Ecological Engineering 102 (2017) 596–611

Contents lists available at ScienceDirect

Ecological Engineering

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

Wet season hydrological performance of green roofs using native species under Mediterranean climate

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ARTICLE INFO

Article history:
Received 22 August 2016
Received in revised form 3 February 2017
Accepted 18 February 2017
Available online 9 March 2017

Keywords:
Urban stormwater management
Urban hydrology
Plant selection
Mosses
Sustainability

ABSTRACT

Urban areas generate considerable amounts of stormwater runoff due to a high percentage of impervious surfaces. In Mediterranean climates, during winter, large volumes of rainfall over short periods of time can cause flooding. Green roofs are emerging as a tool for stormwater management under the Sustainable Urban Drainage Systems philosophy. This paper investigates the influence of rainfall patterns and types of native vegetation cover upon the rainfall-runoff relations of a green roof under a Mediterranean climate during the autumn/winter period. Test beds were installed on a rooftop in Lisbon, Portugal, incorporating a substrate layer 150 mm deep, three native vegetation covers and one non-vegetated control. Rainfall and runoff data were monitored over a 6-month autumn/winter period. Results show that the vegetated systems reduced the stormwater runoff, attenuated peak flow and delayed runoff. Overall, 69 of 184 events did not produce runoff, median retention ranged from 55 to 100% and median peak attenuation from 97 to 100%. The combination of shrubs, grasses and mosses proved to be the most effective vegetation cover. Antecedent substrate moisture and plant rainfall interception significantly influenced green roof stormwater performance for all the vegetation covers. Estimations based on the experimental green roof data, an empirical model and a detailed spatial analysis, revealed that, by greening 75% of the flat roof area of the municipality of Lisbon, approximately 166 500–224 000 m^3 of water could be retained, relieving the drainage systems and preventing floods.

1. Introduction

Stormwater management is a critical challenge for many cities nowadays. The recent expansion of urban areas in both space and density has resulted in the increase of impervious surfaces such as rooftops, driveways, roads, parking lots, and footpaths. These surfaces are usually connected to sewer-drainage systems to receive water from rainfall. However, insufficient infiltration areas and high intensity rainfall events, can overwhelm these drainage systems, causing overflows and floods (Nagase and Dunnett, 2012). In most developed cities, 40–50% of the impervious area is associated with roofs (Stovin et al., 2012). Therefore, runoff from roofs during rainfall events largely contributes to combined sewer overflows and urban water quality problems. Under the Mediterranean climate, in which the rainfall is concentrated in the winter season, this phenomenon is intensified.

The conventional approach to stormwater management involves the efficient capture, conveyance, and sometimes treatment of runoff generated from the impervious surfaces. The Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), or Water Sensitive Urban Design (WSUD) philosophies suggest that the modern approaches to stormwater management need to control both the quantity and the quality of runoff and, at the same time, typically aim to restore pre-development hydrological conditions (Villarreal et al., 2004). LIDs (SUDS or WSUDs) are basically a source reduction approach. These sustainable strategies focus on evaporating, transpiring and infiltrating stormwater on-site through natural and/or engineered soil, vegetation and bioengineering applications to reduce and treat the overland flow that

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http://dx.doi.org/10.1016/j.ecoleng.2017.02.025
0925-8574/

Nomenclature

Symbol	Physical variable	Units
c	Plant cover fraction	dim
D	Duration of an event	h
d_{RF}	Total rainfall depth	mm
d_{RO}	Total runoff depth	mm
$\bar{E}_c$	Mean evaporation rate from saturated canopies	mm h^{-1}
ETo	Monthly reference evapotranspiration	mm
I_{RF}	Maximum rainfall intensity in 10 min	mm h^{-1}
I_{RFa}	Mean rainfall intensity	mm h^{-1}
I_{RO}	Maximum runoff intensity in 10 min	mm h^{-1}
I_{ROa}	Mean runoff intensity	mm h^{-1}
PA	Peak attenuation	%
PD	Peak delay	h
pF	Logarithm of the matric pressure measure in cm	dim
R	Rainfall retention	%
R^2	Coefficient of determination	dim
$\bar{R}$	Mean rainfall rate during saturated conditions	mm h^{-1}
RD	Runoff delay	h
S	Plant storage capacity	mm
WS_R	Relative water storage	%

is limited for most rainfall events in a natural environment (Palla et al., 2010). Green roofs represent a technique following that philosophy, as they reduce and attenuate storm runoff at the source. Furthermore, they provide an opportunity for engineering to work in harmony with natural environmental processes contributing to sustainable urban environments (Stovin et al., 2012).

During a storm event the hydrological mechanisms operating within the green roof are the interception of rainfall by the plant layer, infiltration and storage in the substrate, and reservoir storage in the drainage layer, if present (Stovin et al., 2012). Water will also return to the atmosphere as a result of evapotranspiration. Runoff will be generated when the substrate's and drainage layer water storage capacity is exceeded, or bypass flow occurs, and the excess water will be directed out of the drainage layer into the downstream drainage system.

A green roof changes the rainfall-runoff relation compared with that from a conventional roof through lowering (attenuation) and delaying the peak runoff – there is a time lag between the peaks from a conventional and from a green roof for the same rain event. Literature shows that this relation is mainly affected by the properties of the growing media, namely the thickness, the organic matter content, and the hydraulic properties of the substrate; the movement through the drainage layer to the outlets; and the rainfall intensity and duration. These factors are followed by the vegetation typology and density and the antecedent soil moisture conditions (Fassman-Beck et al., 2013; Harper et al., 2014; Hathaway et al., 2008; Razzaghmanesh and Beecham, 2014; Stovin et al., 2012).

Many studies have tested green roofs' capacity to retain and delay the rainfall water by combining different types of substrates and vegetation, under different climates (Table 1).

In general, test beds or large scale green roofs were compared to common gravel or concrete roofs and, in terms of hydrological performance, all of the studies confirmed the capacity of green roofs to decrease runoff under different conditions and locations (VanWoert et al., 2005; Voyde et al., 2010; Zhang et al., 2015). Globally, rainfall retention varied between 34% and 100% (Yilmaz et al., 2015), and the mean rainfall retention was always above 50%. Literature also demonstrates that a decrease of 60–80% in runoff peak rates is to be expected from a green roof (Hutchinson et al., 2003; Stovin, 2010; VanWoert et al., 2005).

Relatively few studies have been performed under Mediterranean conditions (Beecham et al., 2012; Fioretti et al., 2010; Palla et al., 2010), characterized by mild wet winters with low solar irradiance and hot dry summers with high solar irradiance. In these climatic conditions, the rainfall is concentrated in the season of cooler weather, with large volumes of rainfall in short periods of time. However, the intensity of summer drought, as well as the annual total rainfall, vary considerably from location to location (Hobbs et al., 1995; Razzaghmanesh and Beecham, 2014). Therefore, the need for rainwater retention is higher during the season when plant activity is reduced, and conversely, water availability is lower when the temperatures are higher and plant activity increases. This constitutes the biggest limitation for the green roofs implementation under the Mediterranean climate, as it implies the need for irrigation systems with the associated costs of installation, water, and energy during the summer.

Vegetation can affect the amount of water runoff from a green roof. The interception of water by the canopy provides a direct mechanism by which plants may influence the rainfall-runoff interaction. The water storage capacity varies with the individual plant form (leaf orientation and size, bark roughness and hydrophobicity, branch rigidity, canopy density, etc.). However, the structure of plant communities may also influence the interception behaviour (Nagase and Dunnett, 2012). The below ground structure is also important for water management since the water retention in the substrate may be affected by the plant root structure. Plants forming dense fibrous roots reduce the porosity of the substrate and the volume available to retain water (MacIvor and Lundholm, 2011). Evapotranspiration is the other plant related process that influences runoff production (Lundholm et al., 2010). Species that evapotranspire more from the growing medium will create more space for the capture of water in subsequent rain events (MacIvor and Lundholm, 2011).

In addition to the characteristics of individual plants, vegetation diversity may also influence the hydrological performance of a green roof. The amount of runoff can be reduced by increasing the number of species and its structural types (Rixen and Mulder, 2005). The inclusion of taller species may result in a higher rate of interception loss and evapotranspiration, while mat species that are in contact with the soil may release more moisture from the soil into the sub canopy space. Furthermore, different rooting patterns allow differential exploitation of the soil profile either spatially or temporally (Nagase and Dunnett, 2012).

The plants most commonly used on green roofs in hot and dry climates are succulents, especially *Sedum* sp. (Rayner et al., 2016). Despite its great resistance to drought and to the harsh conditions of a green roof, some authors have explored the advantages and limitations of other types of vegetation. Dvorak and Volder (2010) suggest that the survival of green roof vegetation is correlated to the similarity between roof conditions and those of plants' original habitat, mainly its hydrological dynamics and nutrient cycling. These authors conclude that drought tolerant native and introduced herbaceous plants can be used on green roofs, but deeper substrates and some irrigation may be required, when compared to the exclusive use of succulents. Oberndorfer et al. (2007) also suggest that native plants are ideal to use as vegetation for green roofs, due to their adaptations to the local conditions. Native plants can also play a major role in attracting wildlife (Grant et al., 2003), as they help to mimic, on the rooftop, habitats that appeal to local insects and birds, among others.

Many Mediterranean native plant species (xerophytes) have morpho-functional and physiological adaptations: changes on the leaves (imbricate or often linear, with a thick, waxy cuticle, sunken stomata, pubescent surface), on the roots (deep rooting, hairy sur-