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Assessing the effectiveness of green infrastructures on urban flooding reduction: A community scale study

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ABSTRACT

The risk of urban flooding is increasing as a result of rapid urbanization. Green infrastructure (GI) is an emerging planning and design concept to mitigate urban flooding. A community scale simulation model was developed to quantify the effectiveness of GI on reducing the volume and peak flow of urban flooding. Five scenarios, namely expanding green space, converting to concave green space, constructing a runoff retention structure, converting to porous brick pavement, and combining previous four measures were considered for an urban community in Beijing. The outcomes showed that the model performed responsively to simulate the storm runoffs at varying recurrence intervals under these scenarios. Simulation results showed that, the impervious surfaces have the most contribution to the storm runoffs of the community. The reduction capacity for single GI facility was limited, especially in bigger storm events. The integrated GI configuration has effective reduction percentage, such as the total runoff reduction was ranged from 100% to 85.0% and the peak flow reduced 100–92.8%. This work can guide local planners and decision makers in their actions on green infrastructures in community scale.

1. Introduction

Over half of the people worldwide now live in cities and the percentage is expected to reach eighty by 2050 (Bettencourt and West, 2010). It causes the shortage of natural resources and creates stresses in the already stressed out urban ecosystems (Mentens et al., 2006). As the impervious urban surfaces expanding, crop lands, pastures, wilderness, and forests are displaced by dwellings, office structures, streets, highways, and industrial and commercial establishments. Significant land use modifications that converted the natural landscape to urban settings may have disastrous consequences for urban ecosystems. Impervious surfaces alter the hydrological nature of surface runoffs, prevent the infiltration of surface water into the ground, greatly increase storm runoffs in terms of volumes and peak flow (Goonetilleke et al., 2005; Whitford et al., 2001), and consequently causing floods in cities. The urban flooding endangers life, private properties and public infrastructures, erodes stream banks and channels, and contaminates streams and rivers in urban areas. Urban flooding risk may be intensified as the earth experiences more frequent weather extremes with the global climate change (Foster et al., 2011; Villarreal et al., 2004).

Conventionally, storm water is detaining and conveying through piped drainage systems. However, the conventional approaches fail to address the increases of storm runoff volume and peak flows caused by urban development. The runoffs overburdened the municipal wastewater treatment works and carried pollutants such as trash, bacteria and heavy metals into the receiving waters that degraded the quality of the urban streams. The holistic modeling and ecological risk assessment of urban ecosystems can be used for risk evaluation and urban management to minimize the damage by extreme weather and changing climate from the source of urban flooding (Chen et al., 2013, 2014). In recent years, the green infrastructure (GI) has been widely used in many cities in the USA, and in the UK, Canada, Germany and New Zealand to mitigate urban flooding (Ahiablame et al., 2012). The GI employs principles such as preserving and recreating natural landscape features, implementing some on-site infrastructures that work with nature to reduce the storm water runoff from sources (Graham et al., 2004). It is an economically and environmentally viable approach for developing sustainable and resilient communities, adapting climate change, as well as for promoting smart growth and urban sustainability (Benedict and McMahon, 2002, 2006; Dunn, 2010; Foster et al., 2011; Gill et al., 2007; Mell, 2009).

The GI installations consist of systems and practices that utilize or mimic the natural processes, allowing storm water to infiltrate, evaporate, runoff, and/or be used on-site. For example, reservoirs and ponds may be strategically placed on the flow paths to

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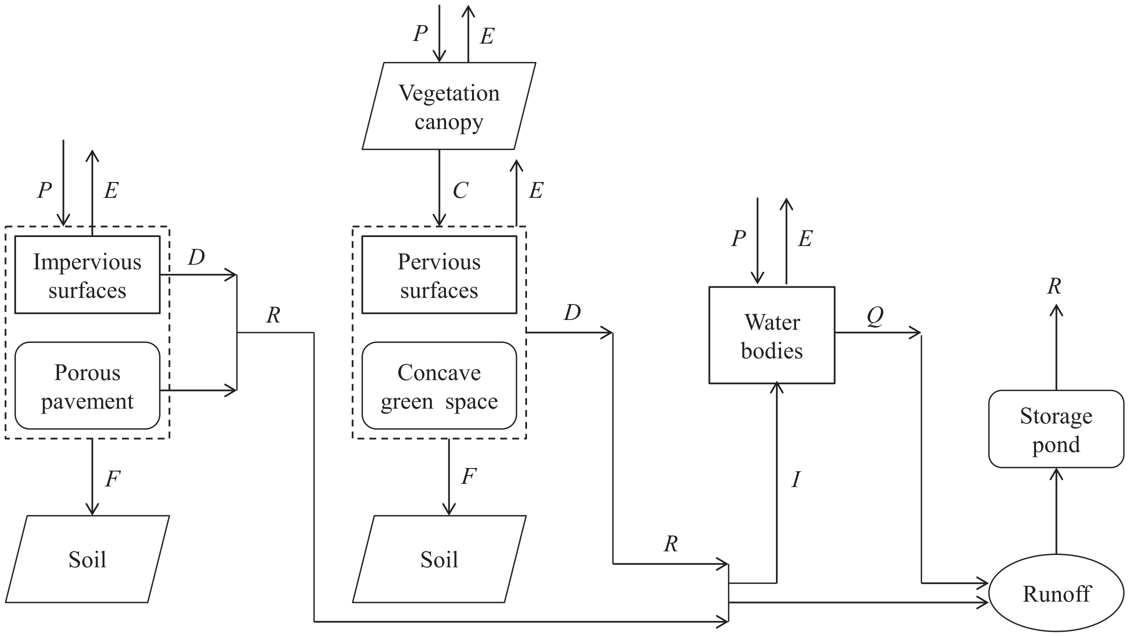

Fig. 1. Schematic depiction of the calculation of urban storm water runoff. *P* is the precipitation, *E* is the evaporation, *C* is the canopy interception, *F* is the soil infiltration, *D* is the depression, *I* is the inflow, *Q* is the outflow, *R* is the surface runoff.

temporary store the surface runoff (Ferguson, 1998; White, 2002) and green spaces where runoff diverted from impervious surfaces may have a chance to infiltrate and/or evaporate (Mentens et al., 2006). GI can be used in a wide range of landscape scales in place of or in addition to traditional storm runoff control elements, as well as maintain or restore an urban ecosystem's hydrologic and ecological functions. Therefore, for effective control of urban flooding, it is imperative to develop tools that optimize the GI configurations according to the urban hydrologic cycle.

The hydrological performance and benefits of GI practices have been shown in numerous studies on laboratory scales, in-situ scales and micro-scales. For example, Alfredo et al. (2009) 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. Dreelin et al. (2006) showed that porous pavements reduced 93% of runoff on two parking lots, and it can be used to control small storms (less than 2 cm). Schneider and McCuen (2006) showed that the effects of cisterns on peak discharge reduction are ineffective for large storms, but very effective for small 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. Qin et al. (2013) concluded that the swale, permeable pavement and green roof are more effective in flood reduction during heavier and shorter storm events compared with the conventional drainage system.

Influences of GI on urban storm runoff reduction can be evaluated by hydrological models such as Storm Water Management Model (SWMM), Urban Volume and Quality (UVQ) and Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (Huber et al., 1988; MUSIC Development Team, 2003; Mitchell et al., 2003). However, these traditional hydrological models are cumbersome and unsuitable to evaluate the effectiveness of GI in mitigating urban flooding because of the difficulties in defining model parameters and the over-simplifications of reactive processes related to GI. Although the GI performance on reducing urban flooding has been extensively investigated, few studies have attempted to examine and compare the reduction effectiveness between integrated GI configuration and single GI facilities under different storm recurrence periods.

In this research, a simple rainfall-runoff model with fewer parameters requirements is developed to describe functions of green infrastructures based on the water mass balance through the processes of urban hydrological cycle. By using the model, the effectiveness of single GI facilities and the integrated GI configuration on urban flooding reductions were evaluated under different storm recurrence periods. A typical community in Beijing is selected for study. This study illustrates a scientifically and ecologically responsible approach for urban storm runoff management and landscape planning.

2. Methodology

In terms of precipitation and runoff, the urban area is divided into four types of surfaces, namely impervious surface (building footprints, roads, pavements, parking lots, etc.), pervious surface (green spaces, lawns, bare soils, etc.), water body (natural and man-made reservoirs, wetlands and rivers), and green infrastructures (Fig. 1). In a precipitation event, the rain would be routed through different processes of the hydrological cycle in each surface, which are depended on the nature of surfaces and dynamic factors. The water routing through each compartment is calculated independently and then sum up the three surfaces' runoffs or the overflows of GIs to obtain the total storm runoff. The impacts of green infrastructures on storm water infiltration, retention and storage capacity are accounted for in calculating storm runoff. The model subroutines are described in the following sections. Based on water mass balance, the storm runoff volume calculation is obtained by selecting simpler calculation equations with fewer parameters from several typical urban drainage models. The reservoir routing is neglected in the peak flows calculations due to the micro-scale of the community.

2.1. Runoff of impervious surface

The calculation of impervious surface runoff is based on the water balance (Mitchell et al., 2003). Rainfall reaches impervious areas beyond the depression storage depth is directly converted to