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Spatiotemporal Dynamics of Coastal Wetlands and Reclamation in the Yangtze Estuary During Past 50 Years (1960s–2015)

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Abstract: Reclamation is one of the fastest-growing land use type developed in coastal areas and has caused degradation and loss of coastal wetlands as well as serious environmental problems. This paper was aimed at monitoring the spatiotemporal patterns of coastal wetlands and reclamation in the Yangtze Estuary during the 1960s and 2015. Satellite images obtained from 1980 to 2015 and topography maps of the 1960s were employed to extract changes of reclamation and coastal wetlands. Area-weight centroids were calculated to identify the movement trend of reclamation and coastal wetlands. The results show that from the 1960s to 2015, the net area of natural wetlands declined by 574.3 km^2, while man-made wetlands and reclamation increased by 553.6 and 543.9 km^2, respectively. During the five study phases, the fastest areal change rate natural wetlands was –13.3 km^2/yr in the period of 1990–2000, and that of man-made areas was 24.7 km^2/yr in the same period, and the areal change rate of reclamation was 27.6 km^2/yr in the period of 2000–2010. Conversion of coastal wetlands mainly occurred in the Chongming Island, Changshu City and the east coast of Shanghai Municipality. Reclamation was common across coastal areas, and was mainly attributed to settlement and man-made wetlands in the Chongming Island, Lianyungang City and the east coast of Shanghai Municipality. Natural wetlands turned into farmlands and settlement, and man-made wetlands gained from reclamation of farmlands. The centroid of natural wetlands generally moved towards the sea, man-made wetlands expanded equally in all directions and inland, and the centroid of reclamation migrated toward Shanghai Municipality. Sea level rise, erosion-deposition changes, and reclamation activities together determine the dynamics of the Yangtze Estuary wetlands. However, reclamation activities for construction of ports, industries and aquaculture are the key causes for the dynamics. The results from this study on the dynamics of coastal wetlands and reclamation are valuable for local government to put forward sustainable land use and land development plans.

Keywords: coastal wetlands; reclamation; remote sensing; dynamics; driving forces; the Yangtze Estuary

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1 Introduction

As the ecotone between terrestrial and marine ecosystems, coastal wetlands offer myriad ecosystem services and play key roles in maintaining coastal biological diversity as well as human welfare (Keddy, 2010; Delgado and Marín, 2013; Jiang et al., 2015; Sun et al., 2015). The coastal area, 4% of the total land area of the Earth, disproportionately supports more than one-third of the population in the world, and experiences intensive reclamation to meet the need for agricultural activity, construction of ports and dams, typically in Netherlands, Japan and Korea (Giosan et al., 2014; Song et al., 2014; Shi et al., 2015; Tian et al., 2016). These human activi-

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ties, coupled with climate change result in degradation and loss of coastal wetlands, and devalue ecosystem services such as habitat supporting, sediment retention, and carbon sequestration (Junk et al., 2013; Costanza et al., 2014; He et al., 2014; Amler et al., 2015; Jin et al., 2016). These direct threats from human activities in coastal areas further increase the uncertainty of scientific management and conservation of coastal wetlands (Wang et al., 2014; Tian et al., 2016). Thus, it is essential to monitor the dynamics of coastal wetlands and reclamation and analyze how coastal wetlands have been historically converted.

Remote sensing has been the most efficient way to the monitor current status of coastal wetlands as well as their temporal dynamics because of its ability for obtaining a synoptic view of targets and historical images. Remote sensing has been applied in a number of previous wetland studies focusing on ecosystem service function, ecosystem structure and landscape pattern, the fragmentation and transition of coastal wetlands affected by climate change, reclamation and human activities (Camacho-Valdez et al., 2014; Murray et al., 2014; Zhang et al., 2015; Francisco et al., 2016; Wang et al., 2016a; Tian et al., 2017). Ke et al. (2011) adopted remote sensing and landscape metrics analysis to gain insight into coastal wetland change resulting from rapid economic development in the Yancheng National Nature Reserve, China. Feng et al. (2014) applied a fuzzy evaluation method and an analytic hierarchy process (AHP) to quantify the suitability of coastal reclamation in order to achieve future sustainable development of the coastal area in Lianyungang, China. Jin et al. (2016) assessed the reclamation intensity using a comprehensive index system with the aim of revealing the response of river delta wetlands to different reclamation activities in the Yangtze River Delta. Wang and Yu (2012) used the geographical information system (GIS) and remote sensing techniques to investigate coastal wetland utilization in the largest city cluster area, the Yangtze River Delta in China in the periods of 1990-2000 and 2000-2005. Although assessing coastal wetlands transition is beneficial for achieving effective protection, the lack of information on wetlands changes and the linkage to different reclamation activities for a long period have been a principal barrier to such efforts.

Shanghai is the most vibrant and largest economic entity in China, and its economic development makes the Yangtze Estuary experience high intensity reclamation from coastal wetlands and sea, causing several wetlands environmental problems (Song and Liu, 2013; Wang and Yu, 2013; Chen et al., 2014; Tian et al., 2016). During 1980 to 2010, natural wetlands of the Yangtze Estuary decreased from 525.48 to 454.82 km^2 and its functionality of wave attenuation and wildlife habitats has been largely compromised (Ren, 2014). Therefore, monitoring coastal wetland changes is critically important for developing proactive conservation strategies which focus on ensuring ecosystem structure and services as well as the regional ecological security. The objective of this study is to: 1) quantify spatiotemporal dynamics of coastal wetlands and reclamation in Yangtze Estuary from the 1960s to 2015, and 2) identify the drivers of these dynamics, particular impacts of reclamation on coastal wetlands. These objectives are addressed by using of land cover transfer matrices, area-weight centroid analysis, and remote sensing images.

2 Materials and Methods

2.1 Study area

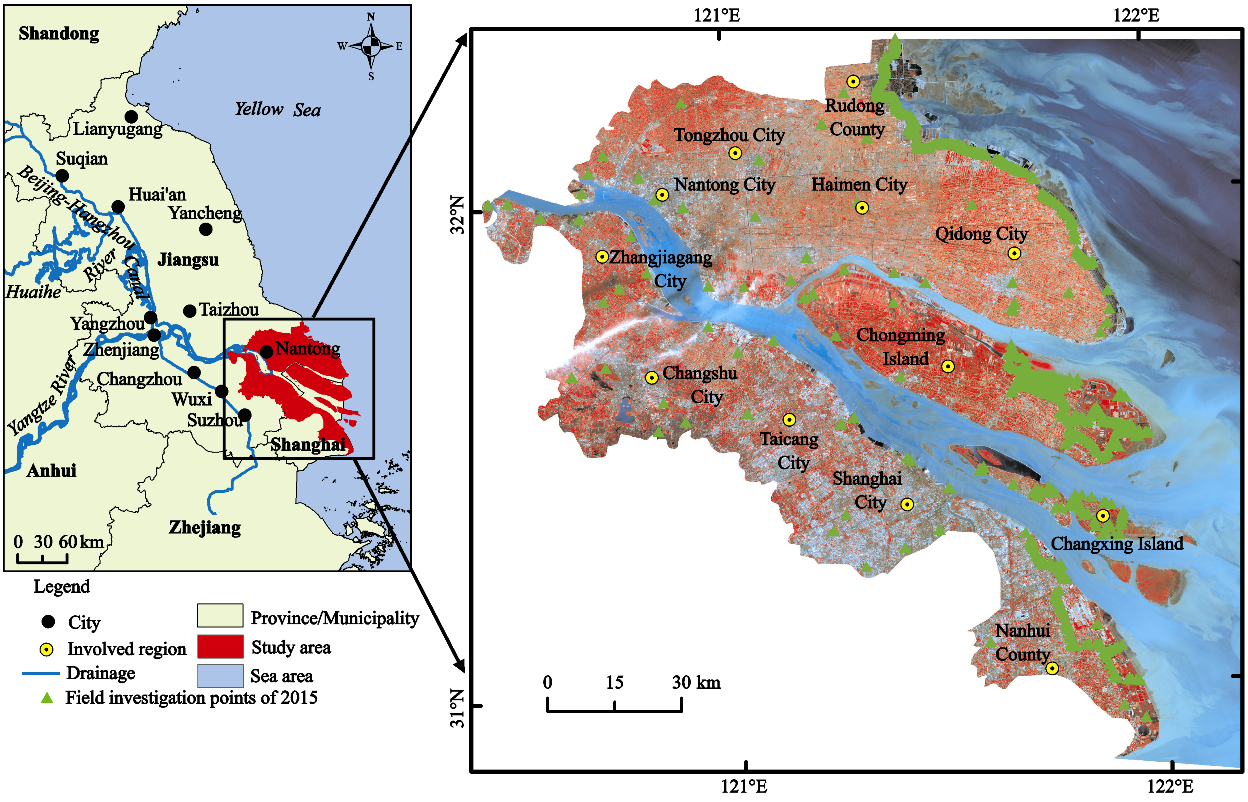
According to vegetation maps and Mou et al. (2015), the Yangtze Estuary in this study was determined by the buffer region (30°50′55″N–32°19′12″N, 120°24′02″E–122°05′20″E) with 10 to 50 km width which took the shoreline as the center. The Yangtze Estuary is situated in northwest edge of the western Pacific, facing the East China Sea on the east, and in north of the Hangzhou Bay. It is a continental-scale alluvial estuary, the third largest in the world; it is also the mouth of Yangtze River, the longest river in China. This estuary has 40% of the fresh water resources and over 67% of the developable waterpower resources of China. It contains the southeast part of Jiangsu Province, involving Rudong County, Qidong City, Haimen City, Tongzhou City, Nantong City, Zhangjiagang City, Changshu City, Taicang City, Shanghai Municipality, Nanhui County, and the coastal area of Shanghai Municipality, including the Chongming Island and Changxing Island, where the economic growth speed and gross scale as well as the quality of urbanization are highest in China (Fig. 1). As one of the most densely populated regions on Earth, the area is home to very extensive transport networks including railways, expressways and ports. This region is characterized by subtropical monsoon where the annual mean temperature is between 15℃ to 17℃ with the annual precipitation of 1000 to 1800 mm. The Yangtze Estuary owns rich beach resources and contains main vegetation types such as *Phragmites autralis*, *Spartina alterniflora* and *Scripus mariqueter* (Ren, 2014). The sediments from Yangtze River settle in the study area, form natural coastal wetlands with fertile soil, and are significant potential land resources for nearby cities like Shanghai. Moreover, this area is the only avenue for upstream and catadromous migration of various animals, and the vital stopover site and wintering ground for migratory waterfowls in the Asian-Pacific region.

2.2 Data and processing

Cloud-free Landsat images acquired by sensors Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper (ETM) and Operational Land Imager (OLI) in the 1980s, 1990, 2000, 2010 and 2015 shown in Table 1 were downloaded from the United States Geological Survey (USGS) Center for Earth Resources Observation and Science (http://glovis.usgs.gov/). Topographic maps in 1∶100 000 and land use maps of the study area produced in the 1960s were collected and referenced in classification. Furthermore, vegetation maps, river and road data, as well as field investigation points recorded in 2015, were used as auxiliary data to achieve an improved land cover classification.

In spite of being geo-referenced already, Landsat images were not comparable because of their inconsistent resolutions and georeference systems. In order to address these inconsistence among image datasets without losing spatial details, Landsat MSS images were resampled to a pixel size of 30 m × 30 m and were geo-rectified against the Landsat TM of 1990, and then all images were projected to the Albers equal-area conic coordinate system for accurately extracting land cover area. The downloaded Landsat images were resampled and rectified with an average root mean square error (RMSE) less than 1 pixel.

The land cover classification system for this study was established by referring to the land cover classification system of China (Wu et al., 2014) and considering the land cover types of the study area, which gave rise to the following major land cover types: forest, grassland, wetlands, farmland, settlement and other land. Wetlands



Landsat OLI false color image in 2015

Fig. 1 Location of study area and distribution of field investigation points

Table 1 General characteristic of the employed Landsat images, including the year, path/row, acquisition data, sensor and spatial resolution

Year	Path/Row	Acquisition date	Sensor	Spatial resolution (m)
1983	118/38	8 February, 1983	MSS	80
	119/38	14 November, 1983	MSS	80
1990	118/38	4 December, 1990	TM	30
	119/38	20 June, 1990	TM	30
2000	118/38	6 June, 2000	TM	30
	119/38	31 July, 2000	TM	30
2010	118/38	23 April, 2010	ETM	30
	119/38	24 May, 2010	TM	30
2015	118/38	3 August, 2015	OLI	30
	119/38	13 October, 2015	OLI	30

Notes: MSS, TM, ETM and OLI represents Multi-spectral Scanner, Thematic Mapper, Enhanced Thematic Mapper and Operational Land Imager, respectively

were divided into natural wetlands and man-made wetlands. Natural wetlands of the study area included lake, salt marsh, freshwater marsh, mudflat and beach, and man-made wetlands covered canal, reservoir/pond, aquaculture pond and salt field.

Classification of land use types was carried out through visual interpretation of the Landsat images except that the land cover types of the 1960s were derived from vectorization of the topographic maps and local land use maps. To accurately extract the area of land reclamation, the boundary of the 1960s' land use was used as the baseline data, and the areal change of the Yangtze Estuary in each phase compared with the basic region were divided into reclamation areas and natural wetlands. In other word, reclamation areas includes forest, grassland, man-made wetlands, farmland, settlement and other land, and the reclamation boundary is between the shoreline in the 1960s and that in each other year.

Among field investigation points, 258 points were selected as helpful auxiliary data during visual interpretation and the remaining 517 points were used to validate the accuracy of the classification results in 2015. The Kappa coefficient and overall accuracy of the confusion matrix were used to assess the agreement between results and ground-truths (Table 2). Comparing the extracted land cover types for year 2015 with the field investigation points indicated an overall accuracy of over 90% for all the land use types, and the Kappa coefficients were above 0.82. Assessment of land use classification accuracy for other study periods was based on the Google earth images and aforementioned auxiliary data, showing an overall accuracy of over 85%. In a word, the classification results are appropriate for analysis of the land cover dynamics in the study area.

Table 2 Accuracy assessment of land cover classification results

Type	1980	1990	2000	2010	2015
Overall accuracy (%)	85	88	87	90	92
Kappa coefficient	0.80	0.84	0.86	0.88	0.90

2.3 Methods

2.3.1 Land cover transfer matrix

The land cover transfer matrix is widely used to characterize the structure and direction of the land cover dynamic change. It describes areal conversions across different land cover types in a certain area from the beginning to the end of a particular period (Zhu and Li, 2003; Qiao et al., 2013; Wang et al., 2016b). In order to quantify conversions of coastal wetlands in the Yangtze Estuary, the land cover transfer matrix is calculated using the ArcGIS software:

$$S_{ij} = \begin{pmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{pmatrix} \quad (1)$$

where S_{ij} is the area of land cover type i transferred to land cover type j; n is the number of land cover types; i and j (1, 2, ..., n) are land cover types before and after a certain transfer process, respectively; Each element on the main diagonal of the matrix represents the area of each land cover type remaining unchanged.

2.3.2 Area-weight centriod

The centroid of an area is defined as the location of a particular land cover type determined by the coordinates of the geometric center of a polygon or multiple polygons, which has been well applied in several landscape dynamic analyses such as land desertification transition, wetland type evolution, thermal environment landscape pattern as well as coastal landscape changes (Feng and Han, 2011; Gong et al., 2011; Meng et al., 2013; Jia et al., 2015). To describe the spatial pattern of land cover change, the centroids of natural wetlands and man-made wetlands in the 1960s, 1980, 1990, 2000, 2010 and

2015, and centroids of reclamation in 1980, 1990, 2000, 2010 and 2015 were calculated and mapped. The area-weight centriod is defined as:

$$X_t = \sum_{i=1}^{N}(C_{ti}\cdot X_i)/\sum_{i=1}^{N}C_{ti},\quad Y_t = \sum_{i=1}^{N}(C_{ti}\cdot Y_i)/\sum_{i=1}^{N}C_{ti} \tag{2}$$

where X_t and Y_t are the longitude and latitude of a centroid of natural wetlands or man-made wetlands or reclamation areas in year t, respectively; C_{ti} is the area of patch i in year t; X_i and Y_i are the longitude and latitude of patch i of natural wetlands or man-made wetlands or reclamation areas, respectively; N is the total patch number of natural wetlands or man-made wetlands or reclamation areas.

3 Results and Analyses

3.1 Areal changes of wetlands and reclamation

In 2015, the area of coastal wetlands was 10.82% of the total study area, where the area of natural wetlands was 37.02% of the area of coastal wetlands. Indeed, natural wetlands were distributed mainly in the Chongming Island, Changxing Island and some small islands. Man-made wetlands were widely dispersed along the coastal boundary of the study area and in nearby cities, such as Changshu City and Tongzhou City (Fig. 2). Most of the sea land reclamation of the study area was man-made wetlands, settlement and farmland and typical in the Chongming Island and the east coast of Shanghai Municipality (Fig. 3).

The area of coastal wetlands in the study area in the 1960s, 1980, 1990, 2000, 2010 and 2015 was 868.5, 1022.6, 1090.9, 1804.0, 880.9 and 1110.9 km^2, while the area for land reclamation in the corresponding periods was 0, 46.9, 71.0, 228.0, 504.5 and 543.7 km^2, respectively. The net area change of natural wetlands decreased from the first phase to the fifth phase (Table 3). From the 1960s to 2015, the net area of natural wetlands declined by 574.3 km^2, while man-made wetlands increased by 553.6 km^2. The area for land reclamation was 543.9 km^2. In the five phases considered in this study, the fastest net area change rate for natural wetlands was –13.3 km^2/yr in the period of 1990–2000, 24.7 km^2/yr for man-made areas in the same period, 27.6 km^2/yr for land reclamation in the period of 2000–2010. Obviously, when coastal wetlands experienced the largest change in the period of 1990–2000, the land reclamation rate was at 15.7 km^2/yr. Man-made wetlands, settlement and reclamation continued to increase, indicating that the study area was subjected to continuous interruption by human activities.

3.2 Conversions of wetlands and reclamation in the Yangtze Estuary

As shown in Figs. 4 and 5, conversions between coastal wetlands and other types were increasingly complex in the study area from the 1960s to 2015. Generally, the conversions occurred primarily between farmland and wetlands, and secondarily between settlement and

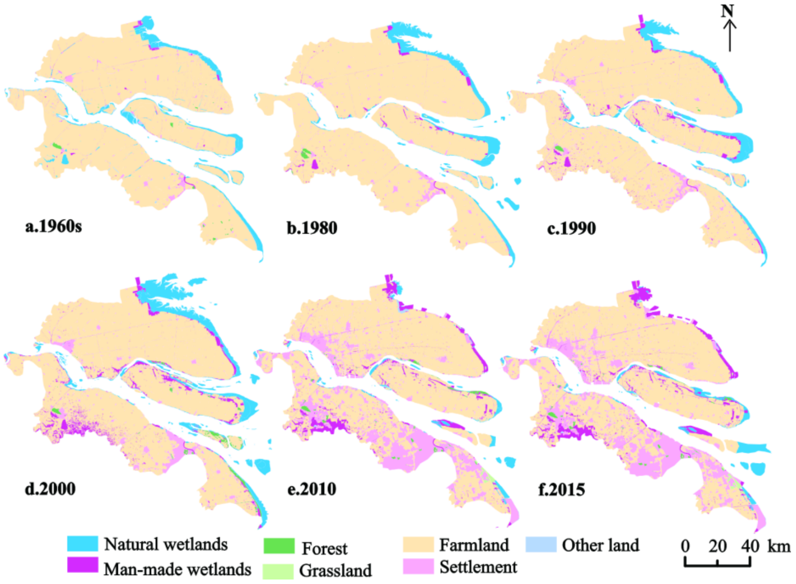


Fig. 2 Coastal wetlands in the Yangtze Estuary

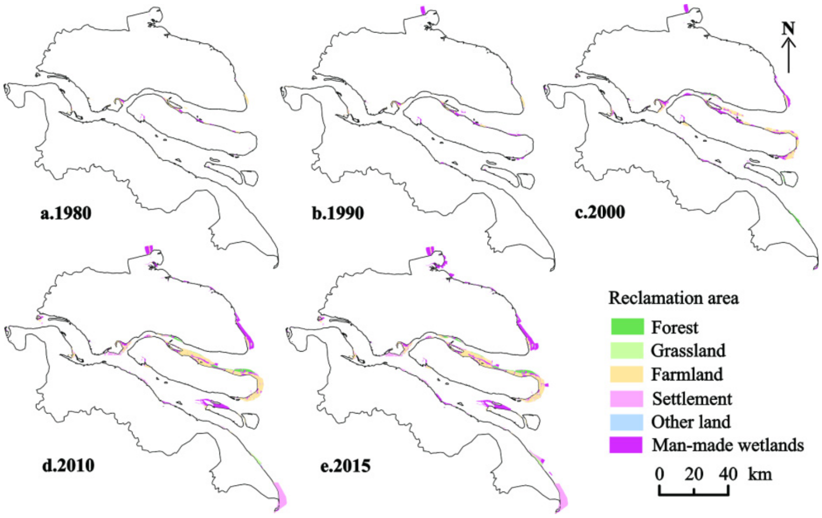


Fig. 3 Reclamation areas in the Yangtze Estuary

Table 3 Areal change of coastal wetlands and reclamation in the Yangtze Estuary during the 1960s and 2015

Classes	Area in the 1960s (km^2)	Area in 2015 (km^2)	Area change (km^2)					Average speed of area change (km^2/yr)				
			1960s–1980	1980–1990	1990–2000	2000–2010	2010–2015	1960s–1980	1980–1990	1990–2000	2000–2010	2010–2015
Natural wetlands	722.5	411.3	–249.3	–28.1	–132.8	–110.4	–53.8	–12.5	–2.8	–13.3	–11.0	–10.8
Man-made wetlands	146.0	699.6	21.1	179.3	246.8	18.7	87.7	1.1	17.9	24.7	1.9	17.5
Reclamation areas	0	543.7	46.9	24.2	157.0	276.5	39.3	2.3	2.4	15.7	27.6	7.9
The study area	9458.3	10265.3	429.2	–58.7	756.1	–554.9	235.4	21.5	–5.9	7.6	–5.6	47.1

wetlands. Specifically, coastal wetlands shrank, and largely turned into farmland and settlement in the period of the 1960s to 1980. This conversion was mainly located in the Chongming Island and the east coast of Shanghai Municipality. Due to booming of man-made wetlands by conversion of farmlands distributed in Zhangjiagang City and the Chongming Island, coastal wetlands increased in contrast to natural wetlands shrinkage during the period of 1980 to 1990. From 1990 to 2000, farmlands were transformed into man-made wetlands in Changshu City, while farmlands were transformed from natural wetlands in the Chongming Island and man-made wetlands in Lianyugang City and Tongzhou City, resulting in the areal reduction of coastal wetlands. During the period of 2000 to 2010, coastal wetlands also shrank owing to the conversion to settlement and farmlands in Qidong City, the Chongming Island and Changshu City, reflecting intensive construction and agricultural reclamation. For 2010 to 2015, the area of coastal wetlands expanded as farmlands and forest were changed into wetlands in Rudong County, Changshu City, the Chongming Island and Changxing Island, although some wetlands changed into settlement in the east coast of Shanghai Municipality and Tongzhou City. Based on the above analysis, the anthropogenic disturbance to coastal wetlands was relatively active in the Chongming Island, Changshu City and the east coast of Shanghai Municipality. Area of the east coast of Shanghai Municipality in the study area was small, so that only coastal wetlands changes in the Chongming Island and Changshu City were showed in Fig. 4.

The area change of different land use types of reclamation during five study phrases was shown in Table 4. Farmland, settlement and man-made wetlands obtained more significant variation than others, and their temporal dynamics specially remarkable in 2000–2010. The dominant reclamation was alternating change among aquaculture/salt extraction, farming and construction during the study period in the Yangtze Estuary (Fig. 6). Indeed, reclamation for farmlands and man-made wetlands were prevalent in the period of the 1960s to 1980, which mainly lay in Lianyungang City, Tongzhou City and the Chongming Island (Fig. 3). In next 10 years,

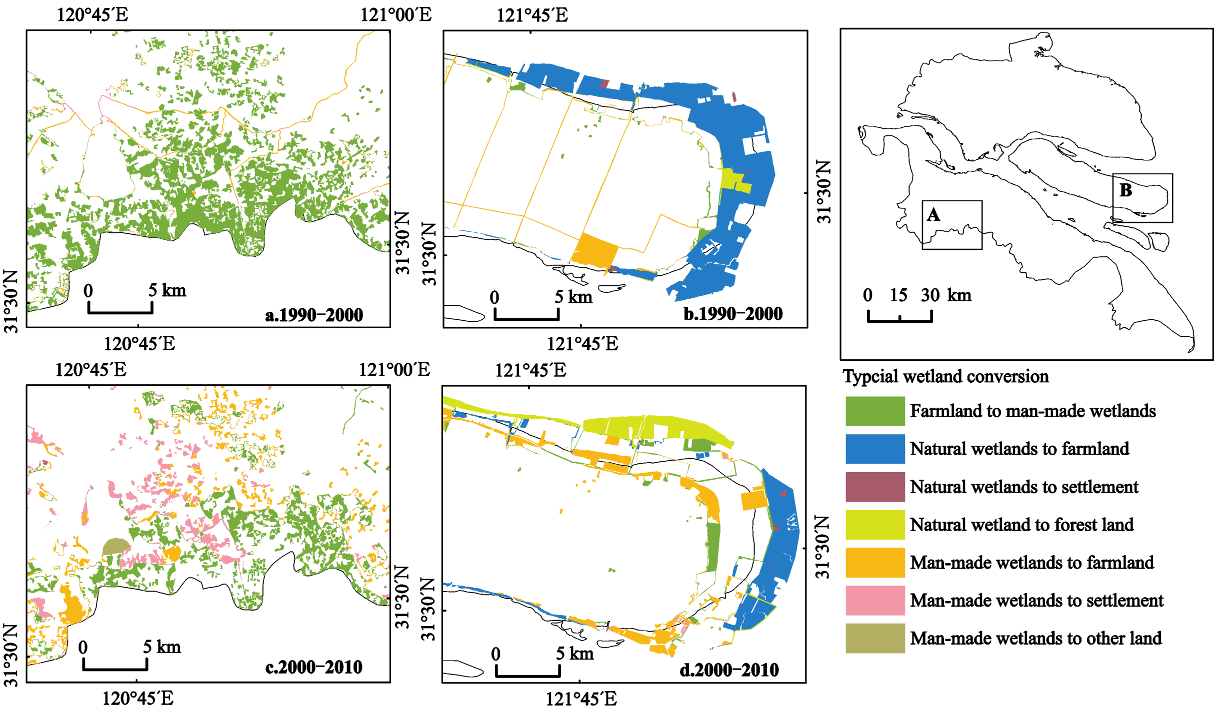


Fig. 4 Typical spatial distribution of coastal wetlands changes in the Yangtze Estuary. A: Changshu City (a, c); B: the Chongming Island (b, d)

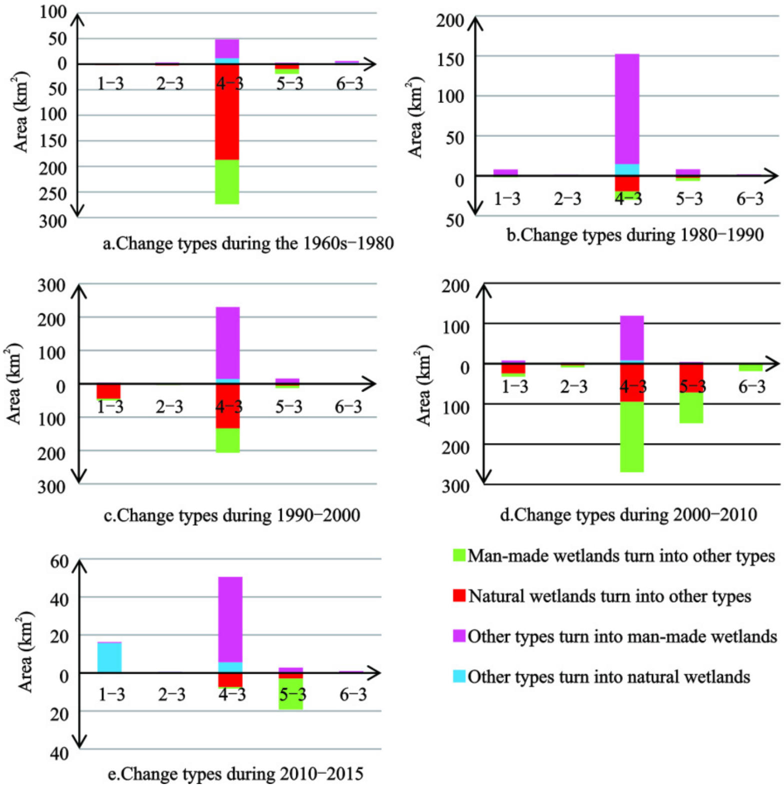


Fig. 5 Areal change between coastal wetlands and other land use types (1–3: between forest and wetlands, 2–3: between grassland and wetlands, 4–3: between farmland and wetlands, 5–3: between settlement and wetlands, 6–3: between other land and wetlands) in the Yangtze Estuary

construction and man-made wetlands reclamation soared mostly in Rudong County and Shanghai Municipality, while farmlands and other land types shrank as a result of quick aquaculture development and construction (Fig. 6), and the situation was not very different from that for the period of the 1960s to 1980. In the period of 2000 to 2010, farmland and man-made wetland reclamation increased mainly in Qidong City and the Chongming Island, and settlement reclamation in the east coast of Shanghai Municipality was obvious. During the following 5 years, farmland reclamation declined sharply in contrast to the increase of settlement and man-made wetlands in the east coastal area of Shanghai Municipality, Taicang City and the Chongming Island. Reclamation of settlement and man-made wetlands escalated during the period of the 1960s to 2015, but farmland reclamation fluctuated wildly (Table 4). Above all, the Chongming Island was influenced most by reclamation activities, and reclamation in the east coast of Shanghai Municipality was chiefly construction activities. In addition, man-made wetland reclamation mainly occurred in Lianyugang City, Tongzhou City and Qidong City, including the construction of canals, reservoirs/ponds, aquaculture ponds and salt fields.

3.3 Movement of coastal wetland centroids and land reclamation in the Yangtze Estuary

On the whole, the centroids of coastal wetlands and reclamation all shifted southwards during the study period (Fig. 7). In details, natural wetlands, fast moved eastward from the water between the Chongming Island and Qidong City during the period of the 1960s to 1980, slowly westwards close to the south coast of Qidong City, and then northwards. During the period of 2000 to 2015, the centroid experienced fast movement to the water between the Chongming Island and east coast of Shanghai Municipality. The centroids of man-made wetlands migrated southwards from the water between the Chongming Island and Haimen City during the first 30 years. Afterwards, they went southwest, reaching the water between the Chongming Island and Taicang City, and then moved directly the northeast to northwest part of the Chongming Island. Moreover, the centroid of reclamation was located in the northern margin of the Chongming Island in 1980, and then migrated northwards, reaching near Haimen City, over the next decade. After that, the centriod repositioned toward southeast, and finally ended in the middle of the Chongming Island in 2015. Furthermore, the centriod evolution of natural wetlands was most complicated mainly distributed in the east part of the Chongming Island, while that of man-made wetlands was relatively simple and took place in the west part of the Chongming Island. The centriod movement of reclamation areas occurred nearby the middle part of the Chongming Island.

Theoretically speaking, when a certain landscape type has the same growth or decline rate in every direction, its centroid remains almost invariant; otherwise, its centroid moves to the direction in which the landscape gains or reduces significantly (Meng et al., 2013). From Fig. 7, it is obvious that the centroid of natural wetlands generally moved towards the sea, indicating natural wetlands declined faster seawards. However, the centroid movement of man-made wetlands expanded relatively equally in all directions and inland. Meanwhile, the centriod path for reclamation shows that reclamation in the Yangtze Estuary was more intensive towards Shanghai Municipality.

4 Discussion

4.1 Factors driving coastal wetland dynamics

The shrinkage of natural wetlands in the Yangtze Estuary was also found by Cui (2016), Xie et al. (2017) and

Table 4 Change area among different land use types of reclamation areas in the Yangtze Estuary

Phrase	Forest		Grassland		Farmland		Settlement		Other land		Man-made wetlands		Reclamation areas
	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)
1960s–1980	0.00	0.00	0.11	0.24	30.20	64.41	0.83	1.77	0.01	0.02	15.74	33.56	46.89
1980–1990	0.03	0.12	–0.11	–0.46	–2.38	–9.86	0.95	3.92	–0.01	–0.04	25.68	106.32	24.16
1990–2000	13.31	8.48	1.09	0.69	80.57	51.33	3.73	2.38	0.00	0.00	58.28	37.13	156.98
2000–2010	16.88	6.11	9.90	3.58	106.27	38.44	85.05	30.76	0.96	0.35	57.39	20.76	276.45
2010–2015	0.47	1.20	0.00	0.00	–23.84	–60.75	18.48	47.08	–0.61	–1.54	44.75	114.00	39.25

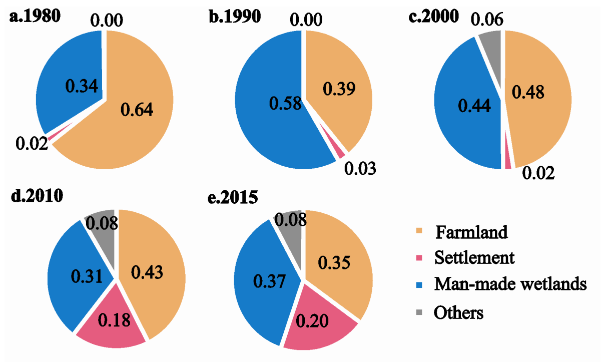


Fig. 6 Reclamation types in the Yangtze Estuary in 1980, 1990, 2000, 2010, 2015

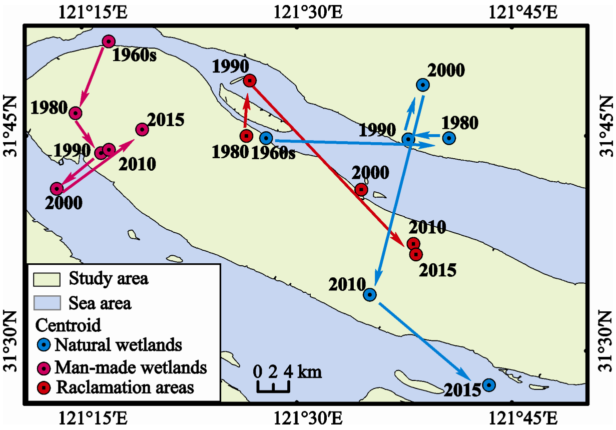


Fig. 7 Area-weight centroids movement for coastal wetlands and reclamation activities in the Yangtze Estuary from the 1960s to 2015

Yu et al. (2017). Abundant studies have found that coastal wetlands are threatened by sea level rise and thus are subjected to areal shrinkage, habitat degradation, and decrease in diversity because the rate mineral deposition and organic matter accumulation fails to pace with sea level rise (Cui et al., 2014; Lovelock et al., 2015; Zhou et al., 2016). Thomas et al. (2016) estimated a global coastal wetlands loss of 78% when a high sea-level rise (110 cm by 2100) occurs and is accompanied by maximum dike construction. As a result of sea level rise, by the 2080s, up to twenty percent of global coastal wetlands may disappear based on a prediction by contemporary global models (Nicholls, 2004; Wang et al., 2016a).

Being at low elevation, coastal wetlands in the Yangtze Estuary are particularly sensitive to sea level rise. According to Chinese Sea Level Bulletin of 2015 (Fig. 8), the sea level in July from Yangtze Estuary to the north of Taiwan Strait obviously increased, 218 mm higher than in normal years of the same period, and was the highest among the same period since 1980. Furthermore, the sea level in the coastal area of Jiangsu Province in 2015 was 107 mm higher than that in normal years and was predicted to rise 80 to 165 mm in the next 30 years. Meanwhile, the sea level of Shanghai Municipality in 2015 was 105 mm higher than the average and may rise 75 to 150 mm in the following 30 years. Based on the SPRC (Source-Pathway-Receptor-Consequence) model, Cui et al. (2015) founded that vulnerability of coastal wetlands in the Yangtze Estuary to sea-level rise would continue to increase in the following 100 years, and areal decrease and loss of habitats and ecosystem services from coastal wetlands would barely inevitable.

In spite of being protected by the feedback between vegetation and landform, coastal wetlands will be eroded and degenerate, even vanish due to sea level rise, dry-up of upstream water, and soil inflow into the sea (Kirwan and Megonigal, 2013; Yang et al, 2005). Indeed, although the area of the Yangtze Estuary kept growing because of silting, with the implementation and completion of the Three Gorges Reservoir and South-to-North Water Transfer projects, the sediment discharge in the Yangtze Estuary constantly decreased causing a slow rate of silting and a regional erosion recession (Yang et al., 2005; Song and Wang, 2014). Song and Wang (2014) discovered that the submerged delta in the Yangtze Estuary experienced an ‘erosion-deposition-erosion’ pattern in 1980–1990, 1990–2000 and 2000 to 2010. Those erosion-deposition processes also affected coastal wetlands in the study area. Moreover, in the study area, *Spartina alterniflora*, a kind of invasive plant also affected coastal wetlands through hastening silting and impacting the distribution of other species as well as carbon and nitrogen cycles (Chen et al., 2007; Zhang et al., 2010).

Meanwhile, extraction of estuarine coastal wetlands

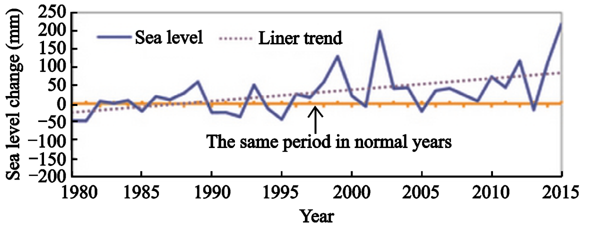


Fig. 8 Sea level change of July from the Yangtze Estuary to the north of Taiwan Strait during 1980–2015 (Chinese Sea Level Bulletin, 2015)

from remote sensing images is affected by fluvial and tidal inundation experienced when images are acquired, which can interfere with the detection of a coastal wetland changes (Allen et al., 2012). Boundaries between natural wetlands such as mudflat and coastal water are fuzzy, and also change with tide level (Gong et al., 2010). Weather limitations (such as cloudy and fog) due to the monsoon climate mean that it is quite difficult to acquire Landsat images in the same tide level so that natural wetland changes with the uncertainty. In the future work, various remote sensing images including microwave and multispectrum etc., as well as tidal conditions will be collected to improve the extraction accuracy of coastal wetlands.

4.2 History and impacts of costal wetland reclamation

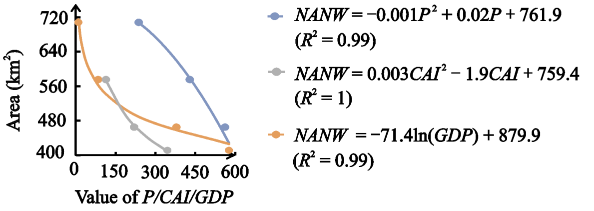
4.2.1 Reclamation evolution

China had a unique reclamation pattern in different historical periods, including salt field in the 1950s, agriculture in the 1960s and 1970s (Bi et al., 2012), aquaculture in the 1980s and 1990s, and industrial construction since the 1950s (Song and Liu, 2013; Wang et al., 2014). Analysis of Landsat images for typical reclamation in the study area indicates, the major types of reclamation were farmland and man-made wetlands in the 1980, 1990 and 2000 and farmland, settlement and man-made wetlands in 2010 and 2015, respectively. The percentages of settlement and man-made wetlands had a sharp rise during the study period. It was also found that the main types of man-made wetlands were canals and salt field in the 1960s, aquaculture pond and salt field in 1980 and 1990, aquaculture pond in 2000, 2010 and 2015, respectively, suggesting that aquaculture dominated reclamation evolution. Moreover, construction of ports made up a high proportion of settlement and industries in the study area, which is in agreement with with the findings by Wang and Yu (2012). Although natural factors such as the coast type and the distribution of tidal flat have some influences on reclamation (Gao et al., 2014; Li et al., 2015), human causes were mainly responsible for the evolution.

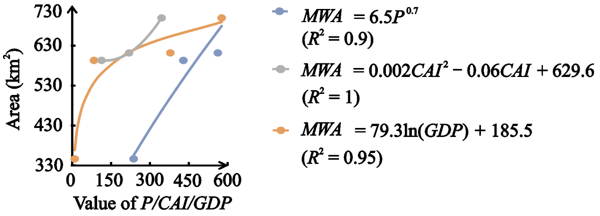
4.2.2 Impacts of reclamation on coastal wetlands

When China started implementing the reform and opening-up policy in the late 1970s, the Yangtze River Delta was firstly chosen as a coastal economic development zone, including Lianyungang City, Nongtong City and Shanghai Municipality as the first tier of open port cities. With only 1% of land and 6% of population of China, this area contributed more than 20% of total national GDP. Particularly, Pudong District of Shanghai Municipality was granted favorable policies in 1990, which was a great promotion of Shanghai as the growth pole for the Yangtze River Delta, and after that the Yangtze River Delta turned to be the focus of the development of China economy (Zhu and Zhang, 2004). The policy support for the Yangtze Delta, such as 'the guidance of State Council on further reform and opening up and economic and social development in the Yangtze river delta region' in 2008, 'regional planning of the Yangtze River Delta region' in 2010, and 'the State Council ratified development planning of the city cluster on Yangtze River Delta' in 2016 *etc*., implies the importance and a rapid development of the Yangtze area. However, increased reclamation in the Yangtze Estuary eases the pressure of a high population density and expands industrial development space (Fig. 3).

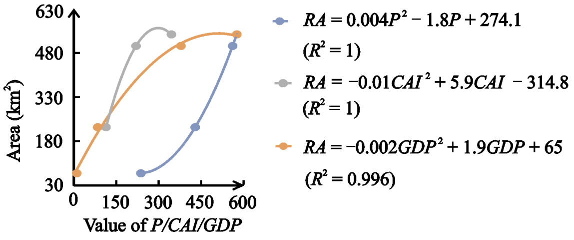
Meanwhile, the urbanization level of this area is generally higher than the national average (Che et al., 2011; Qin et al., 2015), and many ports and wharf have been built up in this area to meet the need for the large trade throughput. This area is one of the most developed tourism areas, especially the Chongming Island, so that the settlement has increased (Table 4). Because of fierce settlement expansion, resource and environmental problems in this area have become prominent, which not only hinders the sustainable development of human and cities, but also harms the health of coastal wetlands ecosystems (Mao, 2008; Tan et al., 2010; Shi et al., 2015). Furthermore, the resource demands for quickly social and economic blossom as well as the fast urbanization process in this area stimulate multiple high-intensity reclamation activities (Wang et al., 2014), such as reclamation of aquaculture, agricultural and construction etc. Ding et al. (2017) founded that conversion of tidal wetlands into paddy soils is a prevalent agricultural practice to meet increasing demand of food in the Yangtze River Delta, which also met results that farmland made up a large proportion of reclamation in Fig. 6. Thus, reclamation areas quickly expanded towards sea while natural wetlands declined faster seawards (Fig. 7). However, intensive reclamation activities directly change the characteristics of regional tidal movement, easily lead to an invasion of sea water to the wetlands and sediment accumulation, and decreases self-purification capacities. All these consequences are harmful to coastal wetland ecosystems and intensify natural disasters (Tian et al., 2008; Li et al., 2014; She et al., 2014; Shi et al., 2015). The statistical data of 1990, 2000, 2010 and 2015 from'China City Statistical Yearbook' and 'China City Construction Statistical Yearbook' were analyzed and presented in Fig. 9. Limited by the number of the study periods, so that the number of scattered points ranges from 3 to 4, which led to the incredibility of the curve-fitting equations. In other words, Fig. 9 is used to show the qualitative relationship. It is clear that the growth of the GDP, population, reclamation and industrial construction is negatively correlated with the net area of natural wetlands significantly plummeted, while the area of man-made wetlands has increased. It indicated that with population and industry booming, reclamation and man-made wetlands climbed up to acquired resources and enormous economic benefits at the cost of natural wetlands.



a. Relationship between *NANW* and *P/GDP/CAI*



b. Relationship between *MWA* and *P/GDP/CAI*



c. Relationship between *RA* and *P/GDP/CAI*

Fig. 9 Population and economy index of Yangtze River Delta Region with area of wetlands and reclamation in Yangtze Estuary. *NANW*, *MWA*, *RA*, *P*, *GAI* and *GDP* represents net area of natural wetlands (km^2), man-made wetlands area (km^2), reclamation area (km^2), population (10^5), construction area of industries (km^2) and gross domestic product (10^{5}yuan), respectively

Above all, reclamation activities, such as construction of ports, industries and aquaculture, were the key cause for the dynamics of coastal wetlands in this area as observed by Ma et al. (2015).

5 Conclusions

This study has resulted several findings. The net area of natural wetlands declined by 574.3 km^2 seawards, which turned into farmlands and settlement during the overall study period. In contrast, man-made wetlands converted from farmlands and gained from reclamation increased by 553.6 km^2 equally in all directions and inland. The reclamation area mainly for settlement and man-made wetlands expanded by 543.9 km^2 towards Shanghai Municipality in the period of the 1960s to 2015. The Chongming Island and the east coast of Shanghai Municipality were the typical regions subject to the shrinkage of natural wetlands, growth of man-made wetlands and reclamation activities in the Yangtze Estuary.

Significant relationships between reclamation factors for the construction of ports, industries and aquaculture *etc*. and coastal wetlands dynamics were also observed. Specifically, quickly expanding in the reclamation area was mainly attributed to man-made wetlands towards sea where natural wetlands declined faster. This demonstrates that the driving force for natural wetland decrease and reclamation boom is human activities such as aquaculture and settlements. Natural factors such as sea level rise, and erosion-deposition processes have influences on conversions of coastal wetlands.

This paper has demonstrated that moderate resolution remote sensing images can be used to effectively extract the dynamics of coastal wetlands and reclamation. The results from this study are valuable for local government to put forward plans for sustainable land use and land development. Future research should be focused on the spatiotemporal patterns of multiple reclamation activities and wetlands in the study area, and conducting quantitative analysis of the forces driving different reclamation activities.

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