



# The Operation of the Three Gorges Dam Alters Wetlands in the Middle and Lower Reaches of the Yangtze River

Gongqi Sun<sup>1</sup>, Guangchun Lei<sup>1\*</sup>, Yi Qu<sup>2</sup>, Chengxiang Zhang<sup>1</sup> and Ke He<sup>1</sup>

<sup>1</sup> School of Ecology and Nature Conservation, Beijing Forestry University, Beijing, China, <sup>2</sup> Nature and Ecology Institute of Heilongjiang Academy of Sciences, Harbin, China

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### \*Correspondence:

Guangchun Lei  
guangchun.lei@foxmail.com

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The operation of the Three Gorges Dam (TGD) has significantly impact on downstream wetland ecosystems. This study applied 3S technology, landscape ecology, and computational models to investigate impact of the TGD on downstream spatial dynamics of floodplains in future. Results revealed the relationship between siltation patterns and wetland types transformation after the operation of the TGD, which are critically important to understand ecological characters dynamics in new environmental setting, and provide science-based conservation and restoration recommendation. After the operation of the TGD, changes between water surface and floodplains areas were spatial heterogeneity. With the increase of distance to the TGD, floodplain erosion force declining gradually. The most important finding is the asymmetric erosion between main river course and its associated floodplain lakes, e.g., Dongting lake. This has significant implications for dam operation in autumn and habitat management. After the operation of the TGD, floodplain in the estuary is driven by both the Yangtze river and ocean currents. The strong hydrological force and reduced sediments of Yangtze river drive erosion of the southern river course in the estuary, whereas, the weakened hydrological force in the northern river course attracts sedimentation.

**Keywords:** floodplains, water surface, three gorges dam, Yangtze River, landscape fragmentation, CA-Markov

## INTRODUCTION

Global wetland changes are affected by climate change and human activities (Vörösmarty et al., 2000; Ramsar Convention on Wetlands, 2018), in particularly, river diversion or damming (Postel et al., 1996; United Nations Department of Economic and Social Affairs, 2015; Jean-François et al., 2016), which have been identified as global aquatic stressors (Etienne et al., 2020), or regional level, such as the Curuai floodplain in the lower Amazon River (Park et al., 2020), West Bengal (India) (Das et al., 2020). Human activities have altered the flow regimes of many rivers, with negative impacts on biodiversity, water quality, and ecological processes (Margaret and Albert, 2019).

The Yangtze River is the third-largest river in the world, and it supports a great amount of biodiversity from 6300 meters above sea level in the Tibetan Plateau to the Eastern China Sea in Shanghai. Its upstream reaches have been identified as global biodiversity hotspots, namely, the Himalayan Mountains and River Valley of the Yangtze River, the Global 200

Ecoregion (Zhao et al., 2000; Barter et al., 2006), the Ecoregion of the Central Yangtze River and Lakes, as well as the Yellow River Ecoregion (including the Yangtze River delta and estuary) (Osion and Dinerstein, 2002).

Since the Three Gorges Dam (TGD) became operational in 2003, worldwide attention has been focused on dam's impact on environment in the middle-lower Yangtze River (Wang, 2010; Pan and Hu, 2015; Zhang et al., 2020). The operation of the TGD changed hydrological regime downstream (Zhang et al., 2016; Tian et al., 2019), through storing water in autumn, and releasing of clear water that disturb balance between riverbed erosion and siltation (Li, 2009; Jiang et al., 2014; Han and Huang, 2018), leading to asymmetric erosion on riverbed and lake (Lu et al., 2018). Such disturbance has significant impact on waterbird habitat (Cao et al., 2008; Guan et al., 2014; Liu et al., 2015), as well as fish populations (Xie et al., 2016).

To date, major research efforts have focused on impact of the TGD on hydrology, or biodiversity based on data from a limited number of hydrological stations (Jiang et al., 2014; Yang et al., 2017; Liu et al., 2018); few studies have focused on hydrological changes and their relationship with siltation patterns and habitat transformation, which are critically important to understand ecological characters dynamics in new environmental setting after the operation of the TGD, and provide science-based conservation and restoration recommendation. This study applied 3S technology, landscape ecology, and computational models to investigate impact of the TGD on downstream spatial dynamics of floodplains in future.

## MATERIALS AND METHODS

### Study Area

Study area covers main river course and its floodplains along the Yangtze River between the TGD in Yichang City and estuary in Shanghai, with a total length of 1771 km (Figure 1). On basis of hydrological station data and impact of river flow downstream, study area was divided into four sections, i.e., Yichang Station-Chenglingji Station (Y-C), Chenglingji Station-Hukou Station (C-H), Hukou Station-Nantong Station (H-N), and Nantong Station-Estuary (N-E).

### Data Collection

Wetland datasets in 1990, 2000, 2005, 2010, and 2015 were produced by extracting floodplain areas from land-use maps obtained from the Resource and Environment Data Cloud Platform<sup>1</sup>. Land-use maps were generated by human-computer interactive software, using Landsat TM/ETM remote sensing images of each period as main data source. Images in early March or late October when water level is stable were selected to avoid influence of water level fluctuation on image interpretation. All selected images were projected in the Conical Projection of Albers Orthogonal Axis with Equal Area and Double Standard Latitude Lines. The reliability of these datasets and monitoring data was

verified and firmly quality controlled before their release. The locations of stations are shown in Figure 1.

### Data Analysis

According to ecological characteristics of the study area, we applied CNLUCC method to generate maps based on a unified land-use and plant classification system and to connect individual remote images. All data analysis was conducted with interactive QGIS software. We first constructed maps within laboratory and then verified them on-site to minimize errors in computer interpretation. Remote sensing data analysis included data collection, false color composite generation, image data correction, image data cutting, and establishment of info-source of remote database.

For standard false color composites, the TM images used bands 4, 3, and 2; MSS4-5 used bands 4, 2, and 1; and MSS1-3 used bands 7, 5, and 4<sup>2</sup>. Since the TGD began operations in 2003, remote sensing data from 1990, 2000, 2005, 2010, and 2015 were used for the interpretation. According to characteristics of wetlands in the middle and lower reaches of the Yangtze River, we divided wetlands into two types, i.e., water surface and floodplains.

Transition matrix were built to characterize impact of the TGD on spatial distribution of wetlands using four periods of remote sensing data and dividing them into time before (1990–2000) and after (2005–2015) TGD operations.

Firstly, we applied transition matrix analysis to identify how wetlands changed after the TGD operation. Then, we conducted a comparative analysis to determine the differences in transition periods and analyze impact of the TGD operation on spatial distribution of wetlands. We calculated two kinds of transition rates,  $P_{S-F}$  and  $P_{F-S}$ :

$$P_{S-F} = A_{W-TF} / A_W, \quad (1)$$

where  $A_{S-TF}$  is total area of water surface that is converted into floodplains, and  $A_S$  is area covered in water surface;

$$P_{F-W} = A_{F-TW} / A_F, \quad (2)$$

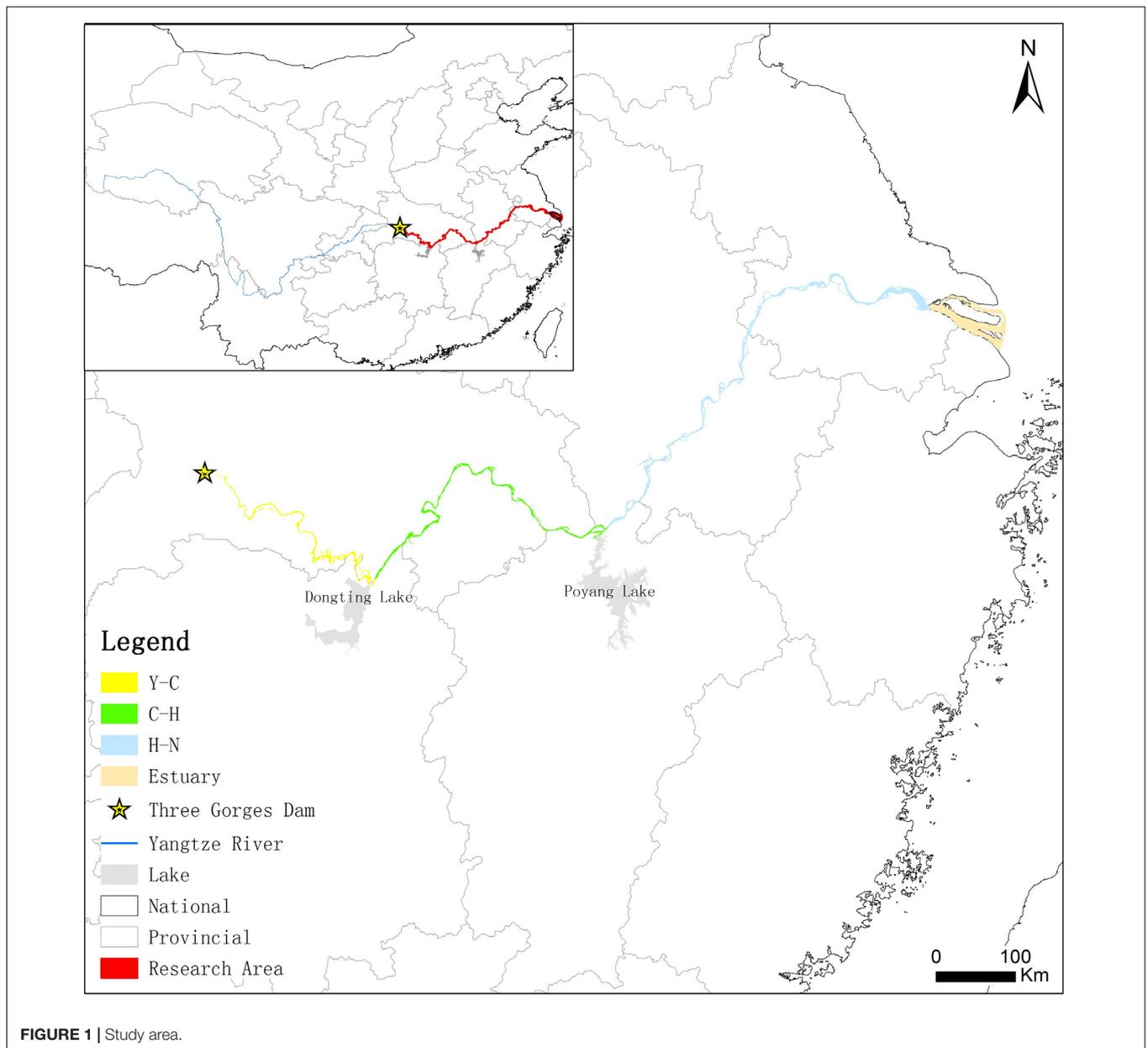
where  $A_{F-TS}$  is total area of floodplain that is converted into all types of water surface, and  $A_F$  is area classified as floodplains.

According to characteristics of different parameters, we chose class and landscape metrics as main parameters to analyze impacts of the TGD on landscape, and we utilized land-use data from 2000 and 2015 for data before and after the operation of the TGD, respectively. We used FRAGSTATS to calculate Percentage of Landscape (PLAND), Number of Patches (NP), Patch Density (PD), and Mean Patch Areas (AREA\_MN) to analyze impacts of the TGD operation on wetland fragmentation.

To predict impact of the TGD operation on spatial distribution of wetlands in the middle and lower reaches of the Yangtze River, we applied a Cellular Automata\_Markov chain (CA\_Markov) model to predict trend of floodplain changes caused by operation of the TGD. This model is a long-term forecasting method based on a Markov chain procedure, which

<sup>1</sup><http://www.resdc.cn/>

<sup>2</sup>[http://www.resdc.cn](http://www.resdc.cn/)



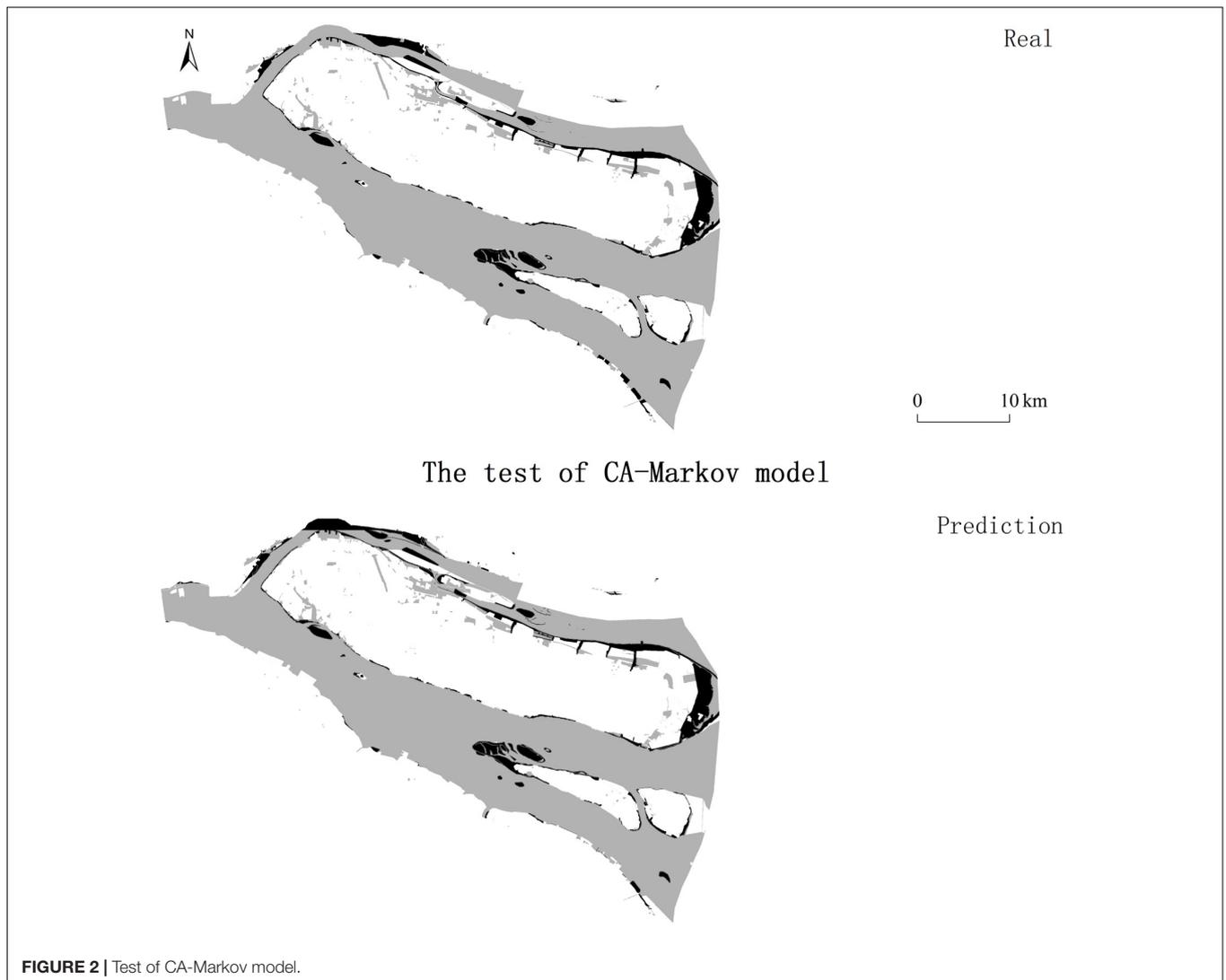
predicts change in every future moment (or period), according to situation and probability of an event at a certain time. Key is to determine probability of event occurrence and transitions (Anderson and Goodman, 1957). CA is a grid dynamic model with discrete time, space, and state variables that has ability to simulate spatiotemporal evolution process of complex systems. The CA\_Markov model is a combination of the Markov chain and CA models in IDRISI software. It makes full use of advantages of the Markov chain to make long-term predictions and ability of CA to simulate spatial variations in complex systems, thereby forecasting future changes based on existing land-use patterns.

**Test of predictive power of CA-Markov model:** We used cross tabulation method to calculate Kappa index for model test,

using 1990 and 1995 data in N-E to predict spatial distribution of wetlands in 2000. Then we did cross tabulation between predictive and real spatial distribution of the N-E wetlands in 2000, with the Kappa index 0.97 which confirm model is reliable (Li et al., 2020; Lu et al., 2020; Wang et al., 2020). **Figure 2** shows comparison results of predictive and real spatial distribution of wetlands in 2000.

1990 and 2000 interpretation data were used to predict spatial distribution of wetlands in 2010 and 2030 under assumption of no TGD. We also used 2005 and 2015 data to predict distribution of wetlands in 2030 under assumption of the TGD operation.

We calculated areas of floodplains and compared distribution of wetlands in simulated and actual 2010 scenarios. We then



**FIGURE 2** | Test of CA-Markov model.

calculated floodplain area in 2030 under both scenarios and siltation rate ( $P_s$ ) difference from 2010 to 2030:

$$P_s = (A_{2030} - A_{2010})/A_{2010}, \quad (3)$$

where  $P_s$  is siltation rate,  $A_{2030}$  is area of floodplain in 2030, and  $A_{2010}$  is area of floodplain in 2010.

## RESULTS

### Changes in Wetland Spatial Structure After the TGD Operation

#### Yichang-Chenglingji Section

In Yichang-Chenglingji section (Y-C), before the operation of the TGD, the floodplain areas increased by 1613.86 ha from 1990 to 2000, due to increased transition rate from water surface to floodplains (W-F), and reduced transition rate from floodplains to water surface (F-W) (Table 1). However, after the operation of the TGD, floodplain area decreased by 1,738.2 ha,

due to increased transition rate from floodplains to water surface (Table 1). We performed spatial overlay analysis on change in spatial structure between water surface and floodplains during (1990–2000) and (2005–2015). Results showed that floodplain areas decreased in upstream section of Y-C and increased with more red-color areas in downstream region of Y-C (Figure 3).

#### Chenglingji-Hhukou Section

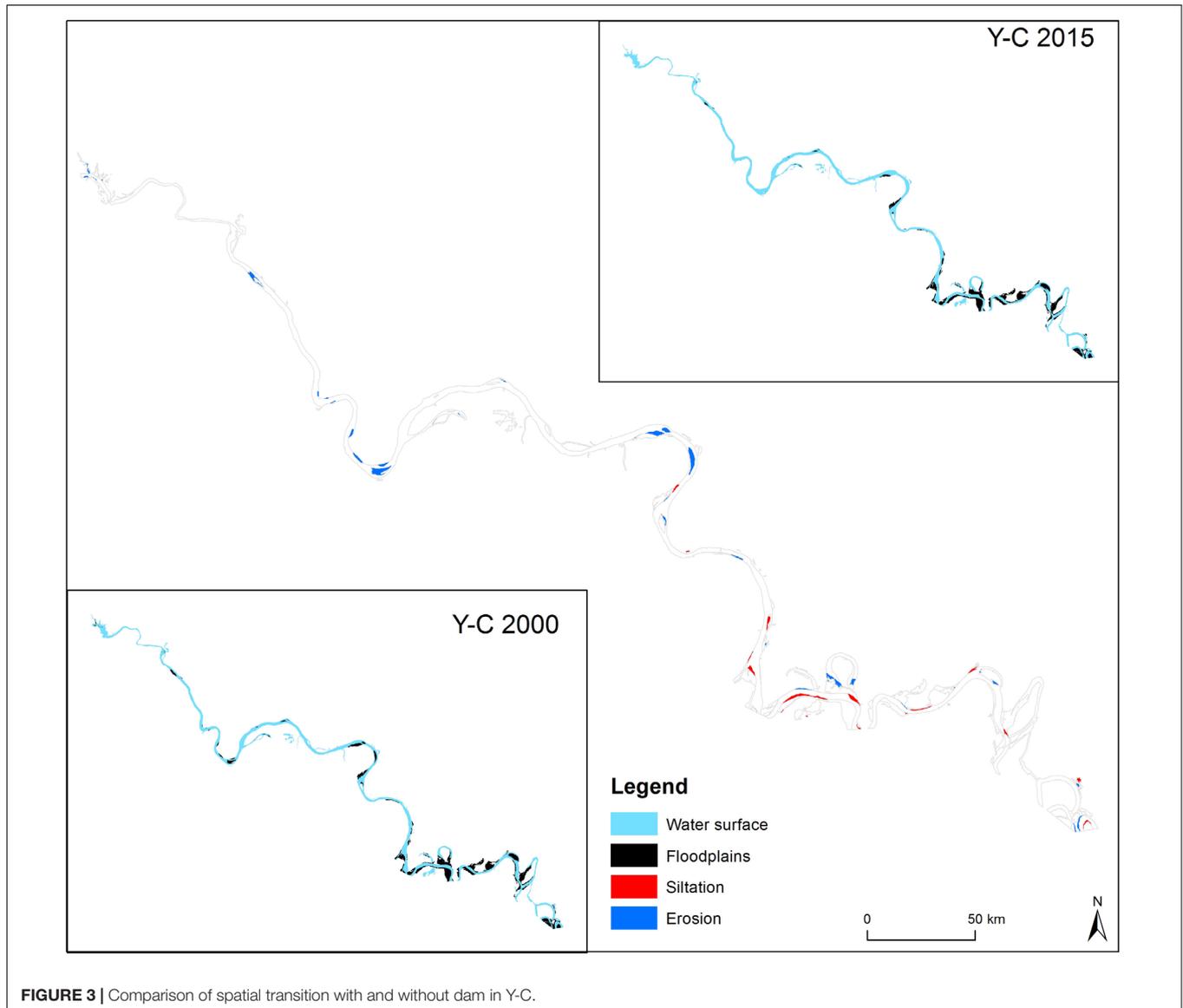
In Chenglingji-Hhukou section (C-H), transition rate from water surface to floodplains maintained as same (1.67%) both before and after the operation of the TGD, whereas transition rate from floodplains to water surface showed increase from 1.38 to 3.77% (Table 2). However, overlay analysis between 2000 and 2015 indicated no clear pattern of spatial transition from floodplains to water surface (Figure 4).

#### Hukou-Nantong Section

In Hukou-Nantong section (H-N), the floodplain areas increased by 4,547.97 ha transition rate from water surface to floodplains

**TABLE 1** | Wetland transition in the Yichang-Chenglingji section between 1990–2000 and 2005–2015 (area unit: ha).

Wetland type	Floodplains 2000	Water surface 2000	Transition rate (%)
Floodplains 1990	16,310.80	407.30	2.44
Water surface 1990	2,021.16	52,519.80	3.71
Wetland type	Floodplains 2015	Water surface 2015	Transition rate (%)
Floodplains 2005	16,846.90	1,861.40	9.95
Water surface 2005	123.20	54,675.80	0.22

**FIGURE 3** | Comparison of spatial transition with and without dam in Y-C.

was 0.33% before and it increased to 2.72% after. Transition of water surface to floodplain were 635.85 ha before the operation of the TGD and increased to 5,183.82 ha afterward (Table 3). Based on spatial overlay analysis of water surface and floodplains in H-N section, the added floodplain area extended around original floodplain patches, and they were mainly distributed in downstream region of H-N section, close to estuary (Figure 5).

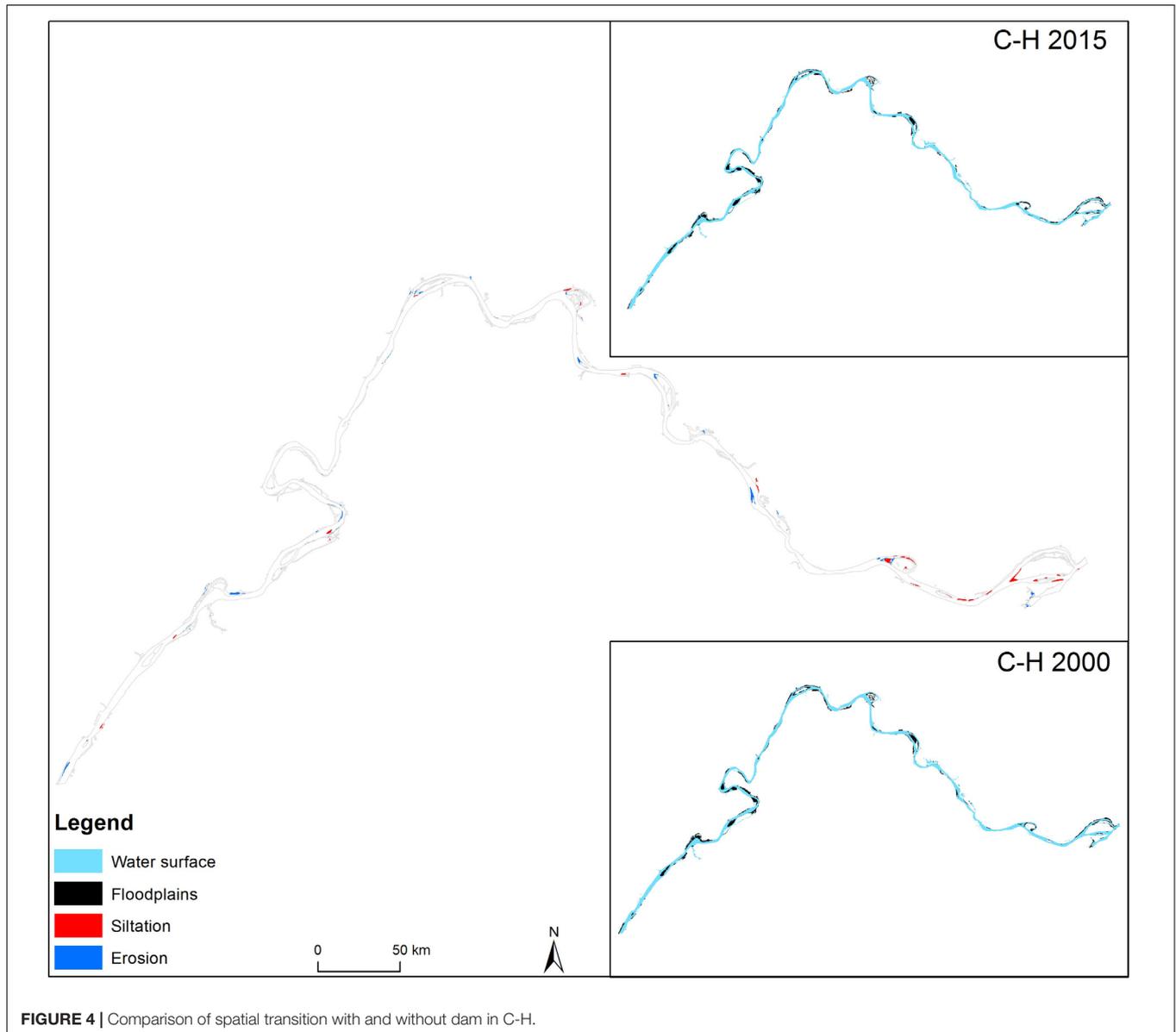
## Impact of the TGD on Wetland Landscapes in the Middle and Lower Reaches of the Yangtze River

### Yichang-Chenglingji Section

After the operation of the TGD, fragmentation of the water surface and floodplain reduced. Results of FRAGSTATS

**TABLE 2** | Wetland transition in the Chenglingji-Hukou section between 1990–2000 and 2005–2015 (area unit: ha).

Wetland type	Floodplains 2000	Water surface 2000	Transition rate (%)
Floodplains 1990	17,640.90	246.15	1.38
Water surface 1990	1,506.27	88,895.30	1.67
Wetland type	Floodplains 2015	Water surface 2015	Transition rate (%)
Floodplains 2005	18,340.50	718.27	3.77
Water surface 2005	1,510.13	89,047.10	1.67

**FIGURE 4** | Comparison of spatial transition with and without dam in C-H.

analysis showed that number of patches (NP) and patch density (PD) indexes of water surface and floodplains decreased in Y-C. Further, percentage of landscape (PLAND) index of water surface increased and that of the floodplain decreased. Mean patch areas (AREA\_MN) index of water surface increased from 138.05 to 404.72 ha,

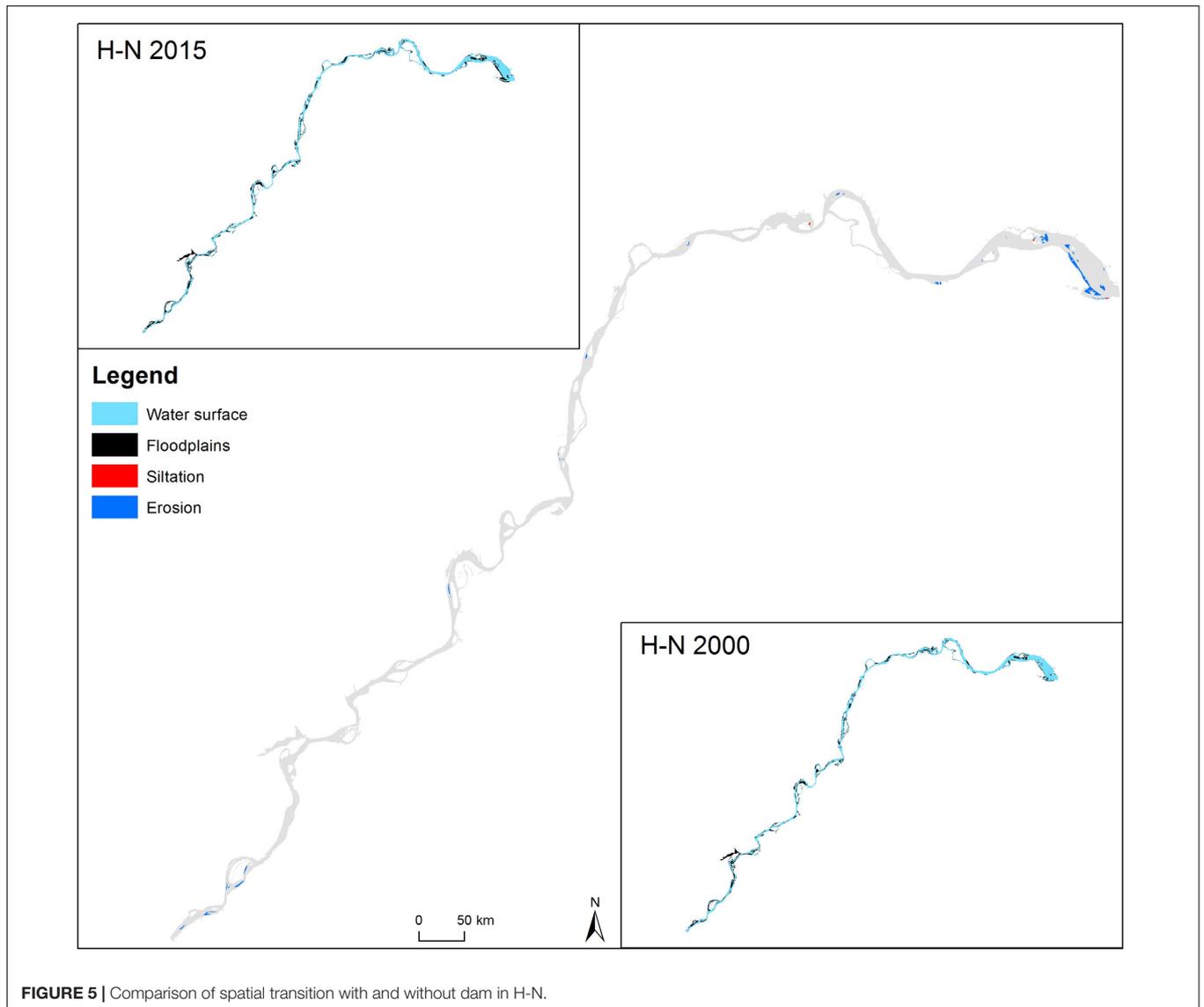
while floodplain increased from 57.69 to 137.99 ha (Table 4).

### Chenglingji-Hukou Section

After the operation of the TGD, fragmentation of water surface and floodplain reduced, siltation was not significant

**TABLE 3** | Wetland transition in Hukou-Nantong section between 1990–2000 and 2005–2015 (area unit: ha).

Wetland type	Floodplains 2000	Water surface 2000	Transition rate (%)
Floodplains 1990	55,259.10	291.74	0.53
Water surface 1990	635.85	190,006.00	0.33
Wetland type	Floodplains 2015	Water surface 2015	Transition rate (%)
Floodplains 2005	5,5726.10	175.33	0.31
Water surface 2005	5,183.82	185,404.00	2.72



**FIGURE 5** | Comparison of spatial transition with and without dam in H-N.

**TABLE 4** | Wetland landscape of Yibin-Chenglingji section in 2000 and 2015.

TYPE	PLAND		NP		PD		AREA_MN	
	2000	2015	2000	2015	2000	2015	2000	2015
Water surface	74.42	76.95	389.00	140.00	0.54	0.19	138.05	404.72
Floodplains	25.58	23.05	320.00	123.00	0.44	0.17	57.69	137.99

**TABLE 5** | Wetland landscape of the Chenglingji-Hukou in 2000 and 2015.

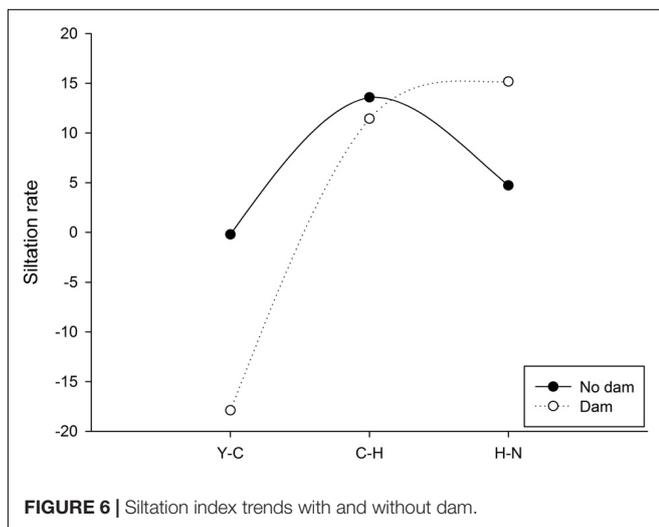
TYPE	PLAND		NP		PD		AREA_MN	
	2000	2015	2000	2015	2000	2015	2000	2015
Water surface	82.19	81.88	517.00	130.00	0.48	0.12	173.04	690.98
Floodplains	17.81	18.12	565.00	251.00	0.52	0.23	34.30	79.18

**TABLE 6** | Wetland landscape of the Hukou-Nantong in 2000 and 2015.

TYPE	PLAND		NP		PD		AREA_MN	
	2000	2015	2000	2015	2000	2015	2000	2015
Water surface	77.31	75.24	286	346	0.12	0.14	665.90	537.72
Floodplains	22.69	24.76	511	435	0.21	0.18	109.39	140.78

**TABLE 7** | No dam and dam siltation areas and rate in the middle and lower reaches of the Yangtze river.

Section	Types	No Dam			Dam		
		2010(ha)	2030(ha)	Siltation rate	2010(ha)	2030(ha)	Siltation rate
Y-C	Floodplains	190.78	190.38	-0.0021	123.87	101.70	-0.1790
	Water surface	455.45	455.65		543.26	520.44	
C-H	Floodplains	178.09	202.28	0.1358	163.28	181.95	0.1144
	Water surface	855.80	830.35		868.66	853.10	
H-N	Floodplains	256.32	268.40	0.0471	257.10	296.11	0.1517
	Water surface	1,848.12	1836.20		1,847.48	1658.94	
N-E	Floodplains	366.11	365.96	-0.0004	161.65	370.40	1.2914
	Water surface	1,336.01	1336.01		1,606.54	1210.27	

**FIGURE 6** | Siltation index trends with and without dam.

in Chenglingji-Hukou section. Results show that NP index of water surface decrease from 517 to 130, the index of floodplains decreased from 565 to 251. PLAND index of water surface decreased, and that of floodplains increased. AREA\_MN index of floodplains and water surface increased, but increasing was relatively small from 34.3 to 79.18 ha (Table 5).

### Hukou-Nantong Section

After the operation of the TGD, fragmentation of water surface area increased and floodplains decreased. NP index of surface water increased from 286 to 346, and PD index of the water surface increased from 0.12 to 0.14. NP index of floodplains decreased from 511 to 435, and PD index decreased from 0.21 to 0.18. PLAND index of water surface decreased, and that of floodplain increased. AREA\_MN index of water surface decreased from 665.9 to 537.72 ha, meanwhile floodplain increased from 109.39 to 140.78 ha, after the operation of the TGD (Table 6).

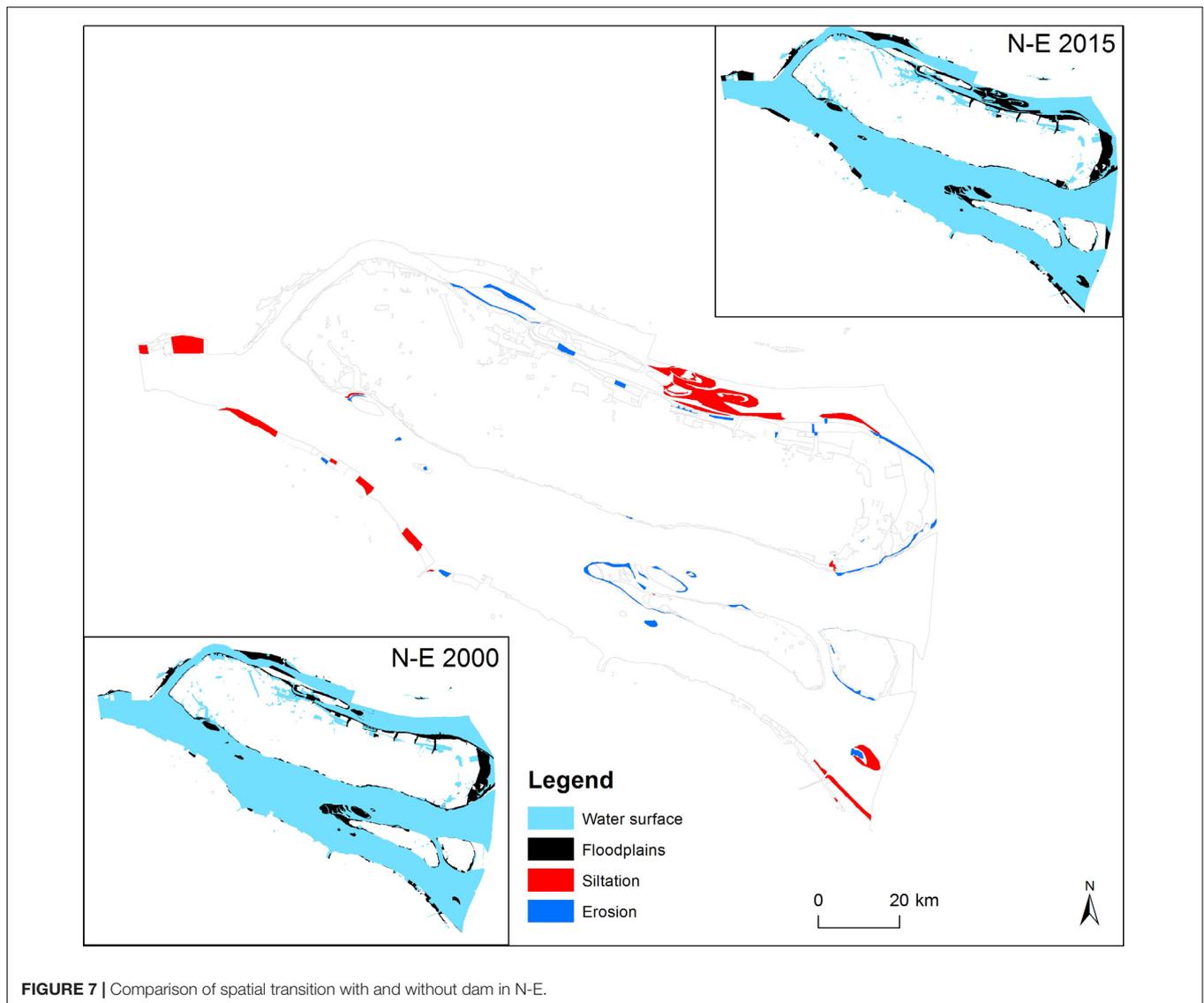
### Predictions of Wetland Changes Along Main Stream of the Yangtze River

CA\_Markov model prediction for 2030 indicates (Figure 6), under the operation of the TGD, immediate downstream, Yichang-Chenglingji section will become more eroded (from 0.0021 to 0.1790), in Chenglingji-Hukou section, siltation rate will be lowered from 0.14 to 0.11, whereas in Hukou-Nantong section, siltation rate will be increased from 0.05 to 0.15 (Table 7).

### Estuary Wetland Spatial Distribution and Landscape Pattern Changes

#### Estuary Wetland Spatial Structure Changes

Before the operation of the TGD, estuary experienced erosion, as transition rate from floodplains to water surface was 12.91%,



and rate of water surface to floodplains was 0.74%. After the operation of the TGD, transition rate from floodplains to water surface decreased to 12.77%, and water surface to floodplains transition rate increased to 3.83%. Overlay analysis indicated that change in floodplains displayed greater spatial heterogeneity, with the floodplains increased in the north but decreased in the south of Chongming Island. On the other hand, water surface areas increased around edges of floodplains and islands (**Figure 7**). Under no dam scenario, floodplains and water surface areas reached balance in 2010, and the floodplain areas reached 36,611 ha in 2010, and 36,596 ha in 2030. However, with the operation of the TGD, floodplains will increase from 16,165 ha in 2010 to 37,040 ha (**Table 7**).

### Estuary Wetland Landscape Changes

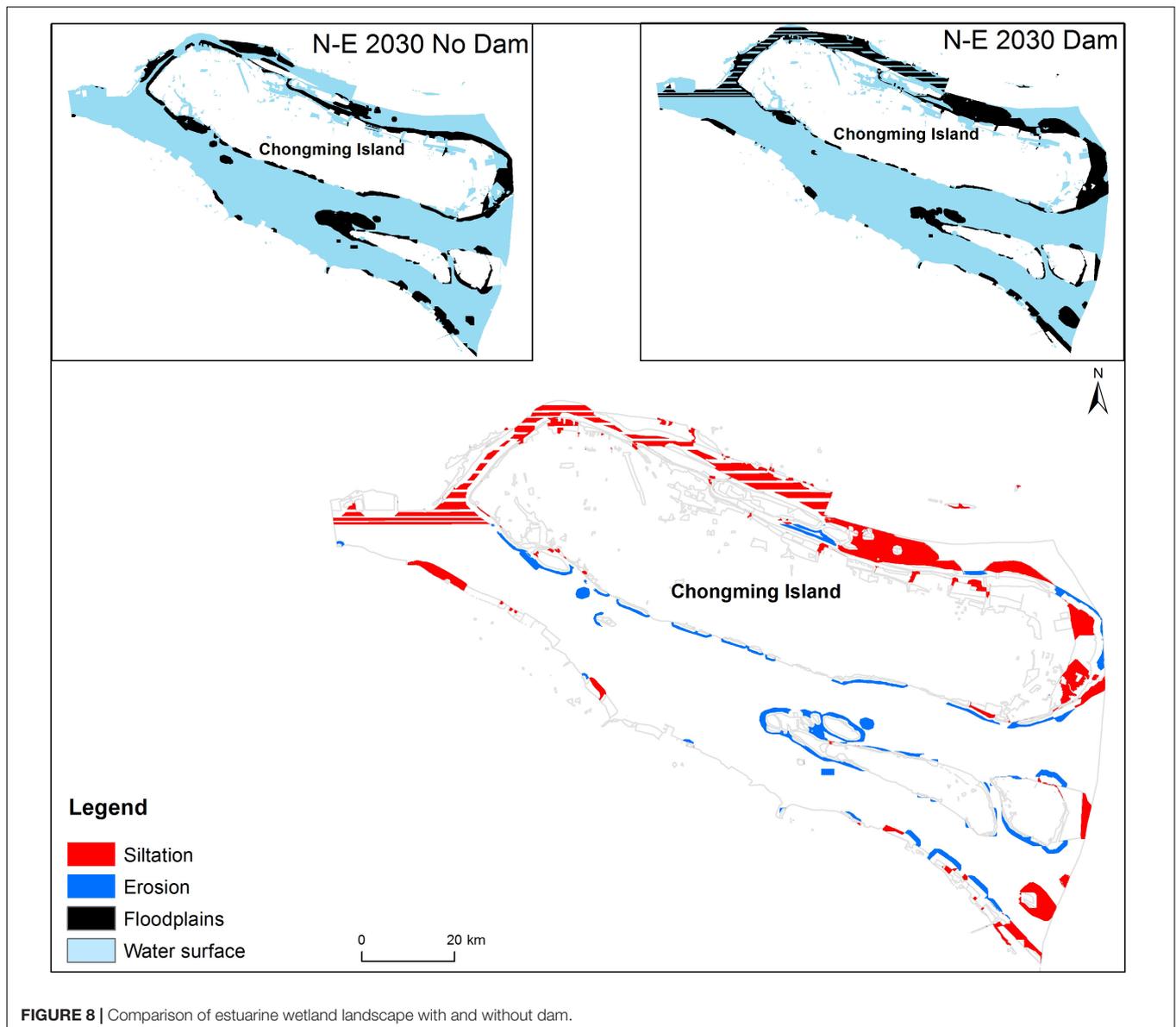
After the operation of the TGD, NP index of water surface decreased slightly from 537 to 523, NP index of floodplain increased from 359 to 520, and PD index of water surface

and floodplain showed the same trend. AREA\_MN index of water surface increased from 317.20 to 319.28 ha, and index of floodplains decreased from 57.28 to 47.31 ha.

## DISCUSSION

### Spatial Heterogeneity of Wetland Changes and Driver

After the operation of the TGD, changes of wetland in the middle and lower reaches of the Yangtze river displayed typical spatial heterogeneity, e.g., erosion at the immediate section downstream (Y-C section), relative stable river section between Dongting Lake and Poyang Lake (C-H section), siltation river section at the lower reaches of Yangtze river. The estuary displayed a complex pattern featured by erosion. Main driver was clear water releasing from the TGD which led to Y-C section erosion, confirms Yang et al. (2017) and Yuan (2014) findings, as well as the turning point



**FIGURE 8** | Comparison of estuarine wetland landscape with and without dam.

between Dongting Lake and Jingjiang River in hydrological regime shift (Lu et al., 2018). The relative stable status in floodplains and water surface areas between Chenglingji and Hukou may be the consequences of water and sediments dynamics of mainstream Yangtze and Dongting Lake, such stable status may continue for a period of time depending the speed of river bed erosion of the lower part of Y-C section. Siltation at H-N section remains similar to the period before the operation of the TGD, which is a continue processes and combination of Poyang Lake (Duan, 1993; Li, 2009; Su et al., 2019).

### Asymmetric Erosion Between Mainstream and Two Lakes

Dongting Lake is one of the largest freshwater lakes in China, and has been listed as one of the most important wetland

biodiversity region. It has been fed by four rivers and three major waterways from Yichang-Chenglingji section of Yangtze River (which is also called Jingjiang River), among which water inflow from Jingjiang River accounts for 50%. However, since the operation of the TGD, clear water released from the dam scoures river bed at Yichang-Chenglingji section, led to decrease of river water level, and shifted permanent river channels to seasonal rivers between Yangtze River and Dongting Lake. Thus causes asymmetric erosion between mainstream and its associated floodplain lakes, in particular, Dongting Lake (Lu et al., 2018). After the operation of the TGD, distribution of siltation and erosion along river changed from “bed scouring and beach building” to “erosion of both river bed and banks” (Xu et al., 2010; Dai and Liu, 2013). Asymmetric erosion between river and two lakes (Dongting and Poyang), also drives water level recession faster than before, and floodplains exposed when

TGD start fill in water, floodplain vegetation, e.g., *Carex* grow quickly in autumn before wintering geese arriving and caused food shortage (Guan et al., 2014, 2016). Shift of river channels between Jingjiang and Dongting Lake has significant impact on migration of fishes and Yangtze finless porpoises (Nabi et al., 2018). With the operation of the TGD in the future, combined with climate change effect, such asymmetric erosion in Jingjiang-Dongting Lake wetland complex may become even worse, and thus urgent mitigation measures are needed.

## Why Estuary Floodplain Areas Increase

Due to dam effect, the estuary lost 80% of the sediments (Cao and Wang, 2015), which should lead to erosion of the floodplains in the estuary, however, our model suggested the opposite. It is important to note that, the increased floodplain areas are mainly in the north river course, whereas, floodplain areas in the south river course are eroding as most studies suggested (Figure 8; Li, 2012). The reason why the estuary floodplains areas increase in the north, may not be linked to the operation of the TGD. Instead, such increase may cause by other two facts. Firstly, the morphological change in Chongming Island drives the northern river cause much less influence by hydrological forces of Yangtze river, and thus the water flow slows down and leads to siltation. Secondly, the sediments deposit in northern river course maybe transport by ocean currents.

## CONCLUSION

The operation of the TGD has significantly impact on downstream wetland ecosystems. Our study revealed the relationship with siltation patterns and wetland types transformation after the operation of the TGD, which are critically important to understand ecological characters dynamics

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After the operation of the TGD, floodplain in the estuary is driven by both the Yangtze river and ocean currents. The strong hydrological force and reduced sediments of Yangtze river drive erosion of the southern river course in the estuary, whereas, the weakened hydrological force in the northern river course attracts sedimentation.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

All authors contribute equally and agreed to be accountable for the content of the work.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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