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Effects of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003–2008

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SUMMARY

The Three Gorges Dam (TGD) has been in operation since 2003. Over the operation period from 2003–2008, data have been collected for preliminary evaluations of actual effects of the TGD on the Yangtze River flow and river interactions with downstream lakes and tributaries. These effects are examined in this study, after the climate influence was minimized by comparing hydrological changes between years of similar climate conditions before and after the operation of the TGD. Major results show that the TGD operation has affected the Yangtze River discharge and water level. The significance of these effects varies seasonally and with different locations along the river. The seasonal variation follows the TGD's seasonal impounding and releasing of water. The magnitude of the effects is dependent on the impounding/releasing rate and the seasonal flow of the river. The most significant effects are confined in the river reach near the TGD and are as great as five times those of sections downstream. The weakening and diminishing of effect of the TGD is primarily because of "dilutions" to the effect by inflows to the Yangtze River from downstream tributaries.

Changes in the Yangtze River discharge caused by the TGD have further altered the interrelationship between the river and Poyang Lake, disturbing the lake basin hydrological processes and water resources. A major consequence of such changes has been a weakening in the river forcing on the lake, allowing more lake flow to the river from July–March. This effect of the TGD may partially fulfill the TGD's mission to mitigate flood risks in the lake basin, especially during the peak wet season of the Yangtze River basin from July–September. In the 6 years since the TGD operation began the annual average number of severe outflow events of rates of $\geqslant 3000\ m^3\ s^{-1}$ from the lake in July–September has increased by 74. It has also resulted in reduction of water storage in Poyang Lake. Results of this study point to strong needs for working strategies to balance the TGD impacts on flood control and water resources as well as their societal and ecological consequences in the Poyang Lake basin. Meanwhile, in the context of studies of impacts of large dams this study shows an example of extending the previous studies in the dam–river setting to a new dam–river–lake construct.

1. Introduction

The Three Gorges Dam (TGD, hereafter) in the middle reach of the Yangtze River in China (Fig. 1) is one of the largest dams in the world. It was built to harness hydropower and to mitigate floods and droughts in the middle and lower reaches of the Yangtze River and connected lake basins and tributaries. Construction of the TGD was a 17-year, tri-phase project. The first phase of "preparation and preliminary constructions" was from 1993–1997. The second phase of "major constructions of the dam and implementations of power generating facilities" was from 1998–2003. On June 1, 2003, upon completion of the second phase, the dam began operation [see China Three Gorges Corporation report at http://www.ctgpc.com.cn/sxslsn]. Six power generators went in service on November 22, 2003 when the reservoir water level reached 139 m above the base. These operations marked the beginning of full functioning of the dam and the reservoir in 2003. The third phase of the project proceeded from 2004–2009 to complete the supplementary facilities.

While the technical achievements in building this monumental structure and making it function as designed are great there are concerns about potential effects of the construction and operation of the dam and reservoir on the hydrological environment, aquatic and terrestrial ecosystems, regional climate, and the lives of millions of people around the dam, in the lower reaches of the Yangtze River, and in southeastern China. While most of these effects were

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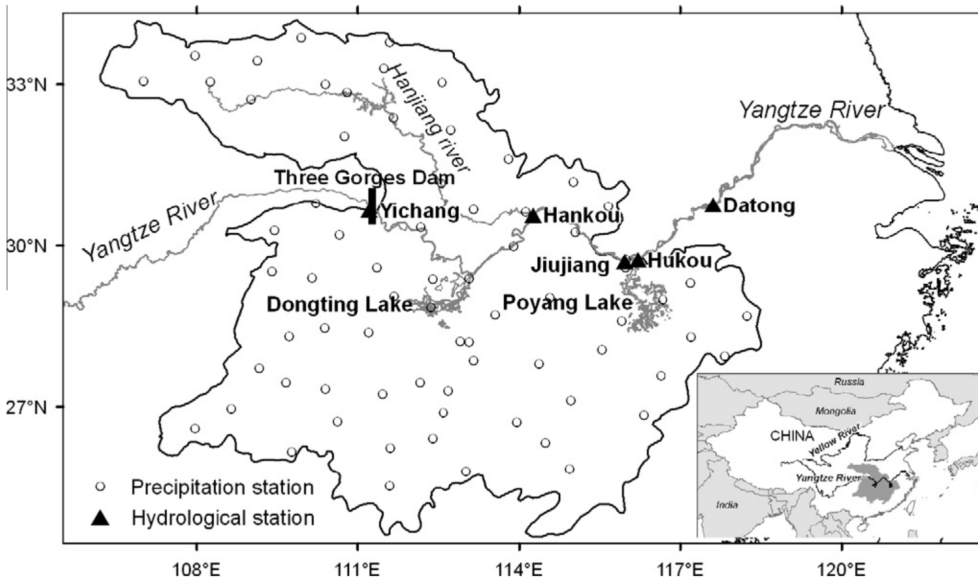

Fig. 1. Map showing locations of the Yangtze River, the Three Gorges Dam (TGD), Poyang Lake, cities, and the locations of hydrological and meteorological stations where data were used in this study. Index map in lower right shows area location in China.

estimated and their consequences assessed during the design stage for the dam (e.g., Wang, 1994; Jiang and Huang, 1997; Hu, 1998), many of the dam's influences have just begun to be evaluated in recent years *after* the dam has been in operation and a certain amount of data has been gathered (e.g., Cao et al., 2006).

Since 2003, there have been observations on discharge, water-level, sediment content and transport, and other hydrological and biological properties of the Yangtze River, and similar observations in lakes and tributaries downstream of the TGD. Although this data collection is still too short for robust tests and evaluation of the TGD impacts these data allow us to start analyzing the *actual* effects of the TGD (vs. *possible* effects of the dam estimated during its design stage). For example, Dai et al. (2008) used 1 year of data from 2006 to show the role of the TGD in reducing Yangtze River discharge during flood season while increasing the river flow in the dry season. Yang et al. (2007) examined the TGD effects on sediment transport in the Yangtze River, and reported that the sediment transport rate was reduced by as much as 31% after the start of TGD operation. Reduced sediment transport was further found to initiate erosion of the riverbed and recession of the Yangtze River Delta (Yang et al., 2006, 2007). Meanwhile, because 85–93% of the annual sediment transport occurs in the wet season of the river basin from July–September and the sediment transport rate is strongly correlated with river discharge (Chen et al., 2001), the observed decrease in sediment transport suggests a reduction of Yangtze River discharge after completion of the TGD. Moreover, because the river discharge affects river–lake interaction (Hu et al., 2007) the decrease in Yangtze River discharge points to potential TGD impacts on interactions of the Yangtze River and the major lakes, Dongting Lake and Poyang Lake (see Fig. 1).

Changes in discharge and water level of the Yangtze River can change the blocking force of the river on outflows from Poyang Lake (Hu et al., 2007) and, thus, affect lake level, water storage, and seasonal variations. These changes can pose serious pressure on communities in the lake basin, e.g., water shortages, forcing changes in water use behavior and economic production. Complex societal responses to such pressure reflect the human aspects of the TGD effects. One such response in the Poyang Lake basin has been the recent public outcry for damming Poyang Lake to protect its water storage (Poyang Lake is a natural lake up to now). The perception is that the TGD-induced reduction in Yangtze River flow during summer has caused increase in Poyang Lake outflow and reduced lake storage. Whether these perceived changes in Poyang Lake are occurring is unclear, however, because some droughts in the years from 2003–2008 (e.g., Dai et al., 2008) could have resulted in decreases of the lake level and in water shortages. To understand both the physical and societal impacts of the TGD it is essential to quantify changes in the Yangtze River discharge caused by the TGD operations and to evaluate and understand their effects on the river and its interaction with Poyang Lake. Even though there are other major hydrological entities along the Yangtze River between the Poyang Lake and the TGD, e.g., Dongting Lake and the Hanjiang River (see Fig. 1), the TGD changes the Yangtze River discharge, subsequently disturbs the interrelationships of the river and these other entities, and affects the river flow and water exchange with Poyang Lake and lake hydrology.

In this study, we will use observational data from 1957–2008 and examine and quantify the TGD effects on the Yangtze River discharge and the impacts of such effects on interactions of the river and Poyang Lake, the largest freshwater lake in China and an essential water resource for a population over 40 million in the lake basin. Putting this study in the context of previous studies of impacts of large dams on rivers in China and countries around the world, we note that most of the previous studies have been on large dams and rivers in the United States (Lawson, 1925; Fiock, 1931; Chadwick, 1978; Williams and Wolman, 1984; Graf, 1999; Magilligan and Nislow, 2005). In a series of studies of hydrological impacts of very large dams (capable of storing $10^9\ m^3$) on downstream river flows Graf (1999, 2001, 2002, 2005, 2006) compared arrays of hydrological parameters for regulated (dammed) and unregulated (natural) reaches of large rivers in the United States. Using differences in those parameters he showed that large dams have caused considerable decreases ($\geqslant$60% on average for all the dams studied) of annual peak discharge and the ratio of annual maximum/mean flow, among other parameters (Graf, 2006). These changes show the severe impacts of very large dams on river hydrology, as well as downstream channel adjustments. Moreover, these impacts vary among dams and rivers because of varying geomorphological and hydrological conditions among individual river systems. The societal consequences, both positive and negative, of these changes caused by large dams also have been evaluated for policy and management decision support (e.g., Namy, 2007; Gottgens and Evans, 2007).

Similar studies of impacts of large dams on downstream river flows have been taking place in China following the economic development and elevated awareness of natural resources and environment in recent decades (e.g., Hu et al., 2008; Yang et al., 2008; Yan et al., 2010). Yan et al. (2010), for example, applied an approach similar to that in Graf (2006) and evaluated effects of dams on downstream flow in the Yellow River, China. Their results show that the flow volume has been reduced and the peak flow in the annual hydrograph has been shifted after operations of large dams on the river.

The Yangtze River in China has a special setting of surface water system in the middle and lower reaches of the river. The river interacts directly with the two largest freshwater lakes in China, Poyang Lake and Dongting Lake (see Fig. 1). Both lakes play buffering roles at varying degrees for the Yangtze River flow. For example, the Poyang Lake basin has its peak precipitation season in April–June and a sharp decrease in precipitation during the period July–October. This distribution of precipitation is nearly reversed from that in the middle reach of the Yangtze River, particularly its northern tributaries, which has its peak annual precipitation in July–September (Hu et al., 2007; Guo et al., 2011a). The high lake level in April–June helps lake water to discharge into the river and to maintain the river flow during dry season in the middle and lower reaches of the river. On the other hand, when the river flow rises in July–September the lake helps to absorb some river flow and "mitigate" the peak flow of the river. As such, the river flow is strongly influenced by the lake. Hence, it is essential to understand the river–lake interactions and their effects on the Yangtze River flow and Poyang Lake level before we evaluate any anthropogenic impacts, e.g., large dams, on the river flow.

In previous studies we examined the Yangtze River–Poyang Lake interactions and developed understanding of major aspects of the river–lake interaction (Hu et al., 2007; Guo et al., 2011a). Using our defined lake forcing on the river and vice versa we delineated interactions of the river and the lake and the roles of their interactions in flood development in the lake and river basins. These prior studies provide a basis for evaluation of the TGD effects on downstream Yangtze River flow, river–lake interactions, and changes in both the river flow and the lake level. This study will provide an extension on impacts of large dams on river flows in a dam–river–lake setting to the existing context of impacts of large dams in the dam–river setting.

Results of this study will help us understand impacts of the Three Gorges Dam on downstream Yangtze River flow and Poyang Lake level and will advance our knowledge of the dam–river–lake interrelationships. Additionally, the objective measures of the Three Gorges Dam impacts from this study will be useful for policy-making in water resource management for both the Yangtze River and the Poyang Lake basins, as well as for similar situations in other regions. The data used in this study are described in the next section (Section 2), major results are discussed in Section 3, and Section 4 contains major conclusions.

2. Data and methodologies

2.1. Data

Daily discharge and water level of the Yangtze River were measured at Yichang, Hankou, Jiujiang, Hukou and Datong from 1957–2008. The locations of these hydrological stations are shown in Fig. 1. These hydrological data were quality controlled at the office of the Hydrological Bureau of the Yangtze River Water Resources Commission in Wuhan, China. Meanwhile, daily data of the Poyang Lake water level were obtained from three stations in the lake, and the water flux across the interface of the lake and the river was calculated using observed flow profiles at Hukou station (Hu et al., 2007). These daily discharge and water level data were used to calculate monthly values of these variables. The monthly values were used to examine variations in Yangtze River discharge and river–lake interaction before and after the TGD operation began in 2003.

In addition to these hydrological data, quality-controlled daily precipitation data from weather stations in the Poyang Lake catchment and across the middle reach of the Yangtze River basin (see Fig. 1 for station distribution) were obtained and used to calculate monthly precipitation from 1957–2008 (Guo et al., 2011a). These monthly data were used in examining precipitation and climate variations in the study region and to identify the "analogous years" from 1957–2002 that had precipitation conditions most similar to those in the years after operation of the TGD (2003–2008). In these "analogous years," the river discharge and river–lake interaction were calculated and then compared and contrasted with those in the years after the TGD to isolate and quantify the TGD effects.

2.2. Methodologies

The analogous years were selected using the following method. We first specified a "target year" from 2003–2008, 2004, for example. Then, the monthly precipitation of the target year was compared and contrasted with the monthly precipitation in each year from 1957–2002 (before the TGD operation). The year that had the minimum difference between its monthly precipitation and that in the target year was selected as the "analogous year" (for year 2004 as in this example). In this procedure, the monthly precipitation difference between a year in 1957–2002 and a target year is calculated from

$$D_i^2 = \sum_{j=1}^{N}\sum_{k=1}^{12} I_{ijk}(X_{ijk} - Y_{jk})^2 \Bigg/ \sum_{j}^{N}\sum_{k=1}^{12} I_{ijk} \quad (1)$$

where X_{ijk} is the monthly precipitation for month k ($k = 1, \ldots, 12$) in year i (i = 1957–2002, before the TGD) at a station j ($j = 1, N, N = 74$), and Y_{jk} is the monthly precipitation for month k at station j for the target year, e.g., 2004 (after the TGD). The function I_{ijk} is an indicator and equal to 1 if both X_{ijk} and Y_{jk} are not missing, and 0, if any of them is missing. By finding the year i that has a minimum D_i in (1) we identified the analogous year whose annual precipitation and monthly variation would resemble most closely those in the target year. A potential caveat in this method is that individual stations that have large annual precipitation and also large interannual fluctuations in precipitation may have a strong effect in (1). In such a case, fluctuations in those individual stations' precipitation could dominate the regional averaged precipitation and skew the result of (1) for the selected analogous year. The possible effect from the caveat on the outcome of (1) is deemed noncritical because the large precipitation from those individual stations would also make the most for the runoff from the study region. Using this method, we have identified six analogous years 1960, 1960, 1985, 1985, 1979, and 1965 for the six target years of 2003–2008, respectively.

Because the precipitation difference between each pair of these analogous and target years, e.g., 1960 and 2004, is minimized the differences in river discharge and river–lake interaction between the pair should have resulted primarily from the TGD effect. However, there are no 2 years with exactly the same climate, and some climate effects do cause differences of river and lake hydrology between the pairs of analogous and target years. Nonetheless, this approach allows us to focus on the hydrological impacts of the TGD by minimizing the climate variation effect.

Using this set of pairs of analogous and target years we compared and contrasted the Yangtze River discharge and river interactions with Poyang Lake and examined the TGD effects on changes in these hydrological processes. Because there are six pairs in the data set, statistical tests could be applied to examine significance of these TGD effects, adding a confidence measure to the results.

2.3. Macro vs. Micro approach

In this "macroscopic" approach to study the TGD impacts on the river discharge and river–lake interaction we use observational data to examine TGD-induced changes in these hydrological processes. While the results of such a study may only show the outcomes and not delineate detailed "microscopic" processes of finer resolutions in both time and space that have caused those outcomes, we learn from these outcomes the net effects of the TGD on the Yangtze River and its interaction with Poyang Lake. This method is also suitable for our current study purpose because coupled river–lake hydrology models and other "microscopic" approaches for this particular complex setting with multiple rivers and lakes are not yet available.

3. Results

Before we describe the results it is important to reiterate the climate and annual variation in precipitation in the middle reach of the Yangtze River and of the Poyang Lake basin. This brief review will help the readers to comprehend TGD impacts on the river and the interaction of the river with the lake discussed in this section.

Poyang Lake receives large recharge from its catchments during April–June (Hu et al., 2007; Guo et al., 2008). The recharge peaks in late June (thick solid line in Fig. 2a) primarily due to the Asian monsoons (Ding, 1994; Qian and Lee, 2000; Wang and Lin, 2002). Fast rising water storage and lake level drive strong outflows from the lake to the Yangtze River from April through June, creating a massive lake force to elevate the river flow.

In July–September, following the northwestward march of the monsoon front and decrease in rainfall in the Poyang Lake basin, recharge to the lake diminishes. Meanwhile, the middle reach of the Yangtze River receives its annual peak precipitation and its discharge increases (thin solid line in Fig. 2a). The rising river flow and water level exert large river forcing on the lake (Guo et al., 2011a), resisting or even reverting its outflow (see examples in Hu et al., 2007). These changes indicate quite different river–lake interactions between July–September and April–June. Outside the wet period from April–September, dryness prevails from October–March, corresponding to both low Poyang Lake level and weak lake discharge into the Yangtze River. These annual variations in river–lake interaction are shown in Fig. 2b by changes in lake and river forcing averaged for 1957–2008 (Guo et al., 2011a).

Because of the varying river–lake interaction over seasons, changes in Yangtze River discharge resulting from the operation of the TGD (Fig. 3) should affect river–lake interaction differently in different seasons. We will therefore evaluate the TGD effects in different seasons, and first examine the effects of the TGD operation on the Yangtze River discharge and then the impacts of such effects on the river–lake interaction.

3.1. TGD effects on Yangtze River discharge

Effects of the TGD on Yangtze River discharge and water-level are shown in Figs. 4 and 5. Fig. 4 compares daily river discharges averaged over all the analogous years and the target years at stations Yichang, Hankou, and Datong (see Fig. 1 for the stations' locations relative to the TGD).[1] The daily discharge curve of each station in Figs. 4 and 5 is highlighted if the difference in discharge between the analogous and target years, or before and after the TGD, is statistically significant at the 95% confidence level (with two-tailed Student *t*-test).

Comparing the station data in Fig. 4, we find more days and months with statistically significant change, either increase or decrease, in river discharge at Yichang station than the other stations further downstream from the TGD. Specifically, there are 153 days, on average for each year, with significant change in river discharge at Yichang station, 124 days at Hankou, and only 38 days at Datong (Table 1). These results indicate that (1) the TGD operation has a significant effect on the Yangtze River discharge in some seasons, and (2) the effect weakens quickly downstream of the TGD and nearly diminishes beyond Datong.

The diminishing effect of the TGD downstream is largely a result of increasing confluent flows into the Yangtze River from tributaries along the TGD. The increase in confluent flows also is shown in Fig. 4. From Yichang to Hankou (Fig. 4a and b), the Yangtze River discharge increases by about 10,000 $m^3\,s^{-1}$, primarily owing to the inflow from the Hanjiang River. An additional 5000 $m^3\,s^{-1}$ is discharged into the river when it reaches Datong (Fig. 4c). This increase of nearly 15,000 $m^3\,s^{-1}$ discharge from Yichang to Datong is more than three times the baseflow or about 50% of the peak flow at Yichang station just downstream of the TGD. While these confluent flows to the Yangtze River substantially raise its discharge, they weaken the effect of the TGD operation and overwhelm its effect downstream from the dam.

In the near field of the TGD, defined here as the river reach from the TGD to Hankou station, the TGD operations have caused large changes in river discharge in some seasons. At Yichang, of the total 153 days with significant changes in discharge, 103 days have had substantial increase in discharge in January–May (Fig. 4a, Table 1). Under similar precipitation conditions in years before and after the start of operation of the TGD, this increase in discharge has to result from large release of water from the TGD. This is consistent with the TGD operation in January–May, shown in Fig. 3. On the other hand, significant decrease in river discharge at Yichang occurs in September and October (see Fig. 4a and Table 1), when the TGD was impounding water, and is especially strong in October (Fig. 3). As also shown in Fig. 4b and Table 1, similar changes in river discharge, though less frequent than in Yichang, have occurred at Hankou.

In the far field downstream from the TGD, defined as the section of the Yangtze River from Datong to further downstream, the effect of the TGD diminishes. There are only 38 days in a year (compared to 153 days in the near field) with statistically significant change in discharge at Datong. Of the 38 days, 28 show increased discharge in January and February, and 10 show decreased discharge in October. The latter is again a direct effect of the massive water impounding by the TGD in October (Fig. 3), while the former is likely a compounding impact of water release by the TGD in those winter months.

Between the far and near field downstream from the TGD, in the river reach between Hankou and Datong (the "mid-field"), there is no station measuring river discharge. Instead, the water-level of the Yangtze River has been measured at Jiujiang station since 1957. Similar water-level measurements also have been made at

[1] Hukou station is located downstream of the Hankou and Jiujiang station (Fig. 1). As shown in Hu et al. (2007), Hukou station is at the interface between the Poyang Lake and the Yangtze River, and measures the lake discharge, instead of the river discharge. Hukou station's discharge and water level variations are shown in Fig. 5 and will be discussed in evaluation of the TGD effect on changes in river-lake interaction later in this section.

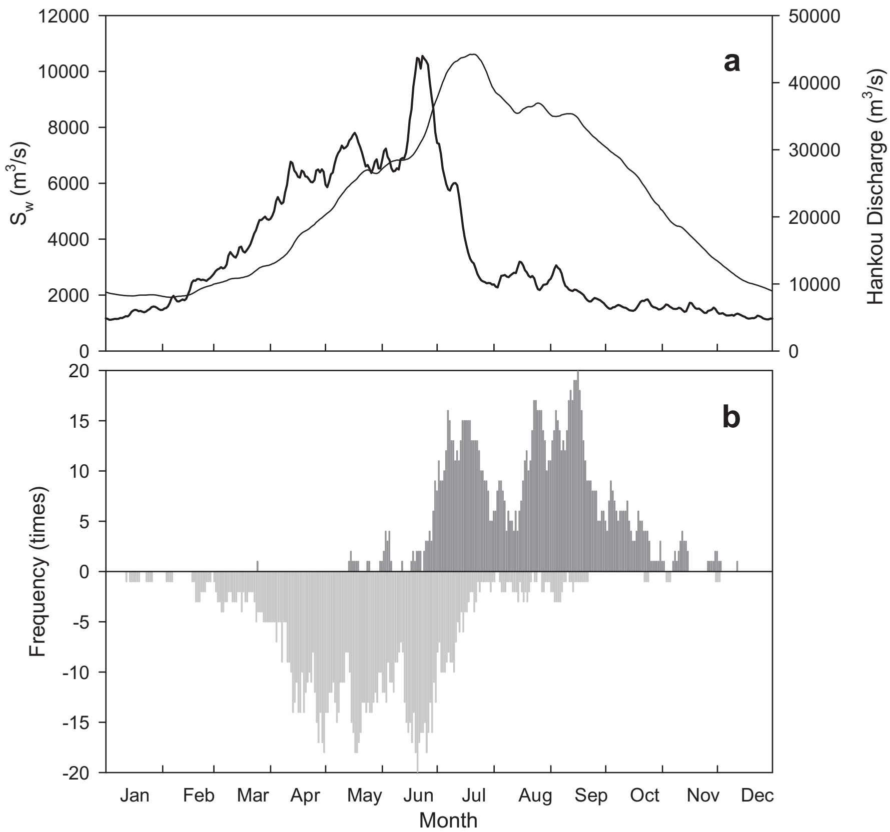

Fig. 2. Averaged (1957–2008) annual variation in (a) discharge to Poyang Lake from its five sub-river basins, S_w (thick solid line), and the Yangtze River discharge at Hankou station (thin solid line), and (b) frequency of Yangtze River forcing on the lake (positive) and Poyang Lake forcing on the river (negative).

Yichang, Hankou, and Datong. These water-level data were analyzed and compared between the analogous years and the years after operation of the TGD. Comparisons of the water-level change at Jiujiang before and after the TGD are shown in Fig. 5a. They indicate a strong TGD effect in decreasing of the water-level in October and early November. On average, there are 43 days in that period when the water-level was significantly lower after the TGD operation began, again largely resulting from the impounding in October. We note that this number of days of significant changes in water-level in Jiujiang is close to that at Datong (41 days), which also happened in October and early November. While these numbers are smaller than that at Hankou (76 days) and Yichang

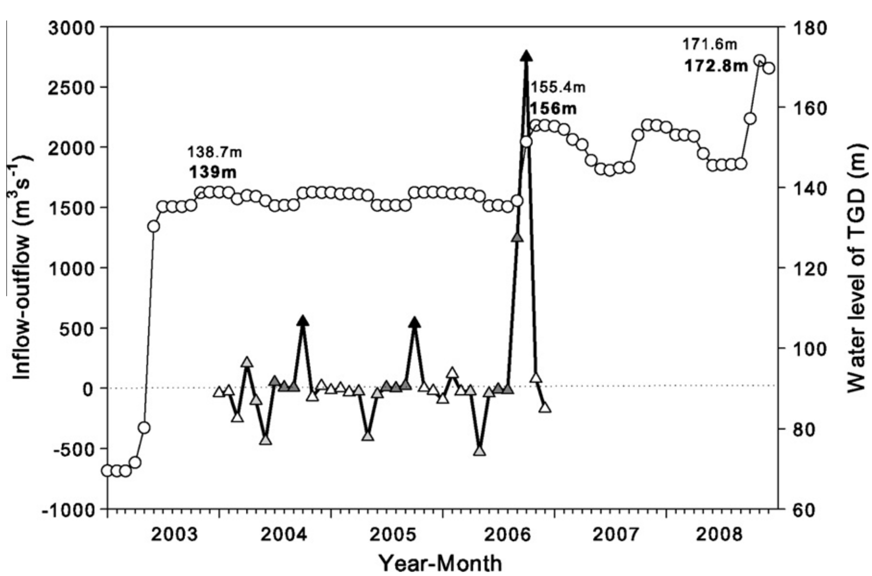

Fig. 3. Water level variations of the TGD (the thin solid line with open circles) from 2003–2008. The three groups of numbers are the average (number on top) and highest water level (number at bottom) of TGD in November 2003, 2006, and 2008, respectively. Thick solid line with triangles shows difference between inflow and outflow of the TGD reservoir from 2004–2006 (positive for impounding and negative for releasing water). Black triangles show October result when the TGD impounds a large amount of water.

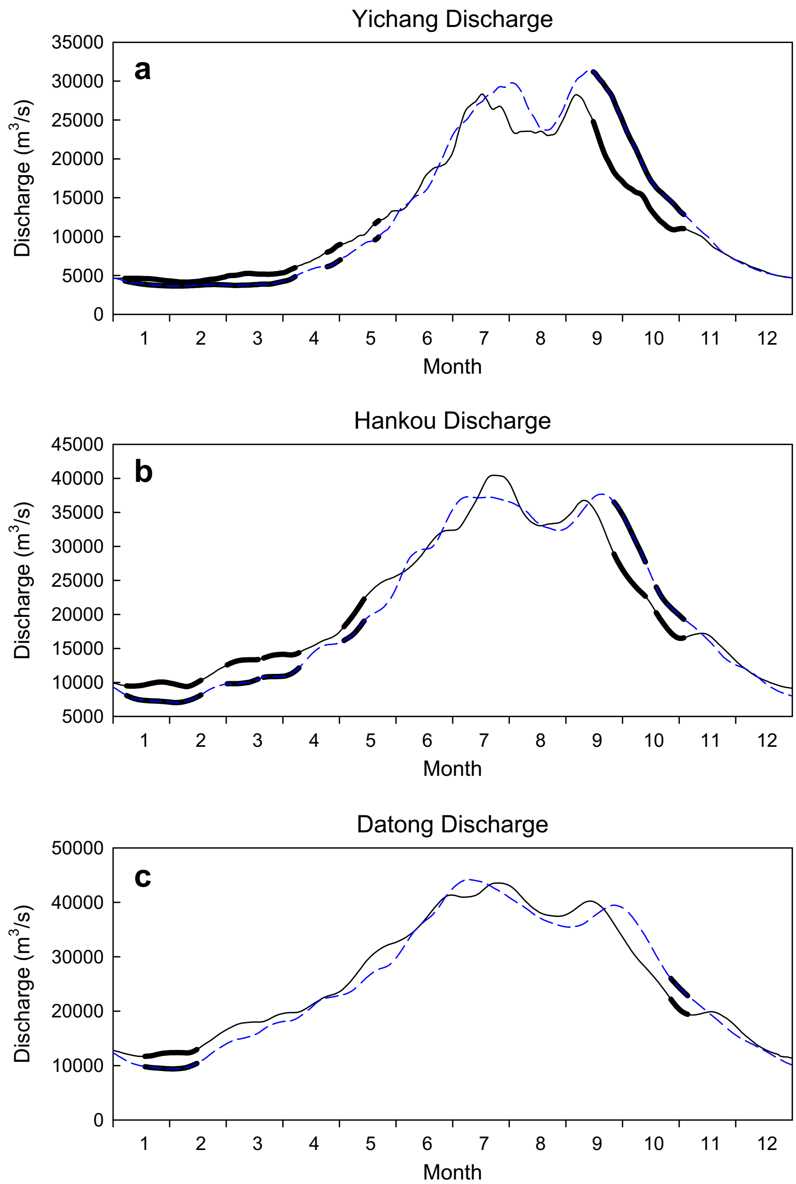

Fig. 4. Average annual variations in river discharge (units: $m^3 s^{-1}$) for 2003–2008 (solid line) and for the analogous years before 2003 (dashed-line) at (a) Yichang, (b) Hankou, and (c) Datong (see text for the analogous years). The days and months with significant differences in river discharge after the TGD are highlighted with thickened lines.

(187 days), where much stronger and more direct TGD effects have caused changes in Yangtze River flow, they confirm that the TGD operation has affected the Yangtze River discharge and water-level in the section of the river connecting to Poyang Lake.

These changes in Yangtze River flow and water level have directly affected the Poyang Lake water level. As shown in Fig. 5b, similar significant decrease in water level has occurred in the Poyang Lake from October–November after the operation of the TGD. According to the result in Fig. 2, the Yangtze River forcing becomes strongly influencing the lake storage and water level from August through November. Towards the later part of this period the water level of the river controls the water level of the lake (Guo et al., 2011b). High water level in the river curbs the lake outflow and keeps the lake level high; low water level in the river allows lake water to drain and lowers the lake level.

To summarize, comparisons of the discharge and water-level of the Yangtze River between the years after the TGD operation began and their analogous years have shown that, under similar precipitation conditions: (1) TGD operations have had statistically significant effects on the Yangtze River flow, increasing the discharge from January-early June and weakening it in September-early November, and (2) these effects are strong in the near field of the TGD, weaken in the mid-field, and diminish in the far field. Because in the mid-field the Yangtze River interacts with Poyang Lake, the effects of the TGD operations on the river discharge will result in changes in river–lake interaction and influence seasonal variations of hydrological processes in Poyang Lake. The question of how the TGD operations have influenced Poyang Lake is addressed in the next section.

3.2. TGD influence on river–lake interaction and Poyang Lake

The river–lake interaction is due to the mutual forcings between the river and the lake. The forcing of the river on the lake measures the strength/pressure of the river in blocking/resisting/reverting the lake outflow (Hu et al., 2007), and the forcing of

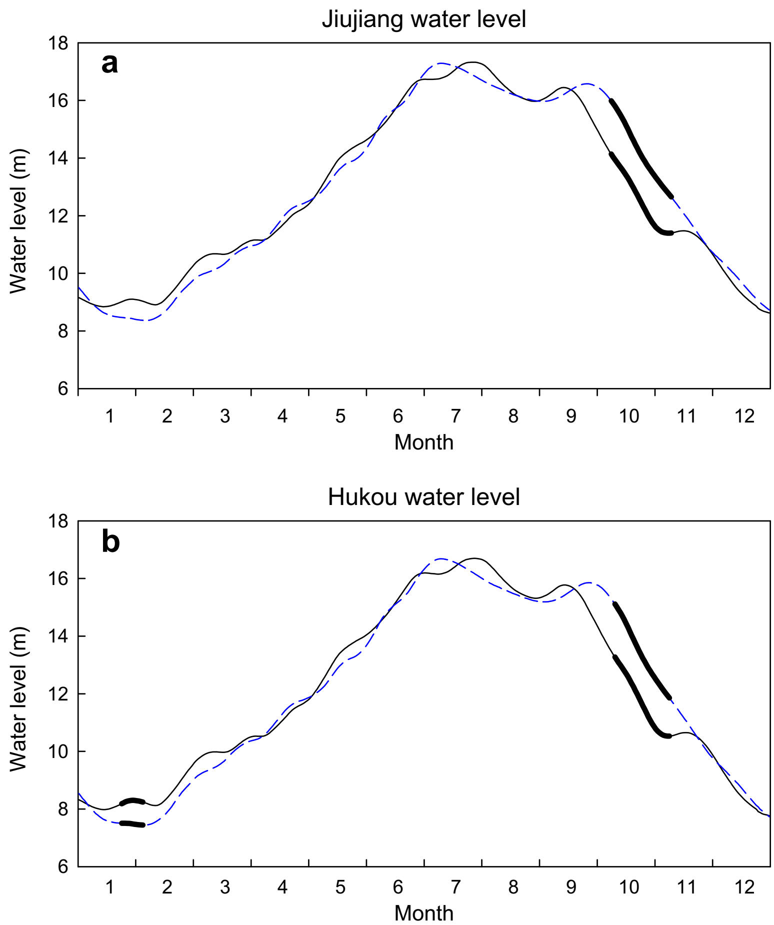

Fig. 5. Average annual variations in water-level in meters for 2003–2008 (solid line) and for the analogous years before 2003 (dashed-line) at (a) Jiujaing, and (b) Hukou. The days and months with significant changes in water-level after the TGD are highlighted with thickened lines.

Table 1
Averaged number of days in a year with statistically significant difference in discharge between 2003–2008 (after TGD operation) and the analogous years (before TGD operation).

Stations	Days with increasing discharge	Days with decreasing discharge	Total number of days of significantly different discharge
Yichang	103	50	153
Hankou	90	34	124
Datong	28	10	38

the lake on the river gauges the strength of the lake outflow (Guo et al., 2011a). The indices measuring these forcings are detailed in Hu et al. (2007) and Guo et al. (2011a), and are evaluated using water level and water flux profile data observed at Hukou station, which is at the interface of the river and the lake. The values of these indices are summarized in Table 2 for the years after the TGD and for their analogous years.

The results in Table 2 show severe weakening of the Yangtze River forcing in October and also in July–September. The weakening river forcing in those months is largely a result of reduction of Yangtze River discharge (Fig. 4) caused by impounding at the TGD reservoir (Fig. 3). Because the largest impounding has occurred in October and has resulted in the largest monthly decrease in river discharge (Fig. 4), the largest decrease of the river forcing occurs in October. The number of days (frequency) in October with significant river forcing on the lake was reduced to near zero after operation of the TGD. While this change is statistically significant, its impact on Poyang Lake is trivial, however, because both the lake catchment and the mid-Yangtze River basin are in their dry period in October and discharge and water-level are low in both the lake and the river (Figs. 2, 4 and 5). This lack of any physical impact from this significant change in the river discharge also is supported by the result in the last column in Table 2 which shows that the Poyang Lake forcing/outflow on the river has no "reaction" to this change in diminishing river forcing in October.

The physical impact of the Yangtze River forcing on Poyang Lake is most significant in July–September when the Poyang Lake level

Table 2
Changes in frequency of the Yangtze River forcing and Poyang Lake forcing.

Yangtze River forcing				Poyang Lake forcing		
Average forcing frequency before/after TGD	April–June	July–September	October	April–June	July–September	October
	1.3/1.7	32.8/20.8	1.2/0.2	14.0/20.8	0.0/0.7	0.0/0.0

is high and the river discharge is substantially increased (Fig. 2). Changes in the river forcing in this period caused by modulation of the river discharge by TGD operations (impounding and thus reduction of river discharge, see Figs. 4 and 5) can strongly affect Poyang Lake. As shown by the result in the third column in Table 2, the frequency of strong river forcing on the lake has decreased in this period by about 37% (12 days) after operation of the TGD. This reduction shows weakening of the river forcing on the lake. With weakened river forcing and blocking effect, more lake water flowed into the river, a result also confirmed by a slight increase in lake forcing in the same period shown in the sixth column in Table 2. This result suggests a more favorable condition for lake flow to the river after operation of the TGD, indicating reduction of flood potential in the lake basin from July to September.

Changes in the river–lake interactions resulting from the TGD operations in April–June are rather interesting although they have produced little net impact on Poyang Lake. As shown by the results in the fifth column in Table 2, the averaged lake forcing in April–June increased by nearly 48%, yet the river forcing (in the second column in Table 2) showed only a slight change after the TGD operation began. Further examinations of monthly activities of these forcings in this period indicate that while the TGD has increased the river discharge by releasing water from the reservoir in April–June (Fig. 3), the released water has been insufficient to raise the river discharge greatly enough to impact the river forcing on Poyang Lake. We note that the river discharge is rather low in this dry period (Fig. 2a). On the other hand, the impounding at the end of this period (June) and, more importantly, the simultaneous annual climax of the Poyang Lake level in June (Fig. 2a) have resulted in net increases in the Poyang Lake forcing/outflow in this period. This net effect also helps reduce the lake basin flood potential.

It should be pointed out that among these changes in the river and lake forcing in these different seasons only the decrease in river forcing in October is statistically significant at the 95% confidence level. The July–September change in river forcing is at a marginal 90% significance level. These results are consistent with the TGD operations, which have a huge impounding of water in October but less distinct and persistent (impounding or releasing) modulations of the river flow in the other seasons. The latter is largely a response of the TGD operations to variations in precipitation and demands for hydropower generation in those different months or seasons. This lack of a significant impact of the TGD on river–lake interaction in all seasons also is consistent with the recent finding in Guo et al. (2011a), who show that the TGD operations have an insignificant annual net impact on the Yangtze River flow and that climate variations remain the primary driver even after the TGD was completed.

4. Summary and concluding remarks

Major results of this study show that:

(1) The Three Gorges Dam (TGD) operation since 2003 has affected the Yangtze River discharge and water level, and the significance of these effects varies between seasons and locations along the river. The seasonal variation largely follows the TGD's seasonal impounding and releasing of water, and the magnitude of the variation is dependent on the impounding/releasing rate and the seasonal flow of the river, which is determined by the region's climate. In the dry, low-flow season from October–March, the particularly large impounding by the TGD in October has reduced the river discharge by as much as 30%, and the reversed operation to meet the hydropower generation demand after October has increased the river discharge. Because the river flow is rather low in these dry months, these large rates of impounding and releasing of water by the TGD create significant fluctuations/changes in Yangtze River discharge. A similar but much less significant situation extended through parts of May and early June when the Yangtze River basin remained dry.

During the rainy season of the river basin from July–September the elevated river flow and its variation overwhelm fluctuations added from low rates of impounding water by the TGD. While the rate of impounding is low, it varies frequently because of the constant adjustment of the rate needed to manage the reservoir storage/level in this flood-prone period. The resulting highly fluctuating TGD effect on the river flow has prevented a steady and statistically significant impact of the TGD on the river discharge in this wet period. On average, the operation of the TGD has shown a noticeable, but only marginally significant, effect on weakening the river discharge in this period.

(2) All these seasonal impacts of the TGD on river discharge weaken quickly along the river as its distance from the TGD increases. As a result, the number of days that have statistically significant change in river discharge at Yichang (the nearest station to the TGD) is about five times as great as that at Datong (the furthest station). This fast diminishing TGD effect along the river is attributed to increases of river discharge from inflows from large tributaries along the Yangtze River. These inflows also bring their own variations and interfere to "dilute" the effects of the TGD on the Yangtze River discharge. Because of this fast dilution, the TGD effect is largely limited in the river section upstream of Datong.

This limited near-field impact of the TGD may also have confined the TGD impacts on sediment transport in the river. Some of the previous assessments on reduction of sediment transport in the river after operation of the TGD (e.g., Yang et al., 2007) were primarily near-field responses to the TGD. The results of our study suggest that as the TGD impact on the river discharge weakens quickly downstream the sediment transport rate may increase again. Thus, the spatial variations in the TGD effect may have complicated the sediment transport processes along the river. Consequently, the questions of if and how the diminishing TGD effect downstream of Datong could have affected the stability of the river morphology and the Yangtze River Delta (e.g., Chen et al., 2001; Yang et al., 2007) deserve further investigations.

(3) In the river reach from Hankou to Jiujiang TGD operations influence the Yangtze River discharge, significant in some months and weak in the others. Because the river interacts with Poyang Lake at Hukou, near Jiujiang, changes in the river discharge have further altered interactions of the Yangtze River and Poyang Lake, disturbing the lake basin's hydrological processes, water resources, and the attitude of the public on the TGD. Our results have shown that the varying severities in impounding of water from late July through October has resulted in weakening of the river forcing on the lake. While the weakening river forcing may partially fulfill the mission of the TGD to reduce the flood risks during the peak wet season of the Yangtze River basin from July–September, it has allowed for more lake water to flow into the river (Fig. 6), thus reducing water storage in the lake. In fact, in the 6 years since the TGD operation began the annual average number of severe outflow events of rate $\geqslant 3000\ m^3\ s^{-1}$ from the lake in July–September has increased by 74. In conjunction with a similar change in the dry season from October–March the TGD operations

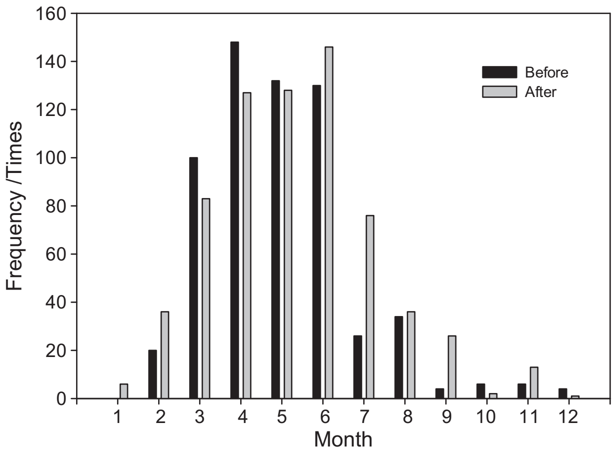

Fig. 6. Monthly total number of events of water outflow from Poyang Lake to the Yangtze River with flow rate $\geqslant 3000\ m^3\ s^{-1}$ for 2003–2008 (gray bars, after operation of the TGD) and for their six analogous years (dark solid bars, before the TGD). The changes in the months of July and September are statistically significant at the 90% confidence level using two-tailed Student *t*-test.

have caused considerable increases in the lake outflow to the river and changes in the hydrological processes in Poyang Lake. Although the rate of the increased outflow from the lake is small in the low-flow season, the prolonged excessive outflow from July–March has resulted in noticeable losses of lake water after the TGD operation began (Fig. 6), triggering public concerns for protection measures. While potential effects of climate anomalies should be examined to fully address these issues, more observations and analyses are required to further quantify the effect of the TGD operation in various climate conditions and to develop working strategies to minimize the TGD impacts on water resources as well as their societal and ecological consequences in the Poyang Lake basin and mid- to lower-Yangtze River basin.

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