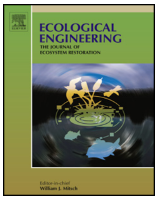
Ecological Engineering 82 (2015) 66–80

Contents lists available at ScienceDirect

Ecological Engineering

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



Hydrological performance of a full-scale extensive green roof located in a temperate climate

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ARTICLE INFO

Article history:
Received 26 July 2014
Received in revised form 18 November 2014
Accepted 29 November 2014
Available online 16 May 2015

Keywords:
Urban drainage
Storm water management
Green roof
Retention
Urbanisation

ABSTRACT

Increasing recognition is being given to the adoption of green roofs in urban areas to enhance the local ecosystem. Green roofs may bring several benefits to urban areas including flood mitigation. However, empirical evidence from full-scale roofs, especially those that have been operational for more than several years is limited. This study investigates the hydrologic performance of a full-scale extensive green roof in Leeds, UK. Monitoring of the green roof took place over a 20 month period (between 30th June 2012 and 9th February 2014). The results indicate that the green roof can effectively retain and detain rainfall from the precipitation events included in the analysis. Retention was found to correspond significantly with rainfall depth, duration, intensity and prior dry weather period. Significant differences in retention values between the summer and winter seasons were also noted. Regression analysis failed to provide an accurate model to predict green roof retention as demonstrated by a validation exercise. Further monitoring of the green roof may reveal stronger relationships between rainfall characteristics and green roof retention.

1. Introduction

Currently over half of the world's population live in urban areas and it is expected to reach 70% by 2050 (UN Habitat, 2013; Willuweit and O'sullivan, 2013). From 2001–2011, the population across England and Wales increased by approximately 7% to reach 56 million (Office for National Statistics, 2012). This unprecedented rate of growth and urbanisation has considerable effects on the surrounding environment as developments replace natural lands with impervious surfaces (Vesuviano and Stovin, 2013). This alters the local hydrological cycle by preventing infiltration of rainfall into soil and increasing surface runoff (Getter et al., 2007; Dowling, 2002). Consequently, when drainage systems are unable to cope with high amounts of runoff associated with precipitation events, pluvial flooding can occur (Berndtsson, 2010; Perry and Nawaz, 2008). Furthermore, it is predicted that in the near future the UK will experience more frequent and intense precipitation events as a result of climate change (IPCC, 2012). This has the potential to increase the frequency and intensity of pluvial floods (Speak et al., 2013; Butler and Davies, 2011).

Traditionally, combined sewer systems, which account for 70% of the total sewerage system in the UK, are used to convey stormwater runoff and wastewater away from urban areas (Butler and Davies, 2011; Hall, 2001). If the system's capacity is reached during a rainfall event, combined sewage overflows (CSOs) are used to discharge any excess flows into nearby water bodies (Vesuviano and Stovin, 2013; Hall, 2001). As a result, untreated sewage often enters rivers and streams (Buccola and Spolek, 2011). This increases the risk of flooding downstream, reduces groundwater recharge and degrades aquatic ecosystems by increasing flows and transporting harmful pollutants to water bodies (Hilten et al., 2008; Carter and Jackson, 2007; Carter and Rasmussen, 2006). The inadequacy of the stormwater drainage system in the UK has been labelled as a major cause of the pluvial flooding that occurred throughout the summer of 2007 (Ellis, 2010). Moreover, despite being designed to provide emergency relief, many CSOs discharge following small rainfall events (Carson et al., 2013; Fassman-Beck et al., 2013). This highlights the need to improve the

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Abbreviations: CSOs, combined sewage overflows; SUDS, Sustainable Urban Drainage Systems; BMPs, best management practices; LIDs, low-impact developments; SUWM, Sustainable Urban Water Management Projects; ADWP, antecedent dry weather period (h); ET, evapotranspiration; AWS, automatic weather station; NCAS, National Centre for Atmospheric Science; TR, total rainfall depth (mm); R, total runoff depth (mm); PR, retention (%); RD, rain duration (h); *i*, rainfall mean intensity (mm/h); Rp, rainfall peak intensity (mm/h); LG1, lag-time (1) (min); LG2, lag-time (2) (min); WFD, Water Framework Directive.

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http://dx.doi.org/10.1016/j.ecoleng.2014.11.061
0925-8574/

conventional urban stormwater drainage systems (Nagase and Dunnett, 2012; Newton et al., 2007; VanWoert et al., 2005).

However, there are over 20,000 CSOs throughout the UK, and it is considered economically unfeasible and impractical to upgrade the entire system (Qin et al., 2013; BBC, 2009; Water UK, 2009). Thus alternative ways to manage urban runoff and reduce urban flood risk are being explored (VanWoert et al., 2005). In the UK, the Environment Agency is promoting the use of Sustainable Urban Drainage Systems (SUDS) as a way of controlling rainfall and runoff at source (Stovin et al., 2012; Stovin, 2010; Seters et al., 2009). SUDS, also known as Best Management Practices (BMPs), Low-Impact Developments (LIDs) and Sustainable Urban Water Management (SUWM) projects can be used to increase infiltration and manage the quantity and quality of runoff in a sustainable manner (Deng et al., 2013; Carpenter and Kaluvakolanu, 2011; Damodaram et al., 2010). They include such designs as infiltration basins, permeable pavements, swales, wetlands, soakaways and green roofs (Stovin et al., 2013; Butler and Davies, 2011; Hall, 2001).

Green roofs in particular, have gained considerable attention in recent years as a potential cost-effective way to mitigate urban flood risk (Stovin et al., 2013; Beck et al., 2011). They are defined as roofs which are partially or completely covered with a growing medium (substrate) and vegetation (excluding pot vegetation) (Mickovski et al., 2013; Berndtsson, 2010; Olly et al., 2011). Whilst most SUDS require large spaces, green roofs require no additional space beyond a buildings footprint (Zhang and Guo, 2013; Stovin et al., 2012). Furthermore, green roofs can be retrofitted onto existing buildings as well as incorporated into new developments (Castleton et al., 2010). This is particularly beneficial in urban areas where roofs can account for a high proportion of the total impervious land area (Carson et al., 2013; VanWoert et al., 2005).

Amongst a range of benefits offered, green roofs allow infiltration and can retain rainfall (Mentens et al., 2006). Some rainfall is used by the vegetation and released back into the atmosphere through evapotranspiration whilst any excess rainfall which is not retained by the roof is slowly released (Zhang and Guo, 2013; Carpenter and Kaluvakolanu, 2011). Consequently, green roofs can delay the initiation of runoff, reduce total runoff volumes, reduce peak runoff rates and discharge runoff over a longer period of time, when compared to conventional roofs (Fig. 1) (Vesuviano and Stovin, 2013; Berndtsson, 2010; Mentens et al., 2006). Additional benefits to the apparent hydrological benefits of green roofs is that they can provide a variety of further environmental and social benefits to the building owner, the occupants and the wider community (see Table 1) (Bianchini and Hewage, 2012; Nagase and Dunnett, 2010; Oberndorfer et al., 2007; Getter and Rowe, 2006).

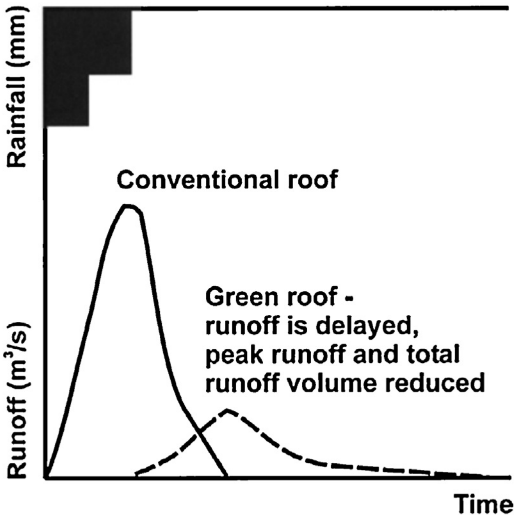

Fig. 1. A schematic diagram showing the rainfall–runoff response from a conventional roof and a green roof (Stovin et al., 2012).

Green roofs can be extensive, intensive or semi-intensive (Gregoire and Clausen, 2011; Berndtsson, 2010). Although despite differences between green roof types, they generally all contain the same principal components including a waterproofing membrane, a root barrier, and a drainage mechanism. Three drainage types have been reported by Conservation Technology (2008) and include Types P, G and M. Drainage Type P utilizes drainage plate, waffled plastic sheets that store water above and drain water below. Drainage plates are lightweight, are easy to install, to help meet the drainage and water storage requirements of almost any green roof. Drainage Type G utilizes a lightweight, porous inorganic granular media embedded with slotted plastic triangular drainage conduit. Granular media is heavier and is more labour-intensive to install than drainage plates, but provides a superior environment for plant root growth. Finally, drainage Type M utilises a drainage mat, a multi-layer fabric mat that combines soil separation, drainage and protection functions into one product. This system is the fastest to install and creates the thinnest and lightest green roof assembly. However, its water storage and drainage capacity is limited, so it is primarily used for sloped roofs not suitable for drainage Type P or Type G (Conservation Technology, 2008).

2. Rationale

Although green roofs appeared in Nordic countries centuries ago, it is widely maintained that the modern green roof movement originated in Germany during the 1970s (Berndtsson, 2010; Oberndorfer et al., 2007; Getter and Rowe, 2006). Since then, green roof construction has increased and it is estimated that 14% of all the flat roofs in Germany are now green (Getter and Rowe, 2006; VanWoert et al., 2005). Several other countries including Japan, Singapore and parts of the US have developed incentive programs to encourage green roof installations (Zhang and Guo, 2013; Mentens et al., 2006). However, barriers preventing widespread installations of green roofs still exist in other countries (Zhang et al., 2012; Williams et al., 2010; Getter and Rowe, 2006).

In the UK, one of the major barriers is a lack of quantifiable data which illustrates the hydrological benefits of green roofs (Fioretti et al., 2010). Experiments which specifically investigate a green roof's ability at effectively managing stormwater have only begun in the last decade and whilst the benefits of green roofs are often claimed, there is insufficient scientific evidence demonstrating their hydrological performance (Zhang and Guo, 2013; Berndtsson, 2010; Dvorak and Volder, 2010), especially of full-scale roof installations. Thus, more research is required on green roofs in the UK to investigate their potential as possible SUDS and their effectiveness at reducing urban flood risk (Vijayaraghavan et al., 2012; Butler and Davies, 2011). This is an essential step which needs to be undertaken before policies and incentives can be developed and implemented to increase green roof uptake in the UK (Green Roof Guide, 2011; Bell and Alarcon, 2009; Carter and Keeler, 2008).

Previous studies investigating the hydrological performance of extensive green roofs have reported various retention values, peak runoff reductions and delays in runoff, when compared to conventional roofs (Li and Babcock, 2014; Berndtsson, 2010). The average retention value observed from previous extensive green roof studies appears to be 57%, although it ranges between 15% and 83% (Table 2). Note that retention here is defined as the percentage of rainfall captured by a green roof following a precipitation event (Carpenter and Kaluvakolanu, 2011). The