Impact of the three gorges reservoir operation on the hydrological situation of Poyang Lake

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Abstract. The operation of Three Gorges Reservoir (TGR) has changed the hydrological situation of Yangtze River and its connected lakes. Based on the hydrodynamic model, the influence of TGR operation from 2009 to 2014 on the Poyang Lake has been evaluated. It is found that TGR impoundment reduced the discharge of the Yangtze River and the water level of Poyang Lake, brought the decreasing of the backflow phenomenon. Especially in October, the discharge and water level of Hukou station (HKS) decreased by 9.6% and 1.09 m respectively, and this effect could be up to the Kangshan area. Meanwhile, TGR operation has also increased the water level of HKS by 0.1~0.56 m from December to May, which only affected the vicinity of Duchang. In addition, TGR operation also increased the maximum water level of HKS from April to June by 0.1~0.34 m, and that from July to August decreased by 0.22~0.4 m which is beneficial to reducing the flood control risk of Poyang Lake. But TGR impoundment changed the water exchange process between Yangtze River and Poyang Lake, and advanced the dry season, which had a certain impact on the water supply and ecological environment of the lake area.

1. Introduction
Poyang Lake is the largest freshwater lake in China, and is also an important international wetland. It has a unique timeless variation of hydrological rhythm, and plays an important role in the protection and development of the Yangtze River Economic Zone as well as the global ecological pattern [1]. In recent years, the evolution of the relationship between the Yangtze River and Poyang Lake has been increasingly affected by global climate change and human activities. At present, Poyang Lake is confronted with many challenges, such as prolonged dry season, excessively low water level, shortage of water resources, reduced water environment capacity, and ecological degradation of wetland [2]. These challenges have affected the water and ecological security, severely restricted the surrounding economic and social development, and been extensively concerned by the society.

In recent years, the influence of the basin-controlled reservoir project has become more and more obvious, and it has become the leading driving force to regulate the relationship of rivers and lakes. In particular, the impact of Three Gorges Reservoir (TGR) impoundment on the hydrological situation of the Yangtze River and its connected lakes has been studied intensively [1]. For example, Guo et al quantitatively studied the impact of the operation of TGR and climate change on the interaction between Yangtze River and Poyang Lake, and found that TGR has not changed the basic characteristics of the Yangtze River and Poyang Lake [2]. Zou et al [3] built the matured forecasting model to conduct a return calculation on the flood process in middle-late July in the upper reach of Yangtze River watershed. The results indicated that TGR operation reduced the water level of the
main stream in every station on mid-lower reaches of Yangtze River effectively during the flood process [3]. Wang et al showed that water level of Poyang Lake would decrease 0.09~1.11m based on the calculation of hydrodynamic model with a steady flow condition, if the discharge of the Yangtze river decreased 1000-7653 m$^3$/s after flood season [4]. In addition, Lai et al clarified that TGR regulations have a significant effect on the water level after flood season in the middle-lower Yangtze River and the lowering of water level induced by TGR regulation was 0.7 m at Luoshan, 0.60 m at Hankou, and 0.41 m at Datong averagely from September 10 to October 31 [5]. Xu et al studied the future trend of low flow situation in Poyang Lake by the observed data and mathematical model, and found that when the TGR and the other key reservoirs in the upper Yangtze River operated, the low flow situation of Poyang Lake would be aggravated. The reason is less runoff in the period of impoundment and larger erosion of main channel [6]. Zhong et al also believed that the gradual use of the controlled reservoir in the upper reaches of the Yangtze River would aggravate the dry conditions of Poyang Lake [7]. Liu et al used observed hydrological data and remote sensing data to study the mass balance of Poyang Lake. The results showed that the sudden change in water level at the end of the Poyang Lake was caused by the impoundment of the TGR [8,9]. Obviously, the operation of TGR has impact on the water regime of Poyang Lake. However, due to the long-term and complex effects of the controlled reservoirs in the upper reaches of the Yangtze River on the water and sediment conditions, the relationship between rivers and its connected lakes is constantly changing. The research on the related impacts and countermeasures still needs to be further expanded.

In this paper, based on the existing research, the river-lake hydrodynamic model in the middle reach of the Yangtze River has been developed to simulate the natural hydrological process since the operation of TGR. Then the impact of the TGR operation on the hydrological situation, e.g. discharge, water level, water exchange and so on, has been evaluated quantitatively. These results provide a reference for understanding the relationship between Yangtze River and Poyang Lake and their mutual influence mechanism. It can also provide a scientific basis for the joint optimization of the reservoirs in the upper and middle reaches of the Yangtze River and the comprehensive management of the Poyang Lake ecological economic zone.

2. Methods

2.1. Hydrological conditions of study
Considering that TGR has not been completely built for impoundment from 2003 to 2008, the impact on the water conditions of lakes is constantly changing. Therefore, this paper mainly focuses on the normal operation phase (after 2009) of TGR to reveal its impact on Poyang Lake. According to the hydrological data, the research period is confirmed to be representative from 2009 to 2014, including the 2010 flood year, the 2011 and 2013 dry years. In line with the operation plan of the TGR, the different dispatching periods such as impoundment period, water replenishment and falling period are comparatively analysed.

2.2. Natural hydrological process restoration
Hydrodynamic modelling of the Yangtze River and Poyang Lake with coupled 1-D and 2-D mathematical models is constructed to simulate and restore the natural hydrological processes that are not affected by the TGR operation. Through the comparison with the observed hydrological process of Poyang Lake, the influence of the TGR dispatching on the hydrological situation is quantitatively studied. First, the natural inflow at Yichang station that is not affected by the TGR needs to be got. According to the water level, outflow and storage-capacity curve of TGR, water balance method [10] is used to restore the natural daily flow of Yichang station. Secondly, the calculation is performed by the hydrodynamic model. The entire model framework is shown in figure 1, including 1-D and 2-D modelling parts.
Figure 1. The entire framework of hydrodynamic model.

2.3. Construction of 1-D hydrodynamic model

Mike11 software developed by Danish Hydraulic Institute (DHI), is synonymous with top quality river modelling covering more application areas than any other river modelling package available [11]. In this paper, Mike11 software is used to develop the 1-D river-lake network hydrodynamic model from Yichang to Balijiang (including Dongting Lake and Poyang Lake). The stream between Yichang and Balijiang is about 894 km long, and is divided into 685 sections, each of which is about 1.6 km away. According to those sections, the middle reaches of Yangtze River are easily described in the model. Some tributaries lacking terrain data are generalized as the incoming point sources.

The inflow of the main stream of Yangtze River in the 1-D hydrodynamic model adopts the daily flow of Yichang station. The inflows of tributaries (e.g. Qingjiang River, Dongting Lake, Hanjiang River and Poyang Lake etc.) are controlled by the observation of 22 hydrological stations. For the interval sub-basin with no observed data, the rainfall-runoff model named NAM is used to simulate the side stream inflow of the model. Stage-discharge relation of Balijiang station is set as the downstream boundary of the model.

Calibrated time of the model is from 2003 to 2007, and the validated period is from 2008 to 2010. The roughness indices of model are determined as 0.02–0.035. Taking Hankou station (HK) and Jiujiang station (JJS) as examples, figure 2 shows the simulated flow fits well with the observed, with the Nash-Sutcliffe coefficient (NS) of 0.97–0.98 and the average relative error (RE) of 0.03%–0.04%.

Figure 2. Flow process verification at HK and JJS.
2.4. Construction of 2-D hydrodynamic model

To obtain more accurate results, the 2-D hydrodynamic model in the Poyang Lake is established by using Mike21 software [11], coupled 1-D hydrodynamic model of the Yangtze River to analyze the influence of the TGR impoundment. Mike21 software also developed by DHI is the most versatile tool for 2-D hydrodynamic modelling, which is widely used to simulate free-surface flows in the overland flooding and lakes or reservoirs [11].

Poyang Lake modelling range has three parts, including the Jiujiang-Balijiang section of the Yangtze River, Poyang Lake and its five tributaries section, as showed in figure 3. The 2-D hydrodynamic model is meshed by a triangular mesh, whose density changes according to the terrain elevation rate of the calculation area. Grid size of the river trough is 80~270 m, that of the tail channel is 20~350 m, and in the lakeside beach is 500~2000 m.

![Figure 3. Modelling range of the 2-D hydrodynamic model in the Poyang Lake.](image)

Inflow of the Poyang Lake is monitored by some hydrological stations located on the seven mouths of its five tributaries, namely Waizhou station for Gan River, Lijiadu station for Fu River, Meigang station for Xin River, Hushan station for Lean River and Dufengkeng station for Chang River, Quijin and Wanjiafu stations for Xiu River. The outflow is monitored by the Hukou station (HKS).

In the 2-D hydrodynamic model, the daily flow of JJS simulated by the 1-D hydrodynamic model is used as the upper boundary of the Yangtze River. The inflow of the five tributaries in Poyang Lake uses the observed values from hydrological stations. Interval water volume of a lake is simulated by rainfall-runoff model. The stage-discharge relation of Balijiang station is set as the downstream boundary of the model.

Flow data for large flood such as 1998 and 2005 are selected to determine the roughness indices of
the model. The determined roughness indices are 0.025–0.035 in the Yangtze River, 0.05–0.06 in the coastal area, and 0.03–0.04 in the river channel.

Validated period of the model is from 2008 to 2010. Taking HKS and Xinzi as examples, the verification of flow and water level process are showed in figure 4. The value of RE between the simulated and observed discharge at HKS is about 3.0%, showing the model can well reflect the hydrological situation of the Hukou. Simulated water levels of stations are highly consistent with the observed, within the average errors of 0.04–0.16 m, also showing the model well reflects the change of the hydrological situation in the lake area.

![Figure 4. Flow and water level process verification in the Poyang Lake.](image)

3. Results

3.1. Influence on the outflow of Poyang Lake

Change of the outflow at HKS reflects the water exchange between Yangtze River and Poyang Lake. Through hydrodynamic model analysis, the impact of the TGR operation is illustrated in figure 5.

![Figure 5. Impact on the outflow of Poyang Lake.](image)

After the operation of TGR, in the impoundment period from September to November, average outflow of Poyang Lake increased by 468 m$^3$/s in September, an increasing of 14.9%, especially in the early September within a highest increase reaching 24.7%. In contrast, the average outflow in October decreased by 352 m$^3$/s, a decreasing of 9.6%. But in November, the flow reduced only by 2.3%.

In the water replenishment and falling periods from December to May, due to the increasing of discharge, the total water level of the Yangtze River had increased, which had slowed the outflow of Poyang Lake. According to the analysis, average monthly outflow of Poyang Lake decreased by
2–428 m$^3$/s, a decreasing of 0.1–5.0%, especially in May.

In addition, backflow occurred at HKS is a special phenomenon in the interaction between the Yangtze River and Poyang Lake. Flow inversion phenomenon usually occurs when the push-up pressure of the Yangtze River to the lake is greater than that of outflow in July to September.

It can be observed in the simulation analysis (table 1) that the backflow at HKS had been reduced owing to the operation of the TGR. In 2009 and 2010, there was no backflow phenomenon. In the period of 2011–2014, total amounts of the backflow were reduced. For example, in 2011, the backflow volumes decreased by 0.1399 billion m$^3$.

![Table 1](https://example.com/table1.png)

**Table 1.** The influences of the backflow in the HKS.

| Date       | Maximum backflow (m$^3$/s) | Total amount of inversion (0.1 Billion m$^3$) |
|------------|----------------------------|---------------------------------------------|
| August 2009| 0                          | 3.41                                        |
| July 2010  | 0                          | 0.86                                        |
| August 2010| 0                          | 1.21                                        |
| August 2011| 39                         | 3.38                                        |
| September 2011| 371                   | 11.33                                       |
| July 2012  | 3940                       | 13.92                                       |
| September 2013| 832                    | 0.17                                        |
| October 2013| 297                       | 0.64                                        |
| September 2014| 880                    | 2.30                                        |

Note: M represents measured data; R represents restoration data by model.

3.2. Influence on the water level of Poyang Lake

Change of water level in the Poyang Lake is affected by the inflow of its five tributaries and the water level of the Yangtze River. Since September, water level of the lake starts to fall, and drops to the lowest in January of the next year. But, from March to August, water level has gradually risen to the highest.

Table 2 gives the impact of TGR operation on the water level of Poyang Lake. In the impoundment period from September to November, the average water level of HKS dropped by 0.58 m~1.09 m, that of the Duchang decreased 0.54 m~0.99 m. Kangshan who is far from HKS only reduced by 0.22 m~0.28 m. If November 1st is used as the starting date of the dry season of Poyang Lake, the dry season of HKS and Duchang was 8 days ahead, but that of Kangshan was barely changed. It shows that the effect of lowering the water level of Poyang Lake only reaches the Kangshan area.

![Table 2](https://example.com/table2.png)

**Table 2.** The influences of the water level in the Poyang Lake.

| Month  | Average water level (m) | Minimum water level (m) |
|--------|-------------------------|-------------------------|
|        | HKS         | Duchang | Kangshan | HKS    | Duchang | Kangshan | HKS     | Duchang | Kangshan |
| January| 0.28        | 0.12    | 0        | 0.27   | 0.08    | 0        | 0.71    | 0.16    | 0        |
| February| 0.56       | 0.21    | 0        | 0.52   | 0.12    | 0        | 0.86    | 0.15    | 0        |
| March  | 0.46        | 0.19    | 0.01     | 0.36   | 0.20    | 0.02     | 0.60    | 0.31    | 0        |
| April  | 0.21        | 0.12    | 0        | -0.06  | -0.04   | -0.03    | 0.73    | 0.20    | 0        |
| May    | 0.47        | 0.35    | 0.17     | 0.34   | 0.26    | 0.24     | 0.62    | 0.43    | 0        |
| June   | 0.55        | 0.49    | 0.41     | 0.10   | 0.15    | 0.16     | 0.89    | 0.63    | 0        |
| July   | 0.06        | 0.06    | 0.06     | -0.22  | -0.1    | -0.07    | -0.09   | -0.08   | -0.03    |
| August | 0.04        | 0.02    | 0.01     | -0.40  | -0.39   | -0.39    | -0.33   | -0.24   | -0.10    |
| September| -0.58  | -0.54  | -0.28    | -0.38  | -0.37   | -0.36    | -0.60   | -0.47   | -0.35    |
| October| -1.09       | -0.99   | -0.22    | -0.30  | -0.31   | -0.31    | -0.84   | -0.69   | 0        |
| November| -0.09      | -0.07  | 0        | -0.15  | -0.25   | 0        | -0.08   | -0.11   | 0        |
| December| 0.10       | 0.06    | 0        | 0.09   | 0.04    | 0        | 0.17    | 0.06    | 0        |

In the water replenishment and falling periods of TGR, average water level of HKS increased by
0.1~0.56 m, and that of Duchang increased by 0.06~0.35 m, mainly concentrated from January to March. But the average water level of Kangshan had basically no change. Similarly, the minimum water level at HKS increased significantly, while that of Kangshan changed little. It can be seen that during the dry season, the effect of the TGR is mainly concentrated from January to March, which only affects the vicinity of Duchang.

The annual maximum water level in the Poyang Lake generally occurs in July to August. Under the flood control of TGR, maximum water level at HKS decreased by 0.22~0.4 m, and that of Kangshan decreased by 0.07~0.39 m, which is beneficial to reduce the flood control risk in the lake area.

3.3. Influence on the lake area and volume of Poyang Lake

Further based on the stage-area and stage-volume relation of Poyang Lake [1], lake areas and volumes under the different water level are obtained to be analyzed. The extent of impact is given in figure 6.

![Figure 6. Impact on the lake area and volume of Poyang Lake.](image)

Change characteristics of lake area and volume are basically the same as the water level. Lake area decreased by 3.5%~27.3% in the period of September to November, while other months increased in varying degrees. For example, due to the water supply of TGR from January to March, the lake area increased by 8.8%~17.2%, and the volume increased by 4%~10.2%. Especially in October, the lake area and volume decreased by 27.3% and 30.0% respectively. This change will affect the wetland ecological environment of Poyang Lake which is a noteworthy issue.

It is worth pointing out that the TGR impoundment has changed the water level of the Yangtze River and its hydrodynamic relationship with Poyang Lake, especially in September and October. In September, the hydraulic gradient will increase due to the drop in the water level of the Yangtze River. Therefore, it will cause an increase in the outflow of Poyang Lake, which leads to a decrease in the water level and water volume of the lake. By October, the water level and volume of the lake have been further reduced, and the leak power will be reduced. So, the outflow has gradually decreased.

4. Conclusions

The 1-D and 2-D hydrodynamic models were used to analyze the impact of the operation of the Three Gorges Reservoir from 2009 to 2014 on the hydrological situation of the Poyang Lake. The main research results are as follows:

- The operation of the Three Gorges Reservoir has changed the water exchange process between the Yangtze River and Poyang Lake. Average outflow increased by 14.6% in September, while decreased by 9.6% in October. Other monthly changes are relatively small, which the outflow decreased by 0.1~5.0% from December to May while increased by 2.7~7.4% from June to July. Simultaneously, the total backflow phenomenon has decreased during the period of July to October.
The hydrological rhythm of Poyang Lake has changed, showing that the dry season is ahead of schedule and the water level drops in October. Under the influence of the Three Gorges Reservoir, the average water level of Hukou station dropped by 1.09 m in October, while increased by 0.1~0.56 m from December to May. The effect of lowering the water level of Poyang Lake could be up to the Kangshan area, while that of raising the water level only to the vicinity of Duchang.

The operation of the Three Gorges Reservoir has increased the maximum water level of Hukou station from April to June by 0.1~0.34 m, and reduced by 0.22~0.4 m from July to August, which is beneficial to reduce the flood control risk of Poyang Lake. The change characteristics of lake area and volume are basically the same as the water level. Lake area decreased by 3.5%~27.3% in the period of September to November, while other months increased in varying degrees.

The Three Gorges Reservoir operation has a certain impact on the hydrological situation of the Poyang Lake. In recent years, the hydrological rhythm changing characteristics have become a normal trend, which has a great impact on the water supply and ecological environment of the lake area. It is necessary to continue to study the countermeasures to eliminate or mitigate the impact on the future.

Acknowledgments
The authors appreciate Bureau of Hydrology, Changjiang Water Resources Commission for the support of data. This research work is financially supported by The National Key R & D Program of China (Item Nos. 2016YFC0400901, Item Nos. 2017YFC0405302) and Three Gorges Fund Project (Item Nos. 17900100000017J094).

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