Investigation of Inner-basin Variation: Impact of Large Reservoirs on Water Regimes of Downstream Water Bodies

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Abstract

Large dams and reservoirs alter not only the natural flow regimes of streams and rivers but also their flooding cycles and flood magnitudes. Although the effect of dams and reservoirs has been reported for some vulnerable locations, the understanding of the inner-basin variation with respect to the effects remains limited. In this study, we analyse the Three Gorges Dam (TGD) built on the Changjiang mainstream (Yangtze River) to investigate the dam effect variations in the system of interconnected water bodies located downstream. We investigated the effect of flow alterations along the downstream river network using discharge time series at different gauging stations. The river–lake interactions (referring to the interactions between the Changjiang mainstream and its tributary lakes i.e. the Dongting and Poyang lakes) and their roles in modifying the TGD effect intensity were also investigated in the large-scale river–lake system. The results show that the water storage of the tributary lakes decreased after the activation of the TGD. Severe droughts occurred in the lakes, weakening their ability to recharge the Changjiang mainstream. As a consequence, the effect of the TGD on the Changjiang flow increase during the dry season diminished quickly downstream of the dam, whereas its impact on the flow decrease during the wet season gradually exacerbated along the mainstream, especially at sites located downstream of the lake outlets. Therefore, when assessing dam-induced hydrological changes, special attention should be paid to the changes in the storage of tributary lakes and the associated effects in the mainstream. This is of high importance for managing the water resource trade-offs between different water bodies in dam-affected riverine systems.

Keywords: Three Gorges Dam, water regime change, mainstream, tributaries and lakes, river–lake interaction.

1. INTRODUCTION

Dams and reservoirs have made a significant contribution to human development. Global databases show that approximately 50,000 large dams (>15 m high) have been constructed to meet the needs of social and economic development throughout the world (Nilsson, Reidy, Dynesius, & Revenga, 2005; The International Commission On Large Dams (ICOLD), 2007; Lai, Jiang, Yang, & Lu, 2014). However, large dams have profoundly altered the basin-scale hydrological regimes, including severe consequences on the ecological and morphological equilibrium of streams (Power, Dietrich, & Finlay, 1996; Nilsson et al., 2005; Syvitski, Vörösmarty, Kettner, & Green, 2005; Ferrazzi & Botter, 2019). Hence, understanding and quantifying the hydrological impacts of large dams on downstream river systems is of great importance; which is the first step in balancing the benefits of the dam and its negative impacts (Wu, Huang, Han, Xie, & Gao, 2003; Poff, Olden, Merritt, & Pepin, 2007; Hecht, Lacombe, Arias, Dang, & Piman, 2019).

Previous studies have revealed a series of hydrological changes caused by dam regulation (James, 1997; Carling, 1988; Jaramillo & Destouni, 2015; Hecht et al., 2019). Existing large-scale investigations have revealed that river impoundments affect the magnitude, frequency, and timing of both high and low flows with an intensity closely related to the storage capacity of reservoirs (Poff et al., 2007; Destouni, Jaramillo, & Prieto, 2012; Ferrazzi & Botter, 2019). These alterations are believed to generate a general reduction of streamflow variability and, consequently, an enhanced homogenization of regional river dynamics (Dai & Lu, 2013; Lai et al., 2014; Dai, Wan, & Yang, 2015; Chen et al., 2016; Lai, Liang, Huang, Jiang, & Lu, 2016). Additionally, these natural flow regime changes, combined with their tendency to capture almost the entire sediment load of rivers, profoundly disrupt the equilibrium between water flow and patterns of erosion and sedimentation, leading to a general rearrangement of channel and floodplain morphology throughout entire river networks (Li, Sun, Liu, & Deng, 2009; Fang, Han, He, & Chen, 2012; Syvitski et al., 2005; Dai & Liu, 2013; Hu, Yang, Wang, Sun, & Bi, 2009). Moreover, at a global scale, Jaramillo and Destouni (2015) revealed a significant enhancement of dams to evapotranspiration, which emphasizes the global impact of local water-use activities.

Notably, significant spatial variations have been observed in dam-induced hydrological changes (Biedenharn & Watson, 1997; Hecht et al., 2019; Xu, Milliman, Yang, & Xu, 2007). For example, Lai et al. (2016) revealed that after the implementation of the Three Gorges Dam (TGD), the dynamic process of flow changes in the middle Changjiang (Yangtze River) downstream of the TGD showed notable spatial heterogeneity. Hecht et al. (2019) found that the hydrological influences of dams on the Mekong River varied in the upper, middle, and lower Mekong Basin. Moreover, they found that the dry-season flow alteration associated with the aforementioned dams could be detected in much further downstream river reaches than the dam's influence on flood control regulation (Hecht et al., 2019). The inner-basin variations of dam impacts can be attributed to many factors (Hecht et al., 2019; Xu & Milliman, 2009; Dai, Yang, Wan, & Li, 2018). For instance, Ferrazzi and Botter (2019) investigated hydrological alterations downstream of 47 isolated dams in the Central Eastern U.S and revealed a strong connection between the anthropogenic use and the hydrological impact of dams. Other studies hold that differences in geology, geomorphology, and river types result in differing river responses (to dam regulations) (Yang et al., 2016; Hecht et al., 2019). Moreover, the local effects of unregulated tributary inflows into the mainstream can also overlay the dam effect at specific sites (Carling, 1988; Dai et al., 2015). Therefore, it is difficult to quantify the inner-basin variation with respect to the dam effect, especially in complex riverine systems. However, developing a comprehensive understanding of such a variation is critical for understanding dam-affected riverine systems; it is a key step towards enhanced water resource management during the post-dam period.

The Changjiang (Yangtze River) is the third-longest river in the world, providing water resources, food security, and livelihoods to millions of people and sustaining great aquatic biodiversity (Milliman & Farnsworth, 2013; Wang, Sheng, & Wada, 2017; Jia, Wang, Zhang, Cao, & Fox, 2018; Wang, Sheng, & Tong, 2014). The TGD is one of the largest dams in the world, located at the starting point of the middle reaches of the Changjiang (China Three Gorges Construction Yearbook Commission, 2011). Downstream of the TGD, the midstream Changjiang forms many tributaries and lakes, creating a system with super complex river–lake interactions (Dai & Liu, 2013; Wang, Sheng, & Wada, 2017). Consequently, the inner-basin variations of the TGD impacts in the middle Changjiang basin is contentious and uncertain (Dai & Liu, 2013; Zhao et al., 2017). For instance, some scientists indicated that the effect of TGD would diminish because of 'dilutions' due to the effect of inflows from the downstream tributary water bodies (Guo, Hu, Zhang, & Feng, 2012; Guo, Su, Zhu, & He, 2018; Wang et al., 2017). However, a significant increase in drought severity associated with the TGD has been detected quite far downstream in the Poyang Lake (approximately 600 km downstream of the TGD), which has experienced more severe drought instances than the mainstream reaches located immediately downstream of the TGD (Liu, Wu, & Zhao, 2013; Zhang et al., 2015; Zhou et al., 2019). Given the potential ecological and livelihood impacts of the TGD in the middle Changjiang basin, a more detailed assessment of the hydrological alterations in the different regions of this area associated with the TGD is required. This study utilized the long-term hydrological data collected from different gauging stations in the middle Changjiang basin to investigate the inner-basin variation of the impacts of the TGD. Our main objective is to provide a deeper understanding of the flow alteration effects of dams on systems of interconnected water bodies located downstream of large dams and reservoirs. Our results can be applied to other complex riverine systems undergoing rapid hydropower development, such as the Amazon, Congo, and Mekong basins. The remainder of this paper is organised as follows. Section 2 briefly introduces the Changjiang basin, along with the data sources and methods used in this study. Section 3 presents the flow alterations with respect to the operation of the TGD at different locations of the Changjiang mainstream, revealing the inner-basin variation of the TGD impacts. It also addresses the hydrological changes in the tributaries and lakes in the downstream area and explains the reasons for the inner-basin variations with a focus on river–tributary (lake) interactions. Section 4 discusses the extent to which confounding changes in lake inflows and lakebed topographies may offset or exacerbate the TGD-induced water regime alterations. The last section presents the conclusions of our study.

2. DATA AND METHODS

2.1 Study area

Changjiang, which runs eastward along the middle portion of China (Fig. 1), is one of the most prominent rivers in the world; it has great ecological and socioeconomic importance (Kanai et al., 2002; Guo et al., 2018). Its catchment covers an area of ~1.9 million km^2 (19.5% of China's land area) and produces an annual streamflow of ~900 billion m^3 (37% of China's total streamflow) (Wang, Jiang, Bothe, & Fraedrich, 2007; Yang et al., 2006). It ranks ninth globally in terms of the drainage area and fifth with respect to water discharge (Milliman & Farnsworth, 2013; Zhao, Zhu, & Zhou, 2000). Geographically, the Changjiang basin can be divided into three sections based on the landscape. The upper basin extends from the headwaters to Yichang (see Fig. 1). The middle basin extends from Yichang to Hukou; and the lower basin extends from Hukou to the delta regions (Chen et al., 2014; Shi, 2008). The TGD is approximately 40 km upstream of Yichang. Downstream of the TGD, there are two lakes and one large tributary river draining into the Changjiang: the Dongting Lake, Poyang Lake, and Han River, whose distances from the TGD are ~365, ~970, and ~575 km, respectively (Fig. 1).

[Insert Figure 1]

Both the Dongting and Poyang lakes occupy areas of low elevation immediately south of the middle Changjiang. The Dongting Lake receives flows from four secondary tributaries and conjuncts the Changjiang mainstream at Chenglingji (Ou et al.,, 2014). Poyang Lake has five secondary tributaries and drains to the Changjiang at Hukou (Shankman, Keim, & Song, 2006). In addition, both lakes can receive spill flows from the Changjiang mainstream during wet seasons (Li, Zhang, Werner, Yao, & Ye, 2017). Hence, these lakes play a profound role in buffering the flows of mainstream Changjiang. The Han River is the largest tributary of Changjiang, which lies north of the middle Changjiang basin and has a control gauging station at Huangzhuang (Zhang et al., 2017). The annual average discharges at the Chenglingji (at the Dongting Lake's mouth), Huangzhuang (control station of the Han River), and Hukou (at the Poyang Lake's mouth) are 260.8, 442.8, and 153.6 billion m^3, respectively. The Changjiang basin is dominated by a typical subtropical monsoon climate (Wan, Dai, & Shankman, 2018). Its precipitation is mostly concentrated in the wet season during the summer and fall months (April to September), while the winter and spring months (October to March) are dry seasons having low precipitation (Ding & Chan, 2005). In a typical year, the monsoon front marches from the southeast to the northwest; thus, the prime rainy season in the south of Changjiang is generally two to three months earlier than that in the north (Shankman et al., 2006). That is, the southern Dongting and Poyang Lake basins have a peak precipitation season from April to June, whereas the northern Han River basin has a peak precipitation season from July to September (Guo, Hu, & Jiang, 2008). Hence, there are varying blocking forces of the Changjiang mainstream to outflows from the two lakes, thus, leading to varying river–lake interactions in this area (Hu, Feng, Guo, Chen, & Jiang, 2007). To be specific, the lakes can drain into the Changjiang mainstream effortlessly during the spring and winter months, while the lake flows are heavily blocked or even reversed by the flow of the Changjiang during the summer and fall months, especially during peak floods (Guo et al., 2012).

The TGD was commissioned in 2003. Its essential functions are flood control, power generation, and the promotion of irrigation and navigation (Qin et al., 2020). The operation of the TGD follows a scheme that stores and flushes water seasonally. In summer (wet season), the TGD does not modulate the Changjiang river's flow, except for peak flood discharges >55,000 m^3/s (Zheng, 2016). Beginning in early autumn (late stage of the wet season), the TGD begins to impound water before the end of the wet season, and in winter and spring (dry season), the TGD releases water gradually until June, when the wet season begins (see China Three Gorges Corporation report at http://www.ctgpc.com.cn/sxslsn). Thus, due to the dam, the flows of the middle reaches of the Changjiang basin immediately downstream of the TGD have become larger during the dry season and smaller during the wet season. The flow alteration additionally propagates downstream to other sections of the middle Changjiang basin, thus, affecting the water regimes to varying degrees.

2.2 Data and methodology

To detect the inner-basin variation of the hydrological effects of the TGD along the middle reaches of the Changjiang and its tributaries and lakes, daily discharges and/or water levels were collected from 12 gauging stations in the middle Changjiang basin downstream of the TGD (Fig. 1). Among these, five stations are located in the mainstream, three stations are located at the mouths of the tributaries and lakes, and four stations are located in the sub-lakes of the two lake basins. The annual water discharge data of the Huangzhuang station (the control station for the Han River) were from 1980 to 2017, with a missing value in 2014. Other data were all continuous from 1980 to 2019, with no missing values. All data were obtained from the Changjiang Water Resources Commission (http://www.nmic.gov.cn/). Table 1 summarises the basic information of the gauging stations.

[Insert Table 1 about here]

At each station, a linear regression analysis was applied to the hydrological data to examine the trends and change rates during the entire study period and on both sides of the TGD. A Student’s t-test at 5% significance level was used to determine the statistical significance of the linear trends. Additionally, the differences in the hydrological data pre- and post-TGD for each gauging station were calculated, which measured the magnitude of the effect of the TGD at that location as a first approximation. On this basis, the inner-basin variation of the TGD effect in the middle Changjiang basin was revealed by comparing the magnitudes of the effect of the TGD at different locations.

Additionally, other hydrological and terrain data, including the lake inflows from the secondary tributaries and the channel profiles of the lake outlets were also used in this study. These data were utilised to reflect the effect of concurrent changes in the climate, water demand, and topography of the region on the impact of the TGD in different locations in the middle Changjiang basin. These data were also obtained from the Changjiang Water Resources Commission.

2.3 River–tributary (lake) interaction analysis

The inner-basin variation of the effect of the TGD was assumed to be modulated by the varying interactions between the Changjiang mainstream and its key tributaries and lakes in the middle Changjiang basin. Hence, the river–tributary (lake) interactions in the area were analysed in detail to determine the reasons for the inner-basin variations in the impact of the TGD on this riverine system.

The interaction of the Han River with the mainstream can be directly reflected by its discharge into the Changjiang because the ability of a tributary to discharge water into the mainstream depends primarily on the flow conditions of the tributary. Conversely, for the Dongting and Poyang lakes, their interactions with the mainstream were found to be quite complex. The mainstream can affect the hydrological conditions of lakes by blocking their outflows to varying degrees. However, the two lakes can also affect the mainstream by recharging the mainstream with different amounts of water.

We used the method illustrated in Fig. 2 to measure the effect of Changjiang on the water regimes of the lakes. The rating curves of each lake outlet were compared under different flow conditions of Changjiang. In each interval, a power–law function was used to fit the rating curve of the outlets as follows (Eq. 1):

$$H_{\mathrm{lake}} = aQ_{lake}^{b}, \qquad (1)$$

where Q_{lake} and H_{lake} are the discharge (m^3/s) and water level (m) of the lake outlet, respectively, and a and b are empirical parameters.

Next, the average distance between the adjacent rating curves was extracted to measure the lake water-level amplitude at equal lake discharges posed by changing Changjiang flows. For further details, please refer to Dai et al. (2018).

[Insert Figure 2]

The water storage of the two lakes determines their abilities to recharge the Changjiang mainstream. Therefore, lake storage changes associated with the aforementioned lake water-level amplitudes were extracted to measure the effect of the two lakes on the downstream Changjiang mainstream. Specifically, lake storage changes associated with specific lake water-level amplitudes were deduced using the water level and surface area relationships in these lakes established in previous studies (Liu et al., 2013; Xu, Kang, & He, 2015). In Dongting Lake, the lake surface area S_1 is a function of the lake water level h_1 (Xu et al., 2015) (Eq. 2).

$$S_1\left(h_1\right) = -3.99h_1^3 + 330.36h_1^2 - 8777.4h_1 + 75845, \qquad (2)$$

For Poyang Lake, the lake surface area S_2 is a function of the lake water level, h_2 (Liu et al., 2013) (Eq. 3).

$$S_2\left(h_2\right) = -7.25h_2^2 + 417.16h_2 - 1772.9, \qquad (3)$$

The lake storage alteration corresponding to a given lake water-level increment from h_a to h_b was calculated as follows (Eq. 4):

$$V = \int_{h_a}^{h_b} S(h)dh, \qquad (4)$$

where V is the water storage variation and h_a and h_b are the starting and ending values of the given water level increments, respectively.

3. RESULTS

3.1 Spatiotemporal changes of Changjiang mainstream flow

The annual flow of the Changjiang averaged from 1980 to 2019 at different gauging stations is shown in Fig. 3. It is noted that the Changjiang's flow exhibited a notable increase from upstream to downstream, with the two largest increments occurring at locations downstream of the outlets of the Dongting and Poyang lakes. The only decrease in the Changjiang flow while moving downstream occurred between the Zhicheng and Jianli stations, which is downstream of the seasonally spilling way of the Dongting Lake. The decreased river flow between the Zhicheng and Jianli stations was mainly caused by the spill flows from the Changjiang mainstream into the Dongting Lake in the flood season. That is, variations in the flow of the Changjiang are closely related to the distribution of its tributaries and lakes (see Fig. 1 for detailed station locations relative to the tributaries and lakes). Thus, the tributary water bodies, especially the two lakes, play important roles in maintaining the Changjiang mainstream discharge.

[Insert Figure 3]

The linear trends of the flow of the Changjiang mainstream at different gauging stations from 1980 to 2019 are shown in Fig. 4 (red dashed lines) and Table 2. The yellow and green dashed lines in Fig. 4 also mark the linear trends of the river flows from 1980 to 2002 (pre-TGD) and 2003 to 2019 (post-TGD), respectively. As shown by the red dashed lines, there were downward trends in the mainstream flow time series at all the gauging stations from 1980 to 2019, among which the most significant decrease occurred at the Zhicheng station ($p< 0.05$) with a change rate of -17×10^8 m^3/year (Table 2). However, the river flows from 1980 to 2002 (marked by the yellow dashed lines) showed no significant tendencies at these stations, whereas the river flows from 2003 to 2019 (marked by the green dashed lines) showed significant increasing tendencies at all the gauging stations (all the significant levels were smaller than 0.01). Hence, we conclude that the decreasing trends of the Changjiang's flow during 1980–2019 were mainly caused by the "drop" in the flow of the Changjiang river due to the initial impounding of the TGD in 2003, when the dam started operation. Other factors of the decrease of average annual flow during the post TGD period, like the altered river–lake interactions and the decreased lake inflows from upstream catchments, etc. are interpreted in the Discussion section.

[Insert Figure 4]
[Insert Table 2 about here]

3.2 Effect and variation of Three Gorges Dam (TGD) along Changjiang mainstream

Figure 5 compares the changes in the flow of the Changjiang river in the post-TGD period compared to that of the 1980 to 2002 average (before TGD) at multiple time scales. As shown in Fig. 5a, the daily cumulative flow changes in the river at different gauging stations showed a similar variation pattern i.e., the river flow increased slightly during the dry season and decreased substantially during the wet season. This was a direct effect of the seasonal impounding and the release of water from the TGD. That is, the TGD increased Changjiang's flow during the dry season and decreased it during the wet season.

The seasonal changes in the flow of the Changjiang river after the functioning of the TGD are shown in Fig. 5b. It can be seen that the increasing effect of the TGD on the dry-season flow of the Changjiang river alleviated quickly from upstream to downstream, while its decreasing effect on the wet-season flow of the Changjiang river aggravated gradually along the mainstream. Furthermore, it was found that both the alleviation and aggravation of its effect were primarily attributed to the non-stationary changes in the Changjiang's flow at the Luoshan and Datong stations, which are downstream of the Dongting and Poyang lakes, respectively. Specifically, the dry-season flow of the Changjiang river increased by 177×10^8 m^3 at Luoshan station and 98×10^8 m^3 at Datong station after the TGD, both of which were lower than those at the other stations (225×10^8 m^3 on average). Moreover, the decreases in the flow of the Changjiang river during the wet season at the two stations were 599×10^8 and 763×10^8 m^3, respectively, which were much larger than those at other stations (539×10^8 m^3 on average). That is, at reaches downstream of the two lakes, the dry-season flow-increasing effect of the TGD was offset, and the wet-season flow-decreasing effect of the TGD was exacerbated. In contrast, its tributary, Han River, offset the external effect of the two lakes on the TGD's effect to some extent.

Figure 5c shows the impact of the TGD on the annual flow of the Changjiang river, which is like that on the wet-season flow of the Changjiang mainstream. The TGD operations caused a general reduction in the flow of the Changjiang river. Moreover, the reduction effect was notably exacerbated downstream of the two lakes, but was slightly diluted at the downstream reaches of the tributary. Overall, the TGD effect gradually aggravated while moving downstream. However, it is noted that although the TGD has a huge regulating capacity of 22.15 km^3, it still stores water during high-flow periods and releases the stored water volumes during low-flow periods. The impacts of the TGD on water regimes during the high-flow periods and that on the water regimes during the low-flow periods should be the same over a longer period, which is not what we observed. Thus, there must be an external driving force that breaks the balance between the seasonal impounding and the release of water from the TGD. Because the inner-basin variations of the TGD impacts are closely related to the distribution of the tributary water bodies in the middle Changjiang basin, we suspect that hydrological changes in the tributaries and lakes could be the primary external driving force for the inner-basin variation of the TGD impacts. Hence, the following section investigates the hydrological changes in these tributaries and lakes after the TGD, along with their roles in modifying the intensity of the impacts of the TGD.

[Insert Figure 5]

3.3 Hydrological changes in tributaries and lakes of Changjiang

Figure 6 shows the hydrological changes in the tributary water bodies of the Changjiang after the operation of the TGD. Results show that there were downward trends in both the water-level time series of the two lakes and the water discharge time series of the Han River during the entire study period (Figs. 6a–6c). However, the downward trends of the Dongting (p=0.10) and Poyang (p< 0.01) lakes were more significant than that of the Han River (p=0.16). The comparisons in the lake water levels and river discharges before and after the implementation of the TGD also support this conclusion (Figs. 6d–6f). Thus, it can be seen that the Han River could recharge the Changjiang mainstream after the TGD operation as it did before the TGD operation. However, severe droughts occurred in the two lakes after the TGD operation, weakening their ability to recharge the mainstream. This is why the annual mainstream flow reduction associated with the TGD was profoundly exacerbated at the downstream reaches of the lakes and was partially offset at the downstream reaches of the tributary.

[Insert Figure 6]

To reveal the observed droughts of Dongting and Poyang lakes after the TGD operations, a detailed comparison of their daily water levels before and after the operation of the TGD was conducted (Fig. 7). It was observed that the water levels post the implementation of the TGD were much lower than those before the TGD was built during most of the year in both the lakes. In particular, the most severe lake water level drops occurred in October and early November, which corresponded to the impounding of the TGD at the end of the wet season. During this period, the maximum water level drops in the Dongting and Poyang lakes were 2.23 and 2.69 m, respectively, which were more severe than those of other dates. In addition, the effect of the TGD in raising the water levels of those lakes during the dry season was also detected, but the effect was weak. Specifically, there were only 68 days in a year during which the water levels of the Dongting Lake were higher than those before the operation of the TGD, while that for Poyang Lake only lasted nine days in a year.

[Insert Figure 7]

3.4 Three Gorges Dam’s contribution to severe lake droughts

As mentioned above, the reduced flow of the Changjiang river post the functioning of the TGD could weaken its blocking effect on the outflow of the lakes. Hence, the lake droughts in the recent two decades may also be attributed to the TGD. This section further analyses the extent to which the Changjiang flow condition can affect the water levels and water storage of the two lakes (Fig. 8).

As shown in Fig. 8a, an increase in the flow of the Changjiang mainstream by an increase of 3000 m^3/s led to a water level rise of 0.31–1.47 m in the Dongting Lake and 0.20–0.76 m in the Poyang Lake. Regarding the lake storages, each 3000 m^3/s change in the flow of the Changjiang mainstream led to a water storage change of 6.05–14.13 million m^3/s in the Dongting Lake and 3.32–21.55 million m^3/s in the Poyang Lake. This indicates that the hydrological conditions of the two lakes are significantly influenced by the Changjiang. This is because the reducing/increasing flow of the Changjiang mainstream is able to cause subsequent water-level drops/rises at the mouths of the lakes, which additionally enlarges/shrinks the water-level gradients in the river–lake connecting channels, thereby fostering faster/slower outflows from the lakes. This results in lowered/elevated water levels and decreased/increased water storage.

Thus, the massive reduction in the flow of Changjiang during the wet season post the operation of the TGD has rapidly depleted the lake water storage of the two lakes (during the wet season), which has resulted in severe lake droughts. Although the following slight increase in the flow of the Changjiang during the dry season reinforces the blocking effect on the lake outflows to some extent, it is not able to offset the lost water storage inside the lakes, and thus, severe lake droughts continually occur during the dry seasons. This is why year-round droughts occur in both the lakes post the TGD’s operation.

[Insert Figure 8]

4. DISCUSSION

In this study, we found that the effect of the TGD on the water regimes in the middle Changjiang basin was not confined to the direct mainstream flow regulation and included the indirect influence of altering water regimes of the tributary lakes. Among these effects, the effect of the TGD on the mainstream flow was more profound at the seasonal scale, while that on the water regimes of the lakes was more pronounced at the annual scale. That is, the TGD primarily modulated the timing and magnitude of the flow in the mainstream. This is partly caused by the fact the large TGD dam started impounding water in 2003, and partly caused by other factors like after the operation of the TGD, the capacity of the tributary lakes to recharge the Changjiang mainstream is lowered. However, in the lakes, the TGD not only changed the seasonal allocation of water resources but also caused a sharp reduction in the total amount of the resources. This variation was inherently caused by the expedited propagation of lake floods to the delta by the impounding of the TGD at the end of the wet season. Therefore, we suggest that dam-induced hydrological processes are affected by not only the magnitude of river discharge but also its timing, duration, and interactions with other water bodies.

However, the water volume reductions in the Dongting and Poyang lakes in the recent two decades are also partly attributed to factors other than the regulation of the TGD. These factors could include lake inflow changes due to variations of climate in the lake drainage basins, along with channel capacity changes in the river–lake connecting channels due to sand mining and lakebed erosion, etc. Therefore, variations in the lake inflows and lake channel profiles were examined to reveal whether these concurrent drivers have exacerbated or offset the severe lake droughts stemming from the TGD (Table 3 and Fig. 9).

Table 3 shows the parameters of the linear trend analysis for the inflows of the Dongting and Poyang lakes, and the negative slopes (except for summer in both the lakes and fall in the Poyang Lake) show downward trends from 1980 to 2019, although these trends are in Not statistically significant. This conclusion coincides with the study of Liu et al. (2013), who revealed that from 1973 to 2010, the annual precipitation in the Poyang Lake basin decreased slightly, and its annual evapotranspiration increased slightly. Thus, the Poyang Lake inflows from its secondary tributaries decreased slightly. Moreover, the reductions in the water spills from the Changjiang mainstream into the two lakes also contributed to lake droughts post the TGD operations. For instance, Guo et al. (2012), Zhang et al. (2012), and Zhao et al. (2017) concluded that the diversion of water from Changjiang to the Dongting Lake via the three inlets and the reverse flow from Changjiang to the Poyang Lake were both significantly reduced since the operation of the TGD, which was also related to the lowered flow of the Changjiang river due to the TGD operations.

Regarding the channel capacities of the lake outlets, it was found that the channel profile changes at the two lake outlets varied widely (Fig. 9). The lakebed erosion at the Dongting

Lake outlet was found to be minimal and occurred only in narrow channels, with the deepest value being 1.76 m over the three decades considered in this study. At the Poyang Lake outlet, however, dramatic lakebed erosion occurred in nearly one-third of the channel, and the maximum erosion depth was greater than 5 m. Hence, the enlarged channel capacity at the Poyang Lake outlet fostered larger lake outflows and exacerbated the lake storage losses induced by the TGD. Overall, we found that the lake inflow decreased in the two lakes, and the channel capacity increased at the Poyang Lake outlet; both exert additional modifications on the TGD-induced lake droughts, which have additionally worsened the water recession in the downstream Changjiang mainstream.

[Insert Table 3 about here]

[Insert Figure 9]

5. CONCLUSIONS

In this study, we used the hydrological data recorded over 40 years (1980–2019) to detect the water regime changes along the Changjiang mainstream and its key tributary water bodies after the operation of the TGD. The reasons for the inner-basin variations in the TGD effect are explained by the altered river–lake interactions in the large-scale river-lake system. In addition, the effect of the confounding factors, including the changes in the inflow and outlet capacities of the lake, in modulating the intensity of the TGD impact are discussed. The primary conclusions are as follows:

(1) The TGD has slightly increased the flow of the Changjiang during the dry season and remarkably decreased it during the wet season. Additionally, the increasing effect of the TGD on the flow of the Changjiang during the dry season alleviated quickly downstream of the TGD, whereas, during the wet season, the decreasing effect of the TGD on the flow of the Changjiang river aggravated gradually while moving downstream.

(2) The inner-basin variation of the TGD effect can be well explained by the hydrological changes in the tributaries and lakes of Changjiang after the TGD operations. Specifically, as the water discharges of the Han River showed no significant changes after TGD operations, the TGD effect diminished at the downstream reaches (near the Han River) because it received more annual runoff and less of the storage of the TGD. However, in the Dongting and Poyang lakes, severe droughts occurred during both the dry and wet seasons, which additionally propagated downstream into the mainstream and offset its dry-season flow augmentation and exacerbated its wet-season flow reduction.

(3) The severe droughts in the Dongting and Poyang lakes after the operation of the TGD were primarily attributed to the impounding of the TGD in the wet season because it significantly reduced the mainstream flow and rapidly depleted the storage capacity of the lakes. In addition, the lake inflow reductions in the two lakes and the channel capacity that showed an increase at the Poyang Lake outlet contributed to the TGD-induced lake droughts.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors (daixue@hhu.edu.cn or rrwan@niglas.ac.cn) upon reasonable request.

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