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Evaluating the impact and risk of pluvial flash flood on intra-urban road network: A case study in the city center of Shanghai, China

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SUMMARY

Urban pluvial flood are attracting growing public concern due to rising intense precipitation and increasing consequences. Accurate risk assessment is critical to an efficient urban pluvial flood management, particularly in transportation sector. This paper describes an integrated methodology, which initially makes use of high resolution 2D inundation modeling and flood depth-dependent measure to evaluate the potential impact and risk of pluvial flash flood on road network in the city center of Shanghai, China. Intensity–Duration–Frequency relationships of Shanghai rainstorm and Chicago Design Storm are combined to generate ensemble rainfall scenarios. A hydrodynamic model (FloodMap-HydroInundation2D) is used to simulate overland flow and flood inundation for each scenario. Furthermore, road impact and risk assessment are respectively conducted by a new proposed algorithm and proxy. Results suggest that the flood response is a function of spatio-temporal distribution of precipitation and local characteristics (i.e. drainage and topography), and pluvial flash flood is found to lead to proportionate but nonlinear impact on intra-urban road inundation risk. The approach tested here would provide more detailed flood information for smart management of urban street network and may be applied to other big cities where road flood risk is evolving in the context of climate change and urbanization.

1. Introduction

Pluvial flash flood (PFF) is among the most common and destructive natural hazards, resulting in considerable direct losses (e.g. personal injury and property damage) and increasing indirect impacts (e.g. interruption of public services and economic activities), especially in the urbanized areas around the world (e.g. Ramos et al., 2005; Mejia and Moglen, 2010; Smith et al., 2012; Wright et al., 2012). PFF is a rapid flood caused by heavy rain and can be distinguished from a regular pluvial flood by a short timescale, generally less than six hours. It is usually by their very fast evolution and occurs within minutes or a few hours of excessive rainfall (Naulin et al., 2013). There exists a broad consensus that the combined effect of climate change and rapid urbanization is generally recognized as the primary cause for more frequent, heavier rainfall–runoff (IPCC, 2013; Du et al., 2012; Suriya and Mudgal, 2012; Zhou et al., 2012). Furthermore, the lack of anticipation of PFF events such as the unavailability of short-term forecasting and warning, combined with insufficient, postponed adaption measures (e.g. inadequate drainage capacity) largely limit the efficiency of urban flood risk management, leading to the enhanced consequences of these events in most cities.

In all the flood prone areas, urban road network may be the major assets affected first by inundations, which cause not only infrastructure damage but also transportation disruption, due to its low-lying nature compared to the neighborhood and high-density throughout urban territory. More seriously, almost half of the flash flood casualties involve people on flooded roads by trapping in their cars or by escaping in the rapid rise of open water (Drobot et al., 2007; Versini et al., 2010a). Over the past several decades, the significant disasters associated with street networks and PFF events have been frequently occurring in different urban environments such as New York and London in developed countries as well as Beijing and Bangkok in developing countries (Pitt, 2008; Hung et al., 2009; NYC Emergency Management, 2014). Road networks of China's cities are particularly vulnerable to PFF events as the conflict between rapid urbanization and the lagging urban

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(infrastructure) planning is emerging onto the surface. This is evidenced by the recent PFF events in major Chinese cities, including Beijing, Shanghai, Guangzhou, Shenzhen, Nanjing, and Hangzhou (Zhang et al., 2012). For example, the July 2012 PFF event in Beijing city led to widespread transportation disruptions and claimed 79 lives, among which a large number of fatalities were caused by road inundations (Yin et al., 2015).

Although there is a huge demand for understanding urban road network risk to PFFs, until now, very few work have attempted to systematically examine the potential impacts of flash flood events on urban road systems largely due to the lack of adequate data and observations concerning road flooding, difficulty in numerically modeling the PFF dynamics and the complexity of cascading effects resulting from temporary flooding on transportation systems (Suarez et al., 2005). Of the existing studies, a number of studies are often conducted for the purpose of flood emergency evacuation (e.g. Chang et al., 2007), accessibility loss (e.g. Sohn, 2006) or traffic delay (e.g. Zhou et al., 2012), while some others address short-term (and even real-time) forecasting or warning of road inundation risk (RIR) at specific intersections of streams and roads. In terms of road flood risk assessment, the extension of distributed hydro-meteorological model to road network scan approach have been usually applied or tested in a number of regions. A representative methodology is Road Inundation Warning System (RIWS) which combines a rainfall–runoff model with a road inundation susceptibility analysis (Versini et al., 2010b). Chang et al. (2010) integrated a hydrologic model (PRMS), a 1D hydraulic model (HEC-RAS) and a travel forecast model into an assessment framework of urban flooding and transportation systems. Moreover, a LRSRM (Local Regional Scale Risk Model) was designed to identify the interruption of a road network due to a hazardous event from a multi-scale perspective by using the biclustering technique (Freiria et al., 2014). The previous studies, however, mainly focus on regional (basin) scale and intercity level, paying little attention to PFF-induced RIR at the intra-urban level. Also, they can not explicitly provide detailed information of 2D surface flood routing on urban road network in time and space to allow a real-time risk management. In recent years, the development of simplified raster-based flood models (e.g LISFLOOD and FloodMap) combined with the existing high resolution LiDAR (i.e. airborne and terrestrial laser scanners) techniques makes it possible to accurately simulate PFF processes on intra-urban roads and the output inundation maps (both flood depth and spatial extent) could further be used to identify the road network at risk and to take the appropriate risk mitigation measures (Bates and De Roo, 2000; Yu and Lane, 2006a, b; Sampson et al., 2012).

Within this study, an integrated methodology is proposed by incorporating flood inundation modeling, transportation disruption (i.e. road closure) detection and risk assessment to measure the impact and risk of PFF on intra-urban road networks. This is the first attempt to apply high resolution 2D hydrodynamic model and flood depth-dependent measure for evaluating the impact of pluvial flooding on road disturbance at the intra-urban level. The city center of Shanghai, China, where roads are in particular prone to pluvial flash flooding, is selected as a case study area. The road inundation risk analysis is focused on transportation disruption rather than on infrastructure damage due to PFFs. The main objectives in this paper are to: (a) develop a step-by-step approach to investigate the transportation impact from temporary pluvial flooding for intra-urban road network; (b) explore the spatio-temporal characteristics of pluvial flash flooding on intra-urban roadways; (c) quantify intra-urban transportation disruption risk under a range of PFF magnitudes. The rest of this paper is organized as follows: Section 2 is devoted to the presentation of the materials and methods, including the introduction of study area, the available data, the description of flood modeling, road impact and risk assessment; Section 3 presents the results and discussions; the conclusions are given in Section 4.

2. Materials and methods

2.1. Study area

The city center of Shanghai, China has been chosen as study site because it exhibits high risk of pluvial flash flooding and also associated impact of transportation disruption. The study area located at the junction of Huangpu River and Suzhou Creek, bordering with South–North Elevated Highway and Yan'an Elevated Highway (Fig. 1). It covers about 3.25 km^2 on the north part of Huangpu District with a mild and low-lying topography (about 3 m above Wusong Datum). The region belongs to a northern subtropical monsoon climate characterized by four distinctive seasons, receiving an annual average rainfall of 1122 mm (Yin and Zhang, 2014). The area is frequently affected by cyclonic storms and intense convectional precipitation occurring especially during the flood season (June to September). According to Quan (2014), pluvial flooding is accounted for more than half of the total flood events from 251 to 2000 in Shanghai, mostly in urban area.

The study site has historically been the city center of Shanghai since its opening to the outside world in the mid nineteenth century. Therefore, it is dominated by various urban landscapes, for instance, crowded buildings, high road intensity and considerable areas of impervious surface except a few green open spaces (e.g. the people's park) in the southwest region. Like most city center, it has a heavy traffic, especially during the morning and evening rush hours. Severe road flooding occurs at least once every few years on average due to flash and heavy rainfalls (Shi et al., 2010; Wu et al., 2012). To protect against intensified pluvial flood hazards, the pumps and sewer systems have been reinforced several times over the past decades. At present, the drainage system in the study area can be divided into two parts: (1) high standard system which is designed to withstand 1 in 3 year rainfall (49.6 mm/h) for the central business district, and (2) general system designed to deal with 1 in 1 year rainfall (36 mm/h) for the other region.

2.2. Data availability and processing

2.2.1. Rainfall data

As the external driving force of pluvial flooding, precipitation information should be used as an input to flood hazard analysis. Most of cities in China have their own municipal models of Intensity–Duration–Frequency (IDF) relationships to account for local precipitation characteristics. On the basis of Shanghai rainstorm IDF formula which is developed by Shanghai Municipal Engineering Design Institute and applied for municipal drainage design, the rainfall intensities with the duration of one hour and the return period of 1 in 5, 10, 20, 50 and 100 years are formulated to cover the probable inundation situations (Yin et al., 2011). The formula can be expressed as follows:

$$q = 1995.84(P^{0.30} - 0.42)/(t + 10 + 7\lg P)^{0.82+0.07\lg P} \quad (1)$$

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

Considering the rainfall temporal variations, Chicago Design Storm, which has been extensively applied in the design storm, is employed to calculate peak intensity and then redistributes the rainfall before and after the peak with the relevant spectrum of durations (Keifer and Chu, 1957). The parameter r (i.e. the ratio of time of the peak to the total), is empirically fixed at 0.4 in Shanghai city. This, in combination with Shanghai IDF analysis,