Retention performance of green roofs in representative climates worldwide

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**Abstract**

The ongoing process of global urbanization contributes to an increase in stormwater runoff from impervious surfaces, threatening also water quality. Green roofs have been proved to be innovative stormwater management measures to partially restore natural states, enhancing interception, infiltration and evapotranspiration fluxes. The amount of water that is retained within green roofs depends not only on their depth, but also on the climate, which drives the stochastic soil moisture dynamic. In this context, a simple tool for assessing performance of green roofs worldwide in terms of retained water is still missing and highly desirable for practical assessments.

The aim of this work is to explore retention performance of green roofs as a function of their depth and in different climate regimes. Two soil depths are investigated, one representing the intensive configuration and another representing the extensive one. The role of the climate in driving water retention has been represented by rainfall and potential evapotranspiration dynamics. A simple conceptual weather generator has been implemented and used for stochastic simulation of daily rainfall and potential evapotranspiration. Stochastic forcing is used as an input of a simple conceptual hydrological model for estimating long-term water partitioning between rainfall, runoff and actual evapotranspiration. Coupling the stochastic weather generator with the conceptual hydrological model, we assessed the amount of rainfall diverted into evapotranspiration for different combinations of annual rainfall and potential evapotranspiration in five representative climatic regimes. Results quantified the capabilities of green roofs in retaining rainfall and consequently in reducing discharges into sewer systems at an annual time scale. The role of substrate depth has been recognized to be crucial in determining green roofs retention performance, which in general increase from extensive to intensive settings. Looking at the role of climatic conditions, namely annual rainfall, potential evapotranspiration and their seasonality cycles, we found that they drive green roof's retention performance, which are the maxima when rainfall and temperature are in phase.

Finally, we provide design charts for a first approximation of possible hydrological benefits deriving from the implementation of intensive or extensive green roofs in different world areas. As an example, 25 big cities have been indicated as benchmark case studies.

**Keywords:**
Greenroof  
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**1. Introduction**

The continuous growth of impervious surface areas leads to increased downstream flows with critical consequences for the functioning of existing sewer systems and triggers water quality degradation in receiving water bodies (Carter and Jackson, 2007; Carter and Rasmussen, 2006). A variety of management practices have been proposed to limit the environmental pressures associated with the altered hydrology of urban areas. In this context, green roofs are an innovative solution for mitigation of the impact of stormwater runoff, with the advantage of recovering green spaces, while preserving environmental quality (Getter and Rowe, 2006). Green roofs are indeed a valid alternative to traditional stormwater design and a low impact development practice (Dietz, 2007). Several authors recommend the use of vegetative roofs as an attractive stormwater management practice in urban watersheds, in order to reproduce the benefits produced by the interception and evapotranspiration processes in the natural water cycle, as in less disturbed environments. Green roofs are now quite familiar in Europe and North America: some cities have built green roof pilot projects and adopted incentives for applying green roof
practices (Dvořák and Volder, 2010), while standards and guidelines are also being set up.

Several environmental benefits can be associated with green roofs, mainly related to the reduction of building energy consumption, mitigation of urban heat island effect, improvement of air quality, water management, increase of sound insulation, and ecological preservation (Berardi and Ghaffarian Hoseini, 2014). An important benefit related to green roofs is that they can efficiently detain and retain stormwater when compared to conventional roofs. In the following we analyze some scientific studies aimed at the evaluation of hydrological performance of green roofs by distinguishing between field experiments and modelling approaches.

Many field experiments have been carried out in order to understand the hydrological behaviour of green roofs and to quantify the water-related benefits in specific climatic and physical conditions. An interesting case has been proposed by Carter and Rasmussen (2006): a paired green roof-black roof test plot was constructed at the University of Georgia (USA) and monitored for one year for the effectiveness of the green roof in reducing stormwater flows. Green roof precipitation retention decreased with precipitation depth; ranging from about 90 percent for small storms to slightly less than 50 percent for larger storms. Moreover, they also found that runoff from the green roof was delayed and that the average runoff lag times increased.

Bengtsson et al. (2005) studied a thin extensive green roof and its water balance in southern Sweden. They observed that runoff from the green roof is substantially reduced when compared to the runoff from black roofs because of evapotranspiration. As a physical interpretation of the water dynamics within the green roof, they associated the beginning of runoff with the condition of soil moisture reaching or exceeding the field capacity, and estimated the consequent runoff as equal to the precipitation excess. They argued that the daily runoff dynamics could be described as a function of daily precipitation, potential evapotranspiration and storage capacity of the green roof.

Czemiel Berndtsson (2010) made a critical review of green roof performances on the basis of results from full-scale installations as well as from laboratory models and looked for factors affecting runoff dynamics. She concluded that geometrical properties (mainly slope), climate (mainly rainfall) and vegetation (its age) are fundamental in determining runoff from green roofs.

Feng et al. (2010) quantified the energy balance components within an extensive green roof installation in the South China University of Technology in Guangzhou (China). They found that, without water limitations, incoming solar radiation was diverted into evapotranspiration of the plant-soil system (60%), long-wave radiation exchange between the canopy and the atmosphere (30%) and net photosynthesis of plants (10%).

Performance of green roofs have been also investigated in the Mediterranean climate by Fioretti et al. (2010) with two full-scale experiments in north-west and central Italy. They concluded that green roofs significantly mitigate storm water runoff generation in terms of runoff volume reduction, peak attenuation and increase of concentration time, although reduced performance could be observed during high precipitation periods. Under sub-tropical climate conditions, Voyde et al. (2010) analyzed field monitoring results from a large extensive green roof in Auckland, New Zealand (NZ). They found that the green roof retained about 82% of rainfall received per rainfall event, with a median peak flow reduction of 93% compared to rainfall intensity. Similarly to other studies, also Voyde et al. (2010) identified in rain depth, rain intensity, climatic variables and antecedent dry days the main key factors influencing the hydrology of green roofs.

DeNardo et al. (2005) studied a green flat roof at Rock Springs, Pennsylvania (USA). They observed a range of rainfall retention from 15% to 96% in seven storms and peak runoff delayed by 2 h. The effect of slope on extensive green roof stormwater retention was instead analyzed by Getter et al. (2007) using 12 extensive green roof platforms constructed at the Michigan State University (USA). They demonstrated that the lower the slope the higher the retention, with an average retention value of about 80%.

Monterusso et al. (2004) analyzed runoff from four commercial green roof systems containing three distinct vegetation types at the Michigan State University (USA). Rainfall retained during their experiments ranged from 39% to 58%. It is worth noticing that their results highlight how differences in water retention can be attributed to substrate depth, rather than drainage system or vegetation type.

Two studies made in the UK by Stovin (2010) and Stovin et al. (2012) demonstrated the important role of mean rainfall intensity, rainfall depth and an antecedent dry weather period, which conditions antecedent moisture conditions. The latter is indeed crucial in determining the performance of green roofs, in terms of retention, peak attenuation and delay under extreme rainfall conditions.

If field experiments, as briefly referred to above, allow the underlying physical processes to be understood, modelling approaches permit phenomena to be mimicked, and consequently to simulate green roof performances even in unmonitored conditions. Hydrological modelling demonstrated that widespread green roof implementation can significantly reduce peak runoff rates, particularly for small storm events (Carter and Jackson, 2007).

Hilton et al. (2008) modelled stormwater runoff data from green roofs with the HYDRUS-1D model (Siminé et al., 2008) in order to determine peak flow, retention and detention time for runoff. Storm data were collected on a green roof in Athens, Georgia, USA, and used to calibrate HYDRUS-1D simulated runoff. The study site consisted of a 37 m² modular block green roof containing engineered soil and vegetation including several sedum species. Simulations highlight the role of rainfall depth in determining water retention: in fact small storms are fully retained while larger storms are partially attenuated.

The work carried out by Palla et al. (2009) advanced the understanding of the unsaturated water flow in the coarse-grained porous media usually employed in green roofs. Using a bidimensional model based on Richards’ law and the Van Genuchten-Mualem functions they were able to simulate the variably saturated flow within the green roof system with a satisfactory reproduction of hydrograph main features, i.e. total discharged volume, peak flow, hydrograph centroid and water content. In a later study, the same authors compared the performance of HYDRUS-1D with those obtained by a conceptual linear reservoir in reproducing the hydrologic response of a green roof system within the urban environment (Palla et al., 2012). They found that, comparing simulations with observations from a field site in Genova, Italy, the HYDRUS-1D model resulted more reliable. However, prediction errors of the conceptual model were still limited, so that outflow hydrographs in terms of both total effluent volume and hydrograph shape were predicted with acceptable accuracy.

While most of the previous mentioned studies focused on event scale or short time windows, there are few examples in literature of long-term green roof performance evaluations, mainly approached with hydrological models. An interesting study in this context was proposed by Stovin et al. (2013). They used a conceptual hydrological flux model for the long term continuous simulation of retention performance of extensive green roofs at 4 locations in the UK, with different annual rainfall (ranging from 500 to 2700 mm/year) and potential evapotranspiration (from 618 to 700 mm/year). A long term analysis was also performed by Carson et al. (2013) who simulated extensive green roof performance in NY using an empirical model, calibrated against observations and forced by historical rainfall (1971–2010). Locatelli et al.
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