Journal of Hydrology 547 (2017) 332–344

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

The impact of green roof ageing on substrate characteristics and hydrological performance

Simon De-Ville [a,*], Manoj Menon [b], Xiaodong Jia [c], George Reed [a], Virginia Stovin [a]

[a] Department of Civil & Structural Engineering, University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, UK
[b] Department of Geography, University of Sheffield, Sheffield S10 2TN, UK
[c] School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK

ARTICLE INFO

Article history:
Received 23 September 2016
Received in revised form 13 January 2017
Accepted 6 February 2017
Available online 9 February 2017
This manuscript was handled by Tim R. McVicar, Editor-in-Chief, with the assistance of Giorgio Mannina, Associate Editor

Keywords:
Green roof
Substrate
Physical properties
Hydrological performance
Ageing
X-ray microtomography

ABSTRACT

Green roofs contribute to stormwater management through the retention of rainfall and the detention of runoff. However, there is very limited knowledge concerning the evolution of green roof hydrological performance with system age. This study presents a non-invasive technique which allows for repeatable determination of key substrate characteristics over time, and evaluates the impact of observed substrate changes on hydrological performance.

The physical properties of 12 green roof substrate cores have been evaluated using non-invasive X-ray microtomography (XMT) imaging. The cores comprised three replicates of two contrasting substrate types at two different ages: unused virgin samples; and 5-year-old samples from existing green roof test beds. Whilst significant structural differences (density, pore and particle sizes, tortuosity) between virgin and aged samples of a crushed brick substrate were observed, these differences did not significantly affect hydrological characteristics (maximum water holding capacity and saturated hydraulic conductivity). A contrasting substrate based upon a light expanded clay aggregate experienced increases in the number of fine particles and pores over time, which led to increases in maximum water holding capacity of 7%. In both substrates, the saturated hydraulic conductivity estimated from the XMT images was lower in aged compared with virgin samples. Comparisons between physically-derived and XMT-derived substrate hydrological properties showed that similar values and trends in the data were identified, confirming the suitability of the non-invasive XMT technique for monitoring changes in engineered substrates over time.

The observed effects of ageing on hydrological performance were modelled as two distinct hydrological processes, retention and detention. Retention performance was determined via a moisture-flux model using physically-derived values of virgin and aged maximum water holding capacity. Increased water holding capacity with age increases the potential for retention performance. However, seasonal variations in retention performance greatly exceed those associated with the observed age-related increases in water holding capacity (+72% vs +7% respectively). Detention performance was determined via an unsaturated-flow finite element model, using van Genuchten parameters and XMT-derived values of saturated hydraulic conductivity. Reduced saturated hydraulic conductivity increases detention performance. For a 1-hour 30-year design storm, the peak runoff was found to be 33% lower for the aged brick-based substrate compared with its virgin counterpart.

1. Introduction

A green roof is an example of a Sustainable Drainage System (SuDS) which provides stormwater quantity management benefits through two hydrological processes. The first is retention (the permanent removal of rainfall) and the second is detention (the transient storage of rainfall as it passes through the roof layers). As green roof systems age, their living components – particularly the vegetation, but also the substrate – are subject to a number of processes that have the potential to alter system-wide hydrological performance (Berndtsson, 2010). Some of these processes are well understood. For example, the daily and seasonal changes in evapotranspiration are known to control a green roof's retention performance (Poë et al., 2015). The effects of other key processes, such as root system development, organic matter turnover,

* Corresponding author.
E-mail address: sde-ville1@sheffield.ac.uk (S. De-Ville).

http://dx.doi.org/10.1016/j.jhydrol.2017.02.006
0022-1694/

weathering and substrate consolidation, are less well understood in the context of green roof hydrological performance (Berndtsson, 2010).

1.1. Green roof hydrological performance

Much of the current research into green roof stormwater quantity control (hydrological performance) focusses on short term studies (<1 year), leading to a single overall retention performance value. For example, Harper et al. (2015) stated that over a 9-month period a vegetated green roof was capable of retaining approximately 60% of rainfall. The multi-year study performed by Nawaz et al. (2015) again provided a single mean value of retention performance (66%) for the entire monitoring period. These two recent examples are representative of the wider literature.

Detention performance metrics are less commonly reported due to difficulties in its characterisation. For example, Stovin et al. (2015a) used peak attenuation to characterise and compare detention performance for 9 green roof configurations over a 4-year period. For events with more than 10 mm of rainfall, mean peak attenuation (5-min resolution) was seen to vary from approximately 40 to 70% depending on roof configuration. Reported values from monitoring studies are influenced by rainfall characteristics and antecedent conditions (retention processes). However, the fundamental hydrological detention processes are essentially independent of these factors and dependant only on the green roof's physical configuration (Stovin et al., 2015b). Whilst differences due to configuration and climate have been considered in some depth, there is very little discussion and understanding of the long-term temporal variation that green roof hydrological performance, both retention and detention, may exhibit as a result of system age.

Green roof hydrological performance is a function of the combined effects of a range of interacting physical processes. These processes are in turn influenced by the substrate's physical characteristics, including pore size distribution, particle size distribution, particle shape and texture. It is these physical characteristics that determine key hydrological properties, including density, porosity, hydraulic conductivity and water holding capacity. Green roof detention performance is largely influenced by porosity and hydraulic conductivity, as these properties define the speed with which water can pass through a substrate. Retention performance is related to the pore size distribution which dictates water release characteristics, in turn determining permanent wilting point (PWP) and maximum water holding capacity (MWHC). The maximum potential retention capacity is defined by the difference between PWP and MWHC (often referred to as plant available water, PAW). Whether this capacity is available at the onset of a specific storm event depends on evapotranspiration in the antecedent dry weather period.

1.2. Green roof ageing

In their extensive review of green roof literature, Li and Babcock (2014) identified very few studies addressing the impact that green roof ageing may have upon hydrological performance over time. Whilst this partly reflects the scarcity of long-term hydrological records, the effect that natural climatic variation has on observed hydrological performance is likely to mask any subtle changes in the underlying hydrological characteristics of the system.

Those studies that have considered green roof age and associated substrate property changes have identified very different trends. Mentens et al. (2006), found no correlation between green roof age and yearly runoff quantity for a series of differently-configured German green roofs when analysing less than 5 years of data. Getter et al. (2007) found that substrate organic content and pore volume both doubled over a 5-year period. Getter et al. (2007) hypothesised improvements to retention performance due to an increase in microporosity (<50 μm), but noted these improvements may come at the expense of detention performance due to an increased presence of macropore (>50 μm) channels. Contrastingly, in a study of green roof establishment, Emilsson and Rolf (2005) observed a net loss of organic matter from 3 to 1% over a single year. Bouzouidja et al. (2016) identified similar falls in organic content over a 4 year-period and reported a reduction in the mass of particles smaller than 2 mm in diameter. The impact that organic matter fluctuations can have on green roof hydrological performance is demonstrated by Yio et al. (2013), where a threefold increase in organic content (Coir) was associated with a peak attenuation increase from 15 to >50%.

Beyond the limited range of green roof ageing literature, other SuDS devices provide evidence of ageing effects. Biofilters are prone to sedimentation and clogging as they age, although the media's hydraulic conductivity may be maintained through the presence of plant roots (Virahsawmy et al., 2014). Further literature from the agro/forestry fields provides evidence of the effects that plant-life can have on soil porosity and infiltration rates. Root growth can reduce pore volumes due to local compression and pore filling (Dexter, 1987), thereby reducing hydraulic conductivity. The decay of dead roots leaves channels which may increase pore spaces and act as flow paths, increasing hydraulic conductivity (Schwen et al., 2011). Plant activity can also influence soil aggregation (Lado et al., 2004) and desiccation cracking (Materechera et al., 1992). However, the majority of agro/forestry literature is based on observations of plant species and growing media not typically found on a green roof, which potentially limits its relevance here.

1.3. Evaluating green roof substrate properties

Many current techniques for the evaluation of green roof substrate properties are invasive and destructive. These methods typically involve the collection and aggregation of several samples into an overall sample, which is then used for physical property evaluation (Emilsson and Rolf, 2005; Thuring and Dunnett, 2014). Such methods lead to the destruction of the original pore space distribution, altering porosity and hydraulic conductivity characteristics. Alternatively, in an effort to maintain the particle and pore size distributions, cores of the substrate can be taken and set in resin. This preserves the internal structure of the core, which can then be cut to examine the internal structure. Whilst this technique does preserve the in-situ characteristics of the green roof substrate, it is only capable of providing 2D perspectives of the core as opposed to the full 3D volume (Young et al., 2001).

X-ray microtomography (XMT) is a non-destructive 3D computed tomography (CT) imaging approach, which is widely used for the visualisation and quantification of an object's internal structure. Improvements in spatial resolution and image reconstruction times since the turn of the century have allowed XMT to become a commonly accepted tool for material analysis (Maire and Withers, 2014). Images are obtained by passing X-rays from a suitable source through the object to be imaged and onto a CCD detector. Typical achievable image resolutions range from <1 μm to 150 μm depending upon object size. The resulting high resolution images can be analysed to show the 3D spatial arrangement of the solid particles and pore spaces in a soil matrix.

XMT is an established technique within the soil sciences field, where the main application has been for the characterisation of physical soil properties (Menon et al., 2015). Several studies have successfully utilised XMT to observe plant roots and their interactions with soils, earthworm burrows, soil insects, and other soil microorganisms (Taina et al., 2008). However, there has been