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Approach for evaluating inundation risks in urban drainage systems

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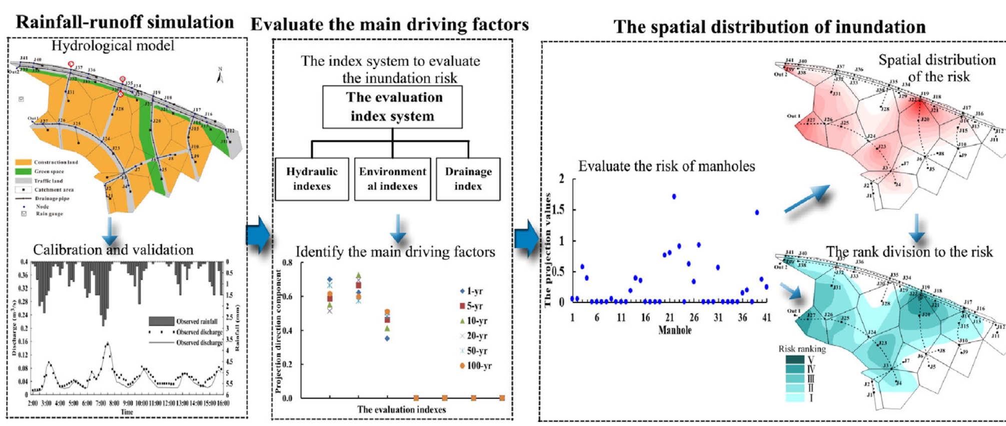
HIGHLIGHTS

- An approach to evaluate the inundation risks in urban drainage systems is developed.
- This approach coupes a hydrological model with an index-based method.
- The projection pursuit method is used to estimate the weights of the indices.
- The approach can identify the main driving factors, hotspots and areas of the risk.
- A case study is presented to illustrate the approach and prove its feasibility.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban inundation is a serious challenge that increasingly confronts the residents of many cities, as well as policymakers. Hence, inundation evaluation is becoming increasingly important around the world. This comprehensive assessment involves numerous indices in urban catchments, but the high-dimensional and non-linear relationship between the indices and the risk presents an enormous challenge for accurate evaluation. Therefore, an approach is hereby proposed to qualitatively and quantitatively evaluate inundation risks in urban drainage systems based on a storm water management model, the projection pursuit method, the ordinary kriging method and the K-means clustering method. This approach is tested using a residential district in Guangzhou, China. Seven evaluation indices were selected and twenty rainfall-runoff events were used to calibrate and validate the parameters of the rainfall-runoff model. The inundation risks in the study area drainage system were evaluated under different rainfall scenarios. The following conclusions are reached. (1) The proposed approach, without subjective factors, can identify the main driving factors, i.e., inundation duration, largest water flow and total flood amount in this study area. (2) The inundation risk of each manhole can be qualitatively analyzed and quantitatively calculated. There are 1, 8, 11, 14, 21, and 21 manholes at risk under the return periods of 1-year, 5-years, 10-years, 20-years, 50-years and 100-years, respectively. (3) The areas of levels III, IV and V increase with increasing rainfall return period based on analyzing the inundation risks for a variety of characteristics. (4) The relationships between rainfall intensity and inundation-affected areas are revealed by a logarithmic model. This study proposes a novel and successful approach to assessing risk in urban drainage systems and provides guidance for improving urban drainage systems and inundation preparedness.

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1. Introduction

Numerous devastating and record-breaking rainfall events have occurred in the past two decades (Piao et al., 2010; Coumou and Rahmstorf, 2012; Chen et al., 2015). Consequently, inundation control and urban drainage systems must overcome substantial challenges (Fu et al., 2011). In recent years, extreme rainfall events have paralyzed many cities and resulted in enormous economic losses, injuries and deaths (Chen et al., 2013). For instance, on August 12, 2002, the weather station of Zinnwald-Georgenfeld recorded the highest rainfall amount (312 mm) in a single day in Germany, and this event caused severe flooding (Becker and Grunewald, 2003). In England, the rain depth for the period from May to July 2007 was 406 mm (the previous record between 1766 and 2007 was 349 mm), but a new 24-h rainfall record (316 mm) was obtained at Seathwaite in Borrowdale in 2009 (Coumou and Rahmstorf, 2012). Extreme rainfall has caused severe flooding and significant losses in England over the past 15 years (Pall et al., 2011). Similarly, record-breaking precipitation events have affected a number of Asian cities. The worst flooding in Pakistan was caused by record rainfall in July 2010. The heaviest rainfall (460 mm of rainfall in 24 h) fell on a hydrological station in Beijing on July 21–22, 2012, and this event caused at least 79 deaths and affected more than 1.9 million people (Jiang et al., 2014). Worse still, more and more studies indicate that the frequency of drainage systems surcharging is expected to increase (Madsen et al., 2009; Larsen et al., 2009). In response to increased inundation risk, managing inundation risk is important (Zhou et al., 2012).

Traditionally, research investigating the load and inundation risk of urban drainage systems considers four primary types of approaches. (1) The historical disaster mathematical statistics method. Nott (2006) proposed that long-term sequenced historical flood materials should be one of the most important references for flood disaster risk assessments. Although the evaluation results generally reflect the complete situation of a study area, the approach requires a substantial amount of data and cannot accurately reflect spatial variability. (2) Geographic information systems (GIS) and remote sensing technologies. Meesuk et al. (2015); Sampson et al. (2012); Fernández and Lutz (2010), and Tanavud et al. (2004) used the GIS and remote sensing method for disaster risk assessments in urban areas and provided technical support for inundation risk assessments. However, the development of different technologies has been restricted by high costs and low precise. (3) Multi-criteria analysis. This approach can generally measure and reflect the conditions of regional risks and has been discussed in a host of studies. Jiang et al. (2009) and Tanavud et al. (2004) analyzed the urban flood disaster risk by constructing an evaluating indicator system with satisfactory results. However, this method features a few drawbacks, such as the influence of subjective factors. (4) Scenario simulation analysis in terms of analyses of flood disaster risk and assessments of different scenarios at varying spatial scales (Willems, 2013). This technique involves geomorphological, topographical, and urban drainage system data. Multiple methods have been utilized in previous studies (Karamouz et al., 2010; Tripathi et al., 2014; Chang et al., 2015).

Indisputably, these four approaches are important ways to assess and manage inundation risk, but the qualitative and quantitative methods for assessing inundation hotspots or areas and the relationship between inundation risk and spatial location remain lacking. Inundation risk evaluation is often only uses one of these approaches to identify hotspot manholes or areas prone to inundation (Cherqui et al., 2015). The application of a combination of these approaches is rare. As inundation risks in urban drainage systems with different manholes have different characteristics and intensities, qualitative and quantitative spatial analysis of inundation impacts should be taken into account (Ahmadisharaf et al., 2015). In addressing this challenge, Wei et al. (2014) coupled an evaluation index system and hydrological models to assess and forecast spatial flood risk in the urban context. In other words, numerical models were coupled to multi-criteria analysis to accounting for spatial variability in the inundations.

Inundation risk management is multifaceted and complex and is affected by different factors, involving different tradeoffs, various environment factors and competing alternatives (Kazakis et al., 2015; Radmehr and Araghinejad, 2015; Schröter et al., 2014). Most of traditional inundation evaluation methods such as the analytic hierarchy process (Saaty, 1988), grey relational analysis (Wei, 2011) and fuzzy comprehensive evaluation (Gong and Jin, 2009), are influenced by contrived factors or homogenization. Thus, a comprehensive evaluation needs a method that can account for multiple inundating characteristics. Under such circumstances, the projection pursuit method can assist inundation management by providing a comprehensive and systematic evaluation to deal with these complex factors (Jin and Zhang, 2002).

However, Ahmadisharaf et al. (2015) revealed that some of inundating characteristics (e.g. duration and velocity) are often ignored, despite being very important for understand the effects of the inundation. Additionally, the need for detailed consideration of duration and velocity has been demonstrated by Kreibich et al. (2009) and Pistrika and Jonkman (2010). Nonetheless, these criteria have not received enough attention in evaluations of inundation management strategies.

This study introduces an approach for assessing the inundation risk of current urban drainage systems. In this approach, a storm water management model (SWMM) and a multi-indices system are coupled to account for spatial variability in manholes inundation risk. The multi-indices system includes duration, velocity, drainage and environmental indices, and the weight of each index is calculated using the projection pursuit method. It was developed to (1) simulate and analyze drainage system responses to different rainfall scenarios; (2) analyze the main driving factors and evaluate the risk to each manhole under different rainfall scenarios; (3) evaluate and analyze the spatial distribution characteristics of inundation risks; and (4) develop a model that reflects the causality between rainfall intensity and the largest area affected by inundation to predict inundation areas under different rainfall scenarios.

2. Research area

The study area (Fig. 1) covers a total area of 0.43 km^2 and is located in the southwest of Guangzhou, China (22.078–23.086°N and 113.201–113.214°E). This area is primarily used for construction, with a small area is used for transportation and green space. The drainage system (with pipe diameter between 600 mm and 1650 mm and slopes between 0.001 and 0.01) has a rain and sewage diversion system, and the designed standard of flooding is based on the scenario of 'once in two years.'

To study the relationship between the runoff and rainfall in this area, three manholes (A, B and C) were selected to monitor the runoff, and three Stingray open channel gages (Greyline Instruments, Inc.; Germany) were used to collect the runoff data (Fig. 1). For the rainfall, a RainLogger™ rain gauge (RainWise, Inc.; USA) was used to record the rainfall data. The rainfall and runoff data were recorded simultaneously, and the interval between measurements was 10 min.

Based on the drainage system, the hydrographic conditions and the principles of the SWMM, the area was divided into 25 subcatchments, and the drainage system generally consisted of 41 pipes, 45 manholes and 2 outlets (Fig. 1).

3. Methodology

The approach to evaluating inundation risks in urban drainage systems is divided into three primary phase. In the first phase, a rainfall-runoff simulation is based on a high-precision rainfall-runoff model of the study area. In the second phase, the projection pursuit method is applied to calculate the weights of the evaluation indices to determine the main driving factors. In the third phase, the inundation distribution