Hydrological impact of green roofs on urban runoff at the watershed scale – Case studies in the Hauts-de-Seine county (France)

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Impact hydrologique des toitures végétalisées sur le ruissellement urbain à l'échelle du bassin versant – Études de cas dans le département des Hauts-de-Seine (France)

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RÉSUMÉ

A l'échelle du bâtiment, l'utilisation de toitures végétalisées a montré une influence positive en termes de ruissellement (ralentissement et diminution du débit de pointe, diminution du volume ruisselé). Le présent travail a pour objectif d'étudier l'éventuel impact de ces toitures à des échelles davantage compatibles avec des problématiques de gestion urbaine (quartier, bassin versant).
Une méthodologie pour évaluer l'impact des toitures végétalisées a été spécifiquement développée. Elle comprend une méthode de définition de scénarios de végétalisation réaliste à l'échelle urbaine et un outil de modélisation capable de représenter le comportement hydrologique d'une toiture et d'être intégré dans le modèle de gestion des eaux pluviales SWMM.
Cette méthodologie a été appliquée sur deux bassins versants des Hauts-de-Seine (France) respectivement soumis à des risques de débordements et de déversements en Seine. Les résultats montrent que la végétalisation des toitures peut réduire la fréquence et l'intensité de ces phénomènes en fonction de la surface de toit couverte. Combinée à d'autres infrastructures, elle représente un potentiel intéressant de réduction du ruissellement urbain dans les années à venir.

ABSTRACT

At the building scale, the use of green roof has shown a positive impact on urban runoff (decrease and slow-down in the peak discharge, decrease in runoff volume). The present work aims to study the possible impact of green roof on a larger scale compatible with urban management issues (quarter, catchment).
A methodology has been proposed to assess the green roof impact at such a scale. It combines a method to define green roofing scenarios by estimating the maximum roof area that can be covered and a modelling tool able to simulate the hydrological behaviour of green roof. This module has been integrated into the SWMM urban runoff management model.
This methodology was applied to two urban catchments (Haut-de-Seine county, France) affected by flooding and combined sewage overflow hazards respectively. The results show that green roof can be useful to reduce the frequency and the magnitude of such problems depending on the covered roof surface. Combined with other infrastructures, they represent an interesting solution for urban water management in the future.

MOTS CLES

Flooding, Green roof, Hydrological modelling, Scale study, Sewage network, SWMM

1 INTRODUCTION

The increase in impervious surfaces typically associated with urban development is responsible for numerous problems both within and outside cities. Storm water runoff affects water quantity and quality causing urban flooding and overflow. It is especially the case in combined sewer system where urban pollution represents an important issue. Many techniques have been developed (storm water ponds, retention basin, open channels, infiltration systems…) to face these problems and limit the saturation of storm water sewage network (Ferguson, 1998; White, 2002, Campisano et al., 2011). These infrastructures aim to temporarily store excess water before sending it progressively back into the network or the environment (by the mean of discharge, infiltration, or evaporation).

These infrastructures require available land spaces which become scarcer in densely built downtown urban areas. To cope with urbanization and this problem of space, storm water source control (SC) has gained relevance over traditional sewer approaches (Delleur, 2003; Urbonas and Jones, 2005; Chouli, 2006; Petrucci et al., 2012). The principle of SC is to develop, simultaneously to urban growth, facilities to manage storm water at a small-scale (about 10^2–10^3 m^2) to solve or prevent intermediate scale (10^4–10^5 m^2) storm water problems. These techniques include green roofs, porous pavements or harvesting tanks, for instance.

Green roofs appear to be particularly relevant because roof areas represent a significant part of the impervious surfaces and may be a contributor of toxic metals to receiving waters (Egodawatta et al., 2009; Gromaire et al., 2011). At the building scale, the main performance of green roofs in quantitative management of storm water is known to be the reduction of runoff volume at the annual scale and the peak attenuation and delay at the rainfall event depending on the green roof structure, the rainfall intensity and the antecedent soil moisture conditions (see Palla et al., 2009 ; VanWoert et al., 2005 ; Jarret et al., 2006 for detailed studies). For these reasons, the diffusion of green roofs is currently underway.

Despite the current spread of green roofs, few works have been published on their impacts on stormwater runoff to solve urban management issues. To our knowledge, most of the previous quoted studies have been focused on the hydrological impact of green roof at the building scale where these impacts would be initially generated (Bengtsson, 2005; Hilten et al., 2008; Palla et al., 2009; Gregoire and Clausen, 2011 for instance). Very few of them assessed the possible impacts at larger scale (the catchment scale), more adapted to management practices (Mentens et al., 2006; Carter and Jackson, 2007; Palla et al., 2008).

Based on these considerations, this paper aims to study how the spatial distribution of green roofs throughout the watershed can reduce the total volume entering into the drainage network. It is particularly focussed on how far the dissemination of green roofs at large scale may impact urban runoff as shown for the building scale.

This work has been conducted on real cases where the current configuration of the sewage network causes risky situations. A methodology has been proposed to assess the green roof impact at the urban scale. It has been applied on two urban basins affected by flooding and Combined Sewage Overflow (CSO) that are presented in Section 2. The methodology, adapted to the case studies, is developed in Section 3. It combines a method defining green roofing scenarios, which estimate the maximum roof area that can be covered, and a modelling tool able to simulate the hydrological behaviour of green roofs. Integrated into an urban runoff management model, this tool has been used to study the consequences of several green roofing scenarios in terms of discharge and CSO reduction (Section 4). Finally, the results are synthesized and discussed in Section 5.

2 CASE STUDIES IN THE HAUTS-DE-SEINE COUNTY

The Hauts-de-Seine county is located west of Paris (France). It is a highly populated and urbanized area (1.5 million inhabitants for a surface of 176 km^2). The northern part is very urbanised and limited by the Seine River, whereas the southern part is less populated with the presence of several forests. The Hauts-de-Seine climate is very close to the rest of the Paris Basin with mild winters, frequent rainfalls in autumn, mild spring and high summer temperatures with possible occurrence of intense rainfalls. The average annual rainfall over the county is about 700 mm, whereas the decennial hourly rainfall is about 35 mm.

Because of the rapid growth of urbanization during the 90's and the difficulty to build new management infrastructures due to its density, stormwater network is very sensitive to intense precipitation which can cause some troubles as local flooding for instance. Since the beginning of the 2000's, the local authority in charge of water management (Water Direction of the Haut-de-Seine county) is concerned to mitigate these problems by the use of Sustainable Urban Drainage System (SUDS). In this context, the Hauts-de-Seine county has set up a grant policy to promote regulated flat roof (an extension of 40 mm with small diameter holes located at the outlet is used to regulate the flow rate entering in the gutter; beyond this level, water overflows without any regulation). This regulated system is not always accepted by green roof professionals, because of the unknown impacts on the vegetation structure. The Water Direction is also interested in studying the impacts of existing and future conventional green roofs on urban runoff in order to refine their approach in urban hydrology. Moreover, the implementation of green roofs is particularly interesting in this county because they potentially represent a significant area on current buildings and new constructions in the future.

As a consequence, two urban watersheds have been chosen, in coordination with the Water Direction, to study the possible impact of green roofs at the basin scale. They are located in Châtillon and Boulogne-Billancourt. Their combined sewer networks are both affected by urban runoff problems during storm events.

Châtillon is a moderate basin of 2.4 km^2 characterized by a quite steep topography with an average slope of 3.5%. The upstream part of the basin is essentially covered by individual housing, whereas the downstream part is rather covered by collective housing and economical activities. Local floodings often occur along the Boulevard de Vanves (see Figure 1), a main road crossing the city center. The pipe along the Boulevard until the outlet is not large or/and steep enough to route the runoff during intense rainfall. It seems that flooding occurs when the discharge exceeds the limit value of 5 m^3/s at the outlet.

Boulogne-Billancourt (5.5 km^2) is a densely urbanized basin near Paris. Most of the basin is occupied by collective housing. The lower periphery is more diversified with offices, parks, equipment and industrial wasteland. The basin is often affected by CSO in the Seine River, which surround a large part of the city (see Figure 1). The frequency of these CSO is approximately monthly with significant volumes that could be rejected during intense storm. During the last significant event, in July 2010, the total monthly overflowed volume reached 150,000 m^3.

Both basins have been represented in Storm Water Management Model (SWMM, see Rossmann, 2004) which is a dynamic rainfall-runoff model especially developed for urban/suburban areas by the United States Environmental Protection Agency (EPA). The sewer network including junction nodes, conduits, and specific infrastructures (weir, orifice, storage unit …), has been designed to simulate and estimate their hydrological behaviour. As SWMM is a semi-distributed model, each basin is divided in several sub-basins on which the water balance is computed.

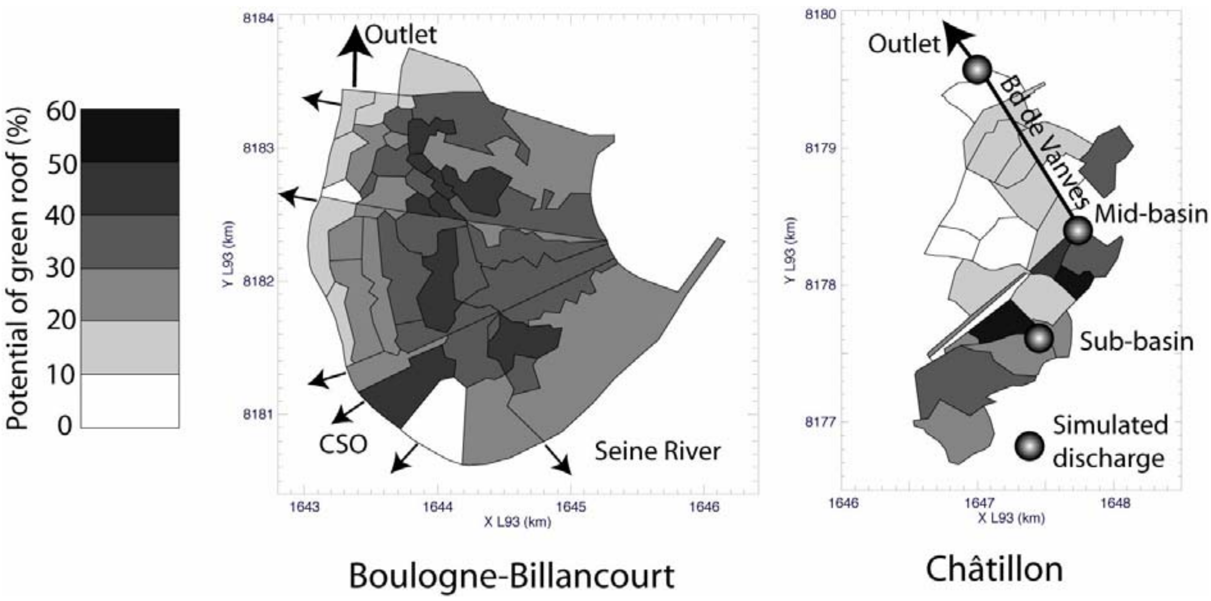

Figure 1. Configuration of the studied basins and spatial distribution of green roofing potential. The locations of management issues (flooding and CSO) are also represented.

3 HYDROLOGICAL MODELLING FRAMEWORK

In order to test the possibility to mitigate the basin vulnerability and to reduce both flooding and CSO risks, the impact of virtual green roof scenarios has been studied. SWMM basin initial representations have been modified to take into account the possible implementation of green roof. First, a potential of green roofing has been defined at the sub-basin scale by combining several geographic data. Second, a specific module representing green roof hydrological behaviour has been developed and added into SWMM structure.

3.1 Potential of green roofing

3.1.1 Methodology

The potential of green roofing is estimated by combining land use (IAU-IDF, 2008) and building data (IGN, 2011). Some specific classes of the land use database have been selected assuming green roof could potentially be implemented. The hypothesis has been made that every building belonging to those classes is mainly covered by flat floor: collecting housing, flat roof, industrial and economic activities, public buildings, equipments… In each class, the roofs areas have been deduced by identifying the buildings areas from the second database.

Finally, the potential of green roofing is defined as the percentage of the sub-basin area that could be covered by green roof. It is a high estimation of the real green roofing potential since it assumes that all selected buildings are effectively covered by flat roof, without micro-structure and technically really “greenable”. These potentials also represent a maximum value for which green roofing scenarios will be deduced by selecting a part of it.

3.1.2 Results

The methodology has been applied on both case studies and the results are illustrated in Figure 1. The potential of green roofing appears to vary significantly from a sub-basin to another. In the Châtillon basin, the downstream part (where individual housing are located) is characterized by a potential lower than 20%, whereas almost all the sub-basins located upstream from the Boulevard de Vanves have a potential higher than 20% and locally reaching more than 50%. The green roof potential is more spatially homogeneous on the Boulogne-Billancourt basin and ranges from 5 to 45%.

3.2 Green roof module

The SWMM module called “Bio-retention Cell” has been modified to simulate the hydrological response of green roof. It is applied at the sub-basin scale on an area representing the total green surface (not at the building scale). This module is based on the model developed by Berthier et al. (2010, 2011) representing each layer of green roof infrastructure (vegetation, growing medium and drainage) by 3 different reservoirs. The model parameters have been adjusted by using an experimental green roof setup on the site of CETE Ile-de-France in Trappes (45 km South-West from Paris, France).

The whole area of the roof (about 400 m²) was split into several compartments differentiated by their type of green roof (type of vegetation, growing medium thickness, type of drainage). A detailed presentation of the experimental site is available in Gromaire et al. (2012). The reservoir model has been especially adjusted for two configurations comprising an extensive vegetation (sedum), a growing medium layer and a drainage layer with expanded polystyrene. Both green roof configurations differ in the depth of the growing medium. For the first one, called SE3Y, the thickness is 3 cm and for the second one, called SE15Y the thickness is 15 cm.

Meteorological and hydrological data (time step of 3 minutes) compiled from June 2011 to July 2012 have been used to calibrate and validate the model. Satisfactory results were obtained for both configurations, especially for the largest rainfall events. Dynamics of runoff was well reproduced with a Nash efficiency (Nash and Sutcliffe, 1970) close to 0.8 at the storm event scale. Moreover, the water balance was correctly respected with an error on volumes close to 10% (this underestimation seems to be related with the overestimation of evapotranspiration and do not affect the representation of peak discharges).

3.3 SWMM simulations

In order to reproduce correctly the hydrological behaviour of both studied basins, SWMM representations have been tested on past events and compared to discharge observations. On Châtillon basin, no continuous measures were available. Simulations have been performed on 3 rainfall events (total precipitation higher than 12 mm) for which temporal discharge observations were made. SWMM simulations appeared to be excellent with a very well representation of the peak discharges and some substantial Nash efficiency higher than 0.85. Concerning Boulogne-Billancourt basin, long continuous discharge time series were available on the 2010-2011 time period. The simulation was evaluated by a Nash efficiency equal to 0.65. As every peak discharge was well represented, it seems the efficiency was deteriorated because of the poor representation of dry weather inflows. These results show that observations and simulations match very well at the event scale.

Finally, as green roof module and SWMM basin configurations provide very satisfactory results, they have been combined for testing green roof impact on flooding and CSO issues.

4 STUDY OF GREEN ROOF IMPACTS

4.1 Methodology

Since both study basins are exposed to a different issue, a specific framework has been defined for each case.

- Concerning the Châtillon basin, affected by flooding, the peak discharge flowing through the Boulevard de Vanves has been studied and the return period of annual maximum peak discharge has been particularly calculated. Moreover, in order to study more specifically the scale effect, the peak discharges have been calculated for 3 spots located inside the catchment (see Figure 1). The first one corresponds to the outlet of a sub-basin (10 ha) characterized by a particularly significant green roof potential. The second one corresponds to an intermediate basin (100 ha) located downstream of the Boulevard de Vanves. The last one corresponds to the entire downstream basin (550 ha).
- For the Boulogne-Billancourt basin, affected by CSO, the volumes overflowing into the Seine River have been studied. The analysed value represents the cumulative overflowed volumes to the receiving environment by the different outlets located around the basin (see Figure 1). As these overflows are very usual, the frequency of the monthly volume has also been calculated.

In both cases, different scenarios of unregulated green roofing have been provided, based on the potential of green roofing computed at the sub-basin scale. They correspond to the covering of 12.5, 25, 50 and 100% of the previously defined green roofing surface. In SWMM, these green roof surfaces have been subtracted from the impervious areas at the sub-basin scale. The green roof module, previously integrated into SWMM, is used to compute runoff for these particular surfaces. The resulting hydrological indicators (simulated discharges and volumes) have then been compared to the initial ones.

Precipitation time series on the 1993-2011 time period (5-minute time resolution) have been used to simulate the hydrological behaviour of both basins. Such a long period seems enough to capture usual events (peak discharge and monthly overflowed volumes) characterized by a return period lower than 10 years. For both basins, 35 storm events for which sewage problems occurred have been particularly analysed to see the possible impact of green roof at the event scale. The accumulated rainfalls of these events reached 2.6 to 120 mm (representing an intensity of 0.8 to 49 mm per 30 minutes, this last value refers to a decennial return period).

4.2 Results

Simulation results for flooding, scale effect and combined sewage overflow issues are presented in the following next sub-sections. For the main rainfall events, no significant difference has been noticed between the results obtained for SE3Y and SE15Y green roof configurations. The decrease in peak discharge or runoff volume due to green roofing obviously appears to be quite higher for SE15Y, but this difference is stronger for the lowest rainfall events. This has also been noticed on the experimental green roof setup in Trappes. For this reason and for a question of clarity, only the results provided for SE15Y are represented in the next figures (2, 3, and 4).

4.2.1 Impacts on flooding (Châtillon basin)

The simulated peak discharges appear to be influenced by the implementation of green roofs when significant roof surface is covered. The statistical distribution of annual peak discharge represented in Figure 3 shows that 50% of the green roofing potential (representing 10% of the total basin area and 25% of the total impervious area) has to be covered to reduce the peak discharge by 15%, whatever is the considered return period. When 100% of the potential is covered, the decrease in peak discharge can reach up to 35%.

The simulated discharge time series for the basin outlet is also represented for the particular storm event of June 2009, for which the value was over the threshold of 5 m^3/s (Figure 2). As for the statistical distribution, a significant decrease in peak discharge (about 20%) only occurs when almost 50% of the potential is covered (a decrease in 35% is noticed for 100% of the potential). Nevertheless, a low covering of the potential (12% or 25%) is enough to reduce the peak discharge below 5 m^3/s and theoretically avoid flooding (see also Figure 2).

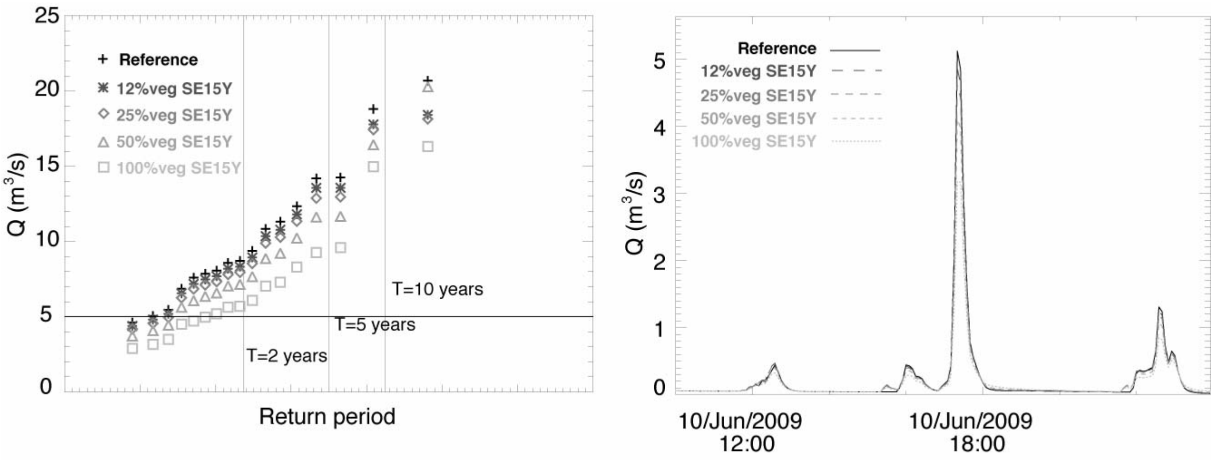

Figure 2. Results of the SWMM simulations for Châtillon basin by using the different green roofing scenarios: the statistical distribution of annual peak discharge is represented on the left (5 m^3/s threshold is indicated) and the storm event of June 2009 is represented on the right.

4.2.2 Scale effect (Châtillon basin)

Scale effect is visible when comparing the results for the three studied scales (sub-basin, mid-basin, basin). The results are clearly related to the green roofing potential of the three entities (see Figure 3). As both basin and mid-basin are characterized by a relatively similar low potential (between 15% and 25%), the impact of green roofing represents a decrease in approximately 35% for peak flow and 15% for runoff volume in the best case (scenario with 100% SE15Y). A significant modification of discharge appears when at least 50% of the potential is covered. In this case, a peak discharge decrease in 15% is observed.

At the sub-basin scale, characterized by a green roofing potential higher than 50%, these modifications are more important, with a maximum decrease in 60% for peak flow and 45% for runoff volume (for the 100% SE15Y scenario). It has to be noticed that a low covering of the potential (25%) appears to be enough to reduce significantly the peak discharge (of about 15%).

As mentioned above, the scale effect seems to depend only on the green roofing potential and not on the size of the studied areas. A low potential has to be compensate by a higher percentage of covering in the same proportion. For this basin, the combination of the specific configuration of the sewage network with the modification of roof coverage does not seem to influence the dynamics of discharge as any concomitance problems has been noticed.

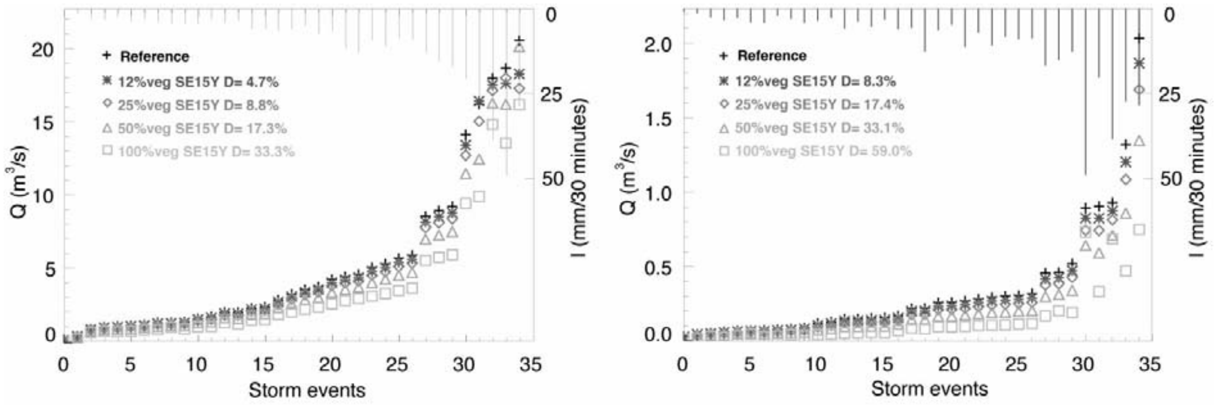

Figure 3. Results of the SWMM simulations for Châtillon basin by using the different green roofing scenarios: modifications of the peak discharge for each storm event are represented for the total basin on the left and for the sub-basin on the right. The decrease in maximum peak discharges (relative to the reference) is also indicated and called Δ. Bars at the top represents rainfall intensity.

4.2.3 Impact on Combined Sewage Overflow (Boulogne-Billancourt basin)

Monthly volumes of CSO have been computed for the complete time series. Their statistical distribution is illustrated in Figure 4. Whatever is the green roofing scenario, the distribution is modified from the very usual values to the rarest ones. The overflowed volume is completely avoided for the more common events (return period lower than 2 months) when 100% of the potential is covered. For less frequent events (2 months < T < 1 year), CSO volumes can be divided by two in the same circumstances. Intermediate scenarios (50% of the potential covered) provide a 30% reduction of these volumes. Note that the reduction in CSO volume seems to be higher for the lowest frequencies.

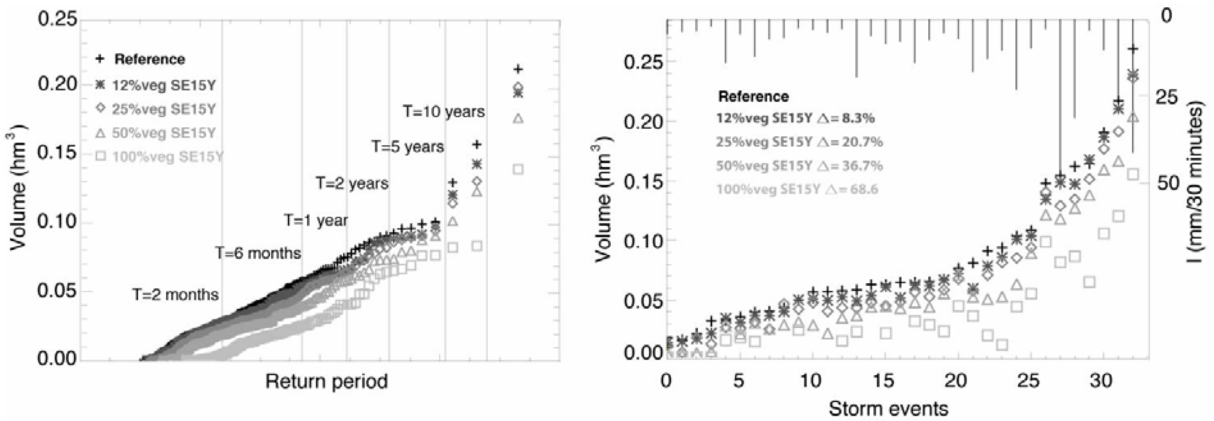

Figure 4. Results of the SWMM simulations for Boulogne-Billancourt basin by using the different green roofing scenarios: the statistical distribution of overflowed volume is represented on the left and modifications of peak discharge by storm event are represented on the right (Bar at the top represents rain intensity).

As for the previous results, it appears that the percentage of covered roof has more consequences than the type of green roof (SE3Y or SE15Y), despite more precipitation is supposed to be infiltrated with the thicker one. Regarding the results for the 35 studied events (Figure 5), the covering of only 12.5% of the potential seems to produce only a low impact in terms of overflowed volume reduction (an average decrease about 7.6%). The covering of 50% causes an average decrease about 35%, whereas the covering of 100% induces a significant decrease reaching 60% of the CSO volume.

5 DISCUSSION AND CONCLUSION

A methodology to study the impact of green roof at the catchment scale has been developed. It includes the design of green roofing scenarios based on a land use analysis and a model simulating the hydrological behaviour of these surfaces. Integrated into an urban runoff management model, this tool has been applied on two urban catchments suffering specific operational issues (flooding and

CSO) in the Haut-de-Seine county.

The presented results illustrate the interest of using green roof to reduce risks due to sewage overflow. The magnitude of both peak discharge and overflowed volumes decrease depends strongly on the effective green roof covering (which is the product of green roof potential and green roof covering). The covering of 100% of the identified implementable roof surfaces involve a very significant decrease in peak discharge (between 30 and 60% depending on the green roofing potential), runoff volume (between 15 and 45%) and overflowed volume (more than 60%). A less covered area (25 to 50 % of the identified potential), more representative of the reality, is supposed to partially reduce the studied problems.

However, these encouraging results are based on a number of implicit hypotheses and limitations that are worth discussing:

- Optimistic estimation of the green roofing potential: as described in this paper, the methodology implemented to estimate the potential of green roofing at the sub-basin scale probably overestimates the real potential. It is assumed that all buildings belonging to the selected land use categories can effectively be covered by green roof, meaning that they have flat roofs, without micro-structure and for which the implementation of green roof is technically possible. Although the green roofing of slightly sloping roofs may be possible, scenarios based on the covering of 100% of the defined potential are clearly unrealistic. Nevertheless, they illustrate the interest of such structures and encourage the implementation of green roof for future rehabilitation and developing projects. The results obtained for intermediate scenarios (covering of 25 to 50% of the potential) demonstrate the covering of a significant -but more realistic- part of roof surfaces can provide satisfactory improvement in terms of urban runoff management. Moreover, this study has been conducted by using traditional green roofs. The use of regulated ones –as encouraged by the Hauts-de-Seine county- could still improve their performance by storing more water on the roof structure.
- Short time period for the calibration of the hydrological model: hydrological model parameters have been adjusted using one year of observed discharge. Nevertheless, from June 2011 to July 2012, no severe event was observed (regarding IDF curves, the maximum exceeded return period is equal to 6 months). That means the model has been developed to reproduce common events, and we assume it is able to represent correctly rarer events characterized by more intense precipitation. For this reason, the observation of experimental green roofs has to continue in order to capture some more significant storm events. These additional data will be used to improve and/or validate the model in the future. However, the use of current data allows to conclude that the implementation of green roof can be useful to limit the consequences of common storm events on sewage network.
- These results have been computed for two particular urban basins belonging to the Hauts-de-Seine county. For this reason, the figures obtained in terms of flooding and CSO reduction can not be generalized and transferred to other locations. Indeed, they depend on the basin configuration, especially on green roofing potential (with the diffusion more or less significant of flat roof) but also on the geometry with the possibility of concomitance problems to occur. The definition of generalized recommendation to reduce urban runoff depending on green roof implementation represents a large perspective for future investigations. It is one of the objectives of the TVGEP project (supporting this work).

Despite these limitations, this study encourages the large implementation of green roof to locally reduce sewage network overflows. In addition to thermal and environmental benefits, green roof can be valuable from an urban water management point of view. This kind of study could be used by policy makers and water management authorities to promote the dissemination of green roof in the future. Combined with other stormwater source controls or/and retention infrastructures, green roof could participate to significantly reduce the quantity of water flowing into the sewage network during storm events.

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