Assessment of building damages and ~~adaptation options~~risk under extreme flood scenarios in Shanghai

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Abstract. ~~Plenty of various measures have been taken to mitigate flood losses in Shanghai over thousands of years, including the construction of sea dikes and floodwalls. However, the combined effects of intensified rainstorms, sea-level rise, land subsidence, and rapid urbanization are exacerbating extreme flood risks and potential flood losses in the fast-developing coastal city. In light of these changes, this~~ This article presents ~~an~~a flood risk assessment ~~of possible exposure and damage losses of~~in Shanghai, doing so will provide an indication of what buildings ~~in Shanghai~~ (including residential, commercial, ~~workplace~~office, and industrial buildings~~). Based~~) will be exposed to flooding and its damage. We developed an integrated flood model and collect data on buildings' shape and storey, land use, and construction cost in Shanghai. The extreme compound flood scenarios ~~caused by storm surges, precipitation,~~ and ~~fluvial floods, current flood-defence standards will soon be overtaken. Further analyses show that the inundation area could reach 9%, 16%, 24%, and 49% of Shanghai (excluding the area of islands) under the 1/200, 1/500, 1/1000, and 1/5000-year flooding scenarios, respectively. This study finds, in terms of the total building damage, the 1/5000-year flood scenario damage is more than ten times the 1/200-year flood scenario. Accordingly~~buildings' metadata were aggregated using a risk analysis chain, according to the damages for different flood scenarios, the average annual loss (AAL) can be calculated and is referred to as building flood risk. The AAL of residential, commercial, office, and industrial buildings are ~~13.9, 2~~12.3, 2.5~~.~~, 3.7, and 3.~~9~~4 million USD~~. Specifically, among~~, respectively. Among the 15 (non-island) districts in Shanghai, Pudong has the highest ~~exposure and AAL at all the four flood scenarios, while the inner city (including seven districts) is also subject to extreme AAL of up to 40% of its total building values. This study further addresses the possibilities of these extreme flood scenarios, and adaptation options such as: strategic urban planning, advanced building protections, and systematic flood management. Conclusions of the study provide~~AAL. The risk analysis chain developed in this study can be reproducible to other megacities. The result provides a clear enough future for building flood risk which links directly to disaster risk management, implies the extent of flood risk in building types, districts, and communities to the Shanghai Master plan, references result to future climate change scenario framework, information for scenario-based decision making and cost-benefit analysis for extreme flood risk management in Shanghai~~ and is applicable to other similar coastal megacities~~. We also discussed different potential adaptation options for flood risk management.

1 Introduction

Coastal cities that have historically suffered from major flood impacts, such as~~:~~ Dhaka, Guangzhou, Miami, Mumbai, New Orleans, and New York, are heavily affected by future rising flood risks to their population and assets (Woetzel et al., 2020a; Nguyen et al., 2021; Chan et al., 2021). By 2050, over 570 low-lying coastal cities and their 800 million inhabitants will face risks from the impacts of floods and rising sea levels, causing economic losses of up to 1 trillion USD (C40Cities, 2018). ~~Frequent floods will also accelerate stresses of water supply (Yang et al., 2013), health care (Paterson et al., 2018), basin management (Yang et al., 2018a), infrastructure maintenance (Yang, 2020; Bubeck et al., 2019), and ecosystem degradation (Tonkin et al., 2018).~~

Although many coastal cities are facing increasing flood risks (Liang et al., 2017), some will be more seriously affected than others due to local climate change effects, high exposure, or limited adaptation capacities. One of the hotspots, which is facing high flood risks already today, is Shanghai.

Compared to other coastal cities, like Dhaka, Manila, and Rotterdam, Shanghai is the most vulnerable city to flooding (Balica et al., 2012). Coupled with factors of human (population exposure and property exposure) and ~~environmental~~environment (low-lying land, land subsidence problems, the threat of sea-level rise, frequent typhoons, and extreme precipitation) relationships, Shanghai is ranked as one of the top 20 cities ~~to~~for flooding in the world (Hallegatte et al., 2013; Wu et al., 2019). As an answer to this obstacle, Shanghai, the most developed financial centre in China, should ~~increasingly install flood protection, with a focus on hard measures.~~ apply a flood risk assessment to simulate multi flooding scenarios with hydrodynamic models, and drive damage based on the damages of tangible economic sectors, such as architectural structures. For Shanghai, it is necessary to consider extreme flood events, which caused dike overtopping and hinterland storage, in the hydrodynamic models. Since the 1950s, hard measures, like seawalls (along the Yangtze River Estuary and Hangzhou Bay) and levees (along the Huangpu River), were constructed in Shanghai (Zhou et al., 2017). However, the seawalls and levees can be easily destroyed due to the ~~lower~~poor structures and lower standards during the various stages of construction (Zhou et al., 2017). Only 23 % of seawalls can withstand a 200-year flooding scenario; 58 % of seawalls can withstand a 100-year flooding scenario while the rest of seawalls withstand less than a 100-year flooding scenario (Wang et al., 2012). The present protection level of the levees along the Huangpu River for the lowest sections~~, according to the study,~~ is around 1/50-year flooding scenario (Ke et al., 2018). Meanwhile, the historical crest heights in the Huangpu River reveals a significant growing trend from 1950 to 2000, with the existing levees failing several times and leading to extreme damage (Ke et al., 2018), posing a greater threat to Shanghai. Overall, to protect Shanghai from a future failure of floodwalls and levees, extreme flood scenarios, and their consequences should be the taken as the first step of an integrative risk assessment.

Reviewing the current literature shows that various flood modelling techniques and flood scenarios have been ~~widely~~ developed ~~and validated~~ for ~~measuring~~estimating flood risks in Shanghai. ~~For example, according to the trend of relative sea level rise and the harmonic analysis of storm surges along the Shanghai coast, Yin et al. (2011) forecasts flood scenarios in 2030 and 2050. One two-dimensional MIKE 21 flow model has been applied in simulating future combined effects (sea level rise, land subsidence, and storm surges) of flood scenarios in 2030, 2050, and 2100 (Wang et al., 2012). Fluvial~~Coastal floods (storm surge from Shanghai's coast) and fluvial floods (river flood from the Huangpu River~~ were also simulated, considering land subsidence, sea level rise, and storm tide, in considering the return periods of 20, 50, 100, 200, 500, and 1000 years in~~) are the two types of floods which have been the focus for Shanghai. Coastal flood scenarios from the Shanghai~~, respectively~~ coast have been forecasted for 2030 and 2050 by Yin et al. (2011), as well as 2030, 2050, and 2100 by Wang et al. (2012). These scenarios have examined the effects of factors like sea-level rise and storm surge (Yin et al., ~~2013). Incorporated with three anthropogenic variables (land subsidence, urbanization, and flood defence),~~2011), or integrated effects like sea-level rise, land subsidence, and storm surge (Wang et al., 2012). In addition to examining the effects on the Shanghai coast, Yin et al. (2013) looked at how sea-level rise and subsidence combined with storm tide-induced river flooding in the Huangpu River floodplain in 2030 and 2050. Yin et al. (2015) used a ~~numerical~~ 2D ~~modelling approach for return periods of~~ hydrodynamic model to estimate 1/10, 1/100, and ~~1000 years. In general, the~~1/1000-year flood scenarios in the Huangpu River floodplain in Shanghai based on historical floodplain data. The flood scenarios produced in most existing studies tended to focus on the possible future flood scenario changes rather than extreme events, e.g., the concern floods over a 1000-year return period~~.~~ (Yin et al., 2011; Wang et al., 2012; Yin et al., 2013, Yin et al., 2015). At the same time, according to the IPCC report, extreme seal level rise events are projected from once per century to once per year (IPCC, 2019) which could increase the frequency of extreme flood events for coastal cities, such as Shanghai, in the future. Therefore, Shanghai demands multiple extreme compound flood scenarios that combine fluvial and coastal flooding.

The previous studies are dedicated to simulating floods or flooding in Shanghai instead of focusing on the overall risks. The consequences of flooding (i.e., construction damage), however, should be taken into consideration. Flood damage to buildings is noticeably a large part of the total flood losses in cities (Chmutina et al., 2014; Park and Won, 2019), in addition to the often devastating human costs (Woetzel et al., 2020a). In 1997, Typhoon Winnie caused large-scale ~~floods~~flooding in Shanghai and affected more than 5000 households (Du et al., 2020). In 2008, floods damaged 160 streets and 13,000 residential buildings in Shanghai. Therefore, local communities and governmental departments are increasingly calling for holistic analyses of possible building damage under extreme flood scenarios in order to accurately understand and assess potential flood impacts (Kelman and Spence, 2004). ~~Accurate loss data play an integral role in assessing the damages of buildings. But obtaining accurate data is a challenge shared in many areas (Middelmann-Fernandes, 2010), especially in assessing the damage of buildings.~~ To estimate building stocks and the values at risk under a 1/1000-year extreme flood scenario, Wu et al. (2019) ~~integrate~~integrated census-level building floor-area data and geo-coded building asset value data. Shan et al. (2019) further assessed the flood losses of residential buildings and household properties in Shanghai based on a stage-damage function, building footprint, and housing prices. Mostly, deeper investigations into the uncertainties (e.g., asset values, damage rate, and flood process) with reliance on flood risks and damages of buildings (e.g., residential, commercial, office, and industrial) are also urgently needed in order to better support decision making which enhances the overall flood resiliency of the city.

To address these questions, we adopted the very extreme flood scenarios with return periods of 1/200, 1/500, 1/1000, and 1/5000~~ years.~~ -year representing a low probability-high impact scenario. The four extreme flood scenarios are assumed as ~~integrative~~combined effects of ~~multiple~~several flood-triggering factors, such as typhoon-induced storm surge, precipitation, fluvial ~~flood~~flooding in combination with a high astronomical tide, to reflect low probability-high impact flood situations in Shanghai. The objective of this paper is to assess flood ~~losses~~damage and its pattern of residential, commercial, office, and industrial buildings under extreme flood scenarios in Shanghai. To achieve ~~the~~this objective, we ~~modeled~~modelled building ~~exposures~~inundations at four extreme flood scenarios with return periods of 1/200, 1/500, 1/1000, and 1/5000-year, respectively. Combining the ~~exposure~~inundation maps with the stage-damage functions, the study evaluated and identified the spatial distribution of ~~losses~~damages for the specific types of buildings in Shanghai. Section 2 of the paper introduces~~ the data and~~ , Shanghai, the study area. Section 3 describe the details of the materials and methods, and section ~~3~~4 presents the data analysis and major results of the study. Section ~~4~~5 discusses future flood scenarios and proper adaptation strategies for building a flood-resilient Shanghai. Final conclusions are described in section ~~5~~6.

2 ~~Data and Methods~~

~~2.1~~. Study ~~Area~~area

Shanghai is the biggest coastal city in China in terms of population (24.3 million in 2019) and is the major trading and financial hub of China. The city has an area of 6340.5 km^2 that lies in the Yangtze River Delta along the northern edge of Hangzhou Bay (Figure 1). Shanghai is prone to flooding because of its flat low-lying terrain, as well as its location on the path of frequent typhoons from the northwest Pacific (Balica et al., 2012). Moreover, the city experienced an average land subsidence of 1.97 ~~meter~~meters from 1921 to 2007 and the trend is continuing (Gong and Yang, 2008) additionally driving flood risks (Quan, 2014).

In addition, according to the ~~total building area in~~ Shanghai ~~reached 1368.8 km^2 (SMBS, 2018)~~Statistical Yearbook, 29.1 billion USD (183.4 billion CNY) is invested in architectural construction in Shanghai which includes residential buildings (~~686.5 km^2~~15.3 billion USD), office buildings (4 billion USD), commercial buildings (~~81.6 km^2), workplace buildings (90 km^2), industrial buildings (283 km^2),~~4 billion USD) and others~~. The total construction industry value is 159~~ (5.8 billion USD) in 2019 (SMBS, ~~2018~~2020).

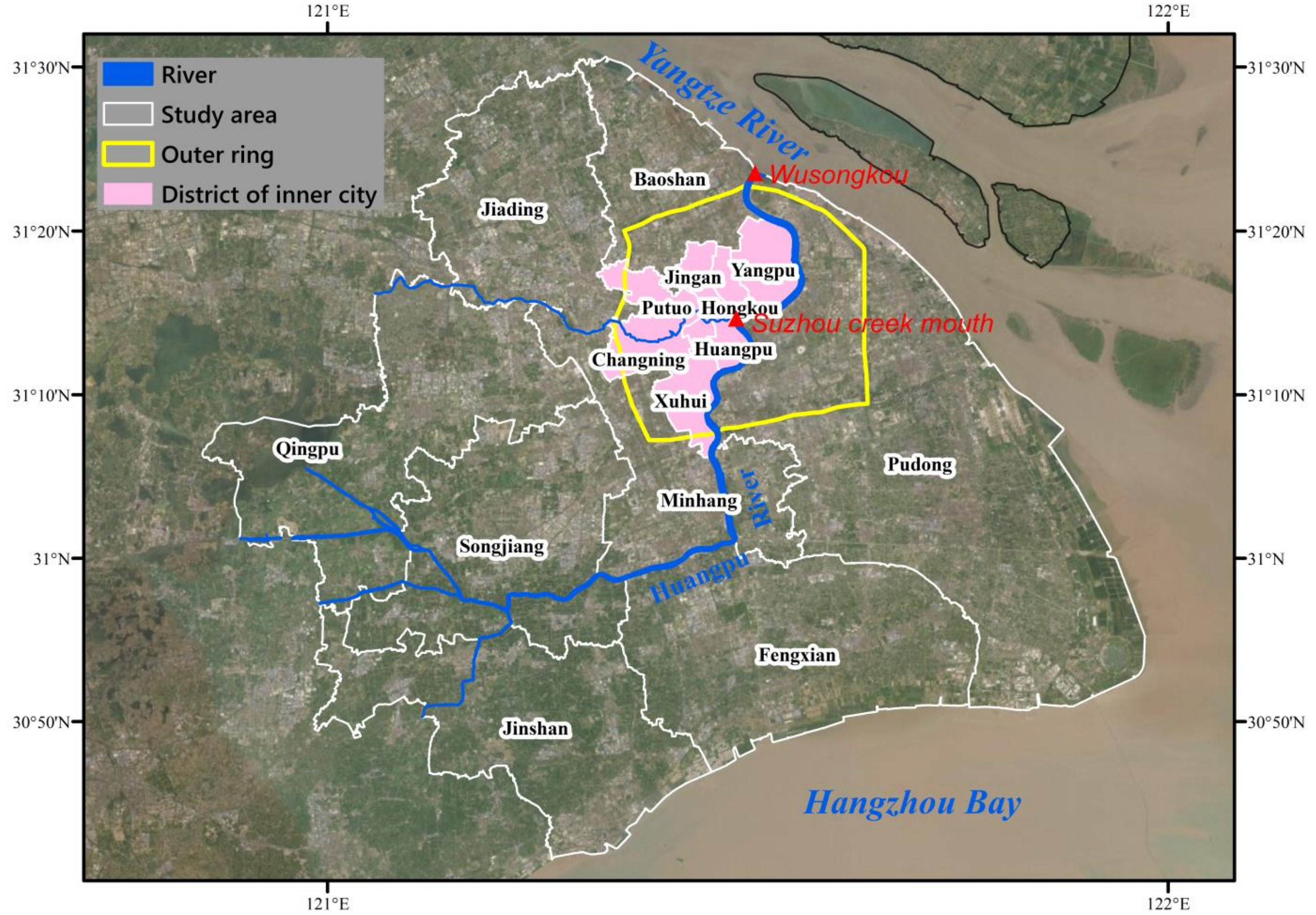


Figure 1. Satellite image-based map of the study area (Shanghai's 15 districts, excluding the city's islands) (The satellite image background is from Esri).

3 Materials and methods

In our study, the flood risks in Shanghai are estimated using three different steps (Figure 2): first, extreme flood scenarios with a return period of 1/200, 1/500, 1/1000, and 1/5000-years are simulated by a hydrodynamic model. This was done in a previous work by Wang et al., (2019). Our study builds upon these results and estimates the damages based on the obtained flood hazard scenarios. Finally, the overall flood risk and its spatial pattern for buildings in Shanghai, described as the estimated average annual loss (AAL). More details of the assessment are introduced in the following sections 3.1 to 3.3.

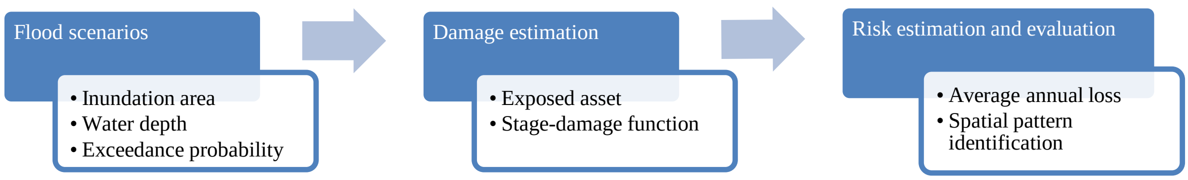


Figure 2. ~~**2.2 Data**~~

~~The study involves the data of four extreme flood scenarios, building maps, land use and land cover data, and the construction costs of different buildings in Shanghai. In this study, we adopted the very extreme flood scenarios with return periods of 200, 500, 1000, and 5000 years. Based on the extreme water levels for different return periods, the hydrodynamic modelling is composed of atmospheric models (Fujita typhoon model), ocean models (TOMAWAC, TELEMAC), and coastal models (MIKE 1D/2D), developed to simulate four extreme flood scenarios, respectively combined with a fluvial flood during Typhoon Winnie in 1997 (Wang et al., 2019). Typhoon Winnie brought the highest recorder water level with 5.72 meters since~~

~~1900, which caused the collapse of 148 meters of floodwalls and overflowed 57 km of floodwalls and 69 km of sea dikes. The rainfall and river discharge data based on Typhoon Winnie in 1997 are superimposed on coastal flood simulations. These four flood scenarios are raster data with a 60-meter spatial resolution.~~

~~The~~Risk analysis chain

3.1 Flood scenarios

The flood scenarios build on the results of Wang et al. (2019), who used an integrated flood model to simulate compound flooding in Shanghai that included fluvial and coastal flooding. Four scenarios with return periods of 200, 500, 1000, and 5000 years were simulated considering atmospheric conditions, oceanic/coastal environments, and river discharge.

For this purpose, the integrated model has applied and coupled several models in three stages: in the first stage, the Fujita model provides the atmospheric conditions on the north-western Pacific Ocean (from 100 - 180 °E for longitude, 0 - 60 °N for latitude). The Fujita model computed and simulated Typhoon Winnie's wind direction, speed, press, and boundary layer. Typhoon Winnie was a typical turning track typhoon, bringing the highest recorded water level of 5.72 meters in Shanghai since 1900 (Dong et al., 2022). Wind data from Typhoon Winnie were required from European Centre for Medium-Range Weather Forecasts (ECMWF). Then the atmospheric conditions integrated with the TELEMAC model provide the oceanic/coastal environment on the Yangtze River Delta (from 120 – 124.5 °E for longitude, 28 - 34 °N for latitude). The TELEMAC model simulates the hydrodynamic and morphodynamical process in oceanic/coastal environments including shallow water horizontal flows and waves from the Pacific Ocean (Hashemi et al., 2015). The first two stages prepare parametric for the coastal flooding from Shanghai's coast. In the last stage, the atmospheric and the oceanic/coastal condition have been integrated with the MIKE model which simulates the river discharge in the study area. Rainfall and river discharge measurement data from Typhoon Winnie were implemented in the MIKE model. The MIKE Model is applicable for the simulation of hydraulic for fluvial flooding from the Huangpu River (MIKE, 2017).

This model offers Shanghai extreme compound flood scenarios with inundation area and depth at a resolution of 60 m. These extreme compound flood scenarios are being shown for the first time in Shanghai with 200, 500, 1000, and 5000 years return periods.

3.2 Damage estimation

3.2.1 Asset value of buildings

From Baidu Map (Baidu Maps, 2017) the data for Shanghai's buildings were acquired ~~from Baidu Map (Baidu Maps, 2017)~~ using a python-based web crawler, and then processed with ArcGIS software. Baidu Maps provide various map services, such as satellite images, street maps, and route planners in China. The shapefile data for Shanghai's buildings include the information of building type, building ground-based area, height, and the number of floors for each building. ~~These~~The data of Shanghai's buildings are ~~used in combination~~combined with land use data to further cluster the buildings into four different types including: residential, commercial, ~~workplace~~office, and industrial.

The land use data of 2013 from the Shanghai Planning and Land Bureau was depicted hierarchically into 3 sectors, 15 subcategories, and 73 subclasses of land use types using ArcGIS 10.6.1. The reclassification of the land use was conducted according to the National Standard of China "GB/T 2010-2017" (CSP, 2017) and covers residential area, commercial area, ~~workplace~~office area, and industrial area. ~~Specially, the~~The land use type of residential ~~areas~~area covers apartment, mixed apartment, rural housing ~~in the rural~~, and empty housing. ~~Commercial areas are the lands that are used for commercial operations. Workplace~~Office areas include land for medical care and health, charity, education, culture, government, research, market, and insurance. ~~Industrial factories are classified into industrial areas.~~

The cost data of building construction used in this study are derived from the 2019 annual report provided by the consulting company Arcadis in Shanghai. ~~The cost per square meter is based on Construction Floor Areas (CFA), which measures to the~~

outside face of the external walls. The data set depicts fourThe data set depicts five different building types (domestic, office/commercial, hotels, industrial, and other), which are further divided into 19 subsectors (Arcadis, 2020). ConstructionDue to the lack of details about the architectural construction, the construction costs of various buildings are averagedequally weighted (Table 1). The average construction cost is derived from the average number of the construction cost in order to get the mean value for eachthe four different building type (table 1).types.

Table 1. Common construction costs of various buildings in Shanghai.

Building Type		Construction Cost (USD/m^2 CFA)	Average Construction Cost (USD/m^2)
Residential	Apartments, high rise, average standard	668—-740	873874
	Apartments, high rise, high end	1554—-1697	
	Terraced houses, average standard	446—-477	
	Detached houses, high end	666—-740	
Commercial	Retail malls, high end	1228—-1585	14071157
Office	Medium/high rise offices, average standard	868-1156	11571406
	High rise offices, prestige quality	1158-1445	
Industrial	Industrial units, shell only (Conventional single story framed units)	432-540	486

The relationship between flood inundation depth and flood loss of a building or other property is depicted by a stage-damage function (Garrote et al., 2016; Mcgrath et al., 2019). Based on actual building damage data from past flood hazard events and previous empirical stage-damage functions in Shanghai (Yu et al., 2012; Wang, 2001), Ke (2014) developed updated stage-damage functions to specific buildings in Shanghai (Figure 2). These stage-damage functions represent the generalized loss of one type of buildings with similar properties, which are adopted in the present study.

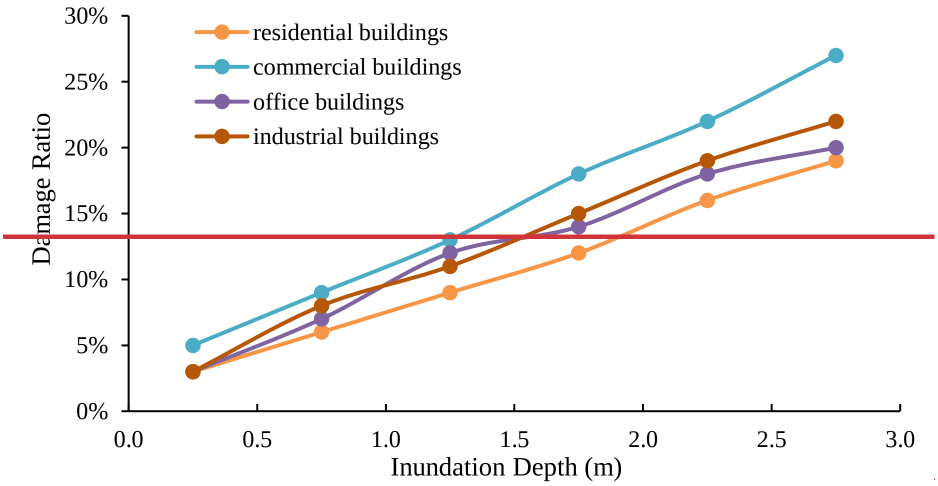


Figure 2. Stage-damage functions for buildings in Shanghai (Adopted from (Ke, 2014)).

2.3 Methods

In our study, the flood damages in Shanghai are estimated within three different steps: first, we calculated the asset values for each building based on the surface area of the building and the average construction cost. Then, the exposed building areas are determined by overlaying the distribution of buildings with the inundation maps for the four extreme flood scenarios. The damage values of a building could be estimated based on the exposed building area and the stage-damage functions. Finally, the overall flood risk for buildings in Shanghai, described as the estimated average annual loss (AAL), is calculated using a polynomial regression analysis. More details of the assessment are introduced in the following sections 2.3.1 to 2.3.4.

2.3.1 Asset value analysis of buildings

Different methods exist in the evaluation of building values. According to the Chinese National Standard (GB/T 50291-2015) and previous studies, there are four main approaches to evaluate the asset value of buildings: method of the sales comparison, method of the income capitalization, method of the construction cost, and method of the hypothetical development (CSP, 2015). The application of different methods depends on the specific study aims and the availability of building-specific data. ~~Method of sale~~Sale comparison is often used when the evaluation of a similar type of building is available~~. Method of~~, whereas the income capitalization is suitable for buildings that yield profits like rents. If a building is newly constructed or (to be) reconstructed after damage, method of construction cost would be suitable for the evaluation. ~~Method~~The method of hypothetical development is applicable to the evaluation of real estate with investment development or redevelopment potentials. Since the present study aims to assess flood damages on buildings, the construction cost method is used with consideration of the building surface area. Then, the asset value of one building can be approximated by the following function:

$$W_n = S_n \times P_n \tag{1}$$

Where W_n (USD) is the asset value ~~of buildings~~ for one building which belongs to the building type n , ~~S~~S_n is the surface area of building n, P_n is the average construction cost (USD/m^2) for the specific type of building n. The surface area is the whole construction area (including wall area and floor area).

Table 2.~~3~~ Examples of building asset value for the four selected building types.

Building id	Building type n	Surface area (m^2)	Average construction cost (USD/m^2)	Asset Value (USD)
1	Residential building	1662	874	1452588
2	Commercial building	1347	1407	1895229
3	Office building	776	1157	897832
4	Industrial building	2463	486	1197018

3.2.2 Evaluation of building damages in flood

~~The water~~The relationship between flood inundation depth ~~of the flooding scenario determines the exposed area of the buildings. If the building is flooded at depth of more than 3 meters, we assume that the exposed area covers two floors instead of one. The potential building~~ and flood damages of a building or other property is depicted by a stage-damage function (Garrote et al., 2016; Mcgrath et al., ~~are determined by~~2019). In this study, the stage-damage functions are adapted from existing studies on the relationship of various building damages rate with water-level depth in Shanghai (Ke, 2014). Based on actual building damage data from past flood hazard events and previous empirical stage-damage functions in Shanghai (Yu et al., 2012; Wang, 2001), Ke (2014) developed updated stage-damage functions to specific buildings in Shanghai. The stage-damage function is used to evaluate the damage values of residential, commercial, ~~workplace~~office, and industrial buildings with the probability of 1/200, 1/500, 1/1000, and 1/5000-years extreme flood scenarios, respectively. ~~The specific~~ As shown in Table 3, the stage-damage functions ~~are derived from existing studies on the relationship~~represent the average damage in dependency of ~~various~~the inundation depth for the four adopted building ~~loss rates with water-level depth in Shanghai (Penning-Rowsell et al., 2013;~~ types. If the building is flooded at depth of more than 3 meters, we assume that the exposed area covers two floors instead of one.

Table 3. Selected stage-damage functions for the study area (Adapted from Ke~~,~~ (2014~~).~~)).

Inundation depth (m)	Residential buildings	Commercial buildings	Office buildings	Industrial buildings
<0.5	0.03	0.05	0.03	0.03
0.5-1.0	0.06	0.09	0.07	0.08
1.0-1.5	0.09	0.13	0.12	0.11
1.5-2.0	0.12	0.18	0.14	0.15
2.0-2.5	0.16	0.22	0.18	0.19
2.5-3.0	0.19	0.27	0.20	0.22

>3.0	0.22	0.31	0.25	0.25

The damage values of one building can be expressed by the following function:

$$f(x) D_n = E_n \times P_n \times T_n \tag{2}$$

Where $f(x) D_n$ represents building damage for building type n, E_n represents the exposed area of buildings for building type n, P_n is the construction cost (USD/m^2) for the specific type of building n, T_n represents the damage proportion from stage-damage function for building n under different water-level depths.

~~2.3.3 Integrative building damages~~

Table 4. Examples of damage values for the four building types at an inundation level of 0.5-1 m.

Building id	Building type n	Exposed area (m^2)	Average construction cost (USD/m^2)	Damage proportion	Building damage (USD)
1	Residential building	123	874	0.06	6450
2	Commercial building	341	1407	0.09	43180
3	Office building	539	1157	0.07	43653
4	Industrial building	29	486	0.08	1127

3.3 Risk Determination and Evaluation

When expressing a city-scale flood damage for different flood scenarios, we use the already well established economic AAL (Hallegatte et al., 2013). The AAL is the sum of the probabilities of~~ the~~ floods for each return period, while considering the approximate areas under the associated risk curve (Ward et al., 2011). In the present study, we considered only the damage value of buildings as a major part of the AAL. Particularly, the AAL represents the integrative building damage for all types of buildings in all the considered flood scenarios in Shanghai. Hence, we get the AAL values for different exceedance probabilities (extreme flood scenarios) as the sum of:

$$\text{AAL} = \sum_{x=rp_{min}}^{rp_{max}-1} \left(f(x) + f(x+1)\right)/2 \times \Delta x \tag{3}$$

$$\text{AAL} = \int x\, f(x)dx \tag{3}$$

Where ~~n is the building type, ~~x is the return period of the flood scenario, and $f(x)$ is the ~~damages~~damage value of ~~one~~a single type of building.

~~2.3.4 Spatial pattern identification~~

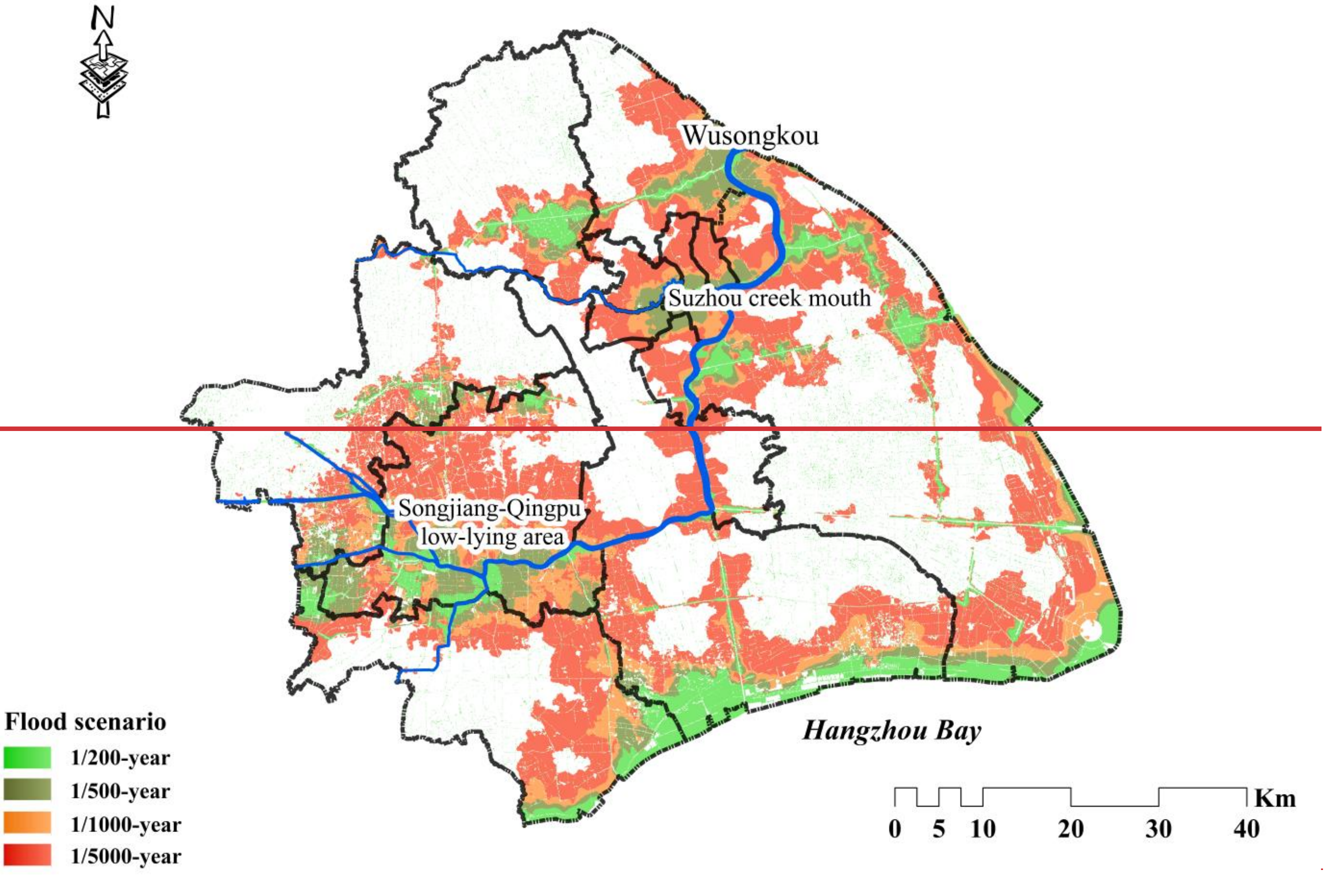
~~In this study, the~~The AAL of all sub-districts and their neighbours were compared with the AAL by Getis-Ord Gi* in ArcMap 10.6. The Getis-Ord Gi*, also known as the hot spot analysis, measures the strength of spatial autocorrelation and tests the assumption of independence between surrounded features (Manepalli et al., 2011). According to the Getis-Ord Gi*, a feature with a positive value and intense clustering of high values, the feature corresponds to hot spot clusters, a feature with a negative value and intense clustering of low values, the feature corresponds to cold spot clusters. The results contain a significant range of high values (hot spots) and low values (cold spots). ~~Hot~~In our study, hot spots mean the ~~AAL~~flood risk of a sub-district has a high AAL value and ~~can be~~is surrounded by other sub-districts with high values~~ as well.~~, and has a higher risk for extreme flooding. Cold spots indicate an opposite situation.

~~**3 Assessment of building damages in extreme floods**~~

~~3~~4 Results

4.1 Mapping the flood scenarios

~~This section presents~~The four extreme flood scenarios present the comparison of the spatial distribution of inundation areas ~~under the four extreme flood scenarios~~ (Figure 3). The inundation areas increase generally, but non-linearly, along with increasing return periods. As shown in figure 3, the inundation areas mainly concentrate ~~on~~in regions around the Wusongkou (the mouth of Huangpu River), the Suzhou creek mouth (~~the~~ central ~~of~~ Shanghai), the Songjiang-Qingpu low-lying area, and the north bank of Hangzhou Bay. The inundation areas expand to inland areas from the coastal region and the rivers as the flood scenario becomes more extreme. For the 1/200-year flood scenario, 9 % (488 km^2) of Shanghai is flooded, mainly along the north bank of Hangzhou Bay. The flooded area of Shanghai increased to 16 % (868 km^2) and 24 % (1302 km^2) in the 1/500-year and 1/1000-year flood scenarios, respectively. The flooded area extended significantly to 49 % (2659 km^2) of Shanghai in the 1/5000-year flood scenario. More specifically in this exceptionally extreme scenario, 32 % of the city would be flooded with a water depth of 0-0.~~5m~~5 m, 11 % with a 0.5-1.~~0m~~0 m depth of water, and 5 % with a water depth of more than 1m (Figure 3).



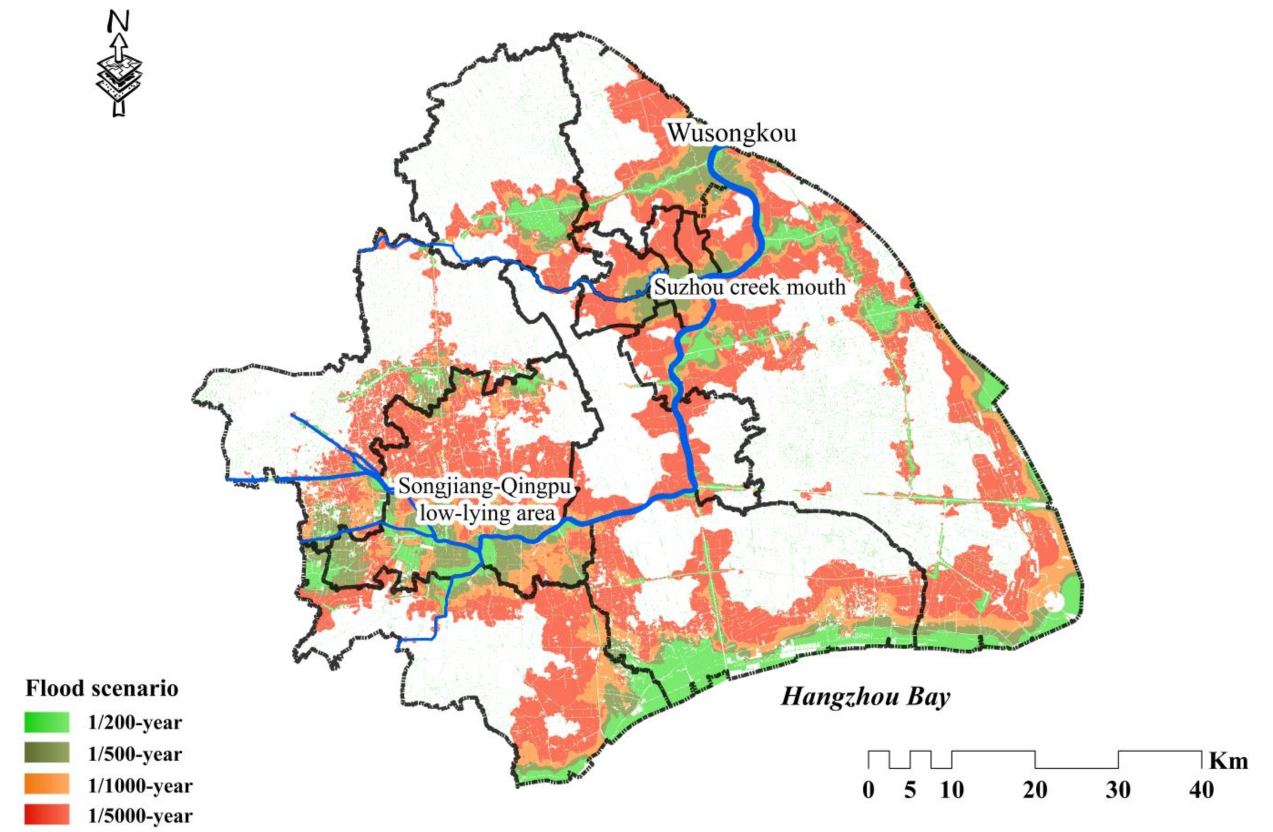


Figure 3. Inundation areas for the four flood return periods in Shanghai (excluding the area of islands).

~~3~~4.2 Estimating the building ~~assets~~damage

This study identified the building ~~floor~~surface area ~~(BFA)~~ of each type of building in 2017, which amounts to ~~816~~2323 km^2, ~~52~~157 km^2, ~~152~~430 km^2, and ~~300~~824 km^2 respectively for the residential, commercial, ~~workplace~~office, and industrial buildings. ~~Accordingly, the building asset values are 2494, 212, 747, and 510 billion USD considering the Average Construction Cost (see Table 1) of each building types in 2019.~~ This is a conservative estimation as the actual present value of the buildings are certainly higher due to new developments in recent years. Every single building's asset value has been computed using equation (1), allowing us to obtain the number of building asset values in residential, commercial, office, and industrial buildings. According to equation (1), the building asset values in Shanghai are 2030, 221, 497, and 401 billion USD considering the Average Construction Cost (see Table 1) of each building types in 2019. The relative numbers show that residential buildings have the highest asset value, followed by office, industrial, and commercial ~~building.~~
~~Figure 4 shows that all types of buildings have higher values within the outer ring of Shanghai. This is consistent with the fact that the central downtown area is densely developed with the accumulation of various buildings.~~buildings. While comparing the building asset values in the 15 districts, the Pudong district has the highest asset value ~~and largest building surface area (Table 2~~(Figure 4) as it is the largest district in Shanghai. Our estimate for the building assets underpins the importance to quantify the value of architectural construction in Shanghai, along with the value of damaged architectural construction.

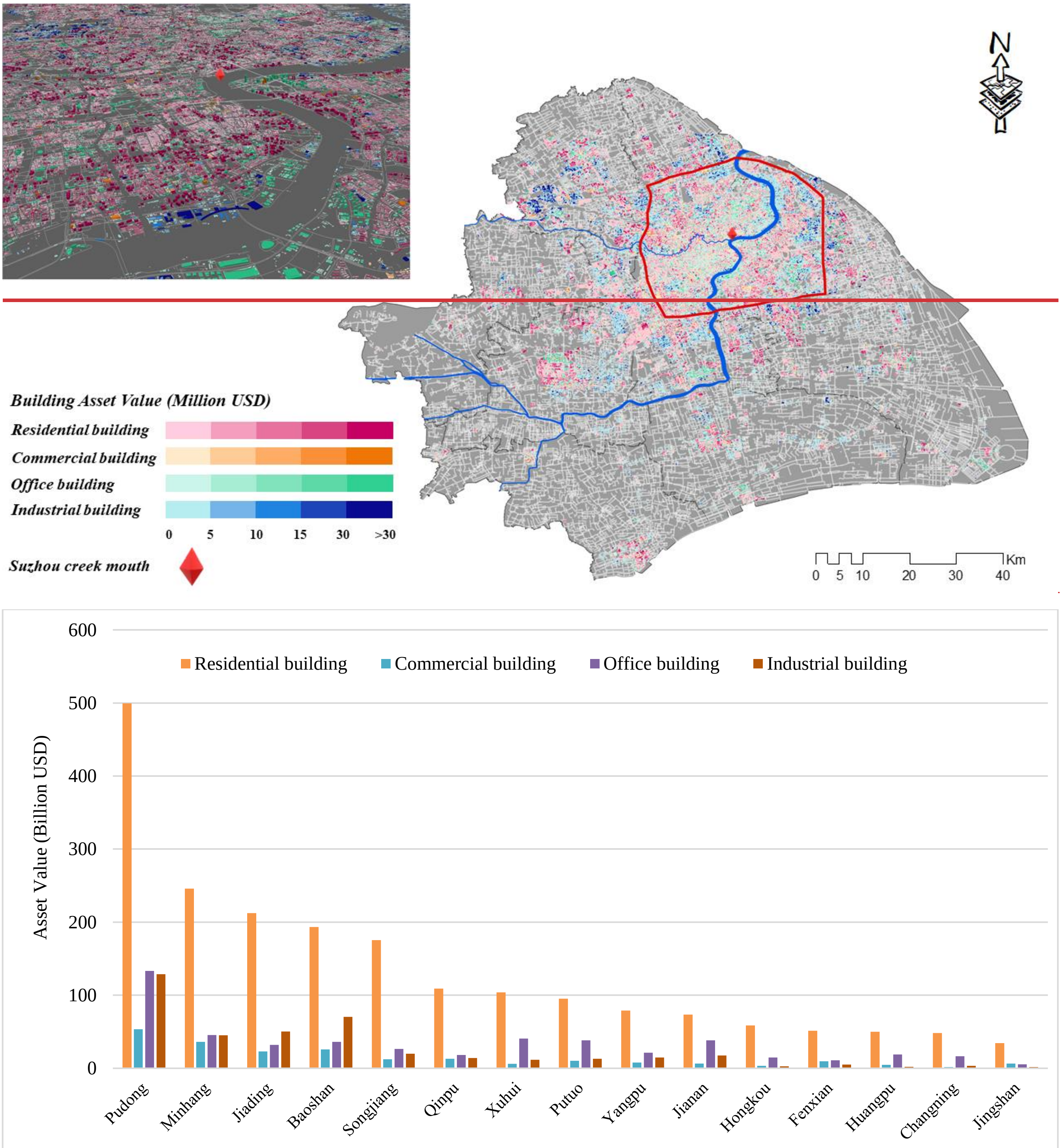


Figure 4. The ~~distribution of~~ building asset values in ~~different types of buildings in Shanghai.~~

~~Table 2. The building asset values and floor areas in~~ the 15 districts of Shanghai.

~~District~~	~~Residential~~		~~Commercial~~		~~Office~~		~~Industrial~~	
	~~Asset Value (Billion USD)~~	~~Surface Area (km²)~~	~~Asset Value (Billion USD)~~	~~Surface Area (km²)~~	~~Asset Value (Billion USD)~~	~~Surface Area (km²)~~	~~Asset Value (Billion USD)~~	~~Surface Area (km²)~~
~~Jiading~~	~~236~~	~~271~~	~~25~~	~~22~~	~~54~~	~~39~~	~~89~~	~~183~~
~~Fenxian~~	~~64~~	~~73~~	~~9~~	~~8~~	~~17~~	~~12~~	~~8~~	~~16~~
~~Baoshan~~	~~260~~	~~298~~	~~22~~	~~19~~	~~48~~	~~34~~	~~64~~	~~131~~
~~Xuhui~~	~~117~~	~~133~~	~~10~~	~~9~~	~~58~~	~~41~~	~~16~~	~~33~~
~~Putuo~~	~~133~~	~~152~~	~~13~~	~~11~~	~~28~~	~~20~~	~~18~~	~~37~~
~~Yangpu~~	~~90~~	~~104~~	~~6~~	~~5~~	~~58~~	~~41~~	~~22~~	~~45~~
~~Songjiang~~	~~217~~	~~249~~	~~12~~	~~10~~	~~40~~	~~29~~	~~27~~	~~55~~
~~Pudong~~	~~616~~	~~705~~	~~51~~	~~44~~	~~200~~	~~142~~	~~164~~	~~336~~
~~Hongkou~~	~~72~~	~~82~~	~~3~~	~~3~~	~~22~~	~~16~~	~~4~~	~~7~~

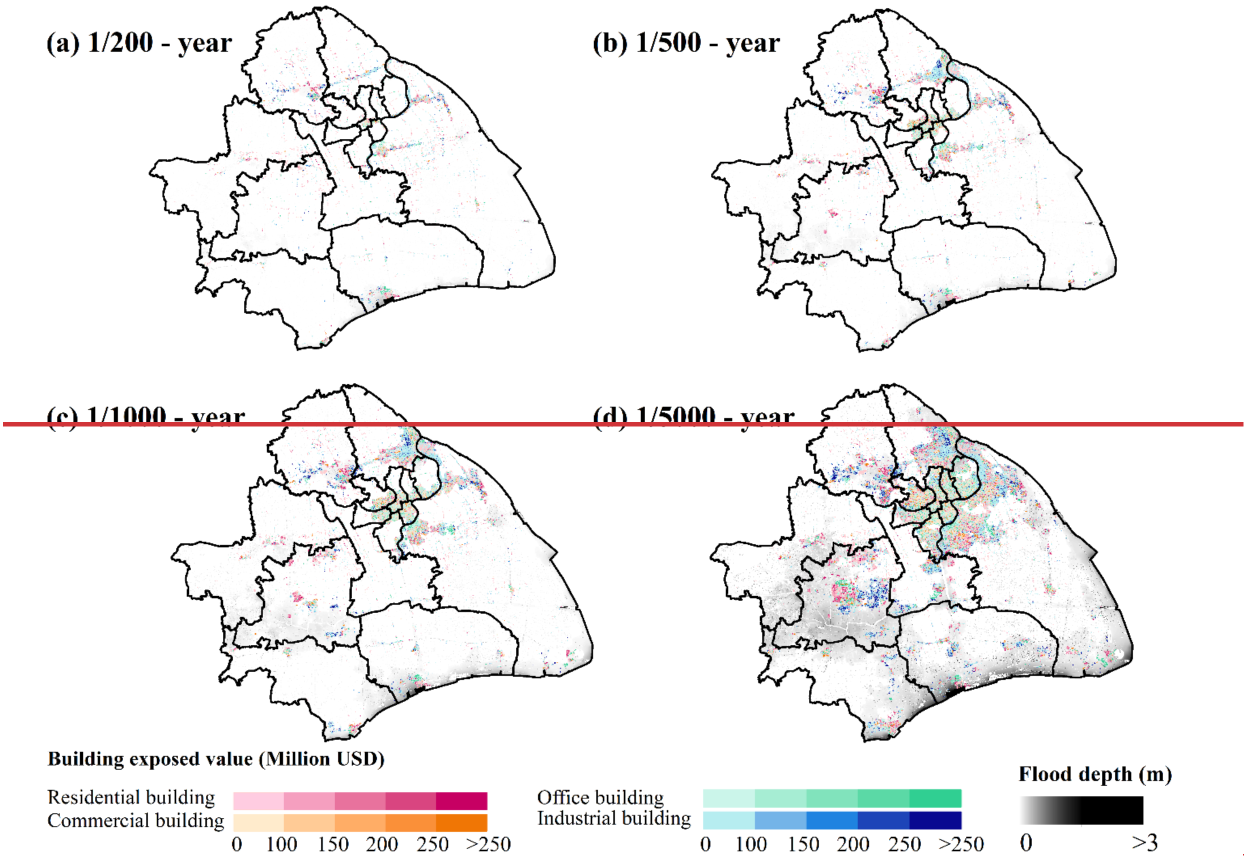
Jingshan	42	48	6	5	8	6	2	4
Changning	59	68	1	1	25	18	4	9
Minhang	303	347	35	30	69	49	58	119
Qinpu	128	146	6	5	59	42	15	31
Jingan	96	110	7	6	32	23	18	37
Huangpu	61	70	5	4	28	20	3	5
Total	2494	2857	212	183	747	531	510	1050

3.3 Exposed building values

The quantitative assessment and mapping generated the spatial extent of exposed buildings and the exposed building values under the four extreme flood scenarios in Shanghai (Figure 5). The assessment shows that the total exposed building values reach 39, 107, 166, and 386 billion USD under a 1/200, 1/500, 1/1000, and 1/5000-year flood scenarios, respectively. Exposed buildings in the 1/200 scenario are located mainly along the coast and rivers, with some exposed buildings in dispersed low-lying places. With an increase of extreme flooding, the exposed areas rise rapidly and become contiguous. Under the most extreme scenario of a 1/5000-year return period, the region around the Suzhou Creek Mouth in the inner city is remarkably exposed in deep water with the highest exposed values. Two contiguous inundation areas, central Shanghai and the Songjiang-Qingpu low-lying area in west Shanghai, are identified as the most seriously exposed regions in the most extreme flood scenario (Figure 5d).

Unsurprisingly, as the residential buildings have the highest asset value, their exposed values are also the highest in the four types of buildings (Appendices Table A1). Further analysis of the exposed values in different districts indicates that Pudong has the highest exposed value for all four flood scenarios (Table 3). The exposed ratio of each district in different flood scenarios is as follows: in the 1/200-year flood scenario, Fengxian has the highest percentage of exposed building values; under the 1/500-year and 1/1000-year flood scenarios, Huangpu has the highest percentage of exposed building values. Under the 1/5000 flood scenario, Hongkou has the highest percentage (Appendices Figure A1).

Water depth is a determinate factor of exposed building values. Though hardly visible in Figure 5, 94% of the exposed buildings are exposed to water levels of 0-0.5m in the 1/200-year flood scenario (Figure 5a). The account declines to 82%, 83% and 67% under the 1/500, 1/1000, and 1/5000-year flood scenarios, due to the increasing proportions of exposures in deeper water. In the case of the most extreme 1/5000-year flood scenario, 24% of exposed buildings are in water of 0.5-1m, and 8% of the exposed buildings are flooded in depth of 1-1.5m (Appendices Figure A2).



~~Figure 5. The distribution of exposed asset values for residential, commercial, office, and industrial buildings under four extreme flood scenarios in Shanghai.~~

~~Table 3. Exposed building values of the 15 districts in Shanghai under the four flood scenarios (Unit: Billion USD).~~

Districts	Flood scenarios (Return Periods)			
	1/5000	1/1000	1/500	1/200
Jiading (JD)	23.27	11.48	9.00	5.96
Fengxian (FX)	9.69	4.03	2.93	2.69
Baoshan (BS)	43.52	25.87	17.39	2.61
Xuhui (XH)	23.43	7.19	4.79	0.70
Putuo (PT)	23.22	11.32	6.76	0.27
Yangpu (YP)	24.75	8.51	3.89	0.36
Songjiang (SJ)	35.67	9.54	3.48	0.96
Pudong (PD)	111.16	46.79	31.95	17.41
Hongkou (HK)	15.53	5.04	3.02	0.05
Jinshan (JS)	8.19	3.69	2.29	1.20
Changning (CN)	13.66	8.28	4.97	0.12
Minhang (MH)	15.56	0.93	0.55	0.62
Qingpu (QP)	5.24	2.62	1.93	1.06
Jingan (JA)	19.41	9.47	8.13	3.02
Huangpu (HP)	13.69	11.56	5.73	1.96
Total	385.98	166.31	106.80	38.99

~~3.4 Damages of buildings in floods~~

The quantitative assessment provides maps of flood damages to different buildings under the four extreme scenarios (~~Figure 6~~Table 5). The total building damages in the 1/5000-year flood scenario is ~~18~~15 billion USD, which is more than ~~10~~13 times the 1/200-year flood scenario (1.~~39~~18 billion USD). Again, residential buildings are the most damaged in all four scenarios with a damage value of up to ~~9.6~~8.2 billion USD in the 1/5000-year scenario. Damages of industrial buildings, office buildings, and commercial buildings would reach ~~1~~2.6, ~~4.0~~2.8, and ~~3.0~~1.6 billion USD respectively under the 1/5000-year flood scenarios.

Table 5. Damage statistics for residential, commercial, office and industrial buildings exposed to extreme flooding under the four return period scenarios in Shanghai's 15 (non-island) districts (Unit: Billion USD).

Asset Damages District	**Return Periods**			
	1/5000	**1/1000**	**1/500**	**1/200**
Jiading	0.71	0.37	0.26	0.17
Fengxian	0.45	0.23	0.17	0.14
Baoshan	2.06	0.89	0.50	0.09
Xuhui	0.88	0.25	0.14	0.02
Putuo	1.05	0.44	0.22	0.01
Yangpu	0.94	0.28	0.11	0.01
Songjiang	1.11	0.29	0.10	0.03
Pudong	4.00	1.44	0.94	0.50
Hongkou	0.65	0.20	0.10	0.00
Jinshan	0.31	0.13	0.08	0.04
Changning	0.66	0.34	0.18	0.00
Minhang	0.47	0.04	0.02	0.02
Qingpu	0.17	0.09	0.05	0.03
Jinan	1.01	0.51	0.38	0.08
Huangpu	0.78	0.44	0.22	0.05
Total	15.26	5.95	3.45	1.18

The damage analysis of different districts shows that Pudong has the highest overall damage in all scenarios (Table ~~4~~5). However, the rankings of the proportion of damages are different. For the 1/200-year scenario, Fengxian has the highest proportion of ~~the~~ asset damages. Jingan has the highest damage proportion in the 1/500-year scenario. While for the 1/1000 and 1/5000-year scenarios, Huangpu is ~~ranking as~~ the ~~most damaged~~ district ~~in terms of the damage~~with highest proportion ~~(Appendices~~ of asset damages (Figure ~~A3).~~ 5).

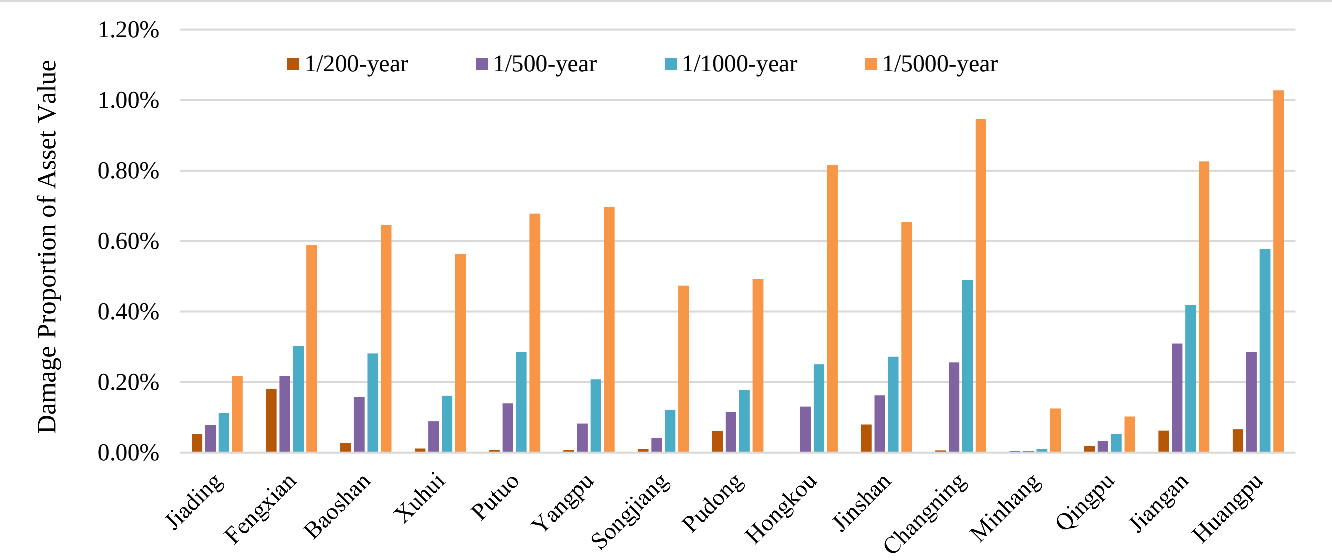
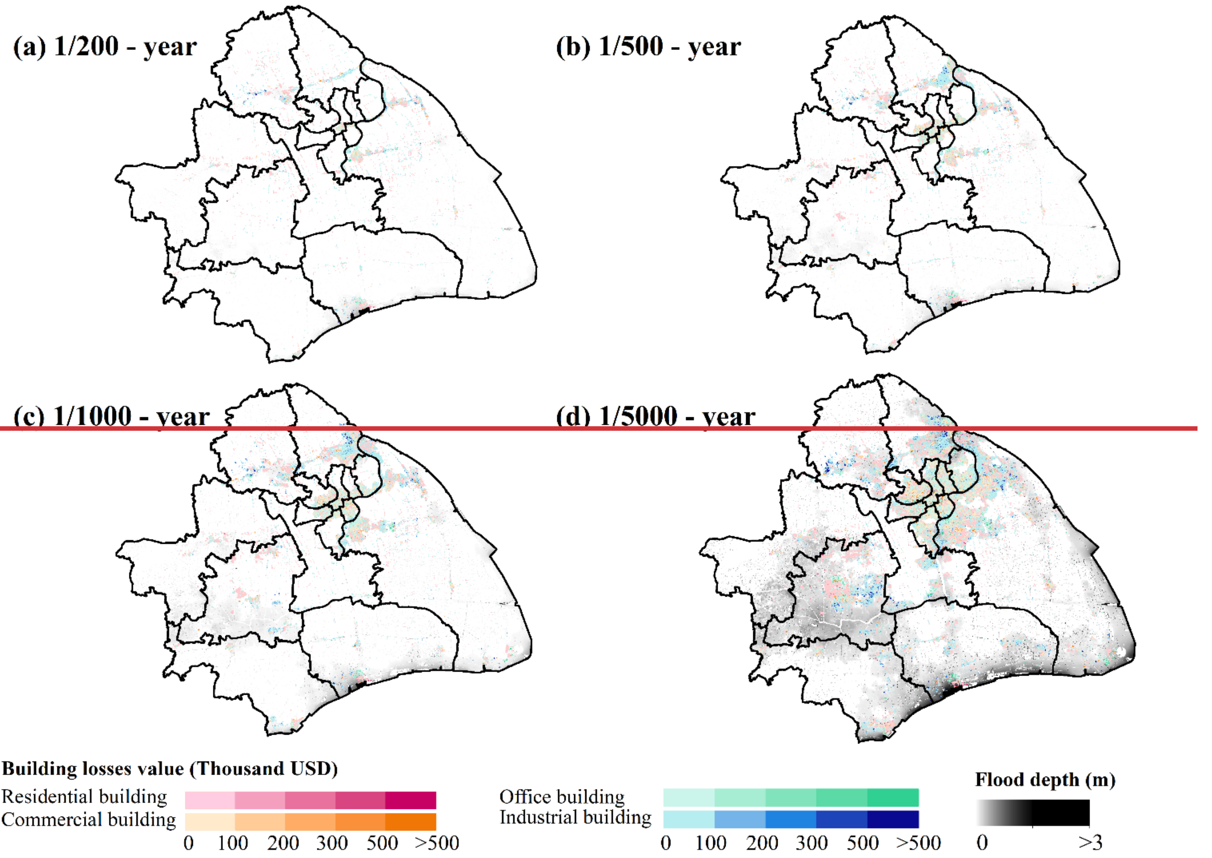


Figure 5. Damage percentages of residential, commercial, office and industrial buildings to extreme flooding under the four return period scenarios in each district.

In terms of damage due to water depths in different flood scenarios, water depths of 0-0.~~5m causes~~5 m caused 83 ~~percent~~% of building damage in the 1/200-year flood scenario. Under 1/500, 1/1000, and 1/5000-year flood scenarios, the ~~proportion~~proportions are 67~~%, 68~~ %, 55 %, and ~~44~~45 %, respectively, with deeper water depths causing more damage. For instance, ~~35~~33 % of buildings are damaged in water depths of 0.5-~~1m~~1 m under the 1/5000-year flood scenario, and ~~17~~18 % of the damages occur in water depths 1-1.~~5m (Appendices Figure A4).~~



5 m (Figure 6~~. The distribution of damaged asset values for residential, commercial, office, and industrial buildings under the four extreme flood scenarios in Shanghai.).~~

~~Table 4. Statistics of damage to residential, commercial, office and industrial buildings to extreme flooding under four return period scenarios in districts (Unit: Billion USD).~~

~~Asset Damages District~~	~~Return Periods~~			
	~~1/5000~~	~~1/1000~~	~~1/500~~	~~1/200~~
~~Jiading (JD)~~	~~0.81~~	~~0.42~~	~~0.30~~	~~0.20~~
~~Fengxian (FX)~~	~~0.55~~	~~0.28~~	~~0.20~~	~~0.17~~
~~Baoshan (BS)~~	~~2.42~~	~~1.04~~	~~0.58~~	~~0.09~~
~~Xuhui (XH)~~	~~1.07~~	~~0.31~~	~~0.17~~	~~0.02~~
~~PuTuo (PT)~~	~~1.24~~	~~0.53~~	~~0.26~~	~~0.01~~
~~Yangpu (YP)~~	~~1.15~~	~~0.34~~	~~0.14~~	~~0.01~~
~~Songjiang (SJ)~~	~~1.31~~	~~0.33~~	~~0.11~~	~~0.03~~
~~Pudong (PD)~~	~~4.74~~	~~1.71~~	~~1.10~~	~~0.59~~
~~Hongkou (HK)~~	~~0.78~~	~~0.24~~	~~0.12~~	~~0.00~~
~~Jinshan (JS)~~	~~0.37~~	~~0.16~~	~~0.09~~	~~0.05~~
~~Changning (CN)~~	~~0.82~~	~~0.42~~	~~0.22~~	~~0.01~~
~~Minhang (MH)~~	~~0.54~~	~~0.05~~	~~0.02~~	~~0.02~~
~~Qingpu (QP)~~	~~0.20~~	~~0.10~~	~~0.06~~	~~0.03~~
~~Jinan (JA)~~	~~1.23~~	~~0.62~~	~~0.46~~	~~0.09~~
~~Huangpu (HP)~~	~~0.95~~	~~0.53~~	~~0.26~~	~~0.06~~
~~Total~~	~~18.18~~	~~7.08~~	~~4.10~~	~~1.39~~

~~**3.5 Integrative evaluation of flood damages in Shanghai**~~

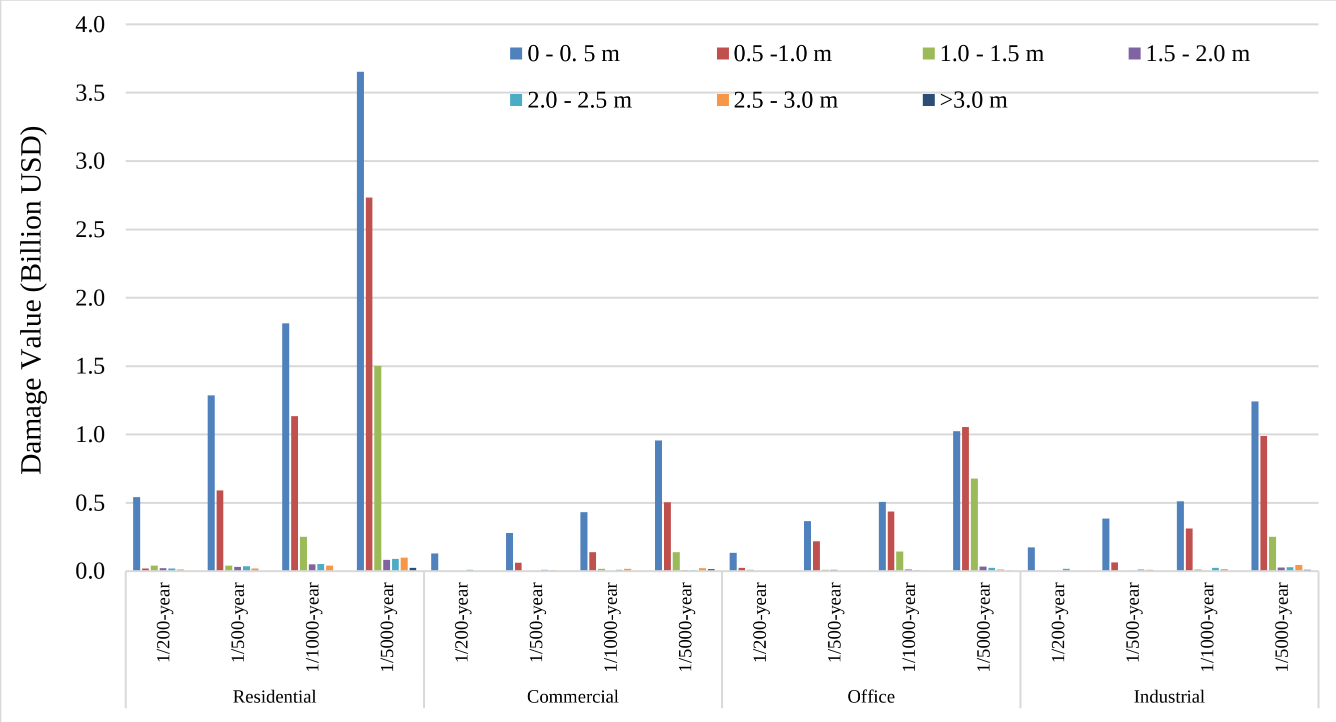


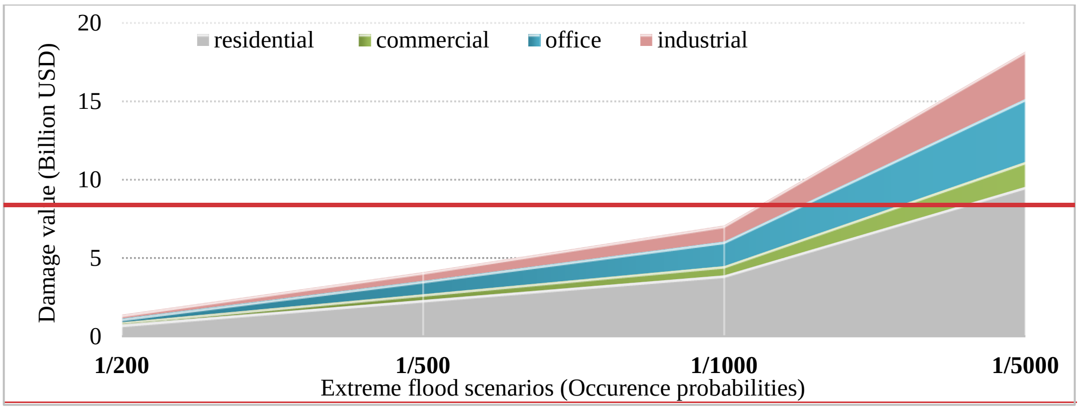
Figure 6. The damage asset for different water depths.

4.3 Risk estimates of buildings and its pattern

By integrating the extreme flood scenarios and associated building damages for the four types of buildings, we plotted ~~the~~ four average annual probability-damage curves (~~Fig.~~Figure 7). The AALs of residential, commercial, ~~workplace~~office, and industrial buildings are ~~18~~12.3, 2.5, 3.~~6,~~ 7~~.8~~, and ~~5.8~~3.4 million dollars, respectively. It ~~is clear~~shows that residential buildings would suffer the highest ~~damage~~risk value among the four types of buildings.

By using the Getis-Ord Gi* statistic tool ~~(Hot Spot Analysis)~~ in ArcMap 10.6, the results reveal the ~~distuibution~~distribution of high and low building ~~damages~~risks for different types of buildings ~~in~~at the community level in Shanghai (~~Fig.~~Figure 8). Apparently, the distribution of hot spots and cold spots for different types of buildings are quite different. For residential buildings, there are six hot spot areas and five cold spot areas. Most of the hot spot areas concentrate in the ~~ciy~~city center, except for one along the north coast of Hangzhou Bay. Further analysis of the commercial buildings indicates a significant hot spot south of the Suzhou Creek Mouth. Figure ~~7c~~8 shows five hot spot areas and two cold spot areas for office buildings with three hot spots located in coastal areas. Four hot spots of industrial buildings concentrate mainly in the north, while the city center is the main cold spot area because there are few industrial buildings ~~are~~ located there.

Overall, the city center is the hot spot area of flood ~~damages~~risk for the residential, commercial, and office buildings (Figure 8a, 8b and 8c). But in contrast, the city center is the cold spot area for the industrial buildings (Figure 8d). Wusongkou is ~~a hotspot for four different types of structures. Wusongkou floods in all four flood scenarios, and the~~affected by flooding with an expanding inundation area ~~expands as the retrun period expands. Another~~under increasing return-periods. One reason for this is that the density of ~~building~~buildings in Wusongkou is higher than in other areas.



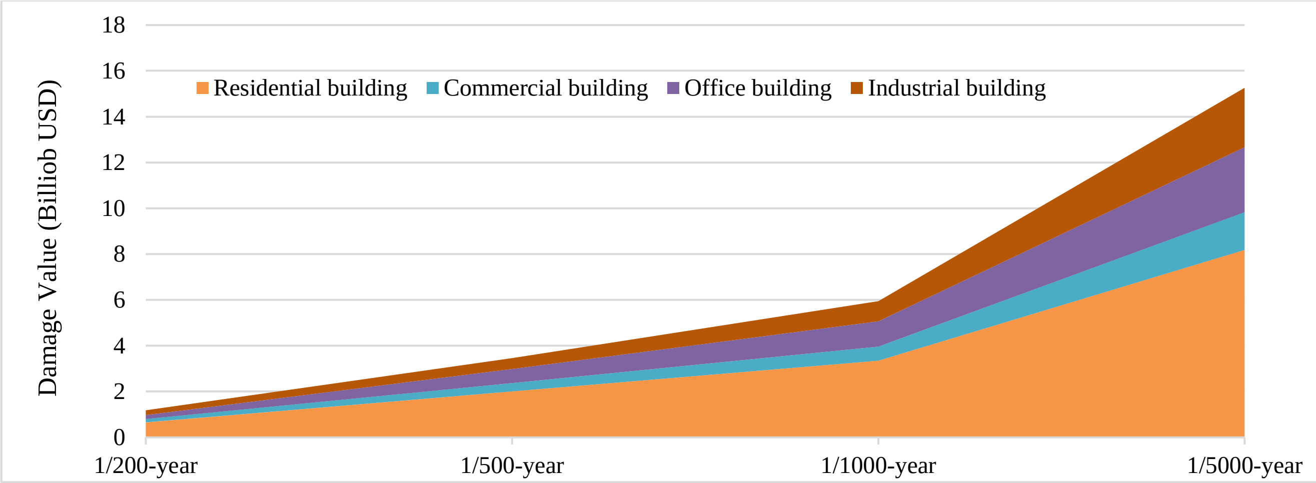
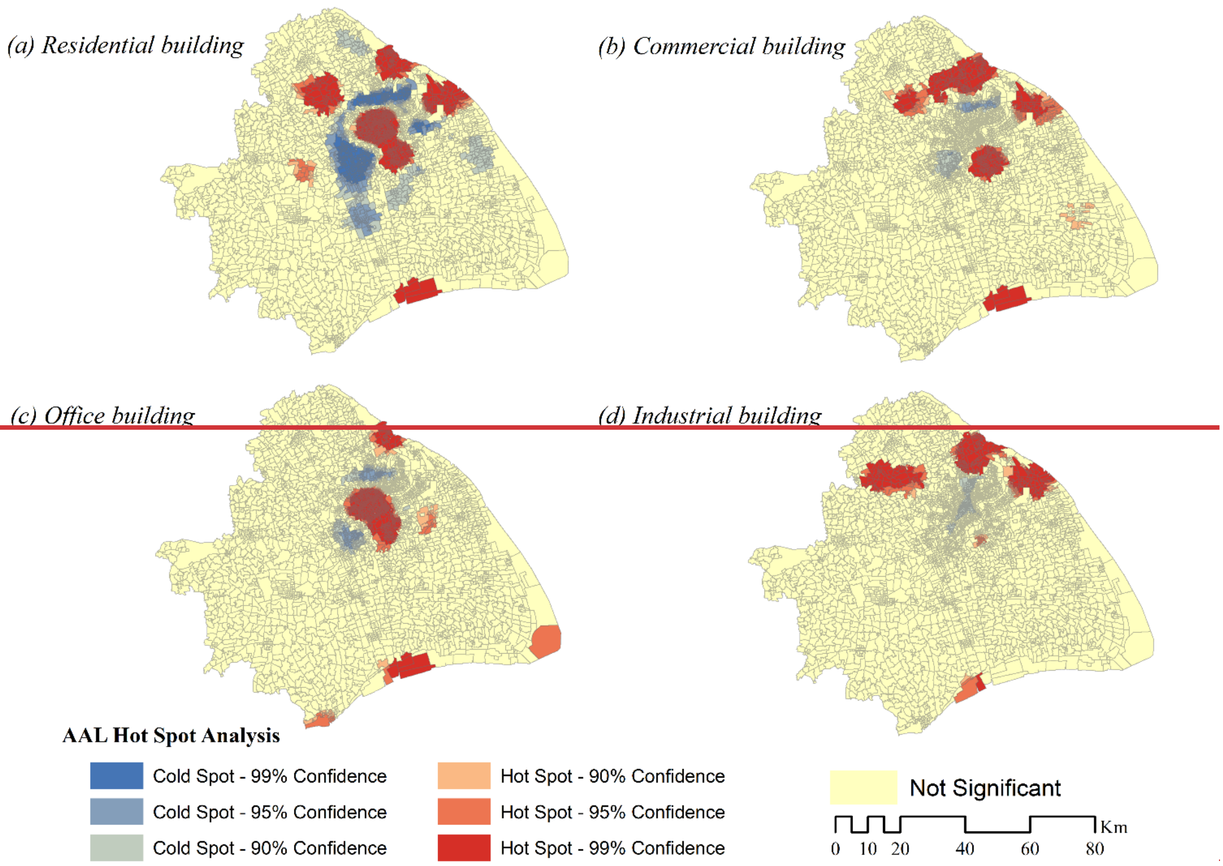


Figure 7. ~~Stage~~Probability-damage curve of extreme flooding for residential~~ building~~, commercial~~ building~~, office~~ building, industrial building and the sum of residential, commercial, office~~, and industrial buildings~~ in Shanghai~~.



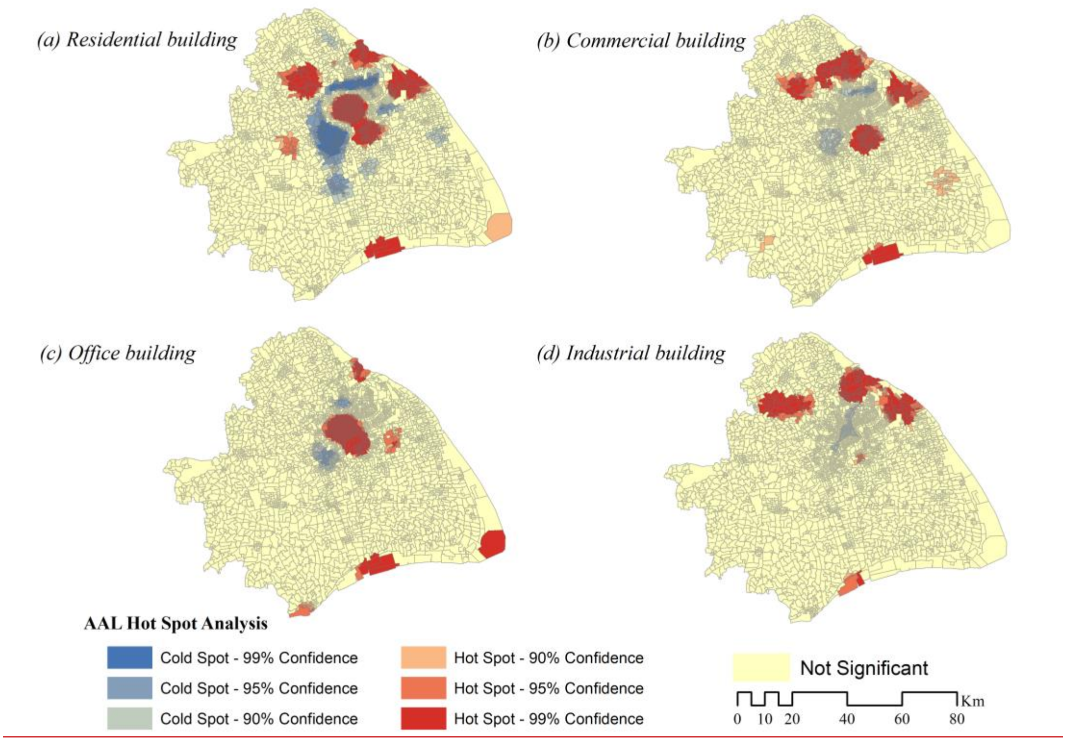


Figure 8. The hot spot analysis of the AAL for buildings at sub-district level in Shanghai.

~~4~~5 Discussion

~~4.1 Evaluation of the flood risk in Shanghai and implications for the future~~

5.1 Uncertainties and limitations

Our study shows that the damage to buildings in Shanghai grows exponentially with the decreasing likelihood of extreme flood scenarios. For instance, the resulting flood damages to residential, commercial, ~~workplace~~office, and industrial buildings under the 1/5000-year flooding scenario is more than ten times higher than the resulting damages ~~from~~for a 1/200-year flooding scenario. As shown in section ~~3~~4.1, the area along the Yangtze River Estuary, Hangzhou Bay, and Huangpu River are broadly flooded under the 1/200, 1/500, 1/1000, and 1/5000-year flooding scenarios. The results of the study show the importance of assessing the risk to extreme events on a regional scale at a high spatial resolution considering the differences in the exposed assets. The hot-spot clusters are distributed over the whole study area and vary from building type to building type. In some areas, the damage is driven mainly by high inundation depths (e.g., the ~~hotspot~~hotspots in the south), whereas other areas face a high risk due to the high vulnerability of the asset values. This ~~shows~~emphasizes the importance of assessing the different drivers of risk on the local scale for the selection and dimensioning of adequate protection measures against extreme events. ~~Concerning increases in climate change, the frequency and/or severity of acute climate hazards and the intensification of chronic hazards will increase the flood risks in Shanghai in the future (Woetzel et al., 2020b). The Sixth Intergovernmental Panel on Climate Change (IPCC) found that global precipitation will intensify and become more frequent in most regions with additional global warming (IPCC, 2021). Extreme precipitation events increased dramatically by 10% to 20% every 10 years during the 1951 - 2001 period in the Yangtze River basin, China (Wang and Zhou, 2005). Concerning Shanghai, after analysing Shanghai's hourly precipitation records (1916 - 2014), Liang and Ding (2017) found a rate increase of 1.5 and 1.8 for heavy precipitation events. Precipitation events now increase the possibility of seawall and levee failures in Shanghai. One 1/1000-year return period flood occurred in Shanghai in 2013~~Our assessment of the building damages is comparatively less than those in similar studies of Shanghai. The major reason is that we adopted the construction cost as the values of different buildings, while many other studies calculated the market value of buildings and the associated properties. For instance, Wu et al. (2019)

estimated the exposed building asset value in Shanghai to be roughly 304.1 billion USD with a total damage of approximately 32.2 billion USD for a 1/1000-year flood event. Shan et al. (2019) estimated the loss of the residential buildings to be 27.1 billion USD using house price data under a 1/1000-year flood event in Shanghai.

The integrative analysis of geospatial building asset maps, flood scenarios, and the stage-damage functions in the study makes it possible to assess the flood damage of buildings in the megacity Shanghai with a high spatial resolution. However, the accuracy of building asset values could still be improved. First, the adopted building data of location, footprint area, height and floors didn't consider the construction materials used and years built. Also, the data from 2017 is not very new, considering the fast development of Shanghai. Second, the classification of different types of buildings is quite straightforward based on the land use/land cover data. However, many buildings with multiple functions (e.g., shopping mall and offices) were identified to a single building type, which causes uncertainties of the building value. Third, existing studies' stage-damage functions for specific types of buildings are used to create the asset building ~~,~~ damages map for the flood risk assessment. The functions could be updated and tailored to more current and specific building conditions, particularly when estimating flood damages in the future (Ke, 2014). These constraints could be overcome by the inclusion of additional information about age, structures, and utilizations of the buildings. At the end, the methodology of four extreme flood scenarios in Shanghai were taken from published models in Shanghai that are induced by the current physical environment (Wang et al., 2019). However, sea level and heavy precipitation are driven by climate change, so that current flood hazard maps for Shanghai may be outdated in the next few decades. This means that a 1/1000-year event may have a much higher probability in the future and emphasizes the need for proactive adaptation measures. Therefore, climate change scenarios (e.g., sea-level rise, heavy precipitation) should be considered in future flood risk studies.

5.2 Future challenge and adaptation strategies

Future challenge, like extreme flooding events, will become more common in Shanghai. The historical data shows how Shanghai's extreme precipitation events have increased dramatically through time (Wang and Zhou, 2005; Liang and Ding, 2017), which increase the possibility of seawall and levee failures. One 1/1000-year return period flood occurred in Shanghai in 2013, for instance, breaking the highest crest record at Wusongkou Datum and causing levees to breakdown (Ke et al., 2018). ~~As a result~~Due to climate change, the frequency and/or severity of climate~~-~~-change~~, extreme flooding events~~ related hazards will ~~become more common in Shanghai.~~

~~Human activities can~~ also increase the ~~likelihood of flood risk in Shanghai. For instance, changes in land subsidence relative to the sea level rise could increase the flood risk to Shanghai. Due to the extraction of ground water, construction of high-rise buildings and underground projects (Gong et al., 2008), the average annual rate of land subsidence was 7 mm between 2007 and 2010 (Wu~~flood risks in Shanghai in the future (Woetzel et al., ~~2012), and then the rate decreased to 5 mm/year after 2010 (Yin, 2011). However, the maximum annual subsidence rate in Shanghai could still have a chance to reach 24.12 mm/year (Wang et al., 2012). On the other hand, sea levels will rise a maximum of 86.6 mm, 143mm, 185.6 mm, and 433.1 mm by 2030, 2040, 2050, and 2100, respectively in Shanghai (Wang et al., 2012; Wu et al., 2012). Future flood damage in Shanghai will be exacerbated by increased precipitation, land subsidence and sea level rise, which further shows the need to adapt to the (currently) low probability-high impact events.~~2020b).

~~4.2 Adaptation strategies to extreme floods in Shanghai~~

~~Effective~~Reviewing these findings from our risk assessment, we highlight the following two points, which in our opinion, might be helpful for advancing the flood risk assessment in the future in Shanghai, or even more broadly in China.

First, the parameters (such as flood hazard maps, damage models, exposure data, etc.) to help perform the flood risk assessment in Shanghai, which are available to the public, are inconsistent and scarce. Flood hazard maps can be an example. Under the current physical environment, coastal flood scenarios with combined effects (sea-level rise, land subsidence, and storm surges) in 2030, 2050, and 2100 that inundate 1.5 %, 37 %, and 50 % of Shanghai, respectively (Wang et al., 2012), have been simulated using a 2D hydrodynamic model (MIKE 21 flow model). On the other hand, fluvial floods from the Huangpu River shows the different inundation area reaches 0 km^2,111.30 km^2, 124.73 km^2, 143.74km^2, 177.96 km^2, and 195.77 km^2 under 1/20, 1/50, 1/100,1/200,1/500, 1/1000-year flood event in Shanghai under the present physical environment (Yin et al., 2013). In our study, the inundation area is 9%, 16%, 24%, and 49% of Shanghai under 1/200, 1/500, 1/1000, and 1/5000-year, respectively. Although we are doing academic research work, it is still important to translate academic findings to everyday language so that inhabitants, stakeholders, and policymakers can improve their capacity for coping with flooding and adapting to it.

Second, effective adaptation to increasing flood risks requires an integrated climate response strategy, which shall include a broad scope of intervention measures such as urban planning, structural flood management measures, early warning systems, nature-based solutions, flood awareness and risk financing instruments (Yang et al., 2015; Jongman, 2018~~). Urbanization~~; UN, 2020). In table 6, we list potential hard, soft, and hybrid implementation measures and their assumed efficacy in Shanghai. On the other hand, urbanization as a confirmed trend in the fast-developing coastal city may increase asset exposures to floods, but can also offer opportunities for improving flood risk management (Garschagen and Romero-Lankao, 2015). A top-down urban master plan, including land use planning, control of runoff, access to data and information, etc. should be updated, by the Shanghai Municipal Government, to involve advanced risk management measures (Zhou et al., 2017). For instance, in its Master Plan 2017~~—~~-2035, Shanghai is going to further develop its five new district centers at Jiading, Songjiang, Qinpu, Fengxian and Nanhui. These five district centers are planned to be nodal areas in Shanghai and provide more public services for the growing population. However, based on ~~the flood scenario maps~~our findings, the Songjiang-Qingpu low-lying area is a hot spot of flood damages. Therefore, future flood protections in these locations, particularly the drainage system and the building structures, must be designed to a higher standard.

~~The hard, soft and hybrid measures must be considered in implementing the planned urbanization process (Table 5). It has been widely proven that the hard strategies can effectively reduce the flood hazard probability. For instance, the direct economic flood loss significantly decreased after a series of integrated flood management followed a mega-flood across central and south China in 1998 (Bryan et al., 2018). The protection level of existing seawalls and levees along the Changjiang Estuary, Hangzhou Bay and Huangpu River do not provide adequate protection to meet Shanghai's current flood defense standards. These structures are not sufficient to protect the increasing urban assets considering the combined impacts of climate change, land subsidence and typhoon events.~~

~~Table 5. Comparison of flood adaptation measures in Shanghai~~

Table 6. Flood adaptation measures and their potential effecting.

Categories of measures	Specific measures	Effects	~~Suitability~~Assumed efficacy
Hard measures	Seawall and levees	Protects areas from being flooded or eroded by extreme storms, floods, astronomical tides, and sea~~-~~-level rise, particularly in low lying areas.	Raise levees and construct a flood barrier in Wusongkou which could lower the flood pressure from Huangpu River (Wang et al., 2011).
	Drainage system	Rapid rainfall discharge to improve transport and safeguard property.	The drainage system should protect Shanghai under 50-year flood scenario. The capacity should be enhanced to the probability period of 100 years in the vulnerability (UPLR, 2018).
	Reservoir	Save part of the precipitation and reduce flood pressure in downstream or lowland areas.	Adjust stock by season or weather forecasting, relieve the pressures of the city flood management during floods.
	Channel	Relieve the flood pressure and speed up drainage within the city.	Ensure that the dam functions could be running on the Huangpu River and Suzhou River.
Soft measures	Warning system	Enable stakeholders or households to prepare for the extreme climate and react to mitigate it.	Could be used in Shanghai, especially preventing people from putting their lives in extreme flood event.

	Dry proofing	Being watertight with all elements substantially impermeable to the entrance of flood and with structural components having the capacity to resist flood loads (FEMA, 2013).	Help the household, especially for householdhouseholds that have experienced regular flooding, to stop the floodwater from their entrance door.
	Wet proofing	Allow water to enter the building but minimizing damage.	Minimizing the damage of property in the building in the flood-prone area.
	Detention and retention areas	Alleviate flood peak by artificially made storage areas (Glavan et al., 2020)	Based onAdapted Sponge City project, to capture, purify and store more water (Griffiths et al., 2020).
	Emergency relief	Personnel evacuation and transfer of property from short-term extreme precipitation.	Adapted in Shanghai, especially residents who lived in inundation areas in the extreme flood scenario.
	Insurance	Increase support for people and groups in financial resilience to floods (Surminski and Oramas-Dorta, 2014).	Meet the needs of vulnerable individuals, households and micro, small, and medium-sized enterprises (MSMEs) in Shanghai (Hess and Fischle, 2019).
	Wetlands	Provide valuable flood storage, buffer storm surge, and assist in erosion control (EPA, 2021). Absorb and slow down the floodwater from storm surge.	The wetland on the north of Hangzhou Bay, the mouth of Yangtze River should be protected to slow down the erosion from the storm surge and sea--level rise.

Particularly for the hot spot areas where huge damages are expected, extra coping strategies must be taken seriously into consideration. For instance, underground water storage and pumping facilities are necessary for the city center, and these shall be systematically planned together with detention and retention regions on the ground. A feasible and practical way is to make use of the old air defense facilities and some underground parking lots (Chen et al., 2018). Researchers have mentioned, and we also recommend, to enhance the bank and build a water wall in the estuary area of the Huangpu River (Chen et al., 2018), because of the large population and assets which deserves a high level of protection. Developing such a flood barrier and upgrading the Huangpu River floodwalls to a protection standard of a 1/1000-year flood event in Shanghai could significantly reduce the expected annual flood damages to 0.07 - 0.5 billion/year in 2100 for the RCP (representative concentration pathway) 4.5 scenario (Du et al., 2020).

Potential flood risks coming from extremely low-probability storm surges can be further reduced by combining the soft strategy. For instance, dry proofing and wet proofing, as well as the coastal wetland strategies can be combined to form a hybrid strategy in specific regions. Although soft measures on their own cannot maintain the future flood risk at a low level, they can play a critical role in reducing potential damages. Additionally, the soft measures such as maintaining coastal wetlands can enhance social welfare by providing multiple ecosystem services. Challenges may rise in that homeowners are on average not inclined to install soft strategies due to the high costs for individual households, even if they live in flood plains (De Ruig et al., 2020). On the other hand, extreme flood scenarios often cause more serious flood damage to households because they occur very soon and leave less time for responding (Yang et al., 2018b). Thus, an efficient forecasting and early warning system is needed which could help individuals, businesses, communities and government leave dangerous zones, transfer house property and improve preparedness with sufficient lead time (UN, 2020). Insurance also plays a very important role in the support of various people and groups to recover from flood hazards, especially for the high-risk regions.

4.3 Uncertainties and limitations of the assessment

The integrative analysis of geospatial building asset maps, flood scenarios and the stage-damage functions in the study makes it possible to assess the flood damage of buildings in the mega city Shanghai with a high spatial resolution. 6However, the accuracy of building asset values could still be improved. First, the adopted building data of location, footprint area, height and floors didn't consider the construction materials used and years built. Also, the data from 2013 is not very new, considering the fast development of Shanghai. Second, the classification of different types of buildings is quite straightforward based on the land use/land cover data. However, many buildings with multiple functions (e.g., shopping mall and offices) were identified to a single building type, which causes uncertainties of the building value. Third, existing studies' stage-damage functions for specific types of buildings are used to create the asset building loss map for the flood risk assessment. The functions must be updated and tailored to more current and specific building conditions, particularly when estimating flood damages in the future (Ke, 2014).

Our assessment of the building damages is comparatively less than those in similar studies of Shanghai. The major reason is that we adopted the construction cost as the values of different buildings, while many other studies calculated the market value of buildings and the associated properties. For instance, Wu et al. (2019) estimated the exposed building asset value in Shanghai to be roughly 304.1 billion USD with a total damage of approximately 32.2 billion USD for a 1/1000-year flood event. Shan et al. (2019) estimated the loss of the residential buildings to be 27.1 billion USD using house price data under a 1/1000-year flood event in Shanghai.

The four extreme flood scenarios in Shanghai were taken from published models in Shanghai that are induced by atmospheric, hydrology, and coastal models (Wang et al., 2019). However, the climatic impact-drives (CIDs) such as the frequency of sea level rise, heavy precipitation, and pluvial floods can be altered as a result of various greenhouse gas (GHG) emissions. For example, every 0.5°C rise in global warming increases the severity and frequency of heat extremes, such as heatwaves and heavy rains, as well as agricultural and ecological droughts in some regions (IPCC 2021). Therefore, the CIDs (e.g., sea level rise, heavy precipitation) should be considered in future flood simulation models and studies.

5 Conclusion

This study presents an integrated impact model of flood damage to buildings based on extreme flooding scenarios in Shanghai. The results show that the inundation area is significantly larger in the low probability of extreme-high impact flood scenarios. In all the four considered scenarios, the areas near the Huangpu River and along the shorecoastal areas are always the affected with building damages. The central downtown areas of Shanghai have a high risk of being exposed to and affected by extreme floods, partly because of its high building density. Besides that, the Songjiang-Qingpu low-lying area in the west of Shanghai has been recognized as a noticeable area to be flooded under a 1/5000-year flood scenario. This calls for special concerns in the near future because the Songjiang-Qingpu area is planned to become an important sub-center node.

Residential buildings account for the mostThe total asset value for the four building types is 3149 billion USD while the total AAL is 21.9 million dollars. Meanwhile, residential buildings face the highest damage rates of the four types of buildings, accounting for 4756 percent of the total AAL, followed by office, industrial, workplace, and commercial buildings, respectively. The total asset value for the four building types is 3963 billion USD while the total AAL is 22.2 million dollars. It is also noticeableIn comparison to other types of buildings, the results show that the total damage for the four types of buildings is 18 billion USD in 1/5000-year scenario, residential buildings are significantly vulnerable to extremein all flooding in contrast to the three other types of buildingsscenarios, which requires attention because residential buildings are a big part of people's daily life.

The presented method offers the possibilitya possible process to estimate the damage values for residential, commercial, workplaceoffice, and industrial buildings in Shanghai under extreme flooding. The hydrodynamic model, damage estimation, and risk evaluation are all methodological components that could be implemented to other cities to analyse building damage under extreme flood events. It increases the accuracy and details of flood damage estimates for different types of buildings by considergingconsidering the direct damage of buildings. The dynamic linkage between the extreme flooding scenarios and the distribution of asset values of the four different types of buildings allows the evaluation of the spatial distribution of flood damages, which would be valuable for individual real eastateestate managers and also for the city government.

Appendices

Table A1. Exposed values of different types of buildings under the four flood scenarios in Shanghai (Unit: Billion USD).

Building types	**Flood scenarios (Return Periods)**			
	1/200	**1/500**	**1/1000**	**1/5000**
Residential building	22	63	97	217
Commercial building	3	6	10	25
Office building	7	22	35	78
Industrial building	7	16	25	66
Total	39	107	166	386

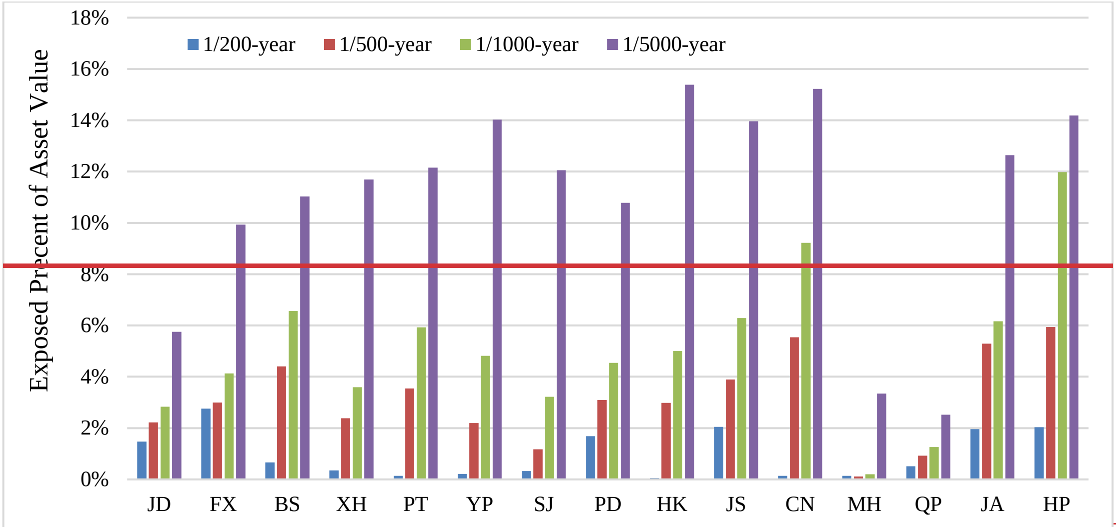


Figure A1. Exposed percentage of residential, commercial, office and industrial buildings to extreme flooding under four return period scenarios in each district.

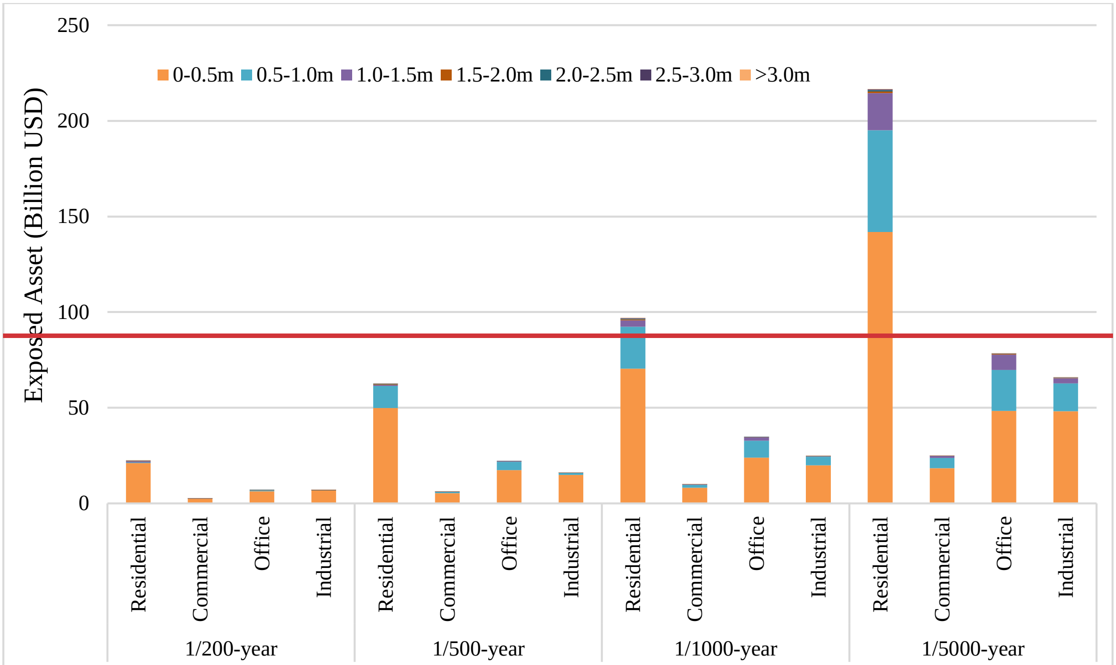
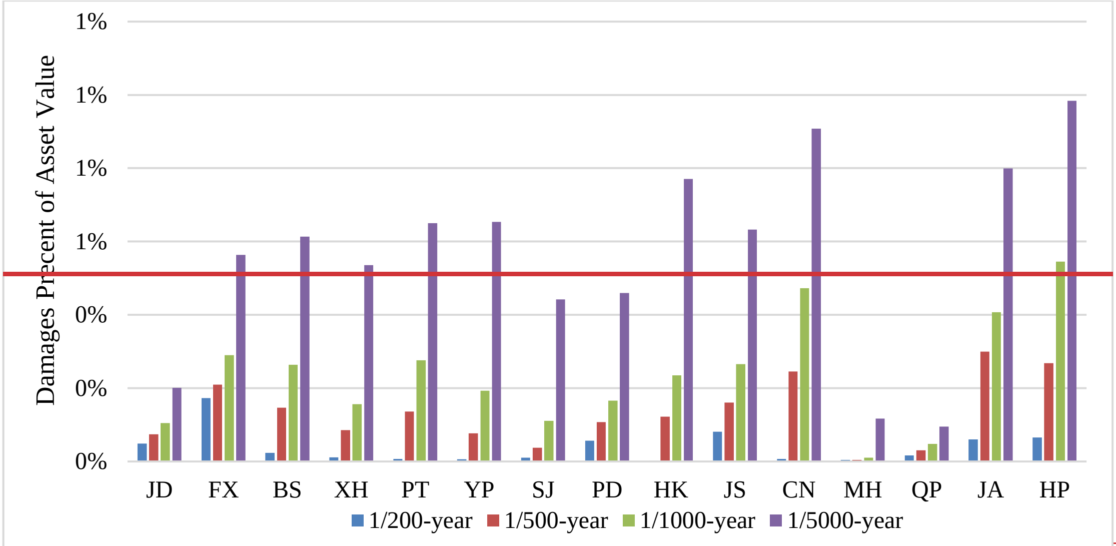
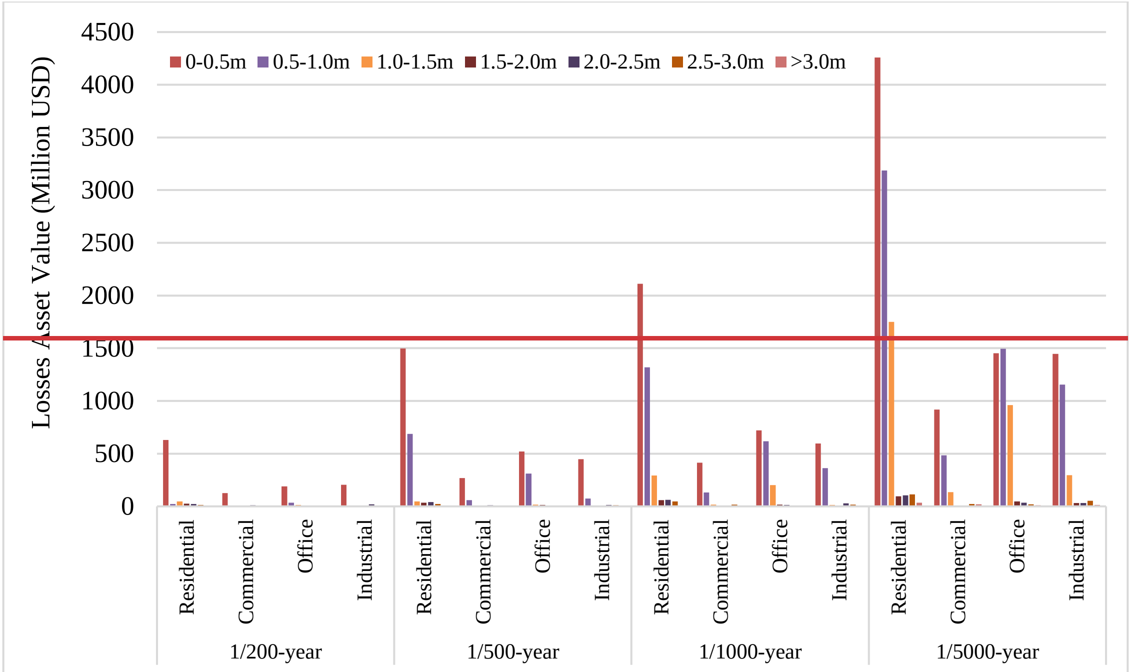


Figure A2. The exposed asset categorized by different inundation depths.



~~**Figure A3.** Damage percentages of residential, commercial, office and industrial buildings to extreme flooding under four return period scenarios in each district.~~



~~**Figure A4.** The losses asset in different water depths.~~

Data availability

Data used in this study are available from the first author upon request.

Author Contributions

J.T. ~~analyzed~~analysed the data, conceived, and wrote the paper; J.W. and L.Y. conceived and co-wrote the paper; A.R., M.G. and S.Y. reviewed and improved the analysis and manuscript; M.Z. and L.W. provided the simulation results of the extreme flood scenarios.

Funding

This research was funded by the National Natural Science Foundation of China (Grant No. 42171080, 41771540, 41871200) and the National Key Research and Development Program of China (Grant No. 2017YFC1503001).

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