Landscape and Urban Planning 136 (2015) 144–155

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

Research Paper

Modelling the anthropogenic impacts on fluvial flood risks in a coastal mega-city: A scenario-based case study in Shanghai, China

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HIGHLIGHTS

- A scenario-based approach is presented to evaluate anthropogenic impacts on urban flood risks.
- Three anthropogenic variables (land subsidence, urbanization and flood defence) are considered.
- Land subsidence and urbanization lead to proportionate but non-linear impact on urban flood risks.
- Flood defences offer considerable benefits in reducing the total inundated areas.

ARTICLE INFO

Article history:
Received 1 May 2014
Received in revised form
15 December 2014
Accepted 15 December 2014

Keywords:
Anthropogenic impact
Urbanization
Land subsidence
Fluvial flood modelling
Huangpu River
Shanghai

ABSTRACT

This paper describes a novel approach to the evaluation of anthropogenic impacts on flood risks in coastal mega-cities by incorporating three anthropogenic variables (land subsidence, urbanization and flood defence) within a scenario-based framework where numerical modelling was undertaken to quantify the risks. The evolving risks at four time points (1979, 1990, 2000 and 2009) were assessed for the Huangpu River floodplain where the city of Shanghai is located. A 2D hydrodynamic model (FloodMap-Inertial) was used to estimate the flood risks associated with each scenario. Flood events with various return periods (10-, 100- and 1000-year) were designed based on a one in 50 year flood event that occurred in Shanghai on August 1997.

Results demonstrate the individual as well as the combined impacts of the three anthropogenic factors on the changing fluvial flood risks in the Huangpu River basin over the last three decades during the city's transitional economy (1979–2009). Land subsidence and urbanization were found to lead to proportionate but non-linear impact on flood risks due to their complex spatial and temporal interaction. The impacts and their sensitivity are the function of the rate and spatial distribution of each evolving factor. While the pattern of response to individual anthropogenic variables is largely expected, the combined impacts demonstrate greater spatial and temporal variation. Flood defences offer considerable benefits in reducing the total inundated areas in the Huangpu River basin over the periods considered, for all magnitude floods. This, to a large extent, alleviates the adverse impacts arising from land subsidence and urbanization.

1. Introduction

Flooding of coastal and fluvial systems is one of the most devastating natural hazards, causing considerable personal injury and property damage globally each year (Jongman, Ward, & Aerts, 2012; Jonkman, 2005; UNISDR, 2009). It is widely recognized that both the natural processes and anthropogenic activities have a large impact on the hydrological dynamics within floodplains, river deltas or coastal zones by altering the spatio-temporal characteristics of rainfall, underlying surface runoff and underground discharge. Increases in sea level and extreme events of rainfall and storms, which are often attributed to potential climate change, have been suggested as the primary cause of exacerbating the

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http://dx.doi.org/10.1016/j.landurbplan.2014.12.009
0169-2046/

physical drivers of flood frequency and intensity (IPCC, 2013). Although the anthropogenic influences on flooding are less well understood than natural impacts, there is a growing awareness of their vulnerability characteristics and positive/negative feedbacks.

Rapid expansion in human settlements occupies floodplains and increases imperviousness which in turn increases peak discharge and surface runoff (Suriya & Mudgal, 2012). Moreover, as urban areas grow, the demand for water and living space gradually increases. Widespread land subsidence caused by excessive groundwater withdrawal and engineering activities (e.g. construction of high-rise buildings and underground projects) further amplifies the harmful effects of flooding by modifying the ground elevation, stream slopes and flow pathways. The negative experience of being flooded can also feed back to human's activities and social development because the human society is a self-adaptive system (Dawson et al., 2011). Indeed, for a long time, people have been seeking to alleviate the adverse consequences of flooding by structural measures (e.g. flood defences) and more recently, non-structural approaches (e.g. flood-resilient buildings and 'green roofs'). Such measures have proved to be robust in some situations while less successful in others. Their effectiveness is being continuously evaluated in an uncertain climatic and anthropogenic future.

Although there are still debates as to whether the number of flood disasters driven by climate variation has increased, in the Asia context, there is an increasing consensus that more intense precipitation events are being observed and recorded in the regional level over the last few decades (e.g. Zhai, Zhang, & Pan, 2005), causing persistent, if not increasing events of flooding at a local level (Wu, Yu, Wilby, & Chen, 2012). Despite the uncertainty in the frequency of flood hazard occurrences, exposure to flooding has undoubtedly increased as a result of more concentrated settlements on floodplains vulnerable to flooding from various sources. Coastal mega-cities are in particular vulnerable to flood risks given their typical low-lying nature, vulnerability to sea-level rise and/or storm surge and increased concentration of population. A number of studies have examined the anthropogenic impacts on the hydrological responses of flooding using distributed models and scenario analysis, focusing in particular on the process of urbanization and/or land cover change (e.g. Du et al., 2012; Suriya & Mudgal, 2012; Xiang & Clarke, 2003; Yin, Ye, Yin, & Xu, 2014). However, only a limited few studies have attempted to quantitatively explore the individual and combined impacts of anthropogenic factors by means of hydrodynamic modelling and/or comprehensive urban-development scenarios.

In this paper, we used a 2D hydrodynamic model (FloodMap, Yu & Lane, 2006a, 2006b, 2011) to quantify flood responses to three major anthropogenic variables (i.e. urbanization, land subsidence and flood defence) in the city of Shanghai, illustrating their underlying influences on flood risks during the city's transitional economy between 1979 and 2009. The main aims of this study are to: (1) develop a scenario-based framework for determining the potential interactions between anthropogenic variables; (2) identify and compare the spatio-temporal characteristics of flooding under different anthropogenic scenarios; and (3) understand and quantify the effects of human induced drivers on flood risks. The remainder of this article is organized as follows. Section 2 introduces the materials and methodology, including the study area, scenario design, data availability, flood modelling and evaluation metrics. The results and discussion are presented and discussed in Sections 3 and 4. Section 5 concludes with the key findings, possible adaption measures and future research directions.

2. Materials and methodology

2.1. Study area

Shanghai is a coastal mega-city located in the frontal alluvial plain of the Yangtze River Delta, with a total area of 6340 km^2. It has a mild and low-lying topography. The average elevation is about 4 m above the Wusong Datum, with most of the region below the high tide level. This area experiences a northern subtropical monsoon climate with four distinctive seasons, receiving most of its cyclonic storms and rainfall during the flood season (June–September). The mean sea level of Shanghai has risen by 115 mm from 1978 to 2007 (China Sea Level Bulletin 2007). Huangpu River (113 km long) originates from the Thai Hu Lake to the west of Shanghai, feeds from its southwest, and passes through the city centre and discharges into the Yangtze River Estuary. Tides and storm surges are the two major controlling factors of water level in the river, which synchronizes with the rise and fall of the tidal level at the estuary. The annual maximum water levels along the Huangpu River have been on an increasing trend since 1949 (Yin, Yu, Yin, Wang, & Xu, 2013b). As the primary flood-prone area in Shanghai, the Huangpu River floodplain extending from the upstream Mishidu to the downstream Wusong estuary (Fig. 1) is chosen as the study area.

A fast progression of anthropogenic context has been presented in the Shanghai metropolitan area over the transitional period (1979–2009), driven by China's 'reform and opening-up' policy in 1978 and the subsequent policies. Permanent population of Shanghai was 11.37 million in 1979 and increased to 19.21 million by 2009, while the GDP increased dramatically from RMB 28.64 billion yuan to 1504.65 billion yuan over the same period (Shanghai Statistical Bureau, 2010). Urban footprint has consequently expanded by approximately 10 folds from 1979 to 2009, leading to a considerable reduction of farmland and green space, mostly in the Huangpu River floodplain (Yin et al., 2011). According to the long-term monitoring data, the entire floodplain exhibited significant subsidence, and the downstream city centre adjacent to the Huangpu River is the hotspot, with a maximum rate of 24.12 mm/a as reported (Wang, Gao, Xu, & Yu, 2012; Wei, Zhai, & Yan, 2010). In addition to the 1–1.5 mm/a neotectonic subsidence (Qian, 1996; Ye, 1996), groundwater withdrawal contributed to over 40% (111 mm) of the anthropogenic subsidence and engineering constructions accounted for the remaining 60% (157.1 mm) in downtown between 1980 and 2007 (Gong, 2008). To protect against intensified flood hazards (e.g. flood events that occurred in August 1974, September 1981 and August 1997), floodwalls and sluices along the Huangpu River have been extended and upgraded several times since the 1970s. At present, the floodplain is protected by an enclosed 480-km long flood defence system which is designed to withstand the 1000-year flood in urban area (283 km in midstream and downstream) and 50-year flood in the upstream rural area (based on the flood frequency analysis in 1984, the so-called '84′ standard). Despite these measures, recent findings have indicated significant population and socio-economic exposure to increased flood risk in the Huangpu River basin in an uncertain future climate (Hanson et al., 2011; Yin, Yu, Yin, Wang, & Xu, 2013a, 2013b).

2.2. Anthropogenic datasets availability

The anthropogenic datasets used in our analysis consist of maps of land uses, land subsidence rates and flood defences in Shanghai for 1979, 1990, 2000 and 2009. Land use and land cover change is the best proxy of the urbanization characteristics (e.g. rate and spatial distribution). Landsat images (Multi-Spectral Scanner data of 1979, Thematic Mapper data of 1990, and Enhanced Thematic