years, scholars have carried out adaptive research at the macro-level (framework and structural system) and micro-level (regulation strategy) in response to the changing environment. At the macro level, Edalat and Abdi (2018) explored a new framework of adaptive water management, described its concept, developed suitable decision support systems, and applied them to developing-country cities. At the micro-level, Brekke et al. (2009) analyzed the risks of climate change to reservoir operation and proposed strategies and methods for adaptive operation of reservoirs. Sowers et al. (2011) analyzed the adaptive strategies of water resources management in the Middle East and North Africa under climate change from the perspective of political, economic, and institutional decision-makers. Maran et al. (2014) focused on analyzing the impact of climate change on hydropower development and utilization in the Alpine Basin from the perspective of adaptive management strategies. Ahmadi (2015) formulated a dynamic optimal operation strategy of the reservoir for climate change scenarios, and the preliminary application in the Karoon-4 reservoir had shown that the adaptive dispatch strategy can effectively improve the reliability and reduce the vulnerability of hydropower generation; Alimohammadid et al. (2020) changed the operation policy of the Karaj hydropower dam reservoir (Iran) to mitigate the undesirable effects of climate change. The above-mentioned macro studies mostly focused on the description of control strategies and management frameworks; the micro studies mostly focused on the single reservoir and lacked research on the adaptive operation of cascade reservoirs.

In general, theoretical and methodological research on adaptive operation of reservoir complexes in changing environments is a hot topic in the field of water resources. However, there is a lack of general theories, models and methods, as well as studies that combine specific adaptive operation with quantitative control effect evaluation. Therefore, in this study, a multi-objective joint operation model of the cascade reservoir system for adaptive operation simulation is constructed, and an evolutionary algorithm is used for model solution. A set of combined schemes based on adaptive operation measures such as optimal adjustment of operation mode and utilization of flood resource is constructed. The adaptive operation effects of different schemes are evaluated by simulation. It is pointed out that non-engineering measures used to improve the utilization of flood resource and to optimize the operation mode of hydropower system are effective to reduce the impact of changed streamflow on the hydropower system.

2 Study Area

The Yangtze River is the river with the most abundant hydropower resources in the world, it also is the longest river in Asia, the third longest river in the world, which is about 6000 km in length. The Upper Yangtze River Basin (UYRB) has enriched nearly 90% of the hydropower resources in the entire basin, with a developable installed capacity of about 2 TW. In this study, we selected the giant cascade reservoirs in the UYRB as the research object, which is composed of Xiluodu, Xiangjiaba, Three Gorges, and Gezhouba. The spatial location of the cascade reservoirs is shown in Fig. 1, and the main control parameters of each reservoir are shown in Table 1.

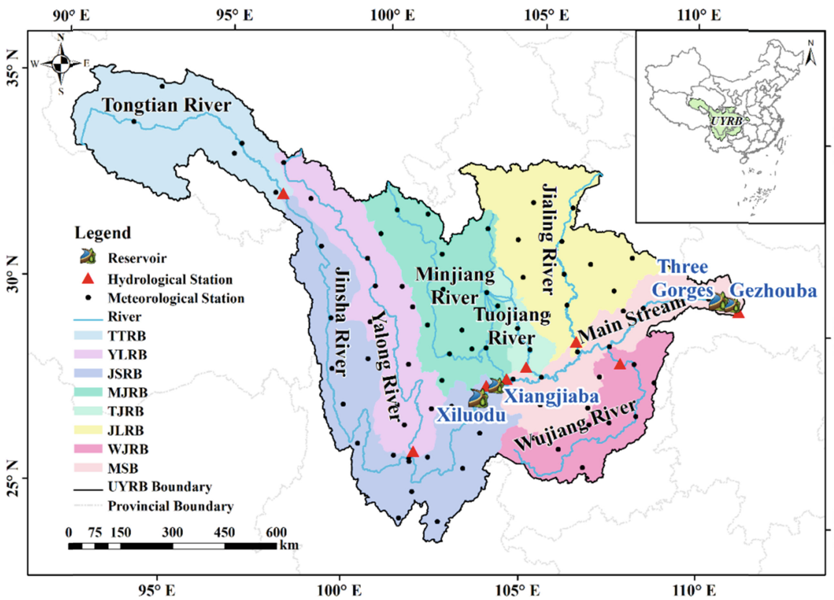

Fig. 1. Location of Xiluodu cascade and Three Gorges cascade reservoirs system.

Table 1. Main control parameters of the four reservoirs.

Reservoir	Normal water level (m)	Flood limited water level (m)	Dead water level (m)	Installed capacity (MW)
Xiluodu	600	560	540	12600
Xiangjiaba	380	370	370	6000
Three Gorges	175	146.5	–	22500
Gezhouba	66	–	63	2950

3 Methods

3.1 Multi-objective Joint Operation Model of Cascade Reservoirs

Currently, the way of single-purpose water resources development and utilization no longer exists, and it is replaced by the way of comprehensive development and utilization, which includes multiple goals such as flood control, water supply, power generation, and shipping. This paper took the restoration of power generation as the objective of adaptive regulation, and other objectives such as flood control, water supply, and shipping are transformed into constraints.

3.1.1 Objective Functions

$$\max E = \sum_{i=1}^{n} \sum_{t=1}^{T} N_{i,t} \cdot \Delta t \tag{1}$$

where, E is the maximum annual power generation of cascade hydropower plants; n is the number of hydropower plants; T is the numbers of time steps in the operation period; $N_{i,t}$ is the output of the ith reservoir at time t; Δt is the hours of the calculation period.

3.1.2 Constraint Conditions

(1) Water balance constraint

$$V_{i,t} = V_{i,t-1} + (Q_{i,t} - q_{i,t} - J_{i,t} - S_{i,t}) \cdot \Delta t \tag{2}$$

where $V_{i,t}$ and $V_{i,t-1}$ refer to the average storage of reservoir i in the tth and ($t-1$)th time steps, respectively; $Q_{i,t}$, $q_{i,t}$, $J_{i,t}$, and $S_{i,t}$ are the inflow, power generation flow, abandoned water flow, and loss flow of reservoir i at time t, respectively.

(2) Water level constraint

$$\underline{Z}_{i,t} \le Z_{i,t} \le \overline{Z}_{i,t} \tag{3}$$

where $Z_{i,t}$ is the average water level of the reservoir i at time t (m); $\underline{Z}_{i,t}$ and $\overline{Z}_{i,t}$ are the minimum and maximum water level limits of reservoir i at time t, respectively.

(3) Discharge flow constraint

$$q_{i,\min} \leq q_{i,t} \leq q_{i,\max} \tag{4}$$

where $q_{i,\min}$ and $q_{i,\max}$ are the minimum and maximum discharge from reservoir i at time t, respectively.

(4) Output constraints

$$\underline{N}_{i,t} \leq N_{i,t} \leq \min\left\{N_{i,t}^{H}, N_{i}^{Y}\right\} \tag{5}$$

where, $\underline{N}_{i,t}$, $N_{i,t}^{H}$, and N_{i}^{Y} are the minimum output, expected output, and installed capacity of reservoir i at time t, respectively.

3.1.3 Solution Method

The Particle Swarm Optimization algorithm (PSO) Zhang et al. (2021a) and Zhang et al. (2021b) was selected in this study to solve the above optimization model.

3.2 Adaptive Regulation

We constructed a series of scenarios of adaptive regulation which includes three control measures, i.e., optimization of the operation mode of the reservoir group, utilization of flood resource, and adjustment of water use behavior, to counteract the impacts of changes in river runoff on the reservoir group. The Control measures and scenarios are listed in Table 2.

Table 2. Control measures and scenarios of adaptive regulation

Scenario	Control measures	Description
A	Optimization of the operation mode of the reservoir group	The cascade four-reservoir joint operation
A	Utilization of flood resourc	The maximum control water level during the flood season is 146.5 m
B		150 m
C		153 m
A	Adjustment of water use behavior	Without considering water saving
D		10% of water-saving
E		20% of water-saving
F	Comprehensive control measures	The maximum control water level of the Three Gorges Reservoir is 150 m during flood season, and 10% water saving
G		150, 20%
H		153, 10%
I		153, 20%

3.2.1 Optimization of the Operation Mode of the Reservoir Group

The measures for the optimization of the operation mode of the reservoir group are through the joint operation of the four cascade reservoirs, changing the disorderly storage and release of the water to the coordinated way, to achieve the purpose of comprehensively controlling the water volume and head and restoring the power generation of the hydropower system. The scenario of the joint operation of cascade reservoirs (Scenario A) is simulated by setting the calculation conditions of the multi-objective joint operation model. At some time, the benefits of the adaptive control measure of joint optimal operation of reservoir group are analyzed by comparing the conventional operation.

3.2.2 Utilization of Flood Resource

The idea of regulating and controlling the utilization of flood resource is to dynamically control the flood limit water level of reservoirs without increasing system risks, improve the utilization of flood resource, and increase the effective runoff replenishment of the reservoir group, to control the water volume and restore the power generation of the hydropower system. The scenarios of flood resource utilization are simulated by setting the calculation conditions of the joint operation model. In the current calculation conditions, the flood limit water level of the Three Gorges reservoir is 146.5 m (Scenario A) during real-time operation. With that, two additional scenarios of flood resource utilization are set up by adjusting the maximum control water level of the Three Gorges reservoir to 150 m (Scenario B) and 153 m (Scenario C) during the flood season.

3.2.3 Adjustment of Water Use Behavior

The idea of adjustment of water use behavior is to reduce the water use outside rivers by adjusting the social and economic structure and promoting the construction of a water-saving society, thereby indirectly increasing the effective runoff supply of the water conservancy and hydropower system, to achieve the purpose of regulating the water volume of the reservoir group and restoring the power generation of the system. The scenarios of the water behavior adjustment are simulated by setting the calculation conditions of the joint operation model. Based on not considering the water-saving scenario (Scenario A), two additional scenarios of water behavior adjustment are set up by 10% (Scenario D) and 20% (Scenario E) of water-saving (accounting for the change in runoff).

3.2.4 Comprehensive Control Measures

The comprehensive control measures for the hydropower system to respond to changes in runoff are set up, which contains three aspects, i.e., optimization of the operation mode of the reservoir group, utilization of flood resource, and adjustment of water consumption behavior. The calculation conditions of the comprehensive control measures are listed in Table 2.

4 Results and Discussion

4.1 Runoff Change and Its Influence on Power Generation

The results show that the measured runoff at Yichang station, a control station on the upper Yangtze River, shows an obvious decreasing trend, with a speed of -0.35 km^3/year. The abrupt change of runoff in the upper Yangtze River occurred in 1993. Notably, the runoff data series used in the preliminary design of the Three Gorges Reservoir is as of 1990. The change will affect the operation mode and comprehensive benefits of the Three Gorges and other large hydropower projects, especially whether these hydropower projects can still play the design benefits under the new runoff conditions. Therefore, the study period is divided into the base period (1951–1993) and the change period (1994–2020). The amount of runoff change between the two periods is -17.2 km^3, and the rate of change is -3.9%, as shown in Table 3.

Table 3 also shows the average power generation of the cascade hydropower plants in the base period and the change period under conventional operation. It can be seen that the power generation of the cascade hydropower plants decreases by 1.9 TWh (1.0%) compared with the base period during the change period due to the reduction in runoff. This means that the runoff change is not completely equivalent to the power generation change of hydropower plants. The power generation changes of each plant in the cascade hydropower plants are 0.8, 0.2, -2.8, and -0.1 TWh, respectively, with corresponding change rates of 1.4%, 0.6%, -3.0% and -0.5%. Among them, the power generation of Xiluodu and Xiangjiaba hydropower plants increase. Although it is verified that the measured runoff at Pingshan station has a weak decreasing trend during the study period (confidence is less than 80%), the average annual runoff in the changing period increases by 0.1 km^3 compared to the base period, so the power generation of the two power stations has increased accordingly.

Table 3. Influence of runoff change on power generation of cascade reservoirs under conventional operation

Subperiod	Average annual power generation/TWh					Average annual runoff/km^3
	Xiluodu	Xiangjiaba	Three Gorges	Gezhouba	Cascade hydropower plants	
Base period	56.57	30.56	91.74	16.49	195.37	438.2
Change period	57.35	30.74	88.98	16.41	193.49	420.9
Change value	0.78	0.18	−2.76	−0.08	−1.88	−17.2
Change rate	1.39%	0.59%	−3.00%	−0.47%	−0.96%	−3.9%

4.2 Processes and Effects of Adaptive Regulation Measures

4.2.1 Optimization of Reservoir Group Operation Mode

The year 2010 was selected as a typical year and focus on analyzing of the control mechanism of Xiluodu and Three Gorges reservoir, which have strong scheduling capacity, and draw the water level process line of joint operation and conventional operation of the reservoir group as shown in Fig. 3. It can be seen that:

(1) Falling period: The Xiluodu's centralized falling time is advanced in the joint operation compared with the conventional operation, and the water level process line is similar in the two operation modes; the Three Gorges's centralized falling time changes little in the joint operation compared with the conventional operation, but the water level process line of the Three Gorges Reservoir is slightly higher than that under the conventional dispatch due to the increase in discharge of Xiluodu during the joint operation.
(2) Flood period: To reduce the invalid abandoned water of the cascade hydropower plants, Xiluodu increases the outflow to maintain the water level at 540–560 m throughout the flood season while ensuring that it can be stored back to the flood limit water level (560 m) in the later stage of the flood season. The total power generation benefit of cascade hydropower plants increases due to the increase in the power generation flow of the Three Gorges. The water level of the Three Gorges maintains at the upper limit of the water level of 146.5 m during the flood season, and the water level process line has no significant difference under the two operation modes.
(3) Water storage period: The Xiluodu synchronously stores water with the Three Gorges under both joint and conventional operation, and the water level process lines almost overlap in the two operation modes. The Three Gorges mainly considers its power generation under the two different operation modes, so there is no obvious difference in the water storage process line.

Therefore, compared with the conventional operation, the joint operation is mainly embodied in reducing the reservoir water level in advance during the falling stage, increasing the discharge flow, thereby increasing the power generation of the downstream cascade power stations, and ultimately achieving the goal of maximum cascade power generation (Fig. 2).

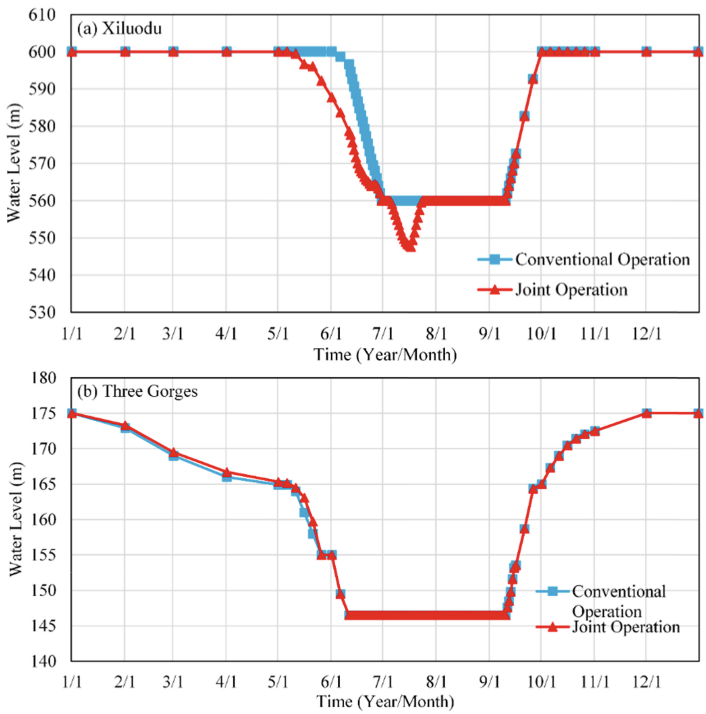

Fig. 2. Water level hydrograph of the Xiluodu reservoir and the three gorges reservoir under joint operation and conventional operation.

The adaptive operation effect is reflected in the recovery of power generation after the joint optimal operation of the reservoir group. Table 4 shows the average power generation in the change period under conventional operation and joint operation of the cascade hydropower plants. It can be seen that the power generation of the cascade hydropower plants increases by 0.59 TWh (0.31%) compared with the conventional operation for joint operation. Specifically, the power generation increase of each power station is -0.37, 0.47, 0.39, 0.10 TWh, respectively, with the increase rate of -0.65%, 1.52%, 0.44%, 0.62%. The power generation changes show that Xiluodu, as the first stage of the cascade hydropower plants, has sacrificed part of its power generation in exchange for increased power generation of other plants by falling in advance to achieve the overall power generation benefit of the cascade hydropower plants (Fig. 3a). The power generation is restored to a certain extent by adopting the mode of joint operation of cascade reservoirs, and the reduced power generation has been reduced from 1.88 TWh (0.96%) to 1.29 TWh (0.66%) due to the reduction in runoff. This means that the adaptive regulation of the reservoirs can alleviate the negative impacts of the reduction of river runoff on the power generation benefits of the cascade reservoirs.

Table 4. Power generation of cascade reservoirs under joint operation and conventional operation.

Scenario	Average annual power generation/TWh				
	Xiluodu	Xiangjiaba	Three Gorges	Gezhouba	Cascade hydropower plants
Conventional operation	57.35	30.74	88.98	16.41	193.49
Joint operation	56.98	31.20	89.38	16.52	194.08
Change value	−0.37	0.47	0.39	0.10	0.59
Change rate	−0.65%	1.52%	0.44%	0.62%	0.31%

4.2.2 Utilization of Flood Resource

Figure 3 shows the water level process line of the Three Gorges Reservoir under different flood limit water level scenarios (Scenario B-D). It can see that:

(1) Falling period: The Three Gorges reservoir water level process under scenarios C and D overlap with scenario B before June 1, and they fall to the flood limit water level from June 1 to On June 10.
(2) Flood period: The water level of the Three Gorges reservoir is maintained at the upper limit of the water level during the flood season under the three scenarios.
(3) Water storage period: The water level of the Three Gorges Reservoir under the three scenarios gradually returns from the flood limit water level to the control water level of 165 m at the end of September. Compared with Scenario A, the water level of the Three Gorges reaches 165 m earlier under scenarios B and C.

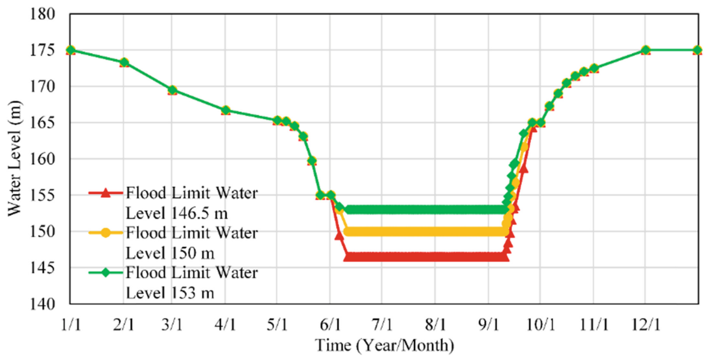

Fig. 3. Water level hydrograph of the Three Gorges Reservoir under scenario A, B, C.

Table 5 shows the calculation results of the average annual power generation of the cascade hydropower plants in the changing period under scenario A, B, C. As the maximum control water level of the Three Gorges Reservoir increases from 146.5 m (scenario A) to 150 (scenario B) m and 153 m (scenario C) during the flood season, the average annual power generation of the cascade hydropower plants during the change period increases from 194.08 to 195.26 and 196.71 TWh. Compared with scenario A, scenarios B and C have increased by 1.18 and 2.63 TWh respectively, and their growth rates are 0.61% and 1.34%. With the increase of the highest control water level in the flood season of the Three Gorges Reservoir, the power generation benefit of the cascade hydropower plants has increased significantly.

The regulation measures of raising the maximum control water level to 150 m (Scenario B) of the Three Gorges during the flood season can reduce the power generation reduction of the cascade hydropower plants due to the reduction of runoff from 1.88 TWh to 0.7 TWh. When the maximum control water level during the flood season of the Three Gorges is raised to 153 m (Scenario C), the power generation of the cascade hydropower plants has exceeded the 195.37 TWh of the conventional operation during the base period. This implies that the disadvantages of the reduction of runoff on the power generation of the cascade hydropower plants have been eliminated under scenario C. due to the increase of its power generation. For the power generation of the cascade hydropower plants, the increase in the maximum control water level of the Three Gorges reservoir during the flood season is mainly due to the increase of its power generation and has little impact on the Xiluodu, Xiangjiaba, and Gezhouba hydropower plants. From the results, it is clear that the utilization of flood resource can increase the effective runoff replenishment, regulate the water volume, and effectively increase the power generation of cascade hydropower plants (Fig. 4).

Table 5. Power generation under different flood control water level of the Three Gorges Reservoir**.**

Scenario	Average annual power generation/TWh					
	Xiluodu	Xiangjiaba	Three Gorges	Gezhouba	Cascade hydropower plants	Increase in cascade power generation
A	56.98	31.20	89.38	16.52	194.08	–
B	56.95	31.20	90.56	16.55	195.26	1.18 (0.61%)
C	56.96	31.21	91.27	16.58	196.71	2.63 (1.34%)

4.2.3 Adjustment of Water Use Behavior

In the long-term optimal operation, we focus on analyzing the regulation process of the Xiluodu and the Three Gorges Reservoir, which has strong regulation ability. Figure 5 shows the water level process line of the two reservoirs under scenario A, D, E. It can be seen that:

(1) Falling period: The water level process line of Xiluodu is slightly higher under the scenario E than scenario D and A due to the increase in incoming water, and it can be seen that the better water saving, the higher the water level process line. The

regulation process of the Three Gorges has the same characteristics, and its operating water levels of different scenarios overlap until the control water level of 155 m is reached on May 25.

(2) Flood period: The Xiluodu increases the outflow while ensuring that it can be stored to the flood limit water level of 560 m in the later stage of the flood season under scenario A, D, E. The water level is maintained within the range of 540–560 m during the entire flood period to reduce invalid abandoned water of other plants. When increasing the outflow of the Xiluodu, there is more water, and the drawdown depth is greater due to the control measures of water-saving. The water level of the Three Gorges reservoir is maintained at the upper limit of the water level during the flood season under scenario A, D, E.

(3) Water storage period: Due to the water-saving control measures, the upstream inflow is increased, and the speed of reservoir storage is faster. At the same time, the 20% of water saving scenario (scenario E) is faster than the 10% of water saving (scenario D) and no water saving scenario (scenario A). After Xiluodu reaches the normal water storage level on October 1, the water level process lines of different water-saving scenarios overlap. On the other hand, the water level of the Three Gorges reservoir reaches the control water level of 165 m before the end of September earlier and reaches the normal high water level on December 1 under water saving.

Fig. 4. Water level hydrograph of the Xiluodu and the Three Gorges Reservoir under scenario A, D, E.

Table 6 shows the average annual power generation of cascade hydropower plants during the changing period under scenario A, D, E. With the adjustment of water use behavior from no water saving (scenario A) to 10% water saving (scenario D) and 20% water saving (scenario E), the average annual power generation of cascade hydropower plants increases from 194.08 to 194.74 and 195.41 TWh during the change period. The increase in power generation is 0.66 and 1.32 TWh, respectively, and the corresponding increase rates are 0.34% and 0.68%. The regulation measures of 10% water saving (scenarios D) can reduce the power generation reduction of the cascade hydropower plants due to the reduction of runoff from 1.88 to 1.22 TWh. When we implement water saving 20% measures the power generation of the cascade hydropower plants has exceeded the 195.37 TWh of the conventional operation during the base period. This implies that the disadvantages of the reduction of runoff on the power generation of the cascade hydropower plants have been eliminated under scenario E.

In combination with Fig. 4, it is clear that the adjustment measures of water use behavior can increase the effective runoff replenishment and water volume of the hydropower system, thereby effectively increasing the power generation of the hydropower system. Together, reducing water outside the river (e.g., direct water consumption by humans) is one of the effective control measures to mitigate the impacts of upstream river runoff reduction on the hydropower system.

Table 6. Power generation of cascade reservoirs before and after the implementation of water-saving.

Scenario	Average annual power generation/TWh					
	Xiluodu	Xiangjiaba	Three Gorges	Gezhouba	Cascade hydropower plants	Increase in cascade power generation
A	56.98	31.20	89.38	16.52	194.08	–
D	57.16	31.28	89.77	16.53	194.74	0.66 (0.34%)
E	57.32	31.36	90.14	16.57	195.41	1.32 (0.68%)

4.2.4 Comprehensive Control Measures

Table 7 shows the average annual power generation of cascade hydropower plants during the changing period under scenarios F-I. The power generation of the cascade hydropower plants with the joint operation of scenarios F-I are 196.90, 197.40, 198.32, and 198.95 TWh, respectively. The power generation of the cascade hydropower plants under all scenarios can exceed the 195.37 TWh of the conventional operation during the base period. Combining with the results of utilization of rainwater and flood resources (scenario B and C) and implementation of water-saving (scenario D and E), it can be seen that the cascade power generation in Scenario B or C fails to recover to the 195.37 TWh of conventional operation during the base period. However, when combining these two measures (scenario F), the cascade power generation is 196.90 TWh (> 195.37 TWh), which can achieve the target of adaptive regulation. Therefore, the comprehensive control measures are effective control methods to counter the impacts of change in river runoff on the hydropower system.

Table 7. Power generation of cascade reservoirs with comprehensive control measures.

Scenario	Average annual power generation/TWh				
	Xiluodu	Xiangjiaba	Three Gorges	Gezhouba	Cascade hydropower plants
F	57.07	31.25	92.01	16.56	196.90
G	57.13	31.33	92.33	16.60	197.40
H	57.08	31.25	93.42	16.56	198.32
I	57.25	31.33	93.77	16.59	198.95

5 Conclusions

Due to the reduction of runoff, the annual power generation of the Xiluodu cascade and Three Gorges cascade reservoirs system reduces by 1.88 TWh during the change period using conventional operation. By adopting the joint operation of reservoir groups, Xiluodu sacrifices part of its own power generation in exchange for different degrees of increase in power generation from downstream power plants, enabling the reservoirs system to generate an additional 0.59 TWh, which restores the power generation of the system to a certain extent.

The utilization of rainwater and flood resources can increase the runoff recharge of the cascade reservoirs system to improve the system power generation. Raising the maximum control level of reservoirs during the flood season is beneficial for reservoirs to increase their own power generation and improve the overall power generation. When the maximum control water level during the flood season of the Three Gorges is raised to 153 m, the power generation of the cascade hydropower plants has exceeded the conventional operation during the base period, effectively eliminating the negative effect of reduced runoff on the power generation of the cascade reservoirs.

Developing water use control measures by adjusting the socio-economic structure, promoting water-saving can increase the runoff recharge of the cascade reservoirs system to improve the system power generation. When saving 20% of water use is implemented the negative effect of reduced runoff on the power generation is eliminated. Sometimes a single control measure cannot completely eliminate the negative effects of reduced runoff, but a combination of control measures is an effective way to hedge against the effects of runoff change on hydropower system.

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