

Numerical evaluation of flow regime changes induced by the Three Gorges Dam in the Middle Yangtze

Xijun Lai, Qiuhua Liang, Qun Huang, Jiahu Jiang and X. X. Lu

ABSTRACT

The full operation of the Three Gorges Dam (TGD) has altered the downstream natural flow regime. Flow regime changes have resulted in profound influences on the utility of water resources and hence a large area with a riparian ecosystem including China's two largest freshwater lakes in the Middle Yangtze. Because of complicated flow regimes in this large-scale river–lake system, the TGD's impacts on flow regimes are highly heterogeneous and require to be carefully addressed. To better understand them, we estimated water level and discharge changes solely induced by the TGD from 2006 to 2011 using a hydrodynamic model that facilitates the separation of the TGD's contribution to flow regimes. Results indicated that water regulation of the TGD caused profound impacts on the flow regimes of the Middle Yangtze. In the impoundment period from mid-September to October, rapid and significant decline of the water discharge downstream the TGD produced a prolonged dry season that occurred around 10 days earlier than before. Our analysis elucidated a pattern of recent changes in the flow regimes caused by the TGD. The findings are useful for addressing the TGD-induced environmental issues, optimizing the TGD's operation, and generating adaptive management strategy for the complex river–lake ecosystem.

Key words | dam impact, flow regime, Three Gorges Dam, Yangtze River

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INTRODUCTION

The Three Gorges Dam (TGD) in China (Figure 1), one of the world's largest dams, has been fully operated with achievement of its comprehensive benefits since 2010 when the normal water level of 175 m above mean sea level was reached. The project was launched in 1993 and started pilot impoundment in June 2003. It carries great expectations in taming the notorious floods of the Yangtze River and providing hydropower energy for China's growing electrical consumption. The construction of the TGD has been controversial since it was first proposed because of

potential environmental impacts, as well as societal impact induced by the relocation of millions of people. Recently, the environmental issues related to the TGD have begun to emerge after the initial impoundment since 2003 (Yang & Lu 2013). To mitigate the negative environmental impacts, the Chinese government has addressed critical problems associated with the TGD, including significant hydrological and ecological changes in downstream rivers and lakes (Qiu 2011).

The waterbodies in the Middle Yangtze basin (here, referring to the stretch from Yichang to Datong) immediately downstream the TGD are highly influenced by the TGD. They include many shallow lakes and low-lying alluvial plains shaped by the interaction between the Yangtze River and large tributaries (Yin *et al.* 2004). China's two largest freshwater lakes, Poyang and Dongting, are located

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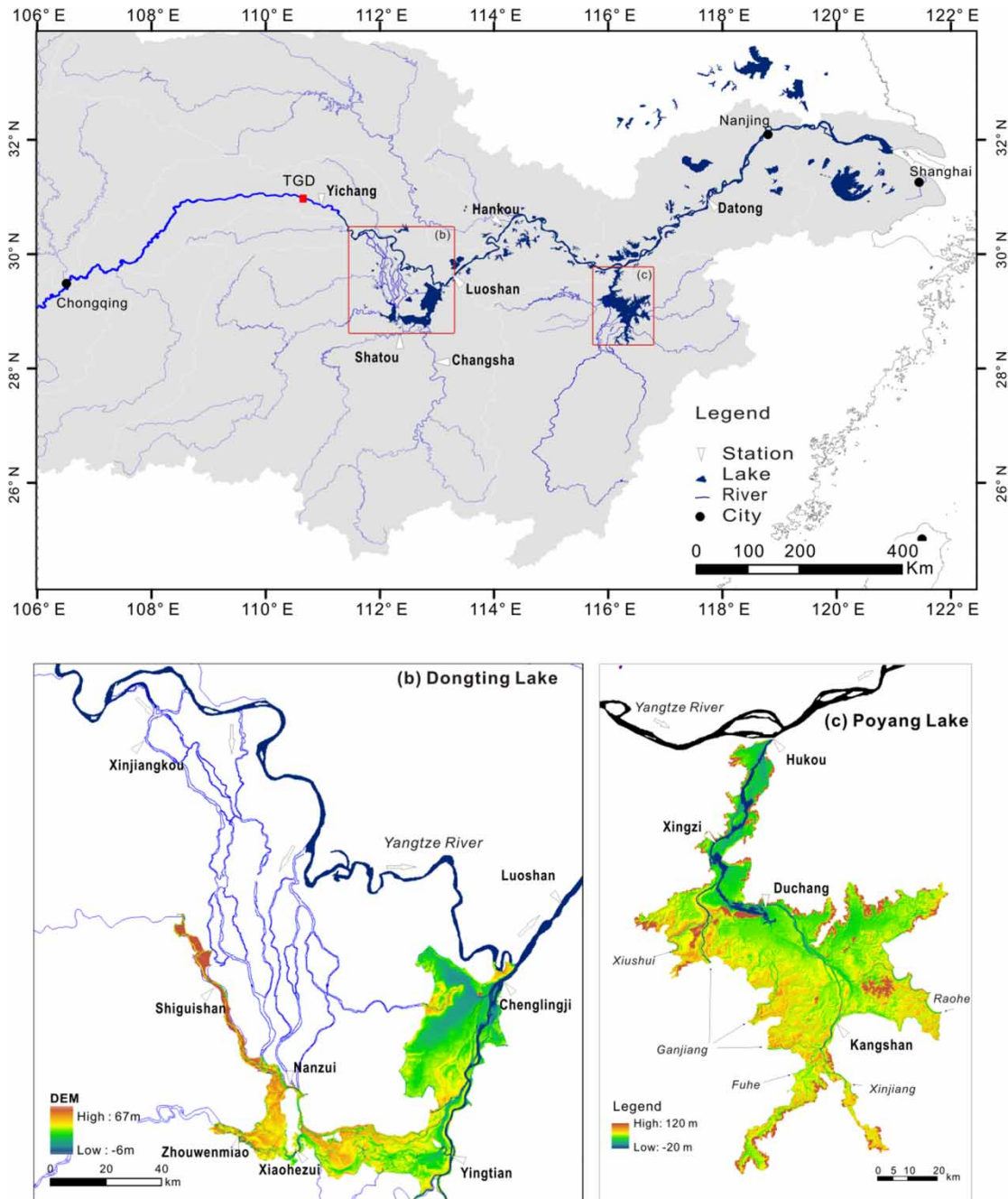


Figure 1 | Location of the Three Gorges Dam (TGD) and water system in the Middle Yangtze including China's two largest freshwater lakes, namely, (b) Dongting and (c) Poyang.

in the region, and naturally interact with the Yangtze River (Zhu & Zhang 1997; Dou & Jiang 2000). The Middle Yangtze, particularly two China's largest freshwater lakes, provides habitats for many important aquatic animals and plants, and migratory birds including a large number of endangered species (Kanai et al. 2002; Fang et al. 2006;

Ji et al. 2007; Harris & Zhuang 2011; Fang et al. 2012a; Dong 2013). However, seasonal hydrological droughts, characterized by extremely low water levels, have been frequently occurring in this region, especially in Poyang Lake, since the TGD operation (Min & Zhan 2012). The extremely low water levels and apparent shrinkage of the

great lakes were continuously observed in 2006, 2007, 2009, and 2011 (Lai *et al.* 2014a). The hydrological changes may break down the long-standing ecological balance and cause biodiversity decline (Milliman 1997; Cao & Fox 2009). Consequently, many efforts have been made to investigate flow regime changes in this region and also their causes (Feng *et al.* 2013; Gao *et al.* 2013; Liu *et al.* 2013, among others). Great attention has been paid to the TGD due to its huge regulating capacity of 22.15 km³. Despite no change in annual total discharge, the operation of the TGD has altered seasonal patterns of flow regimes in the Middle Yangtze by regulating natural discharge downstream. The potentially irreversible changes induced by the TGD may thus increase the risk of the utility of water resources and ecological degradation of wetlands and aquatic ecosystem in the Middle Yangtze.

Various flow regime changes in this region caused by the TGD were investigated, including the river discharge alteration in the mainstream of the Yangtze River (Dai *et al.* 2008; Gao *et al.* 2013), lake inundation area (Feng *et al.* 2013; Liu *et al.* 2013), and water level changes (Fang *et al.* 2012a, 2012b; Guo *et al.* 2012; Zhang *et al.* 2012a; Lai *et al.* 2013a; Nakayama & Shankman 2013) in Poyang and Dongting Lakes. These insightful studies make a strong case that the TGD has altered the river discharge in the mainstream of the Yangtze, and changed the Yangtze interaction with the connected lakes, and their water level changes. However, significant climate variability and other intensive human activities have influenced the Middle Yangtze simultaneously (Chen *et al.* 2001; Gemmer *et al.* 2008; Zhang *et al.* 2011, 2012b; Lai *et al.* 2014c). These various factors complicate the understanding of the TGD's impact on flow regimes. Meanwhile, this system is known for its complicated flow regimes induced by the complex river-lake interaction. Therefore, direct comparison of flow regimes before and after the TGD is inadequate to identify the contribution of the TGD to the flow changes from observed changes. For example, convincing evidence shows that the intensive sand mining along its outflow waterway significantly affects the Poyang Lake level (Lai *et al.* 2014c). Using a hydrodynamic model, the TGD's contribution to the recent extremely low water levels in the main stream was presented by Lai *et al.* (2014a). It clearly shows that the TGD contributes just part of the flow changes

in the mainstream of the middle Yangtze River, even though such changes are dominant in some months. Dynamic mechanism for the hydrological responses of Dongting and Poyang Lakes to the TGD impoundment was also investigated (Lai *et al.* 2014b). However, all of these investigations have not demonstrated the spatial and temporal pattern of flow regimes caused by the TGD in the main waterbodies of the Middle Yangtze. It will influence the administration to take pointed countermeasures for alleviating the TGD's impact on water resources and ecology.

We employed a large-scale hydrodynamic model (Lai *et al.* 2014b) that can well reproduce flow regimes in this river-lake system to quantify the TGD's impact. Specific daily water level and discharge changes caused solely by the TGD based on its real operation during the years 2006–2011 were estimated and the distribution of the TGD's impact on flow regimes in time and space was derived. Our results revealed the contribution component of the TGD to the recent flow regime changes in the Middle Yangtze and identified the TGD's main action time periods and water bodies that have not been fully addressed by previous studies. Our comprehensive analysis of the TGD's influencing magnitude and pattern in time and space on flow regimes in the Middle Yangtze River will be useful for addressing the TGD-induced environmental issues, optimizing the TGD's operation, and generating adaptive management strategies for the complex river-lake ecosystem.

THE THREE GORGES DAM AND ITS OPERATION

The TGD (30°49'N, 111°00'E) in the Yangtze River is located in Sandouping Town, Yichang City, Hubei Province of China. It is about 45 km upstream of Yichang hydrological station, a boundary between the upper and middle streams of the Yangtze River (Figure 1). The dam construction lasted 17 years from the preparatory work in 1993 to its completion in 2009 (<http://www.ctgpc.com.cn/en/>). The water was filled to 135 m above mean sea level in June 2003. The water level of the reservoir fluctuated from 135 m to 139 m and had a relative small alteration of downstream flow regimes. In 2006, the main concrete dam of 185 m high was completed and the reservoir level was then elevated to 156 m for initial pilot operation. From

2008, the pilot impoundment of 170 m was launched. The targeted level of 175 m was reached for the first time on 26 October, 2010. This marked the start of the TGD's operation at full capacity. The impoundment milestones of the TGD are listed in Table 1.

As shown by the measured reservoir water levels, water inflows into and outflows from the TGD during the years 2006–2011 (Figure 2), the TGD regulated the seasonal water to achieve its comprehensive function in flood control, power generation, navigation improvement, etc. Although the TGD's operation depends on real flow regimes in the upstream and downstream, it can be divided into four periods: (1) water impoundment period from mid- or late September to October when river discharge was significantly reduced to impound water to 175 m; (2) normal operation period from November to April when the TGD operates at high level with a discharge of over 5,000 m³/s, larger than natural low flow; (3) water releasing period from late May to early June when the TGD releases water

to the flood restricted level of 145 m for reserving enough capacity to store summer flood; (4) flood-regulating period from June to September when the TGD operates at flood control level to prevent potential flood disasters caused by huge flood waters from the Upper Yangtze River basin.

Such operation of the TGD has obviously altered the temporal allocation of river discharge, although the TGD operation maintains the annual balance of inflow and outflow. The river discharge has a significant reduction in the impoundment period but an obvious increase in the water releasing period. The most significant reduction of river discharge occurs in October, when the TGD starts to store water. The mean discharge reduction reached 3,602 m³/s during the years 2006–2011, only 34.9% of normal discharge in October. The most significant increase was observed in the water releasing period when the TGD dropped the water level to the flood restricted level of 145 m. The discharge in May had an increase of 1,093 m³/s, or 11.4% of normal discharge in that month.

Table 1 | Start date of impoundment, duration days, and the initial and finally reached water levels of the Three Gorges Dam (TGD) reservoir

Start date of impoundment	Duration days of impoundment	Initial reservoir water level before impoundment (m)	Finally reached reservoir water level (m)
25 May, 2003	15	80.3	135.0
20 September, 2006	37	135.5	156.0
28 September, 2008	27	145.0	172.8
15 September, 2009	70	145.9	171.4
10 September, 2010	46	160.2	175.0
10 September, 2011	50	152.0	175.0

DATA AND METHODS

Hydrological data

Daily water level and/or discharge (2006–2011) at over 40 main gauging stations for providing initial and boundary conditions, modeling validation and impact analysis were collected from the Changjiang Water Resources Commission (<http://www.cjh.com.cn>) and other local hydrological agencies. Part of the water level data in 2011 is not available

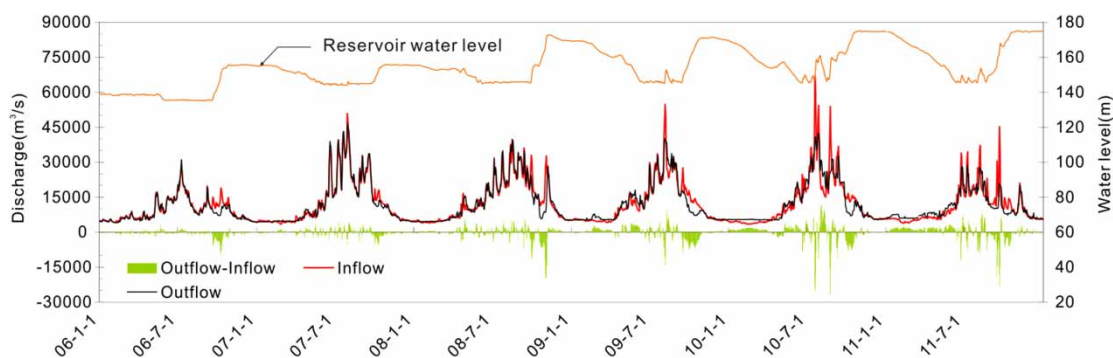


Figure 2 | The hydrographs of inflow and outflow discharge of the TGD, flow alteration (outflow-inflow) and the corresponding reservoir water level fluctuation.

for modeling results validation, e.g., Xingzi in Poyang Lake. The reservoir water level of the TGD, inflow discharge into the TGD, and its outflow discharge data (2006–2011) were acquired from the online platform of the China Three Gorges Corporation (<http://www.ctg.com.cn/inc/sqsk.php>).

Hydrodynamic model for the Middle Yangtze River

Various types of models based on physical mechanism or data are popularly used in the hydrological community. Although there are successful applications of data-based models to forecast streamflow (e.g., [Chau & Wu 2010](#); [Taormina & Chau 2015](#); [Li *et al.* 2016](#)), hydrodynamic models have special advantages in reproducing physically reasonable dynamic processes of water movement. They can simulate hydrodynamics within a given water system with a high spatial resolution, seen in tens of meters. They are the preferred application for demonstrating the details of the TGD's impact over this complex river–lake system. Here, we selected a developed large-scale hydrodynamic model termed 'CHAM' to simulate the flow regimes in the Middle Yangtze with its complex river–lake interaction ([Lai *et al.* 2013b](#)). This model couples the one-dimensional (1D) hydrodynamic model for rivers and the two-dimensional (2D) hydrodynamic model for large lakes. The 1D model was constructed on the 1D Saint-Venant equations and solved by Preissmann scheme ([Cunge *et al.* 1980](#)) using a finite difference method. The 2D model was developed on the 2D shallow water equations and solved by approximate Riemann solver ([Toro 2009](#)) using an unstructured finite volume method. The 1D and 2D model components are dynamically coupled using a four-step procedure ([Lai *et al.* 2013b](#)) by appropriately defining overlapping zones in the computational domains.

Its implementation for the hydrodynamic modeling in the Middle Yangtze River (CHAM-Yangtze) considered the main rivers and the lakes in the middle-lower Yangtze River reach from Yichang to Datong (see the generalized water system in Figure S1, available with the online version of this paper). Particularly, the river–lake interactions are elaborately considered in this model, which allows us to make a robust hydrological analysis in this complex river–lake system. The previous study ([Lai *et al.* 2013b](#)) showed that the CHAM-Yangtze satisfactorily simulated the major hydrodynamic

processes with significant seasonal changes and strong river–lake interactions in this water system. Main parameters of the model, such as terrain data, roughness coefficients, etc., can be referred to in the literature ([Lai *et al.* 2013b](#)).

Computation of flow regime change caused by the TGD's operation

The TGD-induced impact analysis was conducted based on its real operation during the years 2006–2011. Imposing measured discharge (2006–2011) data at all inflow and lateral boundaries, we ran the CHAM-Yangtze under the given rating curve at the outflow boundary at Datong and initial water level and discharge in the Middle Yangtze. The flow processes during 2006–2011 are achieved with a high time resolution (300 s in this computation). The daily water level and discharge are then averaged from these computed time-series data. The hydrograph of daily water level and discharge at selected controlling stations are compared with the measured values (Figures S2–S7, available with the online version of this paper). The well-consistent hydrographs showed that the model satisfactorily reproduced the hydrographs of discharge and water level during the years 2006–2011 in this complex river and lake system.

After model validation, the flow regime changes solely induced by the TGD's operation during 2006–2011 were quantified by subtracting the reproduced flow regime at that time in the Middle Yangtze from the restored one without the influence of the TGD. The restored flow regime was computed by running the same model with the previous model parameters, except the discharge boundary condition at Yichang, whose discharge was altered by the TGD's operation. The discharge (2006–2011) at Yichang without the TGD's operation was restored from the observed inflow discharge to the TGD.

RESULTS AND DISCUSSION

Seasonal river discharge changes

The temporal allocation of river discharge along the mainstream of the Yangtze River from Yichang to Datong has been changed. Corresponding to the TGD's regulation, river discharges decrease significantly in September–November

but increase in other months, especially in February–June (Figure 3). The relative change of river discharge induced by the TGD gradually diminishes along the direction to downstream, such as observed by Guo et al. (2012) and Gao et al. (2013). The relative reductions of river discharge vary from 35% at Yichang to 15% at Datong along the mainstream in October. This diminishing effect along the mainstream was clearly identified. Apart from the dilution of the lateral inflows from various tributaries (Guo et al. 2012), the diffusing or storage effect of the river channels and numerous lakes in this water system played an important role in attenuating the TGD's downstream impact from our modeling results (Figure 3). Highly irregular changes immediately downstream of the TGD were obviously smoothed out by the storage effects (e.g., Yichang versus Luoshan or Datong). This led to a low peak but prolonged impact on river discharge in the region far away from the TGD.

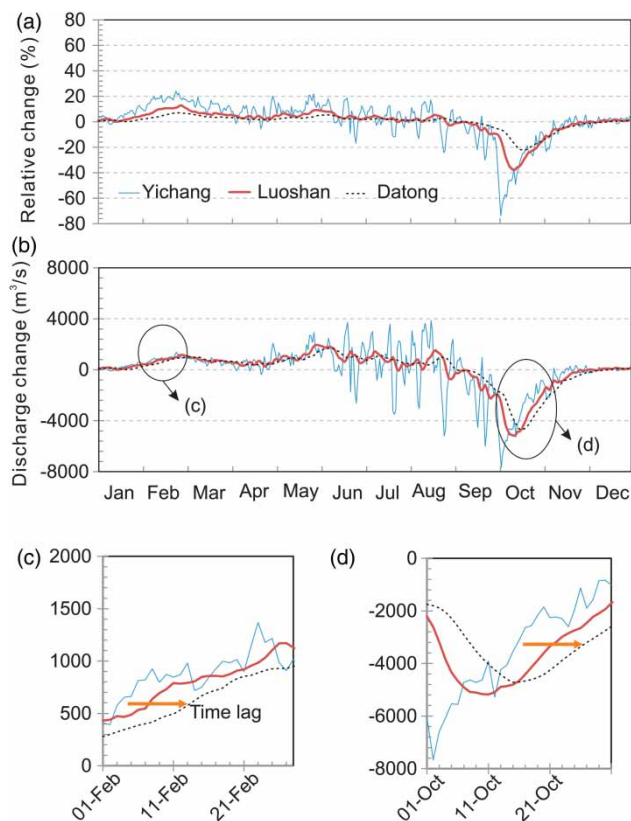


Figure 3 | Daily flow alteration in the main stream of the Middle Yangtze induced by the TGD during the years of 2006–2011: (a) relative discharge change at the Yichang, Luoshan, and Datong stations; (b) the absolute discharge change at three stations; (c) zoomed discharge changes show the time-lag of the TGD's impact on the downstream river.

The phase differences in days shown in the hydrographs of discharge changes induced by the TGD (Figure 3) also identify the propagation speed of its impact. On average, the TGD affected flow regimes with a mean lag-time of 3–4 days at Luoshan and of 8–10 days at Datong. The storage effects of flow also caused a longer influencing time of the TGD's regulation on downstream rivers.

Seasonal water level changes

Natural water level fluctuation in the Middle Yangtze has been altered considerably by the TGD's regulation in some specific time periods in most water areas, especially near the mainstream. The changes of water levels in different water areas have different responses and they are significantly different in each year. However, generally, the alteration in water level fluctuation represents a seasonal pattern being inconsistent with the seasonal flow regulation of the TGD. Results show that the TGD's operation increased water levels in most water areas of the downstream rivers and lakes (except for the positions with little influence) from December to August, and decreased them in the impoundment period from September to November (Figure 4). In the summer season from June to August, TGD plays a role in regulating flood. The average water level may slightly increase because of homogenization of flows, but flood peak can be significantly cut. About a 0.5 m decrease of peak flood level at Hankou in 2010 also clearly showed that the TGD could play a crucial role in alleviating large flood hazards in the Middle Yangtze River if appropriately operated.

Considerable increases of the averaged water level (above 0.18 m monthly increase at Datong) were observed from February to June, compared with slight increases in December, January, July, and August. TGD operation has caused two peaks of water level increase in early March and early June (Figure 4). The causes for those increases are different. The operation of the TGD resulted in the steady discharge of about 5,500 m³/s in early March after its normal operation in 2009, that is larger than the natural flow discharge (about 4,200 m³/s at Yichang averaged during 1956–2002 in January–March, the driest months in the Middle Yangtze). According to its operation guide, the

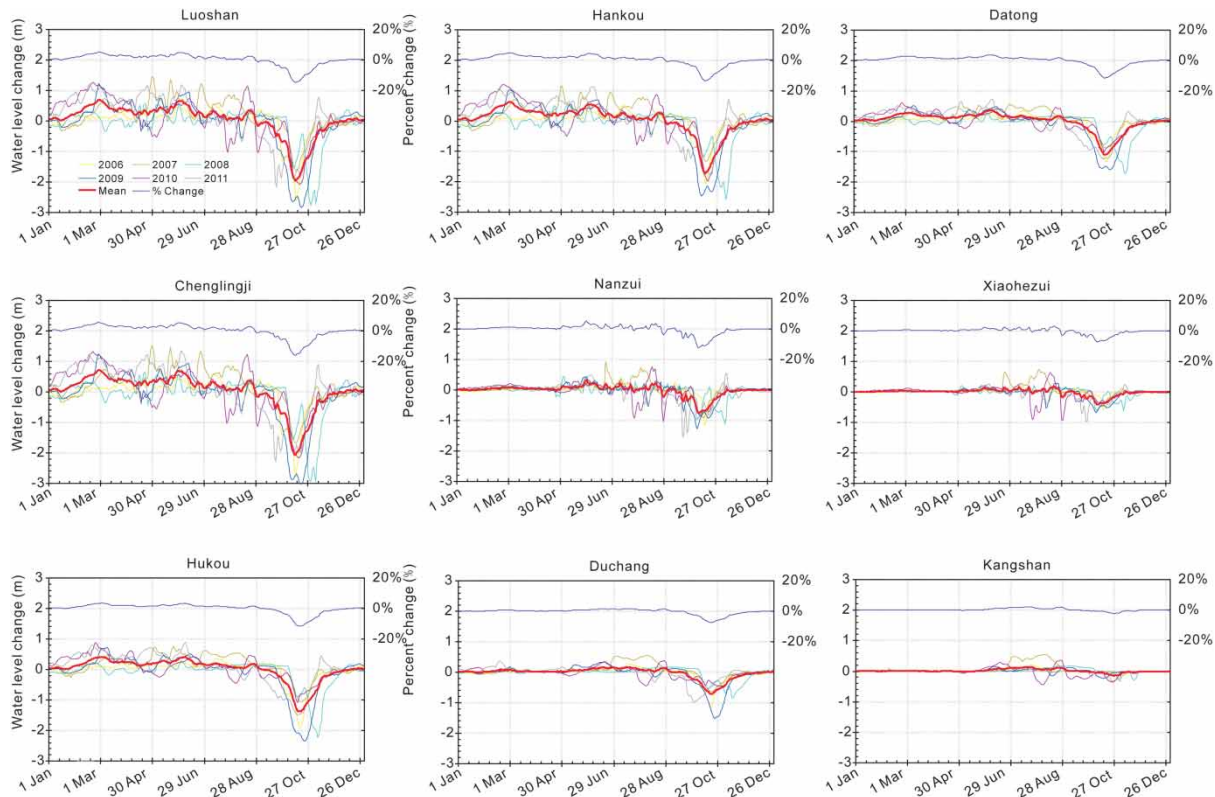


Figure 4 | The absolute and relative (%) change of water level induced by the TGD. The % changes in each individual year from 2006 to 2011 and their averaged changes during this period are both shown.

TGD should release more water than the natural inflow to decrease the reservoir water level to the flood restricted level of 145 m from the normal water level of 175 m before June 10 of a year. The increased discharge caused a significant rise of the water level in late May and early June during recent years.

The most significant drops of water level were found in the impoundment period from September to November. The water levels decreased substantially during this period compared to the natural regime without the TGD's operation. In October when the TGD started to store water, the monthly water level of the main stream decreased by $1.44 (\pm 0.71)$ m at Luoshan, $1.23 (\pm 0.63)$ m at Hankou, and $0.81 (\pm 0.4)$ m at Datong averaged during the years 2006–2011. The water levels at the outlets of Dongting and Poyang lakes decreased by $1.51 (\pm 0.77)$ m (Chenglingji) and $1.03 (\pm 0.57)$ m (Hukou), respectively. The decreased water levels resulted in an earlier start of the dry season in the Middle Yangtze.

Spatial distribution of water level alterations

The water level alteration along the Middle Yangtze caused by the TGD can help us to identify the main water areas that are significantly influenced by the TGD's operation. The identification of those areas has special implication for the management of Dongting and Poyang lakes regarding their ecological importance (Harris & Zhuang 2011). However, it has not been fully investigated as yet, except for Dongting Lake (see Lai et al. 2013a).

The TGD's impacts on downstream water levels in the Middle Yangtze have a regular spatial pattern (Figure 5), despite complex hydrological responses of downstream rivers and lakes to the TGD's flow regulation. Water level changes along the mainstream of the Yangtze River have the same spatial pattern as the river discharge alteration, the TGD-induced water level variations gradually decreased from upper to downstream due to the inflows from the tributaries, the widening of the river channel,

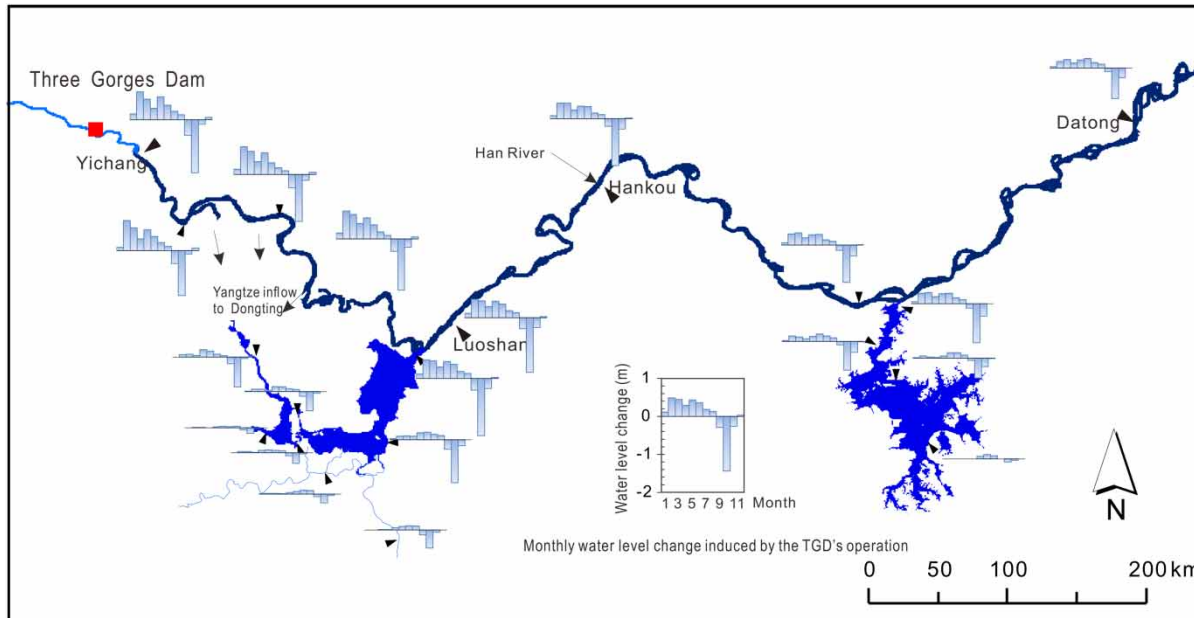


Figure 5 | Spatial distribution of monthly water level change induced by the TGD during the years 2006–2011.

and the lake storage. From Yichang to Datong, the changes of monthly water level varied from 1.40 (± 1.11) m to 0.81 (± 0.4) m in October, and 0.60 (± 0.62) m to 0.21 (± 0.19) m in May.

The TGD has more complex influences on the water levels of Dongting and Poyang lakes. Poyang Lake, the largest freshwater lake of China, connects to the Yangtze River via a single channel. The TGD-induced Yangtze River discharge changes have altered the interaction between Poyang Lake and the Yangtze River. The largest impacts of the TGD on Poyang Lake are observed at the lake mouth (Hukou), and the least impacts further to the south (Figures 4 and 5). The annual largest rise and fall in monthly water level averaged during 2006–2011 was 0.29 (± 0.22) m in March and 1.03 (± 0.57) m in October at Hukou, the lake mouth station; 0.14 (± 0.11) m in June and 0.52 (± 0.35) m in October at Duchang, the middle lake station; 0.07 (± 0.09) m in June and 0.08 (± 0.11) m in October at Kangshan, the southern lake station. The results clearly indicate that the TGD-induced water level variations weaken gradually along the reverse direction of flow from north to south. The TGD's impact on Poyang Lake level represents a spatial pattern with high impact in the north (close to the main channel) but low impact in the south.

Dongting Lake, immediately downstream the TGD, receives water from the Yangtze River via the Sankou Distributary Rivers, but drains water into the Yangtze River via a single outlet at Chenglingji (Figure 1). In the northern area of Dongting Lake, water level variations were gradually weakened from the diversion outlets of the Yangtze River to Dongting Lake due to the direct discharge modification. Mean reductions of water levels in October were 1.11 (± 0.88) m at Xinjiangkou, 0.79 (± 0.53) m at Shiguishan, and 0.51 (± 0.32) m at Nanzui. In the eastern area of Dongting Lake, water level variations were also diminished gradually from the lake mouth to the central lake and the low-lying land of the inflow rivers. Mean reductions of the water levels in October were 1.51 (± 0.77) m at Chenglingji, the lake mouth station; 1.33 (± 0.66) m at Lujiao, the eastern Dongting lake station; 1.13 (± 0.57) m at Yintian, the southern Dongting Lake station; 0.48 (± 0.29) m at Changsha, the Xiangjiang River station; 0.23 (± 0.18) m at Shatou, the Zishui River station. The south-western area of Dongting Lake showed little impact from the TGD. The mean water level reduction of 0.15 (± 0.11) m was observed in October at Zhouwenmiao station. Thus, the TGD's operation can directly change the water discharge into Dongting Lake, as well as reverse propagation of the TGD's impact

against flow direction from the lake mouth. This resulted in a complex spatial pattern of the TGD's impacts on Dongting Lake that can be generalized as strong impact in the north and east, and weak impact in the south and west.

Accelerated river recession and prolonged dry season

The significant water level reduction by the TGD's impoundment in the late flood season from September to October also accelerated the recession of the mainstream river and resulted in an earlier dry season in the Middle Yangtze. The lowering rate of daily water level increased significantly in the first half period of water storing from mid-September to mid-October (Figure 6). Specifically, the lowering rates in

the main stream increased from 0.065 m/d to 0.123 m/d at Luoshan, from 0.067 m/d to 0.115 m/d at Hankou, and from 0.047 m/d to 0.080 m/d at Datong. Both Dongting and Poyang lakes had a fast lowering rate. They increased from 0.058 to 0.114 m/d at Chenglingji in Dongting Lake and from 0.063 m to 0.105 m at Hukou in Poyang Lake (Table 2). In general, the lowering rates have almost doubled the natural rates due to the TGD's impoundment.

The acceleration of the Yangtze River recession means that the Middle Yangtze went into the low water season earlier than the natural regime, causing a prolonged dry season in the Middle Yangtze. Using the mean water levels in November as an example, the dry season started nearly half a month earlier in the lower reach of the Middle

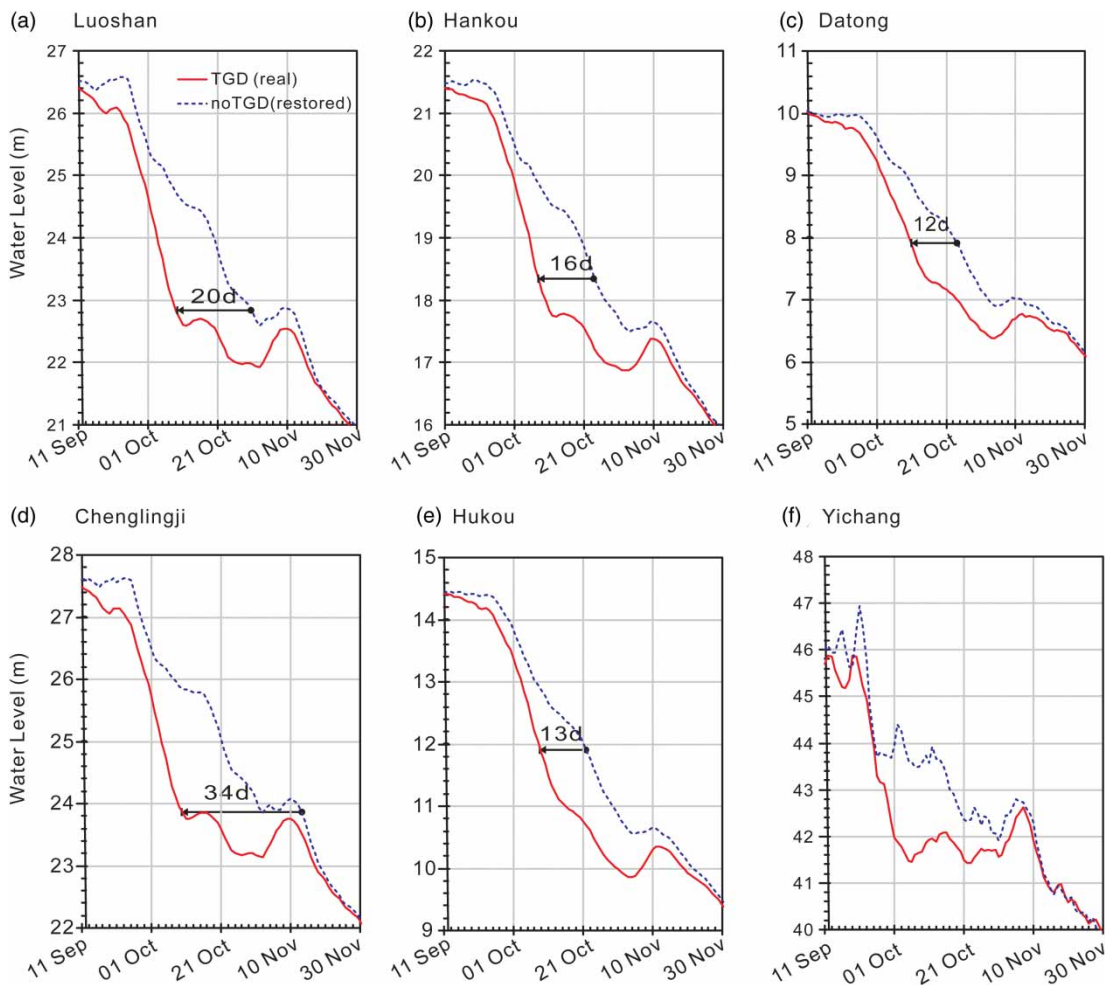


Figure 6 | The earlier lowering of water level in late flood season due to the TGD's impoundment. The measured (with the TGD) and restored (without the TGD) water levels clearly show the rapid and earlier drawdown of the Middle Yangtze River.

Table 2 | Changes in the Yangtze River recession caused by the Three Gorges Dam

Stations	Lowering rate of water level (m/d)		Low flow	
	Measured rate with the TGD	Restored rate without the TGD	Characteristic low water level (CLWL) (m)	Preceding days of its first appearing date of CLWL
Luoshan	0.123	0.065	22.83	20
Hankou	0.115	0.067	18.26	16
Datong	0.080	0.047	7.93	12
Chenglingji	0.114	0.058	23.87	34
Hukou	0.105	0.063	11.94	13

Yangtze. The low water levels appeared 16 d earlier at Hankou, 12 d at Datong, 34 d at Chenglingji, and 13 d at Hukou (Table 2). This earlier start of the dry season may cause various ecological consequences in this region sensitive to flow regimes because October is the month of importance for wetland vegetation and late rice growth.

CONCLUDING REMARKS

The TGD's impact on the complex flow regimes in the Middle Yangtze was estimated by employing a large-scale hydrodynamic model that considered river-lake interaction. We successfully identified the whole pattern of such influences in time and space over this large-scale river-lake system, which cannot be observed or derived from measured hydrographs. The seasonality of the TGD's flow regulation determined the seasonal pattern of the flow regime modification. The operation of the TGD increased the river discharge and the lake water levels from December to August, but decreased them from September to November. The most significant flow regime changes induced by the TGD were observed in October, the main time period of the impoundment. An accelerated river recession rate and a marked decline in magnitude in October produced an earlier and prolonged dry season in the Middle Yangtze. High heterogeneous but regular spatial distribution of the river discharge alterations and of the lake water level fluctuations were mainly attributed to the complex river system and river-lake

interaction. The main areas influenced by the TGD included the main stream of the Yangtze River, Sankou Distributary Rivers that convey water into the Dongting Lake, the east and north of Dongting Lake, and the north of Poyang Lake. In the south-west of Dongting Lake and the south of Poyang Lake, the TGD has very limited effects due to its weak hydraulic connectivity with the Yangtze River. Our study on the TGD's influencing magnitude and pattern clearly indicated the role of the TGD in the recent seasonal droughts, namely, alleviating the droughts in the spring but aggravating them in the autumn.

The operation of the TGD has altered the natural regime of river discharge in the Upper Yangtze River. The altered flow regime has affected the Middle Yangtze, resulting in a series of environmental changes, especially the wetlands highly controlled by water level fluctuation. This study provided essential flow regime data for the TGD-induced environmental impact assessment. Our results may facilitate administration to optimize the operation of the TGD (cf. Yang & Lu 2013) and adjust adaptive management strategy for downstream lakes with significant alterations in their flow regimes. For example, based on the identified main influenced areas and action time, some environmentally oriented operation guides can be suggested for a compromise in the TGD's operation rule.

Dams can produce adjustments in alluvial channels due to sediment trapping and flow regime change. The channel adjustments like channel downcut in return can affect water levels (Lu et al. 2011). The flow-sediment interactions for the TGD's impact are not considered in the present modeling. Considering the facts of large amounts of sediment trapped by the TGD's reservoir and currently observed channel incision, the water recharge effect of the TGD for alleviating droughts in the dry season might be balanced out. Thus, fluvial processes in the Middle Yangtze should also be paid great attention for improving the understanding of long-term impacts of the TGD's operation on downstream rivers and lakes.

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REFERENCES

- Cao, L. & Fox, A. D. 2009 Birds and people both depend on China's wetlands. *Nature* **460**, 173–173.
- Chau, K. W. & Wu, C. L. 2010 A hybrid model coupled with singular spectrum analysis for daily rainfall prediction. *J. Hydroinform.* **12** (4), 458–473.
- Chen, X., Zong, Y., Zhang, E., Xu, J. & Li, S. 2001 Human impacts on the Changjiang (Yangtze) River basin, China, with special reference to the impacts on the dry season water discharges into the sea. *Geomorphology* **41**, 111–123.
- Cunge, J. A., Holly, F. M. & Verwey, A. 1980 *Practical Aspects of Computational River Hydraulics*. Pitman Advanced Publishing Program, London, UK.
- Dai, Z., Du, J., Li, J., Li, W. & Chen, J. 2008 Runoff characteristics of the Changjiang River during 2006: effect of extreme drought and the impounding of the Three Gorges Dam. *Geophys. Res. Lett.* **35**, L07406.
- Dong, Y. 2013 Background information of Poyang Lake and Yangtze finless porpoises. In: *Contingent Valuation of Yangtze Finless Porpoises in Poyang Lake, China* (Y. Dong, ed.). Springer, Dordrecht, The Netherlands, pp. 5–36.
- Dou, H. & Jiang, J. 2000 *Dongting Lake*. Press of University of Science and Technology of China, Hefei, China.
- Fang, J., Wang, Z., Zhao, S., Li, Y., Tang, Z., Yu, D., Ni, L., Liu, H., Xie, P., Da, L., Li, Z. & Zheng, C. 2006 Biodiversity changes in the lakes of the Central Yangtze. *Front. Ecol. Environ.* **4**, 369–377.
- Fang, C.-M., Cao, W.-H., Mao, J.-X. & Li, H.-J. 2012a Relationship between Poyang Lake and Yangtze River and influence of Three Georges Reservoir. *J. Hydraul. Eng.* **43**, 175–181.
- Fang, H., Han, D., He, G. & Chen, M. 2012b Flood management selections for the Yangtze River midstream after the Three Gorges Project operation. *J. Hydrol.* **432–433**, 1–11.
- Feng, L., Hu, C., Chen, X. & Zhao, X. 2013 Dramatic inundation changes of China's two largest freshwater lakes linked to the Three Gorges Dam. *Environ. Sci. Technol.* **47**, 9628–9634.
- Gao, B., Yang, D. & Yang, H. 2013 Impact of the Three Gorges Dam on flow regime in the middle and lower Yangtze River. *Quat. Int.* **304**, 43–50.
- Gemmer, M., Jiang, T., Su, B. & Kundzewicz, Z. W. 2008 Seasonal precipitation changes in the wet season and their influence on flood/drought hazards in the Yangtze River Basin, China. *Quat. Int.* **186**, 12–21.
- Guo, H., Hu, Q., Zhang, Q. & Feng, S. 2012 Effects of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003–2008. *J. Hydrol.* **416–417**, 19–27.
- Harris, J. & Zhuang, H. 2011 *An Ecosystem Approach to Resolving Conflicts Among Ecological and Economic Priorities for Poyang Lake*. Wetlands International–IUCN SSC Crane Specialist Group, Wetlands.
- Ji, W., Zeng, N., Wang, Y., Gong, P., Xu, B. & Bao, S. 2007 Analysis on the waterbirds community survey of Poyang Lake in winter. *Geogr. Inform. Sci.* **13**, 51–64.
- Kanai, Y., Ueta, M., Germogenov, N., Nagendran, M., Mita, N. & Higuchi, H. 2002 Migration routes and important resting areas of Siberian cranes (*Grus leucogeranus*) between northeastern Siberia and China as revealed by satellite tracking. *Biol. Conserv.* **106**, 339–346.
- Lai, X., Jiang, J. & Huang, Q. 2013a Effects of the normal operation of the Three Gorges Reservoir on wetland inundation in Dongting Lake, China: a modelling study. *Hydrol. Sci. J.* **58**, 1467–1477.
- Lai, X., Jiang, J., Liang, Q. & Huang, Q. 2013b Large-scale hydrodynamic modeling of the middle Yangtze River Basin with complex river–lake interactions. *J. Hydrol.* **492**, 228–243.
- Lai, X., Jiang, J., Yang, G. & Lu, X. X. 2014a Should the Three Gorges Dam be blamed for the extremely low water levels in the middle–lower Yangtze River? *Hydrol. Process.* **28**, 150–160.
- Lai, X., Liang, Q., Jiang, J. & Huang, Q. 2014b Impoundment effects of the Three-Gorges-Dam on flow regimes in two China's largest freshwater lakes. *Water Resour. Manage.* **28**, 5111–5124.
- Lai, X., Shankman, D., Huber, C., Yesou, H., Huang, Q. & Jiang, J. 2014c Sand mining and increasing Poyang Lake's discharge ability: a reassessment of causes for lake decline in China. *J. Hydrol.* **519**, 1698–1706.
- Li, Y. L., Zhang, Q., Werner, A. D. & Yao, J. 2016 Investigating a complex lake-catchment-river system using artificial neural networks: Poyang Lake (China). *Hydrol. Res.* **47** (2).
- Liu, Y., Wu, G. & Zhao, X. 2013 Recent declines in China's largest freshwater lake: trend or regime shift. *Environ. Res. Lett.* **8**, 014010.
- Lu, X. X., Yang, X. & Li, S. 2011 Dam not sole cause of Chinese drought. *Nature* **475**, 174–174.
- Milliman, J. D. 1997 Blessed dams or damned dams? *Nature* **386**, 325–327.
- Min, Q. & Zhan, L. 2012 Characteristics of low-water changes in Lake Poyang during 1952–2011. *J. Lake Sci.* **24**, 675–678.
- Nakayama, T. & Shankman, D. 2013 Impact of the Three-Gorges Dam and water transfer project on Changjiang floods. *Global Planet. Change* **100**, 38–50.
- Qiu, J. 2011 China admits problems with Three Gorges Dam. *Nature News*. doi:10.1038/news.2011.315.
- Taormina, R. & Chau, K. W. 2015 ANN-based interval forecasting of streamflow discharges using the LUBE method and MOFIPS. *Eng. Appl. Artif. Intell.* **45**, 429–440.
- Toro, E. F. 2009 *Riemann Solvers and Numerical Methods for Fluid Dynamics: A Practical Introduction*. Springer, Berlin, Germany.

- Yang, X. & Lu, X. X. 2013 [Ten years of the Three Gorges Dam: a call for policy overhaul](#). *Environ. Res. Lett.* **8**, 041006.
- Yin, H., Chen, G., Li, C. & Wei, Y. 2004 [On the siltation of the middle Yangtze River](#). *Sci. China Ser. D* **47**, 463–480.
- Zhang, Q., Liu, Y., Yang, G. & Zhang, Z. 2011 [Precipitation and hydrological variations and related associations with large-scale circulation in the Poyang Lake basin, China](#). *Hydrol. Process.* **25**, 740–751.
- Zhang, Q., Li, L., Wang, Y.-G., Werner, A. D., Xin, P., Jiang, T. & Barry, D. A. 2012a [Has the Three-Gorges Dam made the Poyang Lake wetlands wetter and drier?](#) *Geophys. Res. Lett.* **39**, L20402.
- Zhang, Q., Zhou, Y., Singh, V. P. & Chen, X. 2012b [The influence of dam and lakes on the Yangtze River streamflow: long-range correlation and complexity analyses](#). *Hydrol. Process.* **26**, 436–444.
- Zhu, H. & Zhang, B. 1997 *Poyang Lake*. Press of University of Science and Technology of China, Hefei, China.

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