Science of the Total Environment 621 (2018) 228–234

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Effects of sea level rise, land subsidence, bathymetric change and typhoon tracks on storm flooding in the coastal areas of Shanghai

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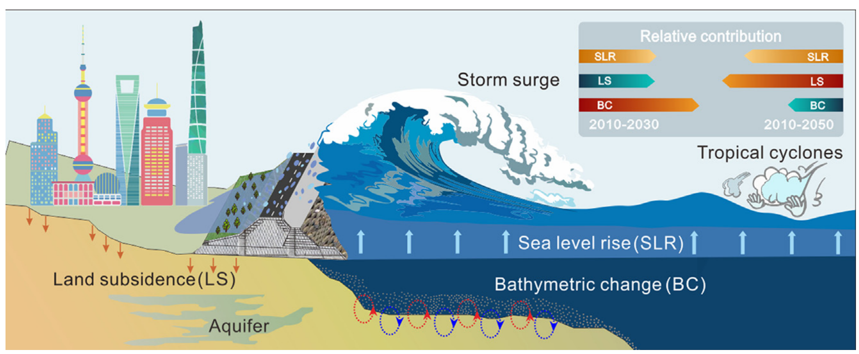
HIGHLIGHTS

- Combined effects of three factors on storm flooding were investigated.
- The sensitivities of storm flooding to each factor are different at two timescales.
- Bathymetry has larger effect on storm flooding to year 2030.
- Sea level rise & land subsidence account for more flooding to year 2050.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 July 2017
Received in revised form 19 November 2017
Accepted 20 November 2017
Available online xxxx

Editor: Prof. G Ashantha Goonetilleke

Keywords:
Typhoons
Compound scenarios
Hydrological simulation
MIKE 21
Compare
Relative Contribution

ABSTRACT

We compared the effects of three key environmental factors of coastal flooding: sea level rise (SLR), land subsidence (LS) and bathymetric change (BC) in the coastal areas of Shanghai. We use the hydrological simulation model MIKE 21 to simulate flood magnitudes under multiple scenarios created from combinations of the key environmental factors projected to year 2030 and 2050. Historical typhoons (TC9711, TC8114, TC0012, TC0205 and TC1109), which caused extremely high surges and considerable losses, were selected as reference tracks to generate potential typhoon events that would make landfalls in Shanghai (SHLD), in the north of Zhejiang (ZNLD) and moving northwards in the offshore area of Shanghai (MNS) under those scenarios. The model results provided assessment of impact of single and compound effects of the three factors (SLR, LS and BC) on coastal flooding in Shanghai for the next few decades. Model simulation showed that by the year 2030, the magnitude of storm flooding will increase due to the environmental changes defined by SLR, LS, and BC. Particularly, the compound scenario of the three factors will generate coastal floods that are 3.1, 2.7, and 1.9 times greater than the single factor change scenarios by, respectively, SLR, LS, and BC. Even more drastically, in 2050, the compound impact of the three factors would be 8.5, 7.5, and 23.4 times of the single factors. It indicates that the impact of environmental changes is not simple addition of the effects from individual factors, but rather multiple times greater of that when the projection time is longer. We also found for short-term scenarios, the bathymetry change is the most

Abbreviations: SLR, sea level rise; LS, land subsidence; BC, bathymetric change; TC, tropical cyclone; SHLD, (typhoons make landfalls) in Shanghai; ZNLD, (typhoons make landfalls) in the north of Zhejiang; MNS, (typhoons) move northwards in the offshore area of Shanghai; TGD, the Three Gorge Dam.

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https://doi.org/10.1016/j.scitotenv.2017.11.224

important factor for the changes in coastal flooding; and for long-term scenarios, sea level rise and land subsidence are the major factors that coastal flood prevention and management should address.

1. Introduction

Storm flooding is a major threat to the safety and sustainability of the low-lying coastal cities. During 2012–2016, the State Oceanic Administration of China estimated the average annual direct economic loss caused by typhoons/storm surges at $1.6 billion (China Marine Disaster Bulletin, 2016, http://www.soa.gov.cn). In particular, Shanghai as the most important metropolis on the coastline of China, is under great threat of typhoons and storm flooding. Despite the high risk of flooding, Shanghai is a tremendous economic center that attracted many large enterprises, such as the Sinopec Shanghai petrochemical Co, Ltd., Pudong International Airport, and the China (Shanghai) Pilot Free Trade Zone. The inhabitants also increased from about 11 million to 24 million during 1978–2015 (http://www.stats-sh.gov.cn/tjnj/tjnj2016.htm). To sustain the economic growth and population agglomeration, Shanghai experienced massive constructions of skyscrapers and excessive extraction of underground water. Land subsidence is accelerating due to compaction from building mass and deformation of underground aquifers. Sea level rise due to global climate change is another uncertain but pressing concern about flooding hazards to this coastal city (Wang et al., 2012; Yin et al., 2013; Yan et al., 2015). The third significant factor of the coastal flooding problem in this area might be the change in topography and bathymetry in the coastal zone owing to reduction of sediment supply attributed to the upper reach engineering works like the Three Gorges Dam (Yang et al., 2005; Deng et al., 2009).

Extensive research works have studied the impact of the environmental changes on the coastal flooding risk, including sea level, land elevation, and estuarine bathymetry and so on (Dixon et al., 2006; Emanuel et al., 2006, 2010; Weaver and Slinn, 2010; IPCC, 2013; Kopp et al., 2014). A common strategy to evaluate the impact of such changes is to build scenarios defined by the change factors and apply them to the simulation models. For example, Webster et al. (2014) built environmental change scenarios by the factors of annual runoff, high tide and sea level rise in the year of 2000, 2025, 2050, 2085 and 2100 respectively, and estimated the scenario risk of storm flooding in Lunenburg in the LaHave estuary. Lin et al. (2012) and Aerts et al. (2014) coupled a GCM-driven hurricane model with hydrodynamic modeling packages to simulate storm flooding in New York City. They evaluated the influence of structural flood defenses and land use/land cover change projected to year 2040 and 2080. Familkhalili and Talke, 2016found that bathymetry change could have a major impact on coastal flooding based on their case study in Wilmington, NC.

Particular studies on Shanghai have also reported the increasing risk of coastal flood due to global and local changes. Wang et al. (2012) assessed storm surge risk of Shanghai in the three projected years 2030, 2050 and 2100. They found the environmental changes would bring higher flood risk to Shanghai. Yan et al. (2015) also assessed the impact of flooding simulated from sea level rise and storm surge models on socioeconomic development on the three future scenarios in 2030, 2050 and 2100. Yin et al. (2013) used the FloodMap program to model the combined impacts of sea level rise and land subsidence on Huangpu River flooding induced by storm tides. These studies consistently reported that the coastal flooding caused by the compound effect of multiple environmental factor changes would be much more severe than that caused by individual ones. Understanding the compound effects of the environmental changes is essential for making strategic plans to alleviate flood damage to the properties and lives of coastal areas. Ke et al. (2016) explored the adaptation pathways of three types of floods: coastal flood, river flood and pluvial flood to select the best set of measures to mitigate the flood risk in Shanghai. Selection and implementation of such mitigation measures depend on our ability to predict the flood scenarios. Questions such as "in a compound scenario which incorporates the effects of multiple factors, how much does each factor contribute to the storm flooding?" and "to which part should the government pay more attention to maximize the reduction of the flood risk given the projected conditions?" have to be answered first through quantitative analyses.

This paper presents an analysis of compound impact of the three key environmental change factors including sea level rise (Warner and Tissot, 2012), land subsidence, and bathymetry change (Ji et al., 2013; Kuang et al., 2013; Kuo et al., 2014) on coastal flooding in Shanghai (Wang et al., 2012; Yin et al., 2013). The research objectives are (1) to estimate the compound effect of multiple environmental change factors including sea level rise, land subsidence, and the bathymetric change, and (2) the percent contribution of each factor to the increase of storm flooding at different time scales. We expect the findings from our research could be useful to decision-making of the adaption of coastal flood defense measures of Shanghai.

2. Material and methods

2.1. Study area

Located in the Yangtze River Delta, Shanghai has a subtropical humid monsoon climate. From June to September in each year, it is often visited by 3–4 typhoons (http://www.mfb.sh.cn) that could bring storm surge damage to the city. On the other hand, the Yangtze River Delta is a low-lying alluvial plain without any natural barriers against storm surges (Fig. 1). In the past two decades, Shanghai was plagued by multiple typhoons such as TC9711 (Winnie), TC0509 (Matsa), TC0716 (Krosa), TC1109 (Muifa), TC1211 (Haikui) and TC1323 (Fitow) (tcdata.typhoon.org.cn). TC is tropical cyclones for short (severe TCs are called typhoons in China). The unique identification of each TC contains the time of the event. For example, the 11th tropical cyclone in 1997 is coded as TC9711. TC9711 caused a considerable loss of over $91 million because the landfall time of TC9711 coincided the highest tide in the history recorded at the Wusong gauge station (China Marine Disaster Bulletin, 1997, http://www.soa.gov.cn). Meanwhile, man-made flooding defenses have been constructed in the past 20 years to protect this area. However, the flood risk is still high due to the rapid changes caused by human activities and the potential sea level rise from global climate change, and the compound effect of these changes will exaggerate the impact from individual changes.

2.2. Scenario construction and simulation

2.2.1. Typhoon scenarios

First, we conducted a frequency analysis of the probability distribution of minimum central pressure (MCP) based on typhoons occurred in Shanghai during 1980–2015 (tcdata.typhoon.org.cn, the datasets are collated by Ying et al., 2014). We found that the occurrence probability of a typhoon with MCP of 900 hPa is approximately 0.004, which is once in a 250-year period. Therefore, in order to estimate the extreme storm flooding hazard, we set the MCP of simulated TCs as 900 hPa. We also selected 920 hPa as the landfall central pressure because it is the lowest pressure record in the Yangtze estuary. Next, we classified the TCs in 1949–2014 by their tracks and extracted the TCs that made landfalls in Shanghai (SHLD), made landfalls in the northern part of Zhejiang