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Scenario-based projections of future urban inundation within a coupled hydrodynamic model framework: A case study in Dongguan City, China

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ABSTRACT

One major threat to cities at present is the increased inundation hazards owing to changes in climate and accelerated human activity. Future evolution of urban inundation is still an unsolved issue, given large uncertainties in future environmental conditions within urbanized areas. Developing model techniques and urban inundation projections are essential for inundation management. In this paper, we proposed a 2D hydrodynamic inundation model by coupling SWMM and LISFLOOD-FP models, and revealed how future urban inundation would evolve for different storms, sea level rise and subsidence scenarios based on the developed model. The Shiqiao Creek District (SCD) in Dongguan City was used as the case study. The model ability was validated against the June 13th, 2008 inundation event, which occurred in SCD, and proved capable of simulating dynamic urban inundation. Scenario analyses revealed a high degree of consistency in the inundation patterns among different storms, with larger magnitudes corresponding to greater return periods. Inundations across SCD generally vary as a function of storm intensity, but for lowlands or regions without drainage facilities inundations tend to aggravate over time. In riverfronts, inundations would exacerbate with sea level rise or subsidence; however, the inland inundations are seemingly insensitive to both factors. For the combined scenario of 100-yr storm, 0.5 m subsidence and 0.7 m sea level rise, the riverside inundations would occur much in advance, whilst catastrophic inundations sweep across SCD. Furthermore, the optimal low-impact development found for this case study includes 0.2 km^2 of permeable pavements, 0.1 km^2 of rain barrels and 0.7 km^2 of green roofs.

1. Introduction

Urban inundation is among the most severe and pervasive hazards, which can not only cause substantial social and economic problems, but also environmental and ecological consequences (Zheng et al., 2016; Yin et al., 2016). There is a consensus that urban inundation is exacerbating under rapid urbanization and climate change, which is challenging current urban flooding adaptations and defenses (IPCC, 2014; Du et al., 2012; Yin et al., 2015). In response to increased urban inundation, an increasing amount of attention has been given to the characterizations of these events, by both researchers and policymakers across the globe (Pall et al., 2011; Cherqui et al., 2015; Meesuk et al., 2015).

Due to hydrological and hydrometeorological variations driven by overall environmental change, urban inundation is becoming less predictable and more complicated, recurring with enlarging uncertainties (Hine and Hall, 2010; Aich et al., 2016). Although urban inundation has been long studied (Kaushik, 2006; Brown et al., 2007; Yu, 2010; Pall et al., 2011; Yin et al., 2011a,b; Zhou et al., 2012; Du et al., 2012; Alfieri et al., 2016), many of the literatures available attempt to address short-term or even real-time spatiotemporal variability of urban inundation with only a single influential factor considered (Yin et al., 2011a). Future evolution of urban inundation is subjected to multiple factors, such as extremes of weather and climate; sea level rise (for coastal cities) and land subsidence, however, are still less understood (Michel-Kerjan and Kunreuther, 2011; Jonathan et al., 2013; Yin et al., 2015). In this regard, the qualification of future urban inundation related to the combined impact of multiple influential factors is a challenging field of study, but it is an urgent need in terms of urban planning and disaster preparedness (Huong and Pathirana, 2013; Temmerman et al., 2013; Jongman et al., 2014; Aerts et al., 2014).

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Numerical simulation of flooding has been identified as a research priority in computational hydraulics (Liang and Smith, 2015). A variety of inundation models have been reported and applied to river (including the adjacent floodplain) inundation estimations (Bates and De Roo, 2000; Horritt and Bates, 2002; Lin et al., 2006; Yu and Lane, 2011; Alfieri et al., 2016). Modeling urban inundation is difficult and challenging, in part due to the complex interaction between sewer system and the overland surface in urban areas (Leandro et al., 2016). An effective way to reflect flow interchange between sewer and overland systems is to couple a one-dimensional (1D) sewer model with a two-dimensional (2D) overland model. Some of the coupled 1D/2D models allow rainwater to flow out of and return to the sewer system depending on the hydraulic conditions, for example, the MIKE 21 (Carr and Smith, 2006), Sobek Urban (Bolle et al., 2006), TUFLOW (Phillips et al., 2005), and the XP-SWMM (XP Software 2013). Nevertheless, a majority of these models acquire costly commercial modules that somewhat limit their uses, and open-source academic research models are relatively scarce until recently. More importantly, although there are a few open-source models developed for research purposes, their 2D routing schemes have the drawback of increased computational cost and sophistication of inundation modeling (Bates and De Roo, 2000). The possibility to propose a simple urban inundation model by integrating open-source 1D sewer and 2D floodplain models, however, has been preliminarily considered in very few publications (Leandro et al., 2009; Seyoum et al., 2012; Leandro and Martins, 2016).

These then are the motivations of our paper, where we disclosed an open-source and simple urban inundation model for academic purpose, and presented future perspectives on urban inundation under different rainstorms, sea level rise and land subsidence scenarios. The model couples the storm water management model (SWMM) with LISFLOOD-FP, both of which are respectively recognized as open-source and robust 1D sewer and 2D overland models with simple model structures (Bates and De Roo, 2000; Rossman et al., 2005). This coupled model does not rely on any commercial modules which can provide researchers another alternative to simulate urban inundation without access to commercial softwares, nor does it require specialized knowledge that is convenient for non-expert users (Bates et al., 2005; Rossman et al., 2005). Another advantage of the coupled model over other models is that the 2D component, LISFLOOD-FP, can be integrated with raster-based Digital Elevation Models (DEMs). This would be particularly useful and convenient under the backdrop of the increasing availability of high resolution DEMs for urban domains and the wide use of Geographic Information Systems (Bates and De Roo, 2000). For the scenario analyses, the Dongguan City located in the Pearl River Delta, China was taken as the case region. The future spatiotemporal variations of urban inundation in a changing environment would contribute to a detailed information for local inundation management and a guidance for inundation evaluations in other cities.

The remainder of this article is organized as follows. Materials and methods adapted are introduced, followed by the results and a discussion section. Finally, the conclusions are listed.

2. Materials and methodology

2.1. Study site

We chose the Shiqiao Creek District (SCD), one of the severest flood prone areas in Dongguan City, China for the case study. SCD is located in the mid-northern part of the downtown of Dongguan City, which covers approximately 2 km^2 with a low-lying topography. It borders with Xinhebei Road, Dongmen Road, Luosha Road, Qifeng Road, Bada Road, Keyuannan Road, and the Dongyin Canal (Fig. 1a). SCD is featured with a subtropical monsoon climate and the annual average rainfall and temperature are 1770 mm and 22 °C, respectively (Liao et al., 2014). SCD is an old downtown where urbanization is rather slow and the land use shows little change after 2000 (Liao et al., 2014). The urban land use accounts for over 80% of the total in this region. The drainage system of SCD can be divided into two parts, one being the sewer network and the other being the Dongyin Canal and Shiqiao Creek. Unlike the Dongyin Canal, the Shiqiao Creek is not an open channel, and is presently covered by Xinhe North Road and Dongmen Road (Fig. 1a). Generally, rainwater in SCD flows into the sewer network and the Shiqiao Creek, and then discharges into the Dongyin Canal. Although the sewer network has been reinforced several times in recent years, some pipes are unable to withstand rainfall with 1 year return period (1-yr hereafter).

Inundation exposure in SCD is increasing over the recent decades, due to local growing populations and assets, frequent extreme rainfall, and the low-lying topography. The inundation event occurred on August 20th, 2005 induced by an extreme storm, causing an economic loss of approximately US$15 million. Again, another extraordinary storm that hit SCD on Jun 13th, 2008 had widely paralyzed the traffic, caused the loss of eight lives, and over US$75 million in economic losses. Consequently, inundation protection in SCD needs to be upgraded and more works should be done to understand the temporal variation and spatial distribution of inundation in the future.

2.2. Data availability and processing

2.2.1. Topographic data

The DEM of SCD was available in the form of a high-resolution (1 × 1 m) elevation data set, which was processed and quality controlled by the Urban Planning Bureau of Dongguan City (UPBDC). In order to represent the blockage effect of buildings on surface flows, the building profiles were distinguished from the original DEM using a Google satellite image and the building heights were set to a fixed value of 10 m (the building layer in Fig. 1c).

2.2.2. Rainfall data

In this research, two major floods that occurred on Jun 13th, 2008 and August 20th, 2005 were used to calibrate and validate the proposed 1D/2D model, respectively. Meteorological Bureau of Dongguan City (MBDC) provided the corresponding rainfall records.

For most cities in China, municipal models of Intensity-Duration-Frequency (IDF) relationships characterizing local rainfall are frequently applied in engineering, particularly for municipal drainage design (Yin et al., 2011b, 2016). The rainfall intensities with the duration of two hours and the 1-yr, 2-yr, 5-yr, 10-yr, 20-yr and 100-yr return periods were formulated for the subsequent scenario analyses. According to the IDF formula of Dongguan rainstorm proposed by MBDC, rainfall intensity can be inferred through the following equation:

$$q = \frac{2094.861(1 + 0.506 \lg P)}{(t + 8.875)^{0.633}} \tag{1}$$

where q is the rainfall intensity, t is the duration of rainfall and P is the return period.

In addition to the IDF formula, the Chicago Hydrographic Model (CHM), which has been extensively used in both research and engineering fields (Yin et al., 2016; Zhu et al., 2016), was utilized to calculate peak intensities of the six design rainstorms and redistribute the rainfall amounts before and after the peaks with the relevant