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The potential effect of a 100-year pluvial flood event on metro accessibility and ridership: A case study of central Shanghai, China

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ABSTRACT

The Shanghai Metro constitutes a sizeable share of the municipal public transit. This paper presents a gravity-based approach for evaluating the potential effect of a 100-year pluvial flood (PF) event on metro accessibility and ridership. Since physical geographers have examined PF hazards and human geographers have analyzed metro accessibility separately, we seek to fill the research gap through examining metro accessibility and ridership together under adverse circumstances. To this end, road inundations are initially modeled by FloodMap-HydroInundation2D. Accessibility to metro stations by three access modes (walking, cycling, and driving) is measured through three impedance functions (inverse power, negative exponential, and modified Gaussian). Ridership measure mainly concerns the distance-decay effect on stations' attraction for passengers. The results indicate that inundation depth on more than 95% of the road links would reach 10–20 cm in the PF scenario, and road links with inundation deeper than 20 cm and 30 cm account for 47% and 15% of the road network respectively, which imposes notable restrictions on access journeys especially by cycling and driving. Metro accessibility in central Shanghai is quite equitable, even in the PF scenario. 87% of the communities can access the metro stations at the *medium* and *medium-high* accessibility levels in the normal scenario, but 80% can access only at the *low* and *medium* levels in the PF scenario. Due to the inaccessibility of neighboring station(s) in the PF scenario, 15 more stations may face the challenge of serving more than 50,000 passengers, which is much larger than their normal ridership. These findings have important implications for the formulation of safer usage of public transport in the face of heavy rainfall and associated flood events.

1. Introduction

Although more and more urban residents in China can afford private cars as a daily transport mode, the usage of public transit (PT) has persistently outpaced that of private automobiles, especially with the accelerated construction of metro systems in several big cities (Chen et al., 2012, 2014; Li et al., 2017; Pan & Zhang, 2008; Wang, Feng, Deng, & Cheng, 2016; Zhao, Deng, Song, & Zhu, 2013). Public transit has both environmental and social advantages. It can alleviate traffic congestion and air pollution (May, Shepherd, & Timms, 2000; Chiou, Jou, and Yang, 2015) as well as promote health by encouraging walking and cycling to and from transit stations (Elias & Shiftan, 2012). Further, through improving access to education, jobs, and other facilities, public transit can help reduce social exclusion and inequity. Individuals without private vehicles also can interact with others or participate in social activities when distance is the major barrier (Farrington & Farrington, 2005; Langford, Higgs, & Fry, 2012; Hine & Mitchell, 2017).

Metro transport (i.e., the public rail transit system) constitutes a sizeable share of public transit in Shanghai. Metro users have doubled during the past decade (*Annual Transportation Report for Shanghai*, 2016). In general, the attractiveness of metro transit depends on three factors: the accessibility to stations, the quality of the metro service, and the characteristics of travelers (Debrezion, Pels, & Rietveld, 2009; Moniruzzaman & Páez, 2012; Karou & Hull, 2014). Among them, improving accessibility to stations is a more economical and flexible way to keep the metro system as a preferred transport mode among various travelers (Brons, Givoni, & Rietveld, 2009; Crockett & Hounsell, 2005). Moreover, metro-based accessibility to different places also largely

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depends on the accessibility of metro stations (Cheng & Chen, 2015; Mavoa, Witten, McCreanor, & O'sullivan, 2012; Weber, 2003). Because travelers do not live and work at metro stations, they need to take some access and egress journeys between the stations and their homes, work places, and other destinations before getting on the metro and after getting off from it (Taniguchi, Thompson, & Yamada, 2013).

Metro ridership is an issue that often accompanies metro accessibility. Obviously, higher accessibility of metro stations can promote greater ridership (Gutiérrez, Cardozo, & García-Palomares, 2011; Lin & Shin, 2008). Using regression models, Sohn and Shim (2010) investigated the effect of the built environment, external connectivity, and intermodal connections on the weekly average boarding at metro stations in the Seoul metropolitan area. Chan and Miranda-Moreno (2013) developed a trip production and station attraction model for the metro network in Montreal, Quebec, and found that improving bus transit connectivity was an effective way to maximize metro ridership. Li et al. (2017) conducted a two-dimensional accessibility analysis of the metro stations in Xi'an, China. One dimension is stations' attraction, which refers to the ease of reaching stations by using certain modes of transport. They concluded that walking connection is a key factor to improve the stations' overall accessibility. Likewise, in the work of Sun, Zacharias, Ma, and Oreskovic (2016), particular attention was paid to walkability to metro stations in three types of built environments in Beijing. They asserted that better connectivity, pedestrian-friendly designs and higher building coverage ratio around the metro station might promote easier walking access and have the potential to capture more metro riders.

To the best of our knowledge, all of the above studies were designed and implemented under normal conditions. However, access and egress journeys to and from metro stations could be inconvenient, unpleasant, or unsafe if there are unexpected barriers or obstacles (Dantas, 2005; Loutzenheiser, 1997), such as construction activities, heavy traffic/traffic accidents, or road flooding. Therefore, understanding and measuring metro accessibility under adverse circumstances may have additional implications for the formulation of safe and sustainable use of public transit. This paper aims to measure the effect of a 100-year pluvial flood event on metro accessibility and potential ridership, and the metro system in central Shanghai, China (i.e., the Shanghai Metro) is used as a case study to present the method. On one hand, Shanghai is a city prone to pluvial floods, which often cause serious traffic disruption due to decreased road network connectivity (Li, Huang, Wang, Yin, & Wang, 2018; Yin, Yu, Yin, Liu, & He, 2016b). On the other hand, the metro system is embedded in the entire transportation network of the metropolitan area. If a metro station becomes inaccessible, it may need to accommodate a large crowd of stranded passengers, or its neighboring stations may have to serve a much larger ridership than usual. For reasons like these, the abnormal increase in the number of passengers who need to be accommodated as a result of adverse events may raise safety concerns (e.g., serious injuries as passengers are crushed or trampled).

Note that to best capture the influence of floods, we ignore the effect of travelers' characteristics and the built environment where metro stations are located. In particular, accessibility and ridership were measured from the perspective of network connectivity and distance-decay effect using ArcGIS Network Analyst. Although pluvial flood hazards and public transit accessibility have been examined separately in past studies, our work contributes to the literature by combining these two issues and filling the research gap of evaluating metro accessibility under adverse circumstances.

2. Study area, data, and methods

2.1. Study area

2.1.1. Pluvial floods in Shanghai

Shanghai is a coastal city with low-lying topography (average elevation is 4 m above the Wusong Datum). With a northern subtropical monsoon climate, it often receives some cyclonic storms and heavy rainfall during the flood season (June–September). In the context of climate change and rapid urbanization, Shanghai's urban area is prone to pluvial floods due to extensive changes of many areas from natural land cover to built-up areas with impervious surface and inadequate drainage systems to accommodate those changes (Yin, Yu, & Wilby, 2016a, 2015). In the past five years, there is constant news and research reporting that the road traffic or metro lines were disrupted by serious road inundations during torrential rains (Chinanews.com, 2013; news.weather.com, 2015; Yin et al., 2016b; Li et al., 2018). Specifically, although most metro stations are constructed with the capability to resist inpouring floods (Quan, 2016), the metro system may fail to perform normally if one or more stations become inaccessible when the roads used to access them are flooded.

2.1.2. The metro system in Shanghai

As the core of the Yangtze River Delta Megalopolis and the nation's center for commerce, finance, and trade, Shanghai has attracted a huge population since the open-door policy of China was implemented in 1978 (http://www.stats-sh.gov.cn/tjnj). Today it supports approximately 24.2 million residents (http://www.stats-sh.gov.cn/tjnj/tjnj2016.htm). To accommodate the rapid population growth and associated large traffic demand, the construction of the Shanghai Metro began in the 1990s. The year 1993 witnessed the completion and operation of the first metro line (Line 1). Meanwhile, Shanghai became the third city (after Beijing and Tianjin) in China to have a metro system. By 2017, just in 15 years, Shanghai has constructed 16 metro lines (Lines 1–13, 16, 17, and the maglev [magnetic levitation]) connected by 389 stations (see Fig. 1). Besides, three new lines (Lines 14, 15, and 18) are under construction, and three existing ones (Lines 5, 10, and 13) are being expanded for larger coverage. The total length of the Shanghai metro lines in operation is 666 km, which is even longer than that of Beijing and any other Chinese cities with a metro system (data is from baike.baidu.com/item/Shanghai Metro). In 2016, the annual average daily passengers by metro transit are about 9.29 million (also greater than the 8.24 million in Beijing), which accounts for almost half of the entire daily passengers by all modes of transport (18.32 million) (*Annual Transportation Report for Shanghai*, 2016). As it were, the introduction of the Shanghai Metro has created a new time-space map in Shanghai (i.e., the relative travel time among destinations has changed drastically).

This study focuses mainly on the central urban area of Shanghai, where the metro network is rather dense, and where almost 70% of the stations are located. Although accounting for only 10% of the city's territory (total area is 6340 km^2), the central urban area supports almost half of its population and economic activities, and it has a very strong ability to agglomerate large commercial centers and important service facilities, inherently associated with plentiful human activities and traffic demand. The metro is largely preferred by various travelers for various trip purposes (e.g., commuting, shopping, and entertaining) to avoid severe traffic congestion in this area.

2.2. Modeling a 100-year pluvial flood

2.2.1. Data requirements

Two important datasets are required as input for modeling the hydrodynamic process of a pluvial flood (PF) event: rainfall data and topography data. The former is the external driving force of flooding, while the latter determines the surface flow direction and the inundation depth at a certain location.

To generate the 100-year PF scenario, we employed the Shanghai rainstorm Intensity–Duration–Frequency (IDF) model to describe the relationships between rainfall intensity and the return period of 100 years with the duration of one hour (see Equation (1)). This model is developed by the Shanghai Municipal Engineering Design Institute and