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*Original Research*

# Wetland Area Change from 1986-2016 in the Dongting Lake Watershed at the Sub-Watershed Scale

**Mingming Geng[1, 2, 3#], Feng Li[1, 2 #], Ye Gao[4, 5], Zhengzui Li[5], Xinsheng Chen[1, 2], Zhengmiao Deng[1, 2], Yeai Zou[1, 2*], Yonghong Xie[1, 2**], Zhiqiang Wang[6]**

[1]Key Laboratory of Agro-Ecological Processes in Subtropical Region, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha, China
[2]Dongting Lake Station for Wetland Ecosystem Research, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha, China
[3]University of Chinese Academy of Sciences, Beijing, China
[4]College of Bioscience and Biotechnology, Hunan Agriculture University, Changsha, China
[5]Hydrology and Water Resources Survey Bureau of Hunan Province, Changsha, China
[6]School of Resource Environment and Safety Engineering, Hunan University of Science and Technology, Xiangtan, China

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**Abstract**

Wetlands are at high risk of degradation worldwide, but the driving mechanisms at different spatiotemporal scales vary and remain unclear. In this study, we used Landsat images from 1986 to 2016 to assess variations in natural wetlands in the five sub-watersheds of the Dongting Lake Watershed (DTLW): the Xiang River Watershed (XRW), Zi River Watershed (ZRW), Yuan River Watershed (YRW), Li River Watershed (LRW), and Dongting Lake Area (DTLA). We also explored the relationships between variations in wetland area and meteorological factors, along with anthropogenic factors. The total area of natural wetlands in the DTLW decreased by 124.12 $km^2$ (2.45%) over the study period, mainly due to the declines in lake and marsh areas. The wetland area decreased in the ZRW and DTLA, but increased in the other three. Mean annual precipitation (MAP) was highly variable over time, while mean annual temperature (MAT) increased significantly in all sub-watersheds. Overall, gross domestic product (GDP), population (POP), cultivated area (CA), and irrigation area (IA) increased from 1986 to 2016. MAT had the maximum correlation with lake and river area changes in the DTLW, while marsh area changes were best correlated with POP. The IA was the greatest contributor of lake area change in XRW, LRW, and DTLA, while the dominant factor for river area change differed

# These authors contributed equally to this work
*e-mail: zouyeai@163.com
**e-mail: yonghongxie@163.com

by sub-watershed. Overall, the most influential factors were meteorological changes in the DTLW as a whole, while anthropogenic activities were more important at the sub-watershed scale.

**Keywords**: Dongting Lake Watershed, wetlands, climate change, anthropogenic factors

## Introduction

The wetland ecosystem is essential for maintaining global ecological balance [1]. Globally, wetlands cover about 12.8 million km$^2$ (approximately 6.4% of total land area), accounting for 45% of total terrestrial ecosystem services [1, 2]. For instance, wetlands account for 15% of total terrestrial carbon storage and play an important role in water purification and erosion prevention [3-5]. Moreover, wetlands support high diversity of aquatic plants and animals (including many rare species). About 75% of the world's population lives close to wetlands [6].

In recent decades, with the ongoing global economic development and climate change, wetland areas have undergone a serious decline, attracting global scientific attention [6-8]. During the 20$^{th}$ century, about 50% of wetlands disappeared in North America, Europe, and Australia [9]. In China, total wetland area declined from 318,326 km$^2$ in 1990 to 257,922 km$^2$ in 2000; by the end of 2008, 33% of wetlands were lost compared to 1990 [10, 11]. Identifying the associated drivers of wetland degradation remains a task for relevant government departments to maintain ecological function of wetlands.

Reductions in wetland area are mainly caused by two factors, human activity and climate change, the effects of which vary greatly depending on the wetland type and scale [12]. Generally, changes in precipitation and temperature are most influential on a large scale, especially when seasonal precipitation is unevenly distributed [13]. For instance, higher temperatures have led to rising water levels in Europe causing the degradation of European coastal wetlands [14]. In comparison, human activity such as the conversion of wetlands to agricultural land or buildings due to urbanization, drives small-scale changes [15, 16]. In Beijing, for example, rapid urbanization and increasing quantities of wastewater is established to have detrimental impact on local wetlands [17].

The Dongting Lake Watershed (DTLW) in south-central China is the second largest watershed of the Yangtze River. It has a convenient geographic position and well-developed water system that has attracted many residents and industries, distributed along the banks of these lakes and rivers [18]. DTLW is an essential intersection zone between the One Belt and One Road and is the featured area of implementation for the Yangtze River Economic Belt Policy [19, 20]. However, rapid economic development and ongoing climate change have seriously reduced wetland area in this watershed, aggravating existing problems such as periodic droughts and flooding while reducing biodiversity [21-23]. These factors make the DTLW an important area for the implementation of Yangtze River Protection Policy [24]. In addition, DTLW is composed of several sub-watersheds [25]. These sub-watersheds are located in separate positions having different geological factors and climatic conditions, resulted in different wetland types among sub-watersheds [26]. The impact of human activities on these wetlands in different sub-watersheds may vary depending on the regional economic development and frequent population imbalance [27]. Hence, studying wetland variations of DTLW may help in shedding light on the reasons behind the changes in the wetland area at sub-watershed scale.

Remote sensing has been proven to be a useful tool in assessing natural resources [28]. It saves time and enhances the accuracy of classifying the nature of wetlands [29]. Remote sensing images have been widely used to evaluate water quality in subtropical marshes or swamps [30], to examine the changes in mangrove distribution [31]. In addition, remote sensing images have been widely used to monitor long-term environmental changes, which may accurately analyze the dynamic phenomena related to wetlands in space and time [32]. For example, researchers have applied remote sensing to explore long-term changes in China's lakes and the associated driving forces, suggesting that climate is the most important factor controlling lake changes in the Tibetan Plateau and the Mongolian Plateau. However, human activities resulted in serious impacts on lakes in the Eastern Plain [33, 34]. Hence, a study based on Landsat images can provide a fast and accurate method to understand the reasons behind long-term wetland area change of DTLW.

In this study, we used 168 Landsat images from 1986 to 2016 to investigate variations of natural wetlands (in areas≥1 km$^2$) in the DTLW; and to investigate meteorological and anthropogenic factors influencing changes in wetland areas within five sub-watersheds of the DTLW. In particular, we aimed to (1) examine the changes in the wetland areas as well as the change of meteorological and anthropogenic factors in the DTLW and five sub-watersheds from 1986 to 2016; (2) identify the dominant factors determining the wetland area change in DTLW and its five sub-watersheds.

## Materials and Methods

### Study Area

Dongting Lake Watershed (DTLW) (24°38′to 30°26′N; 107°16′to 114°17′E) is located in south-central

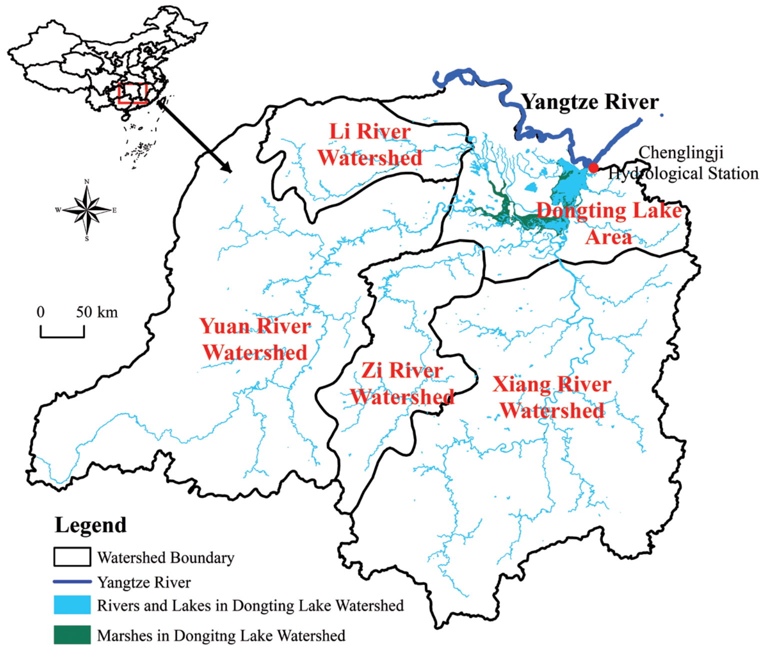


Fig. 1. Location of the study area.

China and accounts for 14% of the Yangtze River Basin (Fig. 1). It is composed of five sub-watersheds: the Xiang River Watershed (XRW), Zi River Watershed (ZRW), Yuan River Watershed (YRW), Li River Watershed (LRW), and Dongting Lake Area (DTLA). The DTLW is covered by plains in the northern part, mostly by hills, basins, and valleys in the middle part, and mainly by mountainous areas in the eastern, southern, and western parts. The total area of the DTLW is approximately 260,000 km$^2$, with elevations ranging from -26 to 2558 m above sea level. The area has a subtropical climate with mean annual temperature ranging from 14-18ºC. The mean annual precipitation is approximately 1376 mm, with most rain falling between June and September. The predominant land use types are forest and farmland. The urban and rural populations in the area are 30 million and 41 million, respectively [25].

## Collection of Landsat Images

We obtained 168 Landsat TM/ETM+/OLI images (30 m resolution) from the United States Geological Survey (www.usgs.gov/), using only images with the cloud cover of approximately 10% or less from seven periods (1986, 1991, 1996, 2001, 2006, 2011, and 2016). If images were unavailable for a given year, the previous or following years were used instead. Most images were collected from June to September due to easier interpretation during the flooding period of the region. All images were pre-processed (including radiation correction, geometric correction, re-projection, and study area extraction).

## Wetland Interpretation

We used the changes in the surface area of three dominant types of natural wetlands (lakes, rivers, and marshes; Table 1), to evaluate wetland changes in the DTLW (definitions of these three were based on the Ramsar Convention and the National Wetland Resources Survey and Detection Technical Regulations of China [35]. The satellite images were chosen and processed based on the framework by Xie [36]. A supervised method was used for the classifications of lake, river, and marsh wetlands. The spectral classes were merged into three representative classes (lake, river, and marsh wetlands) as defined in the classification scheme used as a training set for the supervised classification. Given the spatial resolution and spatial coverage of

Table 1. Classification of wetlands in the Dongting Lake Watershed.

| Category | Description |
|---|---|
| Lakes | Water-covered areas including shallow-water mudflats |
| Rivers | Permanent or intermittent running water (>90 m in width, >5 km in length) |
| Marshes | Permanent and seasonal marshes including moss, grass, shrubs and forest wetlands, saline marshes and green island wetlands, spring wetlands (water coverage<30%) |

Landsat images [34], these three wetland categories with areas ≥1 $km^2$ were extracted and rectified by comparing them with topographic maps, Google Earth images (1.06 m resolution), field survey data, and other reference materials in ArcGIS. Classification accuracy was evaluated using standard error matrix (confusion matrix) [37] that reported overall classification accuracies, and Kappa chance correction statistics were prepared for each image to determine the accuracy of the classifications. We then calculated the changes in the wetland areas in the DTLW over time.

### Meteorological and Anthropogenic Factors

We chose mean annual temperature (MAT; in degrees Celsius) and mean annual precipitation (MAP; in millimeters) to represent meteorological characteristics (obtained from the National Meteorological Information Center, China (http://data.cma.cn/)), and gross domestic product (GDP), population (POP), cultivated area (CA), and irrigated area (IA) to represent anthropogenic activity (obtained from the statistical yearbooks of the relevant provinces), using data for the same years as the Landsat images.

### Statistical Analysis

We firstly documented the change in the wetland area across the DTLW over time. We then documented the trends of six explanatory variables (i.e., MAT, MAP, GDP, POP, CA, and IA), and performed analysis of variance (ANOVA) to indicate the changing strength during study period, which was evaluated for statistical significance at $\alpha$ = 0.05. Finally, we conducted a gray correlation analysis to quantify the relative contribution of each of the six variables to the wetland area change during the study period. SPSS 23.0 (Statistical Product and Service Solutions, USA) and DPS (Data Processing System, version 7.0) were used as calculation platforms.

## Results

### Wetland Area Change

Supervised classification and accuracy assessments were performed for all images. The classification accuracies were all over 85%, and Kappa statistic values of the study period classifications ranged from 0.86-0.90.

The results showed that the lake and marsh areas in the DTLW were mostly located in DTLA (accounts for 90.67%); the wetland type in other sub-watershed was river (Fig. S1). The total area of wetlands in the DTLW displayed an undulating trend during the study period, which increased significantly from 1991 to 2006 (398.85 $km^2$), then decreased sharply from 2006 to 2011 (-322.72 $km^2$) (Fig. 2). The total area of natural wetlands in DTLW decreased significantly from 5075.88 $km^2$ in 1986 to 4951.76 $km^2$ in 2016, with a great rate of decrease (2.45%) mainly due to the loss of lake and marsh (change in total area of 134.09 $km^2$ (4.69%) and

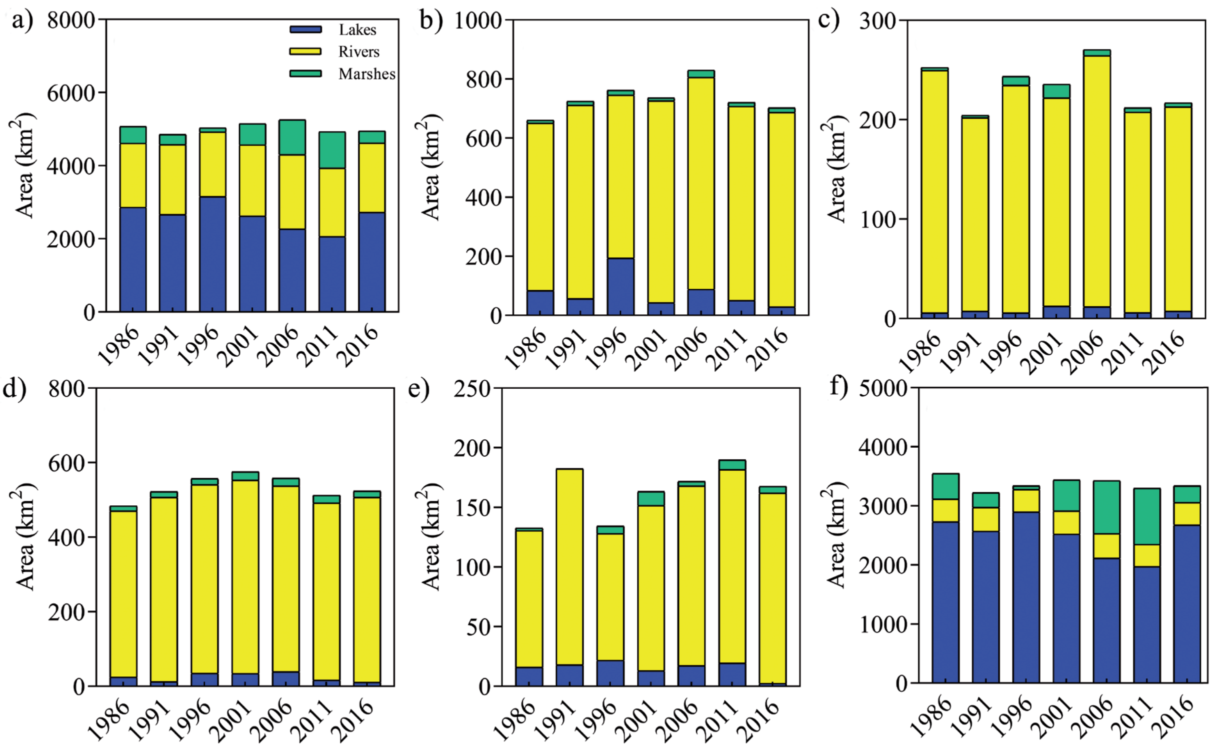


Fig. 2. Changes in wetland area by type from 1986-2016. a) Dongting Lake Watershed, b) Xiang River Watershed, c) Zi River Watershed, d) Yuan River Watershed, e) Li River Watershed, f) Dongting Lake Area.

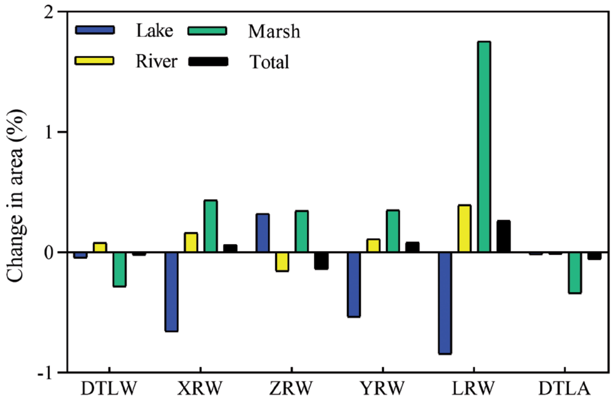


Fig. 3. Changes in wetland area in sub-watersheds from 1986–2016. Dongting Lake Watershed (DTLW), Xiang River Watershed (XRW), Zi River Watershed (ZRW), Yuan River Watershed (YRW), Li River Watershed (LRW), and Dongting Lake Area (DTLA).

131.88 km$^2$ (28.69%), respectively) (Fig. 3). However, the river area increased by 8.08% during the same period.

Moreover, area changes differed significantly by sub-watershed from 1986 to 2016. The wetland area decreased in ZRW (-14.15%) and DTLA (-5.85%), but increased in XRW (6.26%), YRW (8.39%), and LRW (27.89%) (Fig. 3). In addition, lake area reduction mainly occurred in XRW (-65.79%), YRW (-53.79%), LRW (-84.57%), and DTLA (-1.98%) (Fig. 3). The marsh area increased in XRW (43.26%), ZRW (34.74%), YRW (35.23%), and LRW (175.36%), while it decreased considerably in DTLA (-34.15%) (Fig. 3). River area increased in XRW (16.26%), YRW (11.02%), and LRW (39.28%), but decreased in ZRW (-15.81%) and DTLA (-1.54%) which showed an opposite trend compared with that for the total river in the DTLW (Fig. 3).

## Changes in Meteorological and Anthropogenic Factors

MAP showed an undulating trend in the five sub-watersheds, ranging from 1163.00-1700.96 mm (Fig. 4a). MAT increased significantly over time for all sub-watersheds (Fig. 4b). Total POP gradually increased from 1986 to 2006 and then decreased from 2006 to 2011 before rising again by 2016

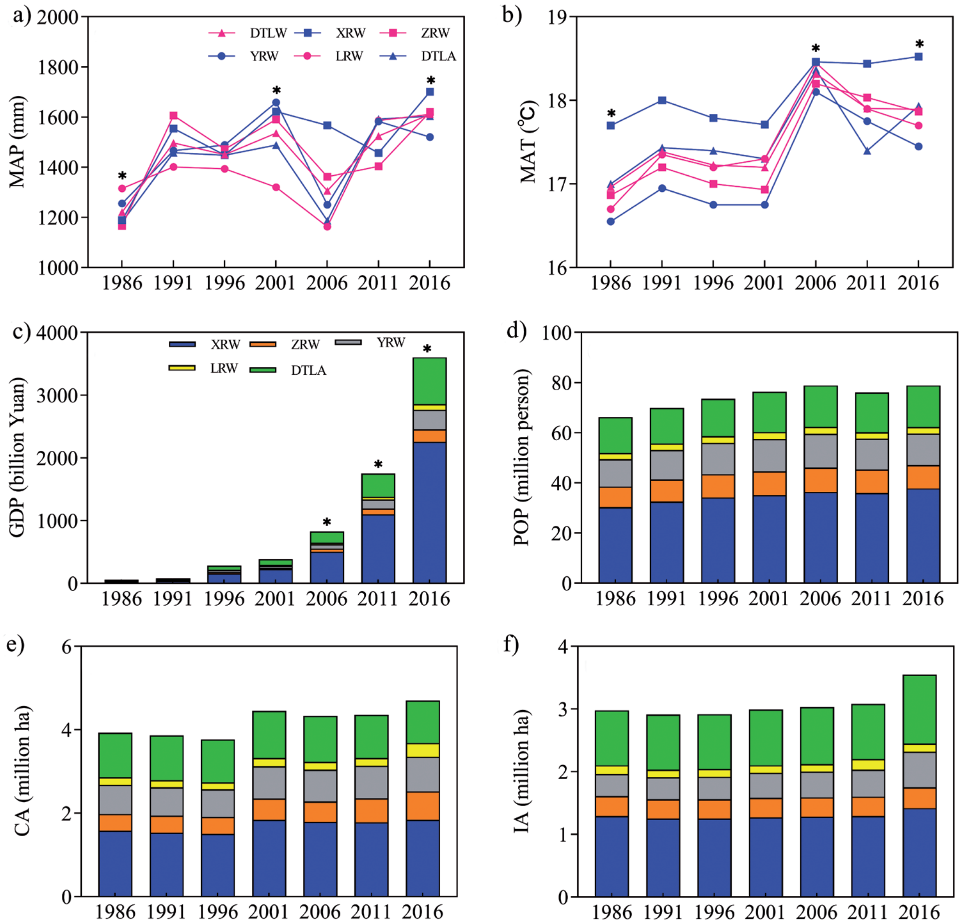


Fig. 4. Changes in meteorological and human factors by study area from 1986-2016: a) mean annual precipitation (MAP), b) mean annual temperature (MAT), c) gross domestic product (GDP), d) population (POP), e) irrigated area (IA), f) cultivated area (CA). Significant changes are marked with an *asterisk* ($p<0.05$).

Table 2. Gray correlation between wetland area and meteorological/human factors in the Dongting Lake Watershed and its sub-watersheds. (mean annual precipitation (MAP), mean annual temperature (MAT), gross domestic product (GDP), population (POP), irrigated area (IA), cultivated area (CA)).

| Watersheds | Factors | Lakes | | Rivers | | Marshes | |
|---|---|---|---|---|---|---|---|
| | | Correlation | Sort | Correlation | Sort | Correlation | Sort |
| Dongting Lake Watershed (DTLW) | MAP | 0.790 | 4 | 0.766 | 5 | 0.485 | 2 |
| | MAT | **0.910** | **1** | **0.888** | **1** | 0.447 | 4 |
| | GDP | 0.284 | 6 | 0.269 | 6 | 0.366 | 6 |
| | POP | 0.822 | 3 | 0.835 | 2 | **0.491** | **1** |
| | CA | 0.778 | 5 | 0.778 | 4 | 0.469 | 3 |
| | IA | 0.871 | 2 | 0.824 | 3 | 0.435 | 5 |
| Dongting Lake Area (DTLA) | MAP | 0.684 | 4 | 0.837 | 3 | 0.466 | 3 |
| | MAT | 0.720 | 2 | **0.885** | **1** | 0.445 | 4 |
| | GDP | 0.304 | 6 | 0.267 | 6 | 0.379 | 6 |
| | POP | 0.695 | 3 | 0.821 | 4 | 0.481 | 2 |
| | CA | 0.650 | 5 | 0.781 | 5 | **0.501** | **1** |
| | IA | **0.731** | **1** | 0.856 | 2 | 0.435 | 5 |
| Xiang River Watershed (XRW) | MAP | 0.457 | 5 | 0.813 | 4 | 0.603 | 3 |
| | MAT | 0.497 | 2 | 0.825 | 3 | 0.606 | 2 |
| | GDP | 0.310 | 6 | 0.264 | 6 | 0.259 | 6 |
| | POP | 0.484 | 4 | 0.826 | 2 | **0.608** | **1** |
| | CA | 0.496 | 3 | **0.844** | **1** | 0.591 | 4 |
| | IA | **0.497** | **1** | 0.765 | 5 | 0.586 | 5 |
| Zi River Watershed (ZRW) | MAP | 0.512 | 4 | 0.648 | 4 | 0.441 | 2 |
| | MAT | 0.523 | 2 | 0.748 | 2 | 0.426 | 5 |
| | GDP | 0.260 | 6 | 0.270 | 6 | 0.334 | 6 |
| | POP | **0.546** | **1** | 0.738 | 3 | 0.432 | 3 |
| | CA | 0.508 | 5 | 0.579 | 5 | 0.429 | 4 |
| | IA | 0.514 | 3 | **0.755** | **1** | **0.449** | **1** |
| Yuan River Watershed (YRW) | MAP | 0.452 | 4 | 0.820 | 3 | 0.662 | 4 |
| | MAT | 0.466 | 3 | 0.854 | 2 | 0.664 | 3 |
| | GDP | 0.259 | 6 | 0.277 | 6 | 0.287 | 6 |
| | POP | 0.474 | 2 | **0.898** | **1** | **0.690** | **1** |
| | CA | **0.478** | **1** | 0.809 | 4 | 0.677 | 2 |
| | IA | 0.431 | 5 | 0.710 | 5 | 0.654 | 5 |
| Li River Watershed (LRW) | MAP | 0.592 | 4 | **0.711** | **1** | **0.398** | **1** |
| | MAT | 0.609 | 2 | 0.709 | 2 | 0.330 | 5 |
| | GDP | 0.326 | 6 | 0.295 | 6 | 0.351 | 3 |
| | POP | 0.594 | 3 | 0.667 | 3 | 0.336 | 4 |
| | CA | 0.507 | 5 | 0.627 | 4 | 0.319 | 6 |
| | IA | **0.662** | **1** | 0.622 | 5 | 0.356 | 2 |

(Fig. 4d). GDP increased significantly from 1986 to 2016 (Fig. 4c), while IA slightly decreased in 1996, rose slightly in 2011, and rose sharply by 2016 (Fig. 4f). CA declined slightly from 1986 to 1996, rose by 2011, declined from 2001 to 2011, and rose again by 2016 (Fig. 4e).

### Gray Correlation Analysis

MAT had the highest correlation with lake and river area in the DTLW, with a correlation coefficient of 0.910 and 0.888, respectively (Table 2). The dominant factor determining the area change of marsh in the DTLW was POP, followed by MAP and CA.

The greatest contributor to the lake area changes in XRW, LRW, and DTLA was IA (correlation coefficients ranging from 0.497-0.731), with POP being the greatest contributor in ZRW (0.546) and CA being the greatest contributor in YRW (0.478). The river area was affected by many different factors, none of which is clearly dominant in all sub-watersheds. Marshes were mainly affected by POP, IA, and CA in the XRW, ZRW, YRW and, DTLA, with correlation coefficients of 0.608, 0.449, 0.690, and 0.501, respectively.

## Discussion

From 1986 to 2016, a total of 124.12 km$^2$ of wetland area was decreased in DTLW, with the marsh area accounting for 28.69% of the total reduction area. This suggests a serious shrinkage of wetlands in DTLW during the study period, with the matching patterns observed in other regions. Junk confirmed that 30-90% of the world's wetlands have already been destroyed or strongly exploited [6]. In the United States, for example, wetlands in the Willamette Valley suffered a 314 ha reduction in area mainly due to the encroachment of agriculture and quarries [16].

Our results also confirmed that wetland area changes had varying trends between different sub-watersheds. During the study period, the wetlands located in XRW, YRW, and LRW increased (mainly due to the river increases), while those in ZRW and DTLA decreased (mainly due to the decrease in all three categories). These results indicated that the change in wetland areas might depend on the type and scale of wetland.

Wetland reduction is mainly due to the combined effect of climate change and human interference; the key factors determining wetland degradation vary significantly by region, scale, and wetland type [38, 39]. In the DTLW, MAT increased by 0.94ºC from 1986 to 2016 and showed maximum correlation with wetland changes. This suggests that wetland degradation was mainly caused by meteorological factors, as higher temperatures could aggravate evaporation and cause drought, leading to a reduction in the wetland area. In comparison, MAT in whole of mainland China rose by 1.24ºC over the last 55 years, due to global warming [40]. Similar results were reported in the Great Hing'an Mountains of China, where permafrost wetlands degenerated rapidly with increasing temperature [41]. Furthermore, high temperatures could also lead to extreme rainfall, potentially fragmenting wetlands and exacerbating degradation [42]. In this study, MAP displayed clear interannual fluctuations during the study period. The combination of increasing temperature and highly variable precipitation could intensify the frequency and effects of drought and flood, leading to increased fragility and degeneration of wetlands in the DTLW.

Our results also confirmed that anthropogenic factors played an important role in determining wetland area change, although their influence varied by sub-watershed. This suggests that the dominant factor might vary depending on the scale of the study. During the study period, all factors (i.e., GDP, POP, IA, and CA) increased significantly in all sub-watersheds. For example, water consumption could increase as a result of rapidly increasing population, which also requires increasing amounts of cultivated land to ensure continuously increasing crop yield demands. Road and building constructions can also lead to the decline in the wetland areas. Previous research in other regions has confirmed that human activity affects wetland loss, potentially having a stronger effect than climatic factors [38]. For example, in Inner Mongolia, coal mining and irrigation resulted in the disappearance of 145 lakes with a total area of 1259.6 km$^2$ from 1987 to 2010 [34]. Wu also suggested that human activity plays an important role in the modification of coastal wetlands through direct exploitation in Shanghai [43].

Although the water level has not been investigated in this study, it is an important factor influencing marsh area in Dongting Lake (located in DTLA) which is a river-connected lake with significant water level changes (8-12 m) [44]. Hence, it deserves further investigation. Generally, the marsh area in Dongting Lake changed dramatically with a reduction during flooding (wet) seasons and an increase during un-flooding (dry) seasons within the same year, and also from year to year. For instance, marsh area increased significantly from 63.77 km$^2$ in 1996 (extreme flooding) to 925.83 km$^2$ in 2011 (extreme drought), with water level ranging from 25.16 m to 23.63 m (Fig. 2). Xie confirmed the similar increasing trends in marsh wetlands due to significant water level reduction in East Dongting Lake from 1995 to 2011 [36].

## Conclusions

Under the background of the continuous global decline of wetlands, both in area and in quality, investigating the wetland changes and the factors influencing these at different spatiotemporal scales is essential for wetland protection. This study aimed to investigate and reveal variations in natural wetlands (lakes, rivers, and marshes) in areas ≥1 $km^2$ in the (DTLW) and its five sub-watersheds. We explored the interrelationship among wetland variation and meteorological/anthropogenic factors. The results showed that the wetland area in the DTLW declined significantly from 1986 to 2016, though the exact pattern varied among sub-watersheds. This was mainly caused by meteorological factors, although human activity played a varying but important role in individual sub-watersheds. The results suggested that studies on wetland degradation and its driving mechanisms need to be carried out at different scales, in order to achieve a comprehensive understanding of the issue. With increasing demands for energy and foods from DTLW, combined with the anticipated drier and warmer climate, these wetland areas are expected to shrink further. Further effective actions, such as controlling the construction of dams and restoring farmlands to grasslands, are urgently required to preserve these valuable wetlands, where restricting devastating impacts is a great challenge.

## Supplementary Material

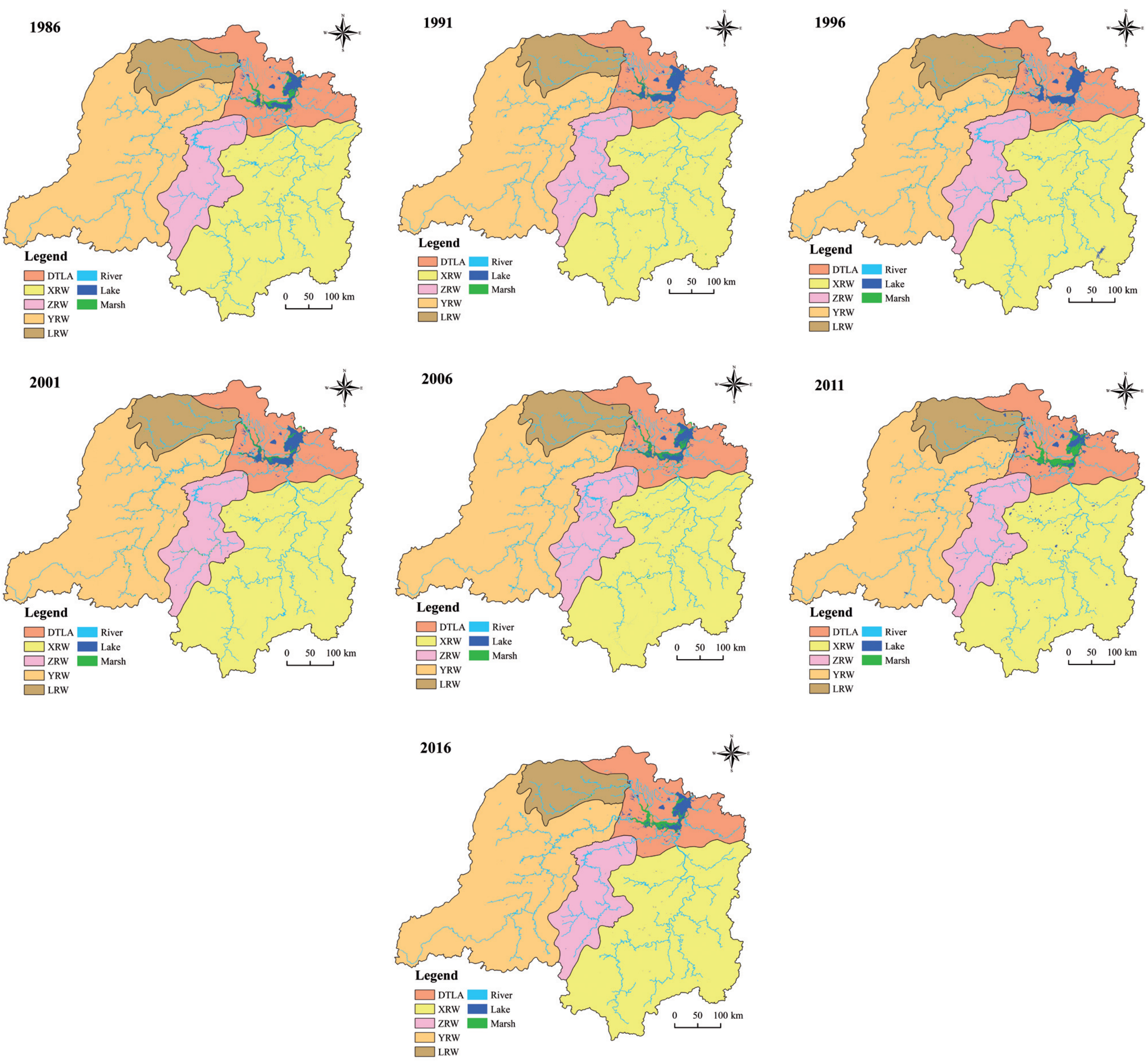


Fig. S1. Wetland type classification in the Dongting Lake Watershed from 1986 to 2016.

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## Conflict of Interest

The authors declare no conflict of interest.

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