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Jean-François Durmont, Jérémie Sage, Marie-Christine Gromaire. How far can we rely on lined green infrastructures for urban runoff control? A case study in Paris conurbation. International Conference on Urban Drainage (ICUD), Jun 2024, Delft, Netherlands. <hal-05196716>

HAL Id: hal-05196716

<https://enpc.hal.science/hal-05196716v1>

Submitted on 2 Aug 2025

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How far can we rely on lined green infrastructures for urban runoff control? A case study in Paris conurbation

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Highlights

- The runoff volume reduction efficiency of a fully lined bioretention swale was evaluated.
- Describing such systems in SWMM, when they include flow-rate control, is not straightforward.
- Lined solutions, that solely rely on evapotranspiration, may not provide adequate runoff-control.

Introduction

Green infrastructures for urban runoff source control have been increasingly promoted over the last years, as they offer multiple benefits extending beyond hydrological and hydraulic management targets. While flow-rate control has been a major management goal in many countries over the past decades, in order to meet urban flooding issues (Petrucci et al., 2013), it is now well admitted that this should not be the only target and that runoff source control structures (SUDS) should contribute to the restoration the water balance in urban areas, with reduced runoff volumes, enhanced infiltration fluxes, groundwater recharge (Burns et al., 2012) but also evapotranspiration. In the context of climate change, which in western Europe is leading to more frequent and intense urban heat waves and droughts, SUDs involving vegetated soils can also contribute to sustainable urban greening for more liveable cities (Prudencio and Null, 2018).

While runoff infiltration, at least for frequent rain events, is today presented as the preferred approach for stormwater management in French guidelines (DRIEE, 2020), some underground contexts (e.g. polluted soils; geotechnical constraints such as quarries, gypsum or swelling clays) actually precludes its implementation. In those cases, it is currently suggested to rely on lined vegetated systems to provide some volume-reduction through evapotranspiration. However, the runoff reduction performance of such systems has not been fully demonstrated yet, and available SUDS design tools might not be completely adequate to describe them.

The objectives of this work were twofold: 1) assess the usability of SWMM to simulate the hydrologic behaviour of complex lined SUDS systems, 2) evaluate the possible contribution of lined bioretention swales to the urban water balance control, based on a case study in Paris conurbation.

Montjoie case study site

The case study covers a 300 m long and approximately 6300 m² street catchment situated within ZAC de la Montjoie, a newly developed district in St Denis, Greater Paris. In Montjoie district, source control of runoff has been generalised on both private and public spaces with the following targets: on site retention of runoff, discharge to the existing combined sewer limited to 10 l/s/ha, promotion of local uses of the stormwater and of vegetated SUDS for runoff abstraction. Due to the presence of gypsum in the underground, exfiltration of runoff to the natural underground was not allowed, and all SUDS implemented in the public area had to be lined. The system used for the management of runoff from the considered street is a lined bioretention swale, divided into 8 reaches, that couples several hydrological functions: runoff abstraction via soil water recharge and evapotranspiration, runoff detention and flow-rate control, open air transport to a downstream discharge point. The swale has a trapezoidal cross section, with a width of 4.4 m, maximum surface storage depth of 40 cm, and an underlying soil layer consisting of 30 cm topsoil and 120 cm earth-stone mixture, lined with a membrane. Its longitudinal slope follows the one of the street (0.5%). Water enters the system as superficial sheet flow runoff from the adjacent pavement and the sidewalk. Flow from one reach of swale to the next is limited with a nozzle. At the downstream outlet, a vortex flow regulator limits the discharge to the sewer to 10 l/s/ha.

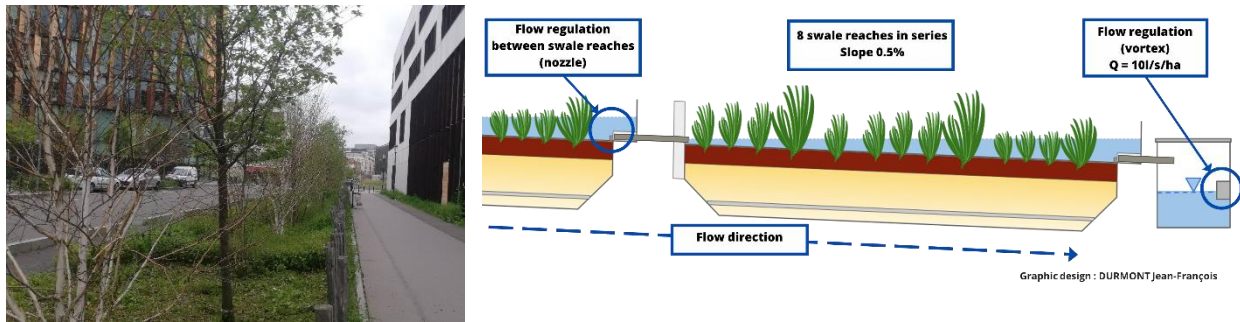


Figure 1. Longitudinal profile of the bioretention swale - Schematic scheme

Methodology

Conceptualisation of the studied system in SWMM

The study site was modelled with SWMM, in order to assess long term effect of infiltration and evapotranspiration in the lined bioretention swale on runoff volume reduction. The LID module of SWMM, which includes transportation swales and lined bioretention systems, does not allow for a flow-controlled surface outlet. On the other hand, storage units used to simulate detention ponds cannot represent infiltration into a soil layer with limited depth. Thus, the studied system was conceptualized as a combination of lined raingardens to represent infiltration and soil water storage in the bioretention swale soil layer, and of a downstream storage unit to represent detention and flow regulation of runoff on the swale surface. Each of the 8 swale reaches was represented by 2 lined raingardens. Raingarden Ri.a represents the sloped embankments of the swale reach n^oi. It receives inflow runoff from two impervious subcatchments representing respectively the adjacent pavement and walkway. Surface outflow from Ri.a is sent to raingarden Ri.b which represents the flat bottom of the swale reach i. Overflow from Ri.b is discharged into the next reach, raingarden Ri+1.b. The last raingarden, R8.b, discharges into an impervious storage unit, whose maximum storage volume is equal to the maximum storage volume over the whole swale system (taking into account the effect of longitudinal slope) and whose discharge is regulated by application of the depth/flow law of the vortex regulator.

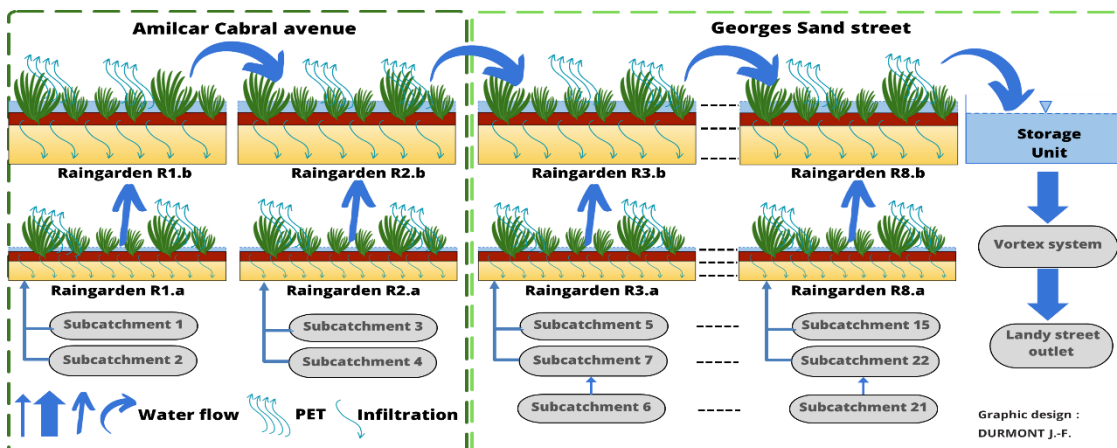


Figure 2. Representation of the case study in SWMM

Sensivity analysis of the model

A water level sensor was initially implemented in the manhole where the vortex is located so as to estimate discharge flows (based on the characteristic height/flow relationship of the vortex device). However, it appeared during the experiment that the regulator is subject to backwater effects due to a check valve. Thus, measured water levels could only be used to identify periods with outflow but not to calculate the discharge. In order to assess to what extent our conceptualisation of the system (e.g raingarden surface ponding) could affect the modelled volume reduction performance, but also to assess the effect of uncertain knowledge of some characteristics of the bioretention swale (e.g. soil parameters) and of some processes (e.g. evapotranspiration), a sensitivity analysis was performed on the main parameters that may affect outlet

runoff volumes. For each parameter, a reference value was considered and variations induced by the modification of this parameter over a test range were simulated (Table 1).

Maximum surface ponding was set to 2.5 mm, with a range 1 to 10 mm, for Ri.a and to 10 mm, with a range 5 to 30 mm, for Ri.b. Soil properties values were based on a set of 4 Best single ring infiltration tests performed on site. The average value derived from the different tests was considered for the reference values, while the range between tests was taken for sensitivity analysis. For evapotranspiration, potential evapotranspiration PET calculated with Penman-Monteith for a lawn (for a distant meteorological station) was used as reference value, and a factor of variation $k = 0.5$ to 3 was considered.

The model was run for rainfall and PET data from 01/01/2022 to 31/05/2023. The period considered for the analysis of the results is 01/03/22 to 31/05/23. Indeed, sensitivity analysis to initial soil moisture condition showed that this parameter did not have any influence anymore after the first two months. Parameters were varied one by one, at a step of 2%, while the other parameters were set to the reference value. For each run, total outflow volume was calculated as well as minimum and average value of the soil water content of the soil in raingardens R1.a, R1.b, R8.a and R8.b. The efficiency in runoff volume reduction was analysed for different k values of ET, at different temporal scales: whole period, month, rain event. It was calculated as $E = (V_{in} - V_{out}) / V_{in}$ with V_{out} the discharged volume at the outlet of the system and V_{in} the total volume from the impervious subcatchments + direct rainfall on the raingarden subcatchments.

Table 1. SWMM model parameters for raingardens – reference value and range of value tested in the sensitivity analysis

		Reference value	Range of variation
Maximum raingarden ponding (mm)	Ri.a	2.5	1 - 10
	Ri.b	10	5 - 30
Distribution of raingarden areas	$Ri.b = \alpha (Ri.a + Ri.b)$	$\alpha = 0.68$	$\alpha = 0.6 - 0.7$
Soil parameters	Soil depth (cm)	150	130 - 170
	K_s (m/s)	6.4×10^{-6}	$10^{-6} - 3 \times 10^{-5}$
	Porosity n	0.485	0.3 - 0.6
	Water content at field capacity W_{fc}	0.235	0.19 - 0.26
	Water content at wilting point W_{wp}	0.114	0.08 - 0.15
Initial soil condition	% of saturation of $(n - W_{fc})$	32.6	0 - 100
Evapotranspiration	$ET = k \text{ PET}$	$k = 1$	$k = 0.5 - 3$

Results and discussion

General model sensitivity

Sensitivity analysis showed that $k = ET/PET$ was the only parameter inducing significant variations in the total outflow volume. Surface ponding depth and soil parameters did not show any significant effect, which probably means that volume abstraction is limited by a relatively limited average storage capacity in the soil over the modelling period. Indeed, for the reference simulation, soil water content remains high all along the simulation period, with an average value over this period in the range 0,424 to 0,464 for all raingardens, and a minimum value over the period of 0,356 for Ri.b and 0,163 for Ri.a. When increasing the k factor, the average and minimum soil water content decrease (respective ranges 0,357 to 0,387 and 0,115 to 0,121). Thus, sensitivity to ponding depth or hydraulic conductivity is likely to increase with increasing k . However, as our sensitivity analysis was done by varying parameters one by one this could not be observed.

Effect of ET/ETP ratio on runoff volume reduction

The impact of $k = ET/PET$ ratio is shown in figure 3a. Expectedly, the influence of this parameter is significant as the latter directly controls the magnitude of the only hydrologic loss applying to the system. E here ranges between 15% and 77%. In other words, conclusions regarding the performance of the system dramatically change depending on the parameterization of ET.

Based on current knowledge, the upper range of tested values (e.g., 2 to 3) should here probably be regarded as quite hypothetical. Although PET provided at a distant weather station may not completely reflect local site and vegetation conditions, such departures from reference PET values seem well above commonly observed ET-rates (Ouédraogo et al., 2023, 2022). For more realistic k values, between 0.5 and 1.5, volume efficiency remains very limited and does not exceed 50%. Corresponding event-based volume reductions

efficiencies are shown in figure 3b. Even for $k = 1.5$, discharge occurs from the systems for most events (efficiencies below 100%) and median efficiency remain very low (less than 30%).

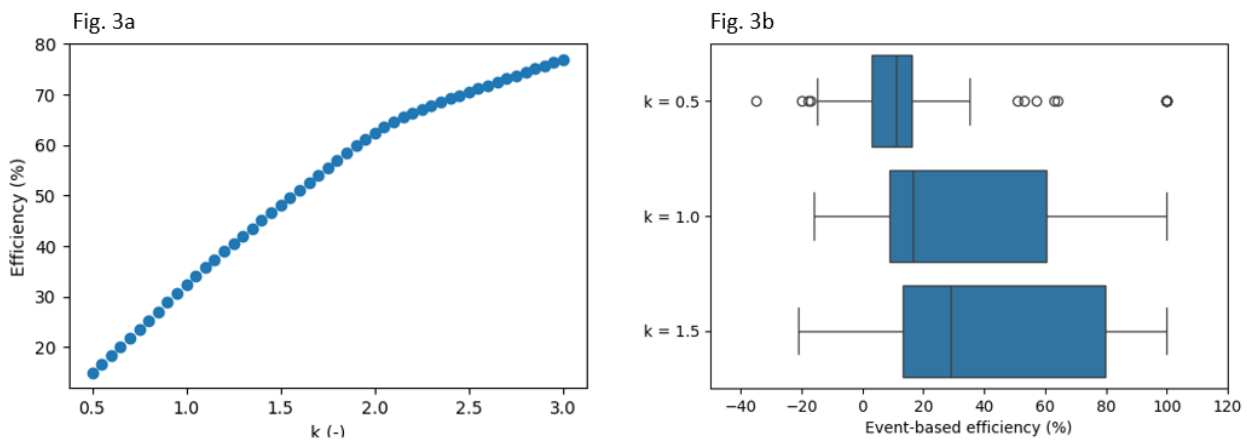


Figure 3. Impact of ET/PET ratio on simulated efficiencies. 3a: Total volume reduction efficiency as a function of $k = ET/PET$. 3b: event-based efficiencies (beginning of runoff inflow to end of discharge) for $k = 0.5, 1.0$ and 1.5

As mentioned above, available observations do not allow to properly evaluate the ability of the model to simulate discharge rates at the outlet of the system for the different configurations. A simple analysis based on the number of events producing discharge however suggests that $k = 0.5$ and 1.0 , with 25 and 21 events for 26 observed events, are closer to reality than $k = 1.5$.

Conclusions and future work

The usability of the SWMM model to describe a complex lined swale system, involving flow-rate control and evapotranspiration (ET) as the only driver for volume reduction, was illustrated. A preliminary application of the model was conducted on a case study in Paris conurbation. Simulated runoff volume reduction efficiencies were found to strongly depend on the parameterization of ET. Despite the limitations of the current approach, results clearly suggest that the runoff-control performance of lined systems, even for small frequent rain events, may often not be as satisfactory as expected. Further examination of the conditions, including climate or SUDS design, under which ET can provide adequate runoff control is probably needed. Finally, if SWMM presumably provides an appropriate basis for the conceptualization of lined solution, the importance of ET in such configurations presumably calls for further assessment of the applicability of the simplistic ET schemes it involves (which is also a trait of other SUDS design tools).

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