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10 YEARS OF THREE GORGES PROJECT'S 175-M TRIAL IMPOUNDMENT: ACHIEVEMENTS AND CHALLENGES

SHUAI LI[(1)], LONG XING[(2)] & YULEI GAO[(3)]

[(1,2,3)] Three Gorges Construction and Operation Management Department,
China Three Gorges Corporation, Yichang, China
li_shuai@ctg.com.cn; xing_long@ctg.com.cn; gao_yulei@ctg.com.cn

ABSTRACT

The Three Gorges Project (TGP) is a backbone project in the development and harnessing of the Yangtze River in China. It has multi-purpose of flood control, power generation, navigation improvement and utilization of water resources. TGP fulfills the yearly impoundment up to its normal pool level of elevation (El.) 175 m, which is of great significance to fully realize its comprehensive benefits. The TGP has been in operation since 2003, following the principle of "impoundment by stages", its 175-m trial impoundment officially started at the end of the 2008 flood season after completion of the phased impoundment to El. 135 m and El. 156 m. In the past ten years since 175-m trial impoundment, the impoundment operation mode of the TGP has been continuously optimizing by carrying out considerable research and practice of key technologies such as impoundment from the late flood season, and some remarkable results are obtained: the TGP has achieved its 175-m impoundment target for 9 consecutive years since 2010. While giving full play to its comprehensive benefits, the TGP try its best to resolve the contradiction between impoundment and downstream water use in the impounding period. However, climate change, simultaneous impoundment of reservoir group in the upper Yangtze River at the late flood season, and higher requirement on further reducing negative impacts of the TGP's impoundment on the downstream hydrological regime during the impoundment period have brought new challenges to the TGP's impoundment operation.

Keywords: Three Gorges Project; 175-m trial impoundment; impoundment by stages; impoundment from the late flood season; ten years

1 INTRODUCTION

As the largest river in China and the third largest river in the world, the Yangtze River is 6,300 km long and has a drainage area of 1.8 million km^2. The Yangtze River Economic Belt relying on this golden waterway has a very important strategic position, which contributes more than 40% of China's total economic output by about one-fifth of China's land area and two-fifth of the total population (Li et al., 2019). As a key backbone project for the development and harnessing of the Yangtze River, the Three Gorges Project (TGP) has multi-purpose of flood control, power generation, navigation improvement and utilization of water resources. Located at the junction of the upper Yangtze River and middle Yangtze River (see Figure 1), approximately 38 km from its downstream Gezhouba hydroproject, the TGP control a drainage area of 1.0 million km^2, with an average annual runoff of 451 billion m^3 (CWRC, 1992). The design operational parameters of the TGP reservoir are listed as follows: the normal pool level is elevation (El.) 175 m with a corresponding storage capacity of 39.3 billion m^3; the check water level is El. 180.4 m with a total storage capacity of 45.0 billion m^3; the flood control limiting level during the flood season is El. 145.0 m; the draw-down water is El. 155.0 m during dry period. It has a corresponding flood control and utilizable storage capacities of 22.15 and 16.5 billion m^3, respectively. The three Gorges power station has an installed capacity of 22.5 GW with an annual average power generation of near 90 TW•h.

Preparations for the construction of the TGP began in 1993, the work commenced in December 1994, and the main river was closed on November 8, 1998 (Zhang and Dai, 1998). In June 2003, the reservoir was impounded to El. 135 m; in July, the first batch of generating units in the left powerhouse began generating power. By 2009, as the main hydraulic structures were completed (Zheng, 2016), the reservoir was fit to be impounded to its normal level of El. 175 m. On 26 October, 2010, the TGP was successfully impounded to its normal pool level of El. 175 m for the first time, and since then it has started to give full play to its huge comprehensive benefits because of achievement of the 175-m impoundment target for 9 consecutive years. In this paper, a comprehensive review on the TGP's optimization of impoundment operation mode and achievements were carried out, and the impounding challenges were prospected and possible solutions were also proposed, hoping to provide some thoughts for continuous optimization of the TGP's impoundment operation mode.

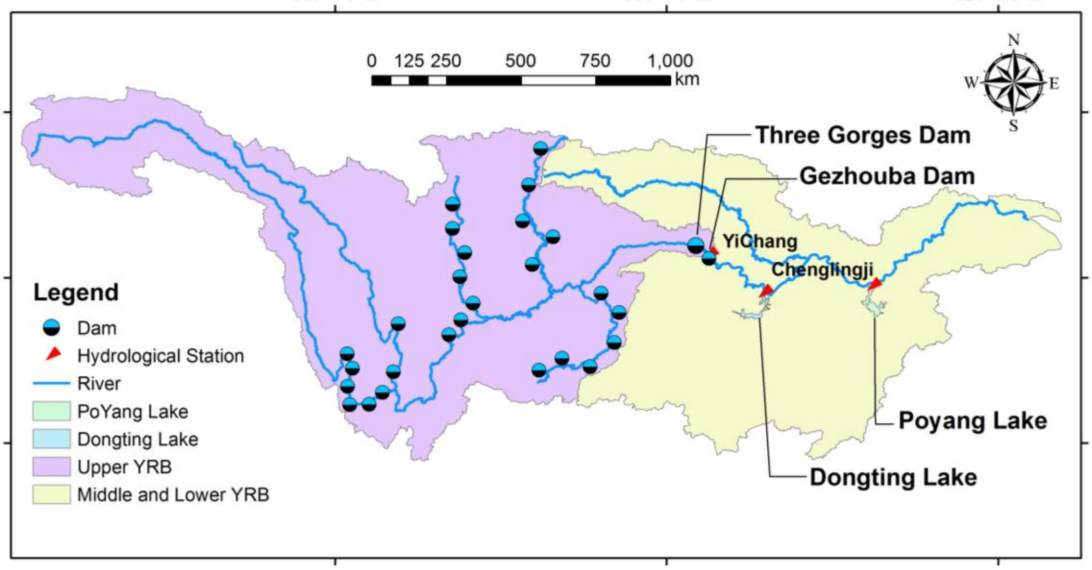

Figure 1. Maps showing the location of the TGP

2 ACHIEVEMENTS

2.1 Optimization of the TGP's impoundment operation mode

"One-grade development, one-time completion, step-by-step impoundment and continuous resettlement" is the TGP's construction principles. The preliminary design of the TGP planned for three phases in the impoundment of its reservoir: the power generation period, with the water retained by a cofferdam; a preliminary operation period; and then a normal operation period (see Figure 2). Pool levels of the TGP reservoir during different periods are El. 135 m, El. 156 m and El. 175 m, respectively.

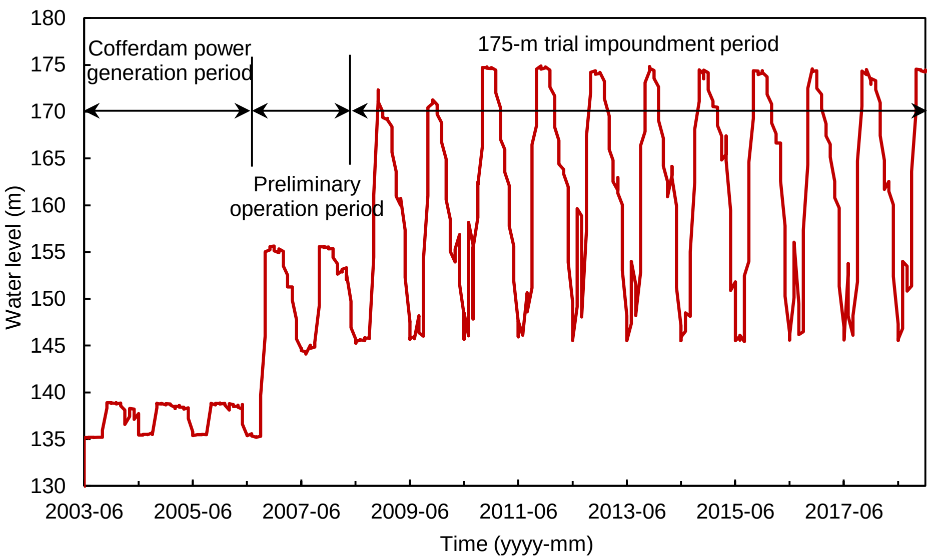

Figure 2. Water level of the TGP reservoir during 2003-2018

How to shorten the duration of both cofferdam power generation period and preliminary operation period as quickly as possible, and bring into play the comprehensive benefits of the TGP at the normal pool level of El. 175 m as soon as possible, which is a problem that the design and operation management personnel of the TGP have been paying attention to. Sediment problem is one of the key factors which affect the dispatching operation and life of the TGP (Hu and Wang, 2014). Many approaches were employed to research the sediment problems of the TGP during its demonstration, planning, design, construction and operation, and many important results were obtained. Among them, the two results have played a key role in promoting the advancement of the TGP's 175-m trial impoundment operation (CTGC, 2016): First, in order to actually observe the influence of sediment deposition at the tail of the TGP reservoir on the channel of the main urban section of Chongqing, the reservoir water level must be raised to El. 172 m. The second is that after entering the 1990s, the annual sediment transport at the Yichang hydrological station has been significantly reduced. The TGP's sediment problem has not become a condition that restricts its impoundment to El. 175 m. Based on comprehensive research, under the conditions of resettlement, geological disaster management and other control factors to meet the gradual uplift of pool level, the water level rise to El. 175 m in 2008 is conducive to comprehensively observe possible problems of sediment and geological disaster management in reservoir dispatching.

With the approval of the State Council, the TGP reservoir began its first 175-m trial impoundment at the late flood season of 2008. In accordance with the principle of “safe, scientific, reliable and gradual”, the highest pool level of TGP reservoir in 2008 was El. 172.8 m. On the basis of a large amount of research work, the State Council approved the “Three Gorges Reservoir Optimal Dispatching Plan” (hereinafter referred to as “Optimization Plan”) for guiding the operation of the TGP reservoir’s 175-m trial impoundment operation in 2009. The “Optimization Plan” is aimed at the situation that the incoming water of the TGP reservoir during the impoundment period is reduced, the upstream reservoirs are impounded in the same period, and the contradiction between storage and discharge of the TGP reservoir because of the increasing downstream water demand. After fully demonstrating the flood control safety and sediment deposition in advance, it is proposed that the TGP reservoir’s 175-m trial impoundment begins on the September 15, the highest pool level at the end of September is El. 158 m, and the outflow discharge standards in September and October are increased. Due to the droughts in the upstream Yangtze River Basin (YRB) and the continuous droughts in the downstream YRB in 2009, the TGP reservoir failed to be impounded to El. 175 m in October, and the reservoir remained unfilled in November, with the highest pool level reaching El. 171.43 m. The practice of TGP reservoir’s impoundment in 2009 shows that when the incoming water is extremely less than the normal level, the impoundment operation mode determined by the “Optimization Plan” is still difficult to meet requirements of the reservoir impoundment and downstream water demand. In view of this, further research proposed to undertake the flood control water level in the early stage, starting from September 10, and further raising the water level to the El. 162~165 m at the end of September. Meanwhile, the flood control operation mode of the TGP reservoir is also optimized for the scientific utilization of flood resources. The operation for detaining small and medium floods was conditionally conducted, i.e., under the premise of controllable flood control risk, the flood control capacity of TGP reservoir was used to intercept the flood with a peak flow less than 55,000 m^3/s, which contributes to alleviate the flood control pressure in the middle and lower reaches of the Yangtze River (MLRYR) and give full play to the power generation and shipping benefits of the TGP. From 2010 to 2018, the TGP reservoir adopted a combination mode of impoundment and flood control operation at the late flood season (see Table 2). Impounding time of the TGP reservoir is further advanced to September 10 (in 2014, due to the large amount of incoming water entering the TGP reservoir in early September, its impounding time was postponed to September 15) with the corresponding reservoir water level of above El. 150 m. The water level of the reservoir at the end of September was higher than El. 162 m (except in 2016 because of the extremely less incoming water of the TGP reservoir in August and September of 2016). After further optimizing the impoundment operation mode, the TGP achieved its 175-m impoundment target for 9 consecutive years, and the outflow discharge standard during the impoundment period in October was raised from the preliminary design of about 5,500 m^3/s to 8,000 m^3/s. The fulfillment of the TGP’s 175-m impoundment provides a guarantee for the full play of the water supply benefit during the dry season.

Table 1. Statistics of the TGP reservoir’s 175-m trial impoundment during 2008-2018

Year	Impounding time			Water level (m)			Storage (billion m^3)	Average outflow discharge of the TGP reservoir (m^3/s)	
	Start	End	Duration(d)	Start	End	Sept. 30		Sept.	Oct.
2008	Sept.28	Nov.11	45	145.27	172.8	150.23	19.8	22,000	11,600
2009	Sept.15	Nov.24	71	145.87	171.43	157.50	18.2	14,600	8,500
2010	Sept.10	Oct.26	47	160.20	175.0	162.84	13.0	20,900	9,640
2011	Sept.10	Oct.30	51	152.24	175.0	166.16	18.3	13,600	8,200
2012	Sept.10	Oct.30	51	158.92	175.0	169.40	13.9	18,900	14,500
2013	Sept.10	Nov.11	63	156.69	175.0	167.02	15.4	15,300	8,000
2014	Sept.15	Oct.31	47	164.63	175.0	168.58	9.6	31,000	13,900
2015	Sept.10	Oct.28	49	156.01	175.0	166.41	15.8	20,400	12,900
2016	Sept.10	Nov.1	53	145.96	175.0	161.97	21.7	10,300	9,350
2017	Sept.10	Oct.21	42	153.50	175.0	166.79	17.5	17,800	20,300
2018	Sept.10	Oct.31	52	152.63	175.0	165.93	18.1	15,300	14,900

2.2 Benefits during the TGP’s 175-m trial impoundment period (2009-2018)

As of 2018, the TGP’s trial impoundment operation at the normal pool level of El. 175 m had been conducted for ten years. According to the optimized impoundment operation mode, the TGP has achieved its 175-m impoundment target for 9 consecutive years since 2010, and the benefits of flood control, power generation, navigation improvement and water resources utilization have begun to fully play.

2.2.1 Flood control

Through measures such as flood interception, peak cutting and peak staggering, the TGP reservoir has successfully avoided encounter of the floods from the upper and the middle-lower reaches of Yangtze River, effectively alleviating the flood control pressure in the middle and lower Yangtze regions. From 2009 to 2018, the flood control operation of the TGP reservoir has been conducted 45 times according to the flood control needs of YRB, and the total flood storage volume is 141 billion m^3 (see Table 2), of which, in 2010 and 2012, it successfully handled 2 floods with magnitude of 70,000 m^3/s, fully exerting its design flood control function (Cai, 2010). Meanwhile, operation for detaining the small and medium floods with peak flow less than 55,000 m^3/s was also conducted under the premise of ensuring flood control safety of the MLRYR, further expanding the flood control benefits of the TGP (Zheng, 2015).

Table 2. Statistics of flood control operation of the TGP reservoir during 2009-2018

Year	Peak flow (m^3/s)	Peak time	Maximum outflow discharge (m^3/s)	Maximum peak cutting (m^3/s)	Numbers of flood control operation	Total flood storage volume (billion m^3)	Highest regulating water level (m)
2009	55,000	Aug.6	39,600	16,300	2	5.7	152.89
2010	70,000	Jul.20	40,900	30,000	7	26.4	161.02
2011	46,500	Sept.21	29,100	25,500	5	18.8	153.84
2012	71,200	Jul.24	45,800	28,200	4	22.8	163.11
2013	49,000	Jul.21	35,300	14,000	5	11.8	156.04
2014	55,000	Sept.20	45,000	22,900	10	17.5	164.63
2015	39,000	Jul.1	31,000	8,000	3	7.5	156.11
2016	50,000	Jul.1	31,000	19,000	3	9.8	158.50
2017	38,000	Sept.10	22,900	20,000	3	10.4	157.10
2018	60,000	Jul.14	42,000	18,000	3	11.8	156.83
Sum		/			45	141.0	/

2.2.2 Power generation

The commissioning of the Three Gorges Hydropower Plant (TGHP) has promoted nationwide power grids, improved the reliability and stability of the grid operation, and effectively solved the power supply needs in Central China, East China and South China (Mei, 2011). Since the first batch of units was put into operation in 2003, the cumulative power generation of the TGHP has approached 1.2 trillion kW•h, and the cumulative power generation in the past decade has accounted for more than 75%. The average power generation in the past decade has exceeded the designed average generation of about 2 billion kW•h. In 2018, the power generation exceeded 100 billion kW•h for the first time (see Figure 3), creating a new record for annual power generation in China domestic single hydropower station.

Compared with thermal power, hydropower, as a clean energy source, provides a green energy for promoting the development of the national economy, and there are huge energy-saving and emission reduction benefits (Jiao, 2014). The TGHP emits 1.2 trillion kW•h of electricity, equivalent to reducing the burning of standard coal by 390 million tons, reducing emissions of 1.04 billion tons of carbon dioxide, 10.91 million tons of sulfur dioxide and 2.84 million tons of nitrogen oxides.

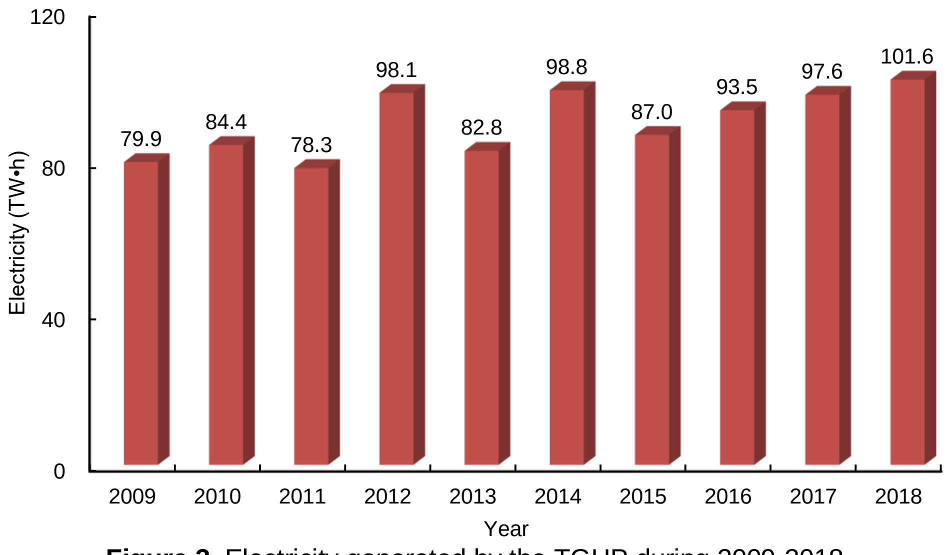

Figure 3. Electricity generated by the TGHP during 2009-2018

2.2.3 Navigation improvement

After the successful impoundment of the TGP reservoir to El. 175 m, the Chuanjiang River below Chongqing was channelized more than 660 km, improving the navigation conditions of the TGP reservoir area and its downstream area, ending the history that the Chuanjiang River was not suitable for navigating at night since the ancient times. The main stream of the reservoir area was upgraded from Grade III to Grade I (Yin et al., 2011). Unit transportation costs have fallen by a third, and the amount of cargo passing the TGP dam has increased year by year (Guo, 2010). In 2011, the freight volume through the Three Gorges ship lock exceeded 100 million tons for the first time, and the design pass capacity was reached 19 years ahead of schedule. In 2018, the freight volume reached 141 million tons, which is nearly 8 times of the highest annual freight volume (18 million tons) of the TGP reservoir. The cumulative freight volume of the past 10 years has exceeded 1 billion tons (see Figure 4).

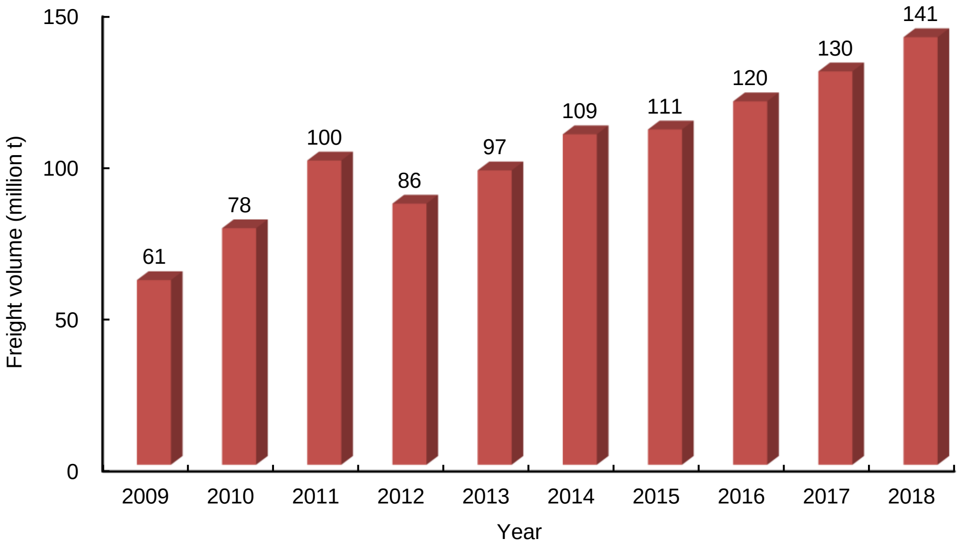

Figure 4. Freight volume through the Three Gorges ship lock during 2009-2018

2.2.4 Utilization of water resources

The TGP reservoir has a powerful function of regulating water resources. The benefits of water resources utilization are mainly shown in three aspects: First, replenishing water for its downstream area (Changjiang, 2011). The TGP reservoir is an important strategic reserve reservoir for freshwater resources in China. From January to April each year, the outflow discharge of the TGP reservoir is controlled at about 6,000 m^3/s. Compared with the natural flow, the increase is about 1,500 m^3/s, an increase of more than 33%, and the average downstream water depth increases by about 0.7 m, which effectively guarantees downstream agricultural, industrial, domestic and ecological water use. Since 2009, the TGP reservoir has accumulated a total of 1,780 days of water replenishment, with a total water supply of 236 billion m^3. The second is to conduct ecological operation (Chen and Li, 2015; Chen, 2018). In May to June of each year, the outflow discharge of the TGP reservoir is regulated to create the best conditions for the survival and reproduction of the rare aquatic organisms and the “four major fish”. In the past 8 years, a total of 12 ecological operation tests were conducted. The fish spawning density at the Yidu section of the Yangtze River was 12 times that of the previous one. The third is to carry out emergency operation. When sudden water environment, water safety incident or maritime crisis occurs, emergency operation by regulating outflow discharge of the TGP reservoir can be carried out. In February 2014, the TGP reservoir increased its outflow discharge, compared with the normal subsidence of 6,000 m^3/s, more than 960 million m^3 of water, effectively inhibiting the salty tide invasion of the Yangtze River estuary in Shanghai (Lu et al., 2015); In the "Eastern Star" shipwreck accident event of 2015, the TGP reservoir reduced the outflow discharge by a maximum of 8,000 m^3/s and lowered the water level at the Jianli section of the Yangtze River by about 0.7 m, creating conditions for the accident rescue.

3 CHALLENGES

During the 10 years of the 175-m trial impoundment operation of the TGP, its operation mode has been continuously optimized for changes in its external conditions, and its comprehensive benefits have finally been fully utilized to ensure flood control safety, shipping safety, water supply safety, ecological safety and energy safety in the YRB. However, the frequency of extreme weather events in the YRB will further increase in the future. A number of large-scale hydroprojects in the upper reach of the Yangtze River will soon be completed and be in operation. The external conditions of the TGP will continue to change, climate change, simultaneous impoundment of reservoir group in the upper Yangtze River at the late flood season, and higher requirement on further reducing negative impacts of the TGP’s impoundment on the downstream hydrological regime during the impoundment period will pose challenges to the TGP’s impoundment operation.

3.1 Climate change

Climatic factors, especially the randomness of precipitation, are the most important natural factors affecting the TGP reservoir operation (Zhang et al., 2000; Zhang and Wang, 2008). Climate change may aggravate the frequency, intensity and extent of droughts in the dry season of the YRB, which will impact the TGP reservoir's impoundment operation (Zhang and Wang, 2008). Since the 1950s, precipitation in the upper reaches of the Yangtze River has shown a significant reduction trend (Li et al., 2018), which is the main reason for the steady decline in incoming water of the TGP reservoir in the past decade (Shu et al., 2016). The most typical example is that the TGP reservoir was not impounded to El. 175 m in 2009, mainly because of the extremely less incoming water of the TGP reservoir in October and the continuous droughts in the MLRYR (Pang et al., 2011). Therefore, strengthening the medium- and long-term precipitation forecasting capacity construction in the upper reaches of the Yangtze River during the impoundment period, improving the forecasting accuracy and extending the forecast lead time will help to formulate an accurate impoundment dispatching plan to improve the TGP reservoir's fill storage rate and the water supply guarantee rate in the dry season of the coming year.

3.2 Simultaneous impoundment of reservoir group in the upper Yangtze River at the late flood season

In the past ten years, the main tributaries of the upper reaches of the Yangtze River have successively built a large number of comprehensive utilization of water conservancy and hydropower projects with large storage capacity. By the end of 2017, 102 large reservoirs (with a total storage capacity of more than 100 million m^3) have been built, with a total storage capacity of more than 8 billion m^3 and a reserve of 39.6 billion m^3 of flood storage capacity (SFCDRHC, 2018). These reservoirs are usually concentrated in impoundment from August to October each year. The impounding time is long, the amount of water to be impounded is large, and the concentrated impoundment of reservoir group in the upper Yangtze River after the flood season results in insufficient incoming water of the TGP reservoir during the impoundment period, increasing the risk of reservoir non-fill storage (Wang et al., 2012; Ding et al., 2012). Under the premise of ensuring controllable risks, it is an effective measure to increase the reservoir fill storage rate by intercepting the floods from the late flood season and improving the water level of the TGP reservoir when impoundment.

3.3 Negative impacts of the TGP's impoundment on the downstream hydrological regime during the impoundment period

The change of hydrological regime in the MLRYR after the impoundment of the TGP reservoir is the result of the combined effects of climate change and human activities (Wang et al., 2012). Through the research and practice of the key technologies for impoundment of the TGP reservoir from the late flood season, its impounding time was advanced from October 1 specified in the "Preliminary Design" to September 15 in the "Optimization Plan", and further optimized to September 10 in the current dispatching rules. The TGP reservoir is impounded in September when runoff in the MLRYR is still relatively abundant, and the impact of impoundment is much smaller than that after October. At the same time, extending the impoundment duration under the condition that the total amount of water storage is constant can reduce the daily average water storage capacity of the reservoir, effectively bring down the reduction of outflow from the TGP reservoir to the MLRYR, and greatly mitigate the impact on the water resources in the MLRYR. However, as the lowest grade reservoir in the upper reach of the Yangtze River, the impact of the upstream reservoir group operation on the MLRYR will be directly superimposed on the TGP reservoir (Huang, 2018). Moreover, with the development of economy and society, the agricultural, industrial, domestic and ecological water use in the mainstream and the Dongting Lake and Poyang Lake regions will put forward higher requirements for the TGP reservoir operation. Therefore, how to minimize the negative effects of reservoir impoundment on the MLRYR is still a problem that needs to be studied in depth.

4 CONCLUSIONS

TGP fulfills the yearly impoundment up to its normal pool level of elevation (El.) 175 m, which is the most critical part of fully realizing its comprehensive benefits. The practice of the TGP's 175-m trial impoundment since 2008 shows that by reasonably lengthening the impounding process, advancing the impounding time and improving outflow discharge of reservoir during the impoundment period, the TGP reservoir has continuously achieved the impoundment goal of El. 175 m in the past nine years. While giving full play to the huge comprehensive benefits such as flood control, power generation, navigation improvement and water resources utilization, it has better coordinated the contradiction between impoundment and downstream water use during the impoundment period.

With the completion of many large-scale water conservancy projects in the YRB, the external conditions of the TGP and the upstream and downstream boundary conditions will continue to change. The impoundment operation of the TGP reservoir will face new situations and new requirements, so it needs to be further optimized from the perspective of the whole YRB, focusing on better coordination of flood control, water supply, shipping and ecological needs during the impoundment period.

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