Risk Assessment of Shanghai Extreme Flooding Under the Land Use Change Scenario

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Abstract

Environmental changes have led to non-stationary flood risks in coastal cities. How to quantitatively characterize the future change trend and effectively adapt is a frontier scientific problem that needs to be solved urgently. To this end, this study uses the 2010 Shanghai land use data as the base and uses the GeoSOS-FLUS model to simulate future land use change scenarios (2030, 2050, and 2100). Based on the results of storm and flood numerical simulations, probabilistic risk, and other multidisciplinary methods, extreme storm and flood risks of various land uses (residential land, commercial and public service land, industrial land, transportation land, agricultural land, and other land) in Shanghai are analyzed and 4 adaptation strategies to deal with extreme flooding have been developed. The research results show that: 1) Under the two emission scenarios, residential, commercial and public service, and industrial land have the highest exposure assets. Under the RCP8.5 scenario, the exposure of assets in 2100, 2050, and 2030 will be 1.7 times, 1.5 times, and 1.3 times that in 2010 for 1/1000-year, respectively; the losses will be 2.7 times, 2.0 times, and 1.8 times that in 2010, respectively. 2) The spatial pattern of loss, which forms the scattered distribution of 1/10-year, is mainly distributed on both sides of the Huangpu River. For 1/1000-year, which is mainly gradually showed a strip distribution, continuous distribution of the city center, and the Qingpu-Songjiang depression in the southwest are high-risk areas for storm floods. 3) The risks are mainly distributed in the city center, the lower reaches of the Huangpu River, the northern shore of Hangzhou Bay, the Qingpu-Songjiang depression in the southwest, and Chongming Island (southwest and northeast). Our work can provide decision-making basis for risk-sensitive based urban planning, flood risk adaptation, and resilience building in Shanghai. The methodology can also provide a reference for risk assessment in other coastal areas.

1 Introduction

Many coastal cities around the world face huge risks of extreme storm floods (Najafi et al. 2021; Wolff et al. 2020; Oppenheimer et al. 2019; Shen et al. 2019; Chan et al. 2018; Nicholls et al. 2014). Under the combined influence of environmental change factors such as climate change, sea level rise, land subsidence, and rapid urbanization, the frequency and losses of future storm floods in coastal cities may increase significantly, posing severe challenges to the sustainable development of coastal cities (Catalao et al. 2020; Sadler et al. 2020; Abadie et al. 2020). There is an urgent need to understand the spatio-temporal dynamics and future trends of flood risk under environmental change scenarios to ensure the sustainable development of coastal cities (Shan et al. 2021; Du et al. 2020; Jongman et al. 2018; Hinkel et al. 2018).

At present, some scholars have carried out research on the dynamic changes of flood risk in coastal cities under the background of sea level rise, land subsidence, and climate change. For example, several researches have focused on the impact of coastal flooding on people and assets under the scenario of sea level rise for New York (Garner et al. 2017; Lin and Shullman 2017; Lin et al. 2016; Reed et al. 2015; Horton et al. 2015; Aerts et al. 2013), London (Hall et al. 2019; Hinkel et al. 2018), Ho Chi Minh City (Ngo et al. 2020; Bangalore et al. 2019; Scussolini et al. 2017), and Jakarta (Ward et al. 2011). Due to rising sea levels, the 1/500-year storm flood in New York City before the Industrial Revolution has currently become a 1/25-year storm (Garner et al. 2017; Reed et al. 2015). Hinkel et al. (2018) discussed the risks of coastal cities under the sea level rise scenario in the 21st century. Among them, Ho Chi Minh City and New York City will face considerable risks. Scussolini et al. (2017) adopted scenarios of sea level rise and socio-economic changes using two risk indicators, asset damage and potential casualties, and assessed the current and future (2050 and 2100) flood risks in Ho Chi Minh City, Vietnam. Other studies usually regard urban land or agricultural land as relatively homogeneous elements at risk, and evenly allocate GDP and assets to pixels of urban land or agricultural land (Winsemius et al. 2016; Jongman et al. 2015).

In recent years, significant progress has been made in the analysis of coastal flood loss and risk in Shanghai (Shi et al. 2020; Du et al. 2020; Shan et al. 2019; Li et al. 2019; Ke, 2014). The low-probability and high-impact compound storm flood risk has always been the focus of researchers (Wu et al. 2019; Shan et al. 2019; Li et al. 2019; Ke, 2014; Hallegatte et al. 2013; Aerts et al. 2014; Wang et al. 2012), because such risks may cause damage and huge losses to infrastructure such as buildings, assets, industries, and transportation, seriously threatening urban safety (Shan et al. 2021; Du et al. 2020; Li et al. 2019; Ke, 2014; Aerts et al. 2014; Hallegatte et al. 2013). These studies reflect the emergence of urban flood disaster risk dynamic changes, which analyzes changes in hazard factors under scenarios such as climate change, sea level rise, and land subsidence, and characterizes the state of the elements at risk with past and current land use to carry out scenarios of possible losses analysis (Du et al. 2020; Yin et al. 2015; Aerts et al. 2014). However, Shanghai's elements at risk are highly dense and complex, and the future storm and flood risk evolution

of elements at risk is not systematically understood. Urban spatial model is an effective tool for understanding the process of urbanization and future scenarios, supporting urban planning and management policies, and evaluating the impact of the urbanization process on the environment and ecosystem (Liu et al. 2017; Filatova et al. 2016). In the field of flood disaster research, urban spatial models such as GeoSOS-FLUS model have been applied to future scenario analysis of elements at risk (Kim and Newma 2020; Liang et al. 2018; Song et al. 2017), so as to better reveal the dynamics of flood risk. Wu (2020) took Chongming's land use as the research object, considered its different future development directions, designed 3 kinds of land use change scenarios, and selected a series of driving factors, then used GeoSOS-FLUS software to predict Chongming distribution of land use in 2035. Wu (2020) takes Chongming's land use as the research object, considers its different future development directions, designs 3 kinds of land use change scenarios, and selects a series of driving factors, and uses GeoSOS-FLUS software to predict Chongming distribution of land use in 2035. Adnan et al. (2020) showed a positive correlation between flood risk and land use changes. It is estimated that the loss of coastal areas in Bangladesh caused by floods in 2030 will increase from US\$ 0.903 billion in 2005 to US\$2.096 billion. Therefore, it is necessary to predict future land use changes based on urban spatial model methods, so as to construct future elements at risk spatio-temporal change scenarios, which not only effectively assess the future risks of storms and floods, but also have important significance for improving the understanding of the dynamic evolution of risks.

Therefore, this study is based on the land use distribution data of the base year (2010), combined with the GeoSOS-FLUS model to predict the future (2030, 2050, 2100) land use distribution pattern, and is combined with the future extreme storm and flood scenarios in Shanghai to carry out different types of land use losses and risk analysis. Our work can provide meaningful information for risk-sensitive urban planning, flood risk adaptation, and resilience building in Shanghai. The methodology can also be used for risk analysis in other coastal cities facing the threat of storm flooding.

2 Data And Methods

2.1 Study Area

Shanghai, located on the eastern edge of the Taihu dish-shaped depression in the Yangtze River Delta, is the world's largest port city with an area of 6,340 km² and a permanent population of 24.28 million in 2019. In terms of topography, the east of Shanghai is slightly higher than the west, with an average altitude of about 4m. It is surrounded by water on three sides, and the Huangpu River and Suzhou River pass through the city (Fig. 1). Shanghai is affected by land subsidence due to loose Quaternary strata and human activities. According to statistics, Shanghai's maximum accumulated subsidence reached 2.99m, and the average land subsidence was 1.37m from 1921 to 2017. The land subsidence was controlled by measures such as restrictions on groundwater extraction and artificial recharge, gradually reducing the subsidence rate, Shanghai's average land subsidence was 5.2 mm in 2017. Storm flooding caused by typhoons is the main natural disaster in Shanghai. An extreme storm flood in 1905 caused nearly 30,000 deaths. Although the construction of flood control measures in the past 50 years has effectively reduced the risk of storm floods, Typhoon Winnie in 1997, the 2005 Typhoon Matsa, the 2013 Typhoon Fitow, and the 2019 Typhoon Lekima show substantial threat of typhoon storm floods to Shanghai. Particularly, during Typhoon "Fitow", the sea winds were fierce and the Hangzhou-Jiaxing-Huzhou area experienced torrential rains and extreme rainstorms. The amount of flood discharge was large. For the first time since 1949, Shanghai suffered the "four encounters" disaster of wind, storm, tide, and flood (Liu et al. 2015). In the context of climate change, relative sea level rise, and urban expansion, Shanghai will face greater risks and challenges from typhoon storm floods in the future (Wang et al. 2018).

2.2 Data

The data used in this work mainly include Shanghai extreme storm flood scenarios in 2010, 2030, 2050, and 2100, land use data in 2010, and land price data in 2010.

2.2.1 Extreme Storm Flood

First, according to the height and structure of the river embankments along the Shanghai coast, the overwhelming and breaching discharges (more than 20 l/m/s) of storm surges in 1/10, 100, and 1000-year are calculated. Secondly, estimation results of absolute sea level rise in the typical RCP scenario of the Yangtze River Estuary and the InSAR inversion is used to predict the settlement of coastal seawalls, it is estimated that the dikes will be flooded and broken in the 1/10, 100, and 1000-year storm surge

scenarios in 2010, 2030, 2050, and 2100. We use a simplified 2D flood inundation model (FloodMapInertial) to simulate dike failure-induced flooding and to derive inundation maps, and the spatial resolution is 50 m by 50 m. The model assumes that the coastal/river floodplain is protected by a continuous, broad-crested embankment through which water flow exchange occurs between the sea/channel and hinterland. A simplified solution has been adopted in the model for the treatment of overland flood routing in a raster based environment. The results show that, in terms of overtopping/overflowing, this floodwall can withstand a 100-year RP event under the current condition (2010), with only two potential failure locations on the left bank of the Huangpu River's middle reach. For the 1/1000-year RP event, wave overtopping and overflowing spread to the upstream reach and the right bank of the Huangpu River (Fig. 2 and Fig. S1), with additional failures scattered throughout the middle reach. In terms of breaching due to structural failure, the floodwall along the Huangpu River is expected to remain intact under the 100-year RP event until 2050, while dike breaching could occur at two locations in the upstream reach of the Huangpu River during the 1,000-year RP event with the baseline sea level (2010). Breaching further spreads to other sections of the upstream reach in the year 2030 and sparsely affects the downstream reach (Fig. 2 and Fig. S1). Chongming Island (southwest and northeast), the Qingsong low-lying area in the west, and the north bank of Hangzhou Bay are the current and future dikes with the lowest safety and the highest inundation risk area (Yin et al. 2020). With the effects of sea level rise and land subsidence, still water levels would increase proportionately at all return periods. Under the RCP 8.5 scenario, the current 10 and 100-year flood levels in Shanghai could be exceeded approximately two times more frequently in 2030, 3-5 times more frequently by 2050, and over 50 times more frequently with a 136-cm rise in relative sea level (50th percentile) by the end of the 21st century. The flood inundation scenarios (degree and depth) caused by flooding increase significantly as the return period increases. Finally, the simulation results are verified. Based on a set of typhoon random events were affecting Shanghai under current climate conditions. The ADCIRC storm surge model is used to simulate the 1/10, 100, and 1000-year storm surge level distributions, and the three most severely impacted Shanghai areas of the 5,180 typhoon storm surge events were extracted. One typhoon landed on Chongming Island head-on, and one landed on Jinshan (due to the asymmetric structure of the typhoon field, the strong wind field on the right caused the Yangtze River estuary to have a higher water level than Hangzhou Bay). All results show that Chongming Island faces the greatest risk of storm surge and flooding.

2.2.2 Future Land Use

The land use type data of Shanghai in 2010 comes from the Shanghai Institute of Surveying and Mapping. The land use type data describes the land use type hierarchically, divided into 3 departments (one-digit code identifier), and then subdivided into 15 sub-sectors (2 Digit code identification), and 73 land use sub-categories (3 digit code identification) that are further divided into 6 categories, which are residential land (including urban residential land and rural homestead), commercial and public service land (including commercial service land, public management and service land), industrial land, transportation land (including railway, highway, port, airport, square, and other transportation facilities), agricultural land (including farmland, garden land, woodland) and other land (including water area, park green space, grassland, land under construction, land for other facilities, unused land, etc.). Shanghai's land use data in 2030, 2050, and 2100 are based on the 2010 land use data and are simulated using the GeoSOS-FLUS model. GeoSOS-FLUS software is a software developed on the Visual Studio 2010 platform based on the C++ language and a series of C++ open-source libraries. It is used to simulate the changes of multiple types land use in the future under the influence of nature and human activities and nature (Liu et al. 2017). The accuracy of the simulation and results similar to the actual land use distribution can be obtained (Liu et al. 2017). It has been credibly verified that the 2030 land use forecast map is relatively uniform with the Shanghai Municipal Land Use Planning Map in 2035 in the "Shanghai City Master Plan (2017-2035)". The prediction results for the spatial distribution of land use in 2030, 2050, and 2100 show the overall spatial distribution trend of land use in the next three phases: agricultural land will gradually be transformed into commercial and public service land and residential land. Commercial and public service land in the city center are relatively dense, and public buildings and residential areas in the suburbs have gradually developed (Fig. 3).

2.2.3 Land Use Price

Land classification and benchmark land price for Shanghai in 2010 is determined based on different uses. The benchmark land price reflects the regional average price within the same level at the benchmark time. The land price data takes into account the influence of time factors, age, floor area ratio, regional factors, individual factors, floors, and other conditions. Among them, the benchmark land price factor correction coefficient considers regional factors (prosperity, traffic conditions, infrastructure conditions, environmental conditions, population conditions, and urban planning), individual factors (frontage conditions, parcel shape, parcel

area), etc. In the end, residential land was 10,706 CNY/m², commercial and public service land was 13,365 CNY/m², industrial and mining storage land was 3604 CNY/m², transportation land was 1927.2 CNY/m², agricultural land was 5 CNY/m², and other land was 840 CNY/m². Since land prices and housing prices are closely related (Du et al. 2011), the estimation of future (2030 and 2050 year) land prices is based on the future average annual growth rate of housing prices in first-tier cities (Chen 2014), land prices in 2100 will should remain the same as in 2050.

2.3 Methods

This research integrates elements at risk modeling, hydrology and hydrodynamic models, and risk analysis to develop a comprehensive research framework and apply it to the future flood risk analysis of Shanghai under the land use change scenario (Fig. 4). First, the two-dimensional hydrodynamic model Floodmap is used to simulate the range and depth of storm flood inundation, and the extreme storm flood inundation maps with different return periods in 2010, 2030, 2050 and 2100 are drawn. Thirdly, the value of Shanghai's land use assets in 2010, 2030, 2050, and 2100 is analyzed with the extreme storm and flood scenarios to obtain exposed assets. Then, the land use vulnerability curve and exposed assets is combined to determine economic losses. Finally, the loss of multiple return periods is integrated, and the expected annual damage (EAD) is quantitatively analyzed.

2.3.1 Asset Value Assessment

Using 2010 as the base year, the asset value can be obtained by evaluating information such as the area and land value of land use in 2030, 2050, and 2100. The calculation formula for the valuation of land use assets is:

$$B_{asset(2030/2050/2100)} = \sum_{i=2010}^{2030,2050,2100} (S \times P) \quad (1)$$

Where $B_{asset(2030/2050/2100)}$ is the value of land use assets; S is the area of land use; P is the land price.

2.3.2 Exposure Analysis

An overlay analysis of extreme storm flooding scenarios and various land use value distribution maps in multiple return periods is used to assess land use exposure assets. The calculation formula is:

$$E_{(2030,2050,2100)} = B_{asset(2030,2050,2100)} \cap H_{(2030,2050,2100)} \quad (2)$$

Where $E_{(2030,2050,2100)}$ is the exposed asset; $B_{asset(2030/2050/2100)}$ is the asset value; $H_{(2030,2050,2100)}$ is hazard.

2.3.3 Loss Analysis

This study uses the relationship between the depth of water accumulation and the loss rate of different land types in Shanghai established by Yin et al. (2012), and finally obtains 6 types of Shanghai residential land, public construction land, industrial and mining storage land, transportation land, agricultural land, and other land use. The economic loss vulnerability curve of land use type (Fig. S2). The vulnerability curve represents the loss rate of each land use under different water depths. The calculation formula for direct economic loss of land use is:

$$T_{loss(2030,2050,2100)} = \sum_{i=1}^n (E_{(2030,2050,2100)} \times R) \quad (3)$$

Where $T_{loss(2030,2050,2100)}$ is the loss; $E_{(2030,2050,2100)}$ is the exposed assets (as shown in formula (2)); R is the loss rate for different submerged depth.

2.3.4 Risk Expression

The estimation of risk adopts the most commonly used method in the world, that is, to express the risk in terms of expected annual damage (EAD) (Du et al. 2020; Lin et al. 2017). The calculation formula is:

$EAD = \int xf(x)dx$ (4)

Where *EAD* is the expected annual loss; *x* is the flood loss (or risk value); *f(x)* is the probability of flood loss. *EAD* in the study area can be used as the basic basis for flood disaster cost-benefit analysis.

3 Results

3.1 Exposure Assets Analysis of Land Use

The asset value of 6 types of land use and its spatial distribution in Shanghai can be estimated based on the area and land prices using Equations (1). The spatial distributions of exposed assets for land use are mapped by overlay analysis to combine the extreme flooding inundation scenarios with the land use asset value maps in Shanghai (Fig. 5).

Our analysis shows that the exposure increases rapidly as the return periods of storm flooding increases under the two emission scenarios (Table 1), and residential, public buildings, and industrial and mining storage land have the highest exposed assets. Under the RCP8.5 scenario, the exposure of assets in 2100, 2050, and 2030 will be 1.7 times, 1.5 times, and 1.3 times that in 2010, respectively; the losses will be 2.7 times, 2.0 times, and 1.8 times that in 2010 (Table 1).

Table 1
Statistics of land use exposed to extreme storm flooding in Shanghai under RCP 8.5 scenarios (unit: million CNY)

地区(市)	2010 year			2030 year			2050 year			2100 year		
	10	100	1000	10	100	1000	10	100	1000	10	100	1000
Residential land	1075	1434	2867	1107	2215	3322	2215	2953	3942	3691	4430	5168
Industrial land	1282	2564	3419	1321	2641	4842	2643	3962	5295	3962	5722	6162
Commercial and public service land	1181	1772	4725	1825	3042	6083	3650	5475	6867	5475	6692	7300
Transportation land	695	1159	1854	1433	2388	2626	1910	2865	3234	2005	2865	3343
Agricultural land	4	9	10	6	13	14	9	14	15	14	15	18
Other land	630	1470	1680	865	1947	2379	1730	2379	2726	2056	2596	3028
Total	4867	8408	14555	6557	12246	19266	12157	17648	22079	17203	22320	25019

3.2 Loss Analysis of Land Use

By combining the exposure assets and vulnerability curves of land use, formula (3) can be used to obtain the direct economic losses caused by extreme storms and floods in different return periods of 2010, 2030, 2050, and 2100 (Table 2) and their spatial distribution (Fig. 6 and Fig. S3). Under the RCP8.5 scenario, the spatial pattern of land use loss during the return period of the three extreme storms and floods is scattered in the 1/10-year, mainly on both sides of the Huangpu River. As the return period increases, the scope and amount of losses continue to increase. When the return period is 1/1000-year, the spatial pattern of loss distribution in 2030 and 2050 is mainly distributed along the banks of the Huangpu River, the main urban area will form a contiguous distribution area in 2100. At the same time, the loss of the city center concentrated on the Suzhou River mouth is gradually increasing (Fig. 6), and is mainly distributed in the city center, the lower reaches of the Huangpu River, the northern shore of Hangzhou Bay, the Songjiang area in the southwest, and Chongming Island (southwest and northeast). In the RCP2.6 scenario, the spatial pattern of loss distribution is similar to RCP8.5 scenario (Fig. S2). Under the RCP8.5 scenario, for 1/1000-year, the losses in 2100, 2050, and 2030 will be 2.7 times, 2.0 times, and 1.8 times that of 2010, respectively (Table 2). Similar to exposed assets, the loss of residential, public buildings, and industrial land accounted for the largest proportion of total losses, accounting for 80.0%.

Table 2
Statistics of land use loss to extreme storm flooding in Shanghai under RCP 8.5 scenarios (unit: million CNY)

Return period (year)	2010 year			2030 year			2050 year			2100 year		
	10	100	1000	10	100	1000	10	100	1000	10	100	1000
Residential land	179	299	1076	185	647	1385	770	1170	1385	1693	2371	2802
Industrial land	46	321	731	48	330	1892	330	881	1956	743	2477	2543
Commercial and public service land	103	206	1238	319	638	1948	956	1771	2452	1069	2550	2657
Transportation land	23	90	258	126	481	623	265	765	893	602	714	960
Agricultural land	1	7	9	4	14	17	7	17	20	17	20	23
Other land	37	193	255	65	338	462	263	522	545	496	619	748
Total	389	1116	3567	747	2448	6327	2591	5126	7251	4620	8751	9733

3.3 Risk Expression

The loss values of the 4 types of storm flood return periods are used to establish the extreme storm flood transcendence probability-loss curve of land use (Fig. S4), and formula (4) is used to obtain EAD. Under the current scenario, Shanghai's land use EAD is 92.4 million CNY. Under the RCP2.6 scenario, Shanghai's land use EAD in 2030, 2050, and 2100 are 114.6 million CNY, 136.1 million CNY, and 337.3 million CNY, respectively (Table S1). Under the RCP8.5 scenario, the EAD of Shanghai's land use in 2030, 2050, and 2100 is 1.7 to 3.2 times that of the EAD under the RCP2.6 scenario, respectively. Residential, commercial and public service, and industrial land have the highest EAD, in 2100 they will be 209.0 million CNY, 220.5 million CNY, and 176.2 million CNY, respectively (Table 3). The risks are mainly distributed in the city center, the lower reaches of the Huangpu River, the northern shore of Hangzhou Bay, the Songjiang area in the southwest, and Chongming Island (southwest and northeast).

Table 3
Expected annual damage of land use under the RCP8.5 scenario (unit: million CNY)

	2010		2030		2050		2100	
	Land price unchanged		Land price rise		Land price unchanged		Land price rise	
Residential land	28.8	46.4	48.0	97.2	100.2	202.9	209.0	
Industrial land	22.0	28.0	28.9	67.0	68.8	171.1	176.2	
Commercial and public service land	21.7	55.0	56.6	140.2	144.2	214.1	220.5	
Transportation land	6.9	32.0	32.9	53.1	54.7	75.4	77.6	
Agricultural land	0.5	1.0	1.0	1.2	1.3	1.8	1.9	
Other land	12.6	21.9	22.5	39.5	40.7	56.5	58.2	
Total	92.4	184.3	189.9	398.2	409.8	721.8	743.5	

4. Discussion

Shanghai is a financial center in China. It has the highest standard of flood control system in China (designed using 1/1000-year standards). However, sea level rise and land subsidence have brought major challenges to Shanghai's flood risk management, which has also caused Shanghai to be considered by foreign research as one of the coastal cities with the highest flood risk and the fastest growth rate in the world. According to estimates by Hallegatte et al (2013), among the 136 largest coastal cities in the world,

Shanghai is one of the cities with the fastest increase in annual expected loss (EAD) (ranking 13th) compared with 2005. Wang et al (2012) have shown that sea level rise, land subsidence, storm surges, and surface runoff work together to cause more complex, variable, and sudden flood disasters. By 2100, half of Shanghai's city will be affected by coastal floods, and 46% of seawalls and flood walls will be overwhelmed. This type of extreme floods caused by simultaneous typhoons, storm surges, astronomical tides, heavy rains, and river floods is a low probability and high impact catastrophe (Aerts et al. 2013). For example, the 2013 Typhoon "Fitow" was the first time since 1949 that Shanghai suffered the "four encounters" disaster of strong winds, storms, tides, and floods; 121,000 people were affected and the direct economic loss was 370 million CNY. Taking into account the superimposed effects of sea level rise, land subsidence, and climate change, the risk of compound extreme storm and floods to Shanghai in the future may be further increased. This kind of low-probability and high-impact extreme compound event is the focus of Shanghai's flood risk adaptation and risk decision-making.

Drawing on the flood control experience of other coastal cities abroad, Shanghai can also implement hard adaptation measures: adaptation measures based on engineering measures such as tidal sluices, flood walls, and sea dikes, which reduce flood risk by changing the probability of flood hazards, and implement soft adaptation measures: adaptation strategies based on non-engineering measures such as building codes and coastal wetlands, which mainly reduce flood risk by reducing exposure and vulnerability. From the results of this study, as the return period of storm floods increases, the city center, the Songjiang district in the upper reaches of the Huangpu River, the north bank of Hangzhou Bay, and the Qingpu-Songjiang depression in the southwest are high-risk areas for disasters and assets exposure. Different measures need to be taken to deal with storm flooding for different regions. 1) Shanghai's city center has dense population and assets. It is necessary to implement rainwater storage and peak reduction facilities such as sponge cities to strengthen the construction of flood control capabilities to enhance the safety of the city center. 2) Shanghai should focus on strengthening the flood control system in the weak sections of the upper and middle reaches of the Huangpu River and newly added urbanized areas, especially in low-lying areas such as the upstream Songjiang, the northern shore of Hangzhou Bay, and the Qingpu-Songjiang area in the southwest. Several flood diversion and discharge areas are recommended. Try not to plan and arrange hospitals, schools, residential areas, and other important units and facilities within 3 kilometers on both sides of the river. In other areas, the flood control wall should be increased according to the latest analysis of Huangpu River tide level to maintain its designed flood control capacity. On one hand, the current defensive capacity of the embankments on some of Shanghai's shores is low, and the defense standards need to be improved, such as the sea embankments on the nearby shores of Chongming North Coast, Chongming Nanmen Port, Baozhen Port, Xijia Port, Wusongkou Port, and Luchao Port. On the other hand, full attention should be paid to the impact of sea level rise and ground subsidence on the defensive capacity of embankments. Land subsidence will significantly change the shape of the underlying surface will lead to, combined with the superimposed effect of sea level rise on the water level, the reduction of the flood control project fortification standards and the weakening of flood control capacity. Therefore, regular monitoring and settlement analysis of the flood control project should be strengthened. Secondly, the construction of large-scale high-rise buildings and large-scale underground projects within 2 km on both banks of the Huangpu River should be strictly restricted to control the land subsidence in Shanghai, especially the land subsidence on both sides of the Huangpu River. Finally, it is possible to make full use of the ecological functions of urban green space, plan park green space, use landscape belts in flood-prone areas on both banks of the Pujiang River as flood buffer zones, and plan temporary flood diversion areas in key sections (Yin et al. 2013). 3) The Qingpu-Songjiang depression on the upper reaches of the Huangpu River should give full play to the water storage and drainage role of the river network, increase the water area of the river and lake, interrupt small river channel, dredge the sediment, control the water level of the river, and prevent the low-lying area from being flooded; 4) Due to coastal erosion at the north of Hangzhou Bay, the beach protection measures should be strengthened, especially in frontier parts of seawalls in Luchao Port and Jinshan Petrochemical Factory, and increasing dam capacity along the beach may be necessary. In addition, it is necessary to improve the local flood control infrastructure including sluices, pumping stations, embankments, and urban drainage systems to ensure the orderly construction and efficient operation of various water conservancy infrastructures are managed precisely and intelligently, and adapting various wet/dry-floodproofing measures to improve the spatial response capacity of risks, and enhance urban resilience.

5. Conclusion

This study presents an integrated modelling framework to analyze the exposure, loss, and risk patterns of Shanghai's various land uses (residential, commercial and public service land, industrial, transportation, agricultural, and other land use) in the future (2030,

2050, and 2100) under extreme storm and flood, and proposes adaptation strategies to reduce flood risk. The main conclusions are as follows:

(1) Under the two emission scenarios, the exposed assets of residential, commercial and public service land, and industrial land are the highest in 2010, 2030, 2050, and 2100, for 1/1000-years, they were 2.6 times, 1.5 times, and 1.8 times that of 2010, respectively. It is 2.6 times, 1.5 times, and 1.8 times that of 2010 when a 1/1000-year event occurs. The exposed assets of residential, public buildings, and industrial and mining storage land accounted for 74% of the total exposed assets in 2100.

(2) Under the two emission scenarios, the spatial pattern of land use loss during the return period of the extreme storm flooding, which forms the scattered distribution of 1/10-year, is mainly distributed on both sides of the Huangpu River. As the return period increases, the scope and amount of losses continue to increase. For 1/1000-year, which is mainly gradually showed a strip distribution in 2030 and 2050, and formed continuous distribution of the city center and the Qingpu-Songjiang depression in the southwest in 2100. In terms of economic loss, the value of land use loss in Shanghai for 1/1000-year in 2100 is 1.7 times that of the 1/10-year under the RCP8.5 scenario. Residential, public buildings and industrial land losses accounted for the largest proportion of total losses, accounting for 26–29%.

(3) Risks are mainly distributed in the city center, the lower reaches of the Huangpu River, the northern shore of Hangzhou Bay, the Qingpu-Songjiang depression in the southwest, and Chongming Island (southwest and northeast). Under the current scenario, the EAD for land use in Shanghai is 0.924 million CNY. Under the RCP8.5 scenario, the EAD of Shanghai's land use in 2030, 2050, and 2100 is 1.899 million CNY, 4.098 million CNY, and 7.435 million CNY, respectively, which is 1.7 to 3.2 times the EAD under the RCP2.6 scenario. Among them, residential, public building, and industrial land have the highest EAD.

(4) Adaptation strategies to deal with the risk of extreme storms and floods in Shanghai include: The city center needs to implement rainwater storage and peak reduction facilities such as sponge cities; Focus on strengthening the flood control system in the weak sections of the upper and middle reaches of the Huangpu River and newly-increased urbanized areas; The Qingpu-Songjiang depression in the upper reaches of the Huangpu River needs to give full play to the storage and drainage role of the river network; Coastal erosion in the northern of Hangzhou Bay should strengthen beach protection measures, especially in frontier parts of seawalls in Luchao Port and Jinshan Petrochemical Factory, and increasing dam capacity along the beach may be necessary. In addition, local flood control infrastructure including sluices, pumping stations, embankments, and urban drainage systems need to be improved.

Declarations

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Conflict of interest The authors declare that they have no conflict of interest.

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Figures

Figure 1

Shanghai's location and elevation Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Inundation maps with extent and maximum depth caused by extreme flooding as a function of return periods under the RCP8.5 scenario Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Prediction for spatial distribution of Shanghai land use in 2030, 2050, and 2100 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

The methodology framework

Figure 5

Distribution of exposed assets per unit area (increased land price) under the extreme flood scenarios in Shanghai under the RCP8.5 scenario Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 6

Distribution of loss per unit area (increased land price) under the extreme storm flood scenarios in Shanghai under the RCP8.5 scenario Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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