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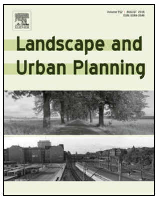

Research paper

Modelling green roof stormwater response for different soil depths

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HIGHLIGHTS

- We model the water retention of green roofs and efficiency in rain-flow attenuation.
- Reduction of stormwater run-off increased proportionally to soil depth.
- Where intensity and duration of rain is high, stormwater discharge efficiency reduces.
- More existing buildings can accommodate shallow soil retrofit without strengthening.

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ABSTRACT

Green roofs have been proposed as a way to mitigate stormwater run-off in urban areas due to the possibility of retrofit to existing buildings. The amount of run-off is influenced by the, humidity, evapotranspiration, as well as soil type and depth. A modelling approach was undertaken to evaluate the response of different soil depths to cumulative rainfall and the efficiency in stormwater flow rate attenuation. The soil hydraulics were modelled using HYDRUS-1D software developed for modelling water flow in variably saturated porous media. Model runs were carried out for three quarterly scenarios to determine run-off peak flow rates and the overall retention, based on evapotranspiration rates of succulent plants and rainfall registers from Auckland, New Zealand. The soil depths modelled ranged from 5 to 160 cm. The efficiencies in peak flow attenuation by the shallowest soil considered were reduced under extreme and longer rainfall events by 3%. Therefore shallow soil or extensive green roofs may, on a wide scale, overcome the performance of deep soils due to their lighter weight which adds limited loads to existing roof structures thereby making them suited to retrofit greater numbers of buildings.

1. Introduction

The increasingly rapid process of urbanization has led to substantial changes in the permeability of land and the use of soil (Berndtsson, 2010). Green areas are being replaced by buildings, driveways and pavements, changing the original permeable conditions to impervious surfaces. Consequently, there has been a considerable increase in rainwater run-off, leading to the risk of floods and decreased groundwater recharge (Lamond, Booth, Hammond, & Proverbs, 2012).

A number of alternative options have been proposed to restore the hydrology of urban areas to their original state as much as possible. Examples include the maintenance of green areas and recovery or restoration of deforested areas, which help to attenuate the effects of storm water discharges in urban areas (Wilkinson, Rose, Glenis, & Lamond, 2014). The adoption of green roofs is posited as an alternative or complementary to cope with this problem (Berndtsson, 2010). Green roofs differ from other types of solutions, such as bio infiltration systems and constructed wetlands, as they are not limited by space availability, since they can be retrofitted to existing buildings, which according to Dunnet and Kingsbury (2004) represent about 40–50% of the impermeable surfaces in urban areas.

When compared to a conventional roof, green roofs change stormwater run-off by attenuating and delaying the peak flow of water (Berndtsson, 2010). Around sixty percent of peak flows on a vegetated roof were delayed up to 10 min when compared to peak flows from conventional roofs, because a certain amount of water is buffered in the soil layer of green roofs (Berndtsson, 2010). Some of this water is drained, and part is retained according to soil field capacity (Berndtsson, 2010). The water retained is sub-

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sequently removed from the soil through the evapotranspiration process (Berndtsson, 2010).

Typically four different layers are found in green roof systems: vegetation; soil; a filter to avoid the loss of soil particles; and drainage material. These systems play a significant role in rainfall retention due to water uptake by plant roots and the soil. According to Hilten, Lawrence, and Tollner (2008), green roofs retain stormwater and thus attenuate the peak flow rate compared to that from impervious surfaces. Many studies have evaluated the efficiency of green roofs in the reduction of total rainfall volume and flow rate (Buccola & Spolek, 2011; Carter & Jackson, 2007; Fassman-Beck, Voyde, Simcock, & Hong, 2013; Hilten et al., 2008; Mentens, Raes, & Hermy, 2006; Monterusso, Rowe, Rugh, & Russell, 2004; Nardini, Andri, & Crasso, 2012; Palla, Gnecco, & Lanza, 2009; She & Pang, 2010; Simmons, Gardiner, Windhager, & Tinsley, 2008; ; VanWoert et al., 2005; Voyde, Fassman, & Simcock, 2010; Wong & Jim, 2014; Yio, Stovin, Werdin, & Vesuviano, 2013). This efficiency varies from 40 to 90% according to the individual depths, types and moisture conditions of soil. However, those authors have not performed evaluations of stormwater response for a wide range of soil depths. As example, VanWoert et al. (2005) considered three shallow soil substrates (2.5, 4.0 and 6.0 cm), where the results did not vary significantly. Buccola and Spolek (2011) and Nardini et al. (2012) examined two soil depths of 5–14 cm and 12–20 cm, respectively. Fassman-Beck et al. (2013) and Yio et al. (2013) analysed four substrates with a maximum depth of 15 cm (5 cm, 7 cm, 10 cm and 15 cm), and Wong and Jim (2014) considered soil depths of 4 cm and 8 cm. It is important to highlight that all the cited studies comprise mostly extensive systems and no depths beyond 20 cm were evaluated. Thus, the present work aimed to evaluate the influence of soil depth in runoff retention and peak attenuation, gathering in the same study, for exactly the same soil substrate, a range of depths from 5 cm to 160 cm using both extensive and intensive green roof systems.

Depending on the soil depth, green roof systems can be classified either as intensive or extensive. According to studies compiled and performed by Berndtsson (2010) the intensive system is comprised of soil layers greater than 10 cm depth, and is thus able to support growth of plants up to the size of small trees. However, it is heavier than the extensive system, requires more maintenance, and in most cases the building structure has to be designed to support this additional load. Extensive green roof systems, in contrast, comprise thinner layers of soil and lighter vegetation, and thus can be retrofitted to most existing buildings without additional strengthening. Although lighter than intensive systems, extensive roofs are not expected to perform better in terms of water retention capacity and flow rate attenuation. However, considering that most existing buildings were not designed to support a substantial extra load, extensive green roof systems might be applied to a larger overall area, thus overcoming the higher efficiency of the intensive green roof system due its greater depth.

Previous studies show that green roofs can mitigate stormwater run-off (Berndtsson, 2010), however the extent of such mitigation depends on soil depth (intensive or extensive green roof system), moisture content, and rainfall distribution. Studies undertaken in Germany reported that intensive and extensive green roofs had annual run-off reductions equal to 65–85% and 27–81% of annual precipitation respectively (Mentens et al., 2006). These results are supported by additional studies cited in Berndtsson (2010). However, the exact values of the percentage reduction achieved must be viewed with caution due to the different conditions experienced in the different studies. Thus, in order to evaluate the influence of soil depth in the mitigation of stormwater run-off, under same soil type and variable meteorological conditions, a modelling procedure is employed, to reduce potential experimental discrepancies, such as variations in soil structure, and setup imprecision.

Numerical models have been developed to assess the hydrologic performance of green roofs in terms of total volume and flow peak reduction, such as EPA's Storm Water Management Model (SWMM), SWMS-2D, Hydrus-1D (Šimůnek, Šejna, Saito, Sakai, & van Genuchten, 2013) among other. SWMM is a dynamic rainfall-runoff simulation model used for simulation of runoff quantity and quality from primarily urban areas. SWMS-2 and Hydrus-1D numerically solve Richards' equation in order to simulate water flow in variably saturated porous media. Hydrus-1D was adopted in this work for one-dimensional modelling of soil water transport considering different soil depths. This is a public domain, Windows-based modelling software, with an interactive graphics interface for data, pre- and post-processing. Additionally, this software has been used in other green roof applications (Hakimdavar, Culligan, Finazzi, Barontini, & Ranzi, 2014; Hilten et al., 2008; Hilten & Lawrence, 2008; Liu & Fassman-Beck, 2014; Palla, Gnecco, & Lanza, 2012; Yang, Li, Sun, & Ni, 2015).

This study consists of an evaluation of stormwater run-off attenuation by green roofs predicated on modelling techniques and rainfall registers from Auckland New Zealand. Soil depths of 5, 10, 20, 40, 80 and 160 cm, planted with succulent Sedum species are considered in the modelling. Besides being common in many parts of the world, succulent Sedum species tend to be low growing plants which provide good soil coverage (Voyde, Fassman, Simcock, & Wells, 2010). They require low maintenance due to their resistance to drought, temperature, solar radiation, rainfall and wind. Furthermore, succulent Sedum species grow rapidly, are lightweight, shallow rooting, and have low fire risk. Succulents store carbon dioxide in their tissue, and this allows the plants to close stomata during the day to conserve water, and open stomata at night, to absorb carbon dioxide under cooler temperatures. As a result of this characteristic, succulents can survive even under drought conditions (Voyde, Fassman, Simcock, 2010); a characteristic that makes them attractive in countries where rainfall can be unreliable, such as Australia and Brazil.

2. Methods

2.1. Model overview

The version of HYDRUS used in this research is HYDRUS-1D, version 4.16 (Šimůnek et al., 2013). HYDRUS-1D is a numerical simulation program for one-dimensional soil moisture fluxes in a soil column of unit area. This program numerically solves the Richards equation for variably saturated water flow and advection-dispersion type equations for heat and solute transport.

In HYDRUS-1D, a soil column of chosen depth, which its geometric characteristics, and hydraulic parameters are specified by the user, is discretised into elements. Time simulation, time steps range and iteration limits, head pressure and water content tolerances are also set as model parameters. Initial and boundary conditions are based on terms of pressure head or water content, sources and sinks. Whenever included in the modelling, sources and sinks such as precipitation and evapotranspiration fluxes, can be considered constant or inputted as a time data sequence. Šimůnek et al. (2013) present a complete description of the model.

2.2. Governing equations

A modified form of the Richards equation, using the assumptions that the air phase does not play a significant role in the liquid flow process and that water flow due to thermal gradients can be neglected, describes the water movement through the soil on the