

# Impacts and Implications of Major Changes Caused by the Three Gorges Dam in the Middle Reaches of the Yangtze River, China

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**Abstract** The impoundment of the Three Gorges Dam (TGD) has disturbed the hydrological regime downstream and has directly affected the relationship between the Yangtze River and Dongting Lake. To trace the realistic and potential impacts, this paper examined the changes of the channel morphology and sedimentology caused by the TGD through a field survey on the channel cross-sections and then analyzed the impact on lake water level through BP neural networks. The possible impacts on inundation patterns in lake wetlands were studied based on the lake basin DEM. The results indicate that drastic sediment decline and severe channel erosion are putting considerable pressure on the river and lake. Changing river channels are evident in some monitoring cross-sections. Dongting Lake, for the first time, changed from trapping to supplying net sediment to the Yangtze River. During the water storage periods of the TGD, the water level decreased 2.03 m in 2006 and 2.11 m in 2009 at the outlet of the lake, with extreme decreases up to 3.30 m and 3.02 m, respectively. These changes have inevitably induced alterations in the inundation patterns of the lake wetlands, which in turn have disturbed the ecological function of lake wetlands as habitats for both migratory birds and aquatic fish. The serious droughts in Dongting Lake recent years were largely connected with the above changes. Therefore, proper attention should be paid to this occurrence.

**Keywords** Yangtze river · Three Gorges Dam (TGD) · Dongting lake · Lake-river relationship · Lake wetlands · Inundation patterns

## 1 Introduction

Global river systems have been increasingly altered by dam construction for water and energy needs (Dynesius and Nilsson 1994; Nilsson et al. 2005). Dams deliver many benefits,

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but often at a high price with adverse and lasting impacts on communities inhabiting (Thomas and Adams 1999). The response of river channels to human intervention has been long recognized and well documented (Fuller et al. 2003; George 1864; Gregory 2006; Lane and Richards 1997; Marsh 1965; Thomas 1955). These anthropogenic disturbances can sometimes induce environmental change more profoundly than those induced by natural events such as floods and droughts caused by hydro-meteorological fluctuations (Dudley and Platania 2007). Some less obvious indirect effects occurring downstream and throughout the basin, however, are much more recently appreciated. The World Commission on Dams has emphasized the wide range of problems associated with dams (Altinbilek 2002). When a dam is constructed right upper the floodplain, the impact easily extends to the connected shallow lakes and floodplain (Kingsford 2000; Yin et al. 2007). Thus, a better understanding of the impacts of dams on large lake-river systems is receiving increasing attention from the fields of engineering design and environmental management.

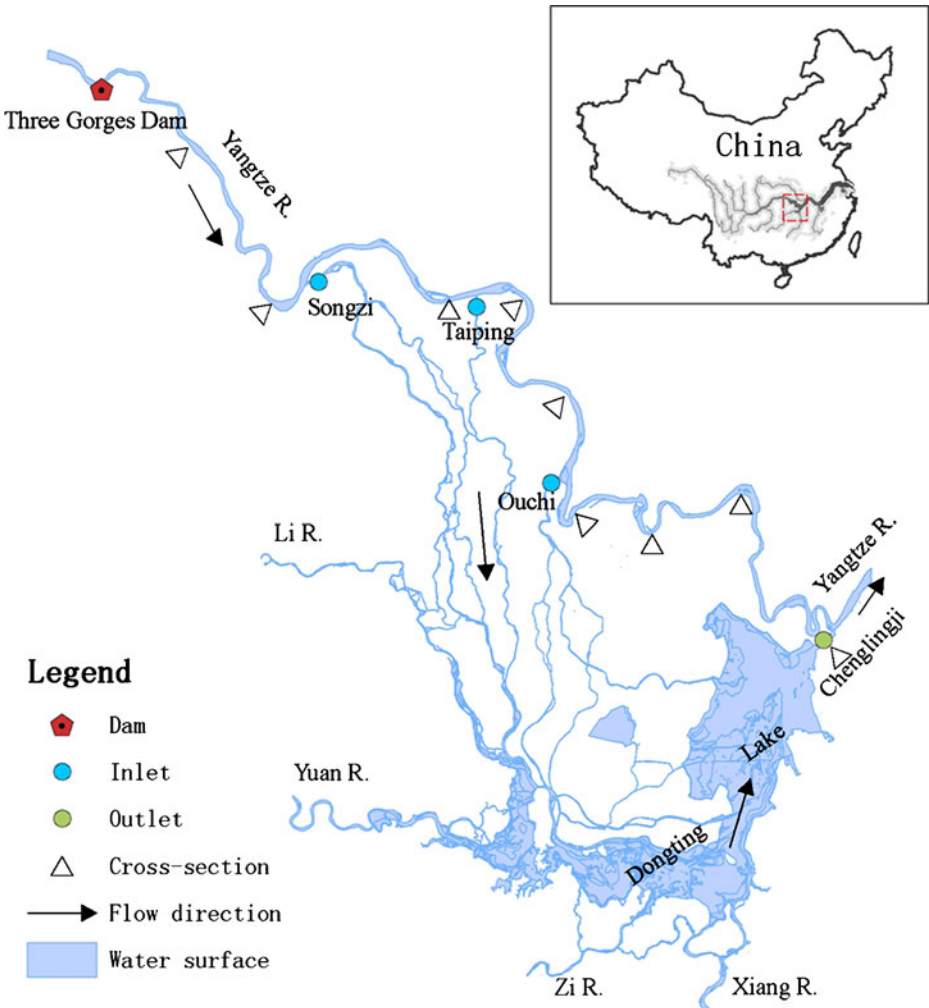
China has been particularly active in dam construction, building more than half of the world's large dams since 1950 (Fuggle and Smith 2000; Lu 2004). In the Yangtze River basin, more than 45,700 dams with 220.0 billion m<sup>3</sup> of total capacity have been constructed (Yang et al. 2009). As one of the world's largest dams, the Three Gorges Dam (TGD) began to impound water and sediment discharge in 2003. With its large water storage capacity, the operation of the TGD may reduce the frequency of major flooding downstream from once every ten years to once every 100 years. However, the TGD project has also resulted in great concern from the scientific community regarding economic, environmental, and human health issues due to its large uncertainties (Dai et al. 2008; Edmonds 1992; Shen and Xie 2004; Xu et al. 2006). Dongting Lake, as the first largest lake regulating runoff and sediment from the Yangtze, will invariably bear the brunt from TGD's operation. Thus, it would be wise to investigate realistic and potential environmental alterations TGD-induced to avoid irreparable ecological damage.

The objectives of this study are: 1) to identify changes in channel morphology and sedimentology using field survey and station gauging data, 2) to quantify the proportion of water level changes in Dongting Lake caused by the operation of the TGD, and 3) to examine and estimate the alterations of inundation patterns for lake wetlands caused by the water storage in the TGD.

## 2 Study Area

Yangtze is the longest river in China, and floods are the big danger in its middle and lower reaches. Frequent flooding has claimed more than one million lives in the past 100 years. The most recent major flood in 1998 causes 14 million homeless and \$24 billion in economic losses (Yin et al. 2007). Therefore, stopping floods may be changed as flood control or flood protection. The core study area is located in the most strikingly meandering and complex stream network section of the middle Yangtze River (Fig. 1). The TGD stretches approximately two kilometers across the river and towering 185 m in height. The TGD's water storage capacity is 39.3 billion m<sup>3</sup>, about 4.5 % of the Yangtze's annual discharge.

Dongting Lake was once the largest fresh water lake connected with the Yangtze River downstream the TGD after the river runs into the floodplain, reaching its maximum surface area of ~6300 km<sup>2</sup> in 1825. However, the present lake surface area is approximately 40 % (~2500 km<sup>2</sup>) of its maximum size (Zhao et al. 2005). It is one of the only two remaining retention lakes (the other is Poyang Lake) for floods within the Yangtze River Basin. The



**Fig. 1** Study area and stream networks between the Yangtze River and Dongting Lake

capacity of Dongting Lake has been reduced greatly in volume due to reclamation and sediment load over the past decades (Li et al. 2007; Yin et al. 2007; Zhao et al. 2005). Currently, a Lake Recovery Project is underway that is aiming to extend the Dongting Lake surface area from the current 2 625 km<sup>2</sup> to 4 350 km<sup>2</sup> (Li et al. 2001). Because the lake consists of a number of highly valuable wetlands, the lake was designated as one of the first seven most important international wetland conservation areas in China and protected by the Convention on the Wetlands of International Importance, especially as Waterfowl Habitat and the endangered Yangtze River dolphin (*Lipotes vexillifer*) (Olson and Dinerstein 1998; Zhao et al. 2005).

The Yangtze mainstem delivers water and sediment into Dongting Lake through three inlets (i.e., Songzi, Taiping, and Ouchi), and it intersects the lake outlet again at Chenglingji. In addition to the other four small independent inlets (i.e., Xiang R., Zi R., Yuan R., and Li

R.) these streams form the complex lake-river network system. When large floods occur in the middle Yangtze River, the slow water flow at the junction of Dongting Lake always leads to a longer flood retention time and a higher flood level due to mutual flow congestion. The fluctuation of the water level is up to approximately 18 m at the outlet.

### 3 Data and Methodology

Hydrographic and current meter data collected in the middle Yangtze River catchment were used to investigate changes in scouring, silting and channel morphology. Based on the topographic map of the Yangtze River channel (at a scale of 1:10 000) in 1996, we surveyed number of sections downstream the dam using an ultrasonic depth sensor and GPS positioning systems in 2008. The sediment data are mainly based on the Bulletin of Yangtze River Sediment between 2001 and 2007.

The water storage of the Three Gorges Reservoir has directly affected the water level in Dongting Lake by decreasing the discharge in the outlet. However, the exact quantity of this impact is difficult to measure, as the water level is also affected by the other four small inlets synchronously. To separate the proportion of the TGD's impact from others, BP neural networks were introduced. In the training phase, the average daily outflow discharge of the TGD and the synthetic discharge of the other four inlets were chosen as inputs, and the water level of Chenglingji Station as the output. In the implementation phase, the outflow discharge of the TGD was replaced with the inflow of the TGD to simulate the water level process without the regulation of the TGD.

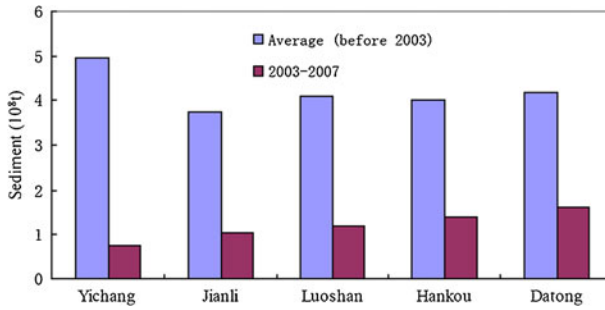
The changes of the inundation patterns in the lake wetlands were analyzed using a coupled spatial model and the lake basin DEM, which was surveyed in 1998 at scale of 1:10 000. These data and tools made it possible to examine scopes that may suffer alterations in the habitat of aquatic and terrestrial ecosystems from the operation of the TGD.

## 4 Results and Discussion

### 4.1 Changes in Sediment Balance

River damming can damage downstream environments by retaining sediments. Sediment problems are always heavily emphasized in discussions of the Three Gorges Project. When the TGD started operating in 2003, the Yangtze downstream entered a stage of sediment reduction. During the first 2 years of impoundment (2003–2004), sediment discharge at Yichang (first station downstream the dam) decreased by 164 million tons (Xu et al. 2006). Figure 2 presents the changes of sediment transport compared with that before the operation of the TGD at five major monitoring stations downstream the TGD from 2003 to 2007. In 5 recent years (2003–2007), the Yangtze River had a discharge similar to 20–40 % of the historical average sediment per year, whereas the water discharge remained relatively stable during the same period.

According to the design of the Three Gorges Project, the Three Gorges Reservoir will provide a buffering period approximately 50–80 years for sediment, during which much of the silt will be trapped in the reservoir and scouring downstream may remarkably increase. This declining trend in sediment transport was further exacerbated by the extreme drought in 2006, when the flood season water level was the lowest in the last 50 years (Dai et al. 2008); the water discharge decreased by ~30 %, and the sediment drastically decreased to 9 Mt



**Fig. 2** Changes in sediment transport at major monitoring stations from 2003 to 2007

(only 2 % of its 1950–1960s level). According to numerical modelling, the sediment load may reach a new balance in 2060–2110 (Yang et al. 2006). However, this situation is also subject to many uncertainties considering the impacts from many other reservoirs in the upper reaches of the Yangtze River (Zhang et al. 2011).

The changes of sediment transport in turn have impacts on the lake environment evolution. Before the Three Gorges Project, the mud and sand were deposited largely in Jingjiang River and Dongting Lake. Table 1 shows the sediment discharge of Dongting Lake from 2003 to 2007. In 2006, Dongting Lake changed for the first time from trapping net sediment from the mainstem to supplying net sediment to the mainstem due to extreme sediment reduction from the three inlets (i.e., Songzi, Taiping, and Ouchi; Songzi and Ouchi divide into two branches when running southward). The short-term ecological impacts of damming on Dongting Lake include a decreased sediment load that may cause suffocation and abrasion to various biota and habitats. Moreover, several studies have suggested that the decreased sediment load caused by the TGD should be a long-term effect.

#### 4.2 Changes in Channel Cross-Sections

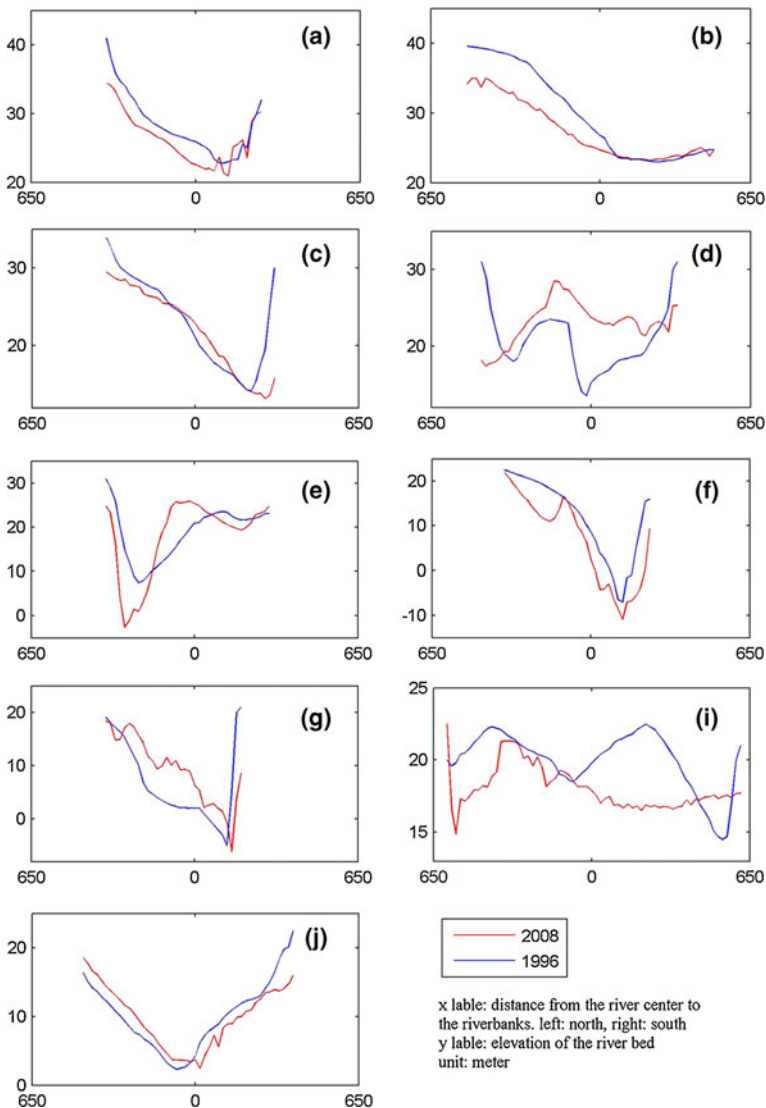
The impact of hydraulic engineering works on hydrology and channel morphology has been a hot issue in conjunction with dam development. Changing river channels are most evident in the channel cross-sections, including changes in size, shape and composition (Gregory 2006). In addition to hydraulic conditions, erosion is also affected by geological features, so several cross-sections at different locations downstream the TGD were adopted for analysis. In order to facilitate the comparison of changes between cross-sections, the cross-section

**Table 1** Sediment discharge of Dongting Lake from 2003 to 2007

	Xiang R	Zi R	Yuan R	Li R	Songzi		Taiping	Ouchi		Chenglingji
					west	east		west	east	
2002	1150	140	269	298	1400	350	600	40	1350	2300
2003	386	15.1	265	1110	775	246	290	40.1	699	1750
2004	256	80.4	384	193	578	167	196	22.4	480	1430
2005	481	87	49	23.4	993	312	361	38	697	1590
2006	975	25.2	10.3	16.9	88.9	15.3	24.6	0.825	32.4	1520
2007	559	10.3	70	176	527	151	173	19.9	459	1120

survey was located nearby some hydrological stations (i.e., Yichang, Zhicheng, Chenjiawan, Shashi, Haoxue, Shishou, Tiaoxiankou, Jianli, Chenglingji; See Fig. 1). Nine cross-sections were examined, which were surveyed in 1996 and 2008, respectively (Fig. 3).

Figure 3 indicates that the river channel had experienced an intense change during the period of 1996 to 2008. In general, the change is a result of erosion, and some remarkable changes can be observed in most of the cross-sections, with the exception of cross-section (d). Among nine cross-sections, six show southward erosion, and only in cross-section (e) has the river eroded the north bank. In some sections, the erosion depth even exceeds 10 m. Severe channel erosion and drastic sediment decline have put considerable pressure on the riverbank, which calls for proper attention to the security of the southern riverbank. The



**Fig. 3** Cross-section changes at nine sites

erosion may gradually threaten the foundation of levees standing along the middle Yangtze River, which are of crucial importance for flood security (Yin et al. 2007).

#### 4.3 Water Level Impact from Flow Regulation by Seasonal Water Storage

Flow regulation can affect estuarine and coastal ecology and reduce the stability of wetlands (Kingsford 2000; Sala et al. 2000). Hydrological regimes of regulated systems often deviate from natural systems by being a dichotomy in moisture conditions (Merritt and Cooper 2000). A study on the potential impacts of large dams on riparian vegetation indicated that vegetation responses will be diverse and change over time but will ultimately result in a markedly different landscape and riparian zone within the Three Gorges Reservoir (New and Xie 2008). This effect is true even for the lake wetland regions, but it has not been well studied and evaluated so far in the study region. The Dongting Lake wetland harbors approximately 1300 species of plants and a wide variety of threatened fish, birds, and mammals. The natural interaction of aquatic and terrestrial ecosystem of the lake wetlands serves as an important habitat for migratory birds and fish. The operation of the TGD altered the downstream discharge by storing water in early autumn and releasing water during winter and spring. The Three Gorges Reservoir has experienced five major impounding periods since the operation in 2003. The simulation results indicate that the water level of the lake outlet during the water storage periods has been significantly impacted (Huang et al. 2011). The water level decreased by 2.03 m in 2006 and 2.11 m in 2009 during the water storage periods, with extreme decreases up to 3.30 m and 3.02 m, respectively (Table 2).

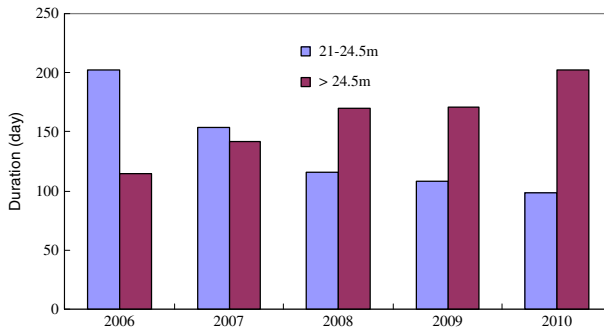
Some of the impacts from the TGD were immediate and obvious, but some disasters may appear gradually, and little attention has been given to the relatively indirect and less obvious changes. Studies suggest that plant species distributions in the humid areas are largely controlled by frequency, duration, and intensity of floods (Merritt and Cooper 2000). The above change associated with seasonal water storage is changing the inundation patterns of the lake wetlands.

#### 4.4 Droughts and Impacts on the Lake Wetlands

During the past years droughts have become an issue of great interest in the Dongting Lake wetlands. These droughts have shown some new characteristics: 1) the low water level period comes earlier. This effect was especially pronounced in 2006 and 2009. The water level of the outlet (Chenglingji Station) decreased to 25 m in the middle of August 2006, which is approximately one and a half months earlier than normal, and it is about 1 month earlier in 2009; 2) the low water level lasts for a longer time, especially for certain wetland regions. Figure 4 shows that although the high water level inundation period did not decrease (>24.5 m), the inundation period between 21 and 24.5 m decreased significantly

**Table 2** The water level changes caused by water storage of the TGD

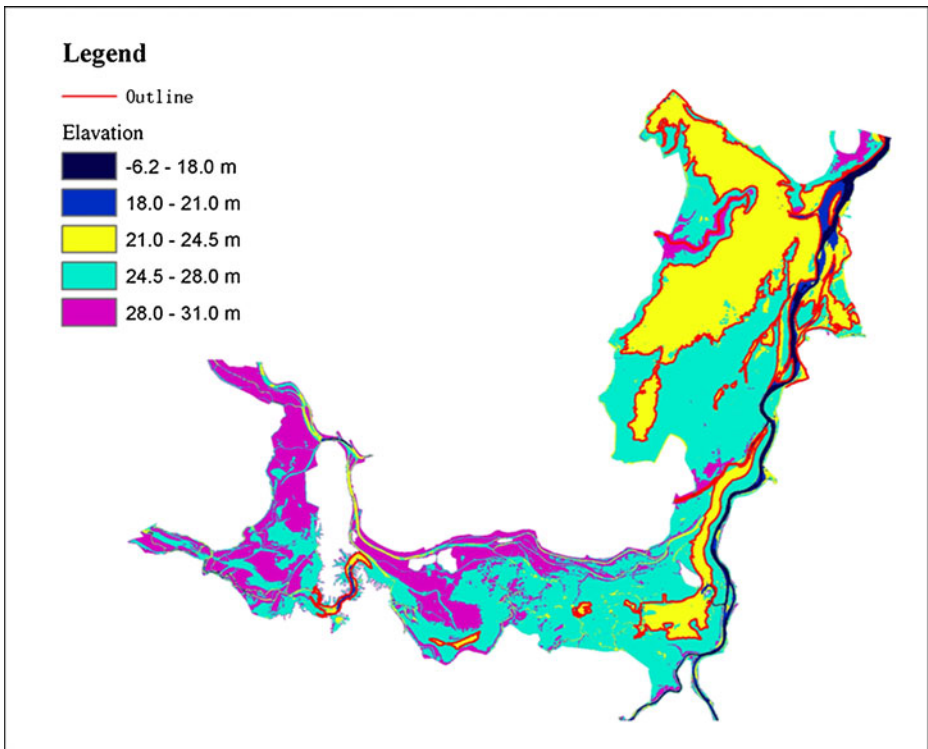
Impounding period	Average decrease(m)	Maximal decrease(m)
2003.6.1–2003.6.10	0.59	1.87
2006.9.20–2006.10.27	2.03	3.30
2007.9.25–2007.10.23	0.63	1.41
2008.9.28–2008.11.4	0.71	1.39
2009.9.15–2009.10.31	2.11	3.12



**Fig. 4** Inundation period changes according to the water level in the lake outlet

from 2006 to 2010. Therefore, the serious droughts in Dongting Lake occur not only because of the extreme low water levels but also because of their duration. In the first half year of 2011, the low water level lasted 2 months longer than previously. These droughts often arouse much controversy about the impacts from the operation of the TGD. Many still believe that the TGD has caused or at least exacerbated the drought.

Based on the gauged water levels in Fig. 4 and the calculated decreases in Table 2, the area most likely to be affected in lake wetlands are identified based on the basin DEM in Fig. 5 (outlined in red). Areas with a shortened inundation time were distributed over a major



**Fig. 5** Regions of inundated patterns affected by the operation of the TGD



part of the eastern Dongting Lake, accounting for approximately 50 % of the area. These areas are important habitats for migratory birds and fish. The alterations of lake habitats have been found to easily influence biodiversity (Elderl 2003; Hill et al. 1998; Ligon et al. 1995). Changes in the inundation patterns of wetlands have triggered environmental threats from decreasing biotic diversity.

Dongting Lake usually serves as the main flood basin of the Yangtze River and is a zone with a very high risk of flooding (Wang et al. 2012). However, when the worst drought hitting Dongting Lake in recent years, we were aware of further concern about the function and impact of the TGD. The water surface area shrank to less than 45% of its usual area in May 2011. More than one thousand hectares of wetlands located on the east side of Dongting Lake have dried up entirely.

#### 4.5 Discussion of Mitigating Countermeasures

The impacts of a dam on a river and lake downstream in terms of hydrology and morphology are determined by a complex mix of variables that include the patterns of water release through the dam and the characteristics of the downstream channel (Yuan et al. 2011; Yang et al. 2007; New and Xie 2008). Although significant erosion has occurred in the downstream riverbed, the erosion has not offset the sediment lost in the reservoir, and the sediment flux into the estuary has decreased by 31 % of the Yangtze delta (Yang et al. 2007). According to the results in Fig. 2, the impact to the lake wetlands may even be serious. The lake wetlands compose an area of long-term sediment accumulation and uncertain erosion and deposition patterns related to the lake's hydrological regimes. This change is of great significance to the well being of the densely populated riparian areas of the lake wetlands.

The operation of the TGD is reducing flooding to these wetlands and altering their ecological systems. Some long-term effects of changes on the lake wetlands include the spread of invasive species to once-watered portions of these wetlands (Ding et al. 2008; Cao and Conner 1999; Hu et al. 2010; Liu and Chen 2001), and some typical floodplain wetlands may eventually turn into terrestrial ecosystems. Increasing evidence indicates that dams can also impact human diseases from *schistosomes* (Li et al. 2000; Seto et al. 2008). Therefore, keeping the area of the lake wetlands and water at a proper level is important. There is already intense debate over the building of another dam at the outlet of Poyang Lake to cope with disastrous water level fluctuations (Jiao 2009).

There is obvious concern about the ultimate impact of sediment storage in the dam on the dynamics of the lake wetlands and adjacent coast, which depends on the trajectory and duration of the erosive responses in the middle Yangtze basin (Chen et al. 2010). Water resource conservancy and risk reduction under climatic instability make the optimal management of large dams more challenging and urgent (Christodoulou 2011). The modelling result shows that the reservoir operation in the upper reaches of the Yangtze River will impact the TGR water storage start time (Zhang et al. 2011).

Maintaining the natural variability of a river's flow regime is one of the most critical strategies sustaining the ecological integrity of aquatic ecosystems. To minimize the negative impacts associated with large dams, an alternative countermeasure is to strengthen ecological flow regulation by a proper environmental impact assessment (Tullos 2009; Suen 2011). Reservoir operation rules are intended to help an operator ensure that water releases and storage capacities are in the best interests of the system objectives. A multi-objective refill operation mode can directly benefit the rules of a multi-purpose reservoir, and a large number of feasible operation policies may exist for multi-reservoir systems (Liu et al.

2010; Ostadrahimi et al. 2012). This issue is of particular significance for the TGD and many reservoirs distributed throughout the middle and upper reaches of Yangtze River.

## 5 Conclusions

The construction of Three Gorges Dam has greatly reduced the downstream sediment discharge, which in turn has changed the morphological evolution of the river channel and the hydrological regime of lake wetlands. The water storage in the Three Gorges Reservoir is changing the inundation patterns of the lake wetlands. Some of the impacts on lake wetland ecological systems may occur slowly, and many uncertainties in ecological responses remain due to the short-term and incomprehensive studies. Thus, proper attention should be paid to monitor those subtle changes to prevent irreparable ecological damage.

The TGD largely reduces the threat of flooding, but with a seasonal impact on water availability downstream. The serious droughts in Dongting Lake recent years were largely connected with the flow regulations. Auditors should also consider the increased risk of damage to the natural wetlands due to changes in inundation conditions, including the habitats both for migratory birds and aquatic fish. Although monitoring is still limited, a continued examination of the possible ecological impacts between lake and river is important for quantifying the resistance and resilience of lake wetland ecosystems.

Sustainable social and economic development needs sound water management strategies. To meet the simultaneous demand for water, energy, and environmental protection well into the future, a broader view of dams and lake-river relationships is needed, particularly for those dams on large rivers emphasizing the wide range of problems associated with dams is urgent. It is only by the refinement of extensive understanding that we can provide good quality habitats for wetland wildlife and make progress in promoting development that is sustainable both economically and environmentally.

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