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Review

Adapting cities to sea level rise: A perspective from Chinese deltas

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Abstract

In recent years, intensifying waterlogging, salt water intrusion, wetland loss, and ecosystem degradation in Chinese delta cities and adjacent regions have generated the pressing need to create an urban form that is suited to both current and future climates incorporating sea level rise. However, adaptation planning uptake is slow. This is particularly unfortunate because patterns of urban form interact with mean sea level rise (MSLR) in ways that reduce or intensify its impact. There are currently two main barriers that are significant in arresting the implementation of adaptation planning with reference to the MSLR projections composed of geomorphologic MSLR projections and eustatic MSLR projections from global climate warming, and making a comprehensive risk assessment of MSLR projections. The present review shows recent progresses in mapping MSLR projections and their risk assessment approaches on Chinese delta cities, and then a perspective of adapting these cities to MSLR projections as following six aspects. 1) The geomorphologic MSLR projections are contributed by the natural tectonic subsidence projections and the MSLR projections by anthropogenic geomorphologic change. The former needs to be updated in a global framework. The latter is accumulated by land subsidence from underground water depletion, water level fall caused by the erosion of riverbeds from a sediment supply decline attributed to the construction of watershed dams, artificial sand excavation, water level raise by engineering projects including land reclamation, deep waterway regulation, and fresh water reservoirs. 2) Controlling MSLR projections by anthropogenic geomorphologic changes. 3) The IPCC AR5 RCPs MSLRs scenarios are expected to be projected to the local eustatic MSLR projections on the Chinese deltas. 4) The MSLR projections need to be matched to a local elevation datum. 5) Modeling approaches of regional river-sea numerical with semi-analytical hydrodynamics, estuarine channel network, system dynamics and adaptation points are perspective. 6) Adaptation planning to MSLR projections requires a comprehensive risk assessment of the risk of flood, fresh water supply shortage, coastal erosion, wetland loss, siltation of ports and waterway in Chinese delta cities and adjacent regions.

Keywords: Mean sea level rise projections; Natural tectonic subsidence; Climate warming; Local elevation datum; Anthropogenic geomorphologic change; Adaptation tipping point

1. Introduction

Since the beginning of the 21st century, it has been well acknowledged that observed and anticipated climate warming and associated future mean sea level rise (MSLR) are likely to have far reaching impacts on coastal zones (Nicholls and Cazenave, 2010; IPCC, 2013; Ding and Wang, 2016), and that delta regions suffer the strongest threat to MSLR (Syvitski et al., 2009; Clifton, 2011; Qin and Zhu, 2015; Ding et al., 2016). Determining adaptation strategies and actions to cope with MSLR are thus of vital importance for the scientific communities and global governments (Kabat et al., 2009; Rosenzweig and Solecki, 2010; Katsman et al., 2011; Klijn et al., 2015).

China has a mainland coastline of about 18,000 km, an island coastline of 14,000 km, and contrasting geological settings. Rapid uplift of the Qinghai-Tibet Plateau by collision

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between the Pacific Ocean plate, India Ocean plate, and Eurasian plate generated large river deltas such as the Yangtze, Yellow, and Pearl Rivers, that have high sediment transport. In addition, there is a mosaic of smaller river deltas located on the Chinese coast, such as Beilunhe, Nanliujiang, Hanjiang, Jiulongjiang, Minjiang, Oujiang, Huaihe, Luanhe, Liaohe, Haihe, Dalinghe, and Yalujiang Rivers (DESCAS, 1994). Both large and small deltas are densely populated, in addition to being economically developed areas with high urbanization rates and containing the current and future major Chinese economic circles, namely city clusters (Fig. 1). These cities are low-lying, and even the elevated city center areas are below the mean high tide level. They are therefore vulnerable to storm and flood disasters. Such risks are now amplified in relation to climate warming and MSLR, and there is thus an increased risk of flood, waterlogging, fresh water supply shortage, wetlands loss and degradation of spawning grounds, loss of life and economy, and could potentially even lead to a social problems (DESCAS, 1994; Shi et al., 2000; Wu et al., 2002; Qin et al., 2015; Ding et al., 2016).

Over the past 30 years, significant research attention has been paid to scenario planning and vulnerability assessments of MSLR projections to improve policies associated with the Chinese coast (Qin et al., 2015). In recent 10 years, intensifying waterlogging (Zhang et al., 2014; Ji et al., 2015; Xia et al., 2017) and salt water intrusion (Qiu and Zhu, 2015; Li et al., 2015) has created a pressing need for adaptation of urban form strategies for Chinese delta cities that are suitable for both current and future mean sea levels. However, there has been limited uptake of adaptation planning (Ding and Wang, 2016; Cheng and Chen, 2016), and creating a

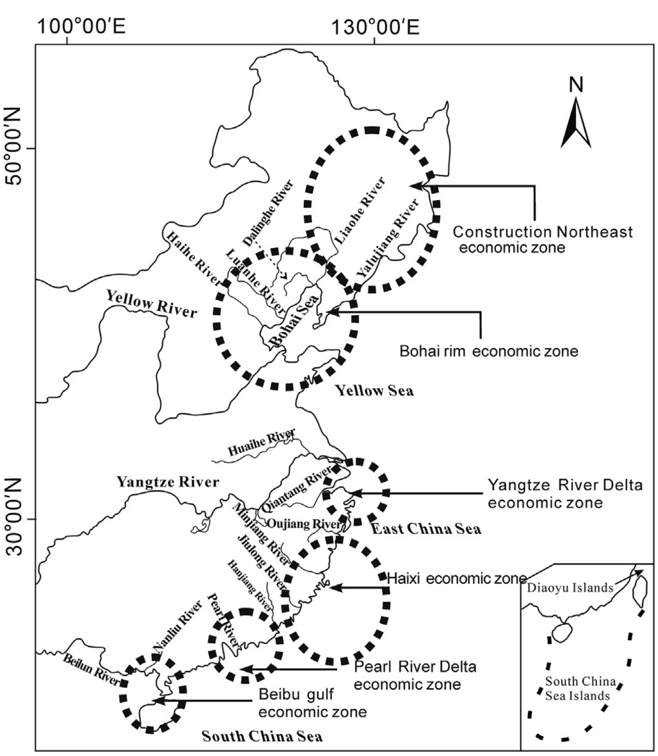

Fig. 1. Major Chinese deltas coast and economic zones.

practical adaptation planning process is difficult given the uncertainties inherent in the physical manifestations of climate change and MSLR, as well as modeling uncertainty in the timing and magnitude of the rise and its impact (Abunnasr et al., 2015). In this respect, policymakers are at a total loss as to how to implement sea level adaptive actions.

As sea level lies at the intersection of solid, liquid, and gaseous components, and in this way the dynamics of the fluid part of the planet are linked with those of the solid part (Conrad, 2013). For a long time, the focus on China's MSLR impact researches relates to one thousand and ten thousand year's geological periods (Yang and Shi, 1995), which is also not helpful in relation to planning adaptation strategies. The eustatic MSLR projections in relation to climate warming have been well applied in coastal management and infrastructure design from the late 1980s to the beginning of the 21st century, which spans a scale of tens to hundreds of years and in combination with natural tectonic subsidence and anthropogenic geomorphologic changes including land subsidence by underground water depletion (Shi et al., 2000; Huang et al., 2000; Ren, 1993; Wu et al., 2002; Xue et al., 2005). However, this has shown to be less effective as a flood defense in protecting against significantly accelerating MSLRs of 3.2 mm per year on the Chinese coast (Fig. 2), as shown by recent decadal variations at multi gauge stations from 1986 to 2015 (COIN, 2016). This is the main reason why an intensifying waterlogging and salt intrusion occurred on the Chinese delta cities in recent 30 years (Xia et al., 2017).

Over the recent decade, greater MSLRs have been seen on the Chinese coast. For example, TOPEX/Poseidon altimetry data has shown a MSLR of 3.5 mm per year on the Bohai coast, 2.9 mm per year on the Yellow sea coast, 2.4 mm per year on the East China Sea coast, and 10.0 mm per year on the South China Sea coast (Zuo et al., 2015). In addition, AVISO altimetry data has shown a MSLR of 3.8 mm per year on the Bohai coast, 3.3 mm per year on the Yellow sea coast, 3.4 mm per year on the East China Sea coast, 5.0 mm per year on the South China Sea coast (Zuo et al., 2015) and 3.72 mm per year on the Pearl River Delta coast (He et al., 2014). This increasing trend and magnitude is greater than the former MSLR projections in the 1990s over a longer temporal scale (Wu et al., 2002), and greater than accelerating MSLR

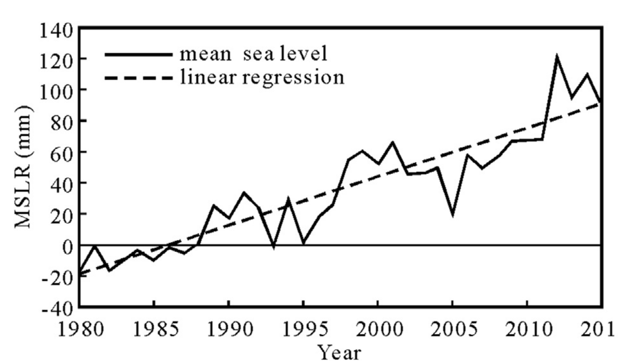

Fig. 2. Mean sea level anomalies on the Chinese coast over 1980–2015 (relative to 1975–1993 mean) (COIN, 2016).

projections based on United States tide gauges and extensions of previous global-gauge analysis (Rahmstorf and Vermeer, 2011; Houston and Dean, 2013). This is attributed both to the accelerating climate warming and to intensifying anthropogenic MSLRs including land subsidence by underwater depletion, falls in water level caused by riverbed erosion and sand excavation, and banked-up water related to engineering projects such as land reclamation, deep waterway regulation, and fresh water reservoirs (Cheng et al., 2015a, 2015b; Cheng and Chen, 2016).

This paper presents a review of recent progress in mapping the magnitude of MSLR projections and risk assessments approaches used for Chinese delta cities, in addition to the worldwide implications of adaptation planning. Based on the progress made, we aim to show a perspective for the adaptation of Chinese delta cities to MSLR projections as following six aspects, which is inherent in the earth system and functioning of the Future Earth research (Lahsen, 2016).

2. Updating the natural tectonic subsidence projections in a global survey framework

The coastal tectonic structures in areas of rising and sinking in China are driven by radioactive energy from the internal Earth. They control types of riverine sediment transport and MSLRs, and finally control the types of deltas (DESCAS, 1994). The first natural tectonic subsidence projection on the Yangtze River Delta coast was initially measured as 1 mm per year on a global scale, using a very long baseline interferometer (VLBI) during 1987–1996 by the Shanghai Astronomical Observatory of CAS (SCWCB, 1996). However, no further global survey data reports on the natural tectonic subsidence projection have been made in the past 20 years. It would thus be useful to consider the new projection of natural tectonic subsidence in Chinese deltas, as there have been frequent strong earthquakes occurring in China, Japan, Nepal, and tsunamis in Indonesia since the 1990s. It is thus imperative to update the natural tectonic subsidence projections in a global survey framework using a new version of VLBI as it is an important component of MSLR projections. GNSS position offsets data provide another opportunity to estimate the natural tectonic subsidence projections in Chinese deltas in a global framework (Griffiths and Ray, 2016) in the future.

3. Controlling magnitude of MSLR projections by anthropogenic geomorphologic changes

Strong land subsidence from anthropogenic underground water depletion in Chinese delta cities has traditionally been recognized as the main anthropogenic contributor to MSLR projections in IPCC reports and Chinese National Assessment Reports over the past 30 year (IPCC, 2013; Qin et al., 2015). Such activity has increased to a large extent with the rapid urbanization on the Chinese delta coast within this time frame (Dong et al., 2013). Over the most recent 20 years, the largest amount of land subsidence has occurred on the Bohai coast located on the thickest and loosest sediment layer of the late Quaternary due to large-scale urban construction (Lei et al., 2016). Intensifying legal legislation and regulations for land subsidence control have been proposed and implemented by the local governments of the Shanghai municipality (Cheng and Chen, 2016), and more stringent legal regulations and legislation have also been suggested to other Chinese delta cities.

The contribution of water level rise to MSLR projections from estuarine and coastal engineering infrastructure works, such as the land reclamation, construction of fresh water reservoirs and deep waterways was qualitatively concerned in the 1990s (DESCAS, 1994). It was quantitatively determined using an analysis of data obtained from tide gauge stations on the Shanghai coast and then simulated using MIKE21 software since the beginning of 21st century. The results show that the sea level raise from anthropogenic geomorphologic changes is much larger than the eustatic MSLR estimated from climate warming (Liu et al., 2008; Yan et al., 2009; Cheng et al., 2015a, 2015b; Cheng and Chen, 2016). Recently, the land reclamation projects have been strictly restricted by both national and local administration systems.

Estimates of the contribution of falling water levels to MSLR from intensifying riverbed erosion, attributed to the sediment supply decline after the Three Gauge Dam (TGD) closure (Ji et al., 2013; Zhang et al., 2015), was previously estimated as being 2–10 cm over the most recent 15 years in the Yangtze estuary, based on the bathymetric data analysis (Cheng et al., 2015a, 2015b). However, no other data have been reported for the other Chinese deltas. In addition, the magnitude of the contribution is difficult to be estimated and required further study using a semi-analytical simulation (Alebregts and Swart, 2016). The reason is that there is a complex feedback mechanism between artificial morphologic change and water level variations (Reeve and Karunarathna, 2009; Mikhailova and Mikhailova, 2010).

4. Projecting RCP scenarios to the local eustatic MSLRs in Chinese deltas

The eustatic MSLRs on the Chinese deltas were projected during the 1980s and 1990s as being 1–2 mm per year, using spectral analysis of data at tide gauge stations established in 1868 (Ren, 1993; Chen, 1994a, 1994b; Qin and Li, 1997; Shi et al., 2000; Huang et al., 2000). It was previously considered that the accelerating MSLR in Chinese deltas since the beginning of the 21st century (Zuo et al., 2013, 2015) was related to increasing sea and air temperatures, and tropical cyclones (Wang et al., 2014).

However, we found no significantly accelerating eustatic MSLR on the Yangtze delta coast, which in actuality has been 2 mm per year over a long term duration from 1921 to 2010, based on the tide gauge station at Wusong (Cheng et al., 2015b) (Fig. 3). Our estimate of the eustatic MSLR is smaller (Cheng et al., 2015a, 2015b; Cheng and Chen, 2016) than the recent results from tide gauge data or AVISO data (Wang et al., 2014; COIN, 2016; Zhang and Fang, 2015) on the Shanghai coast. It is attributed to the location of our reference tide gauge station, Wusong in the inner estuary,

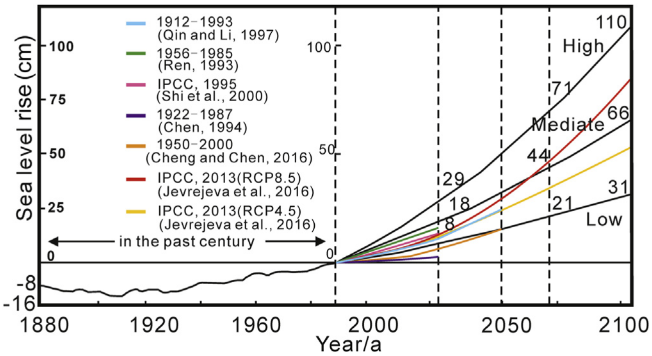

Fig. 3. Measured and predicted sea level rises from various research (combined from Cheng and Chen (2016) and Jevrejeva et al. (2016)).

where behave deeply a complex effect of regional climate change in combination with anthropogenic geomorphologic changes from the local estuarine engineering projects and watershed dams on the eustatic MSLR projections (Cheng et al., 2015b).

Nevertheless, the timing and magnitude of Chinese delta eustatic MSLR projections are expected to be simulated to cope with four scenarios RCP2.6 (26–55 cm), RCP4.5 (32–63 cm), RCP6.0 (33–63 cm), RCP8.5 (45–82 cm) by 2100 with IPCC AR5 (IPCC, 2013; Slangen et al., 2012), new scenarios with warming above 1.5–2 °C (Schaeffer et al., 2012; Jevrejeva et al., 2016) and new estimates of sea level rise rate from a sea level budget approach (Dieng et al., 2017) using the model downscaling processing of the RegCM model and analytical modeling with the CMIP5 models. In addition, it appears that more downscaling model simulations for MSLR projections are necessary for regional sea level trends due to an intensification of the Pacific trade winds (Merrifield and Maltrud, 2011). Furthermore, there is a particular need of analytical or semi-analytical model simulations on account of uncertain physical processes that impact the evolution of global mean sea level in ocean climate models (Griffies and Greatbatch, 2012), and kinematic constraints on glacier contributions to the 21st century sea level rise (Pfeffer et al., 2008).

5. Matching the MSLR projections to the local elevation datum

Almost all MSLRs on the Chinese delta coasts have been estimated using analysis of data from individual tide gauge stations with different time series datasets on different local elevation datum (Sun et al., 2011; Cheng et al., 2012). These MSLR projections are therefore inaccurate because local elevation datum is variable and attributed to the local engineering projects, e.g., a rise of 15–34 cm in the Yangtze River Delta from 1974 to 2011 (MSCSMB, 2013). Thus, the MSLR projections are ineffective for the local coastal protection and flood defense adaption. Subsequently, it is necessary to create a local land-sea united elevation datum (Sun et al., 2011). And feasible MSLR projections are expected to be reworked to be matched to the local elevation datum in a national or regional framework (Cheng et al., 2012).

The IPCC RCP MSLR projections scenarios are useful for quantifying and determining what levels of inundation and flooding (Houston, 2013) may occur in the future, and what the consequences may be. They are consistently to tie local elevation datums in Chinese delta cities for the coastal infrastructure mangers and engineers to assess the threat and draw the adaptation planning (Ding and Du, 2016) as the U.S. Army Corps of Engineer (USACE) guidance (Flick et al., 2013). And then, instantaneous sea level monitoring by remote sensing and ground sensor at a local land–sea united elevation datum will be helpful for the effective flooding risk prediction.

6. Uniting a regional river-sea numerical hydrodynamic model in combined with storm and effects of sediment supply decline

Floods, waterlogging, salt water intrusion, coastal erosion, deep waterway siltation, wetland loss, spawning ground degradation in Chinese delta cities are the most common risks of MSLR projections. They are still not be able to be predicted as expected even if there are many monitoring tide gauge stations, sensors and historical data located in coasts, outer estuaries or inner estuaries. Typhoons 9711, Fitow in 2013, and Goni in 2015 caused serious damage to the Yangtze estuarine delta region, and Yuyao city in Zhejiang province suffered severe flooding where over 70% of the city flooded (TOSMPG, 1977; Wang, 2014). The main reason for the inability to predict floods and waterlogging is attributed to the paucity of continuous river-sea united numerical hydrodynamic model in combination with the effects of storm (Li et al., 2014a) and sediment supply decline from the watershed (Cheng et al., 2012) using semi-analytical simulations or quantified analysis of the probability of flooding (Dawson et al., 2005), which is perspective.

7. Assessing comprehensive risk of MSLR projections on the Chinese delta cities

Numerous studies over the past 30 years have reported the qualitative and quantitative impacts and risks of MSLR projections on the fresh water resources and supply, coastal protection, environment and ecosystem conservation, flood defenses, ports and waterways, fishery resources, and economical and social stability along the Chinese delta coasts (Li et al., 1993; DESCAS, 1994; Chen, 1994a, 1994b; SCWCB, 1996; Huang et al., 1999, 2000; Shi et al., 2000; Wu et al., 2002; Mcleod et al., 2010; He, 2011; Xu, 2012; Li et al., 2014b; Ding and Du, 2016; Cheng and Chen, 2016; Ding et al., 2016; Wang et al., 2016; Wolters et al., 2016).

A risk assessment of flooding and waterlogging relating to MSLR projections was made in consideration with three main coastal protection parameters: design of the high tide level, design of the wave height at the top of a dike, and the tidal current velocity in the Pearl and Yangtze River Deltas.

The impact of MSLR projections on the design of the high tide level was assessed by calculating four design frequencies (0.5%,1%, 2%, and 5%) of the highest tide level in response to

MSLR at tide gauge stations (Chen et al., 2014). The impact of MSLR projections on the design of the wave height at the top of a dike was assessed by calculating four return periods of once in 20 years, once in 50 years, once in 100 years, and once in 200 years, at tide stations using extreme water level analysis and PIII curve fitting analysis (Huang et al., 1999; Feng et al., 2013; Cheng and Chen, 2016). The impact of MSLR projections on tidal current velocity was assessed by simulation using a 3D ECOM-si model with high resolution of the orthogonal curvilinear grid mobile tidal boundary in the Yangtze River estuary and then with a 1D hydrodynamic model of the tidal river network within the three islands and mainland of Shanghai (Qiu and Zhu, 2015; Chen et al., 2015; Cheng et al., 2015a; Cheng and Chen, 2016).

The results of model assessments show that MSLR projections will lead to the existing seawall standard becoming ineffective, which will decrease the flood prevention capacity. Seven grades of flood risk in the city of Shanghai were made for MSLR. Evaluation of the combined risk of sea level rise, land subsidence, and storm surges was conducted using MIKE21 software on the coastal areas of Shanghai (Wang et al., 2012) and the Pearl River Delta (Feng et al., 2013).

For policymakers, coastal managers, development planners, the public are more aware of the timing and magnitude of possible future risks associated with MSLR projections. The approach using adaptation tipping points (ATPs) is a good tool to assess uncertainty relating to timing and magnitude of MSLR projections' risk. A few quantitative risk assessments of MSLR projections on flood, fresh water supply shortage, waterlogging, and port and waterway siltation in Chinese delta cities have been made using ATP (Kwadijk et al., 2010; Abunnasr et al., 2015), with the exception of Shanghai city (Cheng et al., 2015c; Cheng and Chen, 2016).

The authors used an example of the risk assessment involved in the timing and magnitude of MSLR projections on a shortage of fresh water supply in Shanghai city using ATP (Fig. 4). A fresh water supply shortage risk assessment model was built by the authors to predict the magnitude of risk in a reduction of water supply in the Yangtze River estuary under the complex effect of population growth, runoff and sediment supply reduction, and sea level rise (Cheng et al., 2015c; Cheng and Chen, 2016). A system dynamics model was also used to predict the quantity of water required for living, industry, and agriculture from 2011 to 2030. Our 3D ECOM-si model was used to simulate the quantity of water supply in three reservoirs Chenhang, Dongfengxisha, and Qingcaosha in the estuary, assuming an inflow rate of 90%, and in response to the largest MSLR projections. It is considered that the ATP approach could be used to assess the timing and magnitude of a comprehensive MSLR projections risk in future adaptation planning for Chinese delta cities (Walsh et al., 2004).

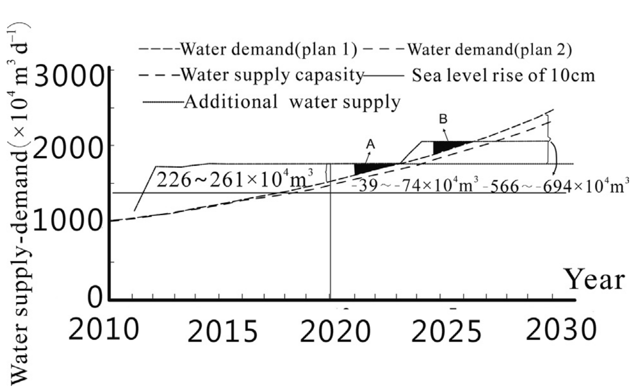

Fig. 4. Timing and magnitude as (A) in 2023 without further fresh water reservoir exploitation; and (B) in 2027 with further exploitation of fresh water supply. Using adaptation tipping points of MSLR10 cm projection in 2020 and 2030, Shanghai city, China, shows major water shortages (taken from Cheng et al., 2015c).

8. Conclusions

We reviewed the magnitude of MSLR projections and the impact and risks involved in adapting Chinese delta cities to MSLR projections. Tracking the history of major barriers to implementing adaptation planning, we showed that these comprise a continuing chain of policy phasing that are optimistic approaches and perspectives in the adaptation strategies and actions to MSLR projections. However, further attention is required in relation to the following issues:

(i) The use of instantaneous sea level monitoring using remote sensing, and moored sensors along coasts and rivers, lakes and urban area is important to provide better estimates of the magnitude of comprehensive MSLR projections at our suggested land–sea united elevation datum with model validation.
(ii) Stochastic process model simulation of MSLR projections' impacts on the delta coast morphology is a controlling approach for the magnitude of MSLR projections risk to flood defenses, port and waterway siltation, and wetland loss.
(iii) Adapting planning for MSLR projections in Chinese delta cities should also cover river watershed areas.

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