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Modelling of green roof hydrological performance for urban drainage applications

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SUMMARY

Green roofs are being widely implemented for stormwater management and their impact on the urban hydrological cycle can be evaluated by incorporating them into urban drainage models. This paper presents a model of green roof long term and single event hydrological performance. The model includes surface and subsurface storage components representing the overall retention capacity of the green roof which is continuously re-established by evapotranspiration. The runoff from the model is described through a non-linear reservoir approach. The model was calibrated and validated using measurement data from 3 different extensive sedum roofs in Denmark. These data consist of high-resolution measurements of runoff, precipitation and atmospheric variables in the period 2010–2012. The hydrological response of green roofs was quantified based on statistical analysis of the results of a 22-year (1989–2010) continuous simulation with Danish climate data. The results show that during single events, the 10 min runoff intensities were reduced by 10–36% for 5–10 years return period and 40–78% for 0.1–1 year return period; the runoff volumes were reduced by 2–5% for 5–10 years return period and 18–28% for 0.1–1 year return period. Annual runoff volumes were estimated to be 43–68% of the total precipitation. The peak time delay was found to greatly vary from 0 to more than 40 min depending on the type of event, and a general decrease in the time delay was observed for increasing rainfall intensities. Furthermore, the model was used to evaluate the variation of the average annual runoff from green roofs as a function of the total available storage and vegetation type. The results show that even a few millimeters of storage can reduce the mean annual runoff by up to 20% when compared to a traditional roof and that the mean annual runoff is not linearly related to the storage. Green roofs have therefore the potential to be important parts of future urban stormwater management plans.

1. Introduction

Urbanization significantly affects the natural landscape turning green areas into built environment. This process creates new impervious surfaces such as roofs, roads, cycling lanes, sidewalks, public squares and parking areas which modify the natural water cycle. Impervious areas increase stormwater runoff peaks and volumes and reduce the time delay between peak rainfall and peak runoff when compared to natural areas (Bengtsson, 2005). Current urban drainage systems have limited capacity to deal with flooding and climate change will increase the risk of flooding from sewers in urban areas (Larsen et al., 2009; Madsen et al., 2009).

Green roofs are one of the many WSUD (Water Sensitive Urban Design; the concept of water sensitive cities was presented by Wong and Brown, 2009), LID (Low Impact Development), SUDS (Sustainable Urban Drainage Systems), LIUDD (Low Impact Urban Design and Development) techniques aimed to improve stormwater management and address future climatic challenges. Green roofs have the great advantage of not using new spaces; in fact they can in some cases be retrofitted onto existing traditional rooftops. The roof area in urban residential areas can be as high as 40–50% of the total impervious area (Palla et al., 2009; Lindblom et al., 2011; Vezzaro et al., 2012). Green roofs are claimed to reduce the risk of urban flooding and to re-establish a more natural water balance (Bengtsson et al., 2005; VanWoert et al., 2005) and to reduce water and contaminant loads to sewer systems (Buccola and Spolek, 2011).

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The German Guidelines for the Planning, Construction and Maintenance of Green Roofing (FLL, 2008) have suggested a classification of green roofs into two different categories:

- Intensive green roofs have thick soil layers (>15 cm) with large plants and moderate slopes, these are heavier and require regular watering and fertilization.
- Extensive green roofs can have soil covers with a thickness of as little as few cm and vegetation which requires hardly any maintenance. When the soil layer is thin and the weight of the green roof is limited, extensive green roofs can often be placed on existing buildings without structural reinforcement and they can reach slopes up to 40–45% (FLL, 2008).

From the 1990s green roofs have become common practice in several countries such as Austria, Switzerland and particularly Germany where green roofs reached 13% of the flat roofs in 2003 (Herman, 2003). Some countries have also released guidelines for implementation of green roofs like the UK, Germany, United States, New Zealand, Australia, etc.

Green roof performance regarding stormwater management may vary among geographic regions due to varying climate, precipitation patterns, building practices and green roof materials. During rainfall events the most important hydrologic mechanisms are the interception of rain by the vegetation layer, infiltration and retention/detention in the soil substrate, and retention/detention in the drainage layer. Any water in excess to the storage capacity will be drained into an outlet and during non-rainy periods water stored in the green roof is lost through evapotranspiration.

Green roofs reduce stormwater runoff compared to conventional roofs due to water retention and subsequent evapotranspiration. Volume retention depends on rainfall intensity distribution, the initial moisture conditions and green roof characteristics (layer thickness, slope, materials, etc.), including the ability of the green roof to dry up. Volume retention also contributes to peak attenuation and delay. The following examples are based on observations from experimental sites. Experimental sites in Germany showed that the annual runoff from intensive green roofs was 15–35% of the annual rainfall, whereas the performance of extensive roofs is reported to be 20–75% of the annual rainfall (Mentens et al., 2006). In Sweden the runoff observed from thin extensive green roofs was 46% of the annual precipitation (Bengtsson et al., 2005). In England Stovin et al. (2012) reported an overall retention capacity of green roofs of 50%. VanWoert et al. (2005) observed a 60% retention in Detroit (Michigan), DeNardo et al. (2005) 45% in Pennsylvania, Voyde et al. (2010) 66% in Auckland (New Zealand), Monterusso et al. (2004) 49% and Carter and Rasmussen (2006) 78% in Athens (Georgia).

Volume detention, defined as temporary storage and subsequent release, results in additional attenuation and time delay of runoff peaks. Volume detention takes place when the initial moisture content is at field capacity (micro- and mesosized pores are water filled) and additional water percolates through macropores. Peak attenuation and delay due to detention depend on the rainfall intensity distribution and the green roof characteristics, including layer thickness, slope, poresize distribution, tortuosity, etc. of the materials. Observed data recorded from experimental green roofs have been reported by several researchers. Peak runoff delay of vegetated roofs was found to vary significantly, for the majority of the observed rain events peak delay was found to be between 0 and 30 min when compared to traditional roofs (VanWoert et al., 2005; Carter and Rasmussen, 2006; Simmons et al., 2008). Getter et al. (2007) observed only minimal runoff delay and Villarreal and Bengtsson (2005) found peak delays to be around 1 min. DeNardo et al. (2005) showed considerable peak reductions for low intensity rains. Stovin et al. (2012) observed a mean peak flow reduction of 60% for rain events of more than 22 mm accumulated rain. Moran et al. (2005) reported 85% peak reductions.

Several models have been developed for the hydrological performance of green roofs. Hilten et al. (2008) used the soil moisture software *HYDRUS-1D* to simulate the single events runoff response from green roofs and validated his results with data collected in Georgia (USA). Palla et al. (2009) used *SWMS_2D* based on Richards' equation to simulate the variably saturated conditions within a typical green roof during individual storm events and validated the model against data collected in Genoa (Italy). Zhang and Guo (2013) presented a physically based analytical probabilistic model to evaluate the average long term hydrological response of green roofs. Villarreal and Bengtsson (2005) analyzed single events runoff from an extensive green roof in Sweden and derived a unit hydrograph. Zimmer and Geiger (1997) proposed a linear/non-linear reservoir model to compute the runoff from an experimental green roof under constant rainfall intensities. Kasmin et al. (2010) used a simple conceptual model, with the runoff described by a non-linear reservoir, in order to evaluate the performance of different methods for modeling evapotranspiration. Sherrard and Jacobs (2012) presented a five parameter water balance model with a daily time step in order to reproduce the volume runoff on a daily and annual basis. Jarret and Berghage (2008) presented one model for annual water balance and one for single event runoff. Stovin et al. (2013) presented a model to quantify long term runoff using continous simulation; results from the model showed volumetric retention values between 0.19 (cool, wet climate) and 0.59 (warm, dry climate) depending on local climate conditions in the UK.

Other studies have derived empirical runoff relations from experimental data. Mentens et al. (2006) gathered experimental data of green roof hydrological performance on seasonal and annual bases from 18 different publications in Germany. Bengtsson (2005) derived Intensity–Duration–Frequency curves for rainfall–runoff prediction from an extensive green roof in Malmo in Sweden. Moran et al. (2005) derived the rational coefficient based on green roof data from North Carolina (USA). Carter and Jackson (2007) used the Curve Number method for predicting green roof performances at large case studies in Georgia (USA) and Getter et al. (2007) derived the curve number for the studied green roof in Detroit (USA).

A review of available WSUD models was provided by Elliott and Trowsdale (2007). The literature review shows that modeling approaches vary, from models for single event runoff to conceptual models applied to simulate distributed urban runoff. None of these studies have presented a single and low computationally demanding model that can continuously simulate both single events with fine time resolution and the annual water balance of single green roofs. The single event hydrological response of green roofs is highly affected by initial moisture conditions which depends on evapotranspiration rates and can be estimated from a continuous simulation; at the same time the long term performance is influenced by single event runoff and evapotranspiration rates. Thus it is relevant to develop a model that can continuously simulate both single events and long term response. This paper is based on the preliminary model results presented in the conference paper of Locatelli et al. (2013).

The first aim of this study is to present a simple conceptual model for the hydrological performance of green roofs that can be integrated into urban drainage models for evaluating the impacts of implementing green roofs at a large scale (e.g. modeling of flood mitigation potential; modeling the potential for reduction of combined sewage volume and combined sewer overflow). Low computational costs and fine time resolutions are thus a requirement. Many of the previously developed green roof models such as *SWMS-2D* and *HYDRUS* have a high computational cost and so are not suitable for large scale urban water modelling.