Impact assessment of the three gorges reservoir on the contribution rate for diversion through the three outlets

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Abstract. The Dongting Lake distributes water and sediment of the Yangtze River through the three outlets. Influencing factors of the diversion capacity are complicated. In order to evaluate the influences of the operation of the Three Gorges Reservoir (TGR) on the diversion of the three outlets, this paper investigates systematically the variation process of the runoff at the three outlets based on substantially raw data and principles of variable control. By using comparative analysis and the calculation method of runoff reduction, the change magnitude of the runoff at the three outlets in different periods were quantified and the contribution rates of different influencing factors were estimated. Results show that (1) Inflow difference from the Yangtze River is the primary factor causing the runoff reduction of the three outlets. After the operation of TGR, the Yangtze River was in dry years. Therefore, over 60% of runoff reduction can be attributed to the variation of natural inflow discharge. (2) As the flow is retained by TGR, the runoff of the three outlets further reduced. From 2003-2008, the contribution rates of natural flow, sediment trapping and reservoir regulation to the runoff reduction at the three outlets were 76.19\%, 13.49\%, 10.32\%, while their counterparts after optimal operation of TGR became 66.05\%, 14.20\% and 19.75\% respectively. (3) Reservoir operation after the flood season showed the most significant impact on runoff of the three outlets, resulting in an increase in the number of shut-off days of the three-distributary channels from September to October, especially at Shadaoguan and Kangjiagang.

Keywords: The Three Gorges Reservoir; Optimal operation; Variation of diversion; Contribution rate

1. Introduction
The flood disaster of the river–lake system is closely related to people's life and property safety and the development of regional economy, which have always been the hot issues in the scientific community [1-3]. Water exchange is the core and carrier of the evolution of river–lake relationship [4-6]. As the second largest freshwater lake in China, the Dongting Lake divides the water and sediment of the Yangtze River through three outlets, e.g., Songzikou, Taipingkou and Ouchikou, which shows a complicated river–lake relationship [7,8]. In the 1950s to 1990s, with the operation of some large–scale water conservancy projects such as the Tiaoxian closure, the lower Jingjiang River cut-off and the Gezhouba Dam throttling, the erosion of the main stream in the Yangtze River was intensified and the
three-distributary channels were silted. The diversion relationship between the Yangtze River and the Dongting Lake had undergone several adjustments [9,10]. The flow diversion ratio of the three outlets was decreased from 29% in 1956-1966 to 14% in 1999-2002 [11]. The decrease of the diversion capacity of the three outlets not only increased the cutoff days, but also raised the water level of the main stream in the Yangtze River during the flood season, which had a great impact on flood control and water resources utilization of the Yangtze River basin [12]. The Three Gorges Reservoir (TGR), as the world's largest dam, started impounding in June 2003 and implement optimal scheduling in 2009 according to the “Scheme of optimal operation for TGR” approved by the State Council. TGR was successfully impounded to 175m in 2010.

In recent years, the drought problem in the Yangtze River Basin has become increasingly serious. Especially in 2006 and 2011, the extreme drought events occurred in the Dongting Lake, which makes the distributary capacity between the Yangtze River and the Dongting Lake become a social hotspot once again and causes widespread concern of many scholars. Research shows that in the initial operation stage of TGR (2003-2008 years), the average annual flow diversion ratio at the three outlets decreased by 2.33% compared with that before impoundment and the amount of water in the lake area during flood seasons is 20.2% less than the multi-year average over the same period [13]. Due to the extreme arid climate, the flow of the Yangtze River during the flood season in 2006 is 20%-30% lower than previous years, which once led to Dongting Lake becoming the "grassland" [14,15]. Zhu pointed out that the trend adjustment of flow diversion of the three outlets was mostly induced by major human activities and catastrophic flood years while the impact of reservoir impoundment on the flow diversion of the three outlets is mainly reflected in the redistribution of the flow within the year [16]. Ou studied the corresponding relationship between the water level and the capacity variation of river–lake diversion [17]. The differences of the river–lake runoff in typical flood, average and dry years were also studied by hydrological data in 1951-2010 [18]. Many scholars have studied the relationship between rivers and lakes by mathematical model as well [19,20]. The research on influencing factors of river–lake distributary capacity together with its change effect has achieved fruitful results [21-24]. Due to the differences of research periods and research priorities between different scholars, the existing results are mostly based the data before 2010 [25,26].

TGR is operated based on the single-year regulation rule, demonstrating that the total water volume per year remains constant while its counterpart per month changes. Especially since the implementation of optimal operation from 2009, the diversion processes for different seasons have witnessed substantial changes. However, the impacts of optimal operation on the diversion process of three outlets during different seasons are still far from clear. Besides, there exists a nonlinear relationship between the diversion capacity and the inflow runoff, mainly influenced by natural flow, sediment trapping and reservoir regulation. Furthermore, substantial field measurements have been conducted since the implementation of optimal operation of TGR from 2009, which provide a unique and systematic set of measured data for investigating the contribution rates of different factors in diversion processes of the three outlets.

Based on the observed data, the present study investigates the diversion capacity of the three outlets by quantifying the whole process change of river–lake relationship in different periods and also estimating the contribution rates of different factors.

2. Study area
The Yangtze River is the longest river in China and the third longest river in the world, whose total length is about 6300 km. The main stream of the Yangtze River flows through 11 provinces, i.e., Qinghai, Tibet, Sichuan, Yunnan, Chongqing, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, and Shanghai before debouching into the East Sea at the Chongming Island. The river from Zhicheng to Chenglingji is called the Jingjiang River with the length of approximately 340 km. Taking Ouchikou as the boundary, the Jingjiang River is divided into the upper and lower Jingjiang River. There were two natural cutoff and an artificial cutoff in the history of Jingjiang River. The upper Jingjiang River flow into the Dongting Lake at Songzikou and Taipingkou through the Songzi River and the Hudu River respectively, while
the lower Jingjiang River flow into the Dongting Lake at the Ouchikou by Ouchi River. The Dongting Lake is the second largest freshwater lake in China, which is located in Hunan Province between 28°–30°N latitude and 110°–113°E longitude. Parts of the water and sediment of the Yangtze River discharged by the three outlets and the water and sediment of Xiangjiang River, Zishui River, Yuanjiang River, Lishui River re-enter the Yangtze River near the Chenglingji after adjustment and storage (Figure 1). It can be seen that the three outlets of the Jingjiang River is the link between the Yangtze River and the Dongting Lake and the river–lake diversion capability can be characterized by the runoff of the three outlets.

![Figure 1. The study area: Yangtze River (Yichang - Chenglingji) and Dongting Lake.](image)

3. Data and methodologies

3.1. Datasets

The hydrological data in this paper comes from the Changjiang Water Resources Commission and the China Three Gorges Corporation, including the inflow and outflow of TGR and the flow data measured at hydrological gauging stations of Zhicheng, Xinjiangkou, Shadaoguan, Mituosi, Kangjiagang and Guanjiapu. Among them, Xinjiangkou and Shadaoguan represent Songzikou; Mituosi represents Taipingkou; Kangjiagang and Guanjiapu are representatives of Ouchikou. Songzikou, Taipingkou and Ouchikou are commonly known as the three outlets of the Jingjiang River.

Figure 2 and Table 1 show a long-term situation of runoff and discharge of the three outlets, as represented by runoff and flow diversion ration against time. Note that flow diversion ratio denotes the ratio of the discharge/runoff in Jingjiang to the counterpart in Zhicheng Station in mainstream. Furthermore, the time lengths in different periods are generally determined by the instants when major hydraulic engineering projects were constructed, e.g., Gezhou Reservoir, Three Gorge Reservoir. Since 1950s, several human activities have had a great impact on the river–lake relationship. The flow
diversion ratio at the three outlets was basically stable at about 29.5% in 1956-1966. Then riverbed erosion happened and the flow diversion ratio at the three outlets decreased when the lower Jingjiang River was systematically cut off in 1967-1972. After cutting off, riverbed erosion of the Jingjiang River continued and the decay rate of distributary capacity of the three outlets accelerated in 1973-1980. The flow diversion ratio at the three outlets slowed down its decay rate significantly, which only dropped from 15.74% in 1981-1998 to 14.04% in 1999-2002 (Table 1). Therefore, the period of 1999-2002 is chosen to study the river–lake diversion ability before reservoir operation. The period of 2003-2008 is chosen to study the river–lake diversion ability in the initial operation of TGR. The period of 2009-2015 is chosen to study the diversion ability after optimal scheduling operation of TGR.

![Figure 2. Runoff and flow diversion ratio of the three outlets, i.e., Songzikou, Taipingkou and Ouchikou.](image-url)

**Table 1.** The changes of flow diversion at the three outlets in different periods.

| periods       | runoff($10^8$m$^3$) | the flow diversion ratio of the three outlets |
|--------------|----------------------|--------------------------------------------|
|              | Zhi cheng | Xinjiang kou | Shadao guan | Mituosi | Kangjia gang | Guanjia pu | the three outlets |                           |
| 1956-1966    | 4515      | 323          | 163         | 210     | 49           | 588        | 1332              | 29.49%                    |
| 1967-1972    | 4302      | 322          | 124         | 186     | 21           | 369        | 1021              | 23.74%                    |
| 1973-1980    | 4441      | 323          | 105         | 160     | 11           | 236        | 834               | 18.79%                    |
| 1981-1998    | 4438      | 295          | 82          | 133     | 10           | 178        | 699               | 15.74%                    |
| 1999-2002    | 4454      | 278          | 67          | 126     | 9            | 146        | 625               | 14.04%                    |
| 2003-2008    | 4064      | 239          | 55          | 94      | 5            | 105        | 499               | 12.27%                    |
| 2009-2015    | 4128      | 232          | 50          | 81      | 3            | 98         | 463               | 11.23%                    |

3.2. Methodologies

The river–lake distributary capacity is affected by both the difference in natural flow (NF) and reservoir operation (HA). Reservoir operation includes regulation of the runoff process (TGPO) and sediment trapping by the reservoir (RLR).
The measured data and the existing research [16, 26] show that, the discharge of the three outlets can be determined from that at Zhicheng station with high coefficients of determination (Figure 3). A power function and positive quadratic polynomial model fit to the data:

\[
\begin{align*}
\text{1999-2002 years:} \\
 f_{\text{pre}}(q) &= \begin{cases} 
2.692 \times 10^{-13} \times q^{3.722}, & q < 7000, R^2 = 0.94 \\
6.719 \times 10^{-6} \times q^3 + 2.757 \times 100 \times q - 309.9, & q \geq 7000, R^2 = 0.99
\end{cases} \\
\text{2003-2008 years:} \\
 f_{\text{post}}(q) &= \begin{cases} 
5.444 \times 10^{-13} \times q^{4.664}, & q < 7000, R^2 = 0.94 \\
5.815 \times 10^{-6} \times q^2 + 4.683 \times 100 \times q - 420.2, & q \geq 7000, R^2 = 0.99
\end{cases} \\
\text{2009-2015 years:} \\
 f_{\text{post}}(q) &= \begin{cases} 
1.307 \times 10^{-12} \times q^{3.568}, & q < 7000, R^2 = 0.95 \\
6.097 \times 10^{-6} \times q^2 + 4.945 \times 100 \times q - 587, & q \geq 7000, R^2 = 0.99
\end{cases}
\end{align*}
\]

\( q \) (m³/s) is the discharge measured at Zhicheng station and \( f(q) \) is the discharge of the three outlets derived through the correlation of the corresponding period.

Under the circumstance of the same discharge at Zhicheng station, the river–lake diversion capacity is mainly determined by the relative elevation of the riverbed and three diversion channels [27]. The construction of the reservoir stores a large amount of sediment which leads to a large range of erosion in the downstream of the dam for a long time.

\[
\triangle Q_{RLR} = \sum [f_{\text{post}}(q_z) - f_{\text{pre}}(q_z)]
\]
\( \Delta Q_{RLR} \) represents the runoff variation of the three outlets caused by sediment trapping of the reservoir; \( q_z \) is the monthly average flow process of Zhicheng station after impoundment.

\[
\Delta Q_{TGPO} = \sum [f_{post}(q_z) - f_{post}(q'_z)]
\]

\( \Delta Q_{TGPO} \) is representative of the runoff variation of the three outlets caused by runoff regulation of the reservoir; \( q'_z \) is the monthly average flow process reduced from \( q_z \). The reduce method is as follow:

\[
q'_z = q_z + q_{in} - q_{out}
\]

\( q_{in} \) and \( q_{out} \) are the inflow and outflow of TGR, respectively. The entire process of reservoir operation’s impact on runoff of the three outlets in different periods of the year can be studied through equation (6).

Obviously,

\[
\Delta Q_{all} = Q_{post} - Q_{pre}
\]

\( \Delta Q_{all} \) is the difference of the annual average runoff before and after impoundment, which comprehensively reflects the effects of natural changes and human activities.

Therefore,

\[
\Delta Q_{HA} = \Delta Q_{RLR} + \Delta Q_{TGPO}
\]

\( \Delta Q_{NF} = \Delta Q_{all} - \Delta Q_{HA} \)

\[
\gamma Q_{RLR} = \Delta Q_{RLR} / \Delta Q_{all} \times 100\%
\]

\[
\gamma Q_{TGPO} = \Delta Q_{TGPO} / \Delta Q_{all} \times 100\%
\]

\[
\gamma Q_{NF} = \Delta Q_{NF} / \Delta Q_{all} \times 100\%
\]

Equation (4)-(12) calculates the proportion of each influencing factor on the variation of the river–lake runoff.

4. Results

4.1. Impacts of reservoir operation on diversion process of the Dongting Lake

During the initial operation of TGR, the effect of reservoir regulation on the flow process within a year is not significant, as shown in Figure 4. After optimal scheduling, the change of flow process within a year is obvious. Both the measured and the reduced monthly average flow at Zhicheng are put into the formula (5) and (6), respectively. The variation of the diversion process by reservoir operation can be achieved.
4.1.1. Reservoir operation in the flood season. Since TGR entered the experimental storage period with the impoundment level of 175 m, a series of experiments have been carried out for peak shaving scheduling in 2009. For example, in the middle of July 2010, continuous heavy rainfall happened in the upper reaches of the Yangtze River basin, causing a large flood. The inflow of 70000m$^3$/s occurred, which was the largest since the establishment of TGR. Seven flood control operations have been carried out, reducing the peak flow for maximum 30000m$^3$/s. The discharge was basically controlled below 40000m$^3$/s. Due to the method of predischarging before the peak and increasing discharge volume after the peak, the flow in June and August after the reservoir operation was slightly larger than the reduced value and was smaller in July. The calculation results of the runoff variation at the three outlets under different scheduling modes in the flood season are shown in Table 2.

**Table 2.** Influence of reservoir operation in flood season on the flow at Zhicheng station and the runoff from the three outlets.

| periods   | items              | June | July | August |
|-----------|--------------------|------|------|--------|
| 2003-2008 | measured flow(m$^3$/s) | 17176 | 26515 | 23569  |
|           | reduced flow(m$^3$/s)  | 17141 | 26786 | 23559  |
|           | the change of runoff($10^8$m$^3$) | 0.22 | -2.54 | 0.09   |
| 2009-2015 | measured flow(m$^3$/s) | 17063 | 27559 | 23456  |
|           | reduced flow(m$^3$/s)  | 17046 | 28134 | 23348  |
|           | the change of runoff($10^8$m$^3$) | 0.11 | -5.87 | 0.95   |

4.1.2. Reservoir operation during the storage period. In order to achieve the water level of 175m, the impounding time of TGR after the flood season is put ahead from early October to the present September 10th. Reservoir impoundment directly intercept some of the water that should have been released to the downstream channel. The measured flow is apparently decreased comparing to the reduced flow and the
runoff diverted into the Dongting Lake is changed as well, as shown in Table 3. Table 4 shows a significant increase of cutoff days in September and October.

**Table 3.** Influence of reservoir operation after flood season on the flow at Zhicheng station and the runoff from the three outlets.

| periods     | measured flow(m³/s) | 2003-2008 | 2009-2015 |
|-------------|---------------------|-----------|-----------|
|             | September           | October   | November  |
|             | 24051               | 13710     | 9406      |
|             | reduced flow(m³/s)  | 24538     | 14543     |
|             | the change of runoff(10^8m³) | -4.21 | -4.62 | -1.69 |
| measured    | 20194               | 11499     | 8981      |
| reduced flow(m³/s) | 22563     | 14211     |
| the change of runoff(10^8m³) | -19.30   | -14.69   | -1.46    |

**Table 4.** Influence of reservoir operation on the number of cutoff days in September and October.

| periods     | Shadaoguan | Mituosi | Kangjiagang | Guanjiapu |
|-------------|------------|---------|-------------|-----------|
| 1999-2002   | 6          | 0       | 25          | 4         |
| 2003-2008   | 9          | 1       | 30          | 5         |
| 2009-2015   | 14         | 3       | 46          | 7         |

4.1.3. **Reservoir operation in the dry season.** With compensation operation in the dry season, the reduced flow at Zhicheng station is smaller than the measured flow, which reflects the compensation effect of TGR in the dry season. However, it is found through the comparison that although the compensation regulation of TGR is effective in the dry season and the mainstream flow of the Yangtze River has increased, the impact on flow diversion of the three outlets is not obvious except for May, as shown in Table 5. The main reason is that during the period of regulation, the discharge of the three outlets was less than the beginning flow. In addition to Xinjiangkou, several entrances were basically shut down.

In May, several operations such as increasing the discharged flow and falling speed of water level were carried out to respond to the upcoming flood and solve the problem of sediment deposition at reservoir tail. The discharge at Zhicheng station after reservoir operation was 1000m³/s larger than the reduced flow. In addition, as seen from Table 6, when the discharge at Zhicheng exceeds 10300 m³/s, the three outlets, except Kangjiagang, started to flow. Therefore, the measured runoff in May of 2009-2015 was 588 million m³ larger than the reduced value. Note that due to changes in annual runoff and temporal distribution of discharge, the instant when the three outlets are cut off also differs.

**Table 5.** Influence of reservoir operation in dry season on the flow at Zhicheng station and the runoff from the three outlets.

| periods     | items                  | December | January | February | March | April | May  |
|-------------|------------------------|----------|---------|----------|-------|-------|------|
| 2003-2008   | measured flow(m³/s)    | 5954     | 4888    | 4649     | 5503  | 7427  | 11145|
|             | reduced flow(m³/s)     | 6000     | 4974    | 4588     | 5626  | 7390  | 11294|
|             | the change of runoff(10^8m³) | -0.03 | -0.03  | 0.02     | -0.06 | 0.13  | -0.69|
| 2009-2015   | measured flow(m³/s)    | 6588     | 6547    | 6464     | 6622  | 8278  | 13221|
|             | reduced flow(m³/s)     | 6274     | 6204    | 5428     | 5978  | 8047  | 12124|
Table 6. The changes of correspond flow at Zhicheng station when the three outlets are cut off.

| periods     | the correspond flow at Zhicheng station when the three outlets are cut off (m$^3$/s) |
|-------------|------------------------------------------------------------------------------------|
|             | Shadaoguan  | Mituosi   | Kangjiagang | Guanjiapu |
| 1999-2002   | 10300       | 7650      | 16500       | 10300     |
| 2003-2015   | 10070       | 7126      | 15854       | 8926      |

4.2. Influence of reservoir sediment trapping on flow diversion

After the operation of TGR, the reservoir intercepts a large amount of sediment and drastic erosion occurs in the dry river channel downstream the dam. The water level of Zhicheng station under the same flow was constantly declining from 2003 to 2015. Table 7 shows the cumulative decline of water level at Zhicheng station after impoundment in the dry season. As the flow remain constant, changes in water level arise from sediment trapping.

Table 7. The changes of water level at Zhicheng station under the same flow.

| flow stage(m$^3$/s) | 2003-2004 | 2003-2005 | 2003-2006 | 2003-2007 | 2003-2008 | 2003-2009 |
|---------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 5000                | 0.01      | 0         | -0.1      | -0.13     | -0.13     | -0.27     |
| 7000                | 0         | -0.02     | -0.18     | -0.25     | -0.25     | -0.41     |
| 10000               | 0.1       | 0.09      | -0.19     | -0.3      | -0.33     | -0.5      |

| flow stage(m$^3$/s) | 2003-2010 | 2003-2011 | 2003-2012 | 2003-2013 | 2003-2014 | 2003-2015 |
|---------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 5000                | -0.29     | /         | /         | /         | /         | /         |
| 7000                | -0.41     | -0.49     | -0.54     | -0.58     | -0.59     | -0.59     |
| 10000               | -0.5      | -0.62     | -0.72     | -0.75     | -0.85     | -0.85     |

The measured flow process after the impoundment at Zhicheng Station is brought into Equation (1)-(4). By quantitative calculation, the runoff decrease caused by riverbed undercutting in the initial operation and after optimal operation are -1.7 billion m$^3$ and -2.3 billion m$^3$ respectively.

4.3. Calculation of contribution rate on runoff variation

The impact of reservoir operation HA on the river–lake diversion capacity has been discussed before including the effect of reservoir regulation on the runoff process TGPO and sediment trapping RLR. Using Equation (7)-(12), the influence of natural flow difference and contribution rates of each factor on runoff variation can be quantitatively calculated, as shown in Table 8.

Table 8. The contribution rate of various factors that impact three outlets diversion.

| periods     | $\Delta Q_{all}$ (10$^8$m$^3$) | $\Delta Q_{RLR}$ (10$^8$m$^3$) | $\Delta Q_{TGPO}$ (10$^8$m$^3$) | $\Delta Q_{HA}$ (10$^8$m$^3$) | $\Delta Q_{NF}$ (10$^8$m$^3$) | $\gamma Q_{RLR}$ | $\gamma Q_{TGPO}$ | $\gamma Q_{NF}$ |
|-------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|------------------|------------------|------------------|
| 2003-2008   | -126                            | -17                             | -13                             | -30                             | -96                             | 13.49%           | 10.32%           | 76.19%           |
| 2009-2015   | -162                            | -23                             | -32                             | -55                             | -107                            | 14.20%           | 19.75%           | 66.05%           |

Results demonstrate that the main reason of river–lake runoff declining is the natural flow. The values of the proportion of NF are 76.19% and 66.05% respectively. Since the optimized operation of the reservoir in 2009, the proportion of reservoir regulation has increased from 10.32% in the early operation to 19.75% due to the large-scale adjustment of the dispatching mode. The proportion of
reservoir sediment trapping is basically stable, only from 13.49% to 14.20%. In general, sediment trapping impacts the diversion of three outlets by changing the riverbed elevation at river mainstream and mouth of three outlets. After Three Gorges Project operation, although both the river mainstream and mouth of three outlets undergo erosion, the flow diversion ratio of three outlets just slightly decreases since 2003. Therefore, compared to natural run-off, bed erosion does not play a governing role is flow diversion of three outlets.

5. Summary and Conclusion
The present work quantifies the contribution rates of different factors in diversion processes of Dongting Lake by employing the comparative analysis and runoff reduction of the measured hydrological data since the operation of TGR. It also investigates the variation processes of diversion runoff during different season since the optimal regulation of TGR.

(1) The difference of natural flow is the governing factor that leads to the diversion runoff variation of the three outlets, of which the contribution rate reaches 66.05%. In recent decade, the Yangtze River is in a relatively drought period since TGR operates. Therefore, the diversion runoff of the three outlets suffer from a reduction, which even leads to the appearance of extreme drought event in 2006 and 2011.

(2) The optimal operation of TGR changes the diversion runoff during different seasons. The water storage after flooding season remarkably reduces the diversion runoff. Quantitatively, the contribution rate of reservoir regulation has risen from 10.32% (2003-2008) to 19.75% (2009-2015). Moreover, the number of cutoff days of the three outlets have increased, especially at Shadaoguan and Kangjiagang.

(3) The low flow channel downstream TGR suffer from a severely erosion since the operation of TGR. Accordingly, the low flow discharge and level at Zhicheng Station decreased remarkably, resulting in that diversion runoff reduce by about 14.20% as compared to that before the operation of TGR.

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