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Research Paper

Identifying keystone meteorological factors of green-roof stormwater retention to inform design and planning

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HIGHLIGHTS

- Antecedent condition and duration play an auxiliary role in green-roof retention.
- Solar radiation and wind speed contributed significantly to retention.
- Urban roofs may experience wider temperature extremes than ground conditions.
- Higher maximum temperatures enhance evapotranspiration and subsequent retention.
- Key factors could inform site choice and green-roof design to maximize benefits.

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ABSTRACT

Green roofs have received considerable attention for multiple ecosystem services which include stormwater amelioration. Offering sustainable stormwater source-control, green roofs utilize otherwise unused impervious urban surfaces to restore pre-development hydrologic functions such as infiltration and retention. Its ability to retain stormwater is related to external and internal factors. Meteorological conditions prior to a rainfall event can influence antecedent evapotranspiration, the only water-exit pathway of the green-roof system besides discharge. Whereas evapotranspiration may be difficult and costly to measure directly, other common meteorological conditions can be monitored conveniently and inexpensively even prior to actual green-roof installation. Identifying salient on-site meteorological factors may provide valuable insights into hydrologic dynamics, and inform green-roof design and planning decisions. A statistical regression approach identified potential antecedent meteorological factors and moisture indicators of extensive green-roof retention. Continuous field-monitoring data revealed the combined effects of rainfall depth, wind speed, solar radiation, and antecedent dry weather period to explain the measured stormwater retention under a humid subtropical rainfall regime. Amongst the studied environmental factors, solar radiation and wind speed contributed notably to green-roof stormwater retention and may provide a dependable basis to assist green-roof site selection when resources are limited. It is important to incorporate site-specific planning and assessment prior to green infrastructure design and implementation to maximize hydrologic and evaporative cooling services in cities with complex topographical features.

1. Introduction

1.1. Urban stormwater challenges and quantitative hydrologic potentials of green roofs

Conventional urban development substitutes natural pervious surfaces with relatively impervious ones to alter the natural hydrologic cycle. Infiltration, evapotranspiration, and groundwater recharge are radically curtailed, contributing to the urban heat island effect. Moreover, under the backdrop of aging infrastructure, accelerating urbanization and changeable climate, the degraded hydrologic cycle can challenge urban drainage and flood defense. When drainage provisions become insufficient, cities are susceptible to costly consequences of flooding and combined sewer overflow. Under the framework of sustainable urban stormwater management, sustainable urban drainage systems, low impact development and water sensitive urban design offer alternative strategies to urban design and planning. These principles

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incorporate on-site refined measures that utilize source-reduction controls such as green roofs to mimic the pre-development natural hydrologic functions (CSIRO, 2006; EPA, 2007).

Stormwater retention is one of the important hydrologic services provided by green roofs (DeNardo, Jarrett, Manbeck, Beattie, & Berghage, 2005; Fassman-Beck, Voyde, Simcock, & Hong, 2013; Fioretti, Palla, Lanza, & Principi, 2010; Getter, Rowe, & Andresen, 2007; Gregoire & Clausen, 2011; Köhler, Schmidt, Grimme, Laar, & Gusmão, 2001; Mentens, Raes, & Hermy, 2006; Schroll, Lambrinos, Righetti, & Sandrock, 2011; Speak, Rothwell, Lindley, & Smith, 2013; Stovin, Vesuviano, & Kasmin, 2012; Teemusk & Mander, 2007; VanWoert et al., 2005; Voyde, Fassman, & Simcock, 2010; Wong & Jim, 2014). Green roofs, also called eco-roofs and living roofs, utilize additional and otherwise unused spaces in the urban environment to foster infiltration and retention. Abstraction of stormwater and redirection to alternative pathways reduce overall discharge and alleviates drainage pressure (Carter & Jackson, 2007). The retained water returns to the atmosphere via evapotranspiration to ameliorate extremes in the urbanized hydrologic cycle. Additionally, it can reduce surface and air temperature via latent heat conversion in built-up areas (Jim & Peng, 2012a, 2012b; Jim & Tsang, 2011a, 2011b).

1.2. Antecedent meteorological conditions

Green roof system's long-term retention capacity is restored solely by evapotranspiration (ET). ET rate is governed by the joint operation of plant, soil, and meteorological factors during the dry period prior to rainfall. Thus, the choice of vegetation, substrate, along with the given antecedent meteorological factors can influence green roof retention. The most direct quantification of ET involves the eddy covariance method, which may be difficult and costly to be widely deployed in green roof site assessment. On the other hand, commonly monitored meteorological conditions can be measured relatively conveniently.

Previous researchers have regarded regional climatic conditions as important factors to green roof hydrologic performance (Stovin, Poë, & Berretta, 2013; Voyde, Fassman, & Simcock, 2010). At the local scale, microclimatic factors can vary between rooftops due to idiosyncratic site characteristics. It may therefore be useful to evaluate sites in relation to green-roof performance objectives to inform relevant policies and design. For example, identifying salient meteorological factors of green-roof retention can help allocate sites to optimize stormwater functions. Such an approach can assist spatially focused green-roof strategic policies (Carter & Fowler, 2008).

1.3. Antecedent moisture condition indicators

The antecedent moisture condition (AMC) of green roofs denotes the storage spaces available for rainwater retention. A common surrogate AMC determinant in hydrologic studies is the antecedent dry weather period (ADWP), or antecedent dry days, which is the duration of dry period prior to a precipitation event. As a temporal-based factor, ADWP regulates the intrinsic AMC of the green-roof system. Since green-roof system requires evapotranspiration to "dry", the time available for retention-capacity restoration prior to rainfall is a necessary but not sufficient factor. Using this indicator alone will omit the varying rate of ET under different meteorological conditions. For example, a green-roof substrate may restore the same retention capacity in two instead of five days if the meteorological conditions are conducive to ET. In other words, for the same initial moisture level and ADWP duration, the final moisture levels may differ considerably under disparate meteorological conditions.

Nevertheless, some studies have employed ADWP as a tool or as an explanatory factor of green-roof stormwater mitigation performance, which may explain contrasting results and interpretations. Palla, Gnecco, and Lanza (2012) considered ADWP as the major parameter affecting the antecedent conditions prior to rainfall, and used it in the calibration procedure of their proposed conceptual hydrologic model. Voyde, Fassman, Simcock, and Wells (2010) also incorporated antecedent dry days into their ET regression model. A subsequent study observed the roles of different factors, including rain depth, rain intensity, antecedent dry days, and climatic variables on performance, concluding that antecedent dry days had the largest influence on retention (Voyde, Fassman, & Simcock, 2010). On the other hand, DeNardo et al. (2005) found no correlation between ADWP and the amount of retained rainfall, but the study only analyzed a few events. Stovin, Vesuviano, and Kasmin (2012) also found tremendous variability and weak association between ADWP and percent retention, and between ADWP and retention depth.

A more direct and precise measurement, such as soil water content, may offer greater experimental stringency. It has been well accepted that the moisture storage of green-roof substrate influences retention heavily (Berndtsson, 2010; Berretta, Poë, & Stovin, 2014; FLL, 2008; Graceson, Hare, Monaghan, & Hall, 2013; Stovin et al., 2012). Hence, substrate's antecedent volumetric moisture content (hereinafter AVMC), or volumetric water content, such as one measured using a time-domain reflectometry (TDR) soil moisture sensor, may offer more rigorous explanatory power to retention performance than ADWP.

1.4. Objectives and approach of this study

Previous studies have attempted to utilize multiple linear regression to develop a prediction model for green roof hydrological performance (Speak et al., 2013; Stovin et al., 2012). The selected explanatory variables primarily focused on ADWP and rainfall parameters such as peak rainfall intensity and duration. But perhaps due to the choice of methodology and selection of data, a concise yet statistically significant model has not been ascertained. Moreover, the relationship between soil moisture and green roof ET or thermal regime has been tackled by a few recent studies (Jim & Peng, 2012a, 2012b; Jim & Tsang, 2011a, 2011b). Its relationship with stormwater retention has yet to be thoroughly evaluated.

Instead of generating prediction models, this investigation employs a modified approach to identify potentially meaningful meteorological factors of green roof retention. It is thought that prior to rainfall, on-site meteorological factors can influence subsequent stormwater retention via ET. Since ET is relatively difficult to monitor for site assessment purposes, this study investigates whether there is a relationship between green-roof retention and other more easily available meteorological data. Thus, this study aims at detecting salient meteorological factors that explain green roof retention under a humid subtropical context. In doing so, it explores the strength of relationships, if any, between antecedent environmental factors (including five common weather parameters with well-established link to ET), antecedent moisture condition indicators (ADWP and AVMC), rainfall input, and green roof stormwater retention performance. The explanatory strengths of ADWP and AVMC were also compared. The exploratory analysis was able to produce a simple and statistically significant explanatory model, thus granting meaningful insights into salient environmental factors that may contribute to green roof stormwater retention performance, as well as important implications to sustainable stormwater management design and planning practices.