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The effects of low impact development on urban flooding under different rainfall characteristics

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ABSTRACT

Low impact development (LID) is generally regarded as a more sustainable solution for urban stormwater management than conventional urban drainage systems. However, its effects on urban flooding at a scale of urban drainage systems have not been fully understood particularly when different rainfall characteristics are considered. In this paper, using an urbanizing catchment in China as a case study, the effects of three LID techniques (swale, permeable pavement and green roof) on urban flooding are analyzed and compared with the conventional drainage system design. A range of storm events with different rainfall amounts, durations and locations of peak intensity are considered for holistic assessment of the LID techniques. The effects are measured by the total flood volume reduction during a storm event compared to the conventional drainage system design. The results obtained indicate that all three LID scenarios are more effective in flood reduction during heavier and shorter storm events. Their performance, however, varies significantly according to the location of peak intensity. That is, swales perform best during a storm event with an early peak, permeable pavements perform best with a middle peak, and green roofs perform best with a late peak, respectively. The trends of flood reduction can be explained using a newly proposed water balance method, i.e., by comparing the effective storage depth of the LID designs with the accumulative rainfall amounts at the beginning and end of flooding in the conventional drainage system. This paper provides an insight into the performance of LID designs under different rainfall characteristics, which is essential for effective urban flood management.

1. Introduction

Urban drainage systems are generally designed to drain surface runoff from urban areas (e.g. paved streets, parking lots, sidewalks and roofs) during storm events. However, excess stormwater exceeding the drainage capacity can cause urban flooding and result in traffic interruption, economic loss, pollution and health issues. An increase in impervious land cover leads to more surface runoff, faster runoff concentration and higher peak flow rate. Thus there is an increasing need to improve drainage capacity to reduce flooding in rapidly urbanizing areas.

Traditionally, the improvement of drainage capacity relies on expanding and upgrading the existing storm drainage system. However, this has been increasingly proven to be unsustainable, costly and even impractical, particularly in densely urbanized areas. Many new stormwater management techniques have been developed to tackle the urban runoff problem, such as green roofs, permeable pavements, swales, bioretention systems. Collectively these techniques have been termed Low Impact Development (LID) in US (or Sustainable Drainage Systems in UK or Water Sensitive Urban Design in Australia). Generally speaking, these techniques rely on distributed runoff management measures that seek to control stormwater by reducing imperviousness and retaining, infiltrating and reusing stormwater on the development site where it is generated (Graham et al., 2004). LID has been recommended as an innovative solution for stormwater management (Andoh and Declerck, 1997; Montalto et al., 2007; Palhegyi, 2009).

The hydrological performance of the LID techniques has been studied on a laboratory and pilot scale as well as an in-situ full scale. For example, Dietz (2007) reported that a green roof can reduce 60–70% of stormwater volume compared to a conventional roof. Alfredo et al. (2010) found that green roofs can delay and prolong the roof discharge and reduce its peak rate by 30–78% compared to a standard roof surface. Abbott and Comino-Mateos (2003)

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measured the outflow from a car park with a permeable pavement system and found that on average, only 22.5% of runoff leaves the system during a storm, and that a 2-h storm event takes two days to drain out of the system. Fassman and Blackbourn (2010) found that the peak flow from a permeable pavement underdrain is less flashy and tends to show less variation overall than that from asphalt surface during storms. Chapman and Horner (2010) reported that a street-side bioretention facility in Washington can achieve 26–52% of runoff retention in real-weather conditions.

Further studies indicated that the LID performance on runoff control is significantly different in the storms with different rainfall intensities. Lee et al. (2012) found that the use of LID facilities in a demonstration district of AsanTangjung New Town can reduce the flood peak discharges of 50- and 100-year return periods by about 7–15% at a wider catchment scale. Holman-Dodds et al. (2003) monitored disconnected impervious areas and recorded reduced runoff at the site, as compared to traditional development. The greatest reduction was observed for small, relatively frequent rainfall events. Hood et al. (2007) compared runoff volume, peak discharge, and runoff coefficient of low impact residential development with traditional residential development in Waterford, Connecticut. The study showed that the effects of LID on runoff reduction were greater for smaller storms with shorter durations. Damodaram et al. (2010) used a hydrologic model to estimate the effects of LID choices on the stream flow of a wastershed located on the campus of Texas A&M University, Texas, and they found that LID is able to control stormwater for small storms, whereas LID is not nearly as effective as conventional detention ponds for flooding events. Therefore, LID approaches cannot completely substitute for the conventional urban drainage systems to control storm runoff. In order to provide control for an entire spectrum of storm events, a more effective strategy would be to incorporate LID approaches into the conventional drainage system (Damodaram et al., 2010; Guo, 2010). Although the LID performance on reducing runoff volumes and peak flow rates has been extensively investigated, few studies have attempted to evaluate the effects of LID designs on urban flooding in a conventional urban drainage system, i.e., how a LID design can affect the performance of urban drainage systems. In addition, research has shown that rainfall characteristics (e.g., total amount, duration and location of intensity peak) have significant effects on flood risk management of conventional drainage systems (e.g., Fu et al., 2011; Hvitved-Jacobsen and Yousef, 1988). However, to date, a holistic evaluation of LID designs under a variety of rainfall amounts, rainfall durations and locations of peak rainfall intensity have not been studied regarding urban flooding.

This paper focuses on analyzing the performance of an urban drainage system in an urbanizing area of Shenzhen, China, where some LID practices are designed to reduce urban flooding. The performance of the urban drainage system is measured by flood volume, which is defined as the total flood volume from the conventional drainage system during a storm event. Using a simulation model, this paper aims to (1) characterize effects of three typical LID designs (swales, permeable pavements and green roofs) on flood volume; and (2) investigate flood volume reduction under storm events with different rainfall amounts, rainfall durations and locations of peak rainfall intensity. A simple method based on the water balance theory is developed to provide a theoretical understanding of the simulation results, i.e., to explain the impacts of various LID designs on flood reduction under different rainfall characteristics. This study provides an overall evaluation of LID effects on urban flooding and can support decision making in urban flood control by integrating LID designs in a conventional drainage system.

The paper is organized as follows. Section 2 describes the hydrological model, design scenarios and method for flood reduction estimation. In Section 3, sensitivity of LID design parameters, effects of various LID designs, and effects of different rainfall characteristics on urban flooding are presented and discussed. And finally conclusions are drawn in Section 4.2 Material and methods.

2. Material and methods

2.1. Study area

The study catchment is located in the southwest of Guang-Ming New District (GMND), which is a newly established district of Shenzhen, southeast China (Fig. 1). GMND has a total area of 156 km^2 and a population of 0.8 million. The study catchment has a drainage area of 0.60 km^2, and is largely covered by Quaternary loose deposits. The soil is mainly sandy gravel with silty clay, mucky soil and silt. The groundwater level in this area is around 2–14 m below the surface. The study area had been a rural area with 90% of pervious land-use before a high speed rail station was built in 2011. According to the local urban planning, the percentage of land uses for residence, high-tech industry, open green, commerce and the rail station (including its service area) will be 28.1%, 9.7%, 12.2%, 42.6% and 7.4% by 2020, respectively.

The study area has a mild, subtropical maritime climate with a mean annual temperature of 22.4 °C and mean annual precipitation of 1933 mm, 85–90% of which falls from April to September. Shenzhen frequently suffers from heavy storms during the typhoon season from June to August. In recent years, with the rapid urbanization, impervious land cover has substantially increased and caused more surface runoff, faster runoff concentration and higher peak flow rate, while the drainage facilities have not been upgraded correspondingly. Urban flooding has become one of the most frequently occurred hazards in Shenzhen. According to the local drainage system planning (Urban Planning & Design Institute of Shenzhen, 2008), the pipe drainage system will be designed to have a capacity to drain the surface runoff from a design storm with a 2-year return period. However, the surface runoff from a heavier storm may exceed the drainage capacity, and cause flooding in some low-lying areas. To resist the runoff from heavier storms, LID has been promoted in GMND, and some LID practices such as swales, permeable pavements and green roofs will be applied for the first time in the study area.

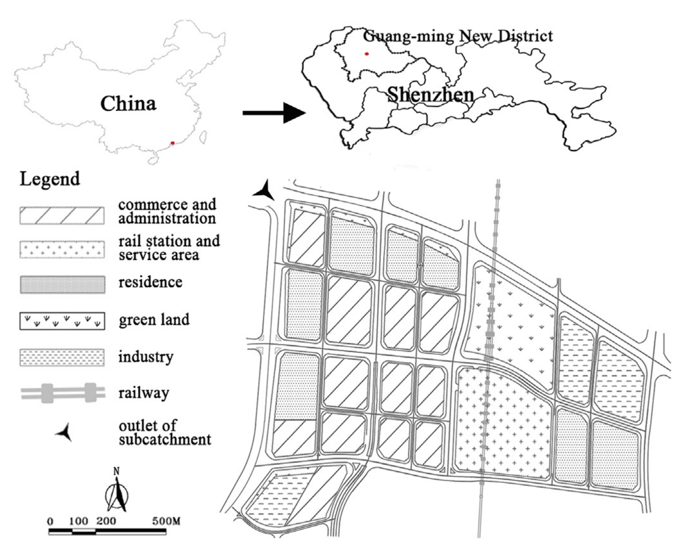

Fig. 1. Planned land uses of the study area.