

LETTER • OPEN ACCESS

A multi-dimensional integrated approach to assess flood risks on a coastal city, induced by sea-level rise and storm tides

To cite this article: Xu Lilai *et al* 2016 *Environ. Res. Lett.* **11** 014001

View the [article online](#) for updates and enhancements.

Related content

- [Flood damage costs under the sea level rise with warming of 1.5 °C and 2 °C](#)
S Jevrejeva, L P Jackson, A Grinsted *et al.*
- [Sea-level rise and storm surges, relationship status: complicated!](#)
T Wahl
- [Over the hills and further away from coast: global geospatial patterns of human and environment over the 20th–21st centuries](#)
Matti Kummu, Hans de Moel, Gianluigi Salvucci *et al.*

Recent citations

- [Assessing Hazard Vulnerability, Habitat Conservation, and Restoration for the Enhancement of Mainland China's Coastal Resilience](#)
Muhammad Sajjad *et al*
- [Assessing the inundation risk resulting from extreme water levels under sea-level rise: a case study of Rongcheng, China](#)
Aiqing Feng *et al*

Environmental Research Letters



LETTER

OPEN ACCESS

RECEIVED
2 July 2015

REVISED
11 December 2015

ACCEPTED FOR PUBLICATION
16 December 2015

PUBLISHED
8 January 2016

Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



A multi-dimensional integrated approach to assess flood risks on a coastal city, induced by sea-level rise and storm tides

Xu Lilai^{1,2}, He Yuanrong^{1,3}, Huang Wei^{1,2} and Cui shenghui^{1,2,4}

¹ Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, People's Republic of China

² Xiamen Key Lab of Urban Metabolism, Xiamen 361021, People's Republic of China

³ College of Computer and Information Engineering, Xiamen University of Technology, Xiamen 361024, People's Republic of China

⁴ Author to whom correspondence should be addressed

E-mail: llxu@iue.ac.cn, heyuanrong@126.com, whuang@iue.ac.cn and shcui@iue.ac.cn

Keywords: sea-level rise, storm tide, flood risks, coastal urban system, multi-dimensional assessment

Supplementary material for this article is available [online](#)

Abstract

Coastal cities are vulnerable to increasing flood risks caused by the combination of sea-level rise (SLR) and storm tides (STs), due to their low-lying topography and densely distributed assets. Faced with this challenge, comprehensive and integrated flood risk information is vital and fundamental for the planning, implementation and optimization of coastal risk adaptation and management. The goal of this study is to propose an integrated assessment approach to sea-level rise- and storm tide-induced flood risks on a coastal urban system by employing a wide range of indicators across ecological, physical and socio-economic dimensions. To demonstrate its applicability, a case study of Xiamen City, China was performed. The results show that this approach is applicable for assessing the specific flood risks on urban ecological, physical and socio-economic system, respectively. Under 4.75 ~ 5.86 m extreme sea-level, 11 600 ~ 17 100 ha land and 440 000 ~ 720 000 population will be flooded in Xiamen City, with flood risks—measured by monetary—of 858 ~ 1134 million, 4744 ~ 10 590 million and 2537 ~ 4175 million RMB of ecological, physical and economic systems, respectively. Coastal ecosystem will suffer flood risks on ecological services, mainly regulation service; and wetland is the dominant ecosystem that will be affected, which imply urgent needs to wetland conservation. Indirect risk on economy accounts for a large proportion of total risks, and should be given adequate weight in the decision-making process.

1. Introduction

Throughout the world, climate change is one of the most serious challenges facing human society, and consequent sea-level rise (SLR) and extreme water events such as storm tides (STs) are becoming major hazards for coastal cities [1–3]. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) projected that global mean sea-level will continue to rise during the 21st century, and the rate of sea-level rise will very likely exceed that observed during 1971–2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets [4]. The frequency and intensity of storm surges are also changing [5–7]. The simultaneous

occurrence of SLR and STs will lead to extreme flooding in coastal cities, causing potentially severe consequences for urban economic, ecological and infrastructure systems [8–11]. These dangers will be especially destructive to low-lying coastal cities in developing countries because of their high population density and rapidly growing economies along with their limited abilities to cope with climate change effects [12]. Therefore, integrated assessment of the impacts of sea-level rise and storm tide is vital for, and fundamental to, the planning, implementation and optimization of coastal risk management, since it comprises the basic information needed for formulating strategies to adapt to risks and minimize their possible consequences.

An increasing body of research concerning the flood risks on coastal area due to sea-level rise and storm surges has been conducted at different spatial extent. At the global scale, the population and the gross domestic product (GDP) are the indicators most widely used to describe flood exposure and risk in the current literature. For instance, Hinkel *et al* applied national population and GDP dataset to develop the Dynamic Interactive Vulnerability Assessment (DIVA) model for quantifying the global flood damage and adaptation costs under 21st century sea-level rise [13, 14]. Hallegatte *et al* translated the exposed population into exposed assets, quantifying the flood losses in the global 136 largest coastal cities [1]. Ecosystem loss, especially wetland loss, is also an important aspect studied at global scale. Nicholls conducted a global scenario study on coastal flooding and wetland loss, and the results indicate that coastal wetlands will be lost due to sea-level rise in all world futures with 5%–20% losses by the 2080s in the IPCC FA1FI world [15]. According to the research carried out by McFadden *et al* on coastal wetlands, there will be a global loss of 33% and 44% under a 36 cm and 72 cm sea-level rise, respectively, in the period of 2000 to 2080 [16]. At a national scale, researchers are mainly concerned about identifying coastal areas which may face either temporary flooding or permanent inundation, and they often study high-resolution geospatial datasets to determine what areas are likely to be submerged [17]. Weiss *et al* and Zuo *et al* applied geospatial dataset to make the national assessments of submerged coastal area for USA and China, and the results reveal that the majority of coastal cities will potentially suffer substantial flooding induced by sea-level rise [18, 19]. At a city scale, indicators and datasets are more available for coastal flood risk assessment, and results of researches are thus more specific and accurate. Lichter and Felsenstein conducted a GIS-based approach to estimate the direct risks of sea-level rise and extreme flood at Tel Aviv and Haifa, Israel, including the exposed residential, non-residential buildings and indoor machinery [20]. Hallegatte *et al* emphasize both direct and indirect impacts in flood risk assessment; their research at Copenhagen attempted to assess not only the direct flood losses on building structure and contents, but also indirect economic losses on production sector and housing services, due to SLR and STs [21]. Generally, previous studies at global and national scale have mapped the anticipated flood areas attributable to extreme water events, and assessed the direct risks as well as wetland losses; however indicators such as population and GDP are too simplified to truly illustrate the risks. Studies at city scale have broaden the scope of indicators, and attempted to explore the indirect risks; however, how coastal ecosystem is affected at city scale is not well studied, and little study has integrated these indicators of ecological, physical and socio-economic dimensions to quantify the

comprehensive direct and indirect flood risks of sea-level rise and storm surges on coastal urban systems.

To address this deficiency, the present study develops a multi-dimensional approach to coastal flood risk assessment, integrating a wide range of indicators across ecological, physical and socio-economic aspects. To demonstrate its applicability, a case study of Xiamen City, China was performed.

2. Data and methods

2.1. Multi-dimensional integrated assessment framework

The framework of the multi-dimensional integrated assessment approach is shown in figure 1. To assess the flood risks induced by the combination of sea-level rise and storm tide comprehensively, a coastal city can be treated as a system consisting of three sub-systems—ecological, physical and socio-economic; thus the flood risk for each sub-system can be estimated separately. As shown in the framework, the coastal flood risks in our model span a wide range of dimensions. Nevertheless, the limitations of the model and the lack of comprehensive data preclude the representation of a complete set covering all aspects that might impact coastal cities.

- a. Natural ecosystem. Generally, natural ecosystems provide four kinds of services for human society: supply service—providing the essential resources of food, water, shelter, and energy; environmental regulation service—mainly including gas regulation, climate regulation, water regulation, waste treatment; environmental support service—soil formation, biodiversity conservation; and cultural service—providing aesthetic landscape [22]. Ecosystem services can be quantified by ecosystem services values that are measures of how important ecosystem services are to people—what they are worth in the monetary way [23]. In this study, the impacts of flooding on ecosystem service—including supply, regulation, support and cultural services in inundated areas—are calculated to represent ecological risks.
- b. Physical system. The concentration of buildings and infrastructure in urban area increases the exposure of an urban system to the impacts of climate change. Here, flood damages to buildings—including structures, indoor property (e.g., equipment and furnishings)—and flood damages to key urban infrastructure such as roads and electricity facilities, are assessed in order to represent physical risks.
- c. Socio-economic system. As for the socio-economic system, the population that would be exposed to risk in the inundated areas is calculated in order to assess social risks, and the

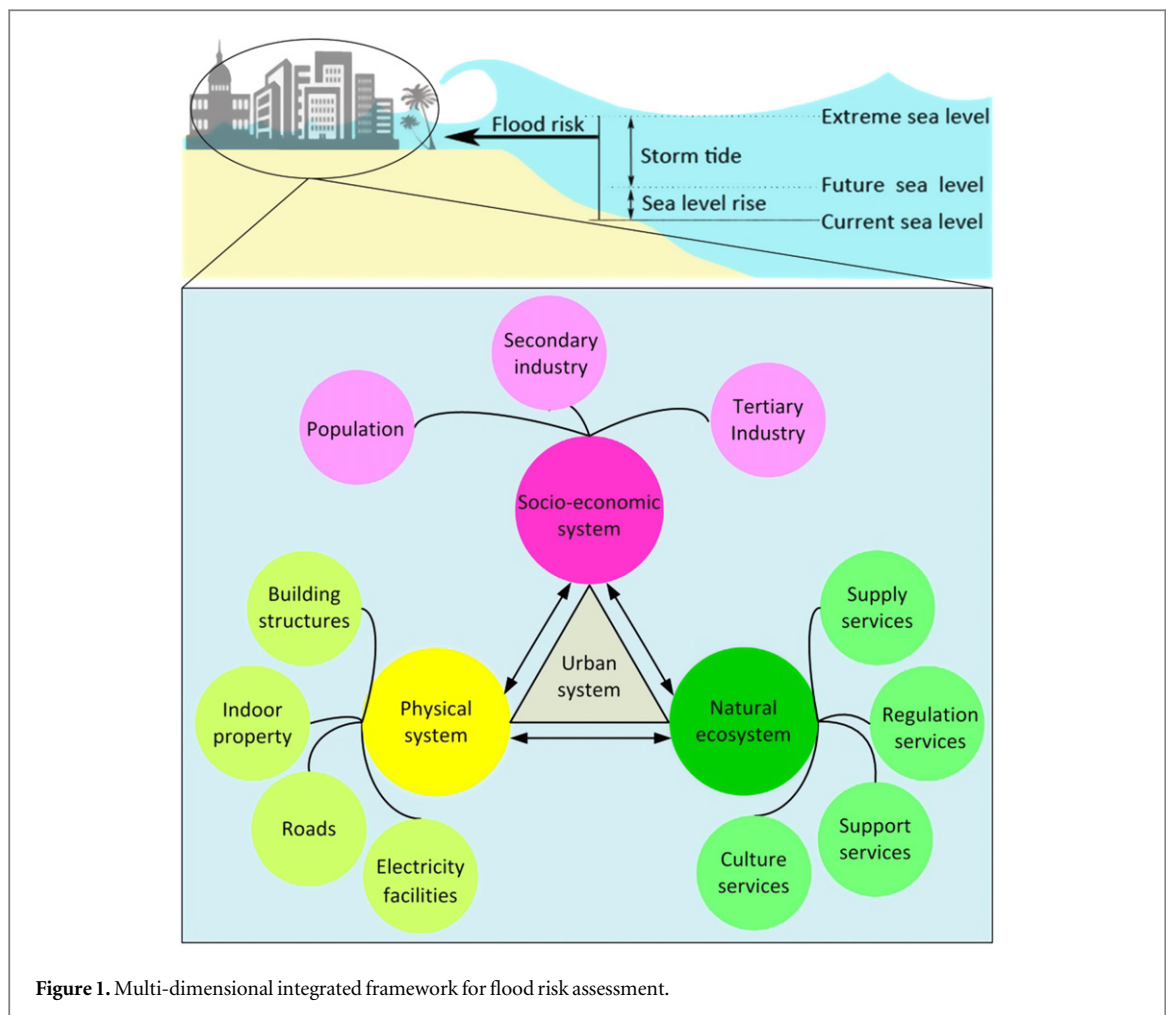


Figure 1. Multi-dimensional integrated framework for flood risk assessment.

Table 1. Introduction of frameworks/models used for coastal flood assessment.

Framework/Model	Description	Elements	Indicators
Framework proposed in this study	A multi-dimensional approach to coastal flood risk assessment, integrating a wide range of indicators across ecological, physical and socio-economic aspects. Information obtained by this approach distinguishes between direct and indirect impacts, and is more complete, systematic and specific.	Ecological risk Physical risk	Ecosystem services, building structures, indoor property, roads, electricity facilities, population, industry
Global Vulnerability Assessment (GVA) [24]	The aim of GVA is to provide a regional to global assessment of socio-economic and ecological impacts of sea-level rise.	Socio-economic risk Population risk Eco-system loss	People in the hazard zone, average annual people flooded, wetland loss, rice production at change
Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model [25]	An integrated assessment model of a wide range of climate change impacts, including the sea-level rise impact assessment.	Agriculture impacts Land loss Coastal protection	Dry land loss, coastal protection costs, wetland loss
Source-Pathway-Receptor-Consequence (SPRC) model [26, 27]	It provides a better instantaneous representation of the physical flooding process with regard to the propagation and consequences of a particular flood event.	Wetland loss People Property Environment	Loss of life, economic damage, pollution

indirect impacts of flooding on secondary and tertiary industries are calculated, to represent economic risks.

The approach presented here is developed based on previous well-known conceptual framework, but it is also different and advanced. The comparison of our framework with previous frameworks/models is shown in table 1.

2.2. Dataset

The dataset required for the assessment model is summarized in table S1. The data requirements for this model are not limited to those shown in this table, but depend on the actual situation of any given city to be studied. The dataset generally consists of hydrological, geographical and statistical data. Hydrological data are mainly used for building extreme-water scenarios, and other two types: for identifying the flood area and for calculating flood risk.

2.3. Design of extreme sea-level scenarios

Extreme sea level is calculated from a combination of sea-level rise and storm tide; here, sea-level rise accounts for both eustatic sea-level rise and vertical land movement (equation (1)).

$$ESL = SLR + ST \quad (1)$$

where ESL is extreme sea level; SLR is local sea level rise; ST is future storm tide.

$$SLR = SLR_e + VLM \quad (2)$$

where SLR_e is the eustatic sea-level rise; VLM is the vertical land movement.

A number of sea-level rise forecasts have been published over the past several years, their results concluded that global sea-levels have been increasing and are projected to continue rising [4]. Under this global trend, there are significant regional or local differences in sea level change owing to changes in ocean circulation and atmospheric pressure [21]. For example, sea-level projection conducted by Slangen *et al* yields a global mean sea-level rise of 0.54 ± 0.19 m and 0.71 ± 0.28 m by the end of 21st century; regionally however, changes reach up to 30% higher in coastal regions along the North Atlantic Ocean and along the Antarctic Circumpolar Current, and up to 20% higher in the subtropical and equatorial regions [28]. Moreover, differential vertical ground motions could aggravate or moderate the impacts of local sea level changes, especially the land subsidence that amplifies the relative sea level [29]. Hence, local sea-level rise scenarios used in the present approach account for both eustatic sea-level rise and vertical land movement.

A storm with low atmospheric pressure and strong winds passing over the sea can cause the increase in water level, leading to a storm surge. If the storm surge coincides with an astronomical high tide—the regular change of water levels caused by the gravitational

attraction of the Moon and sun, without any atmospheric influences—a storm tide may emerge [30]. The frequency of storm tide is measured by return period; for example, if the 100-year storm tide is at 1.50 m, it represents that there is 1% probability that has a storm tide higher than 1.50 m every year. Long-term and high quality tide gauge records can be used to calculate the return period, and the calculation method can refer to Coles *et al* and Gumbel [31, 32]. It also should be noticed that extreme water levels vary along the coastline due to the coastal bathymetric and topographic effects [33]. In the case study, however, we assume that storm tide will exhibit a constant water level along Xiamen coastline due to data deficiency, as well as for simplifying the calculation.

2.4. Flood area extraction

High resolution topographic dataset is the basis of flood area extraction, and its provenance includes ground surveys, Lidar and photogrammetry. The original topographic data needs to experience digitization, and then is applied to create the high-resolution digital elevation model (DEM) which is suitable for the flood modeling; the digitization and DEM generation can be conducted by ArcGIS software [34]. Based on this built DEM, the flood area can be extracted according to the following two criteria: (1) cells of the DEM with elevation values less than or equal to a particular extreme sea level, and with locations adjacent to the sea or connected to cells of equal or lesser level that are adjacent to the sea; (2) cells of the DEM with missing or inadequate protective seawalls and levees. After the flood area is identified, a land-use layer generated from the retrieval of Landsat-spot or other remote sensing images will be overlaid with the flood-area maps to characterize the land-use types in the flood areas. In addition, coastal flood induced by combination of sea-level rise and storm tide is a complex and dynamic process, depending not only on topography but also landscape in the urban environment [33, 35], nevertheless the impact of landscape on flooding has yet to be well studied, and therefore the dynamics caused by these urban landscapes are not considered in this study.

2.5. Calculation of flood risks

In the multi-dimensional integrated assessment model, flood losses on physical systems are calculated by multiplying the exposure information by the corresponding vulnerability curve that graphically represents the relationship between expected losses and varying depths of flood water. Flood exposures are calculated to represent flood risks for both ecosystems and socio-economic systems, because there is no accurate method of determining separate vulnerability curves for the two systems.

2.5.1. Ecological risk

We refer to the methods developed by Costanza *et al*, Xie *et al* and Shi *et al* for the calculation of ecosystem service values exposed in the flood areas (equation (3)) [36–38]:

$$ESV = \sum_i \sum_f A_i \times V_{if} \quad (3)$$

where ESV refers to the total ecosystem service value; i refers to the land-use type; f refers to the ecosystem service type; A_i is the area (ha) for land-use type i ; V_{if} is the per-unit value (value $\text{ha}^{-1} \text{a}^{-1}$) of ecosystem service type f for land-use type i .

2.5.2. Physical risk

By overlaying the spatial distribution maps of major physical elements with the flooded area layers for the different extreme sea-level scenarios, maps of the physical systems exposed to flood can be extracted, from which the monetary values of these exposed physical elements can be calculated. Flood damages to physical elements can also be estimated by multiplying exposures by their respective vulnerability curves.

For building structures, indoor property, we assume that (1) each floor has the same size and shape; (2) only the major types of buildings—residential, office, commercial and industrial—are to be used in the calculation, and all of the building types share the same vulnerability curves. Therefore, flood damages to the structure and to the interior of each floor of each building can be calculated with equations (4) and (5):

$$L_s = C_s \times A_f \times V_s(h) \quad (4)$$

where L_s is the flood loss for the structures; C_s is the construction cost of a building per-unit area; A_f is the area of a single floor; and $V_s(h)$ is the damage rate of a structure at submerged depth h .

$$L_p = C_p \times A_f \times V_p(h) \quad (5)$$

where L_p is the flood loss for the indoor property; C_p is the property value per unit area; and $V_p(h)$ is the damage rate for the indoor property at submerged depth h .

Each flooded road can be divided into several sections according to flood depth; equation (6) shows the flood loss calculation for a single road.

$$L_r = \sum_i C_r \times \text{Len}_i \times V_r(h_i) \quad (6)$$

where L_r is the flood loss for a single road; C_r is the construction cost per unit length of the road; Len_i is the length of road section i ; and $V_r(h_i)$ is the damage rate for road section i at submerged depth h .

For electricity facilities, the flood losses for a single substation and transmission tower can be calculated according to equations (7) and (8):

$$L_{ss} = C_{ss} \times V_{ss}(h) \quad (7)$$

where L_{ss} is the flood loss for a single substation; C_{ss} is the average construction cost per substation; and

$V_{ss}(h)$ is the damage rate for a substation at submerged depth h .

$$L_{tt} = C_{tt} \times V_{tt}(h) \quad (8)$$

where L_{tt} is the flood loss for a transmission tower; C_{tt} is the average construction cost per transmission tower; $V_{tt}(h)$ is the damage rate for a transmission tower at submerged depth h .

2.5.3. Socio-economic risk

Population census data at the community level is allocated to the corresponding administrative boundary, from which a spatial population density map can be generated. By overlaying these data with the flood-area maps, information for the population exposed to each extreme water event can be obtained according to equation (9):

$$P = \sum_i D_i \times A_{ci} \quad (9)$$

where P is the population exposed to flooding; D_i is the population density of community i ; and A_{ci} is the flooded area of community i .

Sea-level rise and storm tide also indirectly impact urban economic activities through their effects on ecosystems and physical systems. In this study, we employed the added values of secondary and tertiary industries as indicators to model an urban economic system, and assessed the indirect flood risks on the economic systems. Annual statistical added values for each industrial park were allocated to their respective spatial boundaries, in order to generate a map of added value per square km. These values were extracted from the flood maps; the flood risk on secondary industries can be calculated according to equation (10):

$$E_I = \sum_i ADI_i \times A_{Ii} \quad (10)$$

where E_I is the added value of a secondary industry exposed to flooding; ADI_i is the per-area-unit added value of industrial park i ; and A_{Ii} is the flooded area of industrial park i .

Following the same processing as for secondary industries, the flood risk for tertiary industries can be calculated according to equation (11):

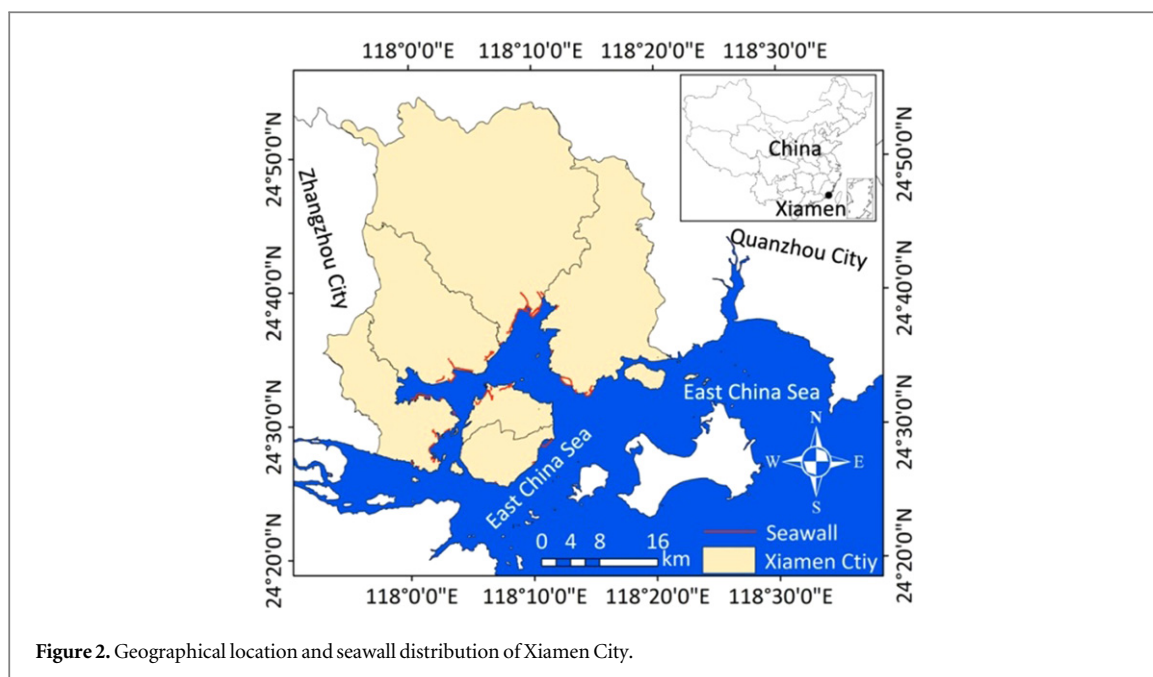
$$E_S = ADS \times A_s \quad (11)$$

where E_S is the added value of a tertiary industry exposed to flooding; ADS is the per-area-unit added value of the tertiary industry; and A_s is the flooded area of commercial and service land.

3. Case study

3.1. Study site

Xiamen City, with a population of 3,730 000 in 2013 and a land area of 1573 square kilometers, is located on the southeastern coast of China. A map of Xiamen City and the distribution of its seawalls are shown in figure 2, and aerial photographs of the coastal landscapes of Xiamen City are shown in figure S1. As one



of the Special Economic Zones in China, Xiamen City has experienced a booming economy and urbanization, but its coastal area has been experiencing vulnerability to land-use change [39, 40]. Xiamen faces the East China Sea with total of 226 km of coastline and 390 square kilometers of marine area, including the Jiulong River estuary, Tong'an Bay, the western port, and the East China Sea to the east and south. Xiamen is a low-lying coastal city with 16% of its land area less than 10 m in elevation. Furthermore, the local historical sea-level rise rate exceeds that of the global mean level. Typhoon storm surges are a common and severe natural disaster facing Xiamen. Historically, 160 storm surges of more than 50 cm above the normal water level hit Xiamen between 1956 and 2012, with an average frequency of 2.8 times a year [41]; according to the records of Gulangyu gauging station, the average water level and biggest storm tide are 0.33 m and 4.54 m, respectively. The storm surge induced by typhoon No 9914 in 1999 killed 13 people, with an additional three people unaccounted for, and was responsible for RMB 1.94 billion in direct economic losses. Currently, although 73.96 km of seawall have been built to withstand extreme water levels, the current seawall is only built to engineering design standards sufficient to withstand a 50-year storm tide, not a 100-year or more serious storm tide, especially if a storm tide occurs in combination with a future sea-level rise [42]. Hence, Xiamen is a typical sea-level rise and storm tide-induced flood-prone city, indicating an urgent need for comprehensive flood risk assessment in order to plan for local adaptation and risk management. Vulnerability curves and other materials for flood risk assessment of Xiamen City are shown in tables S2 to S6.

3.2. Extreme sea-level scenarios

Because there is no authoritative report or research related to future sea-level rise of Xiamen coastline, we assume that eustatic sea-level in Xiamen will follow the global trend published by the fifth report of IPCC, and this global mean sea-level rise is downscaled to obtain a 0.34 ~ 1.18 m eustatic sea-level rise of Xiamen for 2100, referring to the method of Arkema *et al* [43]. According to the *national land subsidence prevention plan* (2011–2020) and Xiamen Geological Engineering Investigation Institute, ground subsidence is unlikely to occur because of its granite geology with few groundwater reserves, and the uplift is also not observed historically [44, 45], thus we assume that vertical land movement is not considered in the case study. The future sea-level rise used in the case study is therefore the eustatic sea-level rise: 0.34 ~ 1.18 m. Using this range as a baseline, three scenarios were modeled: no-SLR, 0.35 m SLR and 1.20 m SLR. The no-SLR scenario was used to estimate the net impact of storm tide alone, and the other two sea-level rise scenarios were used to investigate flood impacts from the minimum and maximum sea-level rise levels. The *Xiamen Municipal Bureau of Water Resources* has calculated the current return periods of storm tides in 2010 [41], and we employed 50-, 100- 200-year ST and also a no-ST scenario; the no-ST scenario was set to assess the net impact of sea-level rise alone. In addition, we hypothesize that future storm tides will maintain their current frequency; hence the historical return period and tide level can be used directly.

Though combining the sea-level rise and storm tide scenarios, 12 extreme-sea-level scenarios were generated and used in the case study; their water levels are depicted in table 2.

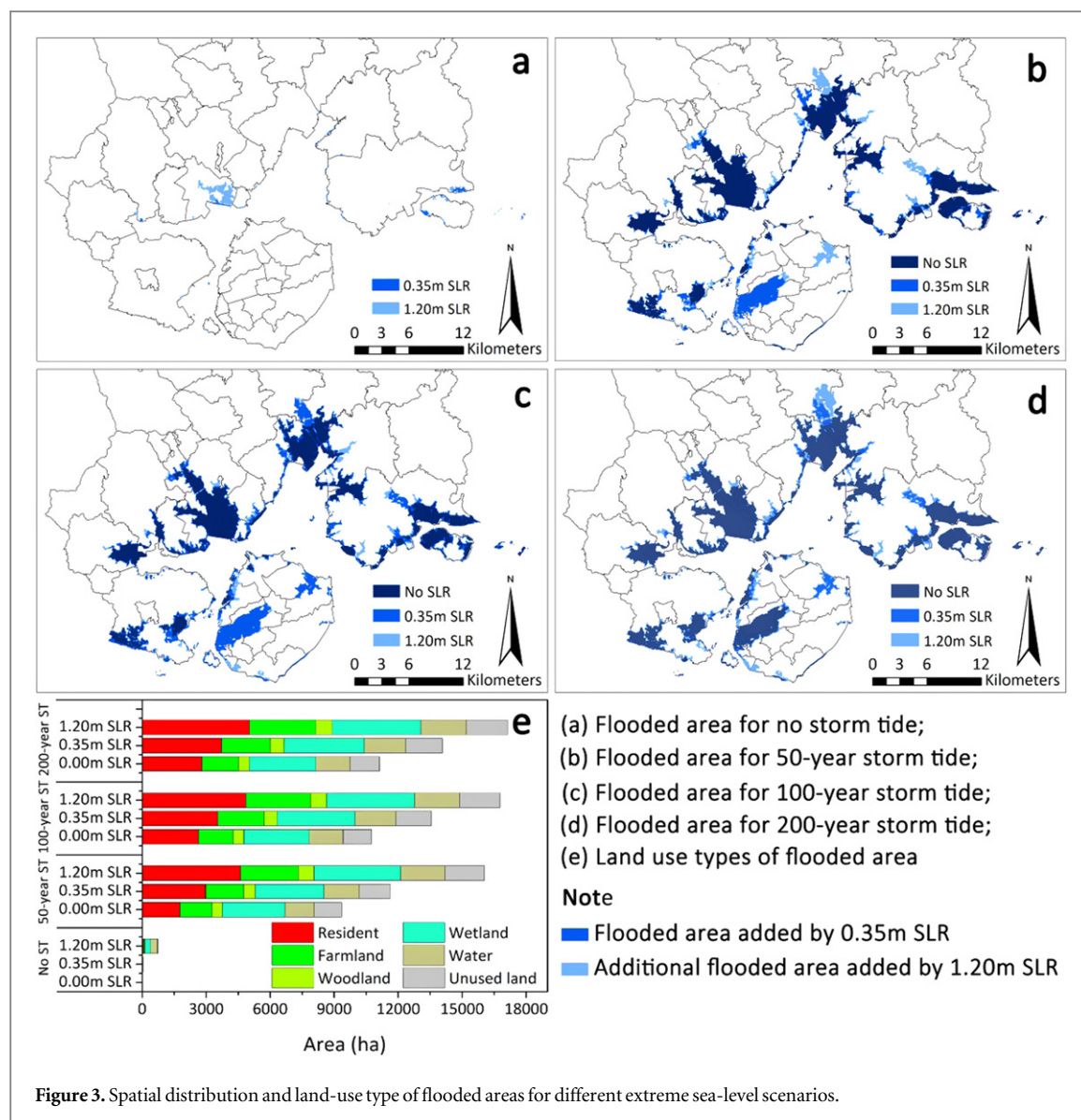


Table 2. Extreme sea-level events combined with sea-level rise and storm tide scenarios (m).

	No ST	50-year ST	100-year ST	200-year ST
No SLR	0.33	4.40	4.53	4.66
0.35 m SLR	0.68	4.75	4.86	5.01
1.20 m SLR	1.53	5.60	5.73	5.86

3.3. Results

3.3.1. Flooded area

The inundated areas and their land-use types are shown in figure 3. Generally, total inundated area increases with the rise of an extreme water level. In the scenarios without storm tide, the permanent inundated land areas from 0.35 m and 1.20 m sea-level rise are 100 and 700 ha, covering only 0.03% and 0.47%, respectively, of Xiamen's land area. In the permanent inundated area, coastal wetland is the dominant land-use type, because wetlands such as beaches and tidal flats are the first regions to be submerged.

Compared with the permanent inundated area, the episodic inundated area is much larger. In the scenarios without sea-level rise, the episodic inundated areas of the currently defined 50-year, 100-year and 200-year storm tide are 9300, 10 700 and 11 100 ha, accounting for 5.97%, 6.86% and 7.10%, respectively, of Xiamen's land area. Considering a future 0.35 m sea-level rise, the episodic inundated areas of the currently defined 50-year, 100-year and 200-year storm tide increase to 11 600, 13 500 and 14 000 ha, accounting for 7.40%, 8.63% and 8.95% of Xiamen's land area, respectively. With a 1.20 m sea-level rise, the episodic inundated areas of the three categories of storm tide increase to 15 300 (9.78% of Xiamen's land area), 16 000 (10.24%) and 16 400 ha (10.46%), respectively. In the case of the combination of sea-level rise and storm tide (4.75 m ~ 5.86 m *ESL*), the total inundated areas range from 11 600 (7.35%) to 17 100 ha (10.94%), in which residential and wetland are the two major land-use types, followed by farmland, water, unused land and woodland.

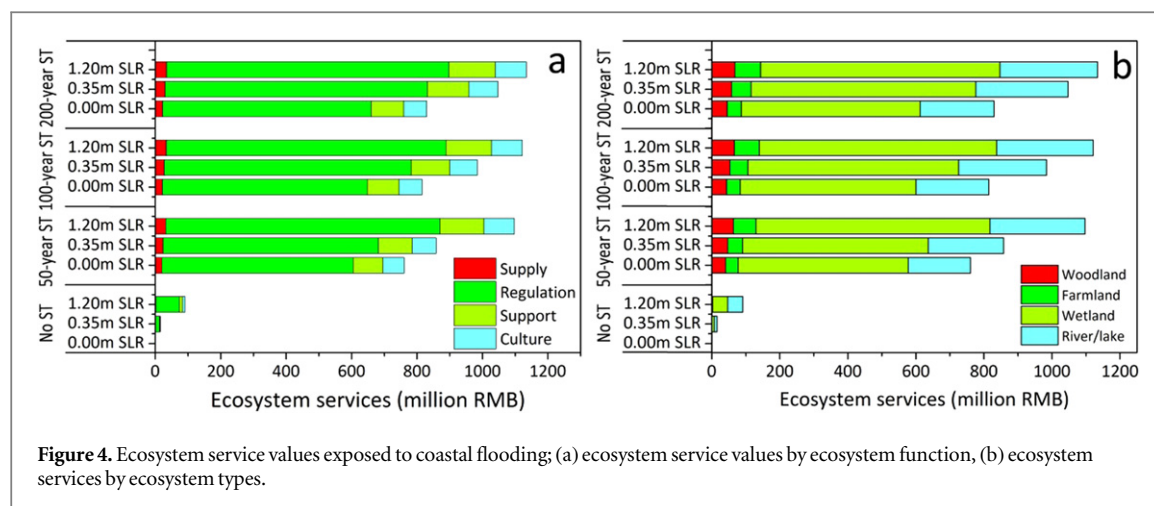


Figure 4. Ecosystem service values exposed to coastal flooding; (a) ecosystem service values by ecosystem function, (b) ecosystem services by ecosystem types.

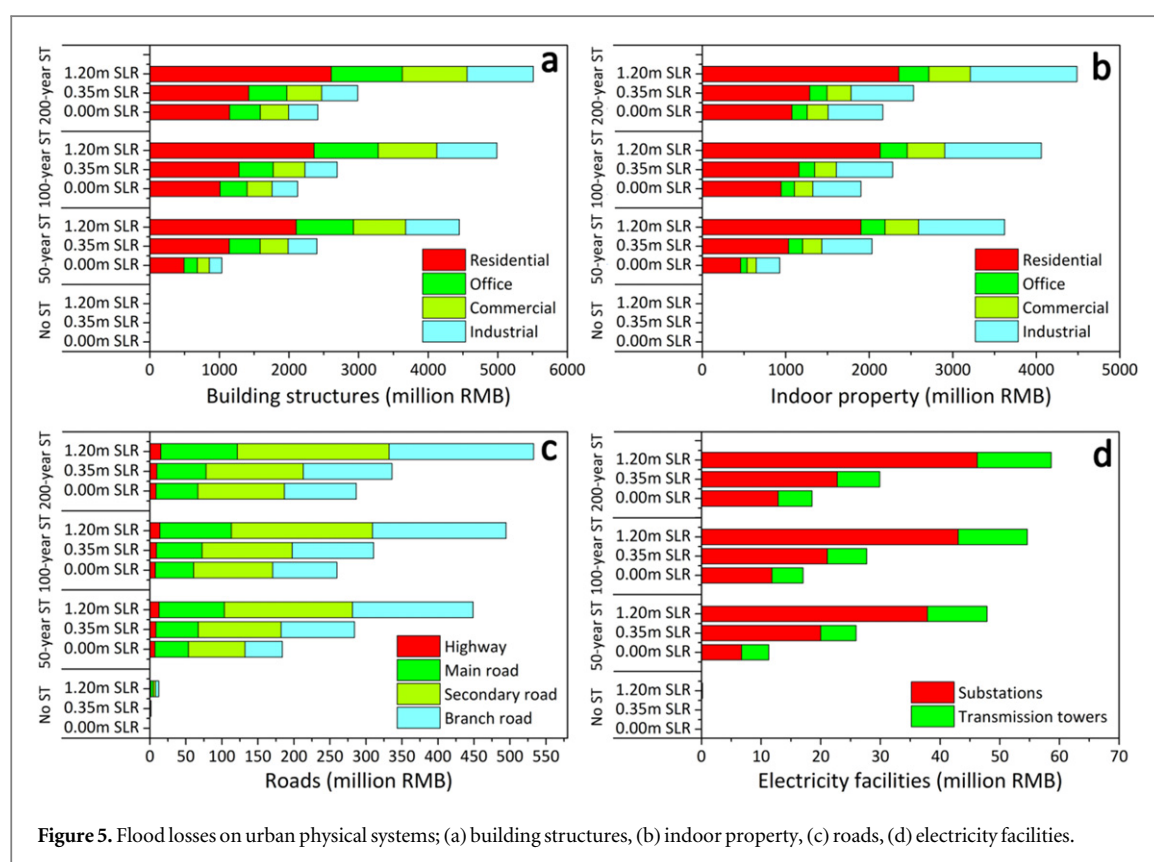


Figure 5. Flood losses on urban physical systems; (a) building structures, (b) indoor property, (c) roads, (d) electricity facilities.

3.3.2. Ecological risk

As depicted in figure 4, exposures of ecosystem services steadily increase with an extreme sea-level rise. Annual ecosystem service exposures under the 0.35 m and 1.20 m sea-level rise are 15 and 91 million RMB, respectively. And the exposures for the 50-year, 100-year and 200-year storm tide alone are 760, 815 and 830 million RMB, respectively. The combination of sea-level rise and storm tide, however, increases the exposures of ecosystem services dramatically; the values under these extreme sea-level scenarios range from 858 to 1134 million RMB. Furthermore, regulation service which includes gas regulation, climate regulation, water regulation and waste treatment, make up the major portion of total ecosystem service

exposures, with an approximate proportion of 75%, followed by support, cultural and supply services (figure 4(a)). In terms of ecosystem types, coastal wetland suffers the most exposure to flood, with a proportion over 60%, followed by river/lake, woodland and farmland (figure 4(b)).

3.3.3. Physical risk

Flood losses on urban physical systems, including building structures, indoor property, roads and electricity facilities are shown in figure 5. Generally, when considering only the 0.35 and 1.20 m sea-level rise, floods cause barely any damage to physical systems. Nevertheless flood losses increase to a huge level under the combination of sea-level rise and storm tide.

Table 3. Population and added value of the economic system exposed to coastal flooding.

Extreme sea-level		Exposed population		Exposed added value of economic system (million RMB)		
		Number of people	% of total population	Secondary industry	Tertiary industry	Total
No ST	0.00 mSLR	0	0.00%	0	0	0
	0.35 m SLR	0	0.01%	1	1	2
	1.20 m SLR	20 000	0.47%	4	3	7
50-year ST	0.00 m SLR	200 000	5.59%	896	392	1288
	0.35 m SLR	440 000	12.58%	1508	1029	2537
	1.20 m SLR	610 000	17.35%	2110	1218	3328
100-year ST	0.00 m SLR	420 000	11.84%	1171	831	2002
	0.35 m SLR	530 000	14.93%	1779	1134	2913
	1.20 m SLR	670 000	19.05%	2549	1337	3886
200-year ST	0.00 m SLR	460 000	13.21%	1275	904	2179
	0.35 m SLR	570 000	16.30%	1919	1223	3142
	1.20 m SLR	720 000	20.52%	2738	1436	4174

According to our calculations, total flood losses on physical systems under scenarios of combined sea-level rise and storm tide range from 4744 to 10 590 million RMB, accounting for 1.69% to 3.76% of Xiamen's GDP in 2012. In physical systems, building structures and indoor property suffer the most loss; these represent approximately 51% and 42%, respectively, of total physical losses. In addition, flood losses on structures and indoor property vary with different building types. Residential buildings suffer the majority of flood losses of any building type, in both structures and interiors, representing almost 47% and 52%, respectively. Although industrial buildings comprise only a small physical part of building-structure losses, the economic loss proportion comprises the second largest portion of indoor property losses because of the huge amount of machinery and equipment inside the buildings. As depicted in figure 5(c), major, secondary and branch roads, and highways, will suffer damage, to different extents, and the flood losses from the combination of sea-level rise and storm tide range from 284 to 533 million RMB, with the secondary and branch roads being the major road types at risk. As for urban electricity facilities, flood losses under the scenarios of combined sea-level rise and storm tide are between 26 and 59 million RMB, in which substations account for about 77%.

3.3.4. Socio-economic risks

Population and the added value of economic systems exposed to coastal floods are shown in table 3. Populations exposed to floods under the various scenarios follow the trend seen for the risks of ecosystems and physical systems: damages increase with the rise of extreme sea-levels. We estimate that between 440 000 and 720 000 people, or 12.58% to 20.52% of the total population, would be exposed to flood risk under the scenarios of combined sea-level rise and storm tide.

Exposures for the added value of secondary and tertiary industries are very small with only sea-level rise, but they increase greatly and reach from 2537 to

4175 million RMB, accounting for 0.90% to 1.50% of the total added value of industry, under the combination of sea-level rise and storm tide. In addition, the exposure of secondary industry is greater than that of tertiary industry, with their relative proportions approximately 60% and 40%, respectively.

4. Discussion

Understanding and characterising both current and future risks are essential for mitigating coastal hazards and managing adaptation to climate change [46], and our study provides an integrated approach for quantifying sea-level rise and storm tide induced flood risks. Climate change is expected to induce global, regional, and local changes in many elements of the climate system [47]. Despite the uncertainties with respect to the impacts of climate change in specific regions and locales, the most certain consequence of climate change is that sea-level will rise in the future [48–50]. The combination of sea-level rise and storm tides, therefore, will pose great flood risks to coastal cities where population and assets are densely distributed, especially to those cities in developing countries that are experiencing rapid urbanization and overdevelopment in flood-prone areas, while lacking sufficient technical skills and financial resources to deal with the issue [51]. Faced with this challenge, it is important that policy makers and coastal managers understand the complex risk mechanisms and assess their impacts. An integrated methodology that is able to gather and interpret accurate and comprehensive information on potential flood risks is urgently needed for risk management. In this study, we have presented a practical multi-dimensional integrated approach to assessing the flood risks for coastal cities, posed by the combination of sea-level rise and storm tide. Unlike previous methods, this one views the coastal city as a system that consists of ecological, physical and socio-economic sub-systems, and assesses their respective

flood risks. The information obtained by this approach not only includes the flood risks on each subsystem but also distinguishes between direct and indirect impacts, and therefore is more complete, systematic and specific, and can be used to design strategies and policies to adapt to increasing coastal flood risks. In addition, the steps and their respective methods of this approach are also provided, so that other coastal cities worldwide can apply it directly; meanwhile, this approach is not limited as described in this paper but can be expanded according to the individual study and data accessibility. Employing this methodology to the case study of Xiamen City has demonstrated its applicability.

Coastal ecosystem serves reduction of hazards induced by climate change, but is negatively affected as well, indicating the need to attach adequate importance on coastal ecosystem both in risk assessment and decision-making. In the human-dominated urban system, ecosystems are particularly important because they serve many functions, especially that coastal ecosystems also provide several additional benefits, such as reducing storm waves and keeping up with sea-level rise [52]. Recently, the positive role of ecosystems on mitigating coastal flood impacts has been receiving increasing attention, and some quantitative studies have revealed that the number of people and the amount of property exposed to hazards can be reduced by half if existing coastal habitats remain fully intact [43]. However, ecosystems are also complicatedly affected by climate change [53]. For coastal areas, future rise in sea-level and storm tides are predicted to have negative impacts on coastal ecosystems, owing to the combination of permanent inundation and episodic flooding [54, 55]. For instance, sea-level rise associated with climate change can drastically inundate, erode, or wash away wetlands and beaches that are important habitats for shoreline dependent organisms [56, 57]. As demonstrated by the results of our case study, coastal ecosystem services—mainly regulation service—will be affected by the flood induced by sea-level rise and storm tide; wetland is the dominant coastal ecosystem suffering risks. The outcomes imply the urgent needs to enhance coastal ecosystem management, particularly wetland conservation, when considering that ecosystem damage or loss is hardly reversible and will in turn accelerate the floods caused by sea-level rise and storm tide over the long run. However, assessing the ecological risks due to sea-level rise and storm tide is complex, owing to the uncertainty caused by key factors such as elevation, accretion and sedimentation [58]. In addition, no general conclusions have been drawn relating sea-level and shoreline changes on a global scale, because shoreline data shortage and gauge limitations of relative sea-level restrict the previous studies [59]. Considering these uncertainties, we didn't analyze shoreline changes especially sedimentary dynamics in this study.

Like most previous studies, the result of our study showed that physical systems including buildings, indoor property and infrastructures are the dominant part facing coastal flood risks. Densely distributed elements of physical systems place coastal cities at the height of exposure to sea-level rise and storm tides, and hence increase the potential of flood risks. According to our study, in the scenarios that considered only sea-level rise, flood risks on the physical system are not significant, but the combination of sea-level rise and storm tides increases these risks to an alarming level. In an urban system, which relies heavily on physical systems, flood damage to buildings and infrastructures will cause a variety of impacts [60]. According to this study, buildings will suffer significant flood risks, both structural and interior, affecting not only residents' activities of daily living, but also commercial activities, office work and industrial production. In addition, the risks for key infrastructure such as roads and electricity facilities are of special relevance both during and after flood disasters, because roads and facilities are the lifelines for economic growth, development and social welfare.

As demonstrated by the case study of Xiamen City, indirect risk on economic system occupies an important part of coastal flood risks. Indirect risks will arise as a consequence of the direct risks of flood on physical systems, ecosystems and the human population. These include disruption to urban economic systems: loss of added economic value due to disruptions in manufacturing, retail, tourism and service sectors [61, 62]. However, the quantification of these indirect risks has received less attention, and research on this has not yet developed a comprehensive and accepted method of prediction or assessment [63]. In the present study, we chose the added values of secondary and tertiary industries as indicators, and quantified the indirect flood risks on urban economic systems. According to our case study, indirect risks accounts for almost 30% of the total risks of floods on ecological, physical and economic systems, revealing that it is imperative to include indirect effects when assessing the impacts of climate change on urban systems. In addition, policy makers must begin to give adequate weight to the indirect risks, in the decision-making process; otherwise the impacts of climate change on human systems will be underestimated, seriously reducing the effectiveness of actions to cope with climate change. Although little research has investigated the indirect risks and existing methods remain too simple to investigate all mechanisms, more and further studies deserve to be conducted on this issue, and existing studies on the direct risks could be used to explore the resulting consequences indirect risk on economic system [63].

While the study presented here expands our understanding of flood impacts on urban systems, it is also under several limitations that future research needs to address. (1) Scenarios for future

demographic/land-use change and adaptation were not set in our approach. Although part of previous studies have taken the demographic/land-use change into considerations, simulating the urban development in a long time scale is challenging and consists of uncertainties, so we didn't adopt this part in this study. Successful adaptation will reduce the coastal flood risks effectively, so that it is urgently demanded in long-term urban planning [64]. This study only assessed the potential risks of sea-level rise and storm tide without considering adaptation, and it should be updated and included in future researches to assess the actual risks. (2) Because the detailed mechanisms of how floods influence urban economic activities are not currently clear, we calculated indirect flood impacts on economic systems in a very simplified way. (3) Like the majority of previous studies, sensitivity analysis was not conducted in this study. Assessing the coastal flood risks at the city level will generate system errors and uncertainties which mainly exist in extreme water level set, food area extraction and risks calculation. Long-term historical observation records of sea-level rise, vertical land movement and storm surge are limited, and their future values is dynamics, so combining them to set the extreme water scenarios is an important source of uncertainties. DEM accuracy is another source because its resolution and vertical error affect the results of flood area extraction greatly. Moreover, error of land-use map and statistic data can also lead to uncertainties in risk calculation. Despite the limitations, this study provides a basic methodological framework and procedure for assessing comprehensive risks of coastal flood from ecological, physical and socio-economic aspects. Further studies thus need to take these limitations into account to arrive at a more sophisticated, complete and integrated assessment model.

5. Conclusions

A multi-dimensional integrated approach for assessing coastal flood risks was proposed in this study. As demonstrated by the case study of Xiamen City, major conclusions can be drawn: (1) this approach is applicable for estimating the specific flood risks on urban ecological, physical and socio-economic system, respectively; (2) future extreme sea-level events induced by sea-level rise and storm tide will cause substantial flood risks to coastal urban system, including not only land and population flooding, but also both direct flood risks on ecological and physical systems, and consequent indirect risks; (3) coastal ecosystem services—mainly regulation service—will be affected, and wetland is the dominant coastal ecosystem suffering coastal floods, which call for enhancing coastal ecosystem management, particularly wetland conservation; and finally (4) while not well studied, indirect risk on economy accounts for an

important part of total risks, and it therefore should be given adequate weight in the decision-making process.

Acknowledgments

The authors gratefully acknowledge financial support from the National Natural Science Foundation of China (41371205), and the National Key Technology R&D Program of the Ministry of Science and Technology (2012BAC21B03).

References

- [1] Hallegatte S, Green C, Nicholls R J and Corfee-Morlot J 2013 Future flood losses in major coastal cities *Nature Clim. Change* **3** 802–6
- [2] Woodruff J D, Irish J L and Camargo S J 2013 Coastal flooding by tropical cyclones and sea-level rise *Nature* **504** 44–52
- [3] Tebaldi C, Strauss B H and Zervas C E 2012 Modelling sea level rise impacts on storm surges along US coasts *Environ. Res. Lett.* **7** 014032
- [4] IPCC 2013 *Climate Change 2013: The Physical Science Basis* (Cambridge: Cambridge University Press)
- [5] Lin N, Emanuel K, Oppenheimer M and Vanmarcke E 2012 Physically based assessment of hurricane surge threat under climate change *Nature Clim. Change* **2** 462–7
- [6] Mendelsohn R, Emanuel K, Chonabayashi S and Bakkensen L 2012 The impact of climate change on global tropical cyclone damage *Nature Clim. Change* **2** 205–9
- [7] Woodworth P L, Menendez M and Gehrels W R 2011 Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea levels *Surv. Geophys.* **32** 603–18
- [8] McInnes K L, Walsh K J E, Hubbert G D and Beer T 2003 Impact of sea-level rise and storm surges on a coastal community *Nat. Hazards* **30** 187–207
- [9] Yin J, Yin Z E, Hu X M, Xu S Y, Wang J, Li Z H, Zhong H D and Gan F B 2011 Multiple scenario analyses forecasting the confounding impacts of sea level rise and tides from storm induced coastal flooding in the city of Shanghai, China *Environ. Earth Sci.* **63** 407–14
- [10] Yin J, Yu D P, Yin Z N, Wang J and Xu S Y 2013 Modelling the combined impacts of sea-level rise and land subsidence on storm tides induced flooding of the Huangpu River in Shanghai, China *Clim. Change* **119** 919–32
- [11] Yoo G, Hwang J H and Choi C 2011 Development and application of a methodology for vulnerability assessment of climate change in coastal cities *Ocean Coast. Manag.* **54** 524–34
- [12] Nicholls R J and Cazenave A 2010 Sea-level rise and its impact on coastal zones *Science* **328** 1517–20
- [13] Hinkel J and Klein R J T 2009 Integrating knowledge to assess coastal vulnerability to sea-level rise: the development of the DIVA tool *Global Environ. Change* **19** 384–95
- [14] Hinkel J, Lincke D, Vafeidis A T, Perrette M, Nicholls R J, Tol R S J, Marzeion B, Fettweis X, Ionescu C and Levermann A 2014 Coastal flood damage and adaptation costs under 21st century sea-level rise *Proc. Natl Acad. Sci. USA* **111** 3292–7
- [15] Nicholls R J 2004 Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios *Global Environ. Change* **14** 69–86
- [16] McFadden L, Spencer T and Nicholls R J 2007 Broad-scale modelling of coastal wetlands: what is required? *Hydrobiologia* **577** 5–15
- [17] Strauss B H, Ziemiński R, Weiss J L and Overpeck J T 2012 Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States *Environ. Res. Lett.* **7** 014033
- [18] Weiss J L, Overpeck J T and Strauss B 2011 Implications of recent sea level rise science for low-elevation areas in coastal cities of the conterminous USA *Clim. Change* **105** 635–45

- [19] Zuo J C, Yang Y Q, Zhang J L, Chen M X and Xu Q 2013 Prediction of china's submerged coastal areas by sea level rise due to climate change *J. Ocean Univ. China* **12** 327–34
- [20] Lichter M and Felsenstein D 2012 Assessing the costs of sea-level rise and extreme flooding at the local level: a GIS-based approach *Ocean Coast. Manag* **59** 47–62
- [21] Hallegatte S, Ranger N, Mestre O, Dumas P, Corfee-Morlot J, Herweijer C and Wood R M 2011 Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen *Clim. Change* **104** 113–37
- [22] Russell R, Guerry A D, Balvanera P, Gould R K, Basurto X, Chan K M A, Klain S, Levine J and Tam J 2013 Humans and nature: how knowing and experiencing nature affect well-being *Annu. Rev. Environ. Resour.* **38** 473–502
- [23] Millennium Ecosystem Assessment 2005 *Ecosystems and Human Well-Being: Synthesis* (Washington, DC: Island)
- [24] Nicholls R J and Hoozemans F M 2005 *Global Vulnerability Analysis* (Dordrecht: Springer)
- [25] Tol R S 2007 The double trade-off between adaptation and mitigation for sea level rise: an application of FUND *Mitigation and Adaptation Strategies for Global Change* **12** 741–53
- [26] Bakewell I and Luff S 2008 *North London strategic flood risk assessment: final report* (UK: DEFRA)
- [27] Thorne C R, Evans E P and Penning-Rowsell E C 2007 *Future Flooding and Coastal Erosion Risks* (London: Thomas Telford)
- [28] Slangen A B A, Carson M, Katsman C A, van de Wal R S W, Kohl A, Vermeersen L L A and Stammer D 2014 Projecting twenty-first century regional sea-level changes *Clim. Change* **124** 317–32
- [29] Cazenave A and Le Cozannet G 2014 Sea level rise and its coastal impacts *Earth's Future* **2** 15–34
- [30] McInnes K L, Walsh K J E, Hoeke R K, O'Grady J G, Colberg F and Hubbert G D 2014 Quantifying storm tide risk in Fiji due to climate variability and change *Glob. Planet. Change* **116** 115–29
- [31] Coles S, Bawa J, Trenner L and Dorazio P 2001 *An Introduction to Statistical Modeling of Extreme Values* (London: Springer)
- [32] Gumbel E J 1941 The return period of flood flows *Annals of Mathematical Statistics* **12** 163–90
- [33] Bilske M V, Hagen S C, Medeiros S C and Passeri D L 2014 Dynamics of sea level rise and coastal flooding on a changing landscape *Geophys. Res. Lett.* **41** 927–34
- [34] Chang K T 2006 *Introduction to Geographic Information Systems* (Boston: McGraw-Hill Higher Education)
- [35] Resio D T and Westerink J J 2008 Modeling the physics of storm surges *Phys. Today* **61** 33–8
- [36] Costanza R *et al* 1997 The value of the world's ecosystem services and natural capital *Nature* **387** 253–60
- [37] Xie G D, Zhen L, Lu C X, Xiao Y and Chen C 2008 Expert knowledge based valuation method of ecosystem services in China *J. Nat. Res.* **23** 911–9
- [38] Shi L Y, Cui S H, Yin K and Liu J 2010 The impact of land use/cover change on ecosystem service in Xiamen *Acta. Geographica. Sinica.* **65** 708–14
- [39] Huang Y F, Li F Y, Bai X M and Cui S H 2012 Comparing vulnerability of coastal communities to land use change: analytical framework and a case study in China *Environ. Sci. Policy* **23** 133–43
- [40] Huang J, Cui S H, Qiu Q Y, Shi L Y and Ma K M 2010 Estimates of exposure of a coastal city to spatial use changes—a case study in Xiamen *Int. J. Sustain. Dev. World Ecol.* **17** 292–8
- [41] Xiamen Municipal Bureau of Water Resources 2010 *Return periods of storm tides for Xiamen City* (http://sl.xm.gov.cn/slj_fxkh/slj_ftzl/gzh2011nd11hqrd/fb/fxftfchsh/314888.htm)
- [42] Xiamen Municipal Commission of Urban Planning 2010 *Master plan of Xiamen: 2010–2020* (<http://xmgh.gov.cn/>)
- [43] Arkema K K, Guannel G, Verutes G, Wood S A, Guerry A, Ruckelshaus M, Kareiva P, Lacayo M and Silver J M 2013 Coastal habitats shield people and property from sea-level rise and storms *Nature Clim. Change* **3** 913–8
- [44] Ministry of Land and Resources of the People's Republic of China 2012 *National land subsidence prevention plan: 2011–2020* (<http://mlr.gov.cn/>)
- [45] Xiamen Evening News 2012 *Xiamen is Unlikely to Occur Land Subsidence* (http://news.xmnn.cn/xmxw/201202/t20120222_2190221.htm)
- [46] Shepard C C, Agostini V N, Gilmer B, Allen T, Stone J, Brooks W and Beck M W 2012 Assessing future risk: quantifying the effects of sea level rise on storm surge risk for the southern shores of Long Island *New York Nat. Hazards* **60** 727–45
- [47] IPCC 2014 *Climate Change 2014: Synthesis Report* (Cambridge: Cambridge University Press)
- [48] Frazier T G, Wood N, Yarnal B and Bauer D H 2010 Influence of potential sea level rise on societal vulnerability to hurricane storm-surge hazards, Sarasota County, Florida *Applied Geography* **30** 490–505
- [49] Wu S Y, Yarnal B and Fisher A 2002 Vulnerability of coastal communities to sea-level rise: a case study of cape may county, New Jersey, USA *Clim. Res.* **22** 255–70
- [50] Hay C C, Morrow E, Kopp R E and Mitrovica J X 2015 Probabilistic reanalysis of twentieth-century sea-level rise *Nature* **517** 481–4
- [51] Hung H C and Chen L Y 2013 Incorporating stakeholders' knowledge into assessing vulnerability to climatic hazards: application to the river basin management in Taiwan *Clim. Change* **120** 491–507
- [52] Temmerman S, Meire P, Bouma T J, Herman P M J, Ysebaert T and De Vriend H J 2013 Ecosystem-based coastal defence in the face of global change *Nature* **504** 79–83
- [53] Scheffer M *et al* 2015 Creating a safe operating space for iconic ecosystems *Science* **347** 1317–9
- [54] Akumu C E, Pathirana S, Baban S and Bucher D 2011 Examining the potential impacts of sea level rise on coastal wetlands in north-eastern NSW, Australia *J. Coast. Conserv.* **15** 15–22
- [55] Tian B, Zhang L Q, Wang X R, Zhou Y X and Zhang W 2010 Forecasting the effects of sea-level rise at Chongming Dongtan Nature Reserve in the Yangtze Delta, Shanghai, China *Ecol. Eng.* **36** 1383–8
- [56] Fujii T and Raffaelli D 2008 Sea-level rise, expected environmental changes, and responses of intertidal benthic macrofauna in the Humber estuary, UK *Mar. Ecol. Prog. Ser.* **371** 23–35
- [57] Galbraith H, Jones R, Park R, Clough J, Herrod-Julius S, Harrington B and Page G 2002 Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds *Waterbirds* **25** 173–83
- [58] Chu-Agor M L, Munoz-Carpena R, Kiker G, Emanuelsson A and Linkov I 2011 Exploring vulnerability of coastal habitats to sea level rise through global sensitivity and uncertainty analyses *Environ. Model Software* **26** 593–604
- [59] Le Cozannet G, Garcin M, Yates M, Idier D and Meyssignac B 2014 Approaches to evaluate the recent impacts of sea-level rise on shoreline changes *Earth-Sci. Rev.* **138** 47–60
- [60] Chinowsky P, Schweikert A, Strzepek N and Strzepek K 2015 Infrastructure and climate change: a study of impacts and adaptations in Malawi, Mozambique, and Zambia *Clim. Change* **130** 49–62
- [61] Jonkman S N, Bockarjova M, Kok M and Bernardini P 2008 Integrated hydrodynamic and economic modelling of flood damage in the Netherlands *Ecol. Econ.* **66** 77–90
- [62] Bosello F, Nicholls R J, Richards J, Roson R and Tol R S J 2012 Economic impacts of climate change in Europe: sea-level rise *Clim. Change* **112** 63–81
- [63] Hallegatte S 2012 A framework to investigate the economic growth impact of sea level rise *Environ. Res. Lett.* **7** 015604
- [64] Nicholls R J and Tol R S J 2006 Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century *Phil. Trans. R. Soc. A* **364** 1073–95