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Abstract
At the basin scale, green roofs can represent an efficient tool to manage stormwater in urbanized areas. Widely implemented and/or completed with additional sustainable urban drainage systems, they show a positive impact on urban runoff: decrease and slow-down of the peak discharge and decrease of runoff volume. To assess green roof performances at this scale, a specific module dedicated to simulate their hydrological behaviour has been developed in the Multi-Hydro rainfall-runoff model. Its distributed structure gives the opportunity to test the susceptibility of green roof response regarding spatial distributions of precipitation. Based on radar rainfall fields, an ensemble of 50 realistic downscaled rainfall fields with a resolution of 10 m in space has been generated by using multifractals downscaling technique. Simulations have been conducted on a small urban catchment close to Paris (France) where most of the buildings roofs are assumed to easily accept the implementation of green roof. Although green roof confirm their ability to reduce urban runoff, these results illustrate that peak discharge reduction seems to be clearly dependant of spatial distribution of precipitation. Implementation of green roof can also produce concomitance situations and higher peak discharges than those produced by impervious roofs.

Keywords
Green roof; precipitation; modelling

INTRODUCTION

Green roofs have become relatively commonplace over the last 20 years in urban areas for many reasons. Indeed, they can perform in: reduction of heat island through increasing evapotranspiration, improvement of the air quality, protection of biodiversity and stormwater management. Their use in urban runoff management is surely the most significant argument used to promote their implementation. At the building scale, the main performance of green roofs in quantitative management of storm water is known to be: (i) the reduction of runoff volume at the annual scale, and (ii) the peak attenuation and delay at the rainfall event depending on the green roof structure, the rainfall intensity and the antecedent soil moisture conditions (Simmons *et al.*, 2008, Stovin *et al.,* 2012, Versini *et al.*, 2015).

As roof areas represent a significant part of the surfaces of city centres where no space is available for new infrastructures, green roof can also appear as a useful tool to solve operational issue at the basin scale by reducing the runoff volume and/or attenuating peak discharge. Most of the work conducted for now on the hydrological impact of green roof were focused at the building scale: Voyde *et al.*, 2010; Gregoire and Clausen, 2011; Stovin *et al.*, 2012. These works usually present the results provided by an experimental monitored green roof, used to collect continuous runoff and precipitation data and also often to develop some specific (global) models (Šimůnek *et al.*, 2008;

Palla *et al.*, 2009). To our knowledge, very few studies (Carter and Jackson, 2007; Palla, 2008; Versini *et al*., 2015b) have been conducted at the basin scale and even less by using a distributed rainfall-runoff model able to take into account the spatial distribution of green roof and precipitation. It is the originality of this paper, which is focussed on the hydrological impact of green roof at the basin scale regarding precipitation fields characterized by high spatio-temporal resolution.

METHODOLGY AND CASE STUDY

To assess green roof impact at the basin scale regarding distributed precipitation, the Multi-Hydro (El Tabach, 2009; Giangola-Murzyn et al., 2012; Gires *et al*., 2014) distributed rainfall-runoff model has been used. It is a numerical platform that makes interact several models representing a specific portion of the water cycle in an urban environment: surface runoff and infiltration depending on a land use classification, sub-surface processes and sewer network drainage. A specific module dedicated to simulate green roof behaviour has been added in Multi-Hydro (inspired from that presented in Versini *et al.,* 2015a, and detailed in Versini *et al.,* 2015c). It has been calibrated to simulate the hydrological behaviour of a green roof structure comprising an extensive vegetation layer (sedum), a growing medium layer (thickness of 3 cm) and a drainage layer. Distributed structure of the Multi-Hydro model enables to analyse the impact of the spatial variability of precipitation and land use, and especially the precise location of green roof.

Multi-Hydro has been applied on the Loup basin (0.5 km^2) in a highly populated and urbanized city (Villepinte, France) located close to Paris. 20% of the basin area is occupied by buildings dedicated to industrial activities. It has been assumed that green roof can be implemented on these roofs – which are all flat. Note that Multi-Hydro was previously applied on the Loup basin with satisfactory results in Gires et al. (2013).

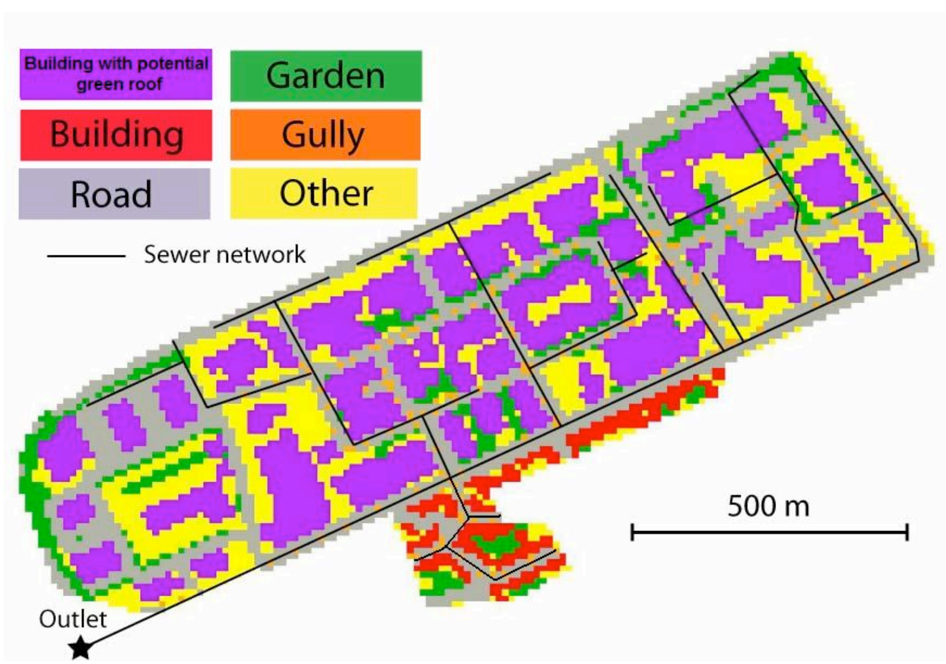

Figure 1. Loup basin: land use spatial distribution with pixel of size 10 m x 10 m, and sewer network inputted on Multi-Hydro

In order to test the impact of spatial variability of precipitation, an ensemble of 50 realistic downscaled rainfall fields with a resolution of 10 m in space was generated from Radar data (1 km-resolution). The downscaling process relies on the framework of Universal Multifractals (Schertzer and Lovejoy, 1987). It is assumed that rainfall is generated through a space-time multiplicative cascade process characterized by two parameters (the mean intermittency and the multifractality index). More details on the downscaling process can be found in Gires *et al.* (2012). The process was applied on two complex events on the studied basin for which radar data was available: (i) a common event (9 February 2009) characterized by a total rainfall depth of 8.3 mm and a duration of approximately 6 h (return period estimated to 1 month), (ii) a severe event (15 August 2010) characterized by a total rainfall depth of 25 mm and a duration of 6h (return period estimated to 2 years).

RESULTS AND DISCUSSION

Multi-Hydro simulations have been carried out for both rainfall events. The results obtained with green roof implementation have been compared to those obtained for the current situation (without any green roof implemented). Related hydrographs are illustrated in Figure 2. Green roof performances on peak discharge and volume runoff have particularly been studied.

First of all, it has to be noticed that current basin response can significantly be modified depending on the spatial variability of rainfall distribution. Peak discharge for the impervious scenario varies between 0.10 and 0.15 m^3/s for the first event and between 0.5 and 0.9 m^3/s for the second one.

When green roofs are implemented, this variation is still significant: between 0.06 and 0.11 m^3/s, and between 0.5 and 1.4 m^3/s for both events respectively. Green roofs appear to impact urban runoff in terms of peak discharge and volume depending on precipitation –total amount and intensity- and initial substrate saturation: the higher the precipitation, the more saturated the substrate, and the lower the reduction in terms of stormwater. Results are less pronounced than those usually observed at the building scale because they depend on the green roof area, representing here only 20% of the basin area. At the roof scale, this low event would be completely retained by the substrate (in dry conditions).

The reduction of volume runoff can reach more than 36% as it can be noticed for the more common event. This reduction is only about 12% for the 2-year return period event characterized by a higher amount of precipitation. Note that the variation of volume regarding the 50 downscaled scenarios is not significant (standard deviation of 1%) as the amount of precipitation falling on the basin is usually always the same for the 50 members of the ensemble.

Peak discharge can also be significantly affected by green roof implementation depending on the rainfall event. Regarding the common event, average peak discharge decrease is about 35% and ranges between 10% and 56% depending on the downscaled scenario, illustrating the influence of spatial variability of precipitation. These satisfactory results are most of all concentrated on the first rainfall peak. Here, basin response to the main rainfall intensity is clearly attenuated but likewise dispersed. Conversely, the response to the second rainfall peak is systematically increased by green roofs (from 0 to 33% with an average value of 10%). The range of simulated values is also more dispersed, increasing the sensitivity of the basin regarding precipitation. First peak decreases and second peak increases are quite correlated, meaning attenuation of the first one seems to cause gain of the second one. In this case, the substrate stores precipitation during the first part of the event, before releasing it simultaneously with the second rainfall peak.

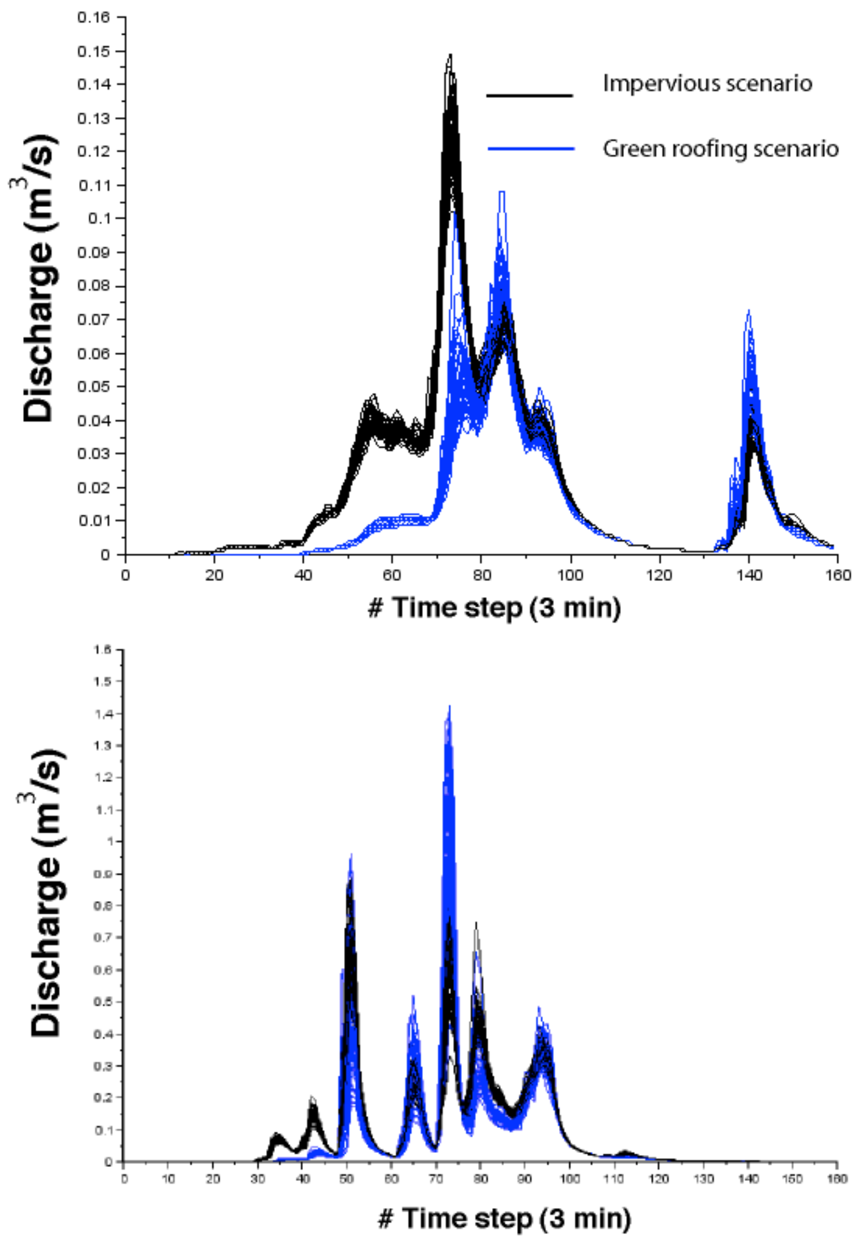

Figure 2. Simulation results obtained by using the 50 downscaled rainfall fields for the 09/02/2009 (top) event and the 15/08/2010 (bottom): current situation (without any green roof) is depicted in black and green roofing scenario in blue.

The same kind of situation is noticed and even more pronounced for the 2010 event. Although green roof can reduce the first peak discharge for most of the downscaled scenarios (between -9% to 65% with an average value of 32%), the response to the second large rainfall peak is systematically increased (average increase of 60%). In a general way, green roof response to successive rainfall peaks can alternatively increase or decrease peak discharge at the basin outlet depending on the spatio-temporal distribution of precipitation.

These examples represent “concomitance” situations. For some events characterized by several rainfall peaks, the fast response of the saturated substrate generated by the “second peak” of the rainfall coincides with the slow response of the green roof produced by the initial portion of the rainfall event. These situations are related to both the spatio-temporal distribution of precipitation and the specific configuration of the studied basin (especially on the basin geometry and land cover, and the sewage network arrangement). The superposition in space and time of responses from impervious and a green roofed areas to a complex rainfall event (composed by several rainfall peaks for example) can generate a peak discharge higher than that produced by the current (impervious) situation.

CONCLUSION

The Multi-Hydro distributed rainfall-runoff model has been used to assess green roof performances in stormwater management regarding high-resolution precipitation fields.

Regarding the presented examples and additional works, green roof implementation appears to reduce urban runoff in terms of peak discharge and volume depending on rainfall event characteristics (in terms on intensity and duration) and the initial state of the substrate saturation. The wide implementation of green roof should be useful to avoid some flooding (or sewer combined overflows) issues in several cases depending on the initial conditions. They will particularly perform to mitigate the effects of common rainfall events and/or very short (but sometimes intense) rainfalls that are expected to be more often in Paris area under climate change.

Nevertheless an important point has to be carefully considered: concomitance situations that can occur for a particular basin configuration and/or a rainfall event. As illustrated with the Loup basin, depending on the considered downscaled rainfall scenario, the combination of basin configuration and precipitation can produce higher peak discharge than that produced in the current situation (impervious roofs).

Finally, spatial variability of rainfall fields seem to influence the basin response as peak reduction can increase/decrease of about +/- 25% regarding the average response. This demonstrates the interest to use high-resolution precipitation data (as those provided by X-band radar for instance) in stormwater management.

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