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Mapping Sea Level Rise Behavior in an Estuarine Delta System: A Case Study along the Shanghai Coast

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ABSTRACT

Sea level rise (SLR) is a major projected threat of climate change that is expected to affect developing coastal cities located in estuarine delta regions. Shanghai is one such city, being located in the Yangtze River Delta (YRD). It is difficult, however, for decision-makers to implement adaptation due to the uncertain causes, magnitudes, and timings of SLR behaviors. This paper attempts to map the causes and magnitudes of SLR behaviors on a decadal scale. We analyze the tidal level records from 11 tidal gauge stations and the corresponding bathymetry measurements around these stations since 1921. We identify three new SLR behaviors along the Shanghai coast due to anthropogenic geomorphologic changes (AGCs), besides the well-known eustatic sea level rise (ESLR), tectonic subsidence (TS), and urban land subsidence (ULS). The first new behavior is regional sea level rise (RSLR), which occurs as a result of land reclamation and deep waterway regulation. The second is regional sea level fall (RSLF), which occurs because the channel bed is eroded due to sediment supply decline in the river catchment. The last SLR behavior is local tidal datum rise (LTDR). Thus, we project that the magnitude of SLR for the Shanghai coast ranges from 10 cm to 16 cm from 2011 to 2030. Clarifying SLR behaviors is important to aid local decision-makers in planning structural and non-structural measures to combat escalating flood damage costs in an estuarine delta system; this field is full of future challenges.

1. Introduction

Mean sea level (MSL) is a geodetic level and a basic parameter used in civil engineering design, especially for coastal, estuarine, and deltaic areas [1–5]. Since the 21st century, global warming has accelerated both the degree and the speed of MSL rise [6–11]. A recent discovery concerning climate change suggests that human activities have committed us to a long-term future sea level of up to 1.9 m higher in 2100 than today, with a further 4.8 m rise in global MSL being possible over the next two millennia under the 1.5 °C and 2 °C global warming scenarios [12,13]. Estuaries and deltas are exposed to the direct threat of MSL rise, and adaptation action strategies have become an important agenda of the scientific community and governments all over the world [3,14–22]. This is also because 80% of large cities with more than a million people lie along estuarine and deltaic regions around the world. Furthermore, the elevations of most of these cities are lower than the local high tidal level [3]. A number of severe coastal floods have recently caused extensive property damage, lengthy service disruptions, and hundreds of fatalities across the Asia-Pacific, Europe, and Australia, leading to an active demand for estuarine and deltaic cities to adapt to sea level rise (SLR) [23–26].

However, it is difficult for policymakers, coastal managers, and development planners to implement adaptation actions due to the uncertain causes, magnitudes, and timings of SLR behaviors. In

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particular, uncertainty arises from the complex system of atmospheric, oceanic, and terrestrial processes and their interactions on a range of spatial and temporal scales. The changing climate, including SLR and anthropogenic geomorphologic changes (AGCs), further exaggerates this complexity and uncertainty [24,27–32].

Nevertheless, this paper attempts to map SLR behaviors on a decadal scale. This new mapping attempt is performed through a comprehensive analysis involving a combination of hydrology, geomorphology, and *in situ* measurement along the Shanghai coast in the Yangtze River Delta (YRD) (Fig. 1). We provide an analysis of SLR up to 2030, which is the year when certain specific objectives of water conservancy planning used in the local socioeconomic management system will be achieved. In Section 2, we clarify the causes of SLR behaviors along the Shanghai coast, and in Sections 3 to 6, we estimate the magnitudes of SLR behaviors. Section 7 provides an accumulation of the total magnitude of SLR projections from 2011 to 2030. In Section 8, we first calculate the local tidal datum rise (LTDR), which is a special SLR behavior. A clarification of SLR behaviors will assist local decision-makers in planning structural and non-structural measures that are necessary to combat escalating flood damage costs in an estuarine delta system.

2. Causes of sea level rise along the Shanghai coast

Shanghai is a megacity that serves as an economic, financial, trade, and shipping center of China. It has a mainland coastline of 211 km and an island coastline of 577 km (Fig. 1). The city is located in the YRD and has a population of 24 million people [33]. Most of its elevation is below the decadal average high tidal level of 3.25 m, with the lowest elevation being 2.2 m above the local Wusong elevation datum (WED) [34]. In addition, more than 70% of fresh water is supplied by reservoirs located on the bank of the mouth bar and tidal flat in the YRD [35]. Therefore, the city of Shanghai is exposed to significant risks of flooding and fresh water supply shortages resulting from mean sea level rise (MSLR) [36–42]. A number of severe floods recently occurred during typhoon storms such as Typhoon Winnie in 1997 and Typhoon Matsa in 2005, as well as during Typhoon Nepartak in 2016 [23]; these events demonstrate the urgent demand to map the causes of SLR behaviors.

In fact, the causes of SLR are a difficult research topic that requires interdisciplinary cooperation. The First Assessment Report (AR1) to Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) and the annual reports on China's response to climate change policies and actions have indicated the causes of SLR as being climate warming, tectonic subsidence (TS), and urban land subsidence (ULS) by the anthropogenic extraction of underground water [3,4].

Following these reports, the first SLR magnitude projections along the Shanghai coast were made in 1996, and indicated increases of 10–25 cm, 20–40 cm, and 50–70 cm from the benchmark year 1991 to the target years 2010, 2030, and 2050, respectively; these years were chosen to achieve specific water conservancy planning objectives [43]. The SLR projection was composed of three components. The first was the eustatic sea level rise (ESLR) projection of 2 $mm{\cdot}a^{-1}$ in the IPCC AR1 [44]. The second was the global TS measurement of 1 $mm{\cdot}a^{-1}$ from 1988 to 1994 by the Shanghai Astronomical Observatory of the Chinese Academy of Sciences. The third was the ULS projection of 6 $mm{\cdot}a^{-1}$ near the reference of the Wusong tidal gauge station (WTGS) [43,45]. This SLR projection has been specified as the reference for local elevation datum for civil engineering and urban planning since that time [43,45].

However, the annual MSL measured at the WTGS [5,45] showed an MSLR of 5.2 cm from 1991 to 2010. This is much less than the projected SLR of 19 cm from 1996 [43]. Thus, mapping the causes of MSLR is essential for the public and for decision-makers.

Here, we clarify the following causes for the significant difference between the measured MSLR and the SLR projections made in 1996 along the Shanghai coast. The first cause is the minor change in ESLR produced by climate warming. The second cause is the small changeable scope of TS that resulted from the lithosphere plate motion and mantle flow, which is similar to the magnitude along the continental borders around the Atlantic Ocean [46]. The third cause is the decline in ULS. The fourth cause is regional sea level rise (RSLR) due to land reclamation and deep waterway regulation. The fifth cause is regional sea level fall (RSLF) due to riverbed erosion, which is attributed to the sediment supply decline caused by dam construction in the river

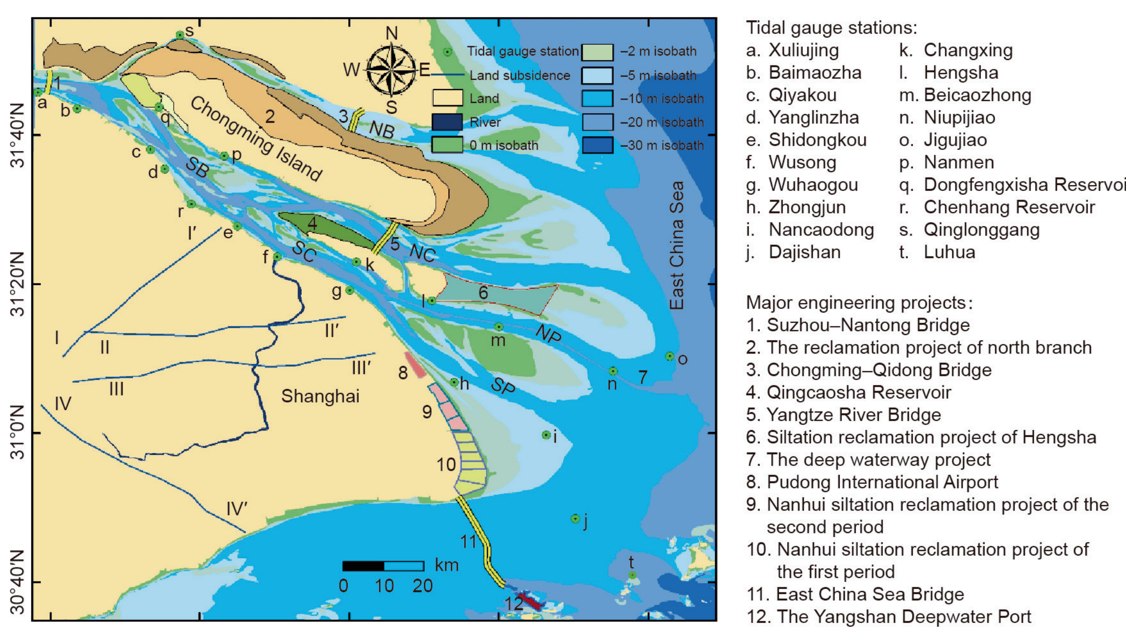

Fig. 1. Bathymetry map showing the distribution of tidal gauge stations, an urban land-subsidence profile, and major engineering projects in the Yangtze River estuary and along the north coast of Hangzhou Bay, Shanghai. SB: South Branch; NB: North Branch; SC: South Channel; NC: North Channel; SP: South Passage; NP: North Passage.