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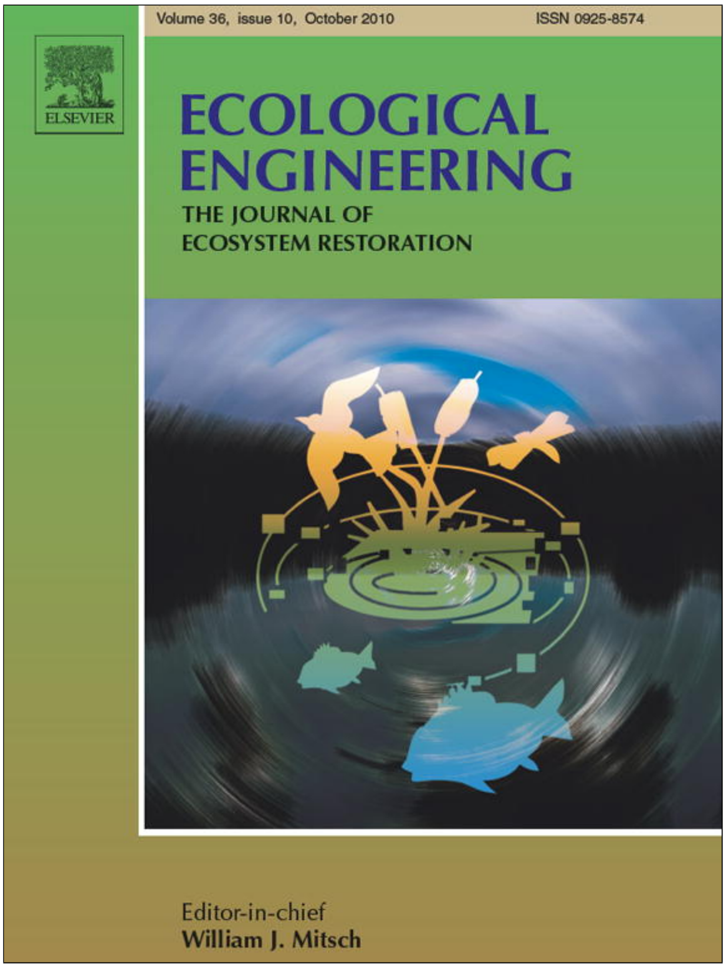
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Forecasting the effects of sea-level rise at Chongming Dongtan Nature Reserve in the Yangtze Delta, Shanghai, China

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ABSTRACT

Located at the mouth of the Yangtze Estuary, the Chongming Dongtan Nature Reserve is extremely vulnerable to climate change and especially to accelerated sea-level rise. We use a variety of data from remote sensing, an *in situ* global positioning system (GPS), tidal gauges, nautical charts, geographic spatial analysis modeling and IPCC sea-level rise scenarios to forecast the potential impacts of increased sea level on the coastal wetland habitat at Chongming Dongtan Nature Reserve. The results indicate that around 40% of the terrestrial area of the Dongtan Reserve will be inundated by the year 2100 due to an estimated 0.88 m increase in sea level. In particular, the *Scirpus mariqueter* communities and bare tidal flats are more vulnerable to sea-level rise. The limitations of this approach and the implication of the results for wetland and ecosystem conservation as well as management are discussed.

1. Introduction

The existence of sea-level rise (SLR) is undeniable. The oceans have the potential to increase in height at the coast at an accelerated rate during this century and thereafter, due to the impacts of increased greenhouse gas concentrations responsible for global warming (IPCC, 2007) and the associated melting of polar and alpine glaciers and changes in ocean currents. Accelerated sea-level rise will have far-reaching impacts on low-lying coastal regions around the world (Nicholls et al., 2007; Poulos et al., 2009; Snoussi et al., 2009). Chongming Dongtan Nature Reserve, one of the largest nature reserves in East Asia, is located at the mouth of Yangtze Estuary (Tian et al., 2008) and is highly susceptible to sea-level rise due to its low elevation and the lack of resources to mitigate such threats (Michener et al., 1997; Fussel, 2007).

Negative impacts of sea-level rise on estuaries include coastal erosion linked to increased storminess, periodic or permanent inundation, increased coastal storm flooding and salinization. Such effects will result in wetland loss, and thus habitat loss for shorebirds and a decline in wetland ecosystem services (Galbraith et al., 2002; Austin and Rehfisch, 2003; Craft et al., 2009). Such impacts on Chongming Dongtan Nature Reserve will create adverse effects on tidal marshes, flats, creeks and channels, which provide important spawning grounds for fish, and nesting and foraging habitats for migratory and residential birds. The potential negative impacts will be spatially non-uniform because such changes depend on the magnitude of the relative sea-level rise, coastal morphology and human intervention (CCSP, 2009). Among these impacts, inundation represents an important component of coastal wetland habitat change. Inundation will be one of the primary responses to increased sea level in Chongming Dongtan Nature Reserve because of the low gradient slope in the coastal wetland region, significantly decreased sand sediment inputs from upstream sources in the Yangtze River and the effects of seawall construction which will prevent inland wetland migration. However, the complex and interrelated processes of coastal dynamics such as erosion, accretion, biological processes and sediment transport balance have yet to be fully examined.

Several methods and modeling approaches have been used to evaluate the impact of increased sea level at different scales in coastal regions. Such techniques include the Sea Level Affecting Marshes Model (SLAMM) (Park et al., 1989), the Process Oriented Site-Specific Model (POSSM) (Morris et al., 2002; Rybczyk and Cahoon, 2002), and the Wetland Change Model (WCM) (Nicholls et al., 2007). These models have various limitations, including coarse resolution levels for landscape-scale models (e.g. SLAMM) and low confidence in site-specific model simulations. In contrast, elevation-based analyses for the assessment of inundation result-

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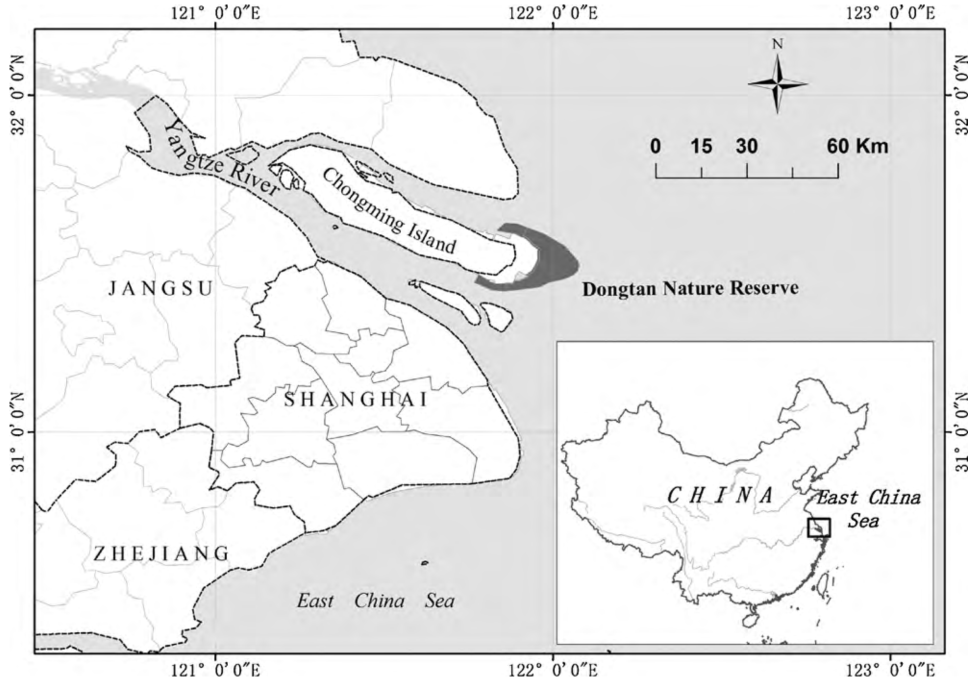

Fig. 1. The location of the Chongming Dongtan Nature Reserve in the mouth of Yangtze Estuary.

ing from increased sea-level rise appear to be simple, effective methods, when supported by valid and accurate elevation data and habitat maps (CCSP, 2009).

The objective of the present study was to assess the quantity and spatial distribution of tidal wetland habitats, and to produce vulnerability maps and statistical summaries of the impact of sea-level rise on the Chongming Dongtan Nature Reserve, according to two SLR scenarios provided by the State Oceanic Administration (SOA) of China and the Intergovernmental Panel for Climate Change (IPCC, 2007). These scenarios provide minimum and maximum SLR estimates of 10–48 cm by 2050 and 22–88 cm by 2100, respectively. Remote sensing and GIS technology have been used extensively for constructing topographic maps, habitat maps and inundation analyses. For information not available from high-resolution Lidar elevation data, Landsat TM, tidal gauge, an *in situ* Global Positioning System (GPS) and nautical chart data have been used to generate digital elevation models covering the land–water areas. High-resolution Quickbird data have been used to map the wetland habitat as tidal marshes and tidal flats in conjunction with object-oriented image approaches.

2. Study area

The study area is located on Chongming Island, which is the largest island at the mouth of the Yangtze Estuary in eastern China. It lies between 31°25′–31°38′N and 121°50′–122°05′E (Fig. 1) and has a northern sub-tropical monsoon climate with an average annual temperature of 15.3 °C. The average summer temperature is c 26 °C, while the winter is cold with an average temperature of 3 °C. Average annual precipitation is approximately 1022 mm, with 60% of rainfall occurring between May and September. The average humidity is about 82%.

The total area of the Dongtan Nature Reserve at the eastern end of Chongming Island is 32,610 ha. The core area, which is east of the 1998 reclamation dyke, covers some 24,600 ha, including 10,000 and 14,000 ha of tidal flats above and below an elevation of 0 m (local Wushong bathymetric benchmark), respectively. The wetland types in this nature reserve include tidal marshes (mainly occupied by *Scirpus mariqueter*, *Phragmites australis*, and *Spartina alterniflora* communities), tidal flats and shallow open waters. The tidal flats with elevations of less than 2 m are characterized by mud flats, without any vascular plants. The tidal flats between 2.0 and 2.9 m elevation are dominated by *S. mariqueter* communities and rarer *Scirpus triqueter* communities. Above 2.9 m, plant communities are mostly *P. australis* with some communities of *Imperata cylindrica*, *Suaeda glauca*, *Juncus setchuensis* and *Carex scabrifolia*.

The intertidal wetland is the main wetland habitat at Dongtan Nature Reserve and is an important area that is exposed at low tide and submerged at high tide, providing shelter for both freshwater and brackish water fish. Each year, more than 300,000 migratory birds use the nature reserve as an important wintering site. The predominant groups are Anatidae, Charadriidae, Ardeidae and Laridae. A maximum of 113 species of birds have been recorded at the nature reserve (Xu and Zhao, 2005) and in the *S. mariqueter* marsh habitats. However, bare tidal flat zones and tidal creeks are the most suitable habitats for these migratory birds.

According to the observation data obtained over a 30-year tide period from 1978 to 2008 in Waigaoqiao tidal gauge station, which is geographically close to the Dongtan Nature Reserve, the local mean sea level is 2.17 m, the mean 'high' water height is 3.5 m, and the mean 'low' water height is 1.03 m in relation to the local Wushong bathymetric benchmark.

3. Method

3.1. Generation of DEM

To bridge the data gap at the land–water interface in the nature reserve with alternative sources of vertical data, various integrated topography and bathymetric datasets were constructed to provide a seamless dataset for inundation-based analysis. Navy nautical charts of the Yangtze estuary (published in 2005) were used to provide depth information. Because topography data and Lidar data were not readily available, the intertidal elevation informa-

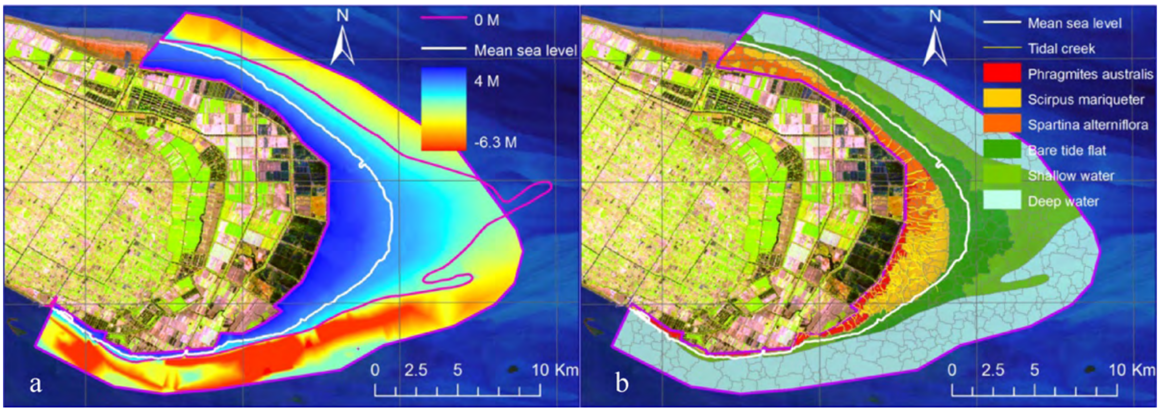

Fig. 2. DEM (a) and wetland habitat map (b) at Dongtan Nature Reserve.

tion was generated using waterline data extracted from Landsat TM, water level and *in situ* GPS data. All topographic, bathymetric, water level and ground elevation data were transferred to the local Wushong vertical datum, which provided a consistent vertical reference frame. All data for analysis of SLR impact were collected starting in the year 2005.

During the construction of the intertidal digital elevation model (DEM), seven Landsat TM images (acquisition dates: 2004-02-26, 2004-06-01, 2004-07-19, 2004-11-24, 2005-5-3, 2005-7-22, 2005-11-27) representing different water level or tidal conditions were selected for waterline measurement. The waterline was defined as an instantaneous contour line of the land–water interface area at a specific tidal condition in a remotely sensed image. The band3/band5 ratio of TM image data was used as the water index and threshold segmentation was performed to extract the waterline from multi-date Landsat TM images.

A hybrid approach, involving both image-to-map rectification and image-to-image registration (Jensen, 2005), was performed to rectify all Landsat TM images to a standard map projection where the images were used in conjunction with other spatial information in a GIS to construct elevation datasets. The November 27, 2005, base image was previously rectified to a Universal Transverse Mercator (UTM) map projection with 30 m × 30 m pixels. Other images were subsequently registered to a rectified November 27, 2005, image and the IMAGE AutoSync add-on module for ERDAS IMAGE software package was used to automatically extract GCPs (Geometric Control Points?) common to the two images; this process can be used for image-to-image registration.

The DEM was generated from interpolation of the elevation data from the waterline, the GPS, and the bathymetric soundings vector data. These vector data contained elevation and depth information obtained using the ArcGIS 3D Analyst Triangular Irregular Network (TIN) Creation tools, and the TIN surface was converted into standard gird data with a 30 m × 30 m resolution.

3.2. Mapping of wetland habitat

Treatments and classification of satellite images were conducted for extraction of polygonal assessment units using object-oriented segmentation for the wetland habitat map. A high-resolution Quickbird Image obtained on September 29, 2005, under ebb tidal conditions was used to map the wetland marsh and tidal flat habitat using ERDAS Imagine software. The satellite image was also geometrically corrected to a UTM map projection, which was used for the Landsat TM image. Quadratic polynomials were applied to correct equations according to the distribution of control points. The image containing multi-spectral and pan band was then sharpened to a resolution of 2.5 m × 2.5 m and the resulting error was less than 1 pixel.

Object-oriented image analysis was used to transform remote sensing data into more accurately classified geographic information for mapping of the distribution of the tidal channel, the tidal flat, the *S. mariqueter*, *P. australis*, and *S. alterniflora* mash communities with the support of eCognition software package. The sharpened Quickbird image was segmented into a polygonal image object according to the image characteristics of spectral value, shape and grain, in conjunction with the geo-spatial data of boundary character and elevation (Benz, 2001; Bock et al., 2005). Finally, a fuzzy classification approach to the nearest neighbor was performed, and heterogeneous areas or image object shapes were merged and refined based on their classification to generate wetland habitat datasets.

3.3. Sea-level scenarios

Relative sea-level change was computed for each site at every time step. SLR is the sum of the historic eustatic trend, the site-specific rate of change of elevation due to subsidence and isostatic adjustment and the accelerated rise depending on the scenario chosen (Titus et al., 1991; IPCC, 2007). Since the 1950s, the Chinese sea level has been rising and the increase has become especially apparent in recent years. The average rate of increase is approximately 1.4–2.6 mm/a. In the past 30 years, the overall sea level of the whole country has risen 90 mm, with the average offshore surface temperature increasing by 0.9 °C. Dongtan Nature Reserve has experienced a sea-level rise of 115 mm. Over the next decade, the SOA forecasts that China's coastal sea level will likely rise by 32 mm (3.2 mm/a). In this study, sea-level rise scenarios are mainly adopted from the IPCC medium emission scenario and predictions of SOA; the increases in sea level range from 0.1 to 0.48 m by 2050 to 0.22 to 0.88 m by 2100, respectively.

3.4. Inundation spatial analysis

We developed an inundation analysis model using the ArcGIS ArcToolbox to assess the impact of SLR. The variables of sea-level rise, the DEM, the wetland habitat map, the boundary data and mean sea level input data were all integrated into this model. The Contour List function was used to extract the submerged contour line with contour values of 0.1, 0.48, 0.22 and 0.88 m sea-level rise adding to mean the current sea level at 2.17 m. The inundation zone was topologically generated along the submerged contour line and the present mean sea level contour line. Using the spatial analysis tools of ArcGIS, the delineated inundation zone was overlaid

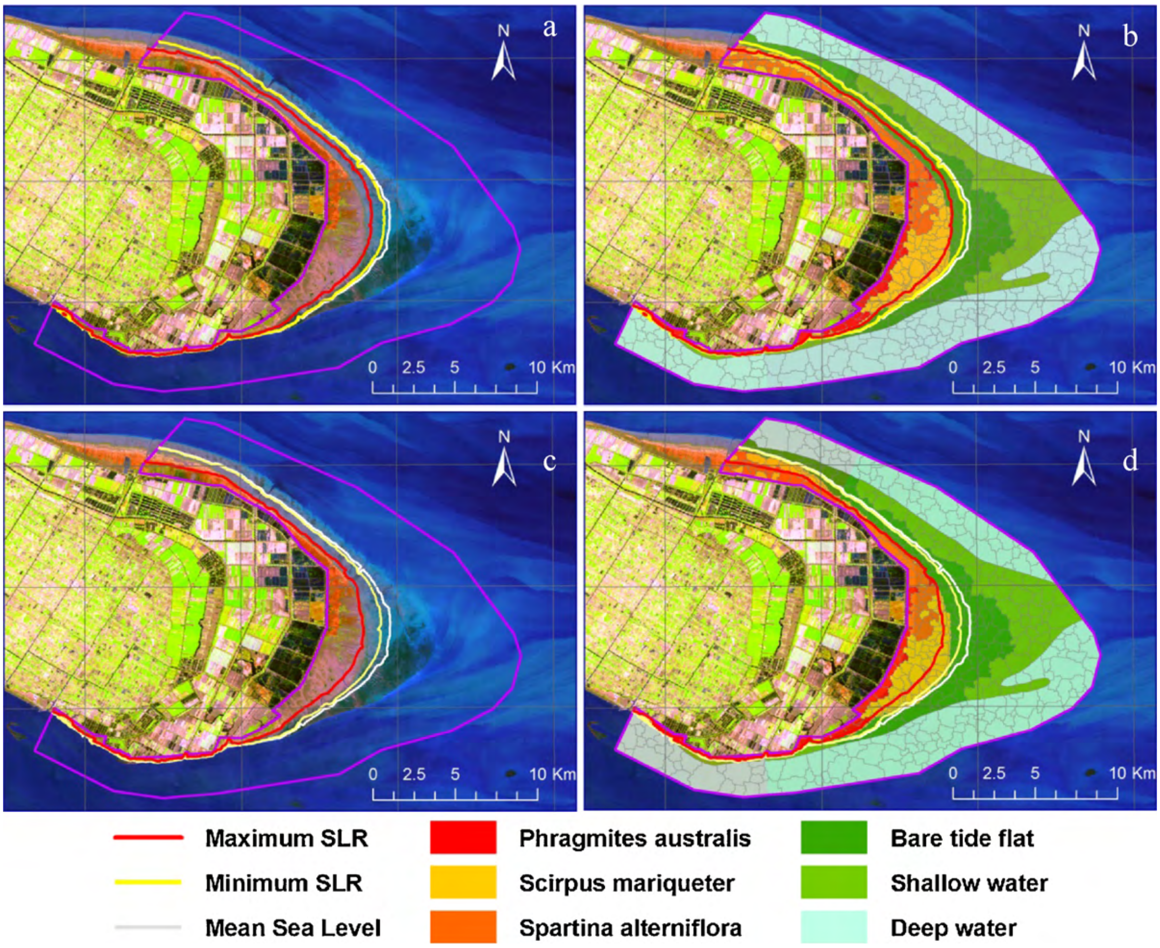

Fig. 3. Impact of sea-level rise on tidal flat and tidal marsh complex by 2050 (a and b) and 2100 (c and d) year at Dongtan Nature Reserve.

Table 1
Potential tidal wetland loss with minimum and maximum hypothesized SLR by the years 2050 and 2100 at Chongming Dongtan Nature Reserve.

Future conservation targets (year)	Minimum hypothesized SLR		Maximum hypothesized SLR	
	Submerge area (ha)	Proportion (%)	Submerge area (ha)	Proportion (%)
Tidal wetland (2050)	328	5.7	1151	20
Tidal wetland (2100)	634	11	2229	38.6

and intersected with wetland habitat variables to map the loss of wetland and to summarize the values of these variables within the potential impact zone.

4. Results

The DEM presented in Fig. 2 shows that the highest elevation is less than 4.2 m (Wu Song benchmark), and the terrestrial area above the present sea level is 5768 ha, which is about 25% of the total reserve area. The habitat map (Fig. 2) shows that the total area of the *S. mariqueter* marsh community is 2087 ha. The potential inundation zone and the impact area of the wetland habitat with the minimum and maximum predicted values for years 2050 and 2100 are presented in Fig. 3.

With the minimum hypothesized value of SLR, Chongming Dongtan would lose 11% of its terrestrial area. In the case of the maximum hypothesized value of SLR (0.88 m), 2229 ha of the terrestrial area in the nature reserve (approx. 39%) would be at risk of submersion (Table 1). This area is mainly occupied by bare tidal flats and *S. mariqueter* (Table 2). By the year 2050, about 937 ha of bare tidal flats and 191 ha of *S. mariqueter* will be submerged under conditions of a 0.48 m maximum increase in sea level. By the year

Table 2
Wetland habitat losses by the years 2050 and 2100 with high estimated SLR.

Year	Wetland habitat	Bare tidal flat	*Scirpus mariqueter*	*Spartina alterniflora*	*Phragmites australis*	Total
2050	Area (ha)	936.87	191.19	11.22	12.39	1151
	Proportion (%)	81.3	16.7	1.0	1.1	100
2100	Area (ha)	1420.15	719.46	49.61	39.76	2229
	Proportion (%)	63.7	32.3	2.2	1.8	100

2100, about 1420 ha of bare tidal flats and 719 ha of *S. mariqueter* will be at risk of inundation under the maximum predicted sea-level rise of 0.88 m. The *S. mariqueter* and bare tidal flat areas will be more vulnerable to sea-level rise, which is important, because these localities represent a vital breeding area for migratory shorebirds.

5. Discussion and conclusions

5.1. Implications for conservation

Climate change and its associated effects, such as sea-level rise, have global implications that will increasingly affect the entire conservation area in the nature reserve. However, due to the complexity of interrelated coastal processes, the tidal wetland change caused by sea-level rise is masked by a multitude of factors including waves, tidal currents, tidal surges, seaward and landward migrations of the marsh, sediment supply balances, crustal motions, ground subsidence and climate change. While numerous studies have focused on shoreline change, estuarine erosion, sediment supply balance, saltwater intrusion and invasive plants on the Chongming Dongtan tidal wetland (Yang, 1999; Jing et al., 2007; Li and Zhang, 2008; Xiao et al., 2009), these studies are insufficient to describe the potential wetland loss and deterioration that will result from climate change. This absence of scientific data and information about the impact of increased sea level will ultimately influence the protective policies, regulations, measurements and decisions about the Chongming Dongtan Nature Reserve.

The identification, mapping and statistical summary of environmental impacts of the projected sea-level rise at Chongming Dongtan Nature Reserve represents an important initial step for decision makers concerned with mitigation of the adverse impacts of sea-level rise. In this study, the inundation-based assessment was developed to inform policymakers, mangers and the public about the amount and spatial distribution of tidal wetland change as a result of sea-level rise. The results indicate the zones most vulnerable to sea-level rise at the Chongming Dongtan Nature Reserve are the *S. mariqueter* zone, the bare tidal flat zone and the tidal creeks, which are the most suitable habitats for migratory birds (Tian et al., 2008). A ~30% loss of the *S. mariqueter* marsh community by the year 2100 would eliminate a rich invertebrate food source and cause deterioration in the estuarine food web for migrating birds (Strange et al., 2008); such a loss could arise from human-induced stressors such as land reclamation, seawall constructions, overfishing and local pollution. As tidal marshes and flats submerge and decline in size and productivity, increased crowding in the remaining areas could lead to reductions in and eventually even exclusion of some local shorebird populations (Galbraith et al., 2002).

The impact assessment of increased sea level at Chongming Dongtan Nature Reserve indicates that it is crucial and necessary to incorporate the potential impacts of future increases in sea level into conservation planning, actions and decision-making. Conservation of these areas requires present-day preparation to reduce the eventual adverse consequences of increased sea level. The direct approaches and fundamental pathways for adapting and mitigating the impacts of increased sea level include armouring, elevation and managed retreat (CCSP, 2009). However, to comprehensively adapt wetland habitats and the wetland ecosystem for conservation, special management actions must be considered, including the protection of *S. mariqueter* community and its tidal flat and reduction of anthropogenic stress (Kareiva et al., 2008).

5.2. Limitation and application

Tidal wetland habitat changes at Dongtan Nature Reserve in response to sea-level rise and related processes may include several structural and functional changes, and inundation is only one of a number of possible responses to sea-level rise (FitzGerald et al., 2008). The complexities of tidal wetland change are not fully understood and are thus difficult to simulate mechanistically. The region of mouth bars in the Yangtze Estuary and the submerged delta nearby are the major locations of sedimentation resulting from the great amount of silt brought down the Yangtze River (Yang, 1999). The eastern fringe of Chongming Dongtan was advancing at a rate of between 150 and 300 m/year in previous decades (Gao and Zhang, 2006). However, the supply of sediment to the intertidal area is presently lower, due to the construction of dams in the Yangtze River and possibly also changes in water delivery by the river. Moreover, recent modeling studies using a variety of approaches (GIS-based statistical models, different deterministic models) have shown that saltmarshes in particular have a high capacity to follow sea-level rise, because any increase in inundation frequency could cause an increase in sedimentation rate (Kirwan and Temmerman, 2009). Inundation modeling is usually a simple, effective method wherein sea level is increased by delineating an area at and below a specified land elevation to create the inundation zone (CCSP, 2009), with unavailable accretion and process data applied across the entire conservation area. The utility and applicability of the results based on inundation analysis would present a base model for a possible suite of scenarios. It would be interesting to compare the prediction to more scenarios based on the rate of sediment accretion in the saltmarshes and mudflat, although it is a very complex task at the present.

Increased sea level is one of the most visible and immediately serious consequences of climate change for the general public and the coastal science community. Appropriate methodologies and models are still needed to obtain reliable information about coastal wetland habitat change, resulting from climate change. Prediction of the consequences of climate change impacts, especially increased sea level, in this nature reserve is a challenge because of the difficulty in identifying, accurately mapping and quantifying the physical response of the tidal wetlands to increased sea level, while taking into account the wide variety of other estuarine and coastal processes as well as other human activities and impacts. To meet the need for more accurate, detailed and up-to-date sea-level rise vulnerability assessments and to incorporate this base model with the sediment accretion models, further studies and more approaches are needed to provide more scenarios.

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