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Research papers

Temporal variations in the potential hydrological performance of extensive green roof systems

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ABSTRACT

Existing literature provides contradictory information about variation in potential green roof hydrological performance over time. This study has evaluated a long-term hydrological monitoring record from a series of extensive green roof test beds to identify long-term evolutions and sub-annual (seasonal) variations in potential hydrological performance. Monitoring of nine differently-configured extensive green roof test beds took place over a period of 6 years in Sheffield, UK.

Long-term evolutions and sub-annual trends in maximum potential retention performance were identified through physical monitoring of substrate field capacity over time. An independent evaluation of temporal variations in detention performance was undertaken through the fitting of reservoir-routing model parameters. Aggregation of the resulting retention and detention variations permitted the prediction of extensive green roof hydrological performance in response to a 1-in-30-year 1-h summer design storm for Sheffield, UK, which facilitated the comparison of multi and sub-annual hydrological performance variations.

Sub-annual (seasonal) variation was found to be significantly greater than long-term evolution. Potential retention performance increased by up to 12% after 5-years, whilst the maximum sub-annual variation in potential retention was 27%. For vegetated roof configurations, a 4% long-term improvement was observed for detention performance, compared to a maximum 63% sub-annual variation. Consistent long-term reductions in detention performance were observed in unvegetated roof configurations, with a non-standard expanded-clay substrate experiencing a 45% reduction in peak attenuation over 5-years. Conventional roof configurations exhibit stable long-term hydrological performance, but are nonetheless subject to sub-annual variation.

1. Introduction

1.1. Background

It has been widely demonstrated that extensive green roof systems offer stormwater management capabilities through two hydrological processes, the retention of rainfall (which subsequently is lost via evapotranspiration and does not become runoff), and the detention of runoff (the transient storage of rainfall as it passes through the roof layers). Stormwater managers typically assume that a green roof's physical characteristics — such as its hydraulic conductivity (which influences detention) and field capacity (which influences retention) — are constant over time, and therefore that the roof's potential to retain and detain runoff are also constant over time. However, these properties may change in response to seasonal factors (vegetation growth cycles, substrate wetting/drying regimes) and/or due to longer-term processes such as compaction (De-Ville et al., 2017). There is therefore a need to determine whether there is evidence of such seasonal or longer-term changes in the underlying potential performance characteristics.

The most frequently reported indicator of green roof hydrological performance is the percentage retention, reported as either a 'mean per-event' or 'total volumetric' retention. Many green roof monitoring programmes have highlighted seasonal trends in observed retention performance, particularly in temperate climates of the northern hemisphere, where there are distinct seasonal variations in temperature, rainfall patterns, and other climatic variables. Retention performance is consistently higher

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in the warmer summer months of the year (Mentens et al., 2006; Uhl and Schiedt, 2008; Poë et al., 2015; Elliott et al., 2016). This is widely attributed to the increased levels of evapotranspiration, resulting in greater recovery of storage capacities between rainfall events. Beyond temperate conditions, however, Voyde et al. (2010) did not observe any seasonal trends in retention performance for a 12-month study conducted in Auckland, New Zealand, owing to the small seasonal meteorological differences in Auckland's climate. In the humid-subtropical climate of Hong Kong, Wong and Jim (2014) identified the weakest retention performance in summer months (over a 12-month period) due to increased levels of rainfall, which prevented sufficient recovery of the green roof's storage capacity between events. Therefore, whilst seasonal variations in observed retention performance are expected and observed in temperate climates, the challenge is to identify whether these variations are wholly due to climate or whether changes also occur in the underlying physical properties that affect the system's fundamental retention characteristics.

Fewer studies have focused on the longer-term (year-on-year) performance evolution of extensive green roof systems. Mentens et al. (2006) and Hill et al. (2016) widely sampled existing green roof systems in Germany and Canada respectively, with both finding no statistical correlation between roof age and hydrological performance. However, no systematic year-on-year comparisons have been published. Whilst this partly reflects the scarcity of long-term hydrological records, it should also be noted that the effect of natural climatic variation on observed hydrological performance is expected to mask any subtle changes in the underlying hydrological characteristics of the system (De-Ville et al., 2017). Observed retention performance is strongly influenced by storm event characteristics and tends to be greatest for small events, as green roofs only have a finite maximum retention capacity (e.g. 20 mm for an extensive system, Stovin et al. (2012)). It is not meaningful to compare annual retention performance (either volumetric or mean per-event retention), as rainfall patterns, temperatures, and other climate variables differ significantly from year-to-year. For example, the same roof configuration undergoing a high rainfall-low Antecedent Dry Weather Period (ADWP) year/season/storm event will have a lower retention performance than if exposed to a low rainfall-high ADWP year/season/storm event. However, the green roof's fundamental capacity for retention, as dictated by its physical characteristics, may be the same in both scenarios.

Similarly, observations of temporal changes in detention performance are typically confounded by the controlling effects of retention (Wong and Jim, 2014; Stovin et al., 2015b), and have therefore rarely been explored in isolation. In summary, the literature clearly identifies patterns in sub-annual hydrological performance, whilst findings on longer-term changes to either retention or detention capabilities are inconclusive. No previous studies have attempted to disaggregate storm event or climate-related forcing factors from potential seasonal or longer-term changes to the roof's underlying hydrological response.

1.2. Objectives

This study aims to test the null hypothesis that neither sub-annual nor long-term temporal variations exist in the potential hydrological performance of green roof systems that have been monitored in Sheffield, UK. This is to be achieved through: 1) the identification of approaches that permit temporal variations in the physical properties that control retention and detention to be quantified; 2) the exploration of a long-term hydrological record of a series of extensive green roof test beds to identify temporal variations in both potential retention (5-year record) and detention performance (6-year record); and 3) an evaluation of the consequences of any predicted changes through the prediction of hydrological performance in response to design storms.

2. Literature review

2.1. Physical controls on potential hydrological performance

A green roof's maximum retention capacity is widely attributed to be approximately equal to the substrate's Plant Available Water (PAW, mm), which is itself a function of the substrate's Field Capacity (Θ_{FC}, %v/v), Permanent Wilting Point (Θ_{PWP}, %v/v), and depth (d, mm):

$$PAW = (\Theta_{FC} - \Theta_{PWP}) \cdot d \tag{1}$$

It is proposed that tracking of these physical properties over time should provide a climatically independent temporal evaluation of the Absolute Retention Capacity (ARC) of the green roof system (equivalent to the maximum potential soil moisture deficit). These independent ARC evaluations may be combined with the observed effects of rainfall, ADWP, and PET in appropriate hydrological models to identify the Potential Retention Capacity (PRC) and Potential Retention Performance (PRP) of the green roof system in response to a specific climate/weather/storm event scenario. Section 3.3 outlines a novel approach to tracking field capacity using in situ moisture content sensors.

As with retention, the system's detention characteristics may also be monitored through the identification of relevant physical properties. Detention processes may be modelled via the application of appropriate unsaturated media flow relationships. However, the governing equations for predicting unsaturated-media flow are complex, require numerous physical characteristics (Palla et al., 2012), and there is therefore scope for large compound errors. Alternatively, semi-empirical descriptions of the fundamental detention characteristics can be achieved with simple hydrological models, whilst maintaining suitable levels of predictive accuracy. Stovin et al. (2015a) proposed the use of a reservoir routing model to describe detention processes, and this approach was successfully deployed to identify differences in detention characteristics between various roof configurations independently of climate.

In summary, conventional retention and detention performance metrics derived from monitored data are poorly suited to the identification of temporal trends in underlying hydrological function. It is therefore proposed that a coupled physical property monitoring programme and validated hydrological modelling approach will better identify changes to the underlying green roof physical characteristics and their impacts on potential hydrological performance over time.

2.2. Temporal trends in green roof physical characteristics

Whilst yearly evaluations of hydrological performance may not exist in the literature, there have been some attempts to characterise temporal changes in green roof physical properties. Exploration of properties thought to directly influence hydrological performance has identified potential for improved hydrological performance in the long-term. Getter et al. (2007) found that pore volume doubled over a 5-year period, and hypothesised that this would lead to improvements in retention performance due to an increase in microporosity ($\leqslant$50 μm). However, Getter et al. (2007) also noted that these improvements may come at the expense of worsened detention performance due to an increased presence of macropore (>50 μm) channels. De-Ville et al. (2017) explored the physical properties of virgin and aged (5-years) green roof substrate, where observed structural differences were inferred