Use of green roofs to solve storm water issues at the basin scale: study in the Hauts-de-Seine County (France)

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4   At the building scale, green roof has demonstrated a positive impact on urban

5   runoff (decrease in the peak discharge and runoff volume). This work aims to

6   study if similar impacts can be observed at basin scale. It is particularly focused

7   on the possibility to solve some operational issues caused by storm water.

8   For this purpose, a methodology has been proposed. It combines: a method to

9   estimate the maximum roof area that can be covered by green roof, called

10   green roofing potential, and an urban rainfall-runoff model able to simulate the

11   hydrological behaviour of green roof.

12   This methodology was applied to two urban catchments affected one by

13   flooding and the other one by combined sewage overflow. The results show that

14   green roof can reduce the frequency and the magnitude of such problems

15   depending on the covered roof surface. Combined with other infrastructures,

16   they represent an interesting solution for urban water management.

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18   Keywords: Flooding, green roof, hydrological modelling, scale study, sewage

19   network, SWMM

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1. Introduction

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

Nevertheless, these infrastructures require available land spaces that are more scarce in densely built downtown urban areas. To cope with urbanization and the problem of space, storm water source control (SC) has gained relevance over traditional sewer approaches (Delleur, 2003; Urbonas and Jones, 2001; Chouli, 2006; Petrucci et al., 2012). The principle of SC is to develop at small-scale (about 10^2–10^3 m^2), simultaneously to urban growth, facilities to prevent storm water problems at intermediate scales (10^4–10^6 m^2). 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 in urban areas (between 40 and 50%, Villarreal and Bengtsson, 2005). 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 scale 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). Moreover, green roofs can avoid the direct contribution of toxic metals as those produced by zinc or lead roof

(Egodawatta et al., 2009; Gromaire et al., 2011). For these reasons, over recent years the spread of green roofs is currently underway in developed countries, and more and more green roofs are established. The annual growth in green roof covering is estimated to be between 0.1 to 1 km^2 in several countries all over the world (Spain, Brazil, Canada, Korea, UK or Japan), while it is estimated to reach 2 km^2 in France and higher than 10 km^2 in Germany (Lassalle, 2012).

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 initially occur. These works usually present the results provided by an experimental green roof instrumented to collect continuous runoff and precipitation data over short periods of time (not exceeding 3 years): see Bengtsson, 2005; Palla et al., 2008a; Voyde et al., 2010; Gregoire and Clausen, 2011; Stovin et al., 2012 for instance. In some cases, a rainfall-runoff model has especially been developed to simulate the green roof response (Hilten et al., 2008; Palla et al., 2009; Berthier et al., 2011). In these cases, the observations provided on the experimental set up are used to calibrate the model. Finally, very few studies assessed the possible impacts of green roof at larger catchment scale (Mentens et al., 2003; Carter and Jackson, 2007; Palla et al., 2008b), and even less to directly test the implementation of green roof to improve storm water management.

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 implementation of green roofs at large scale may impact urban runoff and can eventually solve some operational issues.

This work has been conducted on real cases where the current configuration of the sewage network causes risk situations. A methodology has been proposed to assess the green roof

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1 impact at the urban scale. It has been applied on two urban basins affected by flooding and

2 Combined Sewage Overflows (CSO) that are presented in Section 2. The methodology is

3 developed in Section 3. It combines a method of defining green roofing scenarios which

4 estimate the maximum roof area that can be covered, the green roofing potential and a

5 modelling tool able to simulate the hydrological behaviour of green roofs. Integrated into an

6 urban rainfall-runoff model, this tool has been used to study the consequences of several

7 green roofing scenarios in terms of discharge and CSO reduction (Section 4). Finally, the

8 results are synthesized and discussed in Section 5.

9

10 **2. Presentation of the Case study (the Hauts-de-Seine county)**

11 The Hauts-de-Seine County is located west of Paris (France). It is a highly populated and

12 urbanized area (1.5 million inhabitants for a surface of 176 km^2). The northern part is very

13 urbanized and limited by the Seine River, whereas the southern part is less populated with the

14 presence of several forests. The Hauts-de-Seine climate is very close to the rest of the Paris

15 Basin with mild Winters, frequent rainfalls in Autumn, mild Spring and high Summer

16 temperatures with possible occurrence of intense rainfalls. The average annual rainfall over

17 the county is about 700 mm, whereas the decennial hourly rainfall is about 35 mm.

18 Because of the rapid growth of urbanization during the 90's and the difficulty to build

19 new management infrastructures due to its density, the stormwater network is very sensitive

20 to intense precipitation which can cause local flooding. Since the beginning of the 2000's, the

21 local authority in charge of water management (Water Direction of the Haut-de-Seine county)

22 tries to mitigate these problems by the use of Sustainable Urban Drainage System (SUDS). In

23 this context, the Hauts-de-Seine county has set up a grant policy to promote regulated flat

24 roofs. An extension of 40 mm with small diameter holes located on the top of the downspouts

25 is used to regulate the roof flow rate. 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 green roofs on urban
runoff in order to refine their approach in urban hydrology.

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 basin of 2.4 km^2 characterized by 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 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 up to the outlet is not large or/and
steep enough to route the runoff during intense rainfall. It seems that flooding occurs (almost
every year) 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 with an
average slope of 0.5%, and mainly occupied by collective housing. The southern periphery is
more diversified with offices, parks, and industrial wasteland. The basin is often affected by
CSOs to the Seine River, which surround a large part of the city (see Figure 1). The frequency
of these CSOs is approximately monthly with significant volumes that could be discharged
during intense storm. During the last significant event, in July 2010, the total monthly
overflowed volume reached 150,000 m^3.

In order to assess the hydrological impact of green roofs on both basins, several
geographical, technical and hydrometeorological data have been obtained. They are useful to:
(i) estimate their green roofing potential, and (ii) model their hydrological behaviour. These

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data comprise:

- Land use information: The database, called MOS (for "Mode d'Occupation des Sols" in French, see IAU-IDF, 2008), classifies the land surface into 81 main land use categories.

- Topological information: This database called BD TOPO® data (IGN, 2011) includes surface information on the spatial distribution of buildings, roads, rail or hydrographic network.

- Basin information: basin contours, disaggregation into sub-basins and sewage network data (including the layout and the geometrical properties of pipes and sewage infrastructures, operating rules and dry weather flow data) were provided by the Water Direction of the Hauts-de-Seine county.

- Precipitation and potential evapotranspiration (ETP) data: A continuous precipitation database from a rain gauge located close to both basins was provided by the Water Direction. A continuous ETP database was provided by Meteo-France. They cover a full time period from 1993 to 2011 (excepted 1996) with a time resolution of 5 minutes.

- Discharge data: No automatic continuous stream gauge station is installed in the Châtillon basin, but a monitoring programme was conducted from April to June in 2009 to evaluate the discharge at the outlet. On the other hand, Boulogne-Billancourt basin outlet is instrumented by a stream gauge (characterized by a 5-minute resolution). Flow measurements were provided on the 2010-11 time period.

3. Hydrological modelling framework

In order to test the possibility to mitigate the basin vulnerability and to reduce both flooding

1 and CSO risks, the impact of virtual green roofs has been assessed. Firstly, the studied basins

2 have been modelled to simulate their current response to rainfall. Secondly, this model was

3 used with a specific module representing green roof hydrological behaviour previously

4 developed and presented in details in Versini *et al*. (2014). Finally, the potential for green

5 roofing has been defined at the sub-basin scale by combining several geographic data, this

6 potential is used to compute realistic green roofing scenarios.

7

3.1 Rainfall-runoff simulations with SWMM

9 Both basins have been represented in the Storm Water Management Model (SWMM, see

10 Rossman, 2004) which is a dynamic rainfall-runoff model especially developed for

11 urban/suburban areas by the United States Environmental Protection Agency (EPA). Both

12 sewer networks including junction nodes, conduits, and specific infrastructures (weir, orifice,

13 storage unit …), have been designed to simulate and estimate the hydrological behaviour of

14 the Châtillon and Boulogne-Billancourt basins. As SWMM is a semi-distributed model, each

15 basin is divided into several sub-basins onto which the water balance is computed (see Figure

16 2).

17 In order to reproduce correctly the hydrological behaviour of both studied basins,

18 SWMM representations have been tested on past events and compared to discharge

19 observations. In the Châtillon basin, where no continuous measurements were available,

20 simulations have been performed on 3 rainfall events (total precipitation higher than 12 mm).

21 SWMM simulations appeared to be excellent with a good representation of the peak

22 discharges and a significant Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) higher than

23 0.85. The Boulogne-Billancourt basin simulation was evaluated by a Nash-Sutcliffe efficiency

24 equal to 0.65 over the 2010-2011 time period. As every peak discharge was well represented,

25 it seems the efficiency deteriorated because of the poor representation of dry weather inflows.

8

1 Some examples of these simulations are illustrated in Figure 2: one of the 3 rainfall events

2 available on the Châtillon basin and the most severe rainfall event for the Boulogne-

3 Billancourt basin. These results show that observations and simulations match very well at the

4 event scale.

5

6 *3.2 Presentation of the green roof module*

7 The SWMM module called "Bio-retention Cell" has been significantly modified to simulate

8 the hydrological response of green roofs. This module is based on the model developed by

9 Berthier et al. (2010, 2011) representing each layer of green roof infrastructure (vegetation,

10 substrate and drainage) by 3 different reservoirs. The model parameters have been adjusted by

11 using an experimental green roof setup on the site of CETE Ile-de-France in Trappes (45 km

12 South-West from Paris, France).

13 The whole area of the CETE roof (about 400 m²) was split into several compartments

14 (35 m²) differentiated by their type of green roof (type of vegetation, substrate thickness, type

15 of drainage). A detailed presentation of the experimental site is available in Gromaire et al.

16 (2012). The reservoir model has been especially adjusted (for more details, please refer to

17 Versini et al., 2014), for two configurations comprising an extensive vegetation (sedum), a

18 substrate layer and a drainage layer with expanded polystyrene. Both green roof

19 configurations differ in the substrate depth. For the first one, called SE3Y, the thickness is

20 3 cm and for the second one, called SE15Y the thickness is 15 cm.

21 Meteorological and hydrological data (time step of 3 minutes) compiled from June 2011

22 to July 2012 have been used to calibrate and validate the model. Satisfactory results were

23 obtained for both configurations, especially for the largest rainfall events. Dynamics of runoff

24 were well reproduced with a Nash-Sutcliffe efficiency close to 0.8 at the storm event scale.

25 Moreover, the total water balance was correctly respected with an error in volumes close to

1   10% (this underestimation seems to be related with the overestimation of evapotranspiration

2   but do not affect the representation of peak discharges). Some of these performances are

3   illustrated in Figure 3, where the cumulative runoff and a couple of storm events (one in

4   winter and one in summer) are depicted for SE15Y configuration.

5   Finally, as the green roof module and SWMM basin configurations provide very

6   satisfactory results, they have been combined for testing the green roof impact on flooding

7   and CSO issues. The green roof module is applied at the sub-basin scale on an area

8   representing the total green surface (not at the building scale).

9

3.3 Evaluation of a green roofing potential

3.3.1 Definition

The potential of green roofing is estimated by combining land use (IAU-IDF, 2008) and

building data contained in BD TOPO® (IGN, 2011). The hypothesis has been made that

buildings belonging to some specific classes (collective housing, industrial and economic

activities, public buildings) could be easily implemented with green roofs (assuming that

these roofs are mainly flat). In each class, the roof areas have been deduced by identifying the

building areas from the second database (BD TOPO®).

    Finally, the potential of green roofing is defined as the percentage of the total sub-

basin area that could be covered by such technology. It is a high estimation of the real green

roofing potential since it assumes that all selected buildings roofs: (i) are flat and without any

other equipment (sky-domes, technical materials), (ii) can effectively and technically be

"greenable". Note that the assumption on flat roofs is consistent with both cities urbanism.

These potentials also represent a maximum value. Green roofing scenarios will be deduced by

selecting a part of this potential.

10

1 *3.3.2 Spatial distribution on the studied basins*

2 The methodology has been applied to both case studies and the results are illustrated in Figure

3 1. The potential of green roofing appears to vary significantly from one sub-basin to another.

4 An average green roofing potential value of 20% of the total catchment is calculated for

5 Châtillon basin. The downstream part of the basin (where individual housing are located) is

6 characterized by a low potential, close to 10%, whereas almost all the sub-basins located

7 upstream from the Boulevard de Vanves have a higher potential, locally reaching more than

8 50%. The green roof potential is higher and more spatially homogeneous on the Boulogne-

9 Billancourt basin. The average green roofing value is 29.1% and ranges from 5% in the south

10 part (which is currently a former industrial site) to 45% in the central part (where collective

11 housing and economical activities are concentrated).

12

13 **4. Study of Green roof impacts**

14 *4.1 Methodology*

15 For both studied basins, different scenarios of green roofing have been provided. They are

16 based on the potential of green roofing computed at the sub-basin scale. These scenarios

17 correspond to the covering of 12.5, 25, 50 and 100% of the previously defined green roofing

18 surface by SE3Y and SE15Y configurations. In SWMM, these green roof surfaces have been

19 subtracted from the impervious areas at the sub-basin scale. The green roof module,

20 previously integrated into SWMM, is used to compute runoff for these particular surfaces.

21 Acting in parallel, discharges computed for every contributing surface are added to provide

22 the total sub-basin response.

23   Precipitation time series on the 1993-2011 time period have been used to simulate the

24 hydrological behaviour of both basins. Such a long period seems sufficient to capture current

1   events (peak discharge and monthly overflowed volumes) characterized by a return period

2   lower than 10 years. For both basins, 35 storm events for which sewage problems occurred

3   have been analysed to see the possible impact of green roofs at the event scale. The

4   accumulated rainfalls of these events reached 2.6 to 120 mm (representing an intensity of 2.5

5   to 41 mm per hour). Regarding the Intensity-Duration-Frequency (IDF) curves, these events

6   are characterized by some return periods ranging from one month to more than 10 years.

7   Before being used, potential evapotranspiration data have been adjusted by using a coefficient

8   calibrated on the experimental site (0.5 in winter and 0.7 in summer for SE15Y for example).

9   Since both studied basins are exposed to a different issue (flooding and CSO), a

10 specific framework has been defined for each case:

11 •   In the Châtillon basin, which is affected by flooding, the peak discharge flowing

12   through the Boulevard de Vanves has been studied and the return period of annual

13   maximum peak discharge has been particularly calculated. The corresponding mid-

14   basin (100 ha) is located downstream of the Boulevard de Vanves.

15 •   For the Boulogne-Billancourt basin, which is affected by CSOs, the volumes

16   overflowing into the Seine River have been studied. The analysed value represents the

17   cumulative overflowed volumes to the receiving environment by the different outlets

18   located around the basin (see Figure 1). As these overflows are very usual, the

19   frequency of the monthly overflowed volume has also been calculated.

20 The resulting hydrological indicators (simulated peak discharges and overflowed volumes)

21 have been computed for the different green roofing scenarios. Then, they have been compared

22 to the values corresponding to the current situation (without green roof).

23

12

4.2 Presentation of the results

Simulation results are synthesised in the following sub-sections. First the general impact and scale effect are studied, then the results concerning flooding and combined sewage overflow issues are presented.

4.2.1 General impact on urban runoff and scale effect

Results are synthesized in Table 1. Firstly, it has to be noticed that there is no significant difference between the results obtained for SE3Y and SE15Y green roof configurations. The influence of the total covered area appears to be more important than the substrate thickness. The decrease in total runoff volume, peak discharge or overflowed volume due to green roofing obviously appears to be higher for SE15Y, but this difference is stronger for the lowest rainfall events. In fact, retention depends on the amount of moisture lost by evapotranspiration prior to rainfall intensity. This has also been noticed on the experimental green roof setup in Trappes and in previous studies (Voyde *et al.,* 2010, Versini *et al.*, 2014). For this reason and for a question of clarity, only the results provided for SE15Y are represented in the next figures (3, 4, 5, and 6).

The total annual runoff volume drained by each basin has been computed for every year of the studied time period (not represented here). The impact of green roofs appears to be quite marginal at the annual scale. The runoff volume reduction ranges from 0.1% (for a coverage of 12.5% of the green roofing potential) to 6% (for a coverage of 100%) on the Châtillon basin. As the average green roofing potential is 20%, these values are quite low. The influence of green roofs is more significant for the Boulogne-Billancourt basin: here the runoff volume reduction ranges from 0.1% to 14% depending on the green roofing scenarios and the considered year. The reduction seems to be proportional to the green roofing potential

13

covered.

No 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 and not on the size of the three entities (see Figure 5). A low potential has to be compensated by a higher percentage of covering in the same proportion. As both basin and mid-basin are characterized by a similarly 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 of 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 of 60% for peak flow and 45% for runoff volume (for the 100% SE15Y scenario). It should be noted that a low covering of the potential (25%) appears to be enough to reduce significantly the peak discharge (of about 15%).

4.2.2 Impacts on flooding (Châtillon basin)

The simulated peak discharges appear to be influenced by the implementation of green roofs when large roof surfaces are covered. The statistical distribution of annual peak discharge represented in Figure 4 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 the considered return period. When 100% of the potential is covered, the decrease in peak discharge can reach up to 35%. The performance of green roof is also to be reduced for the larger events. For these cases, the substrate is at field capacity and cannot infiltrate anymore. The effect of the finite retention capacity was already mentioned in previous studies (Carson *et al.*, 2013; Fassman-Beck *et al.*, 2013). Moreover, a seasonal effect

14

1   can be seen. For the reason mentioned above (the substrate is at field capacity), green roof has

2   less impact in winter than in summer.

3   The simulated discharge time series for the basin outlet is also represented for the

4   particular storm event of June 2009, for which the value was over the threshold of 5 m^3/s

5   (Figure 4). As for the statistical distribution, a significant decrease in peak discharge (about

6   20%) only occurs when almost 50% of the potential is covered (a decrease in 35% is noticed

7   for 100% of the potential). Nevertheless, a potential coverage (12% or 25%) is enough to

8   reduce the peak discharge to below 5 m^3/s and theoretically avoid flooding (see also Figure

9   4).

10

11   *4.2.3 Impact on Combined Sewage Overflow (Boulogne-Billancourt basin)*

12   Monthly volumes of CSO have been computed for the complete time series. Their statistical

13   distribution is illustrated in Figure 6. Whatever the green roofing scenario, the distribution is

14   modified from the normal values to the rarest ones. The overflowed volume is completely

15   avoided for the more common events (return period lower than 2 months) when 100% of the

16   potential is covered. For less frequent events (2 months < T < 1 year), CSO volumes can be

17   divided by two in the same circumstances. Intermediate scenarios (50% of the potential

18   covered) provide a 30% reduction of these volumes. Note that the reduction in CSO volume

19   seems to be higher for the lowest frequencies.

20

21   Regarding the results for the 35 studied events (Figure 6), the covering of only 12.5% of

22   the potential seems to produce only a low impact in terms of overflowed volume reduction

23   (an average decrease about 7.6%). The covering of 50% generates an average decrease about

24   35%, whereas the covering of 100% induces a significant decrease reaching 60% of the CSO

1 volume.

2

3 **5. Discussion**

4 These encouraging results are based on a number of implicit hypotheses and

5 limitations that are worth discussing:

6 • Optimistic estimation of the green roofing potential: as described in this paper, the

7 methodology implemented to estimate the potential of green roofing at the sub-basin

8 scale probably overestimates the real potential. It is assumed that all buildings

9 belonging to the selected land use categories can effectively be covered by green roof,

10 meaning that they have flat roofs, without impeding micro-structure and for which the

11 implementation of green roof is technically possible and not already implemented.

12 Although the green roofing of slightly sloping roofs may be possible, scenarios based

13 on the covering of 100% of the defined potential are clearly unrealistic. Nevertheless,

14 they illustrate the potential of such structures and encourage the implementation of

15 green roofs for future rehabilitation and developing projects. The results obtained for

16 intermediate scenarios (covering of 25 to 50% of the potential) demonstrate the

17 covering of a significant -but more realistic- part of roof surfaces can provide

18 satisfactory improvement in terms of urban runoff management. Moreover, this study

19 has been conducted by using traditional green roofs. The use of regulated ones – as

20 encouraged by the Hauts-de-Seine County – could still improve their performance by

21 storing more water in the drainage roof structure.

22 • Short time period for the calibration of the hydrological model: hydrological model

23 parameters have been adjusted using one year of observed discharge. Nevertheless,

24 from June 2011 to July 2012, no severe events were observed. That means the model

16

has been developed to reproduce common events (characterized by a return period lower than 1 year), 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 the conclusion that the implementation of green roofs 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 cannot be generalized and transferred to other locations. Indeed, they depend on the basin configuration, especially in terms of green roofing potential but also on the geometry. In different cases, concomitance problems (when a sub-basin response slowed by green roof coincides now with the response of another sub-basin and finally produce an higher discharge) could occur.

6. 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 rainfall-runoff 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 result in a 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 lower covered area (25 to 50 % of the identified potential), more representative of the reality, is expected to partially reduce the studied problems. It has also appeared that substrate thickness is not really significant regarding the impacts noted at the basin scale.

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. Based on this study, the following conclusions can be provided. One hectare of green roof allows the retention of 4500 m^3 per year (representing 450 mm of precipitation). At the basin scale, if 10% of the basin area is covered by green roof, peak discharge is reduced by 16% and overflowed volume by 20%. It also seems that green roof is more efficient in reducing the overflowed volumes than flooding.

These results encourage the large implementation of green roofs to locally reduce sewage network overflows. Combined with other stormwater source controls and/or retention infrastructures, green roofs could participate to significantly reduce the quantity of water flowing into the sewage network during storm events. In addition to thermal and environmental benefits, green roofs 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 implementation of green roofs in the future.

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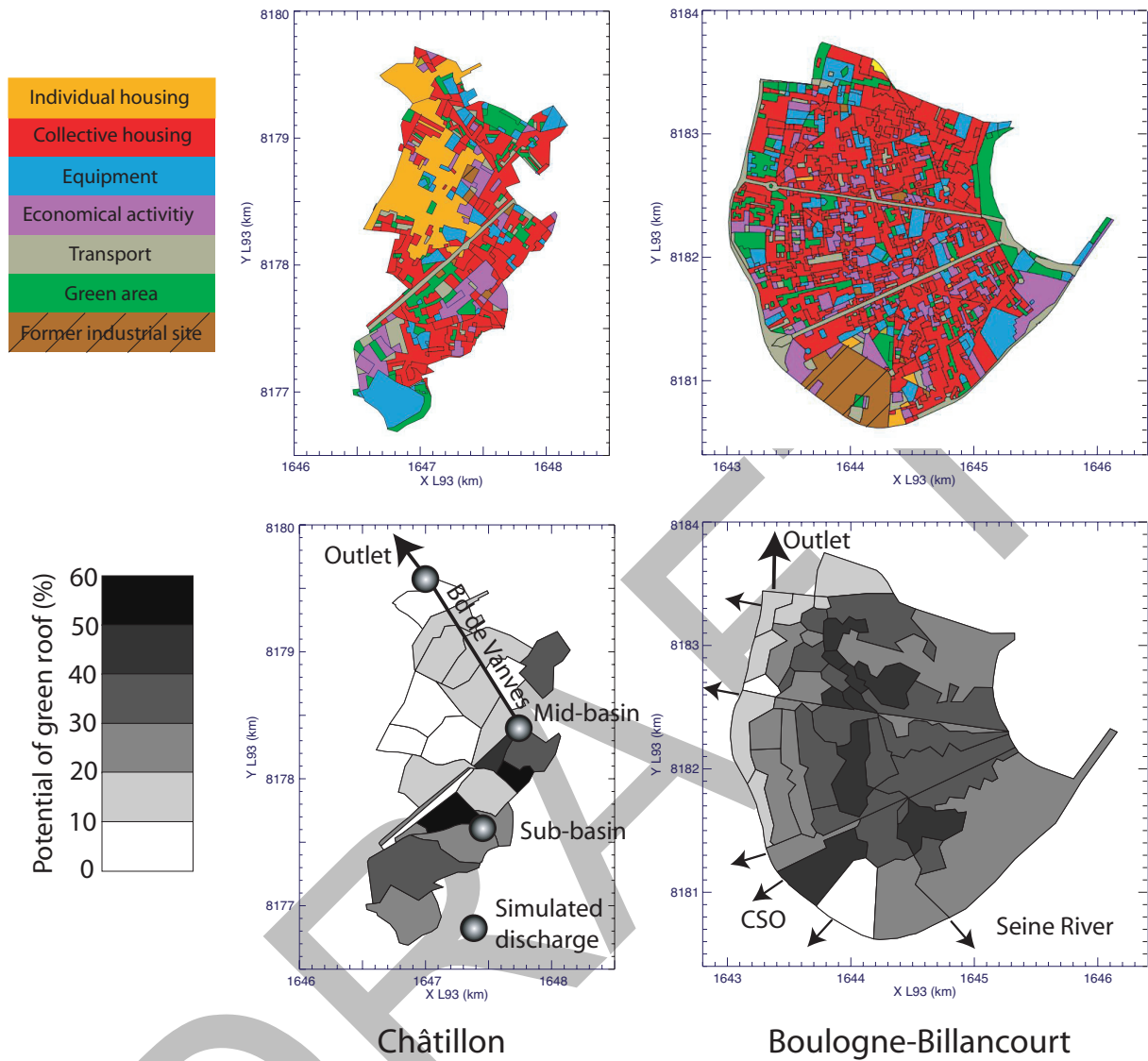47

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1 **Table**
2

3 Table1. At the annual scale, runoff volume reduction (min/mean/max) is computed for every

4 green roofing scenarios on both studied basins (ΔVtot expressed in %). At the event scale,

5 peak discharge reduction (ΔQp) is indicated for Châtillon and overflowed volume reduction

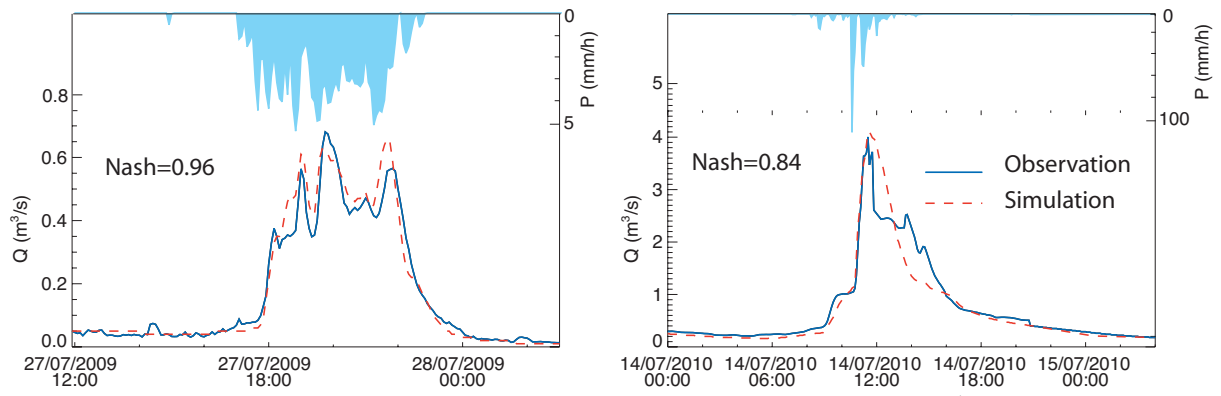6 (ΔVcso) is indicated for Boulogne-Billancourt basin.

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Figures

2

3 Figure 1. Spatial distribution of land use (top) using MOS with 11 categories (IAU-IDF,

4 2008) and green roofing potential (bottom) for Châtillon (left) and Boulogne-Billancourt

5 (right) basins. The locations of management issues (flooding and CSO) are also represented.

6

1

2 Figure 2. Comparison between observations and SWMM simulations for Châtillon (left) and
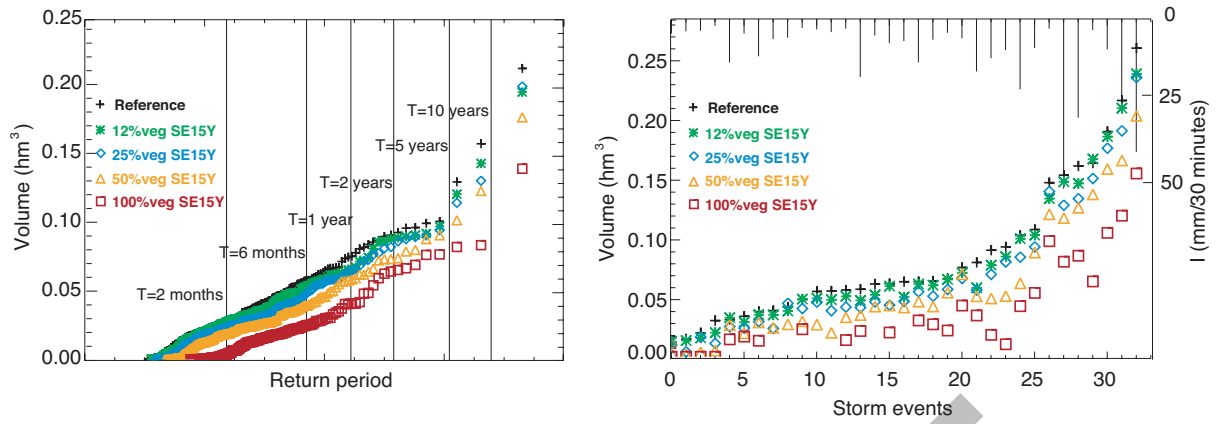
3 Boulogne-Billancourt (right)
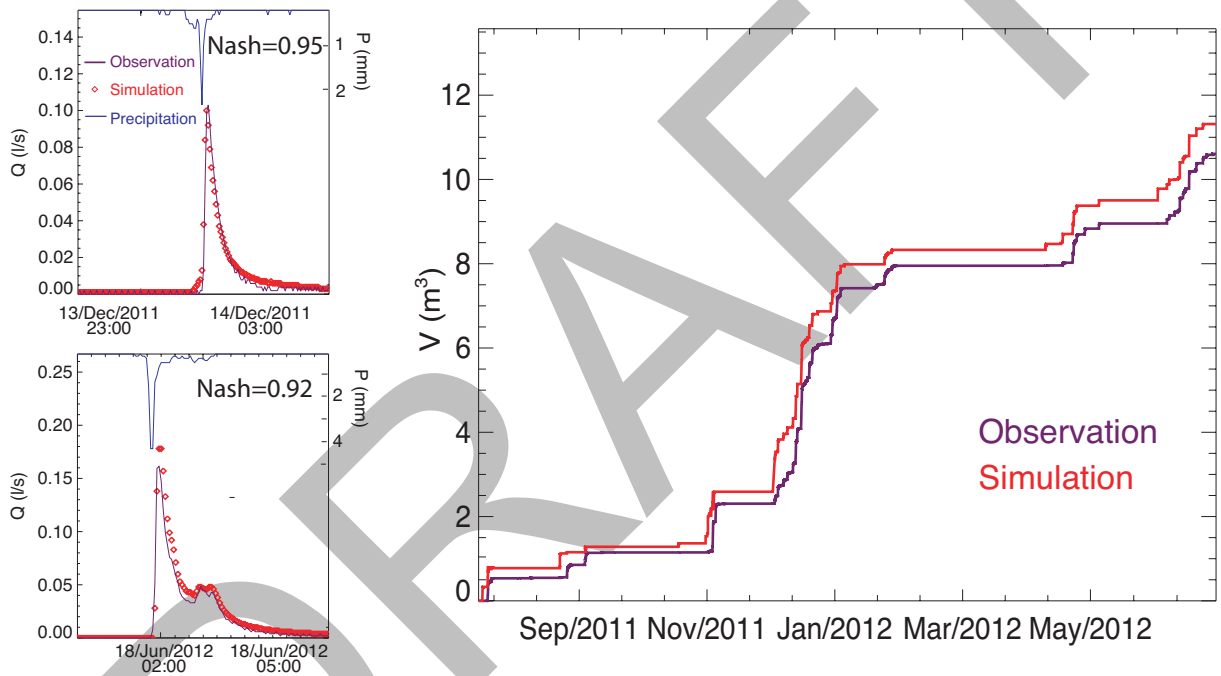
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5 Figure 3. Comparison between observed and simulated discharges for the SE15Y

6 configuration. Two storm events are depicted on the left (one in winter and one in summer).

7 The cumulative runoff is represented on the right.

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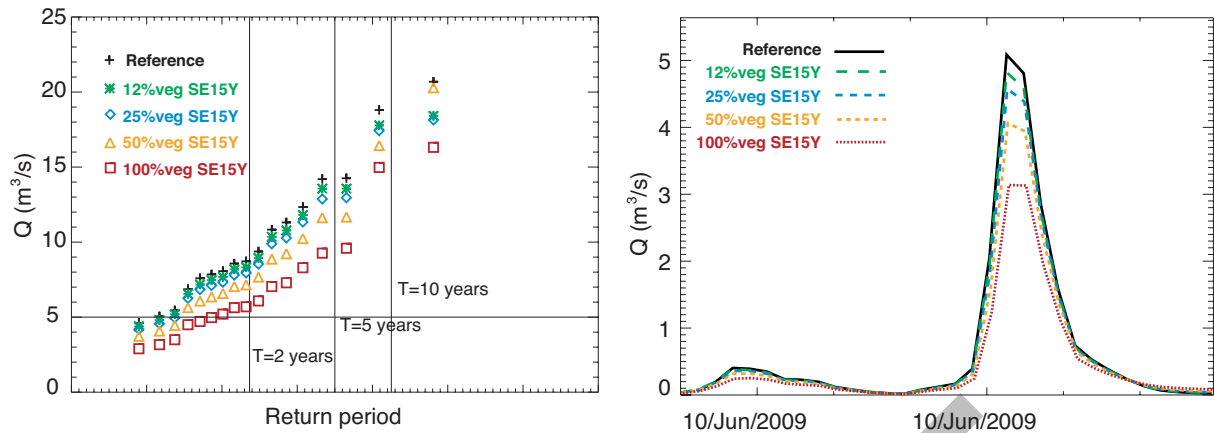
Figure 4. Results of the SWMM simulations for Châtillon basin by using the different green

roofing scenarios: the statistical distribution of annual peak discharge is represented on the

left (5 m3/s threshold is indicated) and the storm event of June 2009 is represented on the

right.

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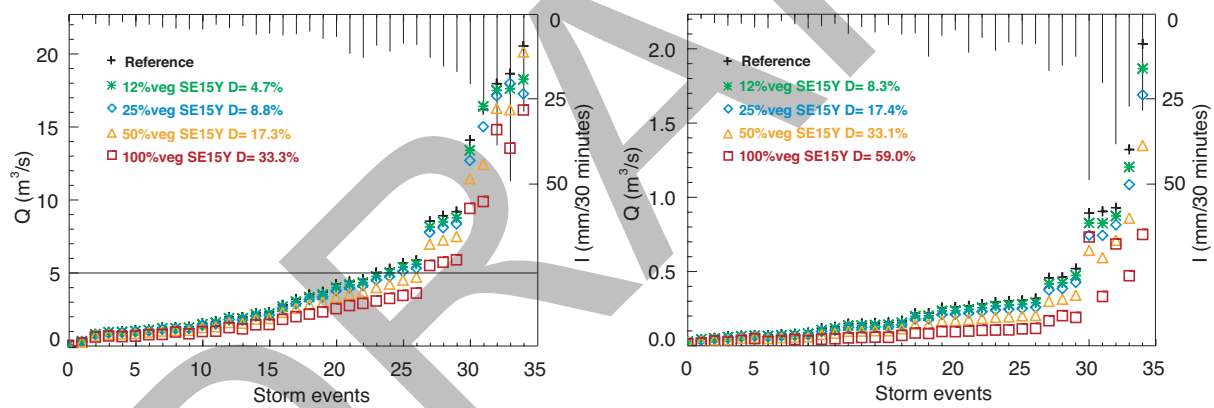
Figure 5. Results of the SWMM simulations for Châtillon basin by using the different green

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. Bars at the top represent

rainfall intensity.

Figure 6. 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).