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Research article

Evaluation of low impact development approach for mitigating flood inundation at a watershed scale in China

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A B S T R A C T

Low impact development (LID) has attracted growing attention as an important approach for urban flood mitigation. Most studies evaluating LID performance for mitigating floods focus on the changes of peak flow and runoff volume. This paper assessed the performance of LID practices for mitigating flood inundation hazards as retrofitting technologies in an urbanized watershed in Nanjing, China. The findings indicate that LID practices are effective for flood inundation mitigation at the watershed scale, and especially for reducing inundated areas with a high flood hazard risk. Various scenarios of LID implementation levels can reduce total inundated areas by 2%–17% and areas with a high flood hazard level by 6%–80%. Permeable pavement shows better performance than rainwater harvesting against mitigating urban waterlogging. The most efficient scenario is combined rainwater harvesting on rooftops with a cistern capacity of 78.5 mm and permeable pavement installed on 75% of non-busy roads and other impervious surfaces. Inundation modeling is an effective approach to obtaining the information necessary to guide decision-making for designing LID practices at watershed scales.

1. Introduction

The risk of extreme urban flooding/sewer flooding has been growing rapidly due to rapid urbanization and climate change, especially in low- and middle-income countries (IPCC, 2013). Minimizing the impact of urbanization and increasing urban resilience is an effective approach to reduce the urban flood risk as emphasized in the Sendai Framework for Disaster Risk Reduction (Kelman, 2015). Low impact development (LID), which is one of stormwater management strategies to preserve or replicate the pre-development natural hydrology of a site using a series of micro-scale control practices (Newcomer et al., 2014), was implemented in recent years to reduce the flood risk and increase urban resilience (Dietz, 2007; Todeschini et al., 2012). The benefits of LID practices on runoff reduction at individual sites have been demonstrated in a number of cases (Scholz and Grabowiecki, 2007; Ghisi et al., 2012; Berndtsson, 2010). For example, Shannak et al. (2014) reported that rainwater harvesting (RH) with an appropriate cistern size reduced total runoff by 45% in a house with a virtual roof and lawn setup. Dreelin et al. (2006) reported that a permeable pavement (PP) parking lot can produce 93% less runoff than an asphalt parking lot.

The performance of LID at watershed scale is substantially affected by their structures and properties (e.g., the percentage of the LID installation area and related drainage areas, Qin et al., 2013), and climate (e.g., rainfall duration and intensity, Gilroy and McCuen, 2009). Some recent studies have evaluated the effectiveness of LID implementation at watershed scale (Palla and Gnecco, 2015; Zhang and Hu, 2014), and several models (e.g. the Storm Water Management Model) have been developed to simulate the hydrologic impact of LID implementation (Elliott and Trowsdale, 2007; Baek et al., 2015; Trinh and Chui, 2013; Morsy et al., 2016; Duan et al., 2016; Chui et al., 2016). For example, LID implementation in a high-density residential community in Nanjing, China, can reduce runoff by 0.6%–36.8% (Zhang et al., 2016).

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Ahiablame and Shakya (2016) demonstrated that LID practices resulted in 3%–47% reduction of runoff in an urban watershed in central Illinois, the USA. Peak flow reduction, runoff volume reduction, and hydrograph delay are widely used to evaluate the performance of LIDs (Palanisamy and Chui, 2015). Lee et al. (2013) found that peak flow was reduced by 6%–16% with a LID system in a small district in Korea. Ahiablame et al. (2013) confirmed that application of LIDs contributed to reduce total runoff volume by 2%–12% in two urbanized watersheds near Indianapolis, the USA. Few studies, however, have considered changes in inundation zones with the implementation of LIDs. Urban sewer flooding always occurs at some low-lying areas. The alterations in peak flow, runoff volume, or hydrograph delay at a watershed may not reflect conditions in specific areas. Using inundation modeling, LID performance at a watershed scale can be clearly shown in flood hazard maps. Visualization of changes in inundation areas contributes to increase public awareness and understanding of the LID benefits and the implementation of LID.

In recent years, heavy sewer flooding and waterlogging hazards have occurred frequently due to extreme precipitation, the low criteria of urban drainage systems, and the large proportion of impervious areas, which has negatively affected social-economy in Chinese mega cities (e.g., Beijing and Nanjing). For example, the extreme stormwater event on July 21, 2012, killed 79 people and led to a more than 10 billion yuan ($1.6 billion) economic loss in Beijing (Sang et al., 2013). To mitigate urban flood disasters, the central government of China proposed plans for constructing “sponge city” nationwidely in 2014, which promoted the application of LIDs to overcome the shortcomings of traditional urban stormwater management. Demonstrations of the performance of LIDs at urban watersheds will make contribution to the widespread application of LIDs in China. In the previous study, we analyzed the cost-effectiveness of RH cistern capacity (Hu, 2012), the potential and feasibility of RH (Zhang et al., 2012), and the performance of RH, PP, and green roofs for reducing runoff (Zhang et al., 2016) in a high-density residential community at the urbanized watershed in China. The performance of LIDs in flood mitigation at the whole watershed, however, is still unclear. Also, variations in water depth and hazard areas induced by the implementation of LIDs are unknown, but they are important for LID placement. Thus, this study applied an inundation model and scenarios of LID implementation to evaluate the performance of LIDs on flood mitigation including water depth and hazard area reductions. Two practices (RH and PP) were studied: RH is relatively easily implemented and collected water can be used widely (Kim and Furumai, 2012; Ghisi et al., 2014); and PP can substantially increase infiltration and has large potential at the built-up area, such as parking lots, squares, roads, even soils with low infiltration rates (Ahiablame et al., 2012; Brattebo and Booth, 2003). The objective of this study is to evaluate and demonstrate LID performances for mitigating flood inundation hazards in an urbanized watershed. This study applied the Flo-2D model to simulate LID performances as a retrofitting technology for urban stormwater management.

2. Methodology

2.1. Flo-2D model

Flo-2D is a two-dimensional grid-based physical process flood-routing model with a number of components (note that the list is not exhaustive) for rainfall, channel flow, overland flow, street flow, levees, infiltration, and sediment transport (García et al., 2004). The grid cell commonly ranges from 3 m to 130 m on a side and the number of grid elements is limited by the computer resources and runtime. There are eight directions for discharge (4 compass and 4 diagonal). The governing equations of the model include the continuity equation and momentum equation:

$$\frac{\partial h}{\partial t}+\frac{\partial hV}{\partial x}=i$$

$$S_f=S_o-\frac{\partial h}{\partial x}-\frac{V}{g}-\frac{\partial V}{\partial x}-\frac{1}{g}\frac{\partial V}{\partial t}$$

where h is the flow depth, V is the depth-averaged velocity in one of the eight flow directions x, and i is the excess rainfall intensity. The bottom friction and bed slope are represented by S_f and S_o, respectively. The Soil Conservation Service curve number and the Green-Ampt infiltration model methods are applied for infiltration calculation (Green-Ampt infiltration model was used in this study). No infiltration is calculated for impervious surfaces. In addition, Flo-2D provides the Grid Developer System (GDS) to spatially edit grid system attributes and the Mapper++ program to automate flood hazard delineation and generate graphical results. Flood hazard is defined by three levels (Table 1); level at the specific location is defined as the discrete combined function of flood intensity and probability (note that the probability was not considered in this study). Flood intensities are defined in terms of the maximum water depth (h) and product of the maximum velocity multiplied by the maximum depth (vh, Table 1). Flood hazard delineation highly depends on the criteria. In this study, the air intake height of domestic automobiles in China (about 0.6 m) was used as the threshold of maximum water depth for medium hazard level because automobiles cannot ignite when the water depth is greater than the air intake height and persons in the vehicles would be in danger. Also, maximum water depth of a high hazard level was defined as double as that of the medium level, 1.2 m. Other criteria were kept the same as defaults of the model. For more information, see the Flo-2D manual (2012). The Flo-2D model is widely used in multiple applications such as in coastal inundation (Hosseinipour et al., 2012), dam breach (Chen et al., 2004), and flooding in alluvial fans (Hübl and Steinwendtner, 2001).

2.2. Study area and data preparation

The study area (Hexi watershed), covering an area of 54.3 km^2, is located in Nanjing, China (Fig. 1). It is an emerging, people-oriented

Table 1
Flood hazard definition (Flo-2D manual, 2012).

Hazard level	Colour	Criteria	Description
High	Red	$h \geq 1.2$ or $vh \geq 1.5$	People are in danger both inside and outside of structures. Buildings are in danger of being destroyed.
Medium	Orange	$0.6 \leq h < 1.2$ or $0.5 \leq vh < 1.5$	People are in danger outside of structures. Buildings may suffer damage or possible destruction depending on construction materials.
Low	Yellow	$0.1 \leq h < 0.6$ and $0.1 \leq vh < 0.5$	Danger to people is low. Buildings may suffer limited damage, but flooding may affect structures.

h is maximum water depth (unit: m) and vh is maximum velocity multiplied by the maximum depth (unit: m^2/s).

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