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1 **Assessment of the hydrological impacts of green roof: from building**  
2 **scale to basin scale**

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16

17 **Abstract:**

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

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

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

41  
42 **Keywords:** Green roof, hydrological modelling, SWMM, flooding, sewage network

43 **1-Introduction**

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

51 Such a success is part of the general policy of urban areas revegetation and can be  
52 explained by two main reasons. First, roof areas represent a significant part of the  
53 surfaces of city centres where no space is available for new infrastructures (about 40-  
54 50% of the impervious areas, cf. Dunnett and Kingsbury, 2004). Secondly, from an  
55 architectural point of view, green roofs may contribute to enhance the aesthetic value of  
56 buildings, but also to reduce heat island through increasing evapotranspiration  
57 (Takebayashi and Moriyama, 2007; Santamouris, 2012), to improve the quality of the  
58 air (Banting *et al.*, 2005), to protect biodiversity (English Nature, 2003) and to manage  
59 urban runoff.

60 This last point - urban runoff management – is a significant argument to promote the  
61 development of green roof. Indeed, in order to cope with urbanization and its related  
62 problem of space, green roofs –as well as porous pavements, harvesting tanks,  
63 soakaways or ponds- are part of the so called stormwater Source Control (SC) which  
64 has gained relevance over traditional sewer approaches (Urbonas and Jones, 2002;  
65 Delleur, 2003; Petrucci *et al.*, 2012). The principle of SC is to develop, simultaneously  
66 to urban growth, facilities to manage stormwater at a small-scale (about 10<sup>2</sup>–10<sup>3</sup> m<sup>2</sup>) to

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

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

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

89 Voyde *et al.* (2010) instrumented six hydraulically isolated plots of about 10-50 m<sup>2</sup> on  
90 the Auckland University (New Zealand) during one year. These plots differed according

91 to their substrate types (expanded clay, zeolite and pumice) and depths (50 or 70 mm).  
92 Except for one specific plot where coconut coir fibre was implemented in the sedum  
93 mat, there was no statistically significant difference in the hydrologic response from the  
94 three different substrate types. During the year-long experiment, 66% of precipitation  
95 was retained and a peak flow reduction ranging from 31% to 100% (median of 93%)  
96 was observed. Moreover, no statistically significant season-related variations were also  
97 recorded for either rainfall or runoff response. On the same site, additional data (2  
98 years) were analysed by Fassman-Beck *et al.* (2013) and similar results in terms of  
99 water balance were obtained. Nevertheless, statistically significant seasonal variation  
100 was observed, demonstrating the importance of long-term monitoring.

101 A larger surface was covered by green roof in Genoa (Italy) where about 350 m<sup>2</sup> were  
102 divided in two plots, each one comprising a substrate of 200 mm and drainage layer  
103 (Palla *et al.*, 2011) differentiated according to their substrate mix. At the event scale, the  
104 study, carried out over 6 months, showed a retained volume varying between 10 and  
105 100% (average of 85%), and a peak flow reduction ranging from 80 to 100% (average  
106 of 97%).

107 Additional studies can be mentioned: Monterusso *et al.*, 2004 ; Bengtsson *et al.*, 2005 ;  
108 Dunnett *et al.*, 2008 ; Gregoire and Clausen, 2011 among others. They all conclude, and  
109 sometimes contradictorily, that green roof response appears not to be link to one only  
110 factor. These numerous contributions show several parameters may have an impact on  
111 hydrological response such as rainfall accumulation and intensity (Carter and  
112 Rasmussen, 2006 ; Simmons *et al.*, 2008), the climatic conditions, seasonality (Mentens  
113 *et al.*, 2006 ; Villarreal, 2007), the antecedent conditions (Bengtsson *et al.*, 2005 ;  
114 Denardo *et al.*, 2005), and to a lesser extent, the substrate species and the depth or roof  
115 slope (Villarreal and Bengtsson, 2005 ; Getter *et al.*, 2007). A detailed review on the

116 influence of these parameters is available in Berndtsson (2010). It has also to be noticed  
117 that recent studies conducted over a longer time period (Carson *et al.*, 2013; Fassman-  
118 Beck *et al.*, 2013) show that rainfall depth appears to be the dominant factor in retention  
119 performance.

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

129 The SWMS\_2D model (Šimůnek *et al.*, 1994), based on Richards' law and the Van  
130 Genuchten–Mualem functions, was also applied to simulate the variably saturated flow  
131 of an experimental green roof system (Palla *et al.*, 2009). Applied on 8 rainfall events,  
132 the model adequately reproduced the hydrographs, as demonstrated by the limited  
133 relative percentage deviations obtained for the total discharged volume, the peak flow,  
134 the hydrograph centroid and the water content along the vertical profile.

135 Simplified procedures were used to model green roof at a greater scale than the building  
136 one. Palla (2008a) used the Soil Conservative Service (SCS) Curve Number (CN,  
137 Mockus, 1957) as infiltration model in an aquifer system to simulate green roof  
138 response at the catchment scale in the Storm Water Management Model (SWMM,  
139 Rossman, 2004). It was calibrated using results from a small size system realized in

140 laboratory then applied on a 18 years simulation period. It was also the case in Carter  
141 and Jackson (2007) where the SCS infiltration method was used to simulate green roof  
142 response with a CN value equal to 86. Using synthetic precipitation events they  
143 evaluated the impact of a widespread green roof application in an urban watershed.

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

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

159 The paper is structured as follows: Section 2 presents the specific model developed to  
160 estimate green roof hydrological response. Section 3 describes the studied basin, the  
161 geographical and meteorological data used. Section 4 presents the modelling framework  
162 and the methodology used in this study. Assessment of hydrological impacts of a green  
163 roof at the roof scale and at the basin scale is presented in Section 5. From a more

164 operational point of view, Section 6 analyses the conditions of these hydrological  
165 impacts on stormwater management and how they can be predicted by taking into  
166 account several hydrometeorological variables. Finally, Section 7 discusses the  
167 hypothesis made in the study and Section 8 summarizes the main results and concludes  
168 on future improvements and possible applications of green roofs for operational issues.

169

## 170 **2- Green roof modelling**

### 171 2-1 Experimental setup

172 An experimental green roof was built on the site of the CEREMA in Trappes (45 km  
173 South-West from Paris, France). The area of an already existing roof was split into 6  
174 different plots of 35 m<sup>2</sup> (7X5 m). These plots were covered by a specific green roof  
175 infrastructure presenting different configuration in terms of vegetation (sedum or grass),  
176 substrate depth (3 or 15 cm) and drainage layer (expanded polystyrene or lava stone).  
177 Rainfall and discharge were continuously monitored at each plot from June 2011 to  
178 August 2012. Rainfall was measured with a tipping bucket raingauge located on the  
179 roof, with a resolution of 0.1 mm. Discharge from each plot was measured continuously  
180 at the outlet of the downspouts with custom-made PVC tipping bucket, having a  
181 resolution of 0.01 mm (i.e. a volume of 350 ml per tip over the 35m<sup>2</sup> plot). Time series  
182 were aggregated to 3 minutes intervals.

183 In this study, observations from two specific configurations of green roof were used.  
184 They combine an extensive vegetation layer made with a mix of Sedum species (S.  
185 Album, S. Sexangulare, S. Reflexum, S. Kamchatikum, S. Spurium, S. Acre), a substrate  
186 with lapillus, peat and green compost (organic part represents 3.4% in mass of the  
187 substrate), a filter layer (geotextile) and a drainage layer with expanded polystyrene of



188 4 cm depth. The two green roof configurations differ in terms of the depth of the  
189 substrate. For the first one, called SE3Y, the thickness is 3 cm and for the second one,  
190 called SE15Y, the thickness is 15 cm.

191 During the study time period, around 100 rain events (for a total rainfall of 827 mm)  
192 were observed for which rainfall accumulation was higher than 1 mm. They were all  
193 quite “soft” events and characterized by low return periods (the highest is about 1 year).  
194 These events produced runoff in most cases for green roof SE3Y plot (59% of the  
195 events) and less often for SE15Y one (45% respectively). It appeared the volumetric  
196 runoff coefficient for both green roof configurations varied significantly from an event  
197 to another, ranging from 0 to 1 with an average value of 0.17 for SE3Y and from 0 to  
198 0.82 with an average value of 0.11 for SE15Y respectively. As mentioned in a previous  
199 study (Voyde *et al.*, 2010), retention efficiency seems to decrease as storm depth  
200 increases and as antecedent conditions reveal a high level of moisture in the substrate.  
201 For the most significant events, volumetric runoff coefficients are quite equal between  
202 both configurations and can occasionally be higher for SE15Y configuration if the  
203 substrate already contained water resulting from a previous event. Due to the short  
204 number of events, for now no definitive conclusion can be stated.

205 Note that more details on the experimental site is available in Gromaire *et al.* (2013). In  
206 this study, this data are only used to develop and calibrate the hydrological model.

207

## 208 2-2 Presentation of the hydrological model

209 Storm Water Management Model (SWMM version 5.0, see Rossman, 2004) has been  
210 used in this study. It is a dynamic rainfall-runoff model especially developed by the  
211 United States Environmental Protection Agency (EPA) for urban/suburban areas. The

212 sewer network including junction nodes, conduits, and specific infrastructures (weir,  
213 orifice, storage unit ...), is designed to simulate and estimate the hydrological behaviour  
214 of a typical basin. As SWMM is a semi-distributed model, each basin is divided in  
215 several sub-basins on which the water balance is computed. The SWMM module called  
216 “Bio-retention Cell” has been used and significantly modified to simulate the  
217 hydrological response of the instrumented green roofs as this original module was not  
218 able to do it accurately. Modifications are inspired by the model developed by Berthier  
219 *et al.* (2011) representing each layer of green roof infrastructure (vegetation, substrate  
220 and drainage) by 3 different reservoirs (Figure 1). The main modifications concern the  
221 vegetation reservoir (that produces discharge only when the field capacity is reached),  
222 the soil reservoir (by using the saturated hydraulic conductivity to produce discharge  
223 and by splitting its output into two components), and a transfer function that has been  
224 added to every reservoir output. This model is presented in detail in the following  
225 sections (note that simulated discharges, precipitation, simulated evapotranspiration and  
226 simulated reservoir levels are all expressed as water levels (mm) over the 35 m<sup>2</sup> plot).

227

228 A first reservoir models the vegetation layer which is supposed to retain a small amount  
229 of rainfall. If the storage capacity of the vegetation layer is lower than the precipitation,  
230 the complementary part of the precipitation ( $Q_{veg}(t)$ ) infiltrates into the substrate:

$$231 \quad Q_{veg}(t) = \max[P(t) - (H_{veg} - N_{veg}(t)), 0] \quad (\text{Eq. 1})$$

232 Where  $H_{veg}$  is the vegetation reservoir depth (i.e. the maximum water depth stored by  
233 the vegetation layer),  $N_{veg}(t)$  is the vegetation reservoir level a time  $t$ , and  $P(t)$  is the  
234 precipitation rate.

235 The second reservoir represents the substrate layer which can produce surface runoff  
 236 when it is saturated ( $Q_{sat}(t)$ ) when it is no longer able to infiltrate water (it has to be  
 237 noticed that this rare situation was not observed on Trappes experimental sites, even for  
 238 the thinnest substrate):

$$239 \quad Q_{sat}(t) = \max[Q_{veg}(t) - (f_{sub} - \theta(t)) \times H_{sub}, 0] \quad (\text{Eq. 2})$$

240 Where  $f_{sub}$  is the substrate porosity, representing the soil fraction where water can be  
 241 stored,  $\theta(t)$  is the volumetric water content at time  $t$ , and  $H_{sub}$  the substrate depth.  
 242  $N_{sub}(t) = H_{sub} \times \theta(t)$  represents the substrate reservoir water level at time  $t$ .

243 The substrate reservoir produces an output discharge ( $Q_{sub}(t)$ ) when the water content  
 244 in the substrate is greater than the field capacity:

$$245 \quad Q_{sub}(t) = \max\left[\frac{K_{sat}}{\Delta t \times H_{sub}} \times (\theta(t) \times H_{sub} - FC), 0\right] \quad (\text{Eq. 3})$$

246 Where  $K_{sat}$  is saturated hydraulic conductivity (in mm/s),  $\Delta t$  is the time step (in s) and  
 247  $FC$  is the field capacity (in mm).

248 A small fraction  $Q_{frac}(t)$  of the output discharge is transferred to a routing reservoir  
 249 representing the water temporary stored in the drainage layer:

$$250 \quad Q_{frac}(t) = Q_{sub}(t) \times \left[ 1 - (1 - f_{dra}) \times \left( \frac{N_{dra}(t)}{H_{dra}} \right)^4 \right] \quad (\text{Eq. 4})$$

251 Where  $f_{dra}$  is the void fraction of the drainage layer,  $N_{dra}(t)$  is the routing reservoir  
 252 water level, and  $H_{dra}$  is the routing reservoir depth.

253 At the output of the substrate, a runoff  $Q_{dra1}(t)$  is directly available while the routing  
 254 reservoir produces a runoff  $Q_{dra2}(t)$ :

255  $Q\_dra1(t) = Qsub(t) - Qfrac(t)$  (Eq. 5)

256  $Q\_dra2(t) = N\_dra(t) + Qfrac(t) - H\_dra$  (Eq. 6)

257 Every contribution to the total discharge ( $Q\_sat(t)$ ,  $Q\_dra1(t)$  and  $Q\_dra2(t)$ ) are first  
 258 routed to the outlet using a transfer function based on Manning-Strickler equation  
 259 before being summed to  $Q\_tot(t)$ :

260  $Q\_rout(t) = \alpha \times Q^*(t)^{\frac{5}{3}} \times \frac{L}{S}$  (Eq. 7)

261  $\alpha = \frac{1.49}{R} \times \sqrt{p}$  (Eq. 8)

262 Where  $Q\_rout(t)$  is the routed discharge assessed from  $Q^*(t)$  ( $Q^*(t)$  represents  
 263 indiscriminately  $Q\_sat(t)$ ,  $Q\_dra1(t)$  and  $Q\_dra2(t)$ ),  $S$  and  $L$  are the width and the area  
 264 of the considered surface,  $R$  is the Manning roughness coefficient and  $p$  is the slope.

265 Evapotranspiration (ET) is estimated for each layer by using potential  
 266 evapotranspiration computed by the French Weather service (PET daily measures in  
 267 Villacoublay which is located 10 km from Trappes). The PET value is representative of  
 268 the evapotranspiration for a short and always irrigated grass. To be more realistic, this  
 269 data has been corrected by using seasonal water balances computed with experimental  
 270 data. PET data has also been adjusted by using a coefficient: 0.7 in winter and 0.9 in  
 271 summer for SE3Y, 0.5 and 0.7 for SE15Y respectively. During dry periods (it is  
 272 assumed that no evapotranspiration occurs during rain periods), water is  
 273 evapotranspired from the top to the bottom, starting with the vegetation reservoir:

274  $Eta\_veg(t) = Min(ET(t), N\_veg(t))$  (Eq. 9)

275  $Eta\_sub(t) = Min(Max(ET(t) - Eta\_veg(t), 0.), (H\_sub - WP) \times f\_sub)$  (Eq. 10)

276  $Eta\_dra(t) = Min(Max(ET(t) - Eta\_sub(t), 0.), N\_dra(t) \times f\_dra)$  (Eq. 11)

277 Where  $ET(t)$  is the estimated adjusted evapotranspiration,  $WP$  the wilting point,  
278  $Eta\_veg(t)$ ,  $Eta\_sub(t)$  and  $Eta\_dra(t)$  the respective simulated evapotranspiration for  
279 vegetation, substrate and drainage layers.

280 At the end of each time step, reservoirs are updated by taking into account the different  
281 inputs and outputs. A Modified Puls method is used for this purpose as proposed in the  
282 initial version of SWMM.

283 The majority of the parameters characterizing the three green roof layers are determined  
284 by their intrinsic properties (geometry of the structure, thickness of the substrate and the  
285 layer of drainage, slope...). Finally, only four parameters have to be calibrated,  
286 essentially according to substrate properties: porosity ( $f\_sub$ ), field capacity ( $FC$ ),  
287 saturated hydraulic conductivity ( $Ksat$ ) and roughness ( $R$ ).

288

289 2-3 calibration and validation procedures

290 Observed precipitation and discharge data compiled from June 2011 to August 2012 in  
291 Trappes have been used to adjust the model parameters for SE3Y and SE15Y  
292 configurations. This observation period was divided into two sub-periods: from June  
293 2011 to January 2012 for calibration and from February 2012 to August 2012 for  
294 validation. Both sub-periods contain a dry and a wet sequence. Wet sequences occurred  
295 in December 2011 (136 mm of the 472 mm have fallen during the calibration period)  
296 and in June 2012 (132 mm of the 345 mm have fallen during the validation period).

297 The model was calibrated by using a Rosenbrock procedure. Nash efficiency (Nash and  
 298 Sutcliffe, 1970) was selected and used as the optimization criterion to evaluate the  
 299 performance of the model (difference between observed and simulated discharges). It  
 300 was computed for non-zero values to focus the calibration on wet sequences:

$$301 \quad Nash = 1 - \frac{\sum_{i=0}^{n-1} (Q_{obs}(t_0 + i \times \Delta t) - Q_{sim}(t_0 + i \times \Delta t))^2}{\sum_{i=0}^{n-1} (Q_{obs}(t_0 + i \times \Delta t) - \overline{Q_{obs}})^2} \quad (\text{Eq. 12})$$

302 Where  $t_0$  is the initial time step,  $Q_{obs}(t_0 + i \times \Delta t)$  and  $Q_{sim}(t_0 + i \times \Delta t)$  are the observed  
 303 and the simulated discharge at time step  $t_0 + i \times \Delta t$ ,  $\overline{Q_{obs}}$  the average observed value and  
 304  $n$  the total number of time steps. Note that Nash criterion can be computed over a long  
 305 time period or over a single event.

306 An additional indicator, the difference between observed and simulated total runoff  
 307 volumes (absolute volume error), has also been computed:

$$308 \quad V\_error = \frac{(V_{obs} - V_{sim})}{V_{obs}} \times 100 \quad (\text{Eq. 13})$$

309 Where  $V_{obs}$  and  $V_{sim}$  are the observed and simulated total runoff volumes.

310 Satisfactory results were obtained for both green roof configurations for both  
 311 calibration/validation continuous time periods. Almost every observed peak discharge  
 312 was simulated and the highest peaks were particularly well represented. Nash  
 313 efficiencies computed over the calibration period were higher than 0.7 (0.72 for SE3Y  
 314 and 0.82 for SE15Y). This difference can be explained by the modest reproduction of  
 315 SE3Y small peaks that are not generated by the SE15Y configuration. Moreover,  
 316 volume errors showed that the water balance was correctly respected with some values

317 lower than 10% (9% for SE3Y and 5% for SE15Y). These figures were slightly lower  
318 on the validation period (Nash equal to 0.64 for SE3Y and 0.80 for SE15Y and volume  
319 error equal to 5% for SE3Y and 9% for SE15Y). This seemed to be related to an  
320 overestimation of evapotranspiration. In this case, runoff volume was underestimated  
321 and some small peaks were not reproduced by the model. As the estimated daily  
322 evapotranspiration values were not realistic, it is a weakness of the model which  
323 influenced the draining of the reservoir during periods without rain.

324 An additional validation procedure was also carried out at the rainfall event scale. The  
325 average individual Nash efficiency and volumetric criteria were computed for every  
326 event for which the observed precipitation exceeded 8 mm (14 events). Average  
327 individual Nash value was 0.56 for SE3Y (volume error equal to 17%) and 0.55 for  
328 SE15Y respectively (volume error equal to 11%). It has to be noticed that the best  
329 results were usually obtained for the most important events of the time period. The  
330 comparison between observed and simulated discharges for the four main events is  
331 plotted in Figure 2 (Note that the first event belongs to the calibration period, whereas  
332 the other ones belong to the validation period). It appears that dynamics of runoff were  
333 well reproduced by the model. For these events, individual Nash efficiency was higher  
334 than 0.8 for SE15Y configuration and quite lower for the SE3Y one because of a delay  
335 of few minutes in the simulated response. For both configurations, the peak intensity  
336 was particularly well simulated with an absolute error lower than 10% in most of the  
337 cases.

338 Calibrated parameters are reported in Table 1. As the model structure is based on a  
339 simplification of the physical phenomena, the calibrated parameters were not always  
340 close to the range of values that might be expected from physical principles alone.  
341 Sometimes quite different values were calibrated for the same type of green roof.”

342 Although they should be equal for both types of green roof configurations, Roughness  
343 ( $R=0.51$  for SE3Y and  $R=0.65$  for SE15Y) and saturated hydraulic conductivity  
344 ( $K_{sat}=104.7$  mm/h for SE3Y and  $K_{sat}=2.0$  mm/h) are different. While the SE3Y  
345 conductivity value is physically reasonable, the SE15Y one is very low, indicating the  
346 model's difficulty in representing the measured hydrological behavior with a simplified  
347 structure. This low value seems to be compensated by a lower Field Capacity (0.39 for  
348 SE3Y and 0.21 for SE15Y) or/and estimated evapotranspiration. As porosity ( $f_{sub}$ ) is  
349 only used in the  $Q_{sat}$  computation, it has not been possible to calibrate it on the study  
350 time period (no surface runoff was observed or/and simulated). The theoretical value of  
351 0.4 has also been used.

352 The aim of this simple model was to obtain an accurate and robust representation of  
353 green roofs' behaviour rather than an accurate representation of physics and parameters.  
354 Finally, despite small inconsistencies not affecting the representation of the main peak  
355 discharges, the results illustrate the ability of this new SWMM module to simulate  
356 green roof behaviour for both green roof configurations; particularly for the most  
357 important runoff that is the main point of interest in this study. Therefore, this model is  
358 used for this work to simulate the hydrological response of every building that could be  
359 covered by green roof at the basin scale. We also assume buildings' roofs are subject to  
360 the same conditions than Trappes ones in terms of geometric constraints (slope) and  
361 climate (French oceanic degraded climate).

362

### 363 **3-Case study: the Hauts-de-Seine county**

#### 364 3-1 Case study framework

365 The Hauts-de-Seine county is located west of Paris (France). It is a highly populated



366 and urbanized area (1.5 million inhabitants for a surface of 176 km<sup>2</sup>). The northern part  
367 is very urbanised and limited by the Seine River, whereas the southern part is less  
368 populated with the presence of several forests. The climate of the Hauts-de-Seine is very  
369 close to the rest of Paris Basin (including Trappes) with mild winters, frequent rainfall  
370 in autumn, mild spring and high summer temperatures with possible occurrence of  
371 intense rainfall. The average annual rainfall over the county is about 700 mm, and rather  
372 constant over the different months, whereas the decennial hourly rainfall is about  
373 35 mm.

374 Because of the rapid urbanization growth during the 90's and the difficulty to build new  
375 management infrastructures due to high density, stormwater network is very sensitive to  
376 intense precipitation which may cause local floodings. Since the beginning of 2000's,  
377 the local authority in charge of water management (Water Direction of the Haut-de-  
378 Seine county) has promoted mitigation solutions as Sustainable Urban Drainage System  
379 (SUDS). In this context, the Hauts-de-Seine county has set up a grant policy to promote  
380 regulated flat roofs and is also concerned with studying the impacts of existing and  
381 future green roofs on urban runoff in order to refine their approach in urban hydrology.  
382 Moreover, the implementation of green roofs is particularly interesting in this county  
383 because of the high development rate expected in this area over the next years.

384 Châtillon basin, chosen as case study, is located southeast of the Hauts-de-Seine county.  
385 It is a moderate urban basin of 2.37 km<sup>2</sup> characterized by a quite steep topography with  
386 an average slope of 3.5%. The downstream part of the basin is essentially covered by  
387 individual housing, whereas the upstream part is rather covered by collective housing  
388 and economical activities (See Figure 3-a). Due to this intense urbanization, the basin is  
389 also characterized by an average impervious coefficient of 55%. Châtillon basin is  
390 equipped with combined sewer network supplied by waste water produced by 29,500

391 equivalent inhabitants. Local floodings often occur along the Boulevard de Vanves (see  
392 Figure 3), a main road crossing the city center. The pipe along the Boulevard until the  
393 outlet is not large or/and steep enough to route the runoff during intense rainfall. Note  
394 that there is a weir downstream of the Boulevard de Vanves and the basin outlet  
395 receives water that passes over this weir. Only the water exceeding the weir level is  
396 routed to the basin outlet. According to Water Direction of Hauts-de-Seine county,  
397 flooding occurs when the discharge exceeds the limit value of  $4.7 \text{ m}^3/\text{s}$  at the outlet  
398 (called “flooding threshold” in the following).

399

### 400 3-2 Hydrometeorological data

401 Regarding the meteorological information, the Hauts-de-Seine county is well covered  
402 by a rather dense raingauge network. A continuous precipitation database from a rain  
403 gauge located close to the Châtillon basin has been provided by the Water Direction of  
404 the county. It covers a full time period from 1993 to 2011 with a time resolution of 5  
405 minutes. Note that, on this time period, the mean annual rainfall was 651 mm (snow is  
406 not considered) for a minimum of 435 mm in 2003 and a maximum of 935 mm in 2001.

407 54 storm events were extracted from this database. They correspond to those for which  
408 the simulated discharge exceeds the flooding threshold. These events differ from their  
409 maximal intensity (from 6.8 to 63.2 mm/h), duration (from 10 minutes to 8.5 hours) and  
410 total rainfall accumulation (from 7.4 to 112.8 mm). They are represented on the  
411 Intensity-Duration-Curve computed from Montsouris station located at 3 km from  
412 Châtillon. 90% of these events are characterized by a frequent return period (between 1  
413 month and 2 years, see Figure 4). Four storms have a return period exceeding 10 years  
414 and among them, one event appears to be particularly rare with an intensity equal to 58

415 mm/h for a duration of one hour. In addition, the four most significant events that  
416 occurred in Trappes during the 2011-2012 campaign (and plotted in Figure 2) have been  
417 reported in Figure 4. Three of these events are characterized by a return period lesser or  
418 equal to 6 months representing very frequent rainfall. The highest is characterized by a  
419 one year return period. That means the hydrological model has been calibrated to  
420 reproduce common events and we assume it is able to represent correctly rarer events  
421 characterized by more intense precipitation.

422 Note that evapotranspiration data computed by the French Weather service in  
423 Villacoublay were available for the same period and has been used as PET input (same  
424 data as those used to calibrate and validate the green roof module, Section 2).

425 No automatic continuous stream gauge station is located on Châtillon basin.  
426 Nevertheless, a campaign was conducted from April to June in 2009 to evaluate the  
427 discharge at the outlet. The response to three rainfall events was registered. They all  
428 correspond to a total precipitation higher than 12 mm.

429

### 430 3-3 SWMM calibration on the current situation of the basin

431 Châtillon basin has been modelled in SWMM to correctly reproduce its hydrological  
432 behaviour. Its modelling representation and parameterization was provided by the  
433 Hauts-de-Seine county that use it for operational issues. The basin is split into several  
434 sub-basins (characterized by an average area of 10 ha, see Figure 3). Each sub-basin is  
435 divided in two areas (an impervious area and an infiltration area). Green roof surface is  
436 deduced from the impervious area. Each discharge component (computed for remaining  
437 impervious area, green roof area and infiltration area) is routed and summed at the sub-  
438 basin outlet. Each sub-basin contribution is then routed in the drainage network by

439 using geometrical information of the pipes.

440 The Châtillon basin representation has been tested on past events. Simulations have  
441 been performed on three 2009 rainfall events for which temporal discharge observations  
442 were made. SWMM simulations (see Figure 5) are satisfactory for this kind of rainfall  
443 event with a good representation of the peak discharges and some Nash efficiencies  
444 higher than 0.85. Whereas these rainfall events are common ones –and in the absence of  
445 additional information and further validation/calibration on more severe events- it has  
446 been assumed that the model will be able to simulate the hydrological basin behaviour  
447 for more severe events (for which green roof effect will be lower).

448

#### 449 3-4 Green roofing scenarios

450 To estimate the potential of green roofing, land use (IAU-IDF, 2008) and building data  
451 (IGN, 2011) have been combined. Some specific classes of the land use database have  
452 been selected assuming green roof could potentially be implemented. The hypothesis  
453 has been made that every building belonging to these classes are mainly covered by flat  
454 roofs and therefore are able to become green roofs: collecting housing, industrial and  
455 economic activities, public buildings, equipment... In each class, the roof areas have  
456 been deduced by identifying the building areas from the IGN database.

457 Finally, the potential of green roofing is defined as the sub-basin area that could be  
458 covered by green roof (Figures 3-b and 3-c). It is a high estimation of the real green  
459 roofing potential since it assumes that all selected buildings are effectively covered by a  
460 flat roof, without micro-structure and where green roof can technically be implemented  
461 (and is not already implemented). These potentials also represent a maximum value for  
462 which green roofing scenarios will be deduced by selecting a part of it.

463 In the Châtillon basin, the potential of green roofing appears to vary significantly from  
464 one sub-basin to another (Figure 3) with an average value of 1.6 ha (representing 17%  
465 of the sub-basin area). The downstream part (where individual houses are located) is  
466 characterized by a potential close to 0 ha, whereas almost all the sub-basins located  
467 upstream to the Boulevard de Vanves have a higher potential locally reaching more than  
468 5.6 ha (corresponding to 50% of the basin area).

469 Different green roofing scenarios have been provided, based on the potential of green  
470 roofing computed at the sub-basin scale. They correspond, for every sub-basin, to the  
471 uniform covering of 12.5, 25, 50 and 100% of the green roofing potential with a SE3Y  
472 or a SE15Y configuration. In addition to these 8 green roofing scenarios, a scenario  
473 corresponding to the current situation without any green roof infrastructure is used to  
474 evaluate the impact of green roofing (called “Reference” for now on). In SWMM, the  
475 green roof surfaces are subtracted from the impervious areas at the sub-basin scale. The  
476 green roof module, previously integrated into SWMM, is used to compute runoff for  
477 these particular surfaces. Acting in parallel, discharges computed for every contributing  
478 surface are added to provide the total sub-basin response.

479

#### 480 **4-Methodology**

481 To assess the hydrological impacts of green roofs on urban runoff and to identify the  
482 main variables influencing these impacts, a two-step methodology has been established.

483 Firstly, the SWMM model has been applied at two scales: (i) on a virtual 35 m<sup>2</sup> green  
484 roof similar to the experimental site, (ii) on Châtillon basin. In both cases, the model  
485 was run continuously by using the 9 previously defined green roofing scenarios on the  
486 1993-2011 time period including the 54 rainfall events. Note that 12.5, 25, 50 and 100%

487 scenarios refer to the percentage of green roofing potential that is effectively covered at  
 488 both scales. As the virtual roof and basin are characterized by different green roofing  
 489 potential, the percentage of the total covered surfaces differs for both cases. Concerning  
 490 the virtual roof, the reference configuration represents a completely impervious surface;  
 491 the 100% green roofing scenario represents the current infrastructure set up in Trappes.  
 492 Concerning Châtillon basin, 12.5, 25, 50 and 100% scenarios refer to the coverage of  
 493 2.5, 5, 10 and 20% of the basin area.

494 For operational purposes, this study has been focussed on the hydrological impacts of  
 495 green roof. These impacts of green roof has been evaluated though the relative  
 496 difference in terms of peak discharge ( $\Delta Qp$ ) and runoff volume ( $\Delta V$ ) with the reference  
 497 situation for each rainfall event (expressed in percentage):

$$498 \quad \Delta Qp = \frac{(Qp_{-ref} - Qp_{-veg})}{Qp_{-ref}} \times 100 \quad (\text{Eq. 14})$$

$$499 \quad \Delta V = \frac{(V_{-ref} - V_{-veg})}{V_{-ref}} \times 100 \quad (\text{Eq. 15})$$

500 Where  $Qp_{-ref}$  and  $V_{-ref}$  refer to peak discharge and runoff volume computed for the  
 501 reference situation whereas  $Qp_{-veg}$  and  $V_{-veg}$  correspond to those computed for the  
 502 different green roofing scenarios.

503 As mentioned above, virtual roof and Châtillon basin are not characterized by the same  
 504 green roofing potential. Moreover, at the building scale, a roof is completely covered or  
 505 not by green roof in practice. In this study, the use of progressive covering scenarios  
 506 aims to compare the simulated hydrological impacts at both scales. The objective of this  
 507 comparison is to study how the impacts noticed at the roof scale (that can be completely  
 508 covered by green roof) can be transposed at the basin scale (that can only partially be

509 covered) taking into account the scale effect.

510

511 Secondly, the main variables influencing the hydrological impacts of green roof at both  
512 scales (in terms of peak discharge and runoff volume reduction) have been studied. The  
513 aim of this work was to compare and eventually to link and/or predict the hydrological  
514 impacts assessed at the roof and the basin scales.

515 In order to analyse how the rainfall event characteristics, but also the antecedent  
516 conditions, influence the green roof impact, the relationship between several  
517 hydrometeorological variables and the maximum reduction of runoff has been studied.  
518 Note that the maximum reduction corresponds to the larger peak discharge or runoff  
519 volume reduction obtained for the different green roofing scenarios. For each of the 54  
520 events, the computed hydrometeorological variables are: maximum 5, 30 and 60  
521 minutes precipitation intensity ( $I_{max5}$ ,  $I_{max30}$  and  $I_{max60}$ ), total amount of  
522 precipitation ( $P_{tot}$ ), rainfall event duration ( $Durat$ ), antecedent precipitation  
523 accumulated during the 15 previous days ( $P_{ant}$ ), and estimated soil saturation at the  
524 beginning of the event ( $SoilSat$ , represented as the level of the SE3Y and SE15Y  
525 substrate reservoirs). Note that every variable has been statistically normalised by  
526 subtracting the mean and dividing by the standard deviation for the remainder of this  
527 study. Results of the regression on normalized data allow easier comparison of  
528 coefficients to determine relative importance in their predictive power.

529 The direct correlation coefficient has been calculated between each  
530 hydrometeorological variable and each hydrological impact ( $\Delta Q_p$  and  $\Delta V$  for SE3Y and  
531 SE15Y). Then a multiple stepwise regression analysis (Brown, 1998) was undertaken to  
532 identify the variables which best explain and predict the hydrological response

533 fluctuations minimizing variables redundancy. An ( $n \times p$ ) matrix consisting of  $n=54$   
534 events and  $p=7$  variables was constructed. Then, ( $p \times p$ ) correlation (*COR*) and  
535 significance (*p*-value) matrices were constructed using statistical software in Matlab. To  
536 assess the statistical significance, we accepted correlations with *p*-value  $<0.05$  using the  
537 Student t-test. Finally, multiple stepwise regression analysis generates a linear equation  
538 that predicts a dependent variable (hydrological impacts) as a combination of several  
539 independent variables (hydrometeorological variables). A final correlation coefficient  
540 has been calculated to assess the linear combination of the selected variables and its  
541 power of predictability. This procedure has been applied on both scales (virtual roof and  
542 Châtillon basin).

543 In this study, a linear model has been chosen because dependent variables are expressed  
544 as relative differences and not directly as hydrological responses (discharge or volume)  
545 for which a multipower model is needed (Bois and Obled, 2003). Furthermore, it is  
546 clear independent variables are not normally distributed. But despite its limitations,  
547 multiple regression analysis represents a simple model sufficient to capture a significant  
548 fraction of the impact variability as it was done in other studies under similar conditions  
549 (Drasko, 1998; Berger and Entekhabi, 2001; Nie et al., 2011). For this reason, it will be  
550 used to analyse and compare the different hydrological impacts computed at both scales.

551

## 552 **5- Assessment of the hydrological impact of green roof**

### 553 5-1 Impact at the green roof scale

554 First of all, it has to be noticed that the hydrological responses of SE3Y and SE15Y  
555 configurations for the considered 54 events are quite similar for the different green  
556 roofing scenarios (It has already been noticed on the experimental site for the four main



557 events, see Figure 2). The decrease in peak discharge due to green roofing appears to be  
558 higher for SE15Y (around 10% higher). The hydrological response for both  
559 configurations essentially differs for the low precipitation events. Most of the smallest  
560 events do not produce any response for the SE15Y configuration (for only 10 of the 40  
561 lowest events in terms of rainfall accumulation, see Figure 6) while small runoff is  
562 generated for the SE3Y one (for 32 of the same events). Concerning the highest events,  
563 discharge tends to reach the same peak value. This has already been mentioned on the  
564 experimental green roof for the highest event of 20 mm (see Section 2-1). For this  
565 reason and for a question of readability, only the results provided with the SE15Y  
566 configuration are represented in the next figures.

567 As expected, the reduction of the hydrological response depends on the level of green  
568 roofing: the higher the covering, the higher the reductions in terms of peak discharge or  
569 volume (see Figure 6). As the percentage of green roof is greater than that defined at the  
570 sub-basin scale (here, the potential represents the entire area whereas at the basin scale a  
571 potential of 100% represents 20% of the total area), the hydrological impact of green  
572 roof is significant. As already mentioned, most of the rainfall events (the smallest ones  
573 in terms of total amount of precipitation) are completely retained by the 100% green  
574 roofing scenario: in this case, only 22 of the 54 rainy events produce runoff  
575 (characterized by a total amount of precipitation ranging 10.6 mm to 112.8 mm). At the  
576 roof scale, reductions of peak discharge and runoff volume are of the same order of  
577 magnitude: about 10% (ranging 6% to 12%) for a covering of 12.5% of the roof, about  
578 20%, 40%, and 85% (ranging 13% to 25%, 37% to 50% and 10% to 100% for peak  
579 discharge) for a covering of 25%, 50% and 100% of the roof area respectively.

580

581 Surprisingly, for some particular events (N° 35, 36, 49 and 51 in Figure 6), some green  
582 roofing scenarios can produce a higher peak discharge (meaning a negative value of  
583  $\Delta Qp$ ) than the one generated by the entire impervious surface (or a smaller coverage  
584 scenario). An example of this situation is presented in Figure 7 (note that the other ones  
585 are similar to this event). This rainfall event that occurred on 1 December 2010 is  
586 characterized by a double rainfall peak spaced in time by 10 minutes (55.2 mm/h and  
587 64.8 mm/h respectively). The total impervious roof responds identically with two peak  
588 discharges reaching 0.45 l/s and 0.61 l/s respectively. As expected, the crescent  
589 covering of green roof tends to reduce both peaks (12.5% and 25% green roofing  
590 scenarios generate a reduction of peak discharge of about 12% and 22%). The 50%  
591 covering implies also a significant decrease for the first peak and a less significant one  
592 for the second peak, combined with a 10-minute delay. This trend is also amplified with  
593 the 100% green roofing scenario. The first rainfall peak is completely stored in the  
594 green roof, but the second part of the event generates a peak discharge (0.61 m<sup>3</sup>/s)  
595 higher than that produced by the total impervious roof. This is due to the concomitance  
596 of the fast response of the saturated substrate generated by the second rainfall and the  
597 slow response of the green roof produced by the first rainfall.

598

## 599 5-2 Impact at the basin scale

600 As already mentioned for the virtual roof, the difference between SE3Y and SE15Y  
601 configurations impacts are not completely negligible. Comparing to the results obtained  
602 for SE3Y, the use of SE15Y green roof implies an additional reduction of peak  
603 discharge ranging 0.3% (for 12.5% potential covering scenario) to 2.3 % (for 100%  
604 potential covering scenario). Although this difference varies from a rainfall event to

605 another, it never reaches more than 10% for a same event (respectively 15% for the  
606 volume).

607 The simulated peak discharges appear to be influenced by the implementation of green  
608 roofs when significant roof surface is covered. Hydrological responses computed for the  
609 different green roofing scenarios on the study basin have been represented from  
610 smallest to largest in Figure 8. Although the impact of green roof varies from one storm  
611 event to another, the covering of only 12.5% on the green roofing potential implies a  
612 small reduction of the peak discharge (average value of 4.7%, from a minimum of 0%  
613 to a maximum of 5.5%). This reduction of peak discharge slightly increases with the  
614 covering of 25% (the reduction ranges from 3.5% to 10.2% with an average value of  
615 9%). For both low green roofing scenarios, the impact on runoff volume is quite  
616 negligible with an average decrease of 6.6% in the best case (25% covering scenario).

617 High green roofing scenarios (covering of 50 or 100% of the potential) have more  
618 valuable consequences in terms of runoff reduction. The 50% scenario leads to an  
619 average peak discharge decrease of about 18.6% (from a minimum of 9.3% to a  
620 maximum of 23.7% depending on the event). The impact of the 100% scenario looks  
621 proportional with an average  $Q_p$  reduction of 35.6% (between 17.4% and 38.7%). The  
622 runoff volume is also significantly reduced with an average value of 25.2% for the best  
623 case, and a stronger fluctuation from a storm event to another (from 14.4% to 53.9%).  
624 Indeed, the hydrological benefit seems to be directly related to the storm event. From an  
625 operational point of view, green roofing of a significant part of the buildings' roofs  
626 implies the reduction of the flooding risk: 14 rainfall events (on 54) now have a peak  
627 discharge lower than the flooding threshold of 4.7 m<sup>3</sup>/s for the 50% scenario, and 26  
628 events for the 100% scenario respectively.

629 The situation presented in the previous section, where peak discharge is increased by the  
630 use of green roof, does not occur at the basin scale. It is explained in part by the specific  
631 configuration of the case study, especially the spatial repartition of the impervious and  
632 green roof surfaces and the attenuation effect of the sewer network.

633

### 634 5-3 Correspondence between virtual roof and basin impacts

635 When comparing results obtained for virtual roof and Châtillon basin, green roof  
636 impacts (on peak discharge or runoff volume) appear to not perfectly match from one  
637 rainfall event to another. The sensitivity to green roof implementation and the  
638 magnitude of these impacts is clearly different because the average green roof potential  
639 is 20% on the study basin while it represents the entire area on the virtual roof. For this  
640 reason, in many situations, runoff is completely avoided on the virtual roof, whereas it  
641 is only reduced (at most 40%) on the basin.

642 Nevertheless, both studied surfaces follow more or less the same trend, and differences  
643 seem to be devoted to the specific configuration of the sewer network and layout  
644 between impervious and green roof surfaces. Although green roof can reduce the  
645 hydrological impact of stormwater, these consequences are conditioned by the intrinsic  
646 properties of the studied basin. The main difference occurred for two severe rainfall  
647 events characterized by a total accumulation of 63.8 and 112.8 mm for a duration of 65  
648 and 515 minutes respectively (Events No 50 and 52, see also Figure 4) for which the 10-  
649 year return period was exceeded. In these situations, the impact noticed at the roof scale  
650 is significantly attenuated at the basin scale. The influence of remaining impervious  
651 areas and the saturation of the substrate seem to cancel runoff reduction abilities of  
652 green roof.

653 At both scales (roof and basin), hydrological impact of green roof seems also to be  
654 related to the specific characteristics of the rainfall event. Regarding Figures 6 and 8,  
655 the relative reduction of peak discharge seems to be higher for the smallest events in  
656 terms of rainfall amount. This observation that has already been mentioned in previous  
657 studies (Carson *et al.*, 2013; Fassman-Beck *et al.*, 2013) and will be studied in detail in  
658 the following.

659

## 660 **6-Condition of urban runoff reduction**

661 Simple correlation and multiple stepwise regression analysis have been undertaken to  
662 identify which variables (*Imax5*, *Imax30*, *Imax60*, *Ptot*, *Durat*, *Pant*, *SoilSat*,) can  
663 explain and can predict hydrological response fluctuations ( $\Delta Q_p$  and  $\Delta V$ ) minimizing  
664 variables redundancy.

### 665 6-1 At the virtual roof scale

666 Regarding the single correlation coefficients (Table 2), precipitation seems to be an  
667 important factor influencing the hydrological response. Despite the 5-minute time  
668 period being close to the response time of the virtual roof (assessed from observation on  
669 Trappes' roof characterized by a time to peak reaching 3 to 6 minutes), the  
670 accumulations on higher time periods (one hour or on total event duration) seem more  
671 predominant. As mentioned in recent studies (Carson *et al.*, 2013; Fassman-Beck *et al.*,  
672 2013), the higher the precipitation, the lower the hydrological impact (in terms of  
673 reduction of peak discharge and runoff volume). These durations are usually close to the  
674 time separating the end of rainfall and the end of runoff (observed as being higher than  
675 30 minutes).

676 Whatever the green roof configuration, the duration of the event and the antecedent  
677 precipitation are weakly correlated with hydrological responses. Antecedent conditions  
678 seem to be better represented by the substrate saturation at the beginning of the event.  
679 The correlation with this variable is also higher for the thicker substrate (around 0.70)  
680 meaning the SE3Y configuration response does not depend much on initial conditions.  
681 As it has a smaller water retention capacity, substrate generally has time to dry between  
682 two events and it is rapidly saturated for the most severe events.

683 The multiple stepwise regression analysis selects almost the same hydrometeorological  
684 variables to optimize the multilinear correlations (see Table 2): total rainfall  
685 accumulation and estimated soil saturation at the beginning of the event for peak  
686 discharge reduction. An additional variable ( $I_{max60}$ ) influences runoff volume  
687 reduction. As  $I_{max5}$ ,  $I_{max30}$ ,  $I_{max60}$  and  $P_{tot}$  are strongly correlated, only one or two  
688 variables among them are considered as statistically significant at the  $<.05$  level. The  
689 selection of  $I_{max60}$  and  $P_{tot}$  for volume reduction can be interpreted as follows: the 1-  
690 hour accumulation close to the concentration time of the roof. If the rainfall event  
691 continues after this duration, most of the precipitation becomes directly runoff,  
692 influencing the total volume.

693 The final correlation computed by using the selected variables is quite good for both  
694 configurations and both hydrological impacts (from 0.68 to 0.90). The scatter plots  
695 comparing observed and simulated hydrological impacts are presented in Figure 9. Most  
696 of the points are located close to the symmetric line. Two main reasons can be proposed  
697 in order to explain the different outliers and the difficulty for the multilinear relationship  
698 to reproduce some specific situations. First, the threshold effect is noticed for several  
699 events for which no runoff is produced by the SE15Y configuration ( $\Delta Q_p$  and  $\Delta V$  are  
700 equal to 100%). Second, singular behaviours can occur as those produced by

701 concomitance situations (as shown in Section 4-2): in these cases, two consecutive  
702 peaks of rain produce a peak discharge reduction not significant as expected, and can  
703 sometimes amplify the reference situation.

704 Similar regression analysis was performed by Stovin *et al.* (2012) for similar results.  
705 They tried to link several hydrometeorological variables to the direct hydrological  
706 consequence of green roof and not the relative differences as in this study. Total rainfall  
707 accumulation appeared to be linked to runoff depth and percentage of retention  
708 (correlation coefficients of 0.72 and 0.33 respectively). The influence of antecedent dry  
709 weather period seemed to be more complex and the combination of several variables  
710 showed it was not possible to predict retention depth for a particular  
711 hydrometeorological situation.

712

#### 713 6-2 At the Châtillon basin scale

714 At the basin scale, the results of correlation are quite similar to those obtained at the  
715 virtual roof scale. As expected, precipitation is strongly correlated to the peak discharge  
716 reduction (the higher the total precipitation, the lower the reduction), while runoff  
717 volume reduction is hardly explained by the independent variables. Only the antecedent  
718 condition in terms of estimated soil saturation seems to influence the volumetric  
719 response and is considered as statistically significant at the  $p$ -value < 0.05 level.

720 The multiple stepwise regression analysis selects almost the same hydrometeorological  
721 variables as at the roof scale (see Table 2): total rainfall accumulation and estimated soil  
722 saturation at the beginning of the event. Note that despite their strong correlation,  
723  $I_{max30}$ ,  $I_{max60}$  and  $P_{tot}$  are selected to explain the peak discharge reduction for SE3Y  
724 configuration. They correspond to different scales of the basin response. Nevertheless,

725 these results from multiple stepwise regressions should be interpreted with some caution  
726 because of: (i) the limited sample data (54 events for 7 independent variables), (ii) the  
727 clearly non-normal distribution of these variables, and (iii) few outliers due to singular  
728 behavior.

729 The comparison between simulated and stepwise computed hydrological impacts is also  
730 well represented on the scatter plots (Figure 10). The peak discharge impacts are well  
731 depicted around the symmetric line and only a few events are located far from the  
732 median values. They correspond to the two main events characterized by a total rainfall  
733 accumulation of 112.8 mm and 63.8 mm. It appears the basin is able to smooth a large  
734 majority of the events and only react to the extreme ones.

735 The distribution of total runoff volume is more erratic with a wide dispersion around the  
736 symmetric line. Estimated soil saturation at the beginning of the event is the only  
737 selected variable explaining  $\Delta V$  fluctuations for the SE15Y configuration. This variable  
738 is characterized by low fluctuations (ranging from 12% to 35% for an average value of  
739 17%). As a consequence, many volume reductions are estimated by a constant  
740 simulated value, representing an unsaturated substrate at the beginning of the event.

741

742 6.3 Is roof scale impacts a good indicator to predict basin scale impacts?

743 Obviously, green roofing impacts are easier to observe at roof scale than at basin scale.  
744 In addition, previous results have shown that the main hydrometeorological factors  
745 influencing hydrological impacts are quite similar at both scales: initial soil moisture  
746 condition and intensity or accumulated precipitation. In order to appreciate how  
747 estimated results at roof scale may help to predict impact at the basin scale, the  
748 hydrological impacts noticed at the basin scale have also been compared to those



749 computed at the roof scale by using the multi-linear regression (Figure 11). Although  
750 correlation coefficients are always lower than those obtained by using the multi-linear  
751 regression calibrated at basin scale, they provide satisfactory results. It appears  
752 correlation coefficients are higher for peak discharge concerning SE3Y (0.84) and for  
753 runoff volume concerning SE15Y (0.71) respectively. This is due to the common  
754 selected hydrometeorological variables (characterized by high correlation) shared by  
755 both case studies: *Ptot* and *SoilSat* for  $\Delta Qp$  and *SoilSat* for  $\Delta V$ . These results show that  
756 impacts estimated at roof scale can globally approximate those expected at basin scale  
757 for a large set of rainfall events by using a reduction coefficient. This approximation can  
758 appear quite rough but can be useful to have an idea of the consequence of green roof at  
759 the basin scale.

760

## 761 **7-Discussion**

762 These encouraging results provided by a modelling approach are based on a number of  
763 implicit hypotheses and limitations that can be discussed:

764 (1) The SWMM representation of green roof at the sub-basin scale. First, the  
765 estimation of the green roofing potential may look optimistic. The methodology  
766 used probably overestimates the real potential. It is assumed that all buildings  
767 belonging to the selected land use categories can effectively be covered by green  
768 roof, meaning that they have flat roofs, without micro-structure and for which  
769 the implementation of green roof is technically possible (and already done). The  
770 consideration of only a fraction of this potential seems to be more realistic. For  
771 this reason, these results illustrate the potential of such structures and encourage  
772 the implementation of green roofs for future rehabilitation and developing

773 projects. Second, green roof areas are considered as a unique entity at the sub-  
774 basin scale (mean area of 10 ha), without taking into account the spatial  
775 distribution of the green roof covered buildings. This may impact the dynamic of  
776 the response by using the Manning-Strickler equation on a virtual area  
777 representing the sum of the different covered roofs. For this reason, we assume  
778 such a representation is adapted to assess the hydrological impact of green roof  
779 at the basin scale but surely not at the sub-basin one.

780 (2) The short time period for the calibration of the hydrological model. The model  
781 parameters have been adjusted by using 1-year observation data during which no  
782 severe event was observed (the maximum exceeded return period is equal to 1  
783 year). That means the model has been calibrated on common events, and we  
784 assume it is able to correctly represent rarer events characterized by more  
785 intense precipitation. This could explain why hydrological impacts computed for  
786 extreme events are often located far from the regression line (linking SWMM  
787 simulated and stepwise computed hydrological impacts). For this reason, the  
788 observation of experimental green roofs has to continue in order to capture more  
789 significant storm events. These additional data will be used to improve and/or  
790 validate the model in the future. However, the use of current data allows us to  
791 conclude that the implementation of green roof can be useful to limit the  
792 consequences of common storm events on sewage network. Moreover,  
793 evapotranspiration has appeared as a key factor influencing initial substrate  
794 saturation during wet periods. The improvement of its estimation could improve  
795 model simulations.

796 (3) The specific configuration of the studied basin. The presented results have been  
797 computed for a particular urban basin belonging to the Hauts-de-Seine county.

798 For this reason, the figures obtained in terms of flooding reduction can not be  
799 generalized and transferred to other locations. Indeed, they depend on the basin  
800 configuration, especially on green roofing potential (with the diffusion more or  
801 less significant of flat roof), the combination of impervious and green roofing  
802 surfaces, but also on the basin geometry and the sewage network arrangement.  
803 For these reasons, it is quite possible that some concomitance situations occur as  
804 noticed at the roof scale in Section 4-2. The superposition of responses from an  
805 impervious area and a green roof area to a complex rainfall event (composed by  
806 several rainfall peaks for example) can generate a peak discharge higher than  
807 that produced by the current (impervious) situation.

808

## 809 **8-Conclusions**

810 Based on experimental green roof observations, a conceptual hydrological model has  
811 been developed and calibrated to reproduce the hydrological behaviour of two different  
812 types of green roof differentiated by their substrate depth. On the other side, several  
813 green roofing scenarios have been produced for a small urban basin, ranging from the  
814 current situation (no green roof is implemented) to a maximum roof area that can be  
815 covered by green roof. Integrated into the stormwater management model SWMM, the  
816 conceptual hydrological model has been applied on a large time series at the basin scale  
817 to assess its impact in terms of urban water management. For comparison, the same  
818 procedure has also been applied at the roof scale. Finally, a complementary analysis has  
819 been conducted to study which hydrometeorological variables can influence the  
820 magnitude of these hydrological impacts at both scales.

821 Whether at the scale of roof or basin, green roof appears to significantly impact urban

822 runoff in terms of peak discharge and volume. At the roof scale, the obtained results for  
823 a complete green roof covering (reduction close to 90% for peak discharge and runoff  
824 volume) are similar to those provided by experimental studies (Voyde *et al.*, 2010 ;  
825 Palla *et al.*, 2011 ; Stovin *et al.*, 2012). At the basin scale of our case study, results are  
826 less pronounced because they depend on the green roofing potential of each sub-basin,  
827 which usually represents around 20% of the sub-basin area (2.37 km<sup>2</sup>). The reduction of  
828 the hydrological response (peak and volume runoff) can reach almost 20% when half of  
829 the potential is covered and more than 35% for the entire area. It seems to be enough to  
830 avoid some flooding issues in several cases as demonstrated on our case study: for 14 of  
831 the 54 considered rainfall events, modified peak discharge are then lower than the  
832 flooding threshold with the 50% green roofing scenario.

833 It has also been noticed that the response of the two SE3Y and SE15Y green roof  
834 configurations (substrate depth of 3 and 15cm) for the 54 studied events are quite  
835 similar. The hydrological responses of both configurations essentially differ for the low  
836 precipitation events, for which the thicker substrate produces less runoff. For the highest  
837 ones, both peak discharges and runoff volumes are of the same order. This has already  
838 been observed on the experimental green roof for the more intense events, but also in  
839 some previous studies. Voyde *et al.* (2010), for example, mentioned that an increase in  
840 substrate depth from 50 mm to 70 mm did not provide a measurable increase in  
841 hydrological performance.

842 By comparing several hydrometeorological variables relative to the rainfall events with  
843 the hydrological impacts of green roof (at roof and basin scale), it appears that  
844 precipitation –generally accumulated during the whole event- and initial substrate  
845 saturation are both influencing variables: the higher the precipitation, the more saturated  
846 the substrate, and the lower the reduction in terms of stormwater. The use of green roof

847 seems to be helpful to mitigate the effects of a rainfall event characterized by a return  
848 period lower than 10 years. For the more severe events, the impact of green roof is  
849 marginal and can not be used to solve operational issues.

850 At both scales (roof and basin), it appears difficult to forecast the hydrological impacts  
851 of green roof only by considering hydrometeorological variables. Multilinear  
852 relationships approximate responses (in terms of peak discharge and runoff volume) to  
853 storm water, but they fail in reproducing them correctly for a large kind of rainfall event  
854 and antecedent condition configurations. They need a more physical tool (a hydrological  
855 model) to estimate the consequences of the involved non-linear processes. Moreover,  
856 the basin response seems to be deeply influenced by its own configuration.  
857 Nevertheless, in a first approximation, the multi-linear relationship adjusted for the roof  
858 can provide correct estimation at the basin scale.

859 Despite some limitations mentioned in the previous section, this study supports the large  
860 scale implementation of green roofs to locally reduce overflows in the drainage  
861 network. In addition to possible thermal and environmental benefits, green roof can be  
862 valuable from an urban water management point of view. As already mentioned in other  
863 studies (Carter and Jackson, 2007), green roofs alone cannot solely be relied upon to  
864 provide complete stormwater management at the watershed scale. Combined with other  
865 stormwater source controls or/and retention infrastructures, green roof could contribute  
866 to significant reductions of the quantity of water flowing into the sewage network  
867 during storm events. A combination of source control management strategies and water  
868 reuse techniques are more cost effective than their traditional centralized counterpart  
869 (Coombes *et al.*, 2002). As a result, this kind of study could be used by policy makers  
870 and water management authorities to promote the dissemination of green roof in the  
871 future.

872

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876 Seine county, especially Pascal Jouve, Christian Roux and Christophe Lehoucq, for  
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878

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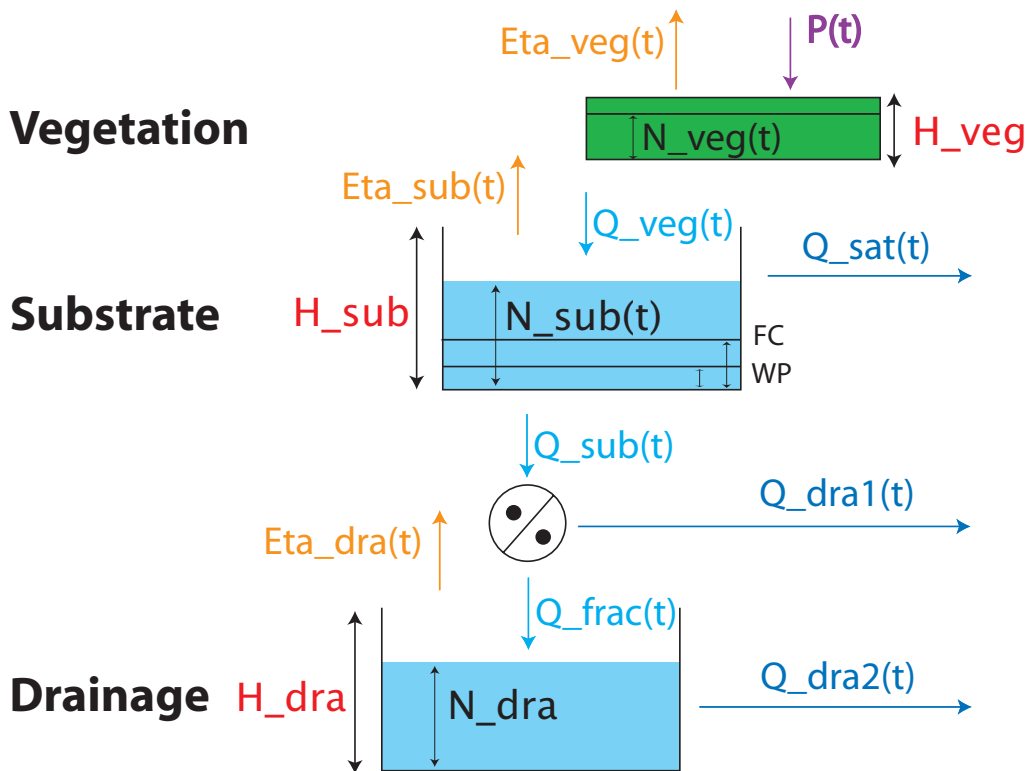
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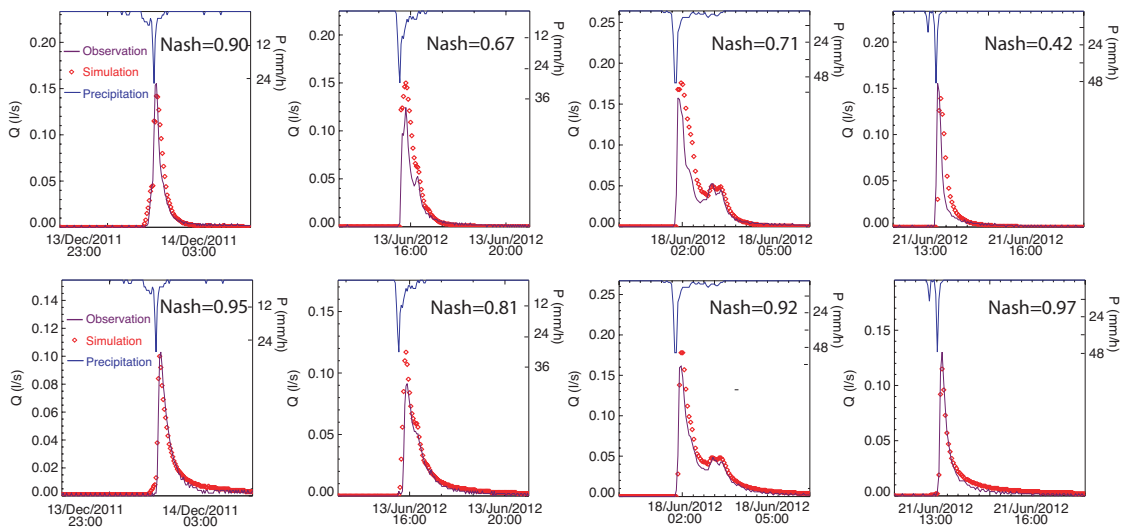




1004

1005 Figure 1: Reservoir model developed in SWMM (notations are explained in the text)

1006



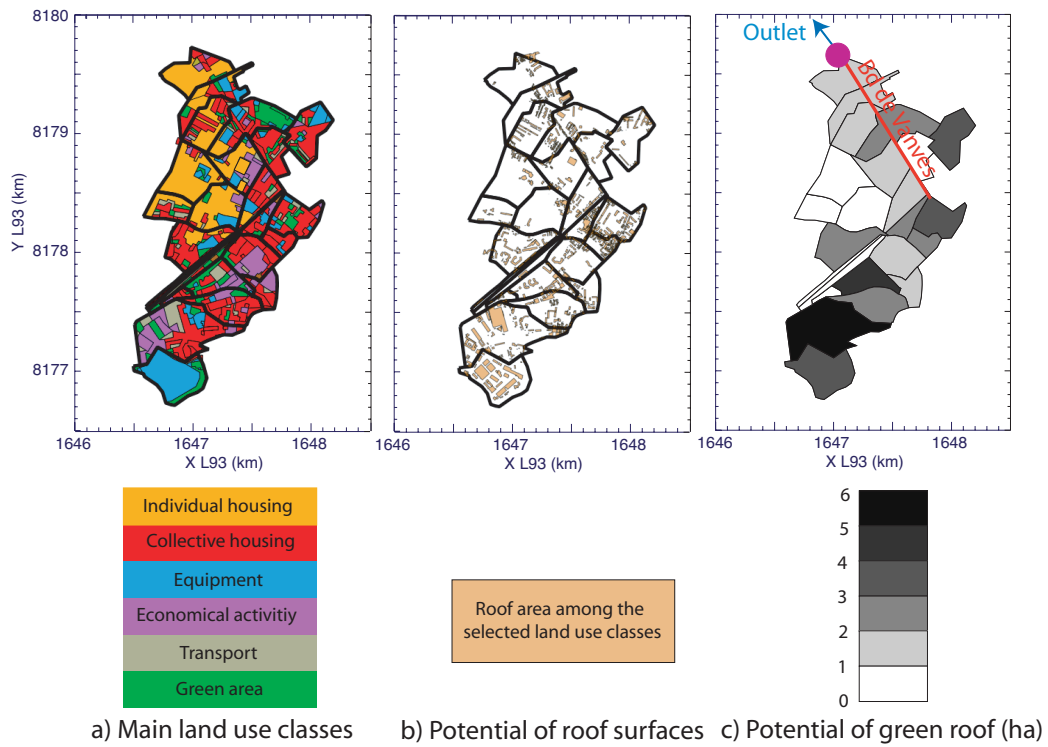
1007

1008 Figure 2: Comparison between observed and simulated discharges computed at the roof

1009 scale. Results obtained for the four most severe events of the study period (June 2011-

1010 August 2012) are presented for SE3Y (top) and SE15Y (bottom) green roof  
1011 configurations.

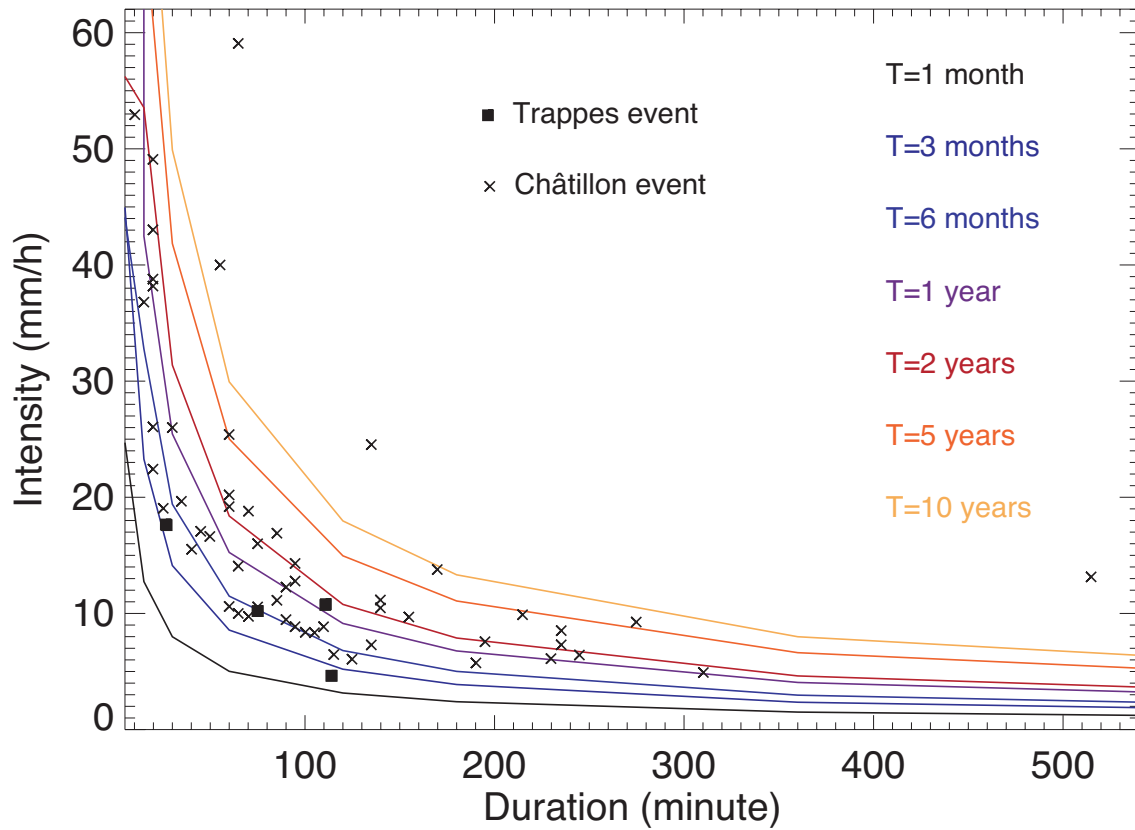
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1013

1014 Figure 3. Châtillon basin disaggregated into 25 sub-basins for SWMM modelling: a)  
1015 land use distribution, b) potential roof surfaces distribution, c) green roofing potential  
1016 distribution

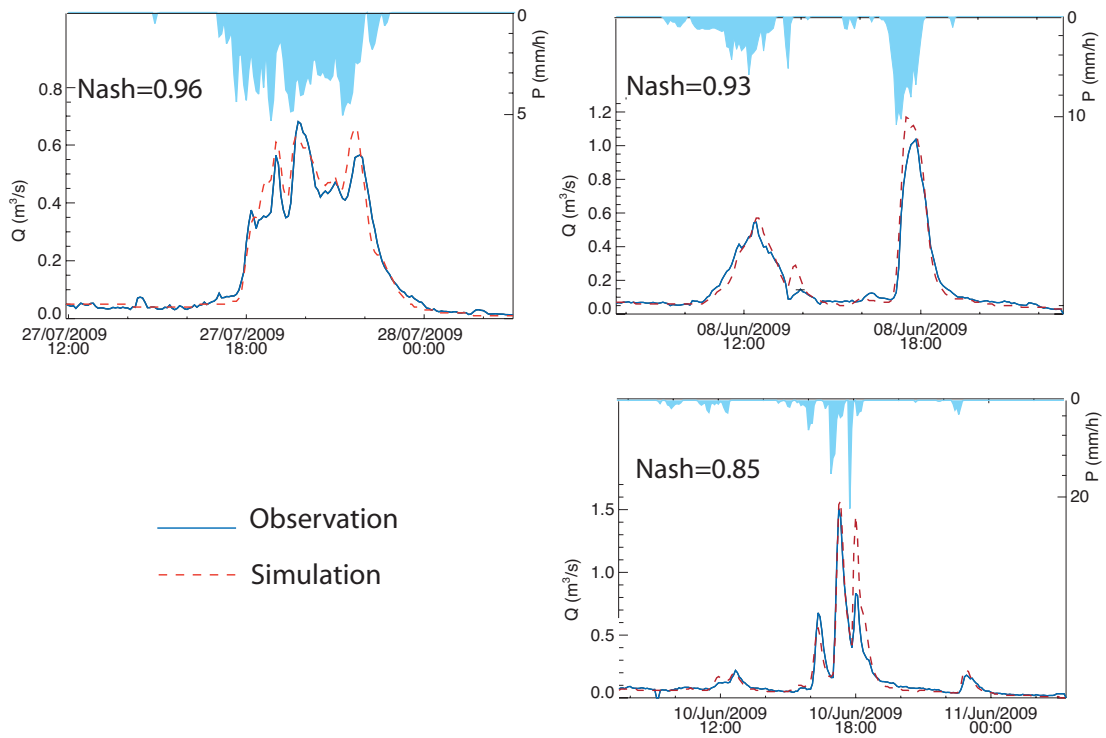
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1019 Figure 4. Characterization of the studied rainfall events in terms of duration and  
 1020 intensity, IDF curves from Montsouris (Paris, France) are indicated. The 54 events  
 1021 computed from Hauts-de-Seine database on the 1993-2011 period are represented by  
 1022 crosses and those computed from the experimental green roof in Trappes on the 2011-  
 1023 12 period are represented by squares.

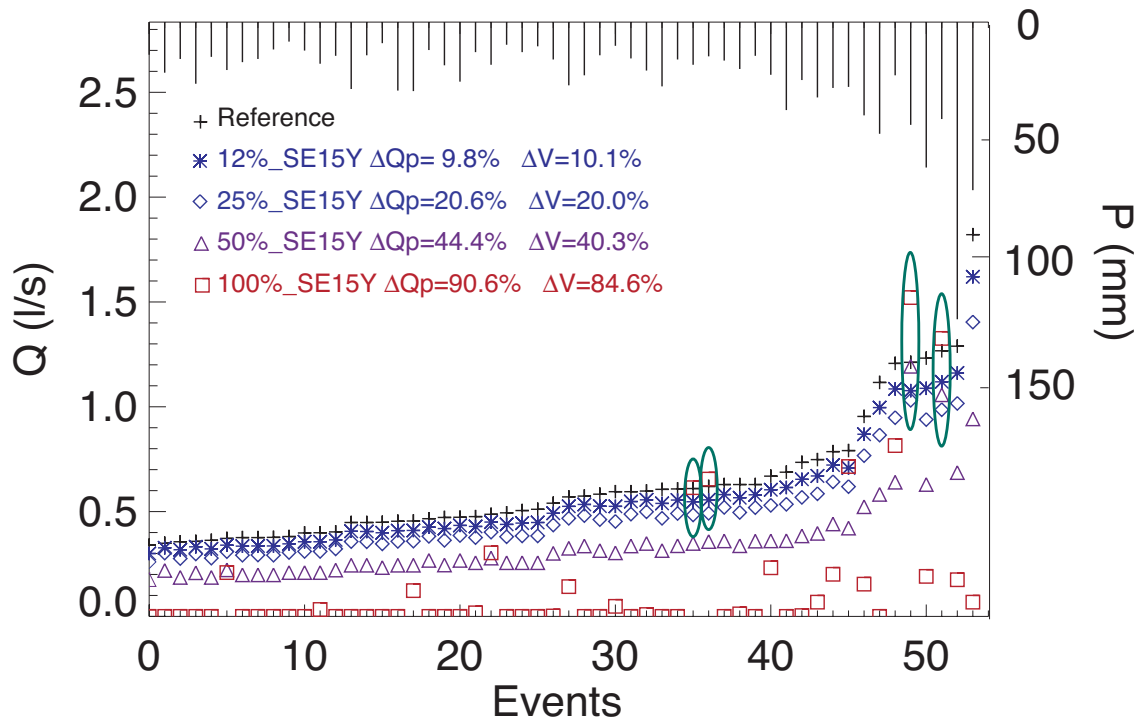
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1025

1026 Figure 5: Comparison between observed and simulated (with SWMM) discharge  
 1027 computed at the Châtillon basin scale. Simulations were performed on three 2009  
 1028 rainfall events for which temporal discharge observations were available.

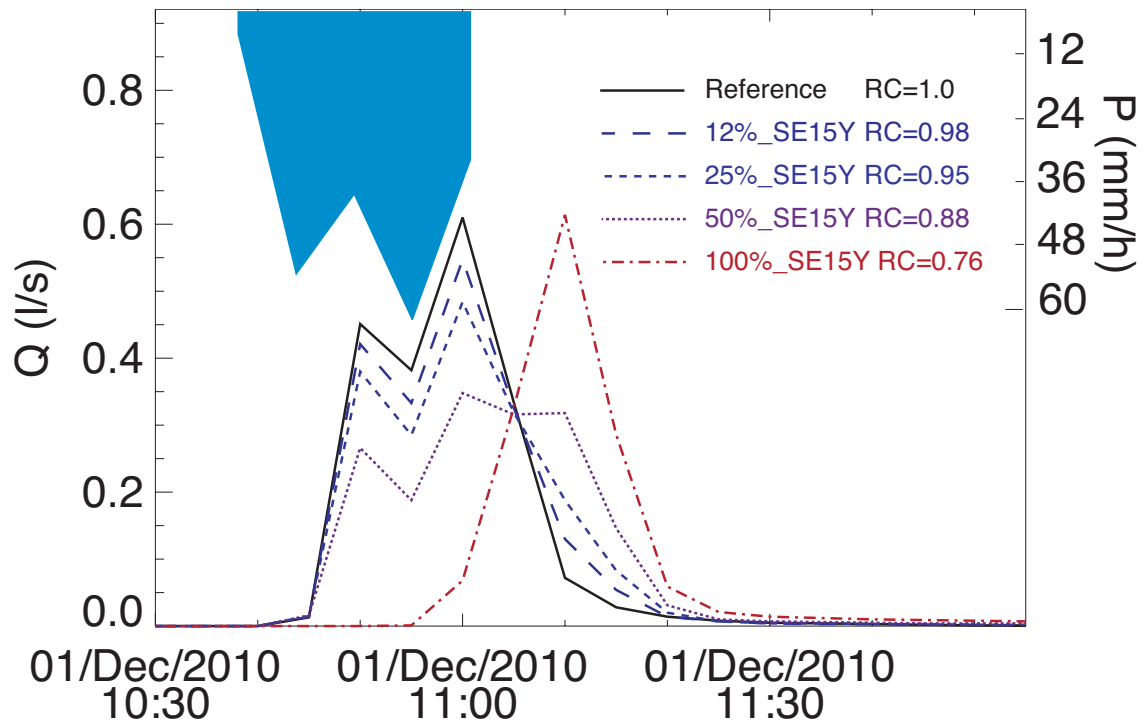
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1030

1031 Figure 6. Impact of the green roofing scenarios on the 35 m<sup>2</sup> virtual roof: peak  
 1032 discharge is represented for the 54 rainfall events (ordered by increasing value of  $Q_p$ ),  
 1033 the average reduction in peak discharge ( $\Delta Q_p$ ) and runoff volume ( $\Delta V$ ) are indicated for  
 1034 the four green roofing SE15Y scenarios. The total amount of precipitation is also  
 1035 represented for every event (bars on inverse axes) and the particular events for which  
 1036 the implementation of green roof produces higher peak discharge are surrounded.

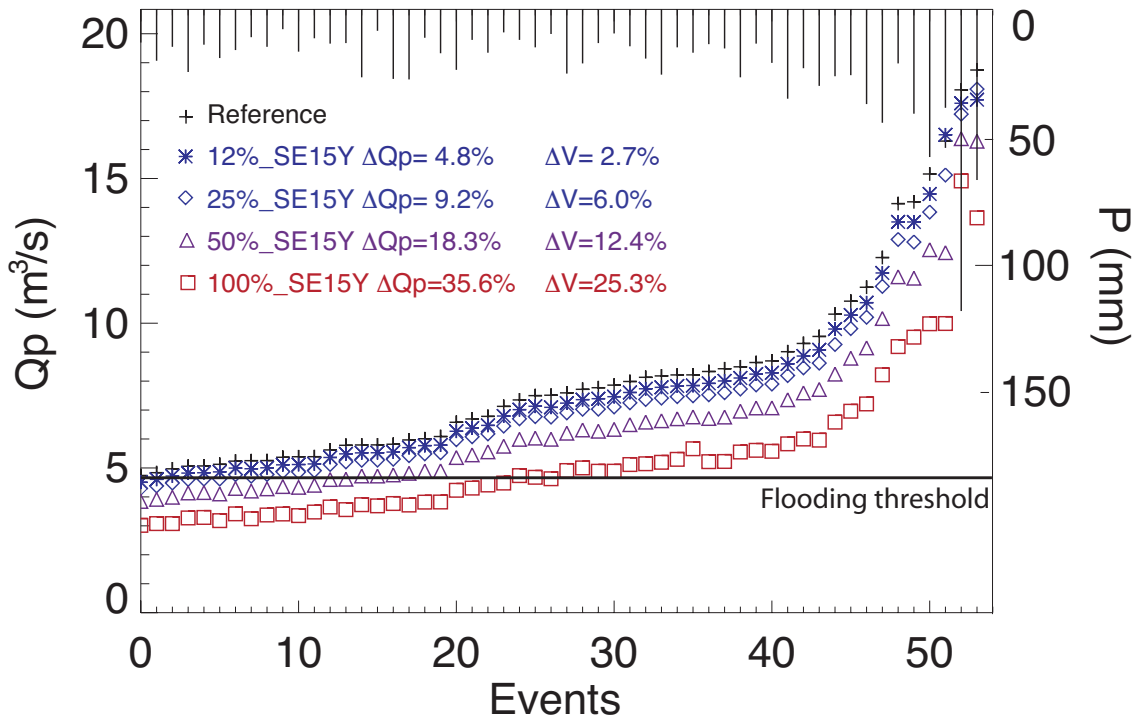
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1038

1039 Figure 7. Hydrological response of the virtual roof for different greening scenarios on  
 1040 the 1st December 2010 rainfall event. Precipitation is represented, in blue, on the  
 1041 inverse axes. Runoff coefficients (RC) are also indicated.

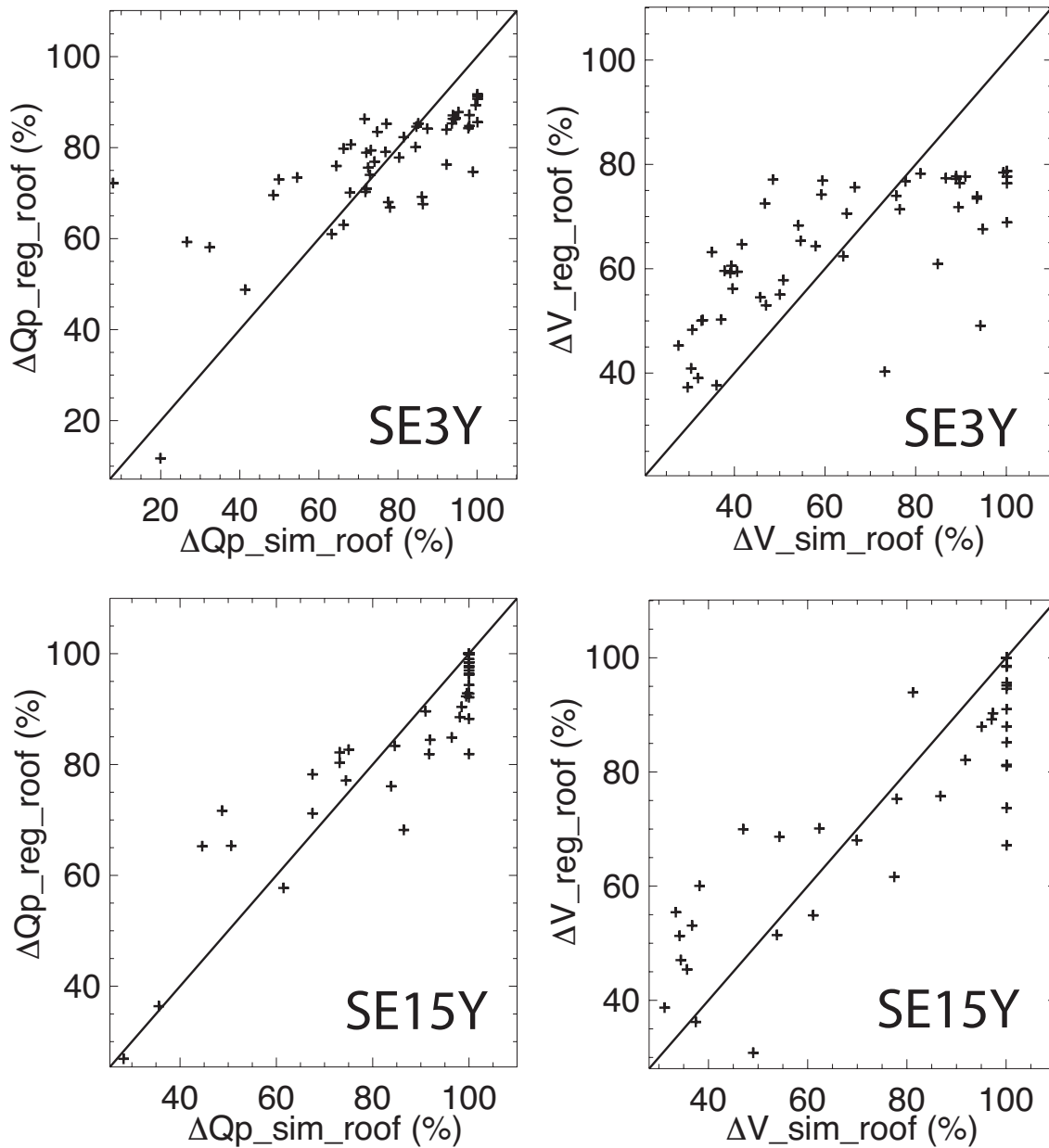
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1043

1044 Figure 8. Impact of the green roofing scenarios on the basin: peak discharge is  
 1045 represented for the 54 rainfall events (ordered by increasing value of  $Q_p$ ): the average  
 1046 reduction in peak discharge ( $\Delta Q_p$ ) and runoff volume ( $\Delta V$ ) are indicated for the four  
 1047 SE15Y scenarios. The total amount of precipitation is also represented for every event  
 1048 (bars on inverse axes).

1049

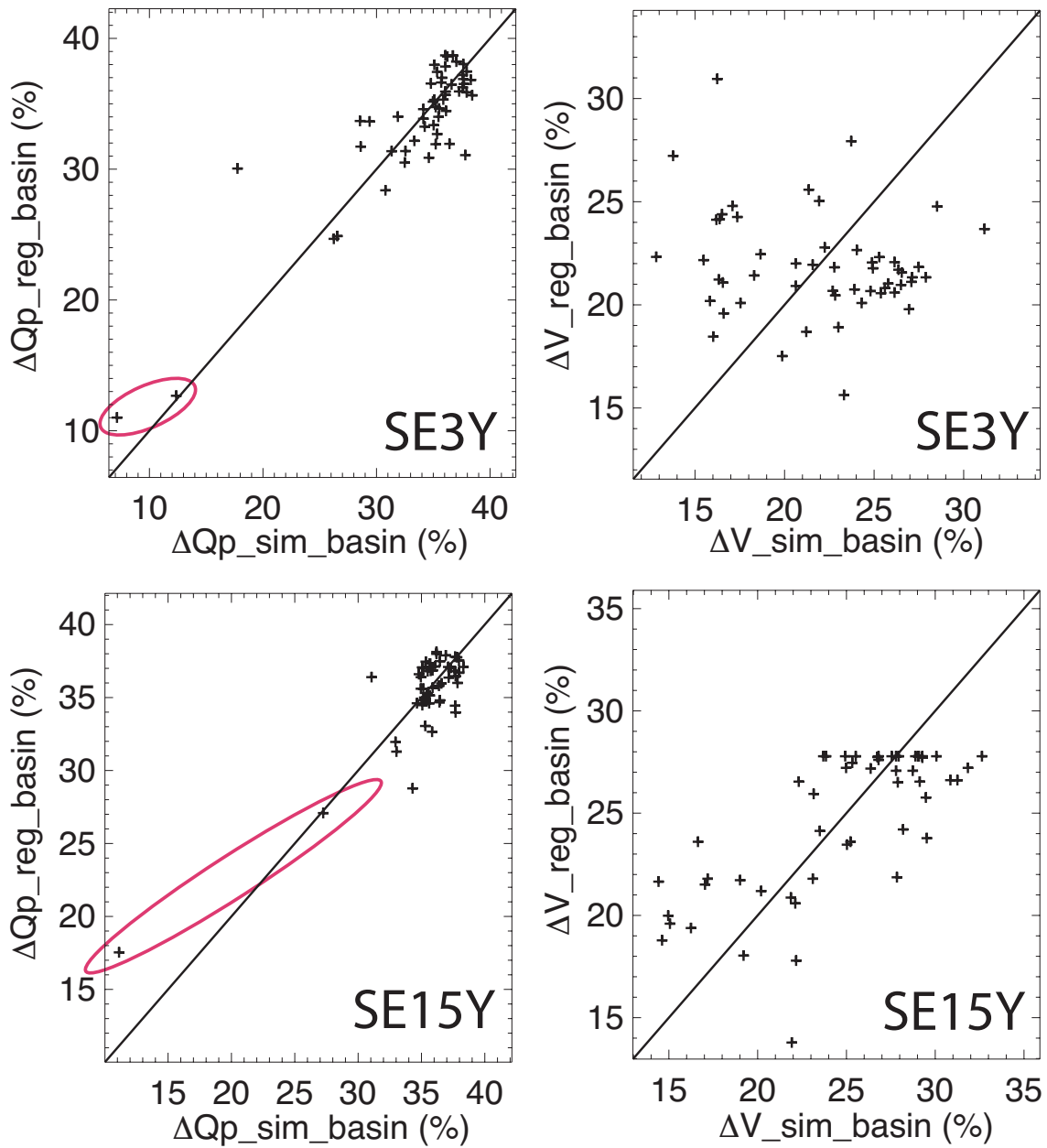


1050

1051 Figure 9. Comparison between SWMM simulated (sim) and stepwise computed (reg)  
 1052 hydrological impacts ( $\Delta Qp$  and  $\Delta V$ ) at the virtual roof scale for SE3Y and SE15Y  
 1053 configurations and the 100% green roofing scenario (the solid line corresponds to the  
 1054  $x=y$  symmetric equation).

1055

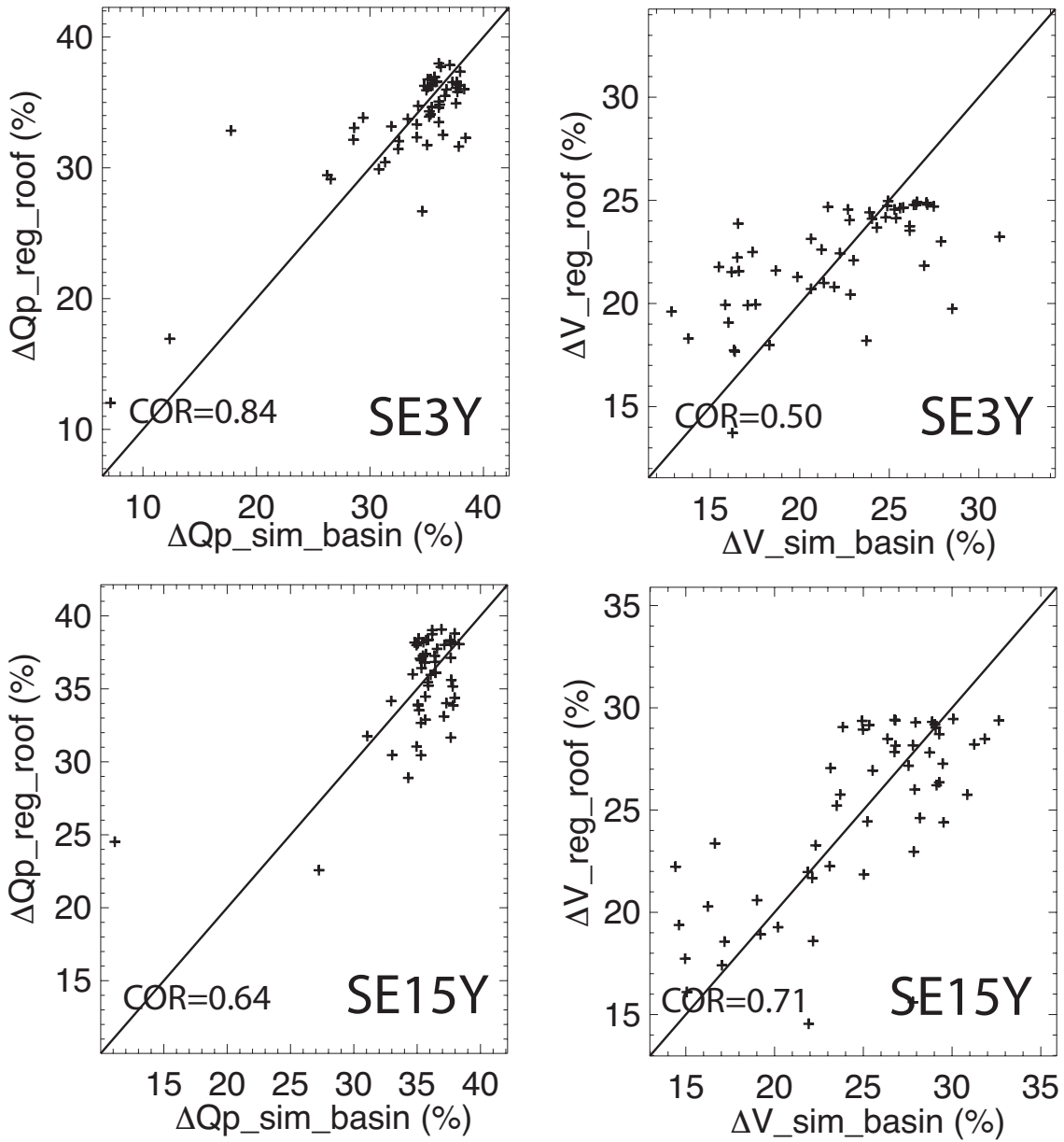




1056

1057 Figure 10. Comparison between SWMM simulated (sim) and stepwise computed (reg)  
 1058 hydrological impact ( $\Delta Qp$  and  $\Delta V$ ) at the basin scale for SE3Y and SE15Y  
 1059 configurations and the 100% green roofing scenario (the solid line corresponds to the  
 1060  $x=y$  symmetric equation). The two more intense events are surrounded.

1061



1062

1063 Figure 11. Comparison between SWMM simulated (sim) at the basin scale and stepwise  
 1064 computed at the roof scale (reg) hydrological impact ( $\Delta Qp$  and  $\Delta V$ ) for SE3Y and  
 1065 SE15Y configurations. The 100% green roofing scenario (the solid line corresponds to  
 1066 the  $x=y$  symmetric equation).

1067

1068

1069

1070 **Table captions**

1071 Table 1. Calibrated parameters values for both SE3Y and SE15Y. Physical values  
 1072 provided by green roof supplier are indicated for comparison.

		$f_{sub}$	$FC$	$K_{sat}$ (mm/h)	$R$
SE3Y	Physical	0.4	0.4	1158	~ 0.4
	Calibrated	0.4	0.39	104.7	0.51
SE15Y	Physical	0.4	0.4	1158	~ 0.4
	Calibrated	0.4	0.21	2.0	0.65

1073

1074 Table 2. Correlation between the hydrological impact and several hydrometeorological  
 1075 variables for virtual roof (top) and the Châtillon basin (bottom): The variables selected  
 1076 by the stepwise procedure are marked in bold. The last column represents the final  
 1077 correlation coefficient computed by using these selected variables.

At the roof scale								
	Imax5	Imax30	Imax60	Ptot	Durat.	Pant.	SoilSat	COR
$\Delta Q_{SE3Y}$	-0.47	-0.69	-0.67	<b>-0.71</b>	-0.44	-0.24	<b>-0.36</b>	0.75
$\Delta V_{SE3Y}$	-0.38	-0.49	<b>-0.48</b>	<b>-0.54</b>	-0.45	-0.27	<b>-0.44</b>	0.68
$\Delta Q_{SE15Y}$	-0.50	-0.71	-0.69	<b>-0.69</b>	-0.40	-0.38	<b>-0.68</b>	0.90
$\Delta V_{SE15Y}$	-0.50	-0.46	<b>-0.46</b>	<b>-0.50</b>	-0.34	-0.44	<b>-0.76</b>	0.89
At the basin scale								
	Imax5	Imax30	Imax60	Ptot	Durat.	Pant.	SoilSat	COR
$\Delta Q_{SE3Y}$	-0.62	<b>-0.84</b>	<b>-0.79</b>	<b>-0.78</b>	-0.40	-0.14	<b>-0.31</b>	0.88
$\Delta V_{SE3Y}$	-0.23	-0.25	-0.22	-0.27	<b>-0.26</b>	-0.27	<b>-0.42</b>	0.52
$\Delta Q_{SE15Y}$	-0.50	-0.76	-0.81	<b>-0.86</b>	-0.54	-0.06	-0.12	0.86
$\Delta V_{SE15Y}$	-0.22	-0.12	-0.10	-0.13	-0.14	-0.45	<b>-0.72</b>	0.72

1078