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Saturation-excess and infiltration-excess runoff on green roofs

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ABSTRACT

Green roofs (GRs), as compared to conventional roofs, can retain a considerable amount of water in the soil layer and hence have been used in many urban areas to mitigate urban flooding. However, a simple yet physical model for describing the rainfall (*P*)-runoff (*R*) relationship over GRs is still lacking. In this study, a physically-based *P*–*R* relationship, which utilizes soil moisture measurements that are often available in field experiments, is proposed based on the water balance equation over flat and horizontally homogenous GRs and evaluated against field measurements. First, the two different runoff generation mechanisms on GRs, namely, saturation-excess (runoff is generated when the soil becomes saturated) and infiltration-excess (runoff is generated when the rainfall intensity is larger than the infiltration rate), are discussed. A water balance analysis is then performed to obtain a physically-based *P*–*R* relationship over flat and horizontally homogenous GRs, which is validated using measurements from a field experiment conducted over a GR site in Beijing, China. Results show that our *P*–*R* relationship is able to estimate the runoff generated on our GR site. The proposed *P*–*R* relationship is also tested against other observational data and empirical models in the literature and shows broad consistency with these previous studies. To further quantify the relative importance of saturation-excess runoff and infiltration-excess runoff, numerical simulations are carried out using HYDRUS-1D. The simulation results indicate that runoff at our GR site is generated by both saturation-excess and infiltration-excess. Nonetheless, the infiltration-excess runoff accounts for a small portion of the total runoff, which suggests that the saturation-excess mechanism is more important for generating runoff over GRs.

1. Introduction

The worldwide rapid urbanization in recent years leads to significant increases in impervious (built) surfaces and concomitant reductions in green spaces. Due to these modifications in cities, various environmental issues occur, of which urban flooding is particularly detrimental. For example, Beijing, the capital city of China, has experienced several serious flooding events over the past decade. The most recent one occurred on July 21, 2012 and resulted in 79 deaths and an economic loss of ¥11.64 billion ($1.9 billion) (Zhang et al., 2013). In order to mitigate urban flooding, different strategies such as retention ponds, rainwater tanks and green roofs (GRs) have been proposed and studied (Mentens et al., 2006; Tillinghast et al., 2013). Among these strategies, the GR strategy features low impact development by utilizing the free rooftop spaces and becomes particular popular in North America (see e.g. Carson et al., 2013; Carter and Rasmussen, 2006; DeNardo et al., 2005; Mentens et al., 2006; Volder and Dvorak, 2014), Europe (see e.g. Fassman-Beck et al., 2013; Fioretti et al., 2010; Palla et al., 2011; Stovin et al., 2012; Teemusk and Mander, 2007), and East Asia (see e.g. Jim and Peng, 2012).

A typical GR usually consists of several layers, namely, a vegetation layer, a medium layer, a filtering-drainage layer, and a roof deck layer; while a typical conventional roof only has a roof deck layer. GRs are usually classified as extensive or intensive according to the medium layer depth: GRs with medium layer depth larger than 15 cm are classified as intensive GRs while those with medium layer depth less than 15 cm are extensive GRs (Carson et al., 2013). Previous studies have found that GRs can retain 27%–81% of the total rainfall and delay the runoff peak by 10 min relative to the precipitation peak (Getter et al., 2007 Mentens et al., 2006; Morgan et al., 2013; Simmons et al., 2008; VanWoert et al., 2005). However, the hydrological behavior of GRs varies across different sites due to different climates, different structure and properties of GRs, as well as different vegetation. A review of studies that focus on the impacts of these factors on the hydrological behavior of GRs is provided in Table 1.

To describe the hydrological behavior of GRs, field experiments and/or numerical simulations are usually conducted. Experimental studies usually try to construct empirical relationships between

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Table 1
A review of studies that investigated the impacts of different factors on the hydrological behavior of GRs.

	Reference	Results summary
Climate conditions	Stovin et al. (2012)	GR provides 50.2% cumulative annual rainfall retention, with a total volumetric retention equivalent to 30% during the significant events.
	Carter and Rasmussen (2006)	An inverse relationship is observed between the depth of rainfall and the percentage of rain that was retained: for small storms (<25.4 mm), 88% is retained; for medium storms (25.4–76.2 mm), more than 54% is retained; and for large storms (>76.2 mm), 48% is retained.
	Mentens et al. (2006); Villarreal (2007)	The retention of GR depends on the season: the warm season (summer) results in higher evapotranspiration and the GR retention capacity regenerates faster.
	Villarreal and Bengtsson (2005)	Climate conditions (dry or wet) affect the retention capacity of GR: in the dry conditions, 6–12 mm rain water is required to initiate runoff, whereas in wet conditions, the response is almost spontaneous.
	Voyde et al. (2010)	Antecedent dry days have the greatest influence on retention. Seasonal differences do not influence runoff response in Auckland's sub-tropical climate.
Structure and soil properties	VanWoert et al. (2005); Uhl and Schiedt (2008); Morgan et al. (2013)	The layer depth dominates the retention effect as compared to other construction details. Steeply sloped roofs tend to increase runoff but only marginally.
	Volder and Dvorak (2014)	Drier green roof substrate provided additional retention benefits for larger rain events.
	Farrell et al. (2013)	Water-retention additives can increase substrate water availability: silicates increased water holding capacity in both scoria and roof-tile substrates, but hydrogel only improved scoria water holding capacity.
	Voyde et al. (2010)	No statistically significant differences were found between the substrate types tested (i.e. clay, zeolite and pumice).
Vegetation	Dunnett et al. (2008b); Monterusso et al. (2004); VanWoert et al. (2005)	The vegetation type and cover do not significantly affect the water retention of GR.
	Steusloff (1998); Wolf and Lundholm (2008); Schroll et al. (2011)	The vegetation plays an important role in water retention, especially in periods with low water availability and higher temperatures.
	Nagase and Dunnett (2012)	A significant difference in amount of water runoff is observed among GRs with different vegetation types.
Review	Czemiel Berndtsson (2010)	This paper provides a review of studies on GR's hydrological behaviors.

runoff characteristics (e.g. runoff amount, runoff delay, peak runoff reduction, etc.) and rainfall characteristics (e.g. precipitation amount, rainfall duration, rainfall intensity, etc.) on an event-to-event basis (Carson et al., 2013; Carter and Jackson, 2007; Fassman-Beck et al., 2013; Mentens et al., 2006; Palla et al., 2012; Stovin et al., 2012). For example, some studies proposed quadratic models to link the amount of runoff to the amount of rainfall (as will be discussed later in Fig. 4). These empirically-based *P*–*R* relationships are based on regression analyses and thus lack physical interpretations. As a result, their applications are limited to places where the regression analyses are conducted. As compared to these empirical relationships, models based on water balance have been proposed by many researchers. For example, simple hydrological models such as the one proposed by Stovin et al. (2013) can perform long-term, continuous simulations to estimate runoff and evaluate drought risks. Vanuytrecht et al. (2014) developed a model based on water balance at daily scales. An analytical, probabilistic model for evaluating the long-term hydrologic performance of extensive green roofs was proposed by Zhang and Guo (2013). These models are typically used at daily or monthly time scales but not on an event-by-event basis. In addition to these empirical and water-balance models, more sophisticated numerical models like HYDRUS-1D (Hilten et al., 2008) and SWMM-2D (Palla et al., 2009; Burszta-Adamiak and Mrowiec, 2013) are widely used to simulate the hydrological behavior of GRs. They have been demonstrated to perform reasonably well in simulating the hydrodynamics in GRs as long as their input parameters are well calibrated (Li and Babcock, 2014). Relatively simpler numerical models such as the Green–Ampt infiltration model are also used (e.g., She and Pang (2010)).

Although various empirical *P*–*R* relationships have been proposed in the literature, a simple yet physical one that can be used on an event-to-event basis is still lacking, which motivates this study. In particular, most field experiments measure the soil moisture at some point in the GR column but this information is usually not used when constructing the *P*–*R* relationship (see e.g. Carson et al., 2013; Fassman-Beck et al., 2013). In this study, we aim to utilize this information of soil moisture in constructing a new and potentially more general *P*–*R* relationship for typical flat and horizontally homogeneous GRs based on the water balance equation. Our new *P*–*R* relationship is thus different from those reported in the literature that are constructed based on regression analyses. Our model is also different from other models that are based on water balance (Stovin et al., 2013; Vanuytrecht et al., 2014; Zhang and Guo, 2013) since our model is applied on an event-by-event basis. We also combine both field experiments and numerical simulations to investigate the hydrological behavior of GRs and validate our *P*–*R* relationship. The paper is organized as follows: we first discuss the two different runoff generation mechanisms on GRs, namely, saturation-excess (runoff is generated when the soil becomes saturated) and infiltration-excess (runoff is generated when the rainfall intensity is larger than the infiltration rate). We then perform a water balance analysis for a typical flat and horizontally homogeneous GR and propose a relationship between the rainfall amount *P* and the runoff amount *R*. A field experiment is conducted to calibrate and validate the *P*–*R* relationship. Numerical simulations via HYDRUS-1D are carried out to further investigate the relative importance of saturation excess runoff and infiltration excess runoff and to assess the applicability of our *P*–*R* relationship.

2. Theory

2.1. Runoff generation mechanisms on GRs

In general, runoff can be generated through two different mechanisms: saturation-excess (i.e, runoff is generated when the soil becomes saturated) and infiltration-excess (i.e., runoff is generated when the rainfall intensity becomes larger than the infiltration rate of water into the soil). The following analysis (done on an event-by-event) summarizes cases with runoff generated by different mechanisms. The subscript '*k*' indicates the k^{th} event.