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Assessment of the hydrological impacts of green roof: From building scale to basin scale

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SUMMARY

At the building scale, the use of green roof has shown a positive impact on urban runoff (decrease and slow-down in peak discharge, decrease in runoff volume). The present work aims to study whether similar effects are possible at the basin scale and what is the minimum spreading of green runoff needed to observe significant impacts. It is particularly focused on the circumstances of such impacts and how they can contribute to storm water management in urban environment. Based on observations on experimental green roofs, a conceptual model has been developed and integrated into the SWMM urban rainfall-runoff model to reproduce the hydrological behaviour of two different types of green roof. It has been combined with a method defining green roofing scenarios by estimating the maximum roof area that can be covered.

This methodology has been applied on a long time series (18 years) to the Châtillon urban basin (Haut-de-Seine county, France) frequently affected by urban flooding. For comparison, the same methodology has been applied at the building scale and a complementary analysis has been conducted to study which hydrometeorological variables may affect the magnitude of these hydrological impacts at both scales.

The results show green roofs, when they are widely implemented, can affect urban runoff in terms of peak discharge and volume, and avoid flooding in several cases. Both precipitation – generally accumulated during the whole event- and the initial substrate saturation are likely to have an impact on green roof effects. In this context, the studied green roofs seem useful to mitigate the effects of usual rainfall events but turn out being less helpful for the more severe ones. We conclude that, combined with other infrastructures, green roofs represent an interesting contribution to urban water management in the future.

1. Introduction

Historically used for isolation purposes in Nordic countries, green roofs have become relatively commonplace over the last 20 years in countries subject to more continental climate as Germany, Austria and Switzerland. In the last years, the spread of green roofs has steadily increased in developed countries. The annual green roof covering is estimated between 0.1 and 1 km^2 in several countries all over the word (Spain, Brazil, Canada, Korea, UK or Japan), while it is estimated to reach 2 km^2 in France and even more than 10 km^2 in Germany (Lassalle, 2012).

Such a success is part of the general policy of urban areas revegetation and can be explained by two main reasons. First, roof areas represent a significant part of the surfaces of city centres where no space is available for new infrastructures (about 40–50% of the impervious areas, cf. Dunnett and Kingsbury, 2004). Secondly, from an architectural point of view, green roofs may contribute to enhance the aesthetic value of buildings, but also to reduce heat island through increasing evapotranspiration (Takebayashi and Moriyama, 2007; Santamouris, 2012), to improve the quality of the air (Banting et al., 2005), to protect biodiversity (English Nature, 2003) and to manage urban runoff.

This last point – urban runoff management – is a significant argument to promote the development of green roof. Indeed, in order to cope with urbanization and its related problem of space, green roofs – as well as porous pavements, harvesting tanks, soakaways or ponds – are part of the so called stormwater Source Control (SC) which has gained relevance over traditional sewer approaches (Urbonas and Jones, 2002; Delleur, 2003; Petrucci et al., 2012). The principle of SC is to develop, simultaneously to urban growth, facilities to manage stormwater at a small-scale

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(about 10^2–10^3 m^2) to solve or prevent intermediate scale (10^4–10^6 m^2) stormwater issues. At the building scale, green roofs have the possibility to control both the quantity and the quality of urban runoff. Qualitatively, it can avoid the direct contribution of metals to receiving water as traditional roofs (Egodawatta et al., 2009; Gromaire et al., 2011). Nevertheless, an increase in phosphorous concentration due to vegetation coverage can be noticed (Gromaire et al., 2013). From a quantitative point of view, the main performance of green roofs in stormwater management is the reduction of runoff volume at the annual scale and the peak attenuation and delay at the rainfall event, depending essentially on the green roof configuration, the rainfall intensity and the antecedent soil moisture conditions.

These quantitative impacts have already been studied by several works based on observation or modelling. Typically, quite small surfaces of experimental green roofs were instrumented to set continuous runoff and precipitation data on short periods of time (not exceeding 3 years). These data are then analysed to study and explain the fluctuation of green roofs responses in terms of peak discharge and runoff volumes.

A very small test bed of 3 m^2 comprising sedum extensive vegetation growing in 80 mm of substrate was conducted by Stovin et al. (2012) in Sheffield (UK). The rainfall-runoff monitoring was performed continuously over a period of 29 months. The annual cumulative retention was 50% and the peak attenuation ranged from 20% to 100% (median of 59%). In this case, it was not possible to establish any relationship between rainfall retention percentage and the storm characteristics or the antecedent weather variables.

Voyde et al. (2010) instrumented six hydraulically isolated plots of about 10–50 m^2 on the Aukland University (New Zealand) during one year. These plots differed according to their substrate types (expanded clay, zeolite and pumice) and depths (50 or 70 mm). Except for one specific plot where coconut coir fibre was implemented in the sedum mat, there was no statistically significant difference in the hydrologic response from the three different substrate types. During the year-long experiment, 66% of precipitation was retained and a peak flow reduction ranging from 31% to 100% (median of 93%) was observed. Moreover, no statistically significant season-related variations were also recorded for either rainfall or runoff response. On the same site, additional data (2 years) were analysed by Fassman-Beck et al. (2013) and similar results in terms of water balance were obtained. Nevertheless, statistically significant seasonal variation was observed, demonstrating the importance of long-term monitoring.

A larger surface was covered by green roof in Genoa (Italy) where about 350 m^2 were divided in two plots, each one comprising a substrate of 200 mm and drainage layer (Palla et al., 2011) differentiated according to their substrate mix. At the event scale, the study, carried out over 6 months, showed a retained volume varying between 10% and 100% (average of 85%), and a peak flow reduction ranging from 80% to 100% (average of 97%).

Additional studies can be mentioned: Monterusso et al., 2004; Bengtsson et al., 2005; Dunnett et al., 2008; Gregoire and Clausen, 2011 among others. They all conclude, and sometimes contradictorily, that green roof response appears not to be link to one only factor. These numerous contributions show several parameters may have an impact on hydrological response such as rainfall accumulation and intensity (Carter and Rasmussen, 2006; Simmons et al., 2008), the climatic conditions, seasonality (Mentens et al., 2006; Villarreal, 2007), the antecedent conditions (Bengtsson et al., 2005; Denardo et al., 2005), and to a lesser extent, the substrate species and the depth or roof slope (Villarreal and Bengtsson, 2005; Getter et al., 2007). A detailed review on the influence of these parameters is available in Berndtsson (2010). It has also to be noticed that recent studies conducted over a longer time period (Carson et al., 2013; Fassman-Beck et al., 2013) show that rainfall depth appears to be the dominant factor in retention performance.

On the other side, few works attempted to simulate the hydrological response of green roof by using adapted models. They were usually devoted to reproduce observed runoff at the experimented roof scale or to extrapolate the green roof impact at the urban catchment scale. Hilten et al. (2008) tested HYDRUS-1D (Šimůnek et al., 2008) which is a soil moisture transport simulation using Richards' equation for variably-saturated water and convection–dispersion type equations. They tried to simulate the hydrological response of a 37 m^2 green roof. Although HYDRUS-1D was able to correctly reproduce runoff for small rain events, it failed for the largest ones by overestimating the peak discharge.

The SWMS_2D model (Šimůnek et al., 1994), based on Richards' law and the Van Genuchten–Mualem functions, was also applied to simulate the variably saturated flow of an experimental green roof system (Palla et al., 2009). Applied on 8 rainfall events, the model adequately reproduced the hydrographs, as demonstrated by the limited relative percentage deviations obtained for the total discharged volume, the peak flow, the hydrograph centroid and the water content along the vertical profile.

Simplified procedures were used to model green roof at a greater scale than the building one. Palla et al. (2008) used the Soil Conservative Service (SCS) Curve Number (CN, Mockus, 1957) as infiltration model in an aquifer system to simulate green roof response at the catchment scale in the Storm Water Management Model (SWMM, Rossman, 2004). It was calibrated using results from a small size system realized in laboratory then applied on a 18 years simulation period. It was also the case in Carter and Jackson (2007) where the SCS infiltration method was used to simulate green roof response with a CN value equal to 86. Using synthetic precipitation events they evaluated the impact of a widespread green roof application in an urban watershed.

Additionally, some efforts were made to build a simple and robust model of green roof hydrological behaviour, in order to be used as a support tool devoted to extensive green roof design (Berthier et al., 2011). Based on a reservoir cascade, this model appeared suitable to reproduce the hydrological behaviour of a 146 m^2 green roof located in Paris region (France) during one year.

Although the literature on green roof hydrological impacts has greatly developed in the last years, still few works have concentrated on to study long time period and on their use to solve urban management issues. Using a modelling system developed from an experimental setup, the work presented herein aims to study the green roof impacts on urban runoff over 18 years comprising a large and heterogeneous set of hydrometeorological situations. By comparing the results obtained at the building scale and at the basin scale, this paper is particularly focused on: (1) how far the dissemination of green roofs at large scale may affect urban runoff as much as for the building scale, (2) what are the main factors conducting the hydrological response at both scales and to what extent are they predictable.

The paper is structured as follows: Section 2 presents the specific model developed to estimate green roof hydrological response. Section 3 describes the studied basin, the geographical and meteorological data used. Section 4 presents the modelling framework and the methodology used in this study. Assessment of hydrological impacts of a green roof at the roof scale and at the basin scale is presented in Section 5. From a more operational point of view, Section 6 analyses the conditions of these hydrological impacts on stormwater management and how they can be predicted by taking into account several hydrometeotrological variables. Finally, Section 7 discusses the hypothesis made in the study and Section 8 summarizes the main results and concludes on future improvements and possible applications of green roofs for operational issues.