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The impact of Three Gorges Dam on the downstream eco-hydrological environment and vegetation distribution of East Dongting Lake

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ABSTRACT

The ecological and environmental consequences of large dam projects have received increasing attention in the recent decades. On the basis of daily water-level data, six periods of TM/ETM+ data and a digital elevation model, the eco-hydrological environments and vegetation area of East Dongting Lake, were compared for the years 1995–2011, spanning periods before and after the implementation of the Three Gorges Dam (TGD) in 2003. Vegetation area (including three types: forestry, reed and grass) continuously expanded, and the minimum elevation of vegetation-covered area (VCA) gradually decreased by 0·88 m from 1995 to 2011. Following the implementation of the TGD, the rates of both vegetation expansion (12·3 vs 14·1 km^2 $year^{-1}$) and the lowering of minimum elevation of VCA (3·1 vs 7·9 cm $year^{-1}$) increased rapidly. Monthly water level decreased considerably from July to November, and annual submergence duration at elevations of 22–26 and 30 m was considerably decreased after the TGD was implemented. The average maximum submergence duration of VCA was 231 days. Almost equal linear equations describing elevation change from 1995 to 2011 indicated that the minimum elevation of VCA identified via analysis of TM/ETM+ images can be represented by the maximum submergence duration evaluated via daily water level. These data indicate that vegetation colonized the non-vegetation area (including mud beach or water body) more quickly after the implementation of the TGD, due to the drastic changes in eco-hydrological environments such as the decreasing water level and the minimum elevation of VCA. The present methodology might allow faster and more reliable assessment of inundation related landscape impacts on a basin scale and thereby contribute to biodiversity monitoring and policy assessment.

KEY WORDS Three Gorges Project; hydrological environment; submergence duration; vegetation succession

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INTRODUCTION

Freshwater lakes store renewable freshwater for human use and provide habitats for aquatic fauna and flora (Johnson *et al*., 2001). Despite their immeasurable value for the development of human society, freshwater lakes have been considerably modified and degraded by human activities, such as the construction of dams and impolders (Beeton, 2002; An *et al*., 2007). Large-scale dams provide significant potential benefits, including flood control, energy production, water supply and increased navigability. However, the ecological and environmental consequences of large dams have received increasing attention in the recent decades (Wilcove *et al*., 1998; Fang *et al*., 2005; Fu *et al*., 2010), because the resulting changes to hydrological regimes and physical habitats profoundly alter the structure and composition of plant and animal communities in freshwater wetlands (Xie, 2003; Xie and Chen, 2008; Yi *et al*., 2010; Moffett *et al*., 2012).

Compared with hydrology and water quality, biological responses to large dams are lagged and comprehensive, which might be the reason for the focus on ecological consequences. Vegetation is an important and basic component in a wetland ecosystem, and plays an important role in the reform and restoration of ecosystem structure and function. The water regime is regarded as the most influential factor in the growth and distribution of vegetation in wetland ecosystems (Van Eck *et al*., 2004; Pennings *et al*., 2005; Luo and Xie, 2009; Duval *et al*., 2012). As a result, plant zonation (different plants distributed along with an elevation) is a common phenomenon in wetlands (Snedden and Steyer, 2013). Dou and Jiang (2000) indicated that the duration of beach

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submergence, water level and sediment deposition might be the most important eco-hydrological factors influencing the distribution of vegetation. Changes in groundwater level lead to vegetation change in an estuarine wetland (Zhao *et al.*, 2005). Plant tolerance to (or survival from) flooding is believed to be closely related to vegetational distribution in wetlands, because flood-tolerant amphiphytes usually determine the lower boundary of plant zonation (Emery *et al.*, 2001). Therefore, submergence duration at the lower boundary might determine the change of vegetational distribution, especially in the seasonal flooding plain (Peng *et al.*, 2007; Xie and Chen, 2008), which requires further confirmation.

The Three Gorges Dam (TGD) Project is the largest water control project in the world, and has been operational since 2003. For the purposes of electricity generation and flood control, larger volumes of water will be discharged from the TGD from December to March but less from July to November relative to pre-project conditions (Tong, 2004). Dongting Lake is the nearest downstream lake connected to the TGD on the Yangtze River (Figure 1). There is about 300 km in distance and about 120–140 m in elevation differences between TGD project and Dongting Lake. As such, its hydrological characteristics have been changed following the implementation of the TGD project, including lower water level and reduced sediment delivery from the Yangtze River, which has been influencing the lake's long-term evolution (Chang *et al.*, 2010; Sun *et al.*, 2012). In this study, using daily water level, TM/ETM+ images and a digital elevation model (DEM), we first identified changes in vegetation area (including three types: forestry, reed and grass), the minimum elevation of vegetation-covered area (VCA) and eco-hydrological environments (water level and submergence duration at different elevations) in East Dongting Lake following the implementation of the TGD. We then calculated the maximum submergence duration of VCA. Finally, we tested whether changes in the minimum elevation of VCA can be predicted by maximum submergence duration of VCA.

STUDY AREA

Dongting Lake (111°40′–113°10′E; 28°30′–30º20′N) in Hunan Province has a surface area of 2625 km^2, and is the second largest freshwater lake in China. The lake consists of three parts: East, South and West Dongting Lake (Figure 1). The lake has seven water inlets, including three channels of the Yangtze River (Songzi, Taiping and Ouchi) and four rivers (Rivers Xiang, Zi, Yuan and Li). The lake has only one outlet, which discharges into the Yangtze River at Chenglingji (Figure 1). Annual fluctuation in water level is approximately 12–14 m, with the maxima in August and minima typically in January or February, which provides the basic hydrological regime for maintaining large areas of beach wetlands, the most dynamic landscape within the Dongting Lake area. The region has also been recognized as one of the 200 global conservation priority eco-regions proposed by the World Wide Fund for Nature, due to its valuable and exclusive biodiversity (Olson and Dinerstein, 1998; Fang *et al.*, 2006), harbouring approximately 1428 plant species, 114 fish species and 217 bird species. Vegetation, especially grass (mostly *Carex*

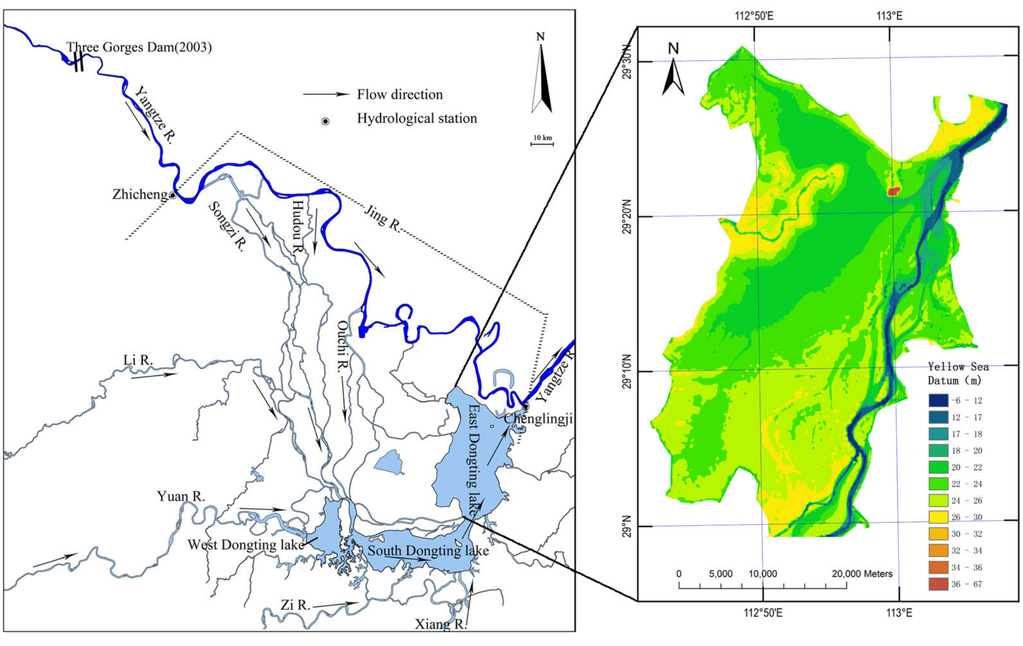

Figure 1. The water system of Dongting Lake and digital elevation model of East Dongting Lake.

community), is important for providing habitats and foods for different protected animal species in the floodplain (Amoros and Bornette, 2002). From East to West Dongting Lake, the topography is upswept, leading to more than 5-m deviation in water level between the two lakes. However, the topography of East Dongting Lake is flat, and comprises approximately half the area of the entire lake.

DATA AND METHODS

In order to evaluate the changes of eco-hydrological environment and land cover in East Dongting Lake after the implementation of the TGD and to identify the relationship between water level and vegetation area, a flow chart of all the steps performed in the analysis is shown in Figure 2.

Data sources and analysis process

A DEM (1:10000) of Dongting Lake in 1995 was produced by Changjiang Water Resources Commission (Ministry of Water Resources, China) using artificially measured elevation data, according to the measuring-point scheme of line distance 1000 m and distance between two points 500 m in a line. In this study, topographical data for East Dongting Lake was extracted from the DEM according to the geographical coordinates.

Daily water level (8:00 AM) at Chenglingji Hydrological Gauging Station (Figure 1) during 1991–2011 was used to represent the hydrological regime of East Dongting Lake, and had been used extensively in previous hydrological studies of that part of the lake (Chang *et al*., 2010; Sun *et al*., 2012).

To avoid erroneous interpretation of remote sensing data due to concealment of vegetation by high water level, TM/ETM+ images were chosen on the basis of a daily water level at Chenglingji of less than 22 m. Average water level during 1991–2011 was lower than 22 m in December, January and February, when potential vegetation was completely visible, according to field investigations by Dongting Lake Station for Wetland Ecosystem Research (Institute of Subtropical Agriculture, Chinese Academy of Sciences). At the same time, this period also corresponds with the winter season rather the growing period for vegetation in Dongting Lake, so the vegetation distribution pattern is relatively stable. In order to increase comparability of remote sensing images between different periods, images were selected that corresponded to a daily water level of approximately 21 m. Finally, six periods of TM/ETM+ images were chosen, as shown in Table I.

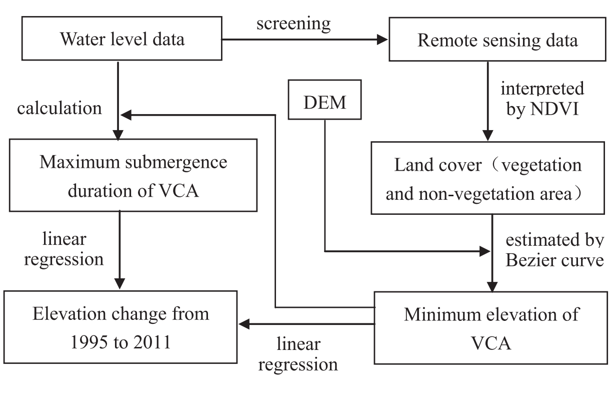

Figure 2. A flow chart of all analysis steps in this study. VCA indicates vegetation-covered area.

Method of extracting vegetation and non-vegetation coverage

The decision tree classification method was used to differentiate vegetation (including three types: forestry, reed and grass),water body and mud beach at different periods. The decision tree model was built on the basis of Band 4 (near infrared band) and Band 7 (middle infrared bands) of TM/ETM+ image and normalized differential vegetation index (NDVI). Taking the year 2011 as an example, a decision tree model was established by NDVI, band threshold of different wetland types determined by spectral characteristic and 387 training samples by visual interpretation. The branch point of the decision tree on 24 February 2011 was adjusted according to the field data (325 samples) from the Dongting Lake Station. During winter, reed was harvested and grass was withered, so the training sample of vegetation area was extracted several times to improve the accuracy of spectral threshold between VCA and mud beach. The area of $NDVI \geq 0{\cdot}3$, Band $4 > 57$ (and white in the images) was identified as vegetation, the area of $NDVI < 0{\cdot}3$, $44 <$ Band $7 \leq 255$, $0 <$ Band $4 \leq 57$ (and from grey to white in the images) as mud beach, and the area of $NDVI < 0{\cdot}3$, Band $7 \leq 44$, Band $4 = 0$ (and black in the images) as water body. The bare land with a few scattered plants was incorporated into the mud beach classification. Additionally, a few unclassified types could be identified via plant investigation resources at the Dongting Lake Station. The area classification in other years, which is slightly different from the spectral characteristic in 2011, could be fine-tuned. Classification accuracy was evaluated using the confusion matrix of NDVI. All processing was conducted using the software ArcGis10.0.

Table I. Dates of TM/ETM+ images.

Date	Image type	Water level (m)
1995-12-05	Landsat4-5 TM	21·49
2000-02-26	Landsat7 ETM+	21·06
2003-1-17	Landsat7 ETM+	21·98
2005-01-06	Landsat7 ETM+	21·18
2008-2-16	Landsat7 ETM+	20·88
2011-02-24	Landsat7 ETM+	21·66

The minimum elevation of VCA

The minimum elevation of VCA was estimated by Bezier curve, which is used extensively to construct smooth curve models in computer graphics. In this study, the Bezier curve was calculated by merging image interpretation into DEM. As a result, the curve relationship between elevation and vegetation area can be estimated for any wetland type in different periods. In this study, mud beach and water body were combined and termed non-vegetation area, because slight variation in water level will lead to changes in the mud beach area. The equation is as follows:

$$B(t) = \sum_{i=0}^{n} \binom{n}{i} P_i (1-t)^{n-i} = P_0 (1-t)^n + \binom{n}{1} P_1 (1-t)^{n-1} t + \cdots + P_n t^n, t \in [0,1]$$

Here, $B(t)$ indicates area integral, Pi tangential area at elevation i, t division ratio between two points (0–1) and n elevation.

On the basis of the continuity of Bezier smooth curve, the vegetation or non-vegetation areas at any elevation can be evaluated by the tangent value of a given elevation (Figure 4). The boundary elevation between vegetation-covered and non-vegetation areas could be considered as the minimum elevation of VCA. The upper elevation was defined as the elevation corresponding to the largest vegetation area in a Bezier curve. Linear regression was applied to estimate the relationship between vegetation area and the minimum elevation of VCA. The rate of change of vegetation area or the minimum elevation was determined as $CR = (I_2 - I_1)/(Y_2 - Y_1)$, where I_2 and I_1 represent vegetation area or elevation at year 2 (Y_2) and year 1(Y_1), respectively.

Monthly water-level deviation

Monthly average water level was calculated on the basis of daily water level at Chenglingji Station. According to the initiation date of 'human projects' (lake restoration from farmland in 1998 and TGD in 2003), monthly water level was investigated at three stages: 1991–1998, 1999–2002 and 2003–2011. Monthly deviation in water level was calculated as the deviation from average water level during 2003–2011 minus that during 1991–1998 or 1999–2002.

Annual submergence duration at different elevations

Theoretically, if the water level exceeds a certain elevation, vegetation at this elevation can be considered as submerged and all land area at this elevation can be classified as water area. Therefore, on the basis of the daily water level at Chenglingji Station, the water-level ranking method is used to calculate annual submergence duration for any elevation. In this study, we calculated the duration of beach submergence for all whole number elevations from 20 to 30 m. The deviation in submergence duration was calculated at a given elevation for the period of 2003–2011, and those from 1991–1998 or 1999–2002 were subtracted from it.

Maximum submergence duration of VCA

In this study, the minimum elevations of VCA in the six periods of images were used to calculate the maximum submergence duration of VCA. Annual submergence duration at the minimum elevation of VCA was calculated from 1991 to 2011, and then linear regression was applied to estimate the maximum submergence duration of VCA in any period. Finally, the maximum submergence duration was calculated as the average of values in the six periods of images. All linear regressions were tested by F-test.

In order to evaluate the accuracy of the estimated maximum submergence duration, we transformed the maximum submergence duration (days) to elevation data (m) from 1991 to 2011 on the basis of the daily water level, using the water-level ranking method; then linear regression was applied to calculate elevation changes from 1991 to 2011. Additionally, another linear regression equation was used to calculate elevation changes from 1995 to 2011 on the basis of the minimum elevation of VCA in the six periods of images. The similarity between both regression lines was analysed by analysis of covariance (ANCOVA) by testing the intercept and slope of regression equations (Rogosa, 1980), with water level as dependent variable and year as covariable.

RESULTS

Vegetation area

From 1995 to 2011, vegetation area increased by 211 km^2 (approximately 13·2 $km^2 year^{-1}$), accounting for 16% of the total area of East Dongting Lake (Figures 3 and 5a), whereas non-vegetation area decreased at the same rate as vegetation area during the last 16 years. During the five periods (1995–2000, 2000–2003, 2003–2005, 2005–2008 and 2008–2011), vegetation area only decreased during 2000–2003 (about 29 km^2). From 2005 to 2008, an area of 118·7 km^2 was transformed into vegetation (about 39·6 $km^2 year^{-1}$), which was the highest rate of vegetation increase during the five periods. Compared with 1995–2003, the rate of increase of vegetation area was higher (14·1 $km^2 year^{-1}$ vs 12·3 $km^2 year^{-1}$) after the implementation of the TGD.

The minimum elevation of VCA

The upper distribution elevation was located at 24·4–24·9 m, and did not differ significantly among the six periods of images (Figure 4). The minimum elevation of VCA gradually

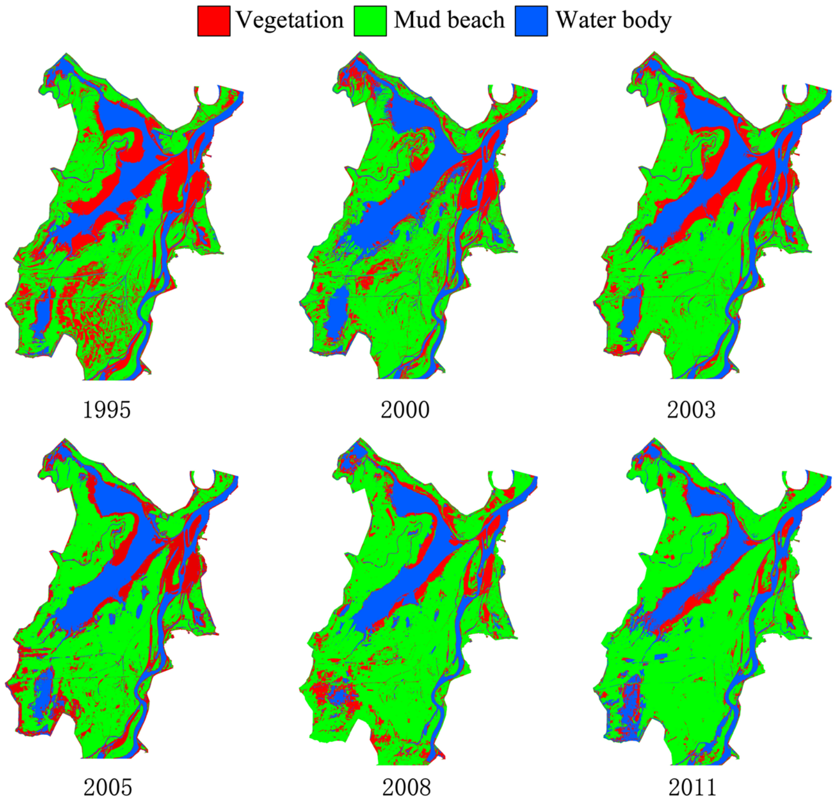

Figure 3. Area changes in vegetation, mud beach and water body in East Dongting Lake.

decreased along with time (23·30 m in 1995, 23·28 m in 2000, 23·05 m in 2003, 23·00 m in 2005, 22·48 m in 2008 and 22·42 m in 2011). The minimum elevation decreased fastest during 2005–2008, at an intermediate rate during 2000–2003, and slowest in the three other periods (Figure 5b). Compared with 1995–2003, the rate of decrease of the minimum elevation of VCA was significantly faster (7·9 vs 3·1 cm year^{-1}) after the implementation of the TGD.

The relationship between vegetation area (y) and the minimum elevation of VCA (x) was highly linear ($y = -210x + 5584$, $R^2 = 0·95$, $F = 79·4$), indicating that vegetation expansion was closely associated with the decreasing minimum elevation.

Monthly water level and annual submergence duration at different elevations

On the basis of daily data at Chenglingji from 1991 to 2011, monthly water level in 2003–2011 generally increased or did not change from January to March, and significantly decreased from April to December compared with 1991–1998 or 1999–2002 (Figure 5c). Water-level deviation exceeded 1 m in April (1·05 m), July (1·90 m), August (1·61 m) and October (1·64 m) for the period 2003–2011 compared with 1991–1998; and was exceeded 1 m in July (1·63 m), September (1·31 m), and October (2·00 m) and November (1·79 m) and was close to 1 m in May (0·84 m), August (0·90 m) and December (0·88 m) for the period 2003–2011 compared with 1999–2002. It was clear that water level considerably decreased from July to November after the implementation of the TGD.

Annual submergence duration at given elevations changed considerably after the implementation of the TGD (Figure 5d). Annual submergence duration was increased at 20-m elevation but decreased from 22- to 30-m elevation. Annual submergence duration decreased by 15 days at 22-m elevation and by more than 20 days (21–33 days) at elevations of 23–26 and 30 m when comparing 2003–2011 with 1991–1998. Compared with 1999–2002, annual submergence duration in 2003–2011 decreased by 12 days at 23-m elevation and by more than 20 days (21–36 days) at elevations from 24 to 30 m. For example, annual submergence duration of beach at 30-m elevation was 51 and 54 days in 1991–1998 and 1999–2002, respectively, but was 27 days in 2003–2011. It was clear that annual submergence duration at 22- to 26 and 30-m elevations was considerably decreased after the implementation of the TGD.

Maximum submergence duration of VCA

On the basis of the minimum elevation of VCA (23·3–22·42 m), annual submergence duration in the six periods of images showed a significant linear decrease ($P < 0·05$). According to

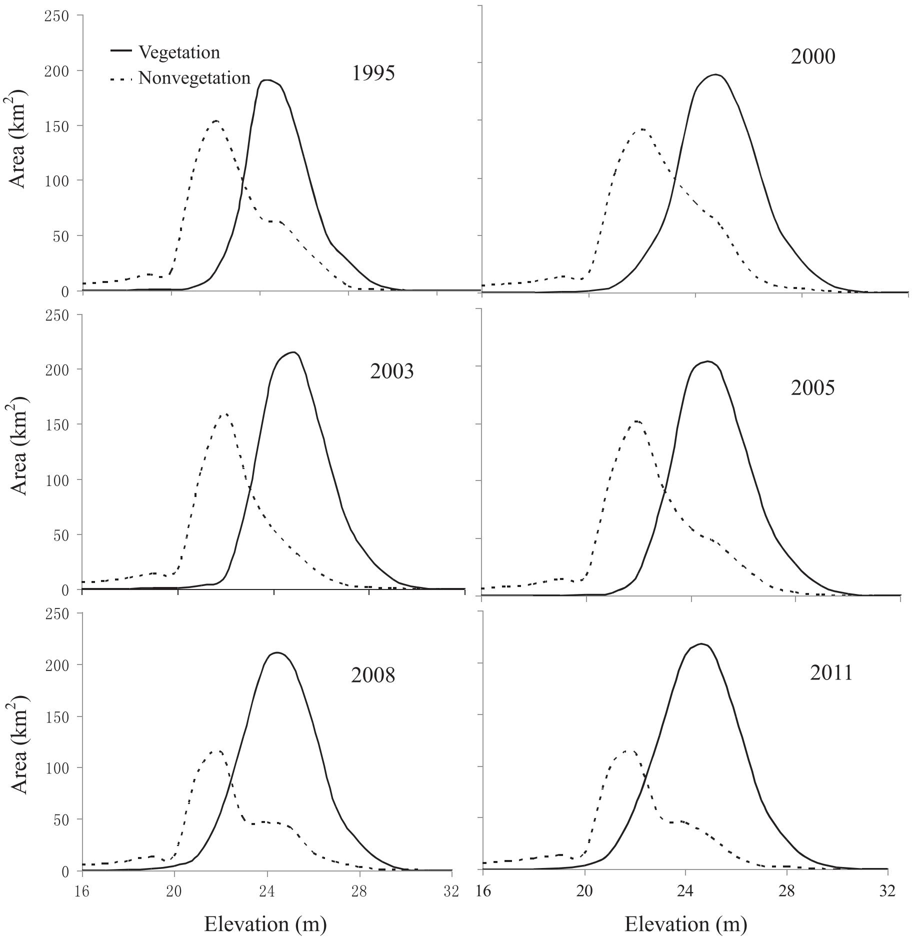

Figure 4. Boundary elevation between vegetation and non-vegetation (mud beach+water body) areas at East Dongting Lake, evaluated via Bezier curve.

the linear equation, the maximum duration of vegetation submergence was 239 days in 1995, 227 days in 2000, 227 days in 2003, 224 days in 2005, 236 days in 2008 and 233 days in 2011. Therefore, the average of 231 days was considered as the maximum submergence duration of VCA.

Elevation change from 1995 to 2011 was linear, as estimated by the minimum elevation of VCA via TM/ ETM+ images ($F = 23{\cdot}4$, $P = 0{\cdot}008$) or by the maximum submergence duration of VCA (231 days) according to water level ($F = 10{\cdot}0$, $P = 0{\cdot}006$) (Figure 6). ANCOVA showed that there was no difference between the two regression lines ($F_{\text{slope}} = 0{\cdot}12$, $P = 0{\cdot}74$; $F_{\text{intercept}} = 1{\cdot}32$, $P = 0{\cdot}264$), indicating that the slopes (0·062 vs 0·058, 6·4% deviation) and intercepts (147·6 vs 139·8, 5·3% deviation) of both linear equations were almost equivalent. Therefore, both methods gave similar estimates of the changes in minimum elevation of VCA.

DISCUSSION

From 1995 to 2011, vegetation area increased by 211 km^2, accounting for 16% of the area of East Dongting Lake, which is consistent with other studies at this site (Wang *et al.*, 2007; Xu *et al.*, 2010; Deng *et al.*, 2012). These results indicate that vegetation has colonized areas of mud beach or water during the last 16 years. Our findings show that the rate of vegetation expansion increased significantly (12·3 vs 14·1 $km^2\ year^{-1}$) after the implementation of the TGD in 2003. Similarly, the minimum elevation of VCA also decreased significantly faster (3·1 vs 7·9 $cm\ year^{-1}$) after the implementation of the TGD. A highly significant linear relationship indicated that the topography is relatively linear in this elevation interval, and that expansion of vegetation area was closely associated with continuously declining minimum elevation of VCA.

Increasing vegetation area and decreasing minimum elevation of VCA might be closely related to changes in hydrological regimes. After the implementation of the TGD, monthly water level decreased considerably from June to November (the growing season for the complete biota), and annual submergence duration at elevations of 22–26 and 30 m was drastically decreased, indicating that vegetation at 22–26 m would be significantly changed. The

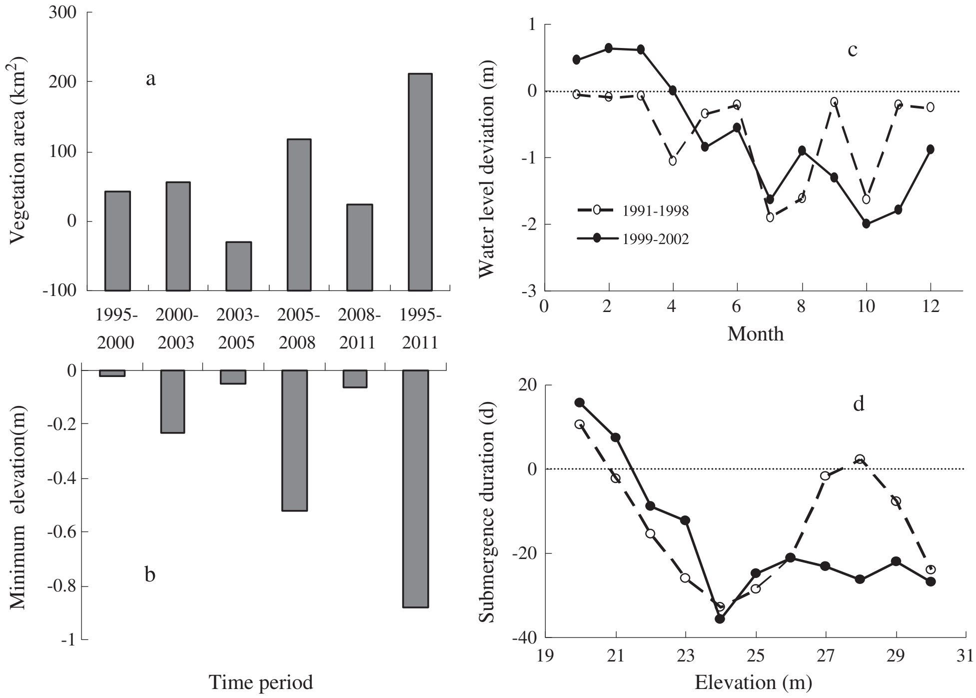

Figure 5. Vegetational and eco-hydrological changes at East Dongting Lake during the different periods. Deviation in vegetation area (a), the minimum elevation of vegetation-covered area(b), monthly water level (c) and submergence duration (d) during 2003–2011 compared with 1991–1998 and 1999–2002.

change in the minimum elevation of VCA (from 23·3 m in 1995 to 22·42 m in 2011) was closely accompanied by significantly increasing vegetation area. Some studies have also shown that water level in Dongting Lake is significantly lower after the implementation of the TGD relative to pre-project conditions, e.g. 1·36, 0·64 and 1·32 m lower than recent 60-year average in the dry years 2006, 2007 and 2008, respectively (Yang *et al.*, 2011). During the water storage periods of the TGD, the water level dropped by 2·03 m in 2006 and 2·11 m in 2009 at Chenglingji station, with extreme decreases reaching 3·30 and 3·02 m, respectively (Sun *et al.*, 2012). The main reasons are concluded as follows. Firstly, total inflow water into Dongting Lake, especially during the flood season, was relatively low in 2003–2008, mainly due to reduced precipitation in the Yangtze River Basin, leading to low annual runoff in Zhicheng Station (a downstream hydrological gauging station near TGD) discharged into Jingjiang River (a section of Yangtze River from Zhicheng to Chenglingji, Figures 1 and 7), which led to consistently lower water level in flood season and rapid water-level decline in non-flood season (Chang *et al.*, 2010). Secondly, because of riverbed scouring, the water level in the Jingjiang River was decreased and flow velocity increased (Mu *et al.*, 2008); this decreases the effects of backwater of the Yangtze River to Dongting Lake at Chenglingji and, in turn, leads to rapid flow of water from the lake into the Yangtze River. Thirdly, because of topographic changes to the Yangtze River, the period of zero flow into Dongting

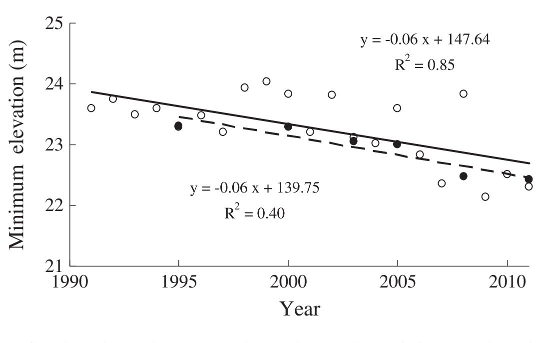

Figure 6. Elevation changes estimated by the minimum elevation of vegetation-covered area and by maximum submergence duration of vegetation-covered area from 1995–2011 at East Dongting Lake.

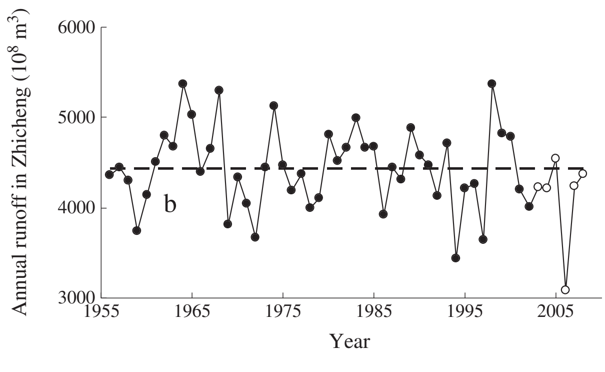

Figure 7. Annual runoff from 1955 to 2008 in Zhicheng Hydrological Gauging Station.

Lake from Yangtze River is significantly increased (Yang *et al.*, 2011), such that input to Dongting Lake is significantly reduced after the implementation of the TGD. Therefore, lower precipitation, lower water discharge into Dongting Lake and rapid outflow from the lake are the main causes of the changes in hydrological regime in the lake after the implementation of the TGD.

The present findings support the suggestion by previous authors, that submergence duration is an important mechanism for determining the minimum elevation of VCA (Peng *et al.*, 2007; Xie and Chen, 2008). It was clear that the minimum elevation determined via TM/ETM+ images can be reflected by maximum submergence duration (231 days) by evaluation of daily water level, because the changes in submergence duration and the minimum elevation of VCA were almost equal for the two methods. Historically, heavy sediment deposition ($64{\cdot}9 \times 10^6$ t year^{-1} from 1996 to 2002) is considered the most important factor driving mud beach and vegetation succession in Dongting Lake (Xie and Chen, 2008). However, sediment deposition is largely reduced ($8{\cdot}5 \times 10^6$ t year^{-1} from 2003 to 2008) following the implementation of the TGD, leading to a dynamic balance between sediment input and output (Chang *et al.*, 2010; Sun *et al.*, 2012). As a result, water level might become the most important factor now after the TGD has been implemented. From 2005 to 2008, a total of 118·7 km^2 non-vegetation area was colonized by vegetation, which might be closely related to the continuous dry period and low annual runoff discharged into Jingjiang River from TGD during 2003–2008 except for 2005 (Figure 7), leading to continuous lower annual average water level, shorter submergence duration at most elevations, followed by vegetation expansion. Therefore, we can conclude that the change in submergence duration at different elevations is the primary reason for the expansion of vegetation area in East Dongting Lake after the implementation of the TGD.

The present methodology might allow faster and more reliable assessment of biodiversity and landscape impacts on a basin scale and thereby contribute to biodiversity monitoring and policy assessment. As an important international wetland, Dongting Lake is a ‘transfer station’ for migratory birds and one of the most important spawning grounds for four major species of Chinese carp, as well as a conservation priority region for endangered species (Fang *et al.*, 2006). For example, approximately 70% of *Anser erythropus* overwinters in Dongting Lake. The changes in hydrological regime will certainly influence the vegetation distribution and human activity in the Dongting Lake wetlands. For example, large-scale poplar plantation in the wetlands since the 1990s has accelerated the succession from wetland to terrestrial ecosystems (Li *et al.*, 2014), because so many poplars were planted directly on reed and grass areas in high-elevation regions ($>$28 m at East Dongting Lake), leading to extensive changes to different vegetation types (Deng *et al.*, 2012). In particular, *Carex*, which provides the most important primary habitat and food source for winter migratory birds, and spawning ground for fish, has declined in coverage from 768 km^2 in 1983 to 499 km^2 in 2007 (Yang *et al.*, 2011), accompanied by increasing forestry area from 87 km^2 in 1983 to 640 km^2 in 2007 across the entire Dongting Lake area (a total of 2625 km^2). Therefore, measures should be introduced to preserve the hydrological regime and to ameliorate changes to the eco-hydrological environment following the implementation of the TGD, particularly in order to recover *Carex* vegetation and to optimize the extent of different types of vegetation cover.

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REFERENCES

Amoros C, Bornette G. 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. *Freshwater Biology* **47**: 761–776.

An S-Q, Li H-B, Guan B-H, Zhou C-F, Wang Z-S, Deng Z-F, Zhi Y-B, Liu Y-H, Xu C, Fang S-B, Jiang J-H, Li H-L. 2007. China’s natural wetlands: past problems, current status, and future challenges. *AMBIO* **36**: 335–342.

Beeton A-M. 2002. Large freshwater lakes: present state, trends, and future. *Environmental Conservation* **29**: 21–38.

Chang J, Li J-B, Lu D, Zhu X, Lu C-Z, Zhou Y-Y, Deng C-X. 2010. The hydrological effect between Jingjiang River and Dongting Lake during the initial period of Three Gorges Project operation. *Journal Geography Science* **20**: 771–786.

Deng F, Wang X-L, Li E-H, Cai X-B, Huang J-L, Hu X-X, Jiang L-Z. 2012. Dynamics of lake Dongting wetland from 1993 to 2010. *Journal of Lake Science* **24**: 571–576.

Dou H, Jiang J-H. 2000. *Dongting Lake*. University of Science and Technology of China: Hefei.

Duval TP, Waddington J-M, Branfireun B-A. 2012. Hydrological and biogeochemical controls on plant species distribution within calcareous fens. *Ecohydrology* **5**: 73–89.

Emery N-C, Ewanchur P-J, Bertness M-D. 2001. Competition and salt-marsh zonation: stress tolerators may be dominant competitors. *Ecology* **82**: 2471–2483.

Fang J-Y, Rao S, Zhao S-Q. 2005. Human-induced long-term changes in the lakes of the Jianghan Plain, Central Yangtze. *Frontiers in Ecology and Environment* **3**: 186–192.

Fang J-Y, Wang Z-H, Zhao S-Q, Li Y-K, Tang Z-Y, Yu D, Ni L-Y, Liu H-Z, Xie P, Da L-J, Li Z-Q, Zheng C-Y. 2006. Biodiversity changes in the lakes of the Central Yangtze. *Frontiers in Ecology and Environment* **4**: 369–377.

Fu B-J, Wu B-F, Lu Y-H, *et al.* 2010. Three Gorges Project: efforts and challenges for the environment. *Progress in Physical Geography* **34**: 741–754.

Johnson N, Revenga C, Echeverria J. 2001 Managing water for people and nature. *Science* **292**: 1071–1072.

Li Y-Z, Qin H-Y, Xie Y-H, Wang W, Chen X-S, Zhang C-M. 2014. Physiological mechanism for the reduction in soil water in poplar (*Populus deltoides*) plantations in Dongting Lake wetlands. *Wetlands Ecology and Management* **22**: 25–33.

Luo W-B, Xie Y-H. 2009. Growth and morphological responses to water level and nutrient supply in three emergent macrophyte species. *Hydrobiologia* **624**: 151–160.

Moffett K-B, Gorelick S-M, McLaren R-G, Sudicky E-A. 2012. Salt marsh ecohydrological zonation due to heterogeneous vegetation-groundwater-surface water interactions. *Water Resources Research* **48**: W02516.

Mu J, Zhang X, Xu Q. 2008. Study on variation of runoff and sediment diversion from three outfalls. *Hydroscience Engineering* **3**: 22–28.

Olson D, Dinerstein E. 1998. The Global 200: a representation approach to conserving the earth's most biological valuable ecoregions. *Conservational Biology* **12**: 502–515.

Peng P-Q, Tong C-L, Qiu S-J. 2007. Variations of flooded days and areas of beach wetlands in Dongting Lake. *Research of Environment in Yangtze Basin* **16**: 685–689.

Pennings S-C, Grant M-B, Bertness M-D. 2005. Plant zonation in low-latitude salt marshes: disentangling the roles of flooding, salinity and competition. *Journal of Ecology* **93**: 159–167.

Rogosa D. 1980. Comparing nonparallel regression lines. *Psychological Bulletin* **88**: 307–321.

Snedden G-A, Steyer G-D. 2013. Predictive occurrence models for coastal wetland plant communities: delineating hydrological response surfaces with multinomical logistical regression. *Estuarine, Coastal and Shelf Science* **118**: 11–23.

Sun Z-D, Huang Q, Opp C, Hennig T, Marold U. 2012. Impacts and implications of major changes caused by the Three Gorges Dam in the middle reaches of the Yangze River, China. *Water Resources Management* **26**: 3367–3378.

Tong Q-M. 2004. The modern evolution of Dongting Lake and succession of wetland ecosystems. *Introduction for Territorial Resources* **1**: 38–44.

Van Eck W-H-J-M, van de Steeg H-M, Blom C-W-P-M, Kroom H-D. 2004. Is tolerance to summer flooding correlated with distribution patterns in river floodplains? A comparative study of 20 terrestrial vegetation species. *Oikos* **107**: 393–405.

Wang H-J, Jiang J-H, Huang Q. 2007. A study on the change of wetland landscape pattern in East Dongting Lake. *Research of Environment in Yangtze Basin* **16**: 732–737.

Wilcove D-S, Rothstein D, Dubow J, Phillips A, Losos E. 1998. Quantifying threats to imperiled species in the United States. *Bioscience* **48**: 607–615.

Xie P. 2003. Three-Gorges Dam: risk to ancient fish. *Science* **302**: 1149.

Xie Y-H, Chen X-S. 2008. Effects of Three-Gorge Project on succession of wetland vegetation in Dongting Lake. *Research of Agricultural Modernization* **29**: 684–687.

Xu Y-B, Lai X-J, Zhou C-G. 2010. Study on remote sensing monitoring of wetland vegetation in East Dongting Lake using ENVISAT ASAR Date. *Research of Environment in Yangtz Basin* **19**: 452–459.

Yang G-S, Zhu C-Q, Jiang Z-G. 2011. *Reports on the Conservation and Development of Yangtze*. Yangtze Press: Wuhan; 144–168.

Yi Y, Wang Z, Yang Z. 2010. Impact of Gezhouba and Three Gorges Dam on habitat suitability of carps in the Yangtze River. *Journal of Hydrology* **387**: 283–291.

Zhao C-Y, Wang Y-C, Chen X, Li B-G. 2005. Simulation of the effects of groundwater level on vegetation change by combining FEFLOW software. *Ecological Modelling* **187**: 341–351.

