Evaluation of the relative roles of a vegetative filter strip and a biofiltration swale in a treatment train for road runoff

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Evaluation des rôles relatifs d'une bande enherbée et d'un fossé filtrant dans un ouvrage de traitement des eaux de ruissellement de voirie

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RÉSUMÉ

Afin de déterminer l'importance relative d'une bande enherbée dans un ouvrage combiné bande enherbée - fossé de biofiltration de traitement des eaux de ruissellement de voirie, le ruissellement et l'infiltration au niveau de la bande enherbée ont été modélisés avec US EPA SWMM. Le modèle consiste en une série de sous-bassins versants représentant la route, la bande enherbée et le talus du fossé. Des simulations ont été menées pour différents scenarios de pluies représentant une variété de conditions climatiques et en menant une analyse de sensibilité sur les différents paramètres du modèle (nature du sol, humidité initiale, rugosité, géométrie…). Cet exercice a montré que pour le système étudié, la grande majorité de l'eau est gérée par la bande enherbée et non pas par le fossé de biofiltration dans lequel peu d'eau arrive, notamment quand l'intensité de la pluie est faible. De plus, il a été observé que la combinaison de l'infiltration de l'eau de voirie sur la bande enherbée et de l'apport en précipitation directe sur l'ouvrage conduit à une dilution significative et variable de l'eau atteignant le fossé. Ces résultats ont des implications importantes pour l'évaluation de l'efficacité épuratoire du système.

ABSTRACT

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

KEYWORDS

Vegetative filter strip, biofiltration, road runoff, infiltration, modeling

1 INTRODUCTION

Although historically designed for stormwater conveyance, changing stormwater management paradigms have led grass swale design objectives to expand to include water quality improvement and retention of runoff on site. Although sedimentation and filtration as water flows through dense vegetation have been shown to improve water quality in traditional grass swales (Stagge et al., 2012; Winston et al., 2012), some studies have shown this effect to be unreliable, varying greatly between storm events. (Bäckström et al., 2006)

One strategy to enhance water quality improvement while retaining more water on site is to encourage infiltration by installing check dams while replacing natural soil beneath the swale with a highly permeable filter medium, optimizing natural depollution processes as in a bioretention or biofiltration system. In linear form, such a system may serve the roles of water retention, depollution and conveyance and is often referred to as a biofiltration swale. (Hatt et al., 2009)

In order to prevent clogging in biofiltration systems, many design guides recommend pretreating road runoff with a vegetative filter strip (Hatt et al., 2009; Prince George's County, 2007; Woods-Ballard et al., 2007). Like grass swales, vegetative filter strips (VFS) remove particulate pollutants through sedimentation and filtration, while infiltration in the strip's soil results in runoff volume reduction (Barrett et al., 1998; Li et al., 2008). In the soil, pollutants may be retained by filtration and sorption processes.

VFS and biofiltration systems are thus often used in succession. In order to better understand pollutant fate in the system, this study seeks to evaluate and compare the proportions of water managed by the vegetative filter strip and biofiltration swale portions of a treatment train using a model constructed in USEPA SWMM. It further aims to identify the environmental and design parameters having the greatest influence on these proportions.

2 MATERIALS AND METHODS

2.1 The Compans case study

The model constructed represents an experimental site located in Compans, a community close to Charles de Gaulle Airport in the Paris region (France). The site consists of a four-lane roadway with a daily traffic of 11,000 vehicles per direction and a sustainable drainage system (SuDS) designed to manage road runoff. At the road's shoulder, stormwater from two traffic lanes runs off directly onto a vegetative filter strip, then down the side-slope of and into a biofiltration swale where it is retained by concrete check dams in order to force its infiltration into a filter medium installed beneath the swale.

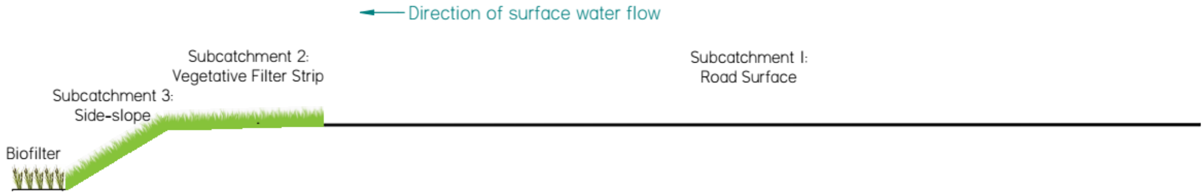

Figure 1: Schema of the Compans system

Two versions of this system are studied: one in which the soil of the VFS has been replaced by the filter medium and in which both the VFS and the swale are drained (but not lined) using a sheet drain. The other version uses native soil in the VFS, and neither the VFS nor the swale are drained. The present modeling exercise was undertaken in order to investigate the hypothesis based on field observations that most runoff is managed by the VFS rather than the swale.

2.2 Vegetative filter strip runoff modeling

The system is modeled within the United States Environmental Protection Agency Storm Water Management Model (US EPA SWMM 5.1) as a series of subcatchments representing the road, the VFS and the swale's side-slope. The system's outlet is the biofilter, which is not represented in the model.

The road is considered to be an impermeable subcatchment, while the VFS and side-slope are considered to be permeable subcatchments, whose characteristics are presented in Table 1. All simulations were carried out using Green-Ampt for infiltration modeling for two different soils (silt loam and sandy loams soils) and two different initial humidity conditions (see Table 2). The model does not allow consideration of different drainage conditions or heterogeneity or anisotropy in soil parameters.

$$C_R = \frac{V_{runoff,side\ slope}}{h_{rain}(S_{road}+S_{VFS}+S_{side\ slope})} \quad (1)$$

where $V_{runoff,\ side\ slope}$ is the volume running off from the side-slope of the system, h_{rain} is total rainfall, S_{road}, S_{VFS} and $S_{side\ slope}$ are the surface areas of the road, VFS and side-slope respectively.

Simulations were run using three types of rain data. Constant rainfalls of different intensities (1, 3, 4.5, 6, 9 mm/h) each with a total rainfall of 18 mm were used to examine the effect of intensity on the system's runoff coefficient (C_R, see equation 1) as well as the model's sensitivity to difficult-to-estimate parameters (depression storage, Manning's roughness coefficient, hydraulic conductivity). Sensitivity analysis was carried out by varying a single parameter at regular intervals across the range of possible values while fixing all other parameters at the best estimate based on field observations; evaporation was considered to be equal to 2 mm/day.

Data from an on-site rain gauge at a 6-minute time step for four individual rain events, varying in both intensity and total rainfall, were used in order to better understand C_R's variability between different events. For these simulations all parameters were fixed at the best estimate values; evaporation was considered to be equal to 2 mm/day.

The fraction of road runoff in the biofilter (F_{RR}, see equation 2), a coefficient taking into account the dilution of the road runoff, was also calculated for each rain event. For its calculation, the pollutant load from direct rainfall was considered to be negligible. It was assumed that direct rainfall and runon were well-mixed on each subcatchment, so that concentrations in infiltration and in subcatchment runoff were equal to each other.

$$F_{RR} = \frac{V_{runoff,road}}{V_{runoff,road}+(h_{rain})(S_{VFS})} \cdot \frac{V_{runoff,VFS}}{V_{runoff,VFS}+(h_{rain})(S_{side\ slope})} \cdot \frac{V_{runoff,side\ slope}}{V_{runoff,side\ slope}+(h_{rain})(S_{biofilter})} \quad (2)$$

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

Subcatchment	Route	Vegetated Filter Strip	Side-slope
Surface area (m²)	*504*	*93.6* (24-168)	*52.8* (0-72)
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 media)	Clay
Hydraulic conductivity (mm/h)		*13.8* (1 - 36)	*23.8* (10-28)	0.254
Suction head (mm)	Humid	*91.1*	*56.3*	316
	Dry	*93.7*	*56.5*	316
Initial water deficit (%)	Humid	*17*	*17*	7.5
	Dry	*33*	*29*	27.5

Table 2: Green-Ampt parameters for soils

Values in italic are best estimates for the site, where possible estimated from measurements taken in the field (Kanso 2015); those in parentheses represent the range used for sensitivity analysis. Clay parameters are typical values (Rossman, 2015), used only to consider the effect of using a less permeable soil.

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

3 RESULTS AND DISCUSSION

3.1.1 Constant-Intensity Simulations

Constant-intensity simulations revealed that the runoff coefficient for the road + VFS + side-slope system is extremely dependent on both rainfall intensity and the hydraulic conductivity of soil. It was observed that at low intensities little or no runoff was generated and that C_R increased with increasing intensity. The very wide range of hydraulic conductivity values measured on site for silt loam led to a high variability of C_R (0-0.76).

VFS and side-slope depression storage are somewhat sensitive parameters, leading to a difference in runoff volume of up to 15% of total rainfall volume across the range of possible values, whereas parameters used for calculating velocity and residence time (roughness coefficient and slope) were found to have very little effect on C_R (at most 2% of total rainfall volume). A limitation of the US EPA SWMM runoff model is its consideration that overland flow is evenly spread over the subcatchment. In reality, at higher slopes and velocities, flow would begin to concentrate, which would limit infiltration.

3.1.2 Individual Rain Events

Simulation of 4 rain events (Table 3) showed that C_R was generally small (the maximum value calculated was 35% for an event with a peak intensity of 138 mm/h, exceptionally high for the Paris region). An event with a peak intensity of 6 mm/h produced no runoff, while others with peak intensities of 12 mm/h and 24 mm/h produced a C_R values of at most 0.1% and 5% respectively. The previous values correspond to initially humid conditions, as the soil's initial moisture conditions play a role in determining C_R – less water runs off if the soil is initially dry. For example, for the events mentioned, C_R in dry conditions for the same silt-loam soil was found to be 0% or 2% respectively. As would be expected, a system with sandy loam soil infiltrates more water than one with a less permeable silt loam soil.

Event date	Total rainfall (mm)	Duration (h)	Peak Intensity (mm/h)	Model results		
				Road runoff volume (m^3)	VFS runoff volume (m^3)	Side-slope runoff volume (m^3)
December 17, 2014	11.2	11.5	6	4.6	0	0
July 21, 2014	14.1	8.2	138	6.3	2.9 - 3.6	2.3 - 3.2
February 22-23, 2015	12.9	9.3	12	5.6	0.02 - 0.9	0 - 0.01
April 30 – May 1, 2015	28.3	29.4	24	12.5	0.8 - 1.8	0 - 0.9

Table 3: Characteristics of real rain events simulated

F_{RR} was found to be variable, covering the range 0-0.60, meaning that concentrations of pollutants reaching the biofilter will be at most 60% of those in road runoff and as little as 0%, the latter case occurring when all runoff has infiltrated in the VFS+side-slope part of the system. One part of this dilution comes from the increase in volume expected from direct rainfall on the permeable parts of the system as the surface of the road represents only 74% of the total surface of the studied system. However, F_{RR} is always below 0.74 because some polluted water is lost to infiltration as it passes through the VFS and side-slope, making the dilution of water remaining on the surface more significant. Because infiltration in the pretreatment system depends on the rain event characteristics and initial moisture conditions, this part of the dilution is highly variable, making the evaluation of the treatment efficiency of the different parts of the system quite difficult. A direct comparison of road runoff concentrations with concentrations in the biofilter outlet could be very misleading.

3.1.3 4-year Rainfall Record

Simulating the behavior of the system over a 4-year period allows a large range of precipitation events to be taken into account.

For all cases, evaporation from the road surface (initial losses for which no runoff was generated) accounted for 27% of total rainfall on the road subcatchment. For the Compans geometry, the biofilter is expected to treat between 12-15% of road runoff generated for silt loam, while the other 85-88% of total runoff volume will be treated by the filter strip + side-slope system (C_R=9-11%, depending on initial soil moisture conditions). The biofiltration swale has a slightly less significant role for sandy loam, treating 9-11% of road runoff as opposed to 89-90% treated by the VFS+side-slope system (C_R=6.8-8.2%). A far greater proportion of

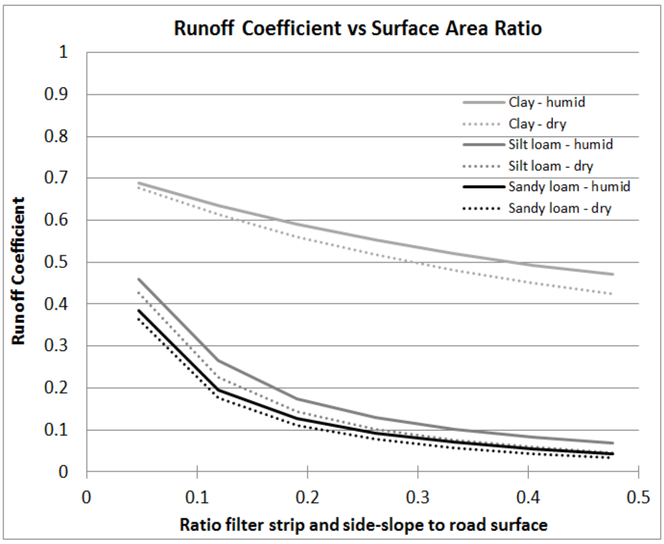

Figure 2 : Evolution of runoff coefficient with the VFS + side-slope to road surface ratio

the pollutant load is treated by the VFS +

side-slope than by the biofilter for both soil types and both initial conditions considered.

In order to understand the effect that varying system geometry or soil type may have on runoff coefficient, Figure 2 shows the runoff coefficient as a function of the VFS+side-slope / road surface ratio for three types of soil and two humidity assumptions. For silt loam and sandy loam, C_R is found to be small even for a very narrow VFS. For clay soil, C_R is less sensitive to surface ratio and more sensitive to initial humidity conditions due to its lower permeability and higher suction head, respectively. Using a clay soil may be useful for limiting infiltration if this is a goal; however, swelling clays should be avoided as their presence could lead to the formation of preferential flows in dry conditions.

4 CONCLUSIONS

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

Sensitivity analysis results show that rainfall intensity and soil hydraulic conductivity are the most sensitive factors influencing whether water is infiltrated or runs off toward the biofilter. As a consequence, geometrically similar systems located in different climates or with different soils may function very differently. In addition, this result underlines the importance of correctly characterizing a site's hydraulic conductivity when constructing a model and using rain data with an appropriate time step. C_R was found to be insensitive to subcatchment slope and Manning's roughness coefficient and moderately sensitive to depression storage values.

Simulation of four real rainfall events and a 4-year rainfall record revealed that the majority of road runoff is managed by the VFS and side-slope of the biofiltration swale rather than the biofilter located beneath the swale. This means that the biofilter's pollutant removal efficiency plays a less significant role in the efficiency of the overall system than that of the VFS and side-slope of the system. Therefore, when studying pollutants in the system, it is important to focus on contaminant fate in the VFS+side-slope part of the system.

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

This study highlights the importance of understanding the hydrologic behavior of a system before planning a water quality analysis. More generally, it shows the necessity of using a model, even a highly simplified one, to study the hydrologic behavior of a SuDS during the design process. If system hydraulic conductivity can be accurately estimated, US EPA SWMM can be a useful tool for predicting the hydrologic behavior of SuDS involving vegetative filter strips, thereby allowing water quality design to focus on the most relevant parts of the system.

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