Science of the Total Environment 499 (2014) 284–296

Contents lists available at ScienceDirect

Science of the Total Environment

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

The hydrological behaviour of extensive and intensive green roofs in a dry climate

M. Razzaghmanesh *, S. Beecham

Centre for Water Management and Reuse, School of Natural and Built Environments, University of South Australia, Adelaide, Australia

HIGHLIGHTS

- Rainfall and runoff data were recorded for a period of almost 2 years.
- The average retention was 74.0% from extensive and 88.6% from intensive roofs.
- An average attenuation time of almost 3 to 17 h was observed.
- A non-linear relationship was observed between rainfall and runoff.
- Rainfall duration, depth, intensity and ADWP influenced the retention performance.

ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form 15 August 2014
Accepted 15 August 2014
Available online 6 September 2014

Editor: D. Barcelo

Keywords:
Green roof
Water sensitive urban design
Stormwater
Roof runoff
Retention

ABSTRACT

This paper presents the results of a hydrological investigation of four medium scale green roofs that were set up at the University of South Australia. In this study, the potential of green roofs as a source control device was investigated over a 2 year period using four medium size green roof beds comprised of two growth media types and two media depths. During the term of this study, 226 rainfall events were recorded and these were representative of the Adelaide climate. In general, there were no statistically significant differences between the rainfall and runoff parameters for the intensive and extensive beds except for peak attenuation and peak runoff delay, for which higher values were recorded in the intensive beds. Longer dry periods generally resulted in higher retention coefficients and higher retention was also recorded in warmer seasons. The average retention coefficient for intensive systems (89%) was higher than for extensive systems (74%). It was shown that rainfall depth, intensity, duration and also average dry weather period between events can change the retention performance and runoff volume of the green roofs. Comparison of green and simulated conventional roofs indicated that the former were able to mitigate the peak of runoff and could delay the start of runoff. These characteristics are important for most source control measures. The recorded rainfall and runoff data displayed a non-linear relationship. Also, the results indicated that continuous time series modelling would be a more appropriate technique than using peak rainfall intensity methods for green roof design and simulation.

1. Introduction

Climate change, increasing population and water scarcity are current problems in many cities in the world (Gill et al., 2007). The consequences of these threats put more pressure on urban water systems and generally adversely changes the hydrological cycle in urban catchments (Beecham et al., 2012). This can lead to urban flooding in cities which can bring many problems for residents. Introducing green infrastructure such as green roofs, which are also known as living roofs, can help ameliorate the hydrological problems associated with urbanisation. One of the important strategies in European sustainable urban drainage systems (SUDS) and Australian water sensitive urban design (WSUD) systems is source control of runoff (Alsup et al., 2010; Voyde et al., 2010). Similarly in the United States, installing green roofs is viewed as a best management practice (BMP) to attenuate peak runoff flows in urban areas. A green roof is an engineered multi-layered structure with a vegetated upper surface. Green roofs are normally categorised as either extensive (depth = 100 mm to 250 mm) or intensive (depth ≥ 300 mm) (FLL, 2002; Berndtsson, 2010). Selecting and optimising each green roof layer is one of the most important design issues. According to Berndtsson (2010), the most significant difference between the outflow hydrographs from conventional roofs and green roofs is the peak flow and the runoff time of concentration from the green roof. That is to say, in green roofs, the time of concentration to the downpipe is greater than the corresponding time in conventional

* Corresponding author at: Centre for Water Management and Reuse, University of South australia, Adelaide, Australia.Tel.: +61 424 478 168.

http://dx.doi.org/10.1016/j.scitotenv.2014.08.046
0048-9697/

roofs. This delay of peak flow and long travel time are the main benefits of green roofs (Stovin, 2010).

Some researchers have used water mass balance equations in order to study the hydrologic behaviour of green roofs (Mentens et al., 2003) as described in Eq. (1) (Vilareal and Bengtsson, 2005).

$$P + Ir – E – Q – D \pm \Delta S = 0 \tag{1}$$

where P = Precipitation; E = Evapotranspiration; Q = Runoff; D = Deep percolation; ΔS = Moisture changes or storage in the system; and Ir = Irrigation.

Deep percolation is often close to zero in green roofs and so by neglecting D from Eq. (1) the mass balance becomes:

$$Q = P + Ir – E \pm \Delta S. \tag{2}$$

In most hydrological and water quantity monitoring studies involving green roofs, the main objective is to estimate the different parts of this equation. Generally, runoff is defined as the total excess water exiting from the green roof systems (Voyde et al., 2010). The outflow runoff is dependent on the green roof retention capacity and in most hydrological studies the green roof performance is evaluated in terms of the estimated retention coefficient. Green roof industries are well developed in Germany and North America. A study of two green roofs was undertaken in Portland, Oregon, USA by Hutchinson et al. (2003). In this study after achieving reliable results from small scale green roofs installed on top of a residential site, a full-scale green roof constructed and monitored the roof of an apartment block. The precipitation retention in this project was calculated as 69% on average and 100% in warm seasons. Voyde et al. (2010) studied the hydrology of a living roof under sub-tropical conditions in Auckland (NZ). They found that for over one year of accumulative precipitation, a 66% volumetric retention can be achieved in a green roof installed on a University of Auckland building. They concluded that disregarding rainfall properties, green roofs can significantly reduce runoff and particularly the maximum runoff. Their results showed in some unique events that green roofs could retain 82% of average rainfall and could reduce peak flow by up to 93%.

Rainfall is one of the most important factors in the mass balance equation and is one of only two potential inflows to the green roof system. In order to design and monitor green roof performance, detailed precipitation information is required. As Mentens et al. (2006) discussed, according to the German guidelines (Losken, 2002) the design storm event is defined as a rainfall of 300 ls^{-1} ha^{-1} (or 27 mm) occurring over 15 min. Furthermore, peak runoff during this storm event is defined as the amount of runoff occurring during the last 5 min of rainfall (FLL, 2002). In addition, as described by Stovin et al. (2012), the prediction of design storm performance is critically dependent on the assumptions made regarding an appropriate antecedent dry weather period (ADWP) and they suggested that the 48 h storm may be adopted as a standard basis for design amongst SUDS and green roof designers in the UK. Also Fassman and Simcock (2008) considered a 25 mm in 24 h event for designing green roof substrates in New Zealand for optimum water quality performance.

In another study Getter et al. (2007) categorised rainfall in three different amounts: light (<2.0 mm), medium (2.0–10.0 mm) or heavy (>10.0 mm). Carter and Rasmussen (2006) found an inverse relationship between the depth of rainfall and the percentage of rain that was retained; for small storms (<25.4 mm) 88% was retained, for medium storms (25.4–76.2 mm) more than 54% was retained, and for large storms (>76.2 mm) 48% was retained. Similarly Simmons et al. (2008) found that small rain events <10 mm were completely retained by the green roofs. For a rain event of 12 mm, the retention between green roofs varied from 26 to 88% depending mostly on the substrate and drainage type. Rain events of 28 mm and 49 mm showed retentions of 8 to 43% and 13 to 44%, respectively. It was further observed that the retention depended not only on the site location but also on the rainfall intensity. Mentens et al. (2006) found that the rainfall–runoff relationship is linear for hard roofs and gravel roofs but includes a quadratic factor in the case of green roofs. They attributed this to the influence of extreme rainfall events, for which retention is lower. Also Bengtsson (2005) found that the water storage capacity of a green roof was related to the rainfall intensity variations and that the vertical percolation process dominated the rainfall–runoff relationship. Some studies have shown that an increase in slope can cause an increase in green roof runoff whilst others do not show any relationship between slope and water retention in green roofs (Berndtsson et al., 2006; Berndtsson et al., 2009). One study even shows that higher roof slopes can reduce outflow and improve the water retention properties of green roof systems (Köhler et al., 2002), although this seems to be counter-intuitive.

As vegetation has a major role in the water balance through processes such as plant uptake and evapotranspiration, the type of vegetation for covering green roofs is very important in water cycle studies. Plants absorb water though their root system and send back the excess water back to the atmosphere from their leaves in a process which is called evapotranspiration. The amount of evapotranspiration depends on the local climatic conditions and on the type of vegetation.

Substrates or growing media are another important factor in the design of green roofs. Substrates are intended to provide a medium in which plants can grow and they can also improve the water retention performance of green roof systems.

However, several studies (Uhl and Schiedt, 2008; EPA, 2009; Stovin, 2010) have used tipping bucket rain gauges to measure rainfall in their green roof experiments. Only one research study has reported that that the accuracy of the rain gauge decreases with increasing intensity. None of these studies, though, have mentioned any kind of rain gauge calibration. Vergroesen et al. (2010) used a RG600M rain gauge and the instrument was calibrated by the manufacturer to tip every 0.2 mm. Various methods have been used to measure green roof runoff. Moran et al. (2005) collected runoff using a V-notch weir box with a level sensor. Mentens et al. (2003) and VanWoert et al. (2005) used rain gauge tipping buckets. Stovin et al. (2007) recorded runoff data by means of a collection tank with a high resolution pressure transducer. Uhl and Schiedt (2008) used collection tanks with a swimmer system for water level measurements to estimate runoff volumes. EPA (2009) used 200 l plastic barrels with a pressure transducer which allowed continuous measurement of water level in the barrel. Voyde et al. (2010) measured rainfall volume using a Sigma 2149 tipping bucket rain gauge.

Most hydrological studies have been conducted in relatively high rainfall regions with established extensive green roofs (Stovin et al., 2012; Fassman-Beck et al., 2013; Speak et al., 2013) whilst few have been undertaken on intensive green roofs. This study is an extension on the earlier study by Razzaghmanesh et al. (2014b) which investigated the performance of full-scale green roof systems located on the top of a high-rise building in the Adelaide Central Business District. Because of the difficulties faced in collecting samples from the drainage outlets of these full-scale green roofs, smaller scaled versions of these were reconstructed at the University of South Australia for this hydrological investigation. In this investigation, the intention was to study the hydrological behaviour of two types of green roofs, namely intensive (media depth = 300 mm) and extensive (media depth = 100 mm) in the dry climate experienced in Adelaide in South Australia.

2. Methodology

2.1. Adelaide climate

The study area is located at 34.55° southern latitude and 138.35° eastern longitudes. Adelaide, as the capital city of the driest state in Australia, has a hot Mediterranean climate based on the Köppen–Geiger climate classification. This generally means it has mild, wet winters