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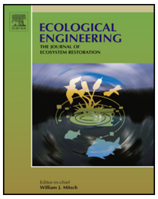

Quantitative hydrologic performance of extensive green roof under humid-tropical rainfall regime

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ABSTRACT

Urbanization replaces permeable surfaces with relatively impervious ones to intensify mass and temporal response of stormwater runoff. Under heavy rainfalls, urban runoff could impose tremendous stress on the drainage systems, contributing to combined sewer overflow and flooding. Green roof offers an on-site source-reduction sustainable stormwater management measure that mimics pre-development hydrologic functions. It can retain and detain stormwater as well as delay and suppress peak discharge. However, previous studies were conducted mainly outside the tropics. Since green-roof hydrologic performance can be notably influenced by local meteorological conditions, dedicated investigation in the tropics are necessary. Moreover, substrate depth has long been regarded as an influential factor in green-roof stormwater retention, but recent findings have implicated that such relationship may be more complex. This study (1) evaluates green roof stormwater mitigation performance and potentials in humid-subtropical Hong Kong; and (2) investigates systematically the effect of substrate depth and addition of rockwool, a high water-retention growth medium, on quantitative performance. Using multiple 1.1-m^2 raised green-roof platforms placed on an urban rooftop, the effect of four substrate-depth treatments on stormwater mitigation performance was examined over a 10-month study period. The results show that, while the retention under Hong Kong's frequent and heavy rainfall regime seems to be less effective, remarkable peak reduction and peak delay were evidently expressed even when the green-roof systems have reached full moisture-storage capacity. No statistical significance was found between treatments, despite the slightly higher mean performance of the 80-mm soil substrate. Satisfactory peak performance of the 40-mm soil substrate implies that a thin substrate can provide effective peak mitigation, especially if building loads are of concern. Extensive green roof remains as a promising alternative mitigation strategy to urban stormwater management in Hong Kong with potential application to other tropical areas.

1. Introduction

1.1. *Urban stormwater challenges and green-roof mitigation potentials*

Urban impervious surfaces generate stormwater runoff that is massive in volume and concentrated in time under heavy rainfalls. With no infiltration capacity and limited depression storage, impervious surfaces rapidly transform precipitation into runoff (Hall, 1984). Even in extreme rainfall events, when imperviousness is relatively less influential in terms of overall runoff volume, peak flow is still elevated significantly (Ogden et al., 2011). When the peak flow exceeds the urban drainage capacity, costly consequences such as flooding may follow.

Sustainable Urban Drainage Systems (SUDS), Best Management Practices (BMPs), Low Impact Development (LID) and Water Sensitive Urban Design (WSUD) offer new dimensions to sustainable urban stormwater management using micro-scale and on-site refined measures (CSIRO, 2006; EPA, 2007). These source-reduction controls, such as green roof and vegetated swales, mimic pre-development natural hydrologic functions. Besides furnishing temporary storage spaces and promoting infiltration, they return water to the atmosphere via evapotranspiration to ameliorate extremes in the altered natural hydrologic cycle.

Green roof, also called eco-roof and living roof, can retain stormwater (Köhler et al., 2001; DeNardo et al., 2005; VanWoert et al., 2005; Villareal and Bengtsson, 2005; Getter et al., 2007; Teemusk and Mander, 2007; Gregoire and Clausen, 2011; Schroll

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et al., 2011; Speak et al., 2013), delay peak discharge time (Carter and Rasmussen, 2006; Spolek, 2008), and attenuate peak discharge volume (Carter and Jackson, 2007; Van Seters et al., 2009; Berndtsson, 2010; Palla et al., 2010; Voyde et al., 2010; Carpenter and Kaluvakolanu, 2011; Stovin et al., 2012). Thus, green roof provides a viable approach to mitigate combined sewer overflows (CSO) and urban flood risks (EPA, 2007; Berndtsson, 2010; Palla et al., 2010).

However, the peak delay (PD) and reduction (PR) behavior of green roof remain unclear. Some researchers contended that exhausted retention capacity of the substrate would lead to discharge following rainfall almost instantaneously. It is believed that PD is a function of retention and not detention, that once the substrate is saturated, PD and PR would be insignificant. This implies that the stormwater mitigation capability of green roof is notably curtailed under such condition.

1.2. Substrate depth and rockwool

Researchers have acknowledged the dominant roles of substrate type and depth in green-roof stormwater retention (Monterusso et al., 2004; VanWoert et al., 2005; Dunnett and Kingsbury, 2008; Uhl and Schiedt, 2008; Berndtsson, 2010; Stovin et al., 2012). Unlike the relatively impervious urban surfaces, green-roof substrate is a porous medium. To reduce surface runoff and prevent flooding on roofs, the substrate should have decent water permeability to facilitate infiltration (Dunnett and Kingsbury, 2008; FLL, 2008; Kasmin et al., 2010; Bousselot et al., 2011; Stovin et al., 2012). The ideal substrate should retain a generous amount of rainwater to reduce discharge volume. The surplus rainwater that cannot be accommodated internally should be temporary detained to delay discharge flow. Given the same conditions, a thicker substrate depth could raise water retention capacity.

Some studies have investigated the effect of substrate depth on green-roof discharge. VanWoert et al. (2005) examined stormwater retention of four green-roof platforms with two slopes: 2% with 25 and 40 mm depth, and 6% with 40 and 60 mm. The platform with the greatest retention was the 2% slope and 40 mm, but the differences among other treatments were minimal. Mentens et al. (2006) evaluated the German literature and found that annual rainfall–runoff relationship is strongly determined by substrate depth. The yearly retention for intensive green roofs with a median depth of 150 mm is 75%; and that for extensive green roofs with a median depth of 100 mm is 45%. Uhl and Schiedt (2008) found that the total green-roof depth (substrate and drainage layers, 50–150 mm) dominated the retention effect, especially in cool seasons.

Voyde et al. (2010) studied the effect of two substrate depths (50 and 70 mm) on stormwater discharge. They found no additional stormwater benefit from the 70 mm substrate. The preliminary findings of Nardini et al. (2012) also aligned with this observation. The precise role of substrate depth on stormwater mitigation thus demands more in-depth investigations.

Rockwool, also known as stone wool and grodan, is a silicate-fiber material derived from the subvolcanic rock diabase. As a synthetic mineral product, rockwool is chemically inert and highly porous. It improves aeration and increases water-holding capacity with a notable portion in the plant-available range (Fonteno and Nelson, 1990). Due to excellent water retention capacity, light weight, and durability, rockwool can be incorporated as an adjunct green-roof substrate layer. It is commonly installed between the drainage and substrate layers to improve water retention capacity and limit weight addition to the green-roof system (Jim and Tsang, 2011a,b). Rockwool acts as a water reservoir as well as a supplementary substrate layer, since roots can penetrate into the slab for water, air, nutrients, and anchorage. Replacing all or part of the soil substrate with light-weight rockwool can reduce the overall load and create more opportunities for retrofitting existing building roofs.

The high water-holding capacity of rockwool can provide the additional benefit of enhancing evaporative cooling in green roofs (Jim and Tsang, 2011a). It also provides acoustic insulation in dry conditions (Van Renterghem and Botteldooren, 2009). However, our current knowledge of rockwool benefits on green roof is limited to thermal insulation and noise reduction. Two stormwater mitigation studies have incorporated rockwool slabs in their green-roof design (Mentens et al., 2003; Teemusk and Mander, 2007). Despite the potentials, the effect of rockwool on stormwater mitigation remains unexplored.

1.3. Seasonal effect

Green-roof moisture storage is affected by extrinsic meteorological factors such as air temperature, humidity, wind speed, and solar radiation, which can influence evaporation and transpiration. Seasons with distinctive meteorological conditions could influence substrate moisture regime. The higher temperature of the warm season permits faster restoration of moisture storage capacity (Mentens et al., 2006; Berndtsson, 2010).

Green roofs demonstrate seasonal variations in stormwater retention performance. Generally, it is higher in summer than in winter (Bengtsson et al., 2005; Mentens et al., 2006; Spolek, 2008; Uhl and Schiedt, 2008; Berghage et al., 2007; Van Seters et al., 2009; Schroll et al., 2011; Stovin et al., 2012). However, the temperate-latitude climate of these studies tends to have warm summer and cold winter, with relatively even distribution of rainfall, or more rainfall in winter. Such findings may not be directly applicable to other climates.

Contrary to other studies, Voyde et al. (2010) did not observe significant seasonal variation in stormwater performance. It was attributed to the small seasonal meteorological variations in Auckland, or other experimental confounding variables.

With even distribution of annual rainfall, it is reasonable to postulate that for regions with dry-warm summer, green-roof stormwater performance should be better in summer than in wet-cold winter. However, for regions with wet-warm summer, such as Hong Kong, summer performance is not as straightforward. Previous findings on seasonal performance may not be generalized to climates with different rainfall patterns.

1.4. Study objectives and approach

Green-roof stormwater mitigation in other regions has been well investigated, but only one study has been conducted in the humid-subtropical climate (Carter and Rasmussen, 2006). Moreover, the rainfall regimes of these studies deviate markedly from humid-subtropical Hong Kong. With uneven temporal distribution of high annual rainfall, Hong Kong's rainfall regime offers a unique opportunity to explore green-roof stormwater mitigation performance. Furthermore, meteorological characteristics can vary greatly within a given climatic zone, which calls for dedicated regional and local studies.

This study examines the hydrological performance of extensive green roof in urban Hong Kong across seasons and under different rainfall events. Continuous discharge and rainfall measurements permit detailed temporal response analysis. Event-based graphical time-series analysis investigates temporal discharge response. Rockwool slab with high retention capacity was used as a water-reservoir-cum-substrate to examine its stormwater behaviors. To this end, this study addresses the substrate depth-performance relationship, and attempts the first systematic investigation