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1 **Title:** Evaluation of the relative roles of a vegetative filter strip and a
2 biofiltration swale in a treatment train for road runoff

3 **Short title:**Relative roles of a vegetative filter strip and a biofilter in a road
4 runoff treatment train

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12 **ABSTRACT**

13 In order to determine the relative importance of a vegetative filter strip and a biofiltration swale in a treatment
14 train for road runoff, US EPA SWMM was used to model infiltration and runoff from the filter strip. The model
15 consisted of a series of subcatchments representing the road, the filter strip and the side slopes of the swale.
16 Simulations were carried out for different rain scenarios representing a variety of climatic conditions. In
17 addition, a sensitivity analysis was conducted for the model's different parameters (soil characteristics and
18 initial humidity, roughness, geometry...). This exercise showed that for the system studied, the majority of road
19 runoff is treated by the filter strip rather than the biofiltration swale, an effect observed especially during
20 periods of low-intensity rainfall. Additionally, it was observed that the combination of infiltration of road runoff
21 in the filter strip and direct rainfall on the system leads to a significant and variable dilution of the runoff
22 reaching the swale. This result has important implications for evaluating the treatment efficiency of the system.

23 **KEYWORDS**

24 Sustainable drainage systems, infiltration, modeling, road runoff, treatment train, filter strip

25 INTRODUCTION

26 New urban water management paradigms such as low impact development (LID), sustainable drainage systems
27 (SuDS) and water sensitive urban design (WSUD) recommend managing stormwater close to the source
28 through on-site integrated control measures encouraging infiltration and evapotranspiration, thereby
29 maintaining the hydrologic behavior of a site close to its natural state (Fletcher et al. 2014). These techniques
30 contribute to water security by managing the flooding risk while maintaining or restoring base flows in streams
31 (Hamel et al., 2013) and groundwater recharge (Stephens et al., 2012). They also contribute to water quality
32 preservation by reducing the discharge of pollutant loads to water bodies for the chronic, nonpoint source
33 pollution associated with urban stormwater (Sage et al., 2015) and, in the case of roadways, by confining
34 pollution potentially generated by automobile accidents.

35 The chronic contamination of road runoff by such pollutants as suspended solids, metals, nutrients, organic
36 carbon and oil and grease has long been a concern within the water quality community (Kayhanian et al. 2012).
37 Recent research has also revealed the presence of organic micropollutants in this type of water (Kalmykova et
38 al. 2013), as well as a certain toxicity toward aquatic organisms (Dorchin & Shanas 2010).

39 In France, road constructors are required to demonstrate that pollution generated by new or renovated
40 infrastructures will not degrade the quality of water resources. The current national design guide suggests
41 grassed ditches or swales as a strategy for particle retention (Cavaillès et al. 2007). While sedimentation and
42 filtration as water moves through dense vegetation have been shown to improve water quality in traditional
43 grassed swales (Stagge et al. 2012; Winston et al. 2012), some studies have shown this effect to be unreliable,
44 varying greatly between storm events. (Bäckström et al. 2006; Leroy et al. 2016)

45 In order to improve particle retention and depollution while imitating predevelopment hydrology, an emerging
46 technique currently being studied for particularly polluted sites is that of a swale with check dams and a
47 planted filter medium, where treatment relies on filtration occurring as water infiltrates into the bottom of the
48 swale. This LID technique is already widely applied in the international context and corresponds to a linear
49 bioretention system (Roy-Poirier et al. 2010) or what Hattet al. (2009) refer to as a biofiltration swale.

50 Because of the presence of the base layers of the road structure as well as safety concerns, these ditches
51 cannot be located in immediate proximity to the road surface. Instead, the base of the road structure is often

52 covered with planted topsoil, forming a vegetated road shoulder over which road runoff flows before
53 continuing on to other treatment devices, such as a biofiltration swale. In this case, the shoulder acts as a
54 vegetative filter strip, pretreating water before it reaches subsequent treatment systems. Internationally, in
55 order to prevent clogging in biofiltration systems, many design guides recommend pretreating road runoff with
56 a vegetative filter strip (Hatt et al. 2009; CIRIA 2015). Like grassed swales, vegetative filter strips (VFS) remove
57 particulate pollutants through sedimentation and filtration and have been shown to effectively remove
58 suspended solids and metals, while infiltration in the strip's soil will result in a reduction in runoff volume
59 (Barrett et al. 1998; Li et al. 2008).

60 In France, however, practitioners rarely consider vegetated shoulders to play a role in water treatment and
61 they are not included in the current national guide for road pollution management (Cavaillès et al., 2007).
62 Neither are they included in the guide for the hydraulic design of road runoff management structures (Gaillard
63 et al., 2006). Their role is generally not taken into account in treatment system design and the extent of
64 infiltration in this part of the system as well as its role in pollutant flux management is poorly understood.

65 Overly simplistic representations of VFS, generally as surface flow devices with no infiltration accounted for,
66 can also be found in various international design manuals. Akan and Attabay (2016) cite state design manuals
67 from Iowa, Washington, New Jersey and Pennsylvania which base VFS sizing only on surface flow
68 considerations. The United Kingdom SuDS manual specifies ranges of acceptable slopes and filter widths,
69 maximal impermeable area width, and maximal flow depth and velocity but does not take into account the
70 hydraulic conductivity of soil (CIRIA 2015). Similarly, a guide from New Zealand recommends a hydraulic
71 residence time calculated using sheet flow velocity and filter width in order to encourage pollutant removal,
72 while qualitatively mentioning that permeable soils will increase system efficiency (Auckland Regional Council
73 2003). Indeed, neglecting the extent of infiltration in a VFS when sizing devices is a conservative approach,
74 which will tend to overestimate system runoff and underestimate pollutant removal. However, it may also lead
75 to a conception of the system which exaggerates the importance of downstream devices in managing pollutant
76 and hydraulic loads, leading to a suboptimal overall design and possible maintenance issues.

77 Several mathematical models of vegetative filter strips can be found in the scientific literature (Akan 2014;
78 Deletic 2001; Muñoz-Carpena et al. 1999). While they vary in their representation of sediment transport, these
79 models all represent system hydrology using a kinematic wave formulation for overland flow and Green-and-

80 Ampt model of infiltration. These modeling studies have also all focused on modeling runoff from VFS at an
81 event scale for either real events or design events.

82 In addition, while they have been successful in research applications, they have not been widely applied in an
83 operational context. In order to make model results more accessible to practitioners, Akan and
84 Atabay(2016) used such a model to create a set of dimensionless charts to be used as an aid for the hydrologic
85 design of vegetative filter strips. While these charts may help to improve simplified design procedures by
86 including the effect of infiltration, they are limited to a certain number of design configurations and were
87 calculated using constant rain intensities and do not, therefore, provide information about system behavior for
88 real rain events.

89 In the present study, a simplified approach of VFS modeling using US EPA SWMM is applied. This model, widely
90 used by practitioners, is user-friendly and open source. While the model presented in this paper only
91 represents the road surface, the vegetated road shoulder (hereafter referred to as a vegetative filter strip or
92 VFS) and the side-slope of the biofiltration swale, SWMM is capable of representing much larger systems and
93 the VFS model could easily be integrated into a more global model of the stormwater management
94 infrastructure of an urban area.

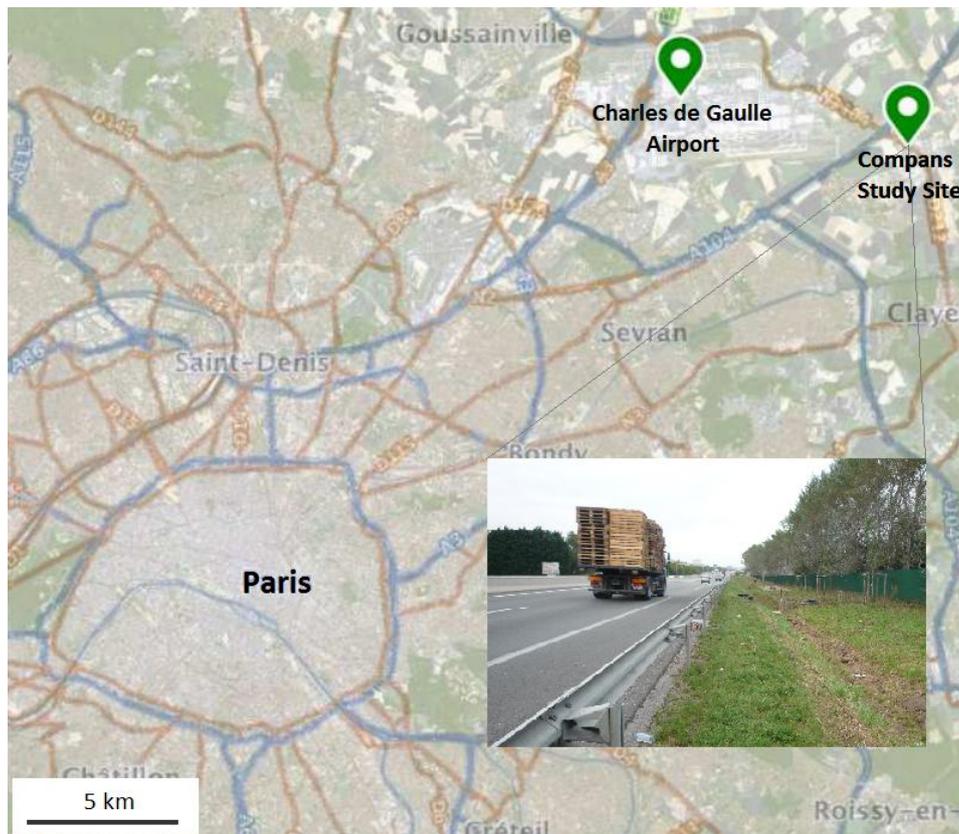
95 Specifically, this work seeks to evaluate the role of a VFS and side-slope in managing road runoff in a treatment
96 train, comparing the proportions of water treated by this part of the system with those treated by a
97 downstream biofiltration swale. It further aims to identify the environmental and design parameters having the
98 greatest influence on these proportions. The current study is unique in its attempt to simulate the hydrologic
99 behavior of a VFS over a long period (4 years) typical of a given climate and in its consideration of the
100 implications of this behavior on the design, evaluation and maintenance of downstream treatment devices.

101 **METHODS**

102 **The Compans case study**

103 The model constructed represents an experimental site located in Compans, a community close to Charles de
104 Gaulle Airport in the Paris region of France. The site, presented in Figure 1, consists of a four-lane roadway with
105 a daily traffic of 11,000 vehicles in each direction and a sustainable drainage system (SuDS) designed to handle

106 the road runoff. At the side of the road, stormwater from two traffic lanes runs off directly onto a vegetative
107 filter strip, then down the side-slope of and into a biofiltration swale where it is retained by concrete check
108 dams in order to ensure its infiltration into the planted filter medium, a sandy loam, beneath the swale.
109 Because runoff is expected to be heavily polluted at this location (in addition to heavy road and air traffic, the
110 site is located in an industrial area), pollution management is an important objective of the system. The current
111 paper is a part of the Roulépur research project, which investigates water quality and the fate of
112 micropollutants in the system.



113

114

Figure 1: Location map and photograph of the Compans case study site

115 Two versions of this system are being studied: one in which the soil of the vegetative filter strip and the side-
116 slope has been replaced by the filter medium and in which both the filter strip and the swale are drained (but
117 not lined) using a sheet drain and one in which typical topsoil (silt loam texture) is used in the vegetative filter
118 strip and the side-slope and neither the filter strip nor the swale are drained. During the design of the system,
119 special attention was given to the choice of both the soil and the plants in the swale in order to optimize
120 depollution processes.

121 However, after three years of operation, observations indicate that less water is present in the swale than

122 expected: the swale's drain has nearly always been dry and plants requiring humid conditions have not
123 survived. The present modeling exercise was therefore undertaken in order to investigate the hypothesis that
124 most runoff infiltrates into the vegetative filter strip and side-slope of the system rather than reaching the
125 swale.

126 Vegetative filter strip runoff modeling

127 The system was modeled within US EPA SWMM 5.1 (Rossman 2015) as a series of rectangular subcatchments
128 representing the road, the vegetative filter strip and the side-slope of the swale as suggested by Gironás et al.
129 (2009). The outlet of the side-slope represents the runoff reaching the biofilter of the swale. . This model
130 represents each sub-catchment as a non-linear reservoir, taking into account the basic hydrologic processes
131 occurring in the system (rainfall, run-on, run-off, infiltration, evaporation) in a simplified manner with a limited
132 number of parameters. A major advantage of SWMM compared to other models existing in the literature is its
133 ability to simulate long periods with a reasonable calculation time, which is necessary to characterize the long-
134 term functioning of the system.



135
136

Figure 2: Geometry of the modeled system

137 The geometry of the system is presented in Figure 2; each sub-catchment is considered to be 48 m wide (note
138 that width here is defined as in SWMM input to be the direction perpendicular to flow, not as width in VFS
139 design guides, which define it as the VFW dimension in the direction of flow), the distance between two check
140 dams in the swale. The road is represented as an impermeable sub-catchment, while the vegetative filter strip
141 and side-slope are considered to be permeable sub-catchments, whose characteristics are presented in Table
142 1. Depression storage and roughness coefficient are typical values for vegetated surfaces (Rossman 2015). All
143 simulations were carried out using Green-Ampt for infiltration modeling for two types of soil (silt loam similar
144 to the typical topsoil and sandy loam similar to the filter medium) and two initial humidity conditions (humid –
145 water content equal to field capacity – and dry – water content equal to the lowest value measured on site, see

146 Table 2). The model assumes a homogenous soil column of infinite depth and is unable to take into account
 147 different drainage conditions. Soil textures were measured experimentally on samples taken in January 2016,
 148 hydraulic conductivity was based on field measurements (Kanso 2015); initial water deficits were based on
 149 continuous field soil moisture content measurements and the suction heads associated were derived from soil
 150 water-retention curves estimated from soil properties using the Rosetta module of the model Hydrus (Schaap et
 151 al. 2001). In order to have an idea of the behavior of the system for a less permeable soil, the long-term
 152 simulation was also carried out for a clay soil, for which the parameters are typical values for the soil type
 153 (Rossman 2015).

154 Simulations were run using three types of rain data: constant-intensity rainfalls, individual rain events and a 4-
 155 year rainfall record. The constant-intensity rainfalls tested each have a total rainfall of 18mm and different
 156 intensities: 1, 3, 4.5, 6, 9 mm/h, corresponding to 4.0, 12.5, 18.8, 25.2, 37.9 mm/h in equivalent rainfall
 157 intensity (i_{eq} , Eq. 1). For comparison, around 55% of rainfall in Paris occurs at an intensity of less than 3 mm/h
 158 and 75% at less than 9 mm/h (Van De Voorde, 2012). These simulations were used to examine the effect of
 159 intensity on the overall system's runoff coefficient (C_R or the total proportion of water reaching the biofiltration
 160 swale, Eq. 2) as well as the model's sensitivity to difficult-to-estimate parameters (depression storage,
 161 Manning's n, hydraulic conductivity). Sensitivity analysis was carried out by varying a single parameter across
 162 the range of possible values while fixing all other parameters at the best estimate.

$$163 \quad i_{eq} = i_{rainfall} \frac{C_{R,road} S_{road} + S_{VFS} + S_{side\ slope}}{S_{VFS} + S_{side\ slope}} \quad (1)$$

164 where $i_{rainfall}$ is rainfall intensity, $C_{R,road}$ is the runoff coefficient for the road surface calculated by the model for
 165 a given intensity, S_{road} , S_{VFS} and $S_{side-slope}$ are the projected surface areas of the road, VFS and side-slope
 166 respectively.

$$167 \quad C_R = \frac{V_{outlet, side\ slope}}{h_{rain} (S_{road} + S_{VFS} + S_{side\ slope})} \quad (2)$$

168 where $V_{outlet, side\ slope}$ is runoff volume exiting the side-slope of the system and entering the biofilter, h_{rain} is total
 169 rainfall, S_{road} , S_{VFS} and $S_{side\ slope}$ are the surface areas of the road, vegetative filter strip and side-slope respectively.

170 Data from an on-site rain gage at a 6-minute time step for four individual rain events, varying in both intensity
 171 and total rainfall, was used in order to better understand the variability in C_R . The fraction of road runoff in the
 172 biofilter (F_{RR} , eq. 3), a coefficient taking into account the dilution of the road runoff at the bottom of the

173 biofiltration swale, was also calculated for each rain event. For its calculation, the pollutant load from direct
 174 rainfall was considered to be negligible. It was assumed that direct rainfall and runoff were well-mixed on each
 175 subcatchment, so that concentrations in infiltration and in subcatchment runoff were equal to each other.

$$176 \quad F_{RR} = \frac{V_{runoff,road}}{V_{runoff,road} + h_{rain}(S_{VFS})} \cdot \frac{V_{runoff,VFS}}{V_{runoff,VFS} + h_{rain}(S_{side\ slope})} \cdot \frac{V_{runoff,side\ slope}}{V_{runoff,side\ slope} + h_{rain}(S_{biofilter})} \quad (3)$$

177 where $V_{runoff,road}$, $V_{runoff,VFS}$, and $V_{runoff,side\ slope}$ are volumes running off of the road, vegetative filter strip and side-
 178 slope respectively, h_{rain} is total rainfall over the event, and S_{VFS} , $S_{side\ slope}$ and $S_{biofilter}$ are surface areas of the
 179 vegetative filter strip, side-slope and biofilter respectively.

Subcatchment	Road	Vegetated Filter Strip	Side-slope
Slope (%)	2	5 (1-10)	66
Length (m)	10.5	1.95 (0.5-3.5)	1.10 (0-1.5)
Depression Storage (mm)	1	5 (1 - 15)	5 (1 - 15)
Roughness coefficient	0.011	0.15 (0.1-0.63)	0.15 (0.1-0.63)

Table 1: VFS and side-slope model parameters

Soil type	Silt loam (native soil)	Sandy loam (filter medium)	Clay
Hydraulic conductivity (mm/h)	23.8 (1 - 36)	13.8 (10-28)	0.254
Suction head (mm)	Humid	91.1	56.3
	Dry	93.7	56.5
Initial water deficit (%)	Humid	17	7.5
	Dry	33	27.5

Table 2: Green-Ampt parameters for soils

Values in italic are best estimates for the site; those in parentheses represent the range used for sensitivity analysis.

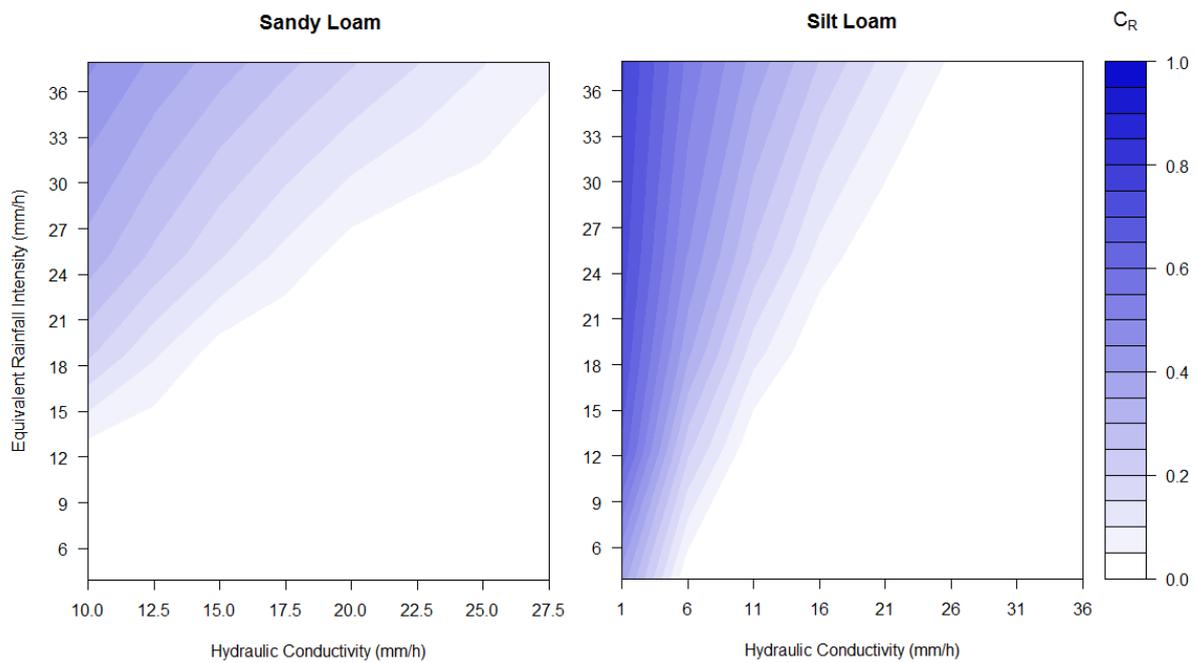
180 Finally, a four-year-long, 5-minute time-step rain record (June 2008-May 2012) from the Paris region was used
 181 to evaluate the volumes of water treated by each part of the system over a long period. A corresponding daily
 182 evapotranspiration record for the same period was used for evaporation modeling. This record was also used
 183 to evaluate the effect that design parameters (filter width, soil type) might have on the overall water balance.

RESULTS AND DISCUSSION

Constant-Intensity Simulations

184 Constant-intensity simulations revealed that the runoff coefficient for the road + vegetative filter strip + side-
 185 slope system is extremely dependent on both rainfall intensity and the hydraulic conductivity of soil (Figure 3).
 186 Indeed, for the silt loam soil, the range of hydraulic conductivity values measured in the field is so wide

187 (between 1-36 mm/h) that for a constant intensity of 9 mm/h, runoff coefficient estimations range from 0 to
 188 0.76. We observe that runoff only occurs when equivalent rainfall intensity (i_{eq}) is superior to the hydraulic
 189 conductivity (K_s) of the soil. It can also be noticed that a slightly higher i_{eq} is necessary to achieve a non-zero
 190 runoff coefficient for the silt loam than the sandy loam. This is because the silt loam's greater suction head
 191 leads to a higher infiltration rate in the Green-Ampt calculation. Results for a lower initial humidity also show a
 192 smaller C_R for the same rainfall intensity and hydraulic conductivity combination due to greater infiltration
 193 rates.



194
 195 **Figure 3 : Runoff coefficient in terms of hydraulic conductivity and equivalent rainfall intensity**
 196 **for (a) sandy loam and (b) silt loam**

197 In terms of system design, these results indicate that soil type and compaction, as well as the ratio of the
 198 surface area of a vegetative filter strip to that of the impermeable, runoff-generating area will strongly affect
 199 the proportion of runoff infiltrated in a VFS. In addition, the importance of rainfall intensity means that the
 200 system's runoff behavior also depends on the precipitation patterns of the location where it is installed. In a
 201 climate like that of Paris, characterized by frequent but generally low-intensity rainfall, one would expect less
 202 runoff than in a climate with more intense rain events.

203 Depression storage is a somewhat sensitive parameter, which may lead to a difference in runoff volume from
 204 the system of up to 15% of total rainfall volume across the range of possible values (Table 3). In the model,
 205 depression storage begins to fill up only when i_{eq} exceeds the infiltration rate. Once the depression storage is

206 filled, the excess volume will run off at a velocity determined by Manning’s equation, which depends on both
 207 the roughness coefficient and the slope. The runoff coefficient is shown to be insensitive to both of these
 208 parameters, as they effectively do not play a role in runoff production but only in the rate at which it occurs. A
 209 limitation of the USEPA SWMM runoff model is its consideration that overland flow is evenly spread over the
 210 subcatchment. In reality, at higher slopes and velocities, flow would begin to concentrate, which would limit
 211 infiltration.

		Silt loam - humid	Silt loam – dry	Sandy loam – humid	Sandy loam - dry
Depression storage	1 – 15 mm	0.20 – 0.35	0.08 - 0.23	0.04 - 0.16	0 - 0.09
Roughness coefficient	0.1 – 0.63	0.30 - 0.31	0.17 - 0.19	0.12 - 0.13	0.05 - 0.06
VFS slope	1 – 10 %	0.30 – 0.31	0.18	0.12 – 0.13	0.05 – 0.06

212 **Table 3: Range of runoff coefficients obtained in sensitivity analysis for a rainfall intensity of 9 mm/h**

213 Despite the simplified representation of this system in SWMM, sensitivity analysis leads to the same
 214 conclusions found by more complex models. Deletic(2001) found total runoff volume to be sensitive to hydraulic
 215 conductivity, but not very sensitive to slope, roughness coefficient or surface retention. Roughness coefficient
 216 and surface retention were most sensitive in an intermediate range of hydraulic conductivity values, wherein
 217 soil was fairly permeable but not so much so that all water infiltrated before reaching the end of the strip.
 218 Muñoz-Carpena et al.(1999) explained that runoff volume is very sensitive to hydraulic conductivity and
 219 somewhat sensitive to initial water content, while the roughness coefficient mainly has an effect on the time to
 220 peak of the hydrograph rather than the runoff volume. Akan and Atabay(2016) showed runoff volume to be
 221 sensitive to the ratio of hydraulic conductivity to rainfall intensity and somewhat sensitive to soil suction (a
 222 combination of suction head and initial water content). Slope and roughness coefficient, regrouped as a
 223 dimensionless coefficient related to Manning’s equation, were sensitive only when this coefficient was small
 224 while hydraulic conductivity and soil suction were high.

225 Individual Rain Event Simulations

226 Characteristics of the simulated events and principal results of these simulations are presented in Table 4. The
 227 peak intensity of July 21, 2014 was the highest measured on site since recording began in 2012 – one would
 228 therefore expect it to have a relatively high runoff coefficient. Although these values (0.25-0.35) are greater
 229 than those estimated for other, less intense rain events (0-0.05), even in this case the majority of road runoff is
 230 treated by the vegetative filter strip + side-slope system rather than the biofilter. For the February and

231 December events, characteristic of typical, low-intensity winter rain events in the Paris region, the quasi-
 232 totality of runoff infiltrates before reaching the biofilter. For the April-May event, characterized by very high
 233 total rainfall and moderate peak intensity, a small fraction (0-0.05) of runoff is treated by the biofilter. The
 234 soil's initial moisture conditions also play a role – less water runs off if the soil is initially dry. As would be
 235 expected, a VFS with sandy loam soil infiltrates more water than one with a less permeable silty loam soil.
 236 Overall, results show that the biofilter's role varies between different types of rain events but is always minor
 237 compared to that of the vegetative filter strip + side-slope system.

Event date	Total rainfall (mm)	Duration (h)	6-minute Peak Intensity (mm/h)	Soil	Initial conditions	Runoff coefficient	Road runoff fraction in biofilter
December 17, 2014	11.2	11.5	4	Silt loam	Humid	0	0
					Dry	0	0
				Sandy loam	Humid	0	0
					Dry	0	0
July 21, 2014	14.1	8.2	56	Silt loam	Humid	0.35	0.60
					Dry	0.29	0.57
				Sandy loam	Humid	0.30	0.57
					Dry	0.25	0.54
February 22-23, 2015	12.9	9.3	6	Silt loam	Humid	0.0014	0.012
					Dry	0	0
				Sandy loam	Humid	0	0
					Dry	0	0
April 30 – May 1, 2015	28.3	29.4	16	Silt loam	Humid	0.05	0.22
					Dry	0.02	0.11
				Sandy loam	Humid	0.01	0.05
					Dry	0	0

238 **Table 4 : Principal results of individual rain event simulations**

239 F_{RR} was found to be variable, covering the range 0-0.60, meaning that even without any pollutant removal,
 240 concentrations reaching the biofilter will be at most 60% of those in road runoff and as little as 0%, the latter
 241 case occurring when all runoff has infiltrated in the vegetative filter strip +side-slope part of the system. One
 242 part of this dilution comes from the increase in volume expected from direct rainfall on the permeable parts of
 243 the system as the surface of the road represents only 74% of the total surface of the studied system. However,
 244 F_{RR} is always below 0.74 because some polluted water is lost to infiltration as it passes through the vegetative
 245 filter strip and side-slope, making the dilution of water remaining on the surface more significant. The extent of
 246 infiltration in the pretreatment system depends on event characteristics; low-intensity rainfall and initially dry
 247 soil conditions both tend to increase the proportion of infiltration, leading to a lower F_{RR} . As a result, the
 248 biofiltration swale inlet concentration cannot be extrapolated from road runoff concentration by any trivial
 249 relationship. This must be taken into account when evaluating treatment efficiency as pollutant removal could

250 not be distinguished from dilution if road runoff concentration is directly compared with the biofilter outlet
251 concentration.

252 **4-year Rainfall Record Simulations**

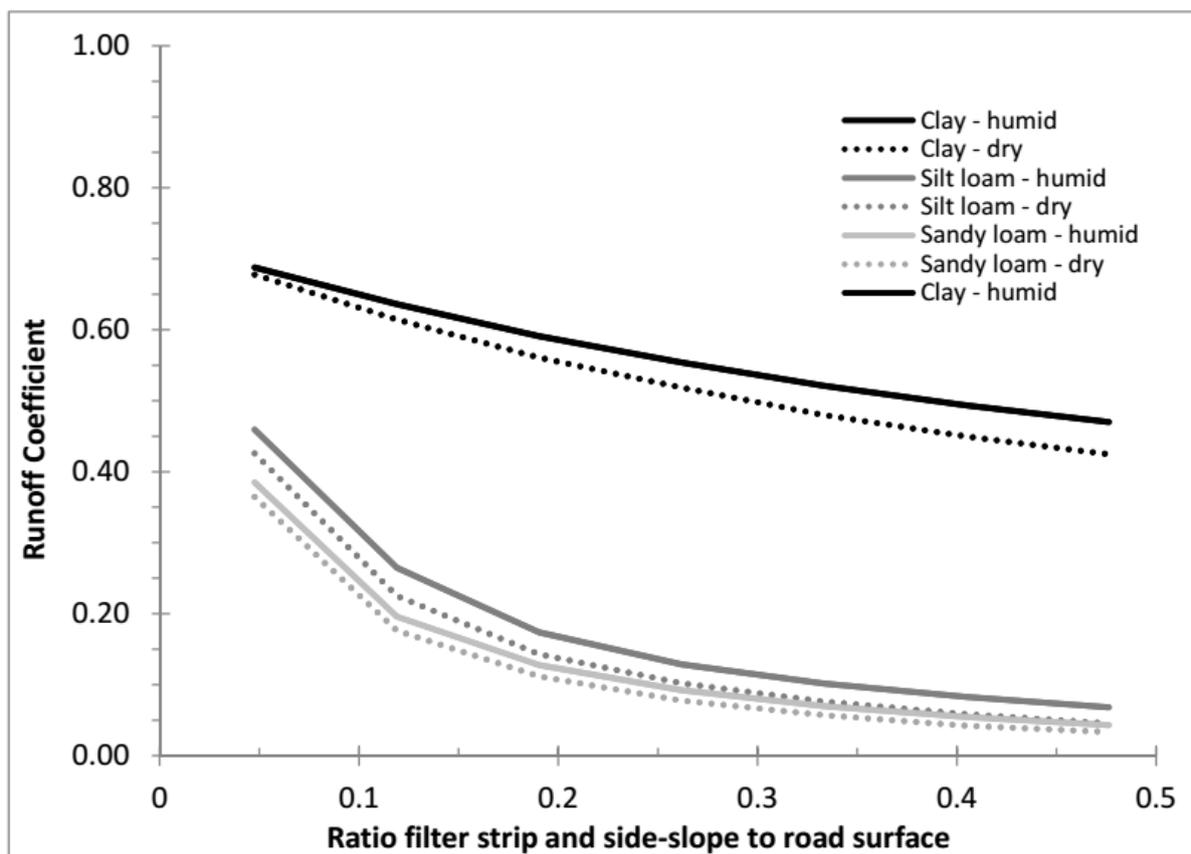
253 Simulating the behavior of the system over a 4-year period allows a large range of precipitation events to be
254 taken into account. Results were again used to calculate a long-term runoff coefficient, representative of the
255 total proportion of rainfall handled by the vegetative filter strip + side-slope system over the period. C_R was
256 found to be 0.090-0.12 for silty loam (depending on initial soil conditions) and 0.068-0.082 for sandy
257 loam. While data records enabling the validation of the model are not available, these results confirm field
258 observations indicating that the ditch rarely receives runoff water, notably that standing water has only been
259 observed in the ditch during one exceptional rain event since its construction, that plants requiring humid
260 conditions have not survived and that non-zero flows measured in the drain beneath the ditch are exceedingly
261 rare.

262 For all cases, 27% of total rainfall was evaporated directly from the road's surface, corresponding to initial
263 losses for which no runoff is generated. For silt loam soil, the biofilter is expected to treat between 11-15% of
264 the road runoff generated, while the other 85-89% would be treated by the vegetative filter strip + side-slope
265 system. The swale's role is slightly less significant for sandy loam, as it will treat 8.6-10% of runoff as opposed
266 to 89-90% treated by the vegetative filter strip + side-slope system. Therefore, a far greater proportion of the
267 pollutant load will be managed by this part of the facility than by the biofilter. In terms of experimental design,
268 this means that when studying the fate of pollutants, the greatest effort should be put into studying the VFS
269 and side-slope part of the system rather than the biofilter itself.

270 **Discussion**

271 These results call for reflection in terms of the SuDS design. When the Compans system was planned, it was
272 assumed that the pollutant load would mainly be handled by the biofilter, the filter strip acting only as a
273 pretreatment, and special attention was paid when choosing its soil and plants in order to optimize pollutant
274 retention and degradation. Less attention was given to the vegetative filter strip + side-slope part of the
275 system. If pollution management is an objective, the retention and degradation of pollutants should be
276 optimized in the part of the system handling the greatest load. Two solutions might allow for a more coherent

277 design: either infiltration could be minimized on the filter strip by minimizing filter width and/or choosing and
 278 compacting a relatively impermeable soil or, as with the biofilter, properties of the filter strip could be chosen
 279 in order to optimize depollution in the soil. If the second solution is chosen, care must be taken to ensure that
 280 the infiltration of water in close proximity to the road does not pose a problem to its structure which may be
 281 situated in part beneath the filter strip.



282

283 **Figure 4 : Evolution of runoff coefficient with the vegetative filter strip + side-slope to road**
 284 **surface ratio**
 285

286 Figure 4 shows the runoff coefficient as a function of the vegetative filter strip + side-slope versus road surface
 287 ratio for three types of soil and two humidity assumptions. These calculations were carried out by varying the
 288 width of the VFS and side-slope across the range presented in Table 1. One can see that even a very narrow
 289 vegetative filter strip + side-slope combination with silt loam or sandy loam soil will infiltrate a substantial
 290 proportion of runoff. This proportion is quite sensitive to the surface ratio at lower values and becomes less
 291 sensitive at higher values, presumably an effect of the probability distribution of rainfall intensity: rainfall
 292 sufficiently intense that it may cause runoff at higher ratios is rare, so a given difference in surface ratio

293 accounts for a smaller volume. Because the clay soil has a very low permeability (0.25 mm/h) compared with
294 that of the other soils, a greater proportion of water reaches the biofilter and the runoff coefficient is less
295 sensitive to surface ratio. It also has a higher suction head, making the infiltration rate more sensitive to soil
296 moisture conditions than the other soils. It should be noted that although clay would provide a low hydraulic
297 conductivity, swelling clays should be avoided as their presence could lead to the formation of fissures and
298 therefore preferential flows in dry conditions.

299 In the absence of data series allowing for the calibration and validation of the model, it is important to be
300 aware of the sources of uncertainty within the model, associated with both the estimation of input parameters
301 and with the model's simplifying hypotheses and limitations. The model's high sensitivity to soil hydraulic
302 conductivity, which varies significantly between in situ measurements, makes this parameter a major source of
303 model uncertainty. To a lesser extent, depression storage, which is estimated based on surface type and to
304 which model results are somewhat sensitive, can also lead to model uncertainty. Although the estimation of
305 Manning's coefficient is also quite uncertain, the insensitivity of the model to these parameters values makes it
306 an insignificant source of uncertainty.

307 Another source of uncertainty in the model lies in its assumption that water is evenly spread across the surface
308 of each sub-catchment and that all runoff from the road enters the vegetative filter strip. In reality, maintaining
309 sheet flow in such a system is a challenge, especially in highly polluted catchments where sediment deposits
310 can block water inflow at some points, leading to concentrated flows at others, which would lead, overall, to
311 less infiltration. In Compans, it has also been observed since that the soil level has risen since the construction
312 of the system in 2012 on the silt loam part of the system. The level of the vegetative filter strip is now a few
313 millimeters higher than the level of the road, leading to lateral flows and smaller volumes of water entering the
314 filter strip than expected. As a system ages, even very small evolutions in topography can lead to major
315 differences in its real behavior from the theoretical behavior represented by the model, leading to significant
316 uncertainty. In future work, it would be useful to develop methods for testing the hypothesis of sheet flow in
317 the field.

318 The US EPA SWMM Green-Ampt infiltration model also makes several simplifying hypotheses which can be a
319 source of uncertainty. One limitation of this model is that there is no accurate mechanism for calculating
320 evapotranspiration from the soil. Rather, after the end of a rain event, the water content will begin to decrease

321 at a rate related to the soil's saturated hydraulic conductivity. After a few days (from complete saturation 4.2
322 days for the silt loam and 3.2 days for the sandy loam), soil moisture returns to its initial value, which is
323 considered to be its minimal water content; it is therefore impossible to account for the variability of soil
324 moisture conditions in a long-term simulation. Evaporation is only calculated for water on the soil surface.
325 Another limitation is its assumption within a rain event of an infinite and homogenous soil column. In the case
326 of Compans, the road's structure is present beneath a large portion of the silt loam vegetated road shoulder,
327 which may limit infiltration during major storm events or especially wet periods. The shoulder made of sandy
328 loam is drained at a depth of about 15 cm; infiltration will not be limited in the same way for wet periods, but
329 the Green and Ampt model's representation of both wetting and drying differs greatly from the real system's
330 behavior. These limitations due to the Green and Ampt model are common to other vegetative filter strip
331 models found in the literature (Akan and Atabay 2016; Deletic 2001; Muñoz-Carpena et al. 1999). Future work
332 should attempt to better represent both evapotranspiration and the influence of the road structure and the
333 drain on infiltration and flow of water in the soil.

334 CONCLUSIONS

335 A model of infiltration and runoff on the vegetative filter strip + side-slope portion of a VFS and biofiltration
336 swale treatment train located in Compans, France was created in USEPA SWMM in order to gain a better
337 understanding of the system's hydrologic behavior.

338 Sensitivity analysis results show that rainfall intensity and soil hydraulic conductivity are the most sensitive
339 factors influencing whether water is infiltrated or runs off toward the biofilter. As a consequence, systems of
340 similar geometry located in different climates or having different soil types, may function very differently. In
341 addition, this result underlines the importance of correctly characterizing a site's hydraulic conductivity when
342 constructing a model; the heterogeneity of hydraulic conductivity within a given site can be an important
343 source of uncertainty in the model. The runoff coefficient was found to be insensitive to sub-catchment slope
344 and Manning's roughness coefficient and moderately sensitive to depression storage estimation. The
345 vegetative filter strip + side-slope to road surface area ratio also has a significant effect on runoff coefficient;
346 the more permeable the soil, the more sensitive results are to this factor.

347 Simulations of synthetic, constant-intensity rain events showed that runoff occurs only when equivalent rainfall

348 intensity is greater than the soil's saturated hydraulic conductivity. This is because runoff will only occur once
349 the depression storage is filled and depression storage will only begin to fill when the equivalent rainfall
350 intensity surpasses the rate of infiltration, which will be equal to or greater than the saturated hydraulic
351 conductivity (when the soil is unsaturated, a suction head is applied which will increase infiltration rate). The
352 time necessary to fill the depression storage depends on the difference between equivalent rain intensity and
353 the infiltration rate.

354 Simulation of four real rainfall events and a 4-year rainfall record revealed that the majority of road runoff is
355 treated by the vegetative filter strip and side-slope of the biofiltration swale rather than the biofilter located
356 beneath the swale. Therefore, the biofilter's pollutant removal efficiency plays a less significant role in the
357 efficiency of the overall system than that of the vegetative filter strip and side-slope of the system. In terms of
358 experimental design for evaluating pollutant removal efficiency, this means that it is more important to
359 characterize treatment in the vegetative filter strip and side-slope part of the system than in the biofilter. In
360 addition, it was found that road runoff reaching the biofilter would be strongly and variably diluted by rain
361 falling directly on the system.

362 Results also have implications for SuDS design, as the system's current design, which aims to optimize pollutant
363 retention and degradation in the biofilter but not in the vegetative filter strip + side-slope, is not coherent with
364 its real hydraulic behavior. In reality, the system is more similar to that proposed by the Swiss Federal Road
365 Office in which water is infiltrated and filters through the soil of an embankment slope after running off across
366 a shoulder where infiltration is minimized (Piguet et al. 2009) than to a biofiltration swale.

367 This study highlights the importance of understanding the hydrologic behavior of a system before planning a
368 water quality analysis. More generally, it shows the necessity of using a model, even a highly simplified one, to
369 study the hydrologic behavior of a SuDS during the design process. If system hydraulic conductivity can be
370 accurately estimated, US EPA SWMM can be a useful tool for predicting the hydrologic behavior of SuDS
371 involving vegetative filter strips, thereby allowing water quality design to focus on the most relevant parts of
372 the system. However, simplifications in its representation of hydrological processes (evapotranspiration,
373 infiltration, surface flow) may lead to differences between modeled and real behavior under certain
374 circumstances. In addition, the model represents the theoretical behavior of an idealized system – therefore, it
375 cannot represent dysfunctions that may occur as the system ages, such as the formation of concentrated flow

376 paths or lateral flows due to an increase in the soil level.

377 The authors have several recommendations for future research. First, for the better understanding of SuDS
378 treatment train behavior, analogous models should be developed and tested for other possible combinations
379 of SuDS devices (a swale followed by stormwater biofilter, for example). Secondly, future work can contribute
380 to improving the present model, notably by improving the representation of water once it is in the soil,
381 including the representation of evapotranspiration and different drainage conditions. The model's uncertainty
382 could also be reduced by developing recommendations for estimating a global hydraulic conductivity value
383 from a series of experimental measurements.

384 Further in situ experimental monitoring would also be useful to improve understanding of real system
385 behavior. The calibration and validation of the current model require continuous measurement of flows
386 entering and leaving the system; this type of monitoring remains a technical challenge. In addition, it has been
387 mentioned that sheet flow, which is usually an objective of filter strip design and is an assumption of the
388 model, may be difficult to achieve in the field. The development of experimental methods for testing whether
389 sheet flow is actually achieved would therefore be useful both in order to verify whether systems are
390 functioning correctly and to evaluate the pertinence of models based on this assumption.

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