# The influence of substrate and vegetation configuration on green roof hydrological performance

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## ABSTRACT

A four-year record of rainfall and runoff data from nine different extensive (80 mm substrate) green roof test beds has been analysed to establish the extent to which the substrate composition and vegetation treatment affect hydrological performance. The test beds incorporated three different substrate components with different porosity and moisture retention characteristics, and three different vegetation treatments (Sedum, Meadow Flower and unvegetated).

Consistent differences were observed, with the vegetated beds showing higher levels of rainfall retention and better detention compared with unvegetated beds. The seasonal Meadow Flower beds had similar hydrological performance to Sedum-vegetated beds. There was a 27% performance reduction in annual volumetric retention attributable to differences in substrate and vegetation. The beds with the most porous/permeable substrates showed the lowest levels of both retention and detention.

As with previous studies, retention efficiency in all nine beds showed a strong dependency on rainfall depth ($P$), with retention typically >80% for events where $P < 10$ mm, but significantly lower when $P > 10$ mm. The effects of vegetation and substrate were most evident for rainfall events where $P > 10$ mm, with the mean per-event retention varying between beds from 26.8% to 61.8%. On average, the test beds were able to retain the first 5 mm of rainfall in 65% of events where $P > 5$ mm, although this ranged from 29.4% to 70.6% of events depending on configuration. In terms of detention, all but one of the test beds could achieve runoff control to a green field runoff equivalent of 2 l/s/ha for more than 75% of events.

Detention was also characterised via the calibration of a reservoir-routing model that linked net rainfall to the measured runoff response. The parameter values identified here – when combined with a suitable evapotranspiration/retention model – provide a generic mechanism for predicting the runoff response to a time-series or design rainfall for any unmonitored system with comparable components, permitting comparison against local regulatory requirements.

## 1. Introduction

### 1.1. Background

Green roofs are widely understood to offer stormwater management capabilities via the retention of rainfall and the detention of runoff. In this context, retention refers to rainfall that is held within the roof system and does not leave the roof as runoff (i.e. initial losses). Retained rainfall may subsequently leave the roof as evapotranspiration. Detention refers to the temporal delay that occurs between rainfall that is not retained hitting the roof and emerging as runoff.

Stormwater management regulations vary across jurisdictions, but most include requirements for both volumetric control (retention) and for detention. Volumetric control requirements are intended to protect the water quality in receiving watercourses, mitigate flood risk, and minimise the volumes unnecessarily treated in, or intermittently spilled from, combined sewers. Detention control is required to reduce the risks associated with pluvial flooding and/or intermittent combined sewer overflows. In England and Wales, for example, developers are encouraged (but not required) to use Sustainable Drainage Systems (SuDS). Current SuDS guidance (Woods-Ballard et al., 2007) includes requirements to prevent runoff from (i.e. retain) the first 5 mm of rainfall, and to attenuate the 6 h duration 100 year return period event to a

greenfield runoff rate equivalent to 2 l/s/ha. Drainage systems specifically need to be designed to avoid causing site flooding in the event of a 1 in 30 year event. This guidance relates to site runoff, and a complete SuDS system may incorporate a green roof upstream of a number of other SuDS devices to form a site-scale treatment train. Within this context, it is clear that a proper understanding of green roof hydrological performance underpins SuDS design to meet regulatory requirements for stormwater management.

Many pilot and full scale monitoring studies have been undertaken (see e.g. Palla et al. (2010) or Li and Babcock (2014) for an overview). Although many authors have provided generalised metrics – such as mean per-event retention – to characterise performance, it is widely acknowledged that runoff responses to specific events depend upon a complex set of processes and interactions involving roof configuration (slope, aspect, drainage layer, substrate type and depth, and vegetation), rainfall characteristics (duration, depth, intensity) and antecedent conditions (in particular the role of evapotranspiration in restoring the substrate's retention capacity).

For test beds located together and subjected to the same climatic influences, it is feasible to identify trends in retention performance related to the specific roof configuration, and in particular to substrate and vegetation characteristics. For shallow systems (25–60 mm substrate) VanWoert et al. (2005) found that beds planted with Sedum species provided marginally greater volumetric retention compared with unvegetated systems, but suggested overall that the substrate physical properties and depth would have greater influence than vegetation. Monterusso et al. (2004) also concluded that the substrate has a greater influence than the vegetation on retention performance. Wolf and Lundholm (2008) found that vegetation enhanced moisture loss in green roof microcosms subjected to controlled irrigation regimes, but only when water availability was very low. Similarly, Nagase and Dunnett (2012) used controlled rainfall experiments to test 12 different plant species, and found that greater plant mass had a positive influence on runoff reduction. However, the effects are likely to have been exaggerated compared with complete green roof systems due to the use of a minimal substrate depth and some fairly substantial plants. Graceson et al. (2013) also demonstrated that the volumetric retention associated with different configurations of green roof test beds was more significantly affected by the physical properties of the growing media, particularly its pore size distribution and the maximum water holding capacity, than by either the vegetation treatment (Sedum or Meadow Flowers) or the growing media depth.

Detention comparisons are less regularly reported. Detention processes are difficult to characterise because many of the reported observable detention effects – such as the time to start of runoff – include the effects of retention at the start of the storm event (Stovin et al., 2015). For example, Whittinghill et al. (2015) compared the runoff profiles from Sedum, native prairie and vegetable-producing green roofs, suggesting that detention effects were more evident with Sedum and prairie grass compared with the vegetables. However, it is unclear exactly how detention was determined in this case.

Green roof detention combines the effects of many elements, including: detention due to plants; delays experienced as the runoff flows vertically downwards through the substrate (dependent on substrate depth and physical characteristics); and interactions between plant roots and the substrate.

In full-scale systems detention effects will also include delays experienced as the runoff drains through the drainage layer (which will be affected by the roof length and drainage layer configuration); and delays occurring in the guttering and downspout (affected by flow path length) upstream of the measurement location. Vesuviano et al. (2014) proposed a two-stage (substrate plus drainage layer) detention modelling approach, but this ignored any effects due to the collection system downstream of the roof. Fassman-Beck et al. (2013) observed that the downstream collection system may have contributed to differences in the 5-min Peak Attenuation observations for four different extensive living roofs in Auckland, New Zealand.

Laboratory studies enable rainfall inputs to be controlled, and for selected components of the green roof system to be considered in isolation. In reality green roofs will generally provide some retention at the start of a rainfall event, which will mean that observed attenuation effects will exceed the benefits due to physical detention processes alone. Where detention performance is the focus of the study, the substrate should initially be brought to field capacity to eliminate retention effects (Villarreal, 2007; Alfredo et al., 2010; Yio et al., 2013). The Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) guidance (FLL, 2008) outlines a standard test to determine the coefficient of discharge, C, based on the ratio of cumulative runoff to cumulative rainfall at the end of a 15-min constant intensity rainfall of 27 mm. The test is undertaken in a 5 m laboratory rainfall simulator, with the substrate pre-wetted to ensure that it is at field capacity. Field capacity corresponds to the moisture that is held within the soil matrix against the force of gravity; in the FLL tests this corresponds to two hours' free drainage following saturation. The resultant value of C can be used to determine worst-case drainage requirements for the roof, and to compare the relative detention performance of different green roof systems. Colli et al. (2010) found that the FLL runoff coefficient increased (i.e. detention was reduced) with increased rainfall intensity, increased slope and decreased substrate depth.

These laboratory studies suggest that detention effects may be dependent on rainfall intensity and substrate physical characteristics (depth, porosity). However, these controlled studies were mainly undertaken with a single vegetation type or on unvegetated substrates, and therefore do not provide significant insights into the detention effects of different vegetation treatments. Buccola and Spolek (2010) varied vegetation treatments, but reported that their findings were inconclusive. There is therefore a requirement for improved understanding of the combined effects of vegetation and substrate configuration on green roof detention performance.

Comparative studies based on field or laboratory monitoring programmes provide useful data on the relative benefits of different configuration options, but they do not directly permit the prediction of runoff responses to arbitrary rainfall events, in particular to the design (extreme) rainfall events that are considered relevant for urban flood mitigation. Stovin et al. (2013) and Locatelli et al. (2014) inter alia have emphasised the value of using empirical data to develop, calibrate and validate modelling tools to enable quantitative runoff prediction and attenuation evaluation. Key to this model development is the need to represent the initial losses (retention) processes and the delay (detention) processes independently. The complex interactions between plant roots and the substrate imply that detention effects are unlikely to be accurately predicted from knowledge of the substrate's physical characteristics alone, so an empirical approach to the identification of suitable model coefficients may be required. Stovin et al. (2015) argued that empirically-calibrated detention modelling parameters provide a unique and fundamental description of a system's detention characteristics, which is independent of retention effects.

In this paper detention model parameter identification will be applied to data from a four-year field monitoring experiment to quantify the combined effects of both substrate and vegetation treatments on green roof runoff detention performance. This approach permits an assessment of the relative performance benefits of alternative vegetation/substrate combinations, and also provides a calibrated set of model parameters to enable each of these system's responses to unseen rainfall events to be predicted.