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Quantitative analysis on the urban flood mitigation effect by the extensive green roof system

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ABSTRACT

Extensive green-roof systems are expected to have a synergetic effect in mitigating urban runoff, decreasing temperature and supplying water to a building. Mitigation of runoff through rainwater retention requires the effective design of a green-roof catchment. This study identified how to improve building runoff mitigation through quantitative analysis of an extensive green-roof system. Quantitative analysis of green-roof runoff characteristics indicated that the extensive green roof has a high water-retaining capacity response to rainfall of less than 20 mm/h. As the rainfall intensity increased, the water-retaining capacity decreased. The catchment efficiency of an extensive green roof ranged from 0.44 to 0.52, indicating reduced runoff comparing with efficiency of 0.9 for a concrete roof. Therefore, extensive green roofs are an effective storm water best-management practice and the proposed parameters can be applied to an algorithm for rainwater-harvesting tank design.

1. Introduction

Various technologies are being applied in new constructions to save energy and costs. The green roof is a popular technology that mitigates urban runoff, decreases temperature and provides an ecofriendly space (Kumar and Kaushik, 2005; Mentens et al., 2006; Stovin et al., 2007; Yang et al., 2008; Berndtsson et al., 2009; Teemusk and Mander, 2009; Castleton et al., 2010). There are two types of green roofs. Extensive green roofs have a thin substrate layer with sedum or lawn. Intensive green roofs have a deeper substrate layer in which shrubs are planted (Castleton et al., 2010). An emerging technology is a rainwater absorption system that reduces runoff in a building. Several research works have been conducted on runoff mitigation by green roofs (Kohler et al., 2002; Han et al., 2003; Beattie and Berghage, 2004; Moran et al., 2005; Carter and Rasmussen, 2006; Carter and Jackson, 2007). Additionally, Jarrett et al. (2006) suggested that an extensive green roof would retain 45%–55% of the annual rainfall volume. This would be beneficial to the control of urban runoff. However, several studies have shown that retention depends strongly on the quantity of rainfall per storm event (Carter and Rasmussen, 2005; Moran et al., 2005; Teemusk and Mander, 2007; Hilten et al., 2008). At an extensive green-roof site, Carter and Rasmussen (2005) showed that retention decreased from 90% in a 1.3-cm storm event to 39% in a 5.4-cm storm event. Teemusk and Mander (2007) observed 85.7% retention in a 0.21-cm storm event while green roofs provided little retention in larger storm events. The water-retaining capacity of a green roof affects flood mitigation. The depth of the green-roof soil column provides a detention volume in which rainfall is temporarily absorbed, and the flood peak flow is delayed by the slow release of water compared with the storm surge associated with impervious rooftops during rainfall events (Hilten et al., 2008).

Many factors should be considered in designing a green roof to mitigate urban runoff, including evaporation and transpiration potential, antecedent moisture conditions, rainfall intensity and soil hydraulic properties (Hilten et al., 2008). To determine the performance of a green roof in mitigating flooding, quantitative analysis of these parameters is essential. An extensive green-roof system should be designed to optimize the factors affecting runoff using engineered soil materials and soil depths (i.e., an engineered soil medium). While the available soil media and depths are limited for an extensive green-roof system and the composition does not differ between manufacturers, engineers should consider variables such as water-holding capacity and hydraulic conductivity for flood control. Several studies have assessed

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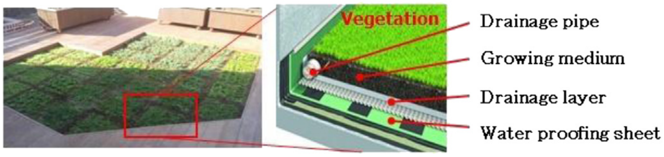

Fig. 1. Nominal construction characteristics of an extensive green roof. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the hydraulic properties of the soil medium, including the wilting point and field capacity moisture content (Hilten, 2005; Hilten et al., 2008). The essential components of a green roof are waterproofing, a drainage layer, a growing medium and vegetation, although the composition differs between manufacturers (Fig. 1).

The main objective of the study was to evaluate the runoff coefficient and storm water performance of an extensive green-roof system in different rainfall events. The runoff coefficient and storm water performance are applied in building a runoff model for the extensive green roof, and the model is used to predict and simulate runoff for the building in individual storms.

2. Methods and materials

2.1. Experimental setup

A green-roof setup with dimensions of 0.5 m (W) × 0.5 m (L) × 0.2 m (H) was built in the laboratory. Grass with a height of 30 mm was used for vegetation (Fig. 2). The 100-mm substrate comprised a 30-mm layer of perlite (50%) and a mix of cocopeat (20%), peat moss (15%) and charcoal (15%). Sedum was used as grass and the substrate was a standard manufacturer's product for an extensive green-roof system. A 65-mm low-drainage plate was placed at the bottom of the substrate and textile was inserted between the substrate and the low-drainage plate. Four drainage pipes with diameters of 10 mm were installed at four corners and a drainage pipe with a diameter of 30 mm was installed at the center of the base of the green roof. One side of the green-roof surface was adjacent to a concrete surface with dimensions of 10 mm (W) × 500 mm (L), which conveyed surface flow directly to the drainage pipes at the corners. There was an inclination of 1° from the concrete side of the green roof to the opposite side to lead surface flow to the drainage pipes. The frame of the green roof was made of acrylic plastic. Various rainfall events were simulated using a Norton Rainfall Simulator (two heads; DIK-6000) developed by USDA-ARS.NSERL at Purdue University, West Lafayette, Indiana.

2.2. Rainfall conditions

The rainfall depth, intensity and duration during historical rainfall events in Korea from 1999 to 2011 were statistically analyzed to obtain rainfall conditions for the experiments. In particular, data of rainfall intensity were obtained from the Korea Meteorological Administration (KMA). Rainfall events were categorized into two simulation groups: group A for spring and autumn and group B for summer. Various rainfall events in groups A and B were simulated by controlling rainfall intensity, depth per event, duration and the number of antecedent dry days, as listed in Table 1.

Table 1
Rainfall conditions in the experiment on green-roof runoff.

Variable	Simulation group	
	A (spring & autumn)	B (summer)
Rainfall intensity (mm/h)	2–20	2–40
Rainfall depth/event (mm)	2–35	2–150
Duration (h)	1–5	1–11
Antecedent dry days	1–5	0.5–3

3. Results and discussion

3.1. Water-retaining capacity in spring and autumn

In the 20 cases of simulation group A, the runoff depended on the total rainfall depth and rainfall intensity. The runoff was almost negligible for rainfall depth per event of less than 30 mm, as shown in Table 2. Fig. 3 shows the results for the most intense rainfall case in simulation group A; the rainfall conditions were duration of 3 h, total rainfall of 35 mm and peak rainfall intensity of 20 mm/h. Even under these rainfall conditions, the green-roof runoff was only 6 mm and 29 mm of rainfall was retained by the green roof. In contrast, concrete-roof runoff was estimated as 31.5 mm.

Fig. 4 shows the change in the water-retaining capacity according to the number of antecedent dry days. Table 3 presents the rainfall conditions in the experiments investigating the water-retaining capacity. Water-retaining capacity changed according to the number of antecedent dry days, as there is evapotranspiration at the surface of a green roof. Water-retaining capacity initially increased almost linearly as the number of antecedent dry days increased and then plateaued at 28 mm after three days.

3.2. Water-retaining capacity in summer

The green roof has a high water-retaining capacity response to summer rainfall events in Korea, and there is no runoff. Tables 4 and 5 show that the green roof reduces runoff in summer

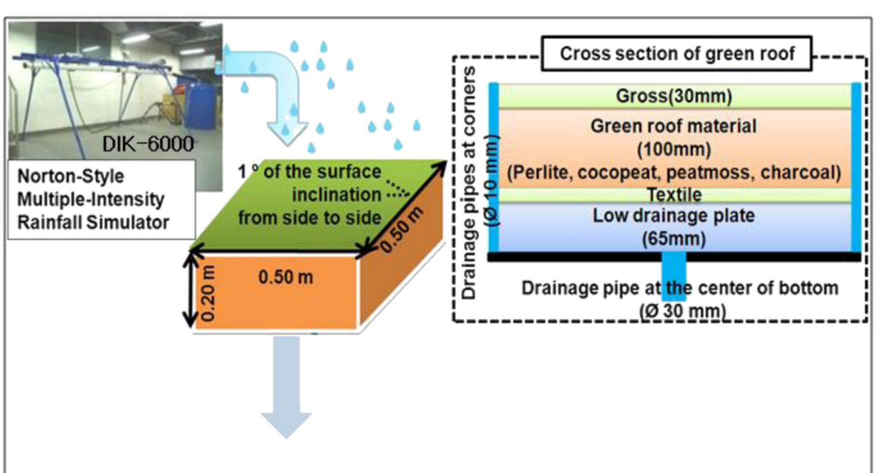

Fig. 2. Experimental setup of green-roof runoff.