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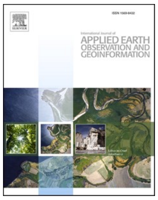

Centennial-scale study on the spatial-temporal evolution of riparian wetlands in the Yangtze River of China

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ABSTRACT

Wetlands play a crucial role in maintaining the ecosystem function and ecological security of the Yangtze River. This study collected multi-source remote sensing image data, including historical topographic maps, Landsat, and Gaofen-2, and established a set of classification and interpretation standards for riparian wetlands in the Yangtze River. The artificial visual interpretation was used to reconstruct the spatial–temporal evolution process of riparian wetlands in the Yangtze River over the past century, clarified its characteristics, and analyzed the impact of climate change, damming, and land development and wetland policies. The results showed that: (1) Riparian wetlands in the Yangtze River generally showed a decreasing trend. Among them, those in the upper reaches showed a decreasing trend, those in the middle reaches increased during 1930–1980 s and decreased since the 1980 s, and those in the lower reaches fluctuated. (2) The spatial–temporal evolution can be divided into three characteristic areas. In the estuary (Shanghai and the coastal), riparian wetlands first decreased and then increased, and changed significantly. The three provinces in the downstream (Jiangsu, Anhui, and Jiangxi) and Chongqing showed a decreasing trend with great changes. The three provinces in the middle and upstream first increased and then decreased with little change. (3) The impact of wetland exploitation and protection policies can be divided into three stages: no wetland protection policies (before 1986), wetland protection policy development (1986–1998), and strict protection (1998–present). This study provides an important scientific foundation for the implementation of coordinated protection of the Yangtze River.

1. Introduction

Wetlands, referred to as “kidneys of the earth”, are one of the most important global ecosystems, as they play a vital role in maintaining regional ecological safety, global ecological balance, and biodiversity. There are 12.1×10^6 km^2 of wetlands around the world, accounting for only 6% of the total land area, but they provide 40.6% of the ecosystem services globally (De Groot et al., 2012; Costanza et al., 2014; Gardner and Finlayson, 2018). However, threatened by human activities, wetlands have been decreasing globally, and their ecological functions and services have also been degrading. Since 1970, global wetland area has decreased by 35% (Reid et al., 2005; Gardner and Finlayson, 2018).

Rivers are the cradle of civilizations, as the four great civilizations all originated close to rivers, and riparian wetlands have been significantly impacted by human development and construction. The Yangtze River is the mother river of China, and its riparian wetlands have faced several serious environmental issues. According to available statistics from the department of forestry, compared with the 1950 s, the area of wetlands in the middle reaches of the Yangtze River has decreased by 70% (Xu et al., 2017), owing to reclamation. High-intensity development and the lack of scientific management have negatively impacted the aquatic environment and ecology, such as increased pollution along the riverbank, decreased water quality, a strained river–lake relationship, and increased eutrophication (Yang and Xu, 2020). Wetland degradation affects the habitat function of wild animals and plants, and as the biodiversity index continues to decrease, many rare species in the Yangtze River are threatened with extinction. The number of eggs and fry of Chinese sturgeon, Darby’s sturgeon (Yangtze sturgeon), Chinese high fin banded shark, and the “four major Chinese carps” have decreased significantly. The threatened fish species in the upper reaches

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of the Yangtze River account for 40% of all species in China; baiji has become functionally extinct, and the finless porpoise is facing a critical situation[1]. Relevant studies have shown that between 2000 and 2015, biodiversity maintenance services declined in more than half of the Yangtze River Belt cities (Xu et al., 2018). Serious ecological and environmental issues have posed threats to the Yangtze River as a national strategic water source and an important ecological support belt.

Understanding the spatial–temporal evolution and driving mechanisms of riparian wetlands plays an important role in wetland protection. In recent studies, various methods have been used to map the distribution of wetlands, including traditional field investigations and remote sensing interpretation methods (Niu et al., 2012; Nguyen et al., 2018; Mahdianpari et al., 2020). Machine learning algorithms, such as random forest, object-oriented method and support vector machine (Han et al., 2015; Zhou et al., 2019; Wang et al., 2020), have also been applied to wetland extraction. Some global or regional wetland datasets were established, mainly including land use data such as Globeland 30, GLC, and Globcover (Hu et al., 2017), coastal aquaculture ponds in India (Prasad et al., 2019), salt marshes along the Atlantic coast in America (Campbell and Wang, 2019; Campbell and Wang, 2020), mangrove forests in Mexico (Cissell et al., 2018), and lakes on Tibet Plateau in China (Mao et al., 2018), etc. Chinese scholars have focused on Baiyangdian lake (Bai et al., 2013; Zhang et al., 2016), wetlands in Sanjiang Plain (Mao et al., 2016), coastal wetlands in river deltas (Ai, 2018; Li et al., 2019), and lakes in the middle and lower reaches in the Yangtze River (Li et al., 2022), involving wetland types such as salt marshes, mangroves, and *Spartina alterniflora*.

The studies on the Yangtze River mainly focus on wetlands in the source area (Du et al., 2015), lakes in the middle and lower reaches (Li et al., 2022) and coastal wetlands in river delta (Ai, 2018; Sun et al., 2018). There are few studies on wetland evolution of the Yangtze River, such as wetland evolution in local section of the mainstream (Zhou et al., 2006). There is a lack of study on the spatial–temporal evolution of riparian wetlands in the whole Yangtze River. At present, the wetland data covering the whole Yangtze River and with good quality include data from wetland surveys carried out by the National Forestry and Grassland Administration of China, national wetland data from 1990 to 2008 published by Niu et al. (Niu et al., 2012), the marsh wetlands (Mao et al., 2020), mangroves (Jia et al., 2018; Jia et al., 2019), *Spartina alterniflora* (Liu et al., 2018; Mao et al., 2019), and coastal aquaculture ponds data (Ren et al., 2019) published by Wang et al., and land use data such as Globeland 30 and the National Land Survey. However, most of the above datasets only focus on a certain wetland type or the wetland classification systems are relatively rough. For example, Globeland 30 data only has wetland and water(Hu et al., 2017). The classification systems of Niu et al. (2012) and wetland surveys(Tang et al., 2013) referred to the provisions of the Convention on Wetlands and the National Forestry and Grassland Administration of China. These above two wetland datasets involved many wetland types, while riparian wetlands were excluded. In addition, the span of these datasets was within 50 years (after the launch of the Landsat Satellite Program), thus historical topographical maps have not been fully utilized and there is a lack of centennial-scale study, especially for the impacts of intensive human activity on wetlands degradation since the founding of the People's Republic of China. It's significant to conduct a centennial-scale study on riparian wetlands change for the strategy of well-coordinated environmental conservation and avoiding excessive development in the Yangtze River.

Therefore, this study aimed to carry out a riparian wetland ecological survey in the Yangtze River based on remote sensing data and historical topographic maps using digital technology methods, and developed a dataset for centennial-scale spatial–temporal wetland evolution (hereafter referred to as "riparian wetland data"). The characteristics of the wetland evolution and the impact of climate change, damming, and policies on centennial-scale were discussed. This study has provided reliable basic data and a scientific foundation for implementing a national strategy of Yangtze River wetland protection.

2. Material and methods

2.1. Study area

The study area is the Yangtze River from Yibin to the estuary, approximately 104°E–122°E and 29°N–33°N (Fig. 1). It covers part of the upper reaches, and all of the middle and lower reaches in the Yangtze River, which flows from west to east through eight provinces and cities including Sichuan, Chongqing, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, and Shanghai.

2.2. Data source and processing

The data from remote sensing images and historical topographic maps used in this study include Gaofen-2 (2017), Landsat TM (1980 s, 1990 s, 2000 s, and 2010 s), and topographic maps (1930 s and 1970 s). The data sources and processing methods are listed in Appendix 1–3. The topographic maps of most of the upper reaches and a small part of the middle and lower reaches are missing in the 1970 s (Fig. 2), and the remote sensing images and topographic maps are complete for the remaining years.

With different precipitation levels, the area and morphology of riparian wetlands can vary considerably, so in some regions, the area of wetlands may be smaller in the normal than wet periods. To reduce the uncertainty caused by precipitation, remote sensing imaging data of both the normal and wet periods have been used, and the exposed parts in both periods have been classified as riparian wetlands. When choosing remote sensing images, the following principles were followed: (1) For the time series study results to be comparable, 1985, 1995, 2005, and 2017 were used as the reference years for images between the 1980 s and 2010 s, and missing images were supplemented by no-cloud images from the closest year in the same decade. (2) Images from May to September were used as wet period images, and those from October to November and March to April were used as normal period images. In addition, since the wetland area of the dry and normal periods are similar in remote sensing images, those from December to February (dry period) were used instead when there are no suitable images from the normal period. (3) Images of normal and wet periods were selected from the same hydrological year as far as possible, and years of serious drought or flooding were avoided. (4) If image quality differed significantly at the junction of two remote sensing images, images with less cloud blockage and higher quality were chosen, and if the quality was similar, images where wetland area was larger were chosen.

2.3. Classification and interpretation of riparian wetlands

2.3.1. Riparian wetland classification

The Ramsar classification system is the most widely applied global wetland classification system at present. It comprehensively considers the distribution scope and characteristics of wetlands in each Contracting Parties, and carries out the classification from the perspective of conducive to wetland management(Li and Liu, 2014). The Second National Wetland Survey of China classified wetlands based on the Ramsar classification system and the needs of the general survey of wetland resources in China, comprehensively considering the factors such as wetland causes and hydrogeology, and published the Wetland Classification of China (Tang et al., 2013). However, riparian wetland types were not considered in this classification. Riparian wetlands were

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[1] Ministry of Ecology and Environment, National Development and Reform Commission, Ministry of Water Resources of the People's Republic of China, 2017, Ecological Environmental Protection Plan for the Yangtze River Economic Belt.

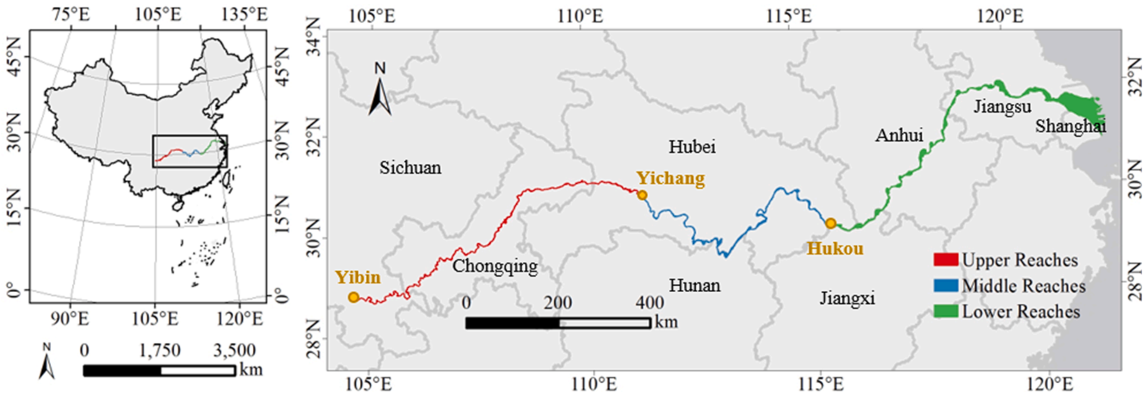

Fig. 1. Location of the study area.

Fig. 2. Missing topographic maps from the 1970 s.

scattered in floodplain wetland, delta, sandbar, sand island, herbaceous swamp and other wetland types. In addition, the floodplain in the reservoir was not considered. The Third National Land Survey of China merged floodplain wetland, seasonal or intermittent river, lake, lagoon, delta, sandbar, sand island, and reservoir pond deducting reservoir water surface or pit pond water surface into inland tidal flat. Although there are still some differences between inland tidal flat and riparian wetland, the wetland classification in the Third National Land Survey of China as the latest wetland classification system has been the most appropriate classification for the study.

Riparian wetlands in this study have been defined as “the flooded lowland submerged by the flood level of rivers and reservoirs, excluding the lowland that has been utilized”, according to the wetland classification system in the Third National Land Survey of China (Technical Committee on Geographic Information Standardization of China, 2017). Riparian wetlands at different locations experience different natural and artificial stresses and have different ecological significance. Based on their positional relationship with the land, they have further been classified into two types, biantan and island wetlands, for research results to be more applicable to the protection, management, and ecological restoration of riparian wetlands in the Yangtze River. Among them, biantan wetlands refer to the wetlands on both sides of the Yangtze River that are closely connected to the land; island wetlands include river islands, sand islands, shoals, and ecological islands, excluding utilized land.

2.3.2. *Interpretation of riparian wetlands*

Based on compilation specifications of 1:250,000 topographic maps (Technical Committee on Geographic Information Standardization of China, 2008b) and 1:100,000 topographic maps (Technical Committee on Geographic Information Standardization of China, 2008a) and considering the actual situation, the minimum identification area of riparian wetlands was set to an area of 10,000 m^2, a width of 100 or 200 m, and a length of 1,000 m for low and narrow wetlands.

The interpretation of riparian wetlands has followed the reduction method, with technical details shown in Fig. 3. First, based on the Gaofen-2 images in 2017, the Yangtze River shorelines were extracted, and then based on the Landsat images of the 2010 s, the utilized land beyond the shoreline was extracted as riparian wetlands. Second, when interpreting the 1980–2000 s images, adjustments were made using the next decade as the benchmark. For example, the interpretation results of the 2010 s were used as a reference for the 2000 s to adjust when conversions between utilized and unutilized land and natural evolution (change of the river course, formation of oxbow lakes, and sediment deposition and erosion) occurred. Among them, the natural evolution needs to be combined with multi-phase images for comprehensive judgment (Appendix 6). For the 1930–1970 s, historical topographic maps were used: topographic maps were scanned, georeferenced, and spliced together to extract shoreline data and the unutilized land beyond the shoreline was extracted as riparian wetlands. The areas that lack information on the map were determined in reference to the riparian wetland data of the following decade. The specific shoreline extraction and wetland determination methods are shown in Appendix 4 and 5.

2.4. *Data accuracy evaluation*

In this study, field verification and high-precision wetland dataset cross-validation methods were used to evaluate data accuracy. In late September 2020, field verification was carried out on 35 wetlands that were either typical or had high uncertainty along the middle and lower reaches of the Yangtze River (Appendix 7), and the field verification accuracy reached 89.3%.

In addition, the shared 2-m pixel high-precision Yangtze River Delta wetland data from the Class A strategic pilot “Beautiful China” Science and Technology Project of the Chinese Academy of Sciences (hereafter referred to as “water wetland data”)[2] were used to cross validate the

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[2] The data sources from “Strategic Pilot Science and Technology Project of Chinese Academy of Sciences (Class A): Demonstration of Collaborative Management and Comprehensive Governance Regional Ecological Environment in the Yangtze River Delta (XDA23020000)”.

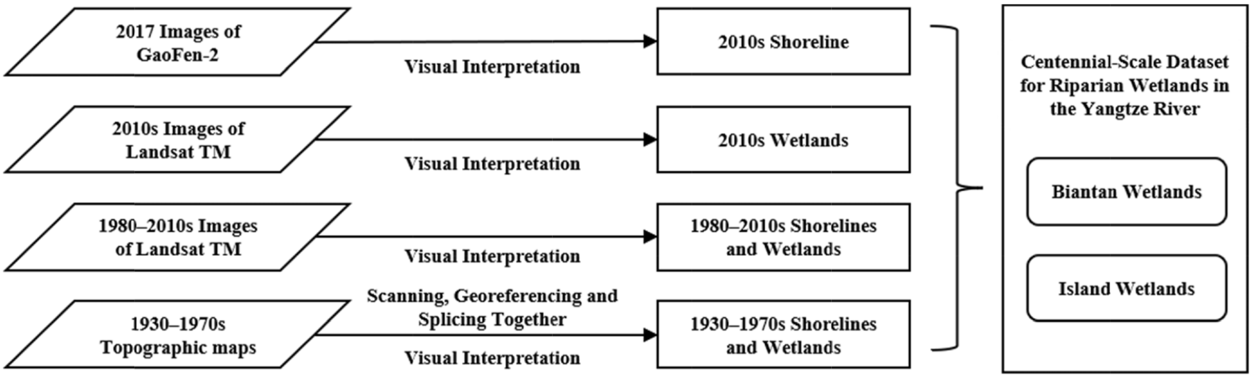


Fig. 3. Technological Roadmap of Remote Sensing Image Interpretation in Different Periods.

riparian wetland data of the 2010 s from this study. First, the blank area in the water wetland data was filled in as "non-wetland". Second, projection conversion and cropping were carried out to make the projection and spatial scope of the two datasets consistent. Then, they were converted into 30 m resolution raster data. Finally, wetland type was converted according to Table1. The area consistency coefficient and spatial position consistency coefficient were used for testing as shown in formulas (1) – (3).

$$C = |1 - (K_i - N_i)/N_i| \times 100\% \tag{1}$$

Where C is the area consistency coefficient, K_i is the area of the i-th type of land in the test set, N_i is the area of the i-th type of land in the reference data. The higher the consistency coefficient, the better the area consistency and vice versa.

$$A_i = T_i/[(M_i + N_i)/2] \times 100\% \tag{2}$$

$$B_i = \sum_i T_i/[(M_i + N_i)/2] \times 100\% \tag{3}$$

Where A_i and B_i represent the spatial consistency and overall consistency of different types of wetlands, respectively, T_i is the number of pixels that are the i-th type in two different datasets at the same location, M_i and N_i are the numbers of i-th type pixels in data product M and N, respectively. The higher the spatial consistency coefficient, the higher the spatial consistency and vice versa.

Results of the consistency test showed that the area consistency of tidal flat wetlands was poor, and the spatial consistency was average, whereas the area and spatial consistency of water wetlands and non-wetlands were relatively high (Table 2). The tidal flat wetlands were confused with water wetlands, and non-wetlands were confused with tidal flat wetlands (Table 3). The errors above are mainly due to the difference in wetland classifications, temporal phase in the data source, and spatial resolution between the two datasets (Niu et al., 2012).

As shown in Fig. 4, A–L are 12 regions with large differences where either field survey or data verification had been carried out. Among them, the field survey results of the parts along the Yangtze River were in B, and regions A, C, G, and I were wetlands, but in the water wetland data, regions A, B, G, and large parts of C and I were identified as non-wetlands, with parts of C and I identified as waters. D, E, F, H, K, and L were wetland parks or wetland nature reserves, most of which were identified as non-wetlands in the water wetland data. Region J was the eastern part of Hengsha Island, which was an artificial wetland created through reclamation, but was identified as non-wetland in the water wetland data. Riparian wetland data were roughly consistent with field survey and related data, but the error was significant in water wetland data, which was owing to difficulty in wetland interpretation.

Table 1
Corresponding Wetland Type Conversion.

Converted Wetland Type	Classification of Riparian Wetland Data	Classification of Water Wetland Data
Tidal Flat Wetland	Biantan Wetland Island Wetland	Inland Tidal Flat Coastal Tidal Flat
Water Wetland	Water	Natural Rivers Artificial Drainage Lake surface Reservoir Surface Pond Surface Sea
Non-wetland	Used Land Other	Non-wetland Freshwater Aquaculture

3. Results

3.1. Spatial-temporal evolution of wetlands on the watershed-scale

In the past century, the Yangtze River riparian wetlands showed a decreasing trend (Fig. 5), except for the 2000 s, with the most significant decrease during the 1980 s by 353.23 km^2. By the 2010 s, riparian wetlands in the Yangtze River decreased by 396.23 km^2, including a decrease of biantan wetlands by 434.19 km^2 and an increase of island wetlands by 37.96 km^2. At present, the Yangtze River has 1, 726.33 km^2 riparian wetlands, which are mainly distributed in the lower reaches, accounting for 73.20%, while the upper reaches with the longest shoreline has only 1.65% of the riparian wetlands.

The riparian wetlands in the upper reaches showed a decreasing trend (Fig. 5). Wetlands did not change much from the 1930 s to the 2000 s. While, due to the impoundment of the Three Gorges Dam, water area in the upper reaches has continued to expand since the 2000 s, submerging the biantan and island wetlands, leading to particularly significant changes in the Yibin-Fuling reach, where almost all the biantan and island wetlands have disappeared during the 2000–2010 s (Fig. 6).

The riparian wetlands in the middle reaches first increased and then decreased, reaching the largest area in the 1980 s (Fig. 5). In the 1960–1970 s, three cutoff works were carried out in the lower Jingjiang reach, cutting off the hydrological connection between the biantan wetland in Zhongzhouzi and the Yangtze River, making it a non-riparian wetland. Oxbow lakes formed after the cutoff work in Shatanzi and Shangchewan, and maintained their hydrological connection with the Yangtze River during the wet season. Meanwhile, through sediment deposition in the narrow par of old meanders, new biantan wetlands were formed, and there was not a significant change in the area of riparian wetlands. But since the 1990 s, biantan wetlands have decreased in this reach due to anthropogenic development and utilization (Fig. 6).

The riparian wetlands showed a fluctuating trend in the lower reaches (Fig. 5). The estuary is a typical area for wetland changes in the lower reaches, similar to the trend of the entire lower reach. Biantan wetlands had a decreasing trend, and the island wetlands fluctuated

Table 2
Comparison of Evaluation Results.

	Tidal Flat Wetland (%)	Water Wetland (%)	Non-wetland (%)	All Wetland (%)	Overall (%)
Area Consistency	−62.04	93.96	80.53	87.02	
Spatial Consistency	43.10	93.20	84.95		84.06

Table 3
Confusion between riparian wetlands.

Confusion Matrix		Riparian Wetland Data		
		Tidal Flat Wetland (%)	Water Wetland (%)	Non-wetland (%)
Water Wetland Data	Tidal Flat Wetland	78.02	20.04	1.95
	Water Wetland	6.97	90.38	2.64
	Non-wetland	21.96	1.36	76.68

(Fig. 6). Impacted by hydrology and hydrodynamics, wetland at the north bank of the estuary expanded due to sediment deposition, whereas that at the south bank decreased due to erosion. At the same time, the development and construction of ports, wharves, and industrial parks at the estuary occupied riparian wetlands, and the impact has become more and more significant since the 1990 s. In addition, impacted by multiple factors, such as hydrology, hydrodynamics, and land reclamation, the island wetlands in the estuary have shown large-scale fluctuations.

3.2. Spatial-temporal evolution of wetlands on the provincial-scale

In the past century, the spatial–temporal evolution of riparian wetlands in the provinces along the Yangtze River showed significant spatial variations. Based on changes in the riparian wetland area in the provinces/municipalities along the Yangtze River, a cluster analysis was carried out to divide it into three characteristic areas (Fig. 7), namely, the three downstream provinces (Jiangsu, Anhui and Jiangxi) and Chongqing, the three middle and upstream provinces (Hubei, Hunan, and Sichuan), and the estuary (Shanghai and the coastal). The spatial heterogeneity was consistent with the spatial distribution pattern of riparian wetlands in the Yangtze River, mainly in the lower reaches and relatively few in the middle and upper reaches. There were larger changes in the regions with more wetlands, thus the whole Yangtze River was divided into two areas – the middle and upper reaches versus the lower reaches. There were different changing trends of riparian wetlands for different provinces/municipalities. The changes of riparian wetlands in Jiangsu, Anhui, and Jiangxi provinces showed a decreasing trend over the past century, while those of Shanghai and the coastal area increased obviously in the 2010 s (Fig. 8). The changes in riparian wetlands in Hunan, Hubei, and Sichuan provinces first increased and then decreased reaching the largest area in the 1990 s or 2000 s, while the changes of riparian wetlands in Chongqing decreased greatly due to the impoundment of the Three Gorges Dam, which was similar to the

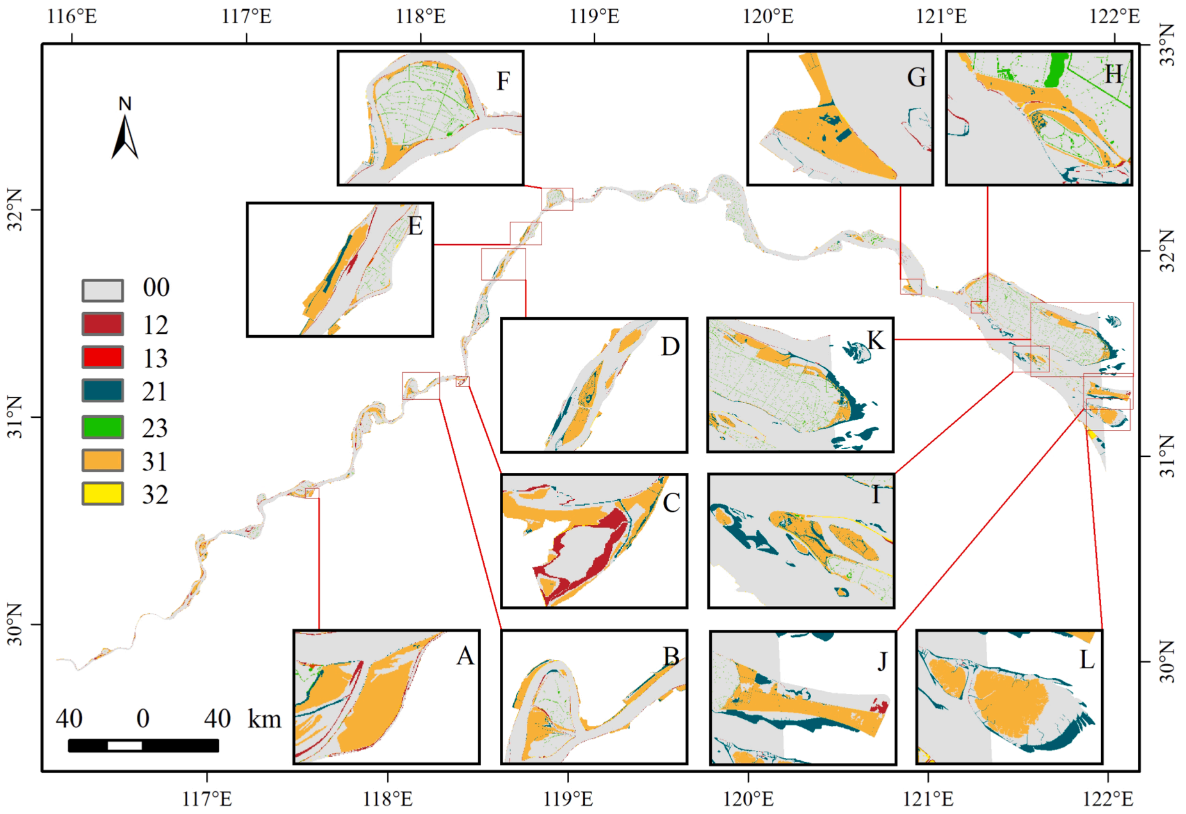


Fig. 4. Confusion between Different Wetland Types. Note: “1” represents Tidal Flat Wetland, “2” represents Water Wetland, and “3” represents Non-Wetland. “12” represents pixel elements labelled “Water Wetland” in the riparian wetland data that are in water wetland data but belong to “Tidal Flat Wetland”, etc. “00” represents that the type is consistent with labelling.

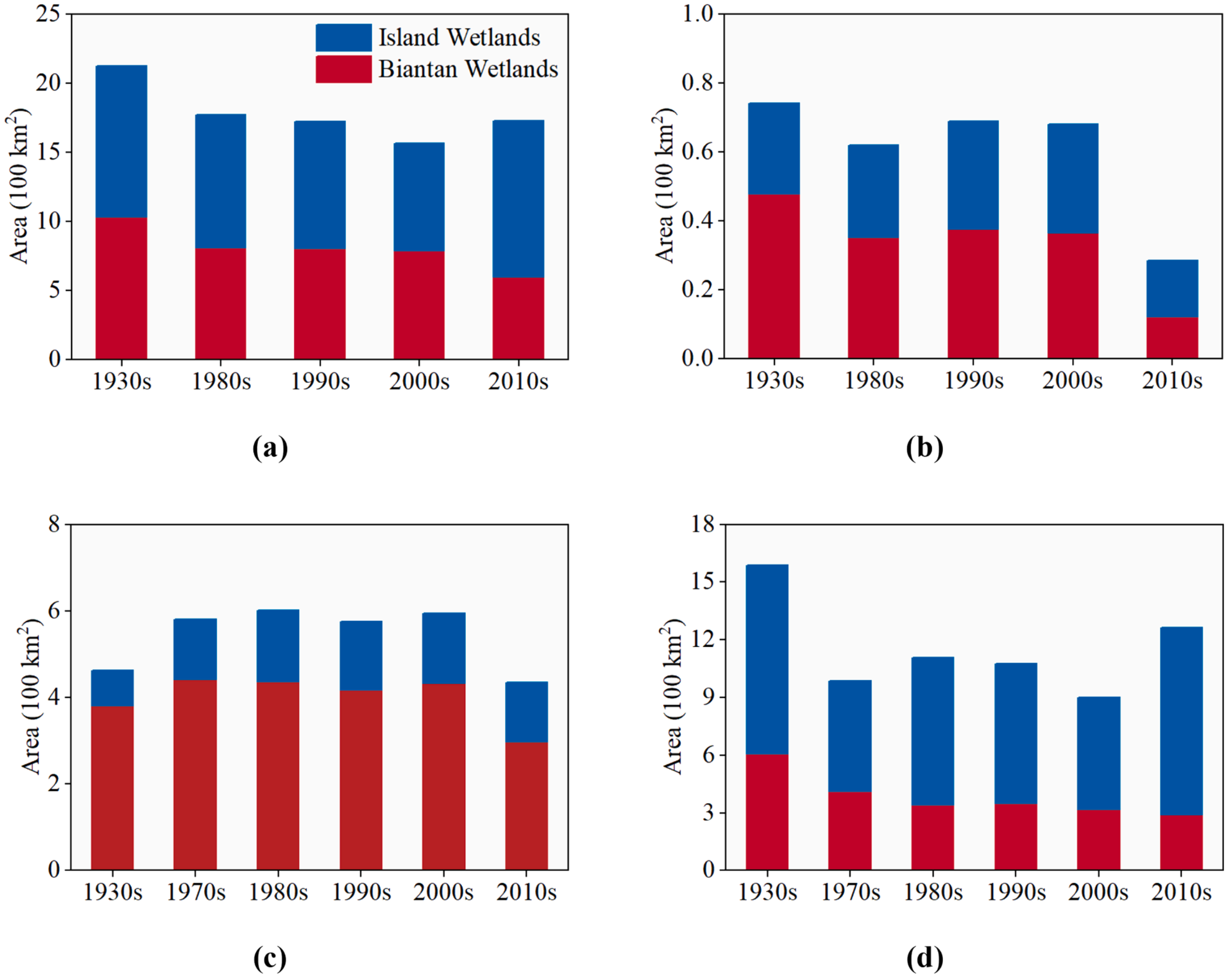


Fig. 5. Change in the area of riparian wetlands in the entire (a), upper reaches (b), middle reaches (c), and lower reaches of Yangtze River (d). Note: Change in area of the riparian wetlands in the upper reaches was not calculated in the 1970 s due to limited data.

changing trends of the three downstream provinces (Fig. 8). Therefore, Chongqing, Jiangsu, Anhui, and Jiangxi provinces were grouped together.

The spatiotemporal changes of different types of wetlands also showed significant spatial variation (Fig. 9). Biantan wetlands decreased significantly in the seven provinces than those of the coastal and Hunan Province. Especially for biantan wetlands in Shanghai, which have almost disappeared. Island wetlands exhibited an increasing trend in the coastal, Anhui, Hubei, and Hunan provinces, especially for a dramatic significant increase in the coastal. Island wetlands decreased in Jiangsu, Jiangxi, Shanghai, Sichuan, and Chongqing, among which the decrease in Jiangsu and Shanghai were largest.

4. Discussion

4.1. Driving mechanism analysis

4.1.1. The impacts of climate change and damming

Climate change affects the growth and decline of wetlands through precipitation and temperature. Most of the riparian wetlands in the study area were mainly recharged by atmospheric precipitation. Some studies indicated that the precipitation in the Yangtze River Basin presented a decreasing trend (Tian, 2016; Yang, 2021), while others pointed out that it was at the increasing trend, especially in the flood season (Yang et al., 2005; Ping et al., 2006; Guo et al., 2021). However, all the studies agreed that the precipitation in the Yangtze River Basin didn’t change significantly. The temperature in the Yangtze River Basin had increased significantly (Tian, 2016; Zhong et al., 2016), and the actual evapotranspiration showed a significant increase with 1.16 mm/a from 1981 to 2017 (Zhan et al., 2021). The rising temperature and the constant precipitation had resulted in the shrinking of wetlands due to water shortage.

In addition, damming is also an important factor influencing seasonal water level changes. In the upper reaches, damming raised the water level and inundated the riparian area (Tombolini et al., 2014). In the lower reaches, damming reduced the flood volume, flood frequency and intensity, which in turn reduced riparian wetlands (Das and Pal, 2017; Zheng et al., 2019). The impact of the construction of the Three Gorges Dam on the riparian wetland was mainly manifested in upstream, especially after the impoundment of 175 m level, which resulted in a decrease of 58.26% for riparian wetlands in the upstream (Fig. 5).

4.1.2. The impact of wetland exploitation and protection policies

Policies on land development and wetland protection have had a significant impact on the spatial–temporal evolution of riparian wetlands in the Yangtze River (Fig. 11), which can be divided into three stages: no wetland protection policies (before 1986), wetland protection policy development (1986–1998), and strict wetland protection (1998–present).

(1) No wetland protection policies (before 1986)

Before 1986, policies in China focused on the development and utilization of wetlands, so there were no policies protecting wetlands. In

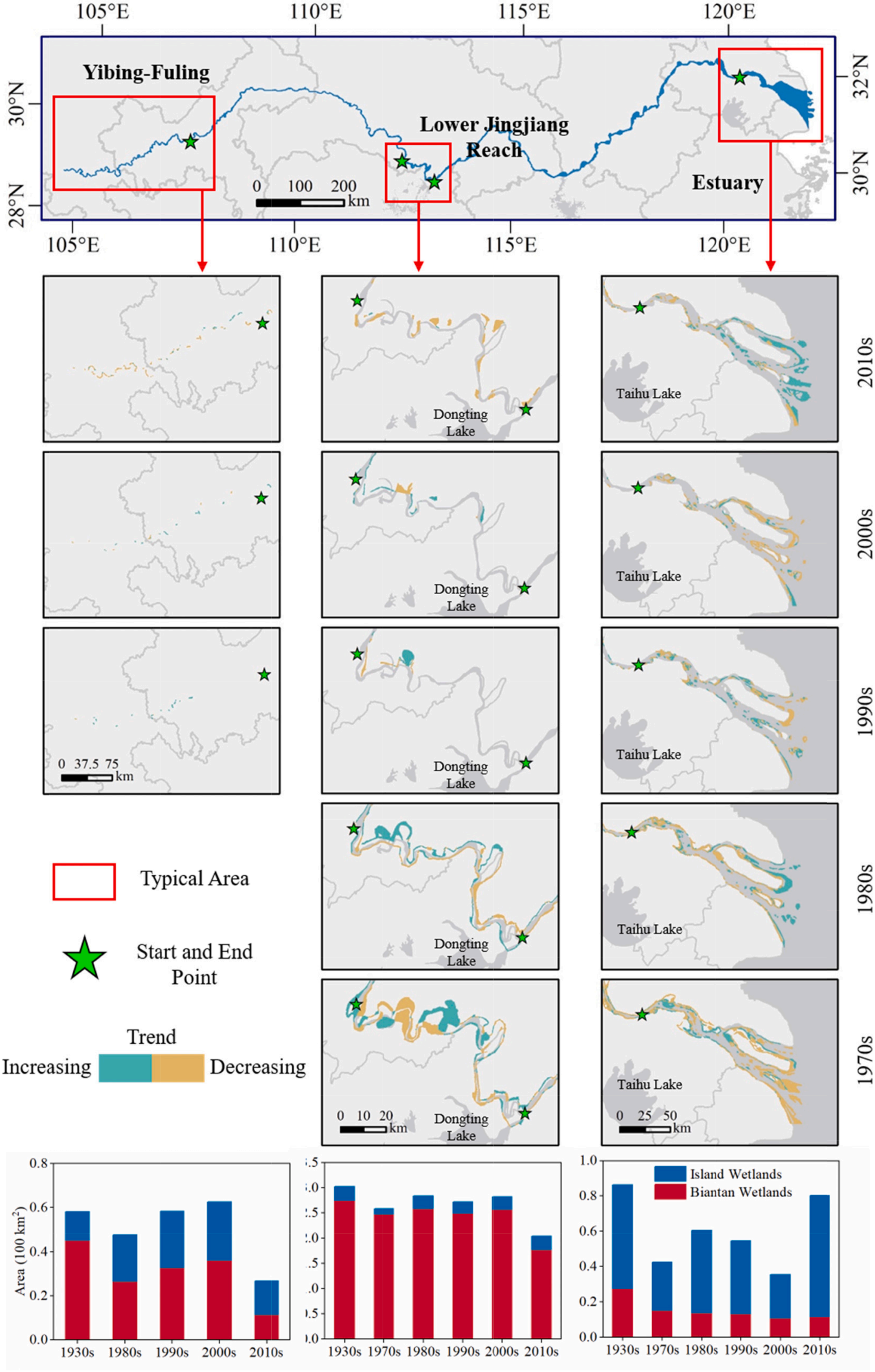


Fig. 6. Changes in Wetland in Typical Regions of the Yangtze River.

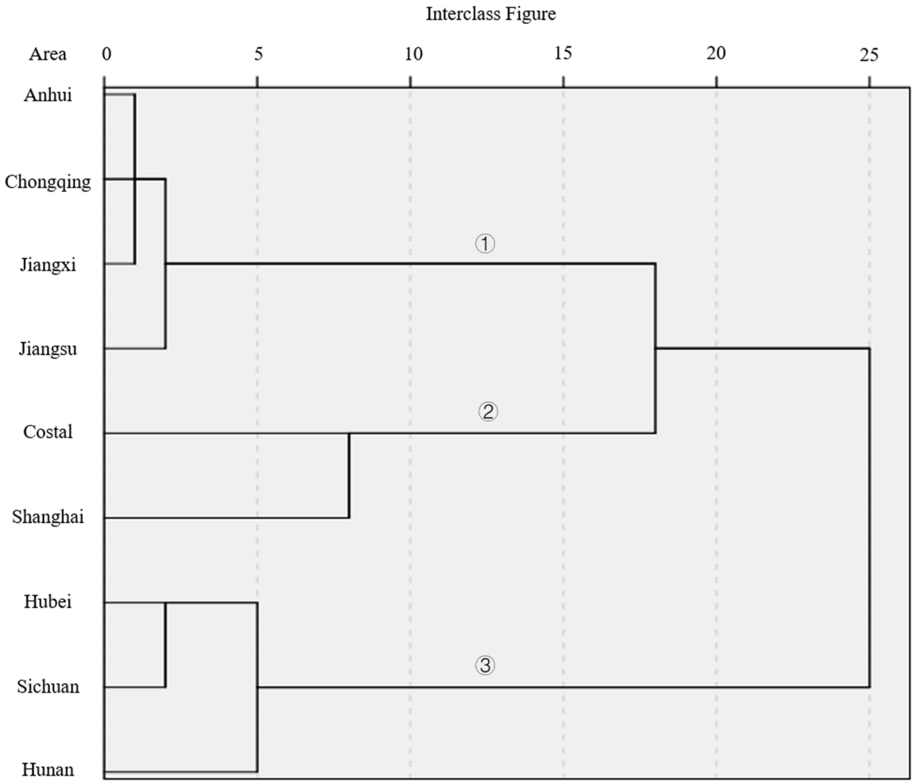


Fig. 7. Cluster Analysis of Changes in Riparian Wetlands in the Yangtze River.

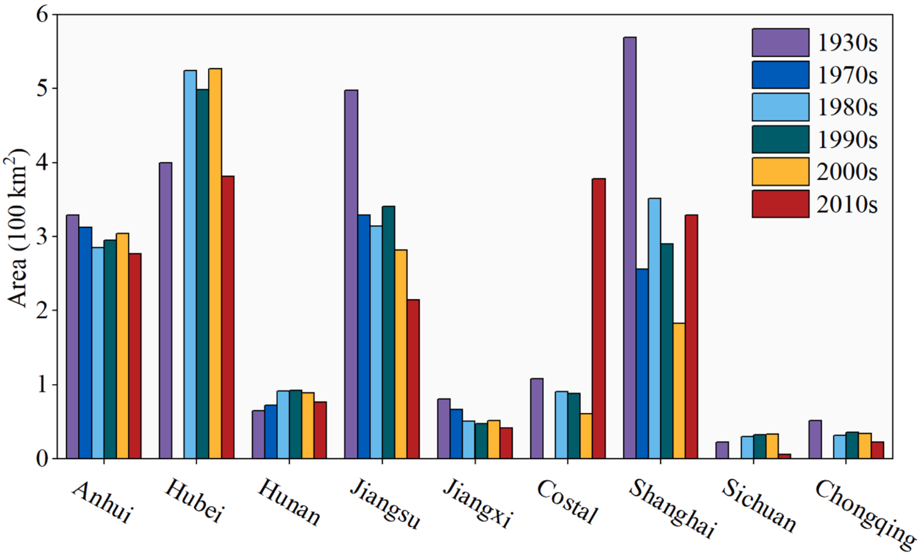
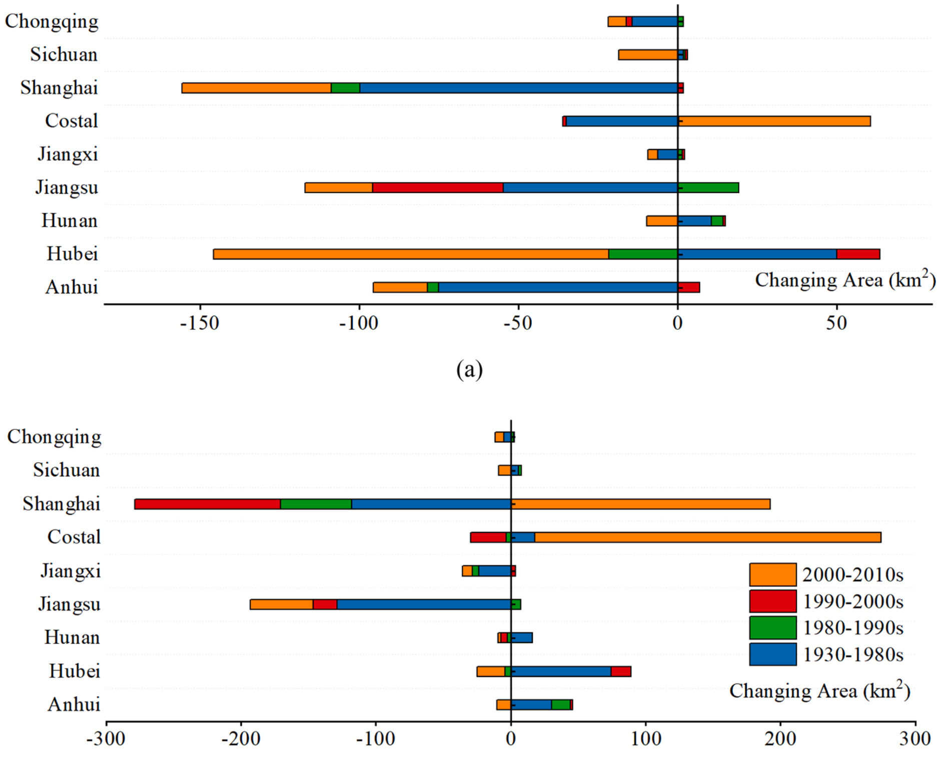


Fig. 8. Change in Riparian Wetland Area in Each Province.

the 1910 s, the government implemented measures and policies that were conducive to economic development, leading to the rapid development of national capitalism industries, especially the textile industry. As an important region of cotton production in China, large amounts of wetlands in the Yangtze River Delta were reclaimed for cotton plantation(Li, 2012; Zhang et al., 2013). In the 1930 s and 1940 s, due to multiple pressures including warfare, imperialist dumping, bureaucratic capitalist exploitation, and the signing of the Sino-American Treaty of Friendship, Commerce, and Navigation, the national capitalism industry was in a dilemma. Wetland reclamation decreased considerably and almost stopped in the 1940 s(Zhang et al., 2013). After the founding of the People's Republic of China, due to the large population and rapid population growth, there was enormous pressure on food supply in China. In 1953, a severe drought devastated vast areas of farmland, which aggravated food shortages. To ensure food supply, China implemented the "grain as the key link" policy. As the land of fish and rice, the plains in the middle and lower reaches of the Yangtze River had wetlands as important land resource reserves that were vastly reclaimed for agricultural production. In the early stage of the Economic Reform and opening up, with the economic system reform, urbanization and industrialization further increased the demand for land, so wetland occupation increased.



(a)

(b)

Fig. 9. Change of biantan wetlands (a) and island wetlands (b).

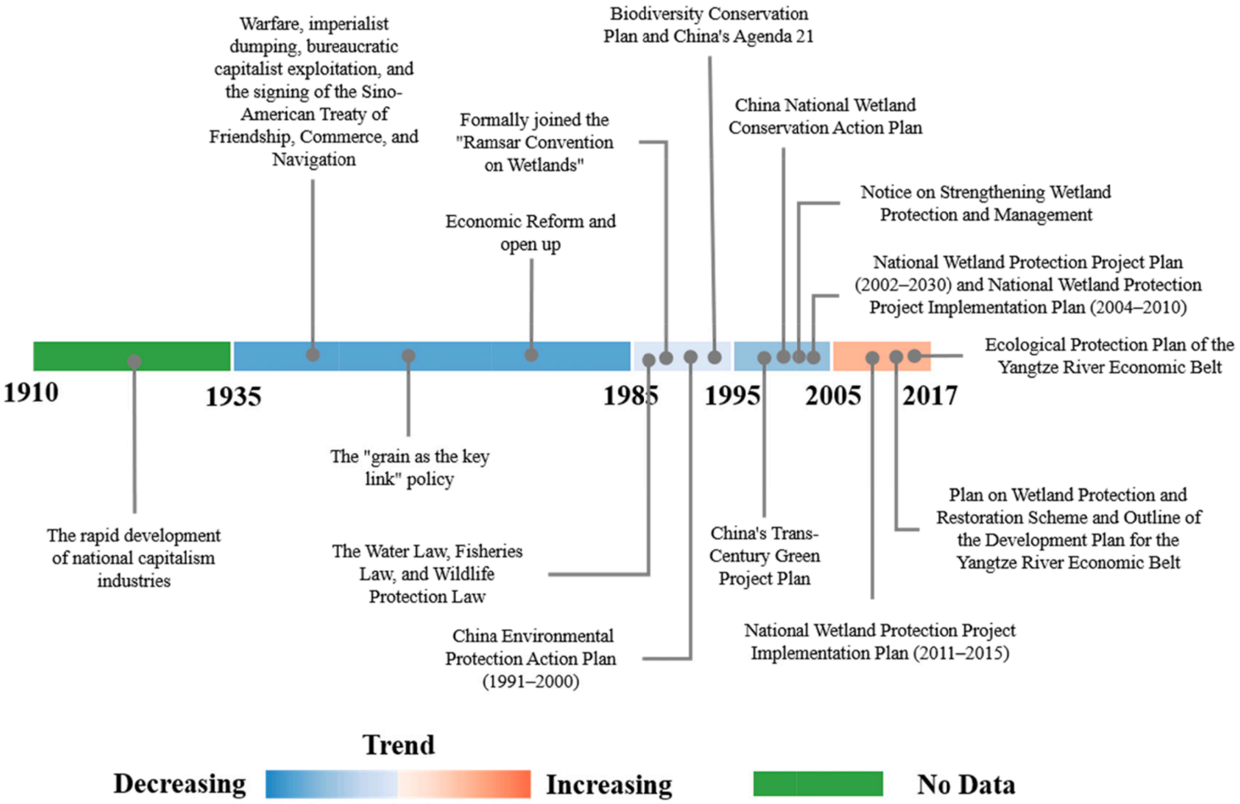


Fig. 11. Development and protection policies and the changing trend of riparian wetlands in the Yangtze River.

(2) Policy development period (1986–1998).

In the late 1980 s, policies started to be implemented in China to strengthen wetland protection. From 1986 to 1998, China promulgated laws and regulations such as the Water Law, Fisheries Law, and Wildlife Protection Law to indirectly protect wetlands, which did not have a positive impact due to the weak awareness of wetland protection and the lack of central planning and strict approval procedure for wetland utilization. In 1992, China formally joined the "Ramsar Convention on Wetlands", to professionally protect wetlands and manage their utilization. "Wetlands" gradually started to emerge as a proprietary concept in related plans and policies. In 1993, the State Council approved the "China Environmental Protection Action Plan (1991–2000)", which for the first time stipulated specific goals for wetland protection in the national plan and adopted the construction of wetland nature reserves as one of the important goals. In 1994, the "Biodiversity Conservation Plan" and "China's Agenda 21" included plans for biodiversity conservation and the sustainable utilization of wetlands. In 1996, "China's Trans-Century Green Project Plan" introduced four requirements for wetland protection, including the construction of wetland nature reserves of international significance. At this stage, wetland protection awareness awakened in China, and a special wetland protection plan emerged, wetland occupation and destruction decreased, and the decrease in wetland areas slowed down.

(3) Strict protection period (1998–present).

The catastrophic flood in the Yangtze River Basin in 1998 prompted the government to further strengthen the protection of the Yangtze River wetlands. In 2000, the National Forestry and Grassland Administration led the implementation of the "China National Wetland Conservation Action Plan", which pointed out that it was necessary to "effectively slow down the degradation of wetlands and curb wetland decline caused by human activities" and prioritize returning farmland to lakes. Wetland protection and restoration in the Three Gorges Reservoir area, the middle and lower reaches of the Yangtze River, Poyang Lake, Dongting Lake, Chongming Island, and the construction of the Yangtze River National Wetland Nature Reserve were listed as priority projects. In 2004, the "Notice on Strengthening Wetland Protection and Management" made the first policy statement on wetland protection. From 2003 to 2005, the "National Wetland Protection Project Plan (2002–2030)" and "National Wetland Protection Project Implementation Plan (2004–2010)" planned to restore wetlands in the middle and lower reaches of the Yangtze River by returning land to forests, lakes, beaches, grasses, as well as soil and water conservation. During the 12th Five-Year Plan period, the "National Wetland Protection Project Implementation Plan (2011–2015)" began to focus on improving the overall function of wetland ecosystems. In 2016, the "Plan on Wetland Protection and Restoration Scheme" promoted the establishment of systematic and complete wetland protection and restoration scheme. In the same year, the "Outline of the Development Plan for the Yangtze River Economic Belt" clearly stated that the protection and restoration of the ecological environment of the Yangtze River should be of the highest importance, "promoting well-coordinated environmental conservation and avoiding excessive development". In 2017, the "Ecological Protection Plan of the Yangtze River Economic Belt" strictly prohibited the reclamation of lakes and required further protection of plateau wetland ecosystem, increasing the area, protection rate, and ecological function of natural wetlands, and planned to establish the Jianghuai Ecological Corridor based on the clean water corridor from the Eastern Route of the South-to-North water transfer project and surrounding lakes. At this stage, China had adopted a strict protection policy for the Yangtze River wetlands, their degradation was effectively curbed, and their function gradually improved. However, to ensure stable social and economic development, major projects such as the Three Gorges Reservoir, South-to-North Water Transfer, and land reclamation were still carried out, coupled with the influence of natural factors, such as climate change, the area of Yangtze River riparian wetlands has not increased significantly.

4.2. Limitations

As the time frame of this study spans nearly a century, it is impacted by missing data, difficulty in data collection, and data source complexity, leading to the following limitations: (1) Part of the topographic maps in the 1970 s were missing. Only those from the middle and lower reaches of the Yangtze River and parts of the upper reaches were collected (Fig. 2), while most of the upper reaches (denoted in red) were missing, resulting in incomplete data in the 1970 s, so the database remains to be improved. (2) There are certain uncertainties in the use of topographic maps. First, topographic maps are affected by factors such as scanning, georeferencing, map splicing, and inaccurate information on the topographic map, so there are certain uncertainties in the wetland spatial distribution data obtained through vectorizing topographic maps. Second, certain uncertainty in the spatial distribution of wetlands in different years can be caused by different sources and spatial resolution of the two topographic maps and remote sensing images. In the future, it is necessary to collect additional historical documents and other related research results to verify and improve the accuracy of the early riparian wetland data. (3) This paper only conducted a qualitative analysis of the impact. It is necessary to further collect relevant data on other driving factors and quantitatively analyze the impacts of each driving factor.

5. Conclusion

This study established a set of classification and interpretation standards, and analyzed the spatial–temporal evolution characteristics and driving mechanisms of riparian wetlands in the Yangtze River. The Yangtze River has 1,726.33 km^2 of riparian wetlands in the 2010 s, and the riparian wetlands showed a decreasing trend over the past century with a total reduction of 396.23 km^2. There was a great spatial heterogeneity of riparian wetlands changes among the upper, middle and lower reaches. Riparian wetlands showed a decreasing trend in the upper reaches, firstly increasing from 1930 s to 1980 s and then decreasing from 1980 s to 2010 s in the middle reaches, and fluctuating in the lower reaches. On the provincial-scale, riparian wetlands firstly decreased and then increased with significant changes in the estuary. There were large shrinkages in the three downstream provinces and Chongqing, and firstly increased and then decreased with little change in the three middle and upstream provinces. Water level and policy have great impacts on riparian wetlands. The rising temperature and the construction of the Three Gorges dam have altered the hydrology and water cycle in the Yangtze River, reducing the riparian wetlands. National policy intervention is effective to protect riparian wetlands. In the future, it needs to strengthen the riparian wetland data with higher accuracy and the impact if climate change, and analyze the current situation and conservation deficits of riparian wetlands in the Yangtze River. It's necessary to establish nature reserves and parks, and delimit key protection and restoration reaches to protect riparian wetlands in the Yangtze River.

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CRediT authorship contribution statement

Minkun Chen: Conceptualization, Methodology, Visualization, Investigation, Formal analysis, Writing – original draft. **Xibao Xu:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Xinghua Wu:** Data collecting. **Chuang Mi:** Data collecting.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jag.2022.102874.

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