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Real-time dynamic control of the Three Gorges Reservoir by coupling numerical weather rainfall prediction and flood forecasting

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Abstract Combining numerical weather rainfall prediction and flood forecasting to enhance forecast accuracy of inflow and extend the lead-time can effectively improve reservoir operation mode. In this study, the Regional Spectrum Model (RSM), which is developed by the Japan Meteorological Agency, was used to forecast rainfall with 5 days lead-time in the upper region of the Three Gorges Reservoir (TGR). The Xinanjiang Model was applied to forecast inflow to the TGR. In terms of relative error of inflow, relative error of flood peak and time difference of flood peak the performance of these combined forecasts was compared with that of a forecast based on using observed inflow and assuming that no further rain would fall. Taking the largest flood event in 2012 as an example, all inflow forecasting results were used to implement real-time dynamic control of the FLWL of the TGR. Compared with the designed operation rule, operation results showed that the dynamic control scheme significantly improved hydropower generation without increasing flood risk.

Key words numerical weather rainfall prediction; flood forecasting; flood limited water level; real-time dynamic control; Three Gorges Reservoir

INTRODUCTION

The flood limited water level (FLWL) corresponds to the top reservoir content during the flood season. Conventional reservoir operation is implemented based on fixed reservoir operation rules. Its basic principle is that reservoir water levels are generally not allowed to exceed the FLWL in order to provide enough storage for flood control during the flood season. The rule-based operation can ensure the reservoir's flood control standard, but implies that water has to be discarded during the process of flood control and the reservoir is unable to refill to the normal water level after the flood, resulting in a huge waste of water resources. In order to improve water resources utilization rate, it is essential to change the current reservoir flood control operation mode and implement real-time dynamic control of the FLWL.

Real-time dynamic control of the FLWL should meet the requirements of reservoir filling and the discharge capacity without reducing flood control standards, according to weather forecasts of the basin, flood forecasting information, current hydrological-engineering and disaster information, to determine the specific value of the FLWL in the lead-time. Dynamic control of the FLWL mainly focuses on medium and small-sized floods (less than a 20-year flood) and aims at raising the water level appropriately in a short period, thus reducing the flood control pressure on reservoirs downstream and improving hydropower generation, navigation and others.

Research on the FLWL stems from the US Army Corp of Engineers (1998), which divided the flood season into multiple sub-seasons, advocated of storage for flood control should be varied seasonally and adopted the seasonal FLWL. The result indicated that using a seasonal FLWL resulted in higher economic profits without increasing the flood risk. Liu *et al*. (2008) developed a simulation-based optimal seasonal FLWL model to simultaneously maximize benefits under the condition that the seasonal FLWL risk was less than that of an annually designed one. Yun & Singh (2008) proposed two approaches, multiple duration limited water level and a dynamic limited water level, to increase water storage of a reservoir while maintaining its security for flood control.

Compared with traditional annual limited water level, multiple duration limited water level employs a multiple duration design storm and the dynamic limited water level is based on conditional probabilities of large storms. Li *et al*. (2010) proposed a dynamic control operation model that considers the inflow forecasting error and uncertainty of the flood hydrograph shape. The model consists of three modules: a pre-release module to estimate the upper dynamic control bound based on inflow forecasting results, a refill module to retain recession floods, and a risk analysis module to assess flood control risk, and was applied to the Three Gorges reservoir. The application results indicated that the dynamic control of the reservoir FLWL can effectively increase hydropower generation and the floodwater utilization rate without increasing the flood risk.

Reservoir flood control mainly relies on high-quality and timely forecasts of inflows. However, the inflow forecasting information used by all the above-mentioned research on the FLWL are based on observed rainfall assuming that no further rain would fall. On the one hand, this makes it difficult to obtain higher forecast accuracy. On the other hand, the length of lead-time is limited and there is no amount of time available for the implementation of flood control. Recently, some efforts in inflow forecasting have focused on gaining precipitation information ahead of its occurrence and using it as input to a rainfall–runoff model. Yu *et al*. (1999) proposed a methodology for linking the mesoscale meteorological model (MM5) and the hydrologic model system (HMS) to simulate the streamflow at the outlet of the Upper West Branch of the Susquehanna River Basin. Results indicated that the linked model system simulated the basin outflows moderately well. Anderson *et al*. (2002) adopted the MM5 model and the rainfall–runoff model (HEC-HMS) to predict runoff of the Calaveras River watershed. The conclusion was that translating precipitation forecasts into runoff forecasts can greatly improve the runoff forecast lead-time. Collischonn *et al*. (2005) used quantitative forecasts of rainfall given by a regional numerical weather prediction model to drive a distributed hydrological model. Results obtained for the large flood in 2001 showed that there is plenty of scope for improving the use of rainfall forecasts. Zhang *et al*. (2008) coupled a daily Variable Infiltration Capacity (VIC) distributed hydrological model with MM5 model to simulate the daily runoff process in the Hanjiang basin. It showed a good performance in predicting flood information with the lead-time up to 3 days.

In this study, the Regional Spectrum Model (RSM), which is developed by the Japan Meteorological Agency, was used to forecast rainfall with 5 days lead-time in the upper region of the Three Gorges Reservoir (TGR). Then the rainfall forecasts were translated into runoff forecasts by the Xinanjiang Model. The performance of these forecasts was compared with that of forecasts obtained by assuming that no further rain would fall. All flood forecasts were employed to carry out real-time dynamic control of the FLWL of the TGR.

CASE STUDY

The Three Gorges Reservoir (TGR), intercepting the upstream of Yangtze River (Fig. 1), was selected as a case study. The Yangtze River, the longest river in Asia and the third longest in the world, is about 6300 km long, flowing from its source in the Qinghai province eastward into the East China Sea at Shanghai city. The TGR is a typical river channel-type reservoir, with a surface area of about 1080 km^2 and an average width about 1100 m.

The TGR is the largest water conservancy project in China, consisting of three major parts: the large dam, the hydroelectric power station houses, and the navigation structures. The total reservoir storage capacity is 393 × 10^8 m^3, of which the flood control storage is 221.5 × 10^8 m^3 and the conservation regulating storage volume is 165 × 10^8 m^3. There are 14 and 12 sets of hydraulic turbo generators installed in the left and right powerhouses, respectively. Thus the 26 sets of hydraulic turbo generators, with 700 MW for each set, provide in total 1820 × 10^4 kW in installed capacity, and produce an annual electricity output of 847 × 10^8 kWh. Besides the comprehensive benefits in flood control and power generation, the TGR can also improve the navigation conditions of the waterway in the reservoir area and downstream, promote the development of fishery in the reservoir as well as tourism and recreational activities, and improve water quality of the middle and lower reaches during the dry season (Liu *et al*., 2011).

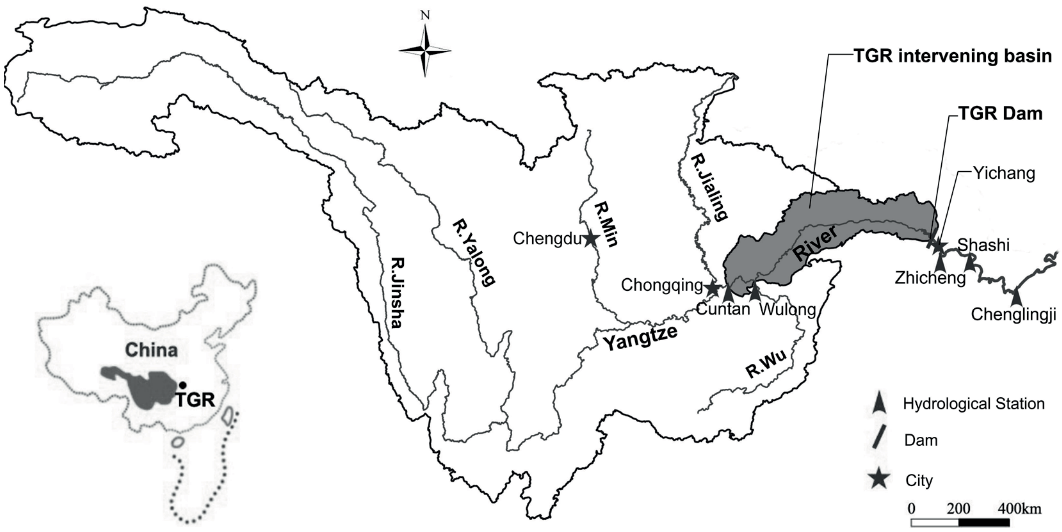

Fig. 1 Location of the TGR in the Yangtze River Basin in China.

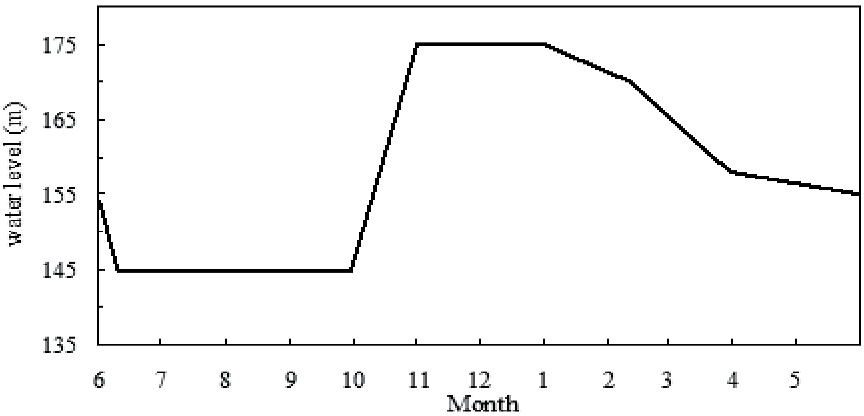

Fig. 2 Designed operation water levels during an annual cycle in the TGR.

METHODOLOGY

Designed operation rules of the TGR

The designed operation water levels of the TGR are shown in Fig. 2 (CWRC, 1997). During the flood season (from 1 June to 30 September), flood control is dominant and the water level should be kept at 145 m to vacate enough flood storage capacity, so huge amounts of flood water have to be spilled. The inflow exceeding the release capacity of the power station will be released through the spillways. Only if the reservoir outflow surpasses the safety discharge of downstream protection point, will the reservoir be permitted to keep the floodwater. During the dry season, hydroelectric energy and navigation improvement become dominant. Therefore, the water level is raised gradually to the normal level of 175 m in October. From November to the end of April in the following year, the water level should be kept as high as possible to generate power. In May, the water level should be reduced to be ready for flood control, but should not fall below 155 m in order to satisfy navigation conditions.

Although the designed operation rules are easy to implement, there are several problems in these rules. One problem is that the reservoir inflow during the flood season accounts for approximately 62.4% of total annual runoff, but the power generation during this period is only about 50% of the annual total. The floodwater utilization rate is relatively low; another problem is that the reservoir cannot be refilled to the normal level at the end of October during most dry

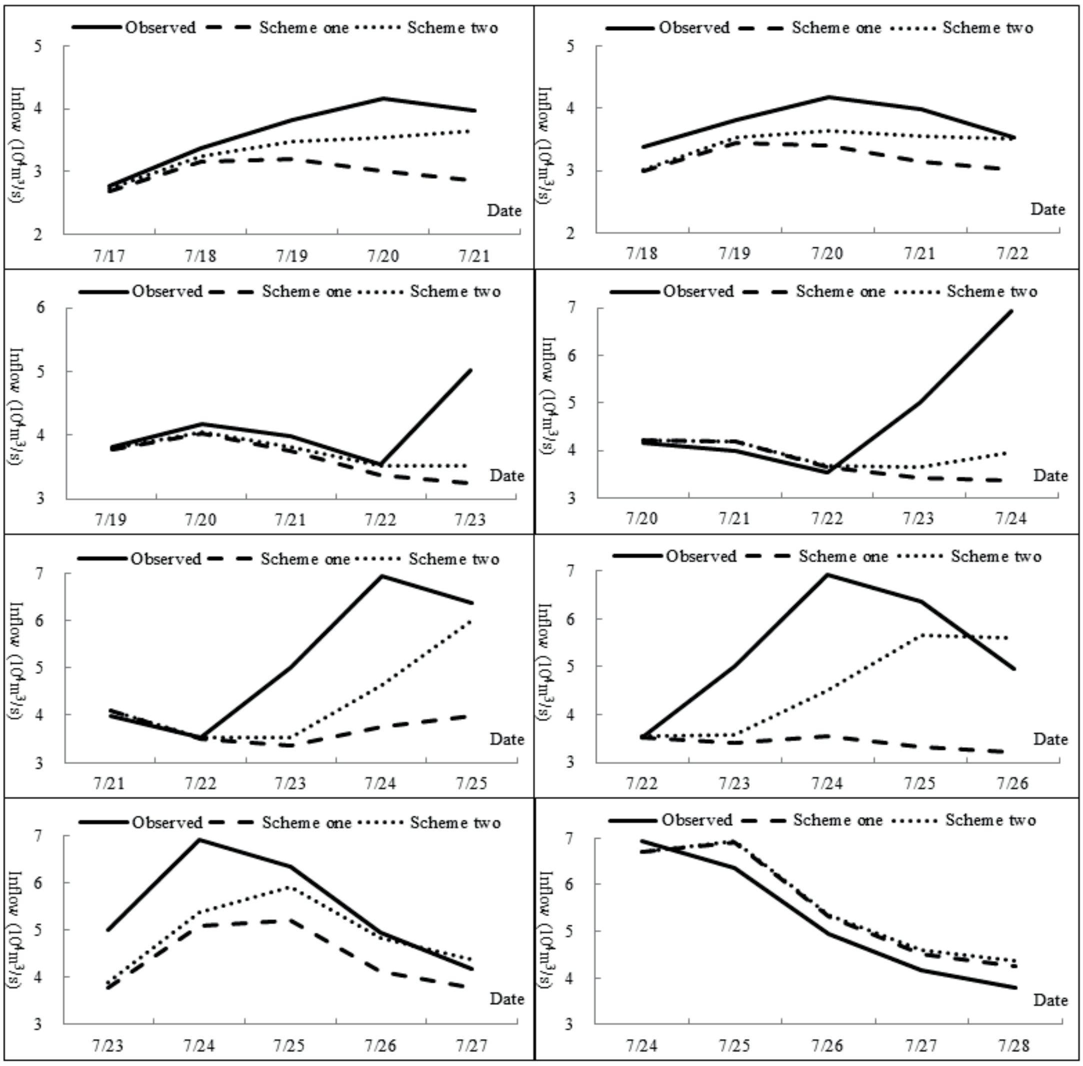

Fig. 3 Comparison of inflow forecasting results of different schemes for the TGR.

years (Li *et al*., 2010). However, the implementation of the TGR FLWL dynamic control can provide a solution for the above-mentioned problems. This is because the TGR has enough release capacity to pre-release the water over the FLWL before a forecasted large inflow occurring. The total release capacity of the TGR can reach 65 500 m^3/s and 69 500 m^3/s when the water level is 145 m and 150 m, respectively.

Dynamic bound of reservoir FLWL

In order to avoid two problems, which are "the FLWL is too low for enhancing flood control capacity" and "the FLWL is too high for increasing conservation benefits", a reasonable dynamic control bound of the reservoir FLWL must be estimated. This paper used the pre-release forecast method to determine the dynamic bound of reservoir FLWL. The expression is described as follows (Zhou *et al*., 2006):

$$Z_u \le f[(Q_{out} - Q_{in}) \times T_c] + Z_0 \quad Q_{out} < Q_s \tag{1}$$

where Z_u is the upper bound of the FLWL; Z_0 is the current FLWL; $f(*)$ is pre-discharge–water level transition function; T_c is effective lead time of inflow forecasting; Q_{in} and Q_{out} is the average inflow and outflow during the effective lead time T_c, respectively. Q_s is the safety discharge in the downstream flood protection section.

Dynamic control operation model

The Jingjiang River, from the Zhicheng to Chenglingji hydrological stations as shown in Fig. 1, is the most important river reach for flood control in the Yangtze River. The Shashi hydrological station is the hydrologic control in the Jingjiang River reach. Its water level is a key parameter to measure the safety of the flood control system in the Yangtze River. In the original design, the warning water level and the safety-guaranteed water level at the Shashi hydrological station are 43 m and 44.5 m, corresponding to the TGR's discharge of 39 900 m^3/s and 53 900 m^3/s, respectively. In this study, the middle and small inflow that are less than 35 000 m^3/s are mainly applied for FLWL dynamic control.

According to the boundary conditions and dynamic control bound of the TGR FLWL, a reasonable dynamic control decision of the FLWL can be made. On the basis of real-time rainfall and inflow forecasting results, the relationship between the current water level and future flood can be built.

$$Z_{t_c} = \begin{cases} Z_u & \hat{Q}_t^{\max} \leq 35000 \\ f_1(V(Z_u) - w) & \hat{Q}_t^{\max} > 35000 \end{cases} \tag{2}$$

$$w = \left(\hat{Q}_t^{\max} - 35000 \right) \cdot \Delta t / L \tag{3}$$

where t_c is the current time; Z_{t_c} is the current water level at time t_c, $Z_{t_c} \in [Z_0, Z_u]$; $\hat{Q}_t^{\max}$ is the forecasted maximum inflow during the effective lead-time; $f_1(*)$ is water level-capacity relational function; w is the current allowed pre-discharge water; Δt is the time interval; and L is the length of time from the time of $\hat{Q}_t^{\max}$ occurring to t_c.

According to equations (2) and (3), if the forecasted maximum inflow $\hat{Q}_t^{\max}$ is less than 35 000 m^3/s, it means that the future floods during the period L are small. In that case, the reservoir water level can be refilled to the upper bound of the FLWL meeting the requirement that the release of generating firm capacity is 499×10^4 kW. If $\hat{Q}_t^{\max}$ is more than 35 000 m^3/s, the excess should be released to provide adequate flood storage before the forecasted maximum inflow occurs, but the reservoir water level cannot be lower than the lower dynamic control bound.

RESULTS AND ANALYSIS

Since the TGR was put into operation in 2003, the maximum peak discharge happened on 24 July 2012. Therefore, this paper selected the observed inflow of this flood event, compared it with inflow forecasting results and used 5-day lead-time inflow forecasting results to implement the real-time dynamic control of the FLWL.

Inflow forecasting results of the TGR

In this study, two kinds of inflow forecasting results were compared: the first assumes that no further rain would fall and the forecasted inflow is obtained from observed precipitation; the other considers the further rain. Based on the 5-day-ahead forecasts of precipitation given by the regional spectrum model, the rainfall forecasts were translated into runoff forecasts by the Xinanjiang model. For brevity, the first method is named scheme one, and the second method is named scheme two.

Figure 3 represents the 5-day-ahead inflow forecasting results of the TGR. Comparing with observed inflow, it can be seen that all forecast inflows are lower before the flood peak occurs on

24 July, but all forecast inflows are higher after the flood peak. Comparing the two kinds of inflow forecasting results, the forecasting result considering the future rain has a better accuracy and its forecast flood process is much closer to the observed. As for the forecasting time of flood peak occurrence, they both predict that it will occur on 25 July and the time lags one day. However, Scheme two can predict it on 20 July, but Scheme one only predicts it on 22 July. It demonstrates that scheme two can extend the lead-time of inflow forecasts.

Moreover, the 5-day-ahead inflow forecasting precisions of the two schemes are listed in Table 1. Relative error of inflow, relative error of flood peak and time difference of flood peak were selected to evaluate the prediction performance. Scheme one has a poor performance because of the lack of rainfall information, especially in predicting the flood peak. The maximum relative error value of flood peak is –48.64%. Scheme two exhibits a better precision. All relative error values of inflow are kept within ±20%. Except for the relative error value of flood peak on July 19 reaching –39%, flood peak precisions are improved and their relative error values are also kept within ±20%.

Table 1 Inflow forecasting accuracy of different schemes.

Date	Scheme one			Scheme two		
	RE (%)	RE of flood peak (%)	Time difference of flood peak (Day)	RE (%)	RE of flood peak (%)	Time difference of flood peak (Day)
7/16	–17.56	–22.97	1	–8.04	–12.47	–1
7/17	–15.25	–17.27	1	–8.69	–12.65	0
7/18	–11.43	–19.73	3	–8.78	–19.15	3
7/19	–20.38	–39.07	4	–16.65	–39.00	4
7/20	–27.64	–41.08	3	–15.70	–13.62	–1
7/21	–36.31	–48.64	0	–14.54	–18.47	–1
7/22	–19.80	–24.70	–1	–10.99	–14.42	–1
7/23	5.62	–0.35	–1	6.74	–0.03	–1
7/24	0.79	2.13	0	1.20	2.15	0

Real-time dynamic control results of FLWL in the TGR

For comparison, a perfect scheme assuming that rainfall forecasts are equal to the rainfall actually recorded was made in this study. The 5-day-ahead inflow forecasting results of three schemes were used to implement dynamic control operation of the TGR and the operation process of a flood hydrograph can be seen in Fig. 4. Before 20 July, water level of Scheme three is higher than other schemes. On this day it predicted that a flood would occur in the next 5 days, so the discharge increased and the water level decreased in order to provide adequate flood storage. Scheme two also has the same prediction that a flood would occur in the next 5 days. However, the forecasted value is lower than the observed, so the discharge is lower than that of Scheme three, but it is higher than that of Scheme one. As for Scheme one, the prediction time (on 21 July) of flood is later than other schemes, so the pre-release time delays one day and it keeps a higher water level during operation. Moreover, its precision is the worst, with a relative error value of –48.64%. This shows that the forecast peak flood is apparently smaller. Hence, the discharge of Scheme one is smallest and its water level is highest. Because of this, the hydropower generation of Scheme one is slightly higher. During the flood recession period, the forecasted inflow of scheme one and two are higher than the observed, so the discharge from them increase. However, Scheme three has begun to reduce the discharge in order to meet conservation demands.

Real-time dynamic control results of the FLWL are listed in Table 2. Compared with designed operation rules, all FLWL dynamic control schemes reduce the discharge volume, increase the floodwater utilization rate and improve the hydropower generation (an increment of 12.7–13.1%). From the perspective of flood control, scheme one keep the highest water level during the whole operation process, among which the highest water level reaches to 152.6 m and is higher than other schemes. Therefore, the flood control benefit of scheme one is lower than other schemes. It also shows that the accurate flood forecasting can effectively decrease flood risk and ensure the reservoir safety.

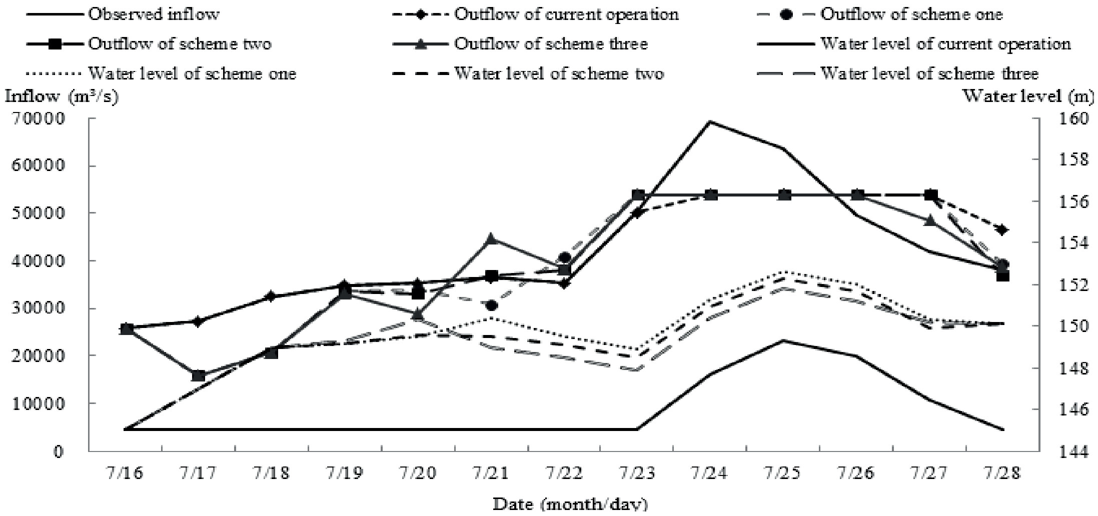

Fig. 4 Operation process of TGR for 20120724 flood based on different forecasts.

Table 2 Operation results of TGR for 20120724 flood with 5 day lead time based on different schemes.

Flood event	20120724			
Operation scheme	Designed operation rules	Scheme 1	Scheme 2	Scheme 3
Maximum inflow (m^3/s)	69250	69007	69227	69250
Maximum outflow (m^3/s)	53900			
Highest water level (m)	149.3	152.6	152.3	151.8
Inflow water ($*10^8 m^3$)	466.6			
Discarded water ($*10^8 m^3$)	313.0	171.9	172.2	172.1
Floodwater utilization rate (%)	32.9	63.2	63.1	63.1
Hydropower generation (10^8kW.h)	49.9	56.5	56.3	56.3
Increment of hydropower generation (10^8kW.h)	—	6.6	6.4	6.4
Increment rate (%)	—	13.1	12.7	12.7

CONCLUSION

At present, the inflow forecasting information used by most research on the FLWL is based on observed rainfall, assuming that no further rain would fall. On the one hand, this makes it difficult to obtain higher forecast accuracy. Also, the length of lead-time is very limited, and there is no amount of time available for the implementation of flood control. Coupling the numerical weather rainfall prediction and flood forecasting, accurate forecasts of the TGR inflows resulting from precipitation forecast results were implemented in this study. The performance of these forecasts was compared with the observed inflow and that of forecasts obtained by assuming that no further rain would fall. All inflow forecasting results were used to implement real-time dynamic control of the TGR FLWL. The main conclusions are as follows:

(1) Compared with forecasts obtained by assuming that no further rain would fall, the forecasts considering the future rainfall can effectively improve prediction accuracy and extend the lead-time.

(2) Compared with the designed operation rules, the implementation of a FLWL real-time dynamic control operation in the TGR can effectively increase the floodwater utilization rate from 32.9% to 63.1%. Without increasing flood control risk, the hydropower generation increases by $6.4 \times 10^8 - 6.6 \times 10^8$ kWh.
(3) Compared with operation results without considering further rainfall, operation results considering the future rainfall can ensure the flood control benefit of the TGR, while its hydropower generation is slightly lower than the former.

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