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Geographic information system-based assessment of mitigating flash-flood disaster from green roof systems

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ABSTRACT

Urban flooding is a severe problem and a growing development challenge for many cities around the world. However, urban impervious areas have sharply increased owing to booming construction activities, and this land-use change leads to more frequent flood inundation in urban flood-prone areas. A green roof system is regarded as an effective mechanism to manage rainwater and reduce flooding disaster, as it is capable of retaining rainwater, thus reducing rainfall-runoff. There is still a lack of assessment of this stormwater management tool for flash floods. The issue of flood inundation associated with green roof systems needs to be explored and developed. To evaluate the effects of green roofs on urban flood inundation, this paper aims to construct a framework for modelling urban inundation integrating a hydrological model of green roofs. The approach addresses both urban rainfall-runoff and underground hydrological models for traditional impervious and green roofs. To accurately calculate the spatial variation, we have proposed a hydrological model to evaluate regional runoff on the basis of a catchment mesh. The Deakin University Waurn Ponds campus in Geelong was then chosen as a community-based study case. From geographic information system (GIS) simulation, the results reveal that the green roofs generated varying degrees of mitigation of urban flash floods with storms of different return periods.

1. Introduction

There has been consistent growth in urbanised areas because of the construction of buildings and infrastructure in urban environments. The ongoing expansion of impervious ground surfaces, which is replacing previous land covers such as grasslands, inevitably leads to serious problems such as urban heat islands (Rizwan, Dennis, & Liu, 2008) and air pollution (Moore, Gould, & Keary, 2003). Another consequence could be more frequent and longer duration of flooding in urban flood-prone areas.

Urban flooding is the inundation of land or property in a built environment and is a growing development challenge for many cities around the world (Ran & Nedovic-Budic, 2016). This global phenomenon can result in damage to buildings, personal injuries, business disruptions, environmental pollution and transport interruption. Flooding events in Australia over the past 40 years have resulted in personal injury and deaths, and have cost the economy hundreds of millions of dollars. In January 1974, a flooding event induced by 900 mm rainfall in Brisbane resulted in 16 deaths, rendered 9000 people homeless and cost approximately AU$700 million (SCARM, 2000). In February 2007, thunderstorms caused local flooding in western Sydney, washing cars off roads and flooding buildings. Approximately 25,000 homes lost power (Bureau of Meteorology (BOM), 2015a). In addition, a severe thunderstorm drenched Geelong, Victoria's largest provincial city, on 19 February 2014 such that transportation was interrupted by ponding water of about 1 m depth (Mills, 2014). An estimated annual cost of more than AU$377 million means that flood inundation is the most expensive natural hazard in Australia (Middelmann, 2009).

Therefore, there is an urgent need to introduce mitigation measures through managing rainwater to reduce storm runoff. To date, several feasible measures, such as retention ponds (Yang, Li, Sun, & Ni, 2015), rainwater harvesting (Wu, Yu, Chen, & Wilby, 2012) and green infrastructure (Zellner, Massey, Minor, & Gonzalez-Meler, 2016), have been used to address the problem. Among these, greening of roofs can be considered an effective solution in storm water management as green roofs are capable of retaining rainwater and reducing peak runoff discharge (Locatelli et al., 2014). It is thus worthwhile to explore the mitigation effects on urban flash floods of green roof systems. This paper aims to construct a framework for estimating mitigation effects from green roofs on urban floods and to provide an approach to visualising the mitigation effects using geographic information system (GIS) mapping technologies.

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2. Research on urban flooding and green roof stormwater retention

An important step in evaluating mitigation measures is appropriately modelling urban flooding for the identification of vulnerable areas and prediction of flood extents through maps of potential floodwater distribution (Al-Sabhan, Mulligan, & Blackburn, 2003).

Flooding is roughly categorised into *riverine floods* and *flash floods* by the BOM, as most events are predominantly caused by heavy rains (BOM, 2013). Riverine floods occur following heavy rainfall when watercourses do not have the capacity to convey the excess water. Flash floods result from relatively short, intense bursts of rainfall, often from thunderstorms, when urban drainage networks do not have the capacity to convey the excess rainwater. It is possible that rapid urbanisation increases disaster risk and resultant damage. For instance, booming building and infrastructure construction have replaced much raw land with impervious ground surfaces, which translates to growth in rainfall-runoff volumes. It may result in more frequent storm-induced flood inundation (Booth, 1990).

Extensive research has been conducted into flash floods and case studies have been presented over the past two decades, such as flooding in Macau (Zhao et al., 2009), central urban areas of Shanghai (Quan, 2014) and Riyadh city (Nahiduzzaman, Aldosary, & Rahman, 2015). In summary, there are two common flash-flood models: a one-dimensional (1D) sewer model coupled with a 1D surface network; and a 1D sewer model coupled with 2D surface flow. Previous research indicates that the 1D/1D model could provide a satisfactory approximation with low computational cost. However, this model is insufficient to compute flow paths over complex surfaces with dense buildings and infrastructure (Mark, Weesakul, Apirumanekul, Aroonnet, & Djordjević, 2004). The other model, coupling 1D pipe flow and 2D overflow, is considered an effective model for real urban terrain and it can generate relatively accurate results (American Society of Civil Engineers, 1993).

Next, it is essential to address the hydrological performances of green roofs to evaluate the improvement in urban flooding mitigation. A typical green roof consists of a growing medium covered with vegetation, a filter layer, drainage layer, protection layer, root barrier and waterproofing over a roof deck (Vila, Pérez, Solé, Fernández, & Cabeza, 2012), as shown in Fig. 1. Among these features, the growing medium is critical to the roof's rainwater retention capability. A green roof with a growing medium thicker than 150 mm is classified as *intensive*. In contrast, an *extensive* green roof has a thin soil layer to support plant life, which means that low additional loads do not require strengthening of existing building structures (Kosareo & Ries, 2007).

Green roofs have been widely applied in stormwater management (Y. Li & Babcock, 2014). There are generally four methods of evaluating their hydrological responses to stormwater: linear/non-linear storage reservoirs; curve methods; physical models; and water-balance models (She & Pang, 2010), as listed in Table 1. Specifically, a non-linear reservoir was adopted to investigate the performances of different methods for modelling evapotranspiration in 2010 (Kasmin, Stovin, & Hathway, 2010). Thereafter, Locatelli et al. (2014) developed this model and applied it to the evaluation of the average annual runoff of green roofs. The mean annual runoff was then simulated as a function of the retention capacity. The authors indicated that green roofs had the potential to be important elements of future urban stormwater management plans, as even a 5 mm storage capability could reduce the mean annual runoff by up to 20% compared with a traditional roof.

As an approximation of eco-roof filtration, the curve method was used to measure the impacts of green roof systems on an urban watershed (Carter & Jackson, 2007). In addition, Hilten, Lawrence, and Tollner (2008) tested the hydrological response of a modular block green roof through the soil moisture software HYDRUS-1D. The authors considered that HYDRUS-1D was only capable of correctly reproducing runoff induced by small rains, because it overestimated the peak discharge in storm events. Stovin, Poë, and Berretta (2013) presented a continuous simulation program through the development of a hydrological flux model. Their results revealed that the long-term volumetric retention of green roofs varied because of the effects of evapotranspiration before storms. Moreover, soil water-balance models were used to examine the long-term rainwater gains and losses resulting from green roofs (Razzaghmanesh & Beecham, 2014; Roehr & Kong, 2010). In 2015, Yang et al. (2015) proposed a water-balance analysis of flat green

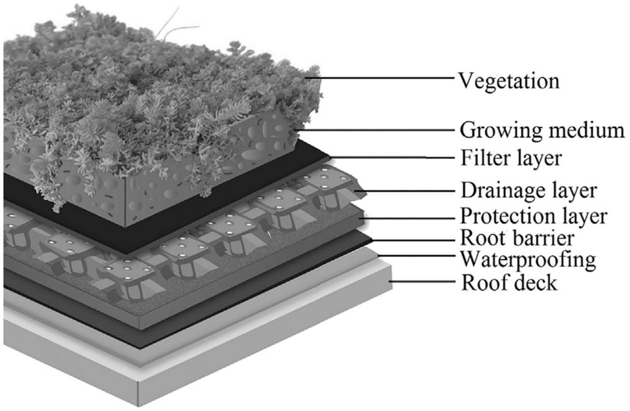

Fig. 1. Structure of a green roof. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Reading grid of green roof stormwater retention models.

Modelling approach	Related papers	Results
Linear/nonlinear storage reservoir models	Zimmer and Geiger (1997)	A linear/nonlinear reservoir model was proposed to compute the efficiency of experimental green roofs. The investigated green roofs showed very good retention effects for rain intensities up to 200 L/s/ha.
	Kasmin et al. (2010)	Evapotranspiration rates on the Sheffield test rig were likely to range from <0.5 mm per day in winter to approximately 3 mm per day in summer.
	Locatelli et al. (2014)	A nonlinear reservoir model was presented for the hydrological response of green roofs and demonstrated a 20% reduction in mean annual runoff.
Curve number models	Carter and Rasmussen (2006)	The curve number of green roofs were estimated at 86 according to precipitation and runoff data.
	Carter and Jackson (2007)	Detailed spatial analysis demonstrated that widespread green roof implementation provided additional stormwater storage and reduced peak runoff rates, particularly for small storm events.
Physical models	Hilten et al. (2008)	A 37 m^2 modular block green roof demonstrated that a HYDRUS-based model was only capable of correctly reproducing the runoff induced by small rainfalls.
	Stovin et al. (2013)	The long-term volumetric retention of green roofs was significantly affected by evapotranspiration before storms.
Water-balance models	Roehr and Kong (2010)	Studies of green roofs showed precipitation and evaporation were important to the annual water gains and losses of green roofs.
	Razzaghmanesh and Beecham (2014)	The average retention was 74% from extensive and 88.6% from intensive green roofs in a two-year observation.
	Yang et al. (2015)	Simulation results indicated that the infiltration-excess runoff accounted for only a small proportion of the total runoff.