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Modelling the impact of land subsidence on urban pluvial flooding: A case study of downtown Shanghai, China

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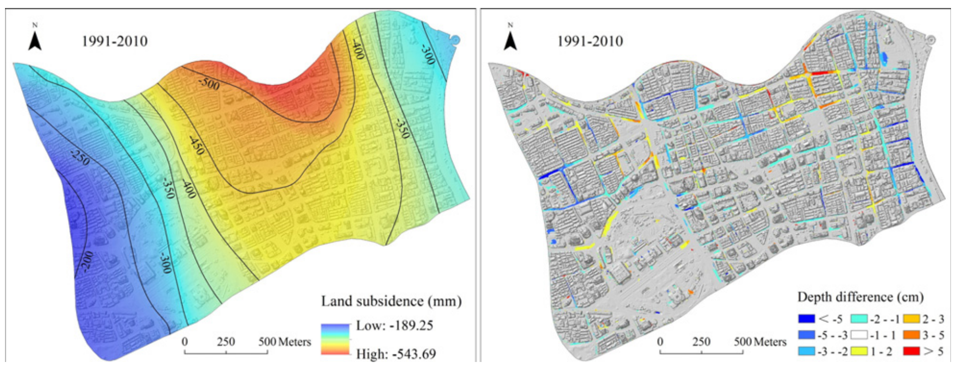
HIGHLIGHTS

- Land subsidence can lead to non-linear response of pluvial flood characteristics.
- The impact is generally minor and limited to areas with lowest-lying topographies.
- The impact depends on the interplay between subsidence pattern and microtopography.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents a numerical analysis of pluvial flooding to evaluate the impact of land subsidence on flood risks in urban contexts using a hydraulic model (FloodMap-HydroInundation2D). The pluvial flood event of August 2011 in Shanghai, China is used for model calibration and simulation. Evolving patterns of inundation (area and depth) are assessed over four time periods (1991, 1996, 2001 and 2011) for the downtown area, given local changes in topography and rates of land subsidence of up to 27 mm/yr. The results show that land subsidence can lead to non-linear response of flood characteristics. However, the impact on flood depths is generally minor (<5 cm) and limited to areas with lowest-lying topographies because of relatively uniform patterns of subsidence and micro-topographic variations at the local scale. Nonetheless, the modelling approach tested here may be applied to other cities where there are more marked rates of subsidence and/or greater heterogeneity in the depressed urban surface. In these cases, any identified hot-spots of subsidence and focusing of pluvial flooding may be targeted for adaptation interventions.

1. Introduction

Pluvial flooding is one of the most common natural hazards in many parts of the world and is attracting growing public concern. This coincides with an intensified hydrologic cycle associated with climate variability and change, combined with rapid urbanization (IPCC, 2007a; Du et al., 2012; Suriya and Mudgal, 2012; Zhou et al., 2012; Wu et al., 2012). There are both direct impacts (e.g. personal injury and property damage) and indirect consequences (e.g. interruption to public services), particularly in many cities worldwide where rapid urban has growth outpaced the capacity of storm sewer drainage. For example, a pluvial flood event in Beijing in July 2011 led to 79 deaths

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and damages of $1.86 billion. Critical infrastructure such as traffic and power systems and residents' livelihoods were seriously affected (Yin et al., 2015a). Pluvial flooding is increasingly being reported in developed countries. For example, a government commissioned report found that the majority of the damages caused by the 2007 floods in the UK were due to overloaded storm sewer systems in developed areas (Pitt, 2008). Indeed, pluvial flooding appears to be increasing in many parts of the world (e.g. Wu et al., 2012) and it is receiving increased media coverage and policy attention.

Localized factors such as land subsidence may also play a role in urban pluvial flooding. However, the spatial-temporal effect of land subsidence on pluvial flood risks has not been fully understood. Widespread occurrence of land subsidence caused by natural processes (e.g. tectonic activities) and/or anthropogenic activities (e.g. extraction of oil, gas and groundwater) has been reported in many urban environments (e.g. Waltham, 2002; Marfai and King, 2008; Brown and Nicholls, 2015). Land subsidence is recognized as a chronic hazard affecting urban flooding, especially in coastal/delta megacities such as Tokyo, Osaka, Shanghai, Taipei, Bangkok, Jakarta, Manila and New Orleans (Dixon et al., 2006; IPCC, 2007b; Syvitski et al., 2009; Jago-on et al., 2009). The underlying impacts of land subsidence on urban pluvial flood can be seen in the form of changes in runoff and flow patterns locally on the land surface. Hence, it is important to evaluate pluvial flood hazard by taking into account the temporal variations of urban topography induced by land subsidence.

There is a general awareness that sinking land may be responsible for increasing pluvial flood risk in subsidence prone cities (e.g. Chan et al., 2012). However, few studies have numerically investigated the relationship between land subsidence and pluvial flooding in complex urban communities, largely due to the lack of high accuracy and multi-temporal topographic data. However, the advent of Light Detection And Ranging (LiDAR) techniques (i.e. airborne and terrestrial laser scanners), combined with the geodetic techniques (e.g. levelling surveys, GPS surveys, and InSAR technique) (e.g. Abidin, 2005; Cabral-Cano et al., 2008; Osmanoglu et al., 2011; Yan et al., 2012), and advances in high resolution flood modelling techniques (Sampson et al., 2012) have enabled the numerical modelling of dynamic urban pluvial flood risks in the context of land subsidence.

In this study, we explore the role of land subsidence in modulating pluvial flooding within an urban centre. Downtown Shanghai is used as a case study because the area is prone to flooding from pluvial sources and has been experiencing significant long-term land subsidence. We begin by analysing the spatio-temporal characteristics of urban pluvial flooding corresponding to historical land subsidence occurrences. We then interpret probable mechanisms controlling the flood patterns. Section 2 describes the materials and methods, including the study site, data availability, model description, model construction and evaluation metrics; Section 3 presents the results and discussion. The conclusions and some suggestions for further research are given in Section 4.

2. Materials and methods

2.1. Study site

The watershed selected lies in the central Shanghai metropolitan area (the North Huangpu District), bordering the Huangpu River to the east and Suzhou Creek to the north (Fig. 1). The watershed is a closed system with two elevated highways on the western (South–North Elevated Highway) and southern (Yan'an Elevated Highway) boundaries. The floodwalls along the rivers, combined with the elevated highways act as barriers to flow. As such, no water exchange occurs across the boundary. The area is ~3.25 km^2 and has low-lying topography with an average altitude of about 3 m above Wusong Datum. The region experiences a northern subtropical monsoon climate and receives annual precipitation of ~1100 mm. Heavy and extreme rainfalls frequently hit this region during the flood season (June to September) due to the city's location in the path of tropical cyclones (Yin and Zhang, 2015).

The study area has been the downtown part of Shanghai since the mid to late nineteenth century. It therefore comprises a typical urban landscape with dense buildings, heavy traffic, impermeable surfaces, and few open green spaces (such as the People's Park, Fig. 1). Storm drainage in the form of pumps and sewer systems is the only way to take excess storm water from the site. The drainage capacity was generally designed to cope only with a 1 in 1 year rainfall (36 mm/h) after the 1990s. The drainage system for the central business district (CBD) has been improved to withstand a 1 in 3 year rainfall (49.6 mm/h) since 2002.

Land subsidence has been surveyed in central Shanghai through a combination of levelling (since the 1920s) and GPS (since the 1990s). Long term subsidence is due to: (i) relatively constant rates of tectonic subsidence (1 mm/year); and (ii) non-uniform compaction of sediments (more than 20 mm/year on average between 1921 and 2007) due to groundwater withdrawal, construction of high-rise buildings, and underground engineering (Yin et al., 2013). In some areas, cumulative

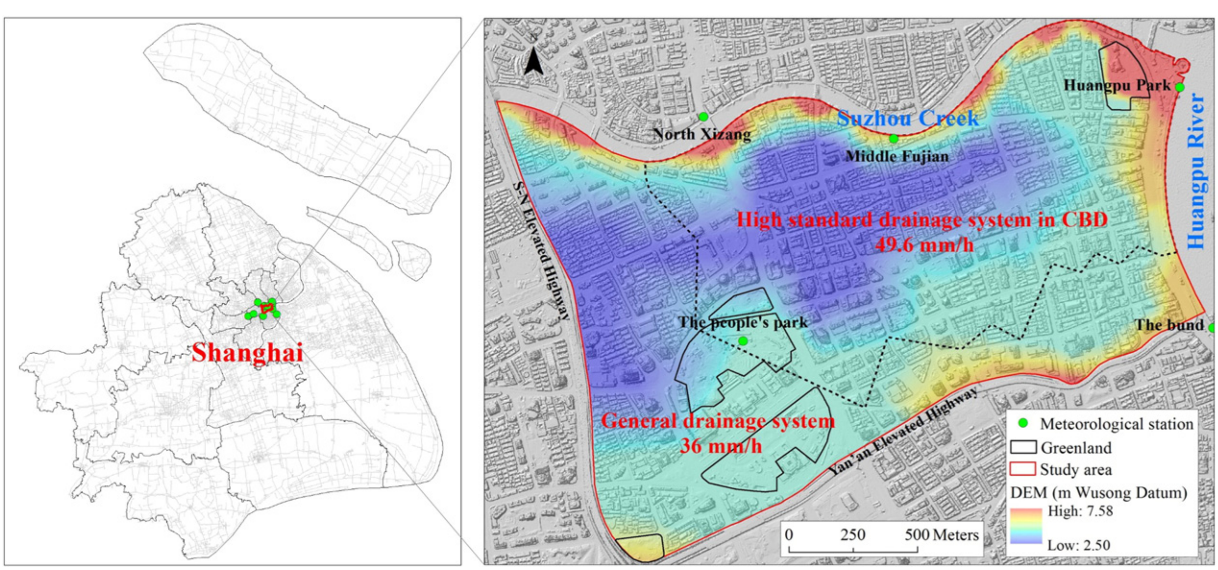

Fig. 1. Location of the study area, the black dot line divides the area into two parts (i.e. higher standard drainage area-CBD and general drainage area).