Observatoire des Polluants URbains (OPUR)

Action R3.2 : Performance hydrologique des jardins de pluie : mesures en conditions controlees et modelisation pour une diversite de contextes

BACKGROUND AND OBJECTIVES

Nowadays, due to the rapid urbanisation and climate change impact, the traditional grey drainage systems are under challenges. For instance, combined sewer overflow, reduction of infiltration (less groundwater recharge), drought, lack of water resources and urban heat islands (Benedict & McMahon, 2002). All these challenges introduce the need for new paradigms in stormwater management, such as Sustainable Urban Drainage System (SuDS). As one of the Sustainable Urban Drainage System facilities, bioretention is widely studied around the world for its hydrological performance and quality control (pollutant removal) performance. However, there are still gaps and questions remaining in the long-term performance monitoring, as well as on the detailed understanding of various hydrological processes, especially under different design and local contexts.

The main objective of this research action is to elucidate the impacts of various bioretention design characteristics on their hydrological performance, with special focuses on their ability to limit runoff volumes and potential for restoring the natural hydrologic balance. Detailed objectives were further defined as follows:

Objective 1: To have a better understanding of the dominant hydrologic processes (water movement in the substrate media, the role of vegetations) and establish the linkage between bioretention designs, local contexts and hydrological performance, especially for the local contexts in Paris.
Objective 2: To represent one of the experimental bioretention systems in HYDRUS-1D model, understand the limitations and representing capability of HYDRUS-1D model.
Objective 3: To evaluate the robustness of modelling a system's performance and hydrodynamics in HYDRUS-1D under the limited or uncertain knowledge of inputs (e.g., boundary condition, soil and vegetation properties, underground conditions, etc.).
Objective 4: To provide scientific recommendations for bioretention design and implementation, considering local context constraints in Paris region (e.g., controlled exfiltration) and design objectives (performance priorities).

METHODOLOGY

To achieve the objectives of this action, an approach consisting of three parts was adopted. Part I involved a literature review, in which current studies on bioretention monitoring and modelling were investigated. Through this review, some linkages among bioretention design, local contexts, and performance were established, and research gaps related to Objective 1 were identified as well. Part II comprised monitoring and field measurements based on three bioretention prototypes with different designs and local contexts in Paris region, where Objective 1 and the research gaps from Part I were further explored. Part III involved representing one field bioretention prototype in HYDRUS-1D to evaluate the model's capability in representing different hydrological processes (Objective 2). Additionally, different levels of input parameter knowledge from Part II were used for sensitivity analysis, to evaluate the robustness of HYDRUS-1D modelling results on the water balance performance and soil moisture dynamics (Objective 3). By combining conclusions from all three parts, design recommendations were formulated (Objective 4).

1. Part I: Investigate knowledge based on the existing literatures

This part investigated the variety of designs and local contexts covered by the existing literatures, as well as the means for assessing the hydrological performance of a bioretention system. The review was conducted through i) direct takeaway messages synthetised from the various articles; 2) construction and analysis of a database with detailed information on 128 bioretention devices extracted from 75 articles and dissertations. This part discussed the adequacy of experimental setups or models for the evaluation of different performance indicators, and summarised current knowledge regarding the impact of local context or design parameters on the hydrologic functioning of bioretention systems.

2. Part II: Experimental work on the three bioretention prototypes

This part conducted continuous monitoring and field investigations on three bioretention prototypes in Paris region (as shown in Figure1) to explore their hydrological performance under unfavourable subsoil conditions (e.g., limited or forbidden exfiltration), the relative importance of different hydrologic processes and the ways to enhance them. The prototypes consisted of i) Two lined systems, each with a low Hydraulic loading ratio (HLR, ie the ratio between total catchment area and bioretention area) of 4 and a fine-textured substrate (Figure1a); ii) An unlined system with a HLR of 13 over clay soil (Figure1b).

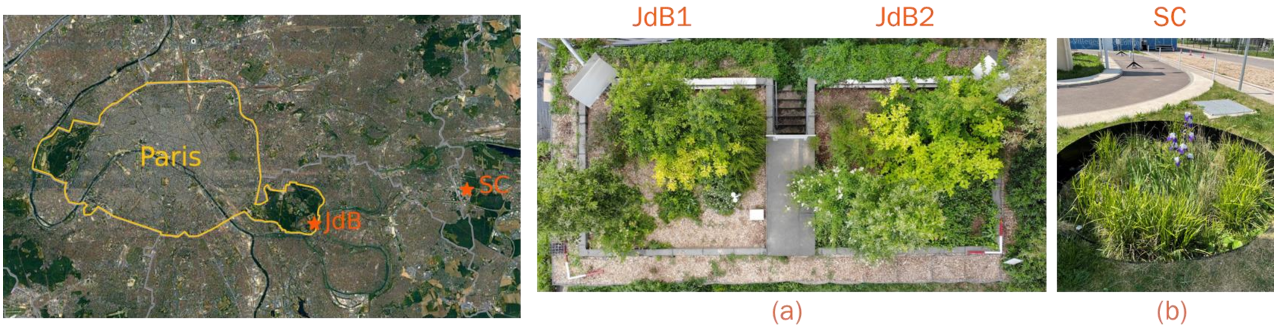

Figure 1: Location of the three experimental bioretention cells; (a) the two Jardin du Breuil (JdB) device (photographed by a drone in June 2023); (b) Sense City (SC) device (photographed with a hand-held camera in May 2022)

JdB1 and JdB2 are lined systems with small HLR (3.9), thick substrate layer (~140 cm) and fine substrate media (silt loam). The design purpose of these two cells was to test a typical garden design in Paris with underground constraints (situations where exfiltration is not allowed or should be limited), as well as to test the impact of the presence (JdB2) or absence (JdB1) of an internal water storage gravel layer (IWS). SC is a partly lined (bottom unlined) cylindric cell with high HLR (13.4), shallower substrate (48 cm) and engineered substrate media (sandy loam). It represents a more conventional bioretention cell design but has a low permeability clay subsoil which was compensated by a thick IWS and a raised underdrain. This experiment part included continuous hydrological monitoring and field/lab investigations. The summary of design configuration and parameters for the three prototypes are provided in Table1.

The hydrological processes (inflow, outflow, soil moisture at different depths of substrate, water level at surface (only for SC) and in the IWS, as well as meteorological data each has been monitored at each bioretention cell. The details of monitoring system set up and sensor calibration can be found in the PhD thesis (Huang, 2025).

In addition, due to the impact of perched groundwater in SC, a reservoir model has been introduced to reconstruct the "no-intrusion" scenario. Same model was also used for scenario analysis regarding to different exfiltration rates and bottom gravel storage layer thickness. The details of this reservoir model can be found in the PhD thesis (Huang, 2025).

Table 1: Design configuration and parameters comparison for JdB1, JdB2 and SC bioretention systems

	JdB 1	JdB 2	SC
Catchment area	72.5 m2		85 m2
Surface area	25.1 m2		7 m2
Hydraulic loading ratio	3.9		13.4
Linner condition	Lined		Partly lined (bottom open)
Berm/overflow height	Approximately 10 cm		25.5 cm
Vegetation type	Herbaceous, shrubs and tree		Herbaceous
Mulch layer	Yes		No
Substrate type	Silt loam		Sandy loam
Substrate thickness	138 cm	143 cm	45cm (centre) to 58 cm (edge)
Transition layer	Geotextile		Sand (10 cm)
Drainage type	Outlet hole (Diameter=11cm) in gravel well		DN 100 mm Perforated HDPE pipe
Drainage layer thickness (above drain slots/outlet)	62 cm	-	8 cm (thickest point)
Storage type	Gravel		Gravel
Storage layer thickness (below drain slots/outlet)	-	57 cm	42 cm
Underlying soil	-	-	Native Clay

Based on the validated long-term monitoring data (7 months for JdB; 42 months for SC), hydrological analysis such as long-term cumulative water balance, event-based hydrological performance and dry period analysis (mainly focusing on evapotranspiration (ET)) were conducted, the performance indicators used in this report are defined as follow:

- Overall volume reduction rate : $VRR_{Total}[\%] = 1 - \frac{\sum V_{out}}{\sum V_{in}}$, $\sum V_{out}$: total outflow volume (mm), $\sum V_{in}$: total incoming water (mm).
- Mean of event volume reduction rates : $\overline{VRR_{Event}}[\%] = \frac{\sum_{i=1}^{N}(1-\frac{V_{out_i}}{V_{in_i}})}{N}$, N: the total number of events.
- Exfiltration rate : Exfil [%] $= \frac{V_{recharge}}{V_{in}}$; $V_{recharge}$ is the volume of exfiltration (mm) which enters the subsoil.

3. Part III: Modelling extension based on one of the monitoring prototypes

In this part, one of the prototypes (SC bioretention) was modelled with HYDRUS-1D model. HYDRUS-1D is a model for simulating water movement in saturated/unsaturated porous media (Šimůnek et al., 2013). A Python package Phydrus (Collenteur et al., 2020) was used to conduct HYDRUS-1D simulations with a Python interface, making it easier to conduct parameters/configurations adaptation and batch simulations.

Due to the fact that only one bottom boundary condition can be represented at a time in HYDRUS-1D, the simulation cannot be conducted with both drainage pipe and bottom exfiltration. Thus, only the surface ponding layer (14.6 cm), substrate layer (48 cm of sandy loam) and transition layer (10 cm of sand) of the selected case were modelled in HYDRUS-1D (the blue part in Figure 2). A complementary reservoir model (Huang et al., 2024) was used to represent the hydrological behaviour of drainage and bottom gravel layers and obtain the volume of exfiltration and drainage (the pink part in Figure 2).

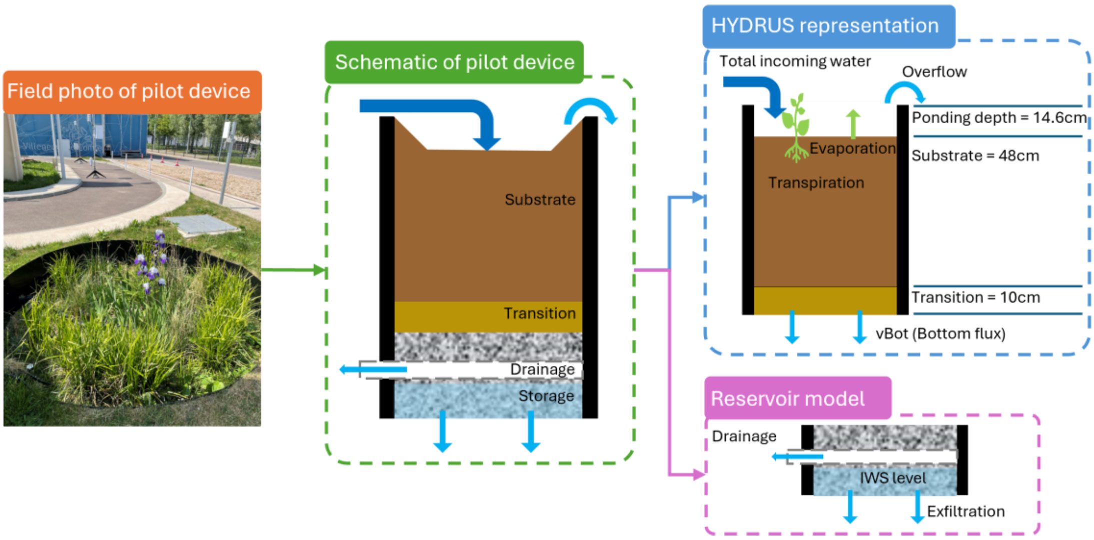

Figure 2: Hand-held field photo of SC pilot bioretention device, schematic of the pilot device and HYDRUS-1D and Reservoir model representation

Based on this model framework, a two-step sensitivity analysis was conducted. To address the impact of uncertain or incomplete knowledge of different input variables to the model fitting and model performance, a sensitivity analysis is necessary. It is conducted in two steps in order to reduce the number of simulations and facilitate the interpretation of the results.

As shown in Table 2, Step1 focused on testing the sensitivity to bottom boundary conditions, media hydrodynamic parameter sets and PET scenarios, with a fixed vegetation parameter setting (i.e., observed surface coverage fraction (SCF), grass root uptake models and a 48 cm depth triangular root distribution profile). Based on the result of step1, for each bottom boundary condition and potential evapotranspiration (PET), a most suitable media hydrodynamic parameter set was selected to test the sensitivity to vegetation inputs (4 SCF scenarios, 4 root uptake models and 3 root distribution profiles) for Step2.

Table 2: Variables used in HYDRUS sensitivity analysis

Required model inputs	Input variables	Number of sets
Bottom boundary condition[1]	Seepage face; Free drainage	2
Media hydrological parameters[1]	(substrate: 11 BEST-infil test + 3 Rosetta settings) × (transition: 3 settings with Rosetta)	42
PET[1]	PET- *in-situ*; PET-Torcy	2
SCF[2]	Observed SCF[1]; average SCF (growing season); 1; 0 (no transpiration)	4
Root uptake model[2]	Grass[1]; Alfalfa; Wheat; Corn	4
Root distribution profile[2]	Triangular (48cm[1]; 15cm); Uniform (48cm)	3

[1]Tested in Step1 of analysis; [2]Tested in Step2 of analysis

During the sensitivity analysis, the dynamic of simulated and monitored substrate moisture at different depths was compared using Kling–Gupta efficiency (KGE) as a fit goodness indicator. KGE involves three terms, i.e., correlation, bias and variability (Kling et al., 2012). Different hydrologic performance indicators were also evaluated for each, those indicators represented different terms of the annual water balance (i.e., ET, volume which leaves from substrate layer, exfiltration and drainage), water stock in the soil and an indicator for drought stress. The performance indicators used in this report are described as follows:

- ET [%]: $\frac{ET}{V_{in}}$; ET= Total ET (cm) calculated by HDRUS over the 1 year simulation period, V_{in}= total inflow (cm) over the 1 year simulation period.
- vBot [%]: $\frac{V_{Bot}}{V_{in}}$; V_{Bot} = the volume (cm) which leaves from the bottom boundary face of HYDRUS model, calculated by HYDRUS.

- Average media water content [cm3/cm3]: average water content in substrate and transition layer, calculated by HYDRUS.

RESULTS

1. Knowledge and gaps from the existing literature

The investigation on literature indicated several key gaps in the current bioretention studies: 1) Underrepresentation of local contexts and designs. Some local contexts (e.g., regions with high seasonal rainfall variability) are underexplored in existing literature. 2) Lack of long-term or overall water balance monitoring and performance evaluation. Due to the difficulty of long-term monitoring or complete water balance monitoring, current research often focuses on short-term runoff control (e.g., volume reduction or peak flow reduction) while neglecting long-term and overall water balance performance. In this situation, the result might be misleading since part of water balance is not captured (e.g., overestimation in volume reduction when the water bypasses the system through urban karst). 3) Interactions with surrounding soil. In the case of unlined systems, the interaction between bioretention systems and the surrounding soil is not adequately studied, these interactions can potentially make large difference in their water balance. 4) Call for more environmental-friendly bioretention designs. Use local materials instead of the non-renewable or non-biodegradable materials resource (e.g. gravel or geotextile).

2. Field experiment

- Long-term water balance

During the monitoring period, the outflow of SC is threefold the incoming water volume. Combining with the evidence of water level in the nearby manhole and the low permeable native subsoil, an intrusion issue can be identified from the perched lens. Based on the water level measurement in the bottom gravel storage, this intrusion issue has been observed at various moments of the year, suggesting it could occur at any period. A reservoir model (Huang et al., 2024) was used to reconstruct the data of SC, therefore reproduce the scenario of no groundwater intrusion.

$$Q_{inflow} + \sum P_{direct} \cdot A = Q_{outflow} + \sum PET \cdot A + \Delta V_{soil\ water} + \Delta V_{gravel\ water} + V_{exfil} + V_{closure}$$

SC only

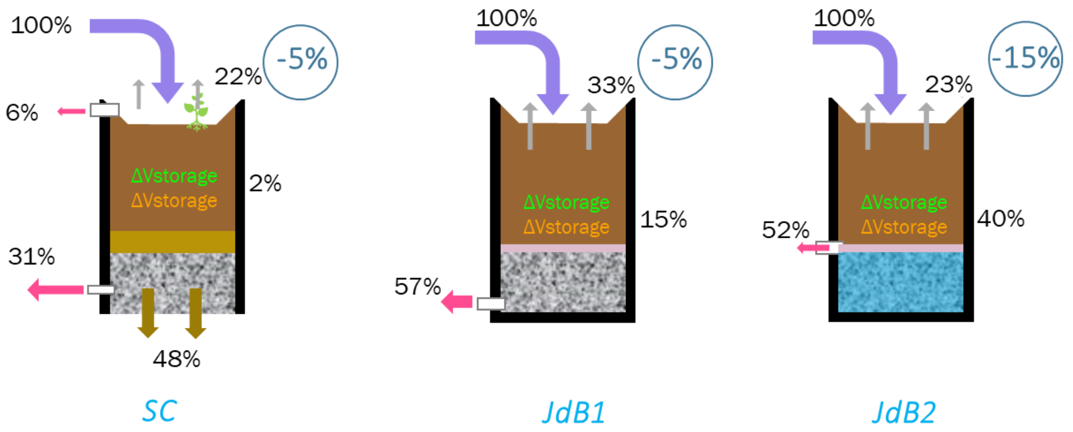

Figure 3: Fluxes in water balance and long-term water balance statistic for the three bioretention cells (for SC, the water balance is based on the reconstructed, no-intrusion scenario)

Figure 3 presents a water balance equation on the top, which contains different water fluxes and storages. At the bottom of the figure, three schematics are used to represent the long-term water budget for the three bioretention cells. Terms in the equation correspond to components in the schematic using the same colour. The closure error of each cell is marked as number in circle.

Overall, under the current hydraulic loading ratio of 3.9, the two JdB bioretentions could abstract almost half of the incoming water (43.0% for JdB1, 48.1% for JdB2). JdB2 (with an IWS) shows slightly higher ability to abstract water compared to JdB1 (without IWS). This difference may however be due to the initial filling of the additional storage provided by the gravel layer. For the SC bioretention, it can theoretically abstract 48.1% of total incoming water over the studied period even though the underground soil has a very low permeability. The closure term is not negligible in the long-term water balance. It covers the uncertainty from the direct measurement, uncertainty from different data processing (e.g., the method to estimate soil storage, or reconstruct inflow) and also the difference between Actual ET and PET. The long-term closure is very high, especially for JdB2 (-15.3%). This high closure error can be explained by the large sensor error from a few big events. However, for ET analysis, focusing only on dry periods simplifies the calculation and eliminates the uncertainty in inflow and outflow measurements.

- Dry period analysis

The ET estimated during the dry periods which lasted more than two days are shown in Figure 4, where each dot represents a daily ET or PET. Each bioretention cell contains one column (on the left) of ET estimated by water balance and another column (on the right) for PET calculated from the in-situ climate data. The unrealistic ETs, such as <0 mm/d or > 10 mm/d were excluded during the data processing. Also note that the drying period of different cells are not always overlapping, thus the cumulative ET and PET cannot be compared in between different cells.

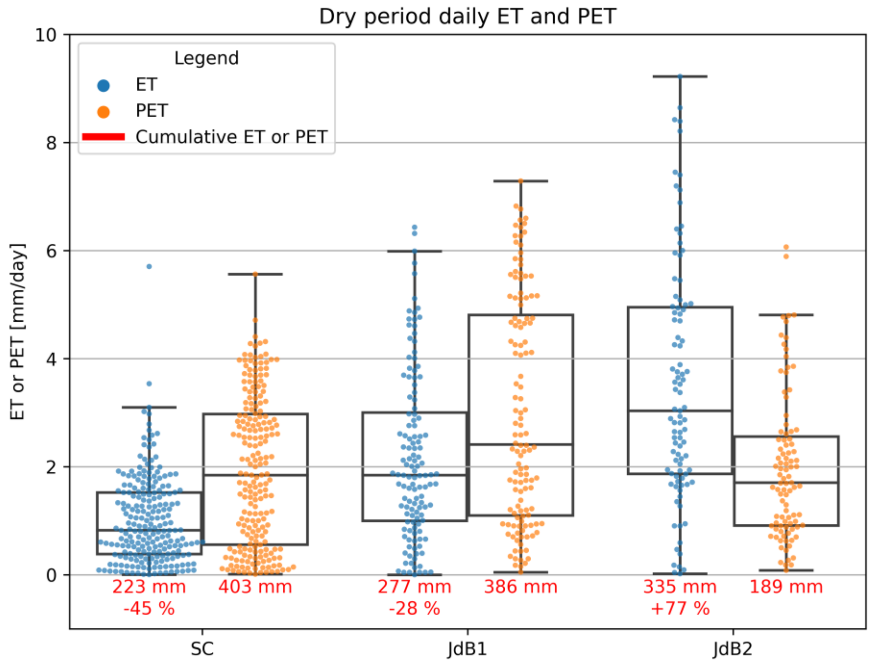

Figure 4: Boxplot of daily ET and PET estimated during dry periods on the three cells ; the number under each boxplot indicates the cumulative ET or PET flux within this plot, plus the percentage difference between ET and PET at the same site.

Overall, JdB2 has the highest daily ET over the three cells, even higher than PET. This situation is consistent with the high-water content in JdB2, which results from the direct contact between the IWS and the substrate layer. In contrast, the daily ET from JdB1 and SC are both lower than the corresponding PET, which is due to the fact that the IWS in SC is located well below the transition layer, and JdB1 does not have an IWS.. For SC, these deviations between estimated ET and in-situ PET may be due to the system being set below the ground surface, with vertical sides that likely limit incoming air circulation and light. + shadow effect from the wall

Considering only the common dry periods for JdB1 and JdB2, the cumulative ET estimated by water balance were 58 mm (JdB1) and 132 mm (JdB2) for the 2022 observation period, while for the observation period 2023 they were of 71 mm (JdB1) and 194 mm (JdB2). The ET difference between IWS cell and non-IWS cell are more than 128% (for 2022) and 172% (for 2023). In a weight-lysimeter study in the same region with same hydraulic loading ratio (Ouédraogo et al., 2022), ET for the bioretention cell with IWS was reported to be 87% higher than for the non-IWS cell in summer and 18% higher during the autumn.. In another study from Hess et al. (2017), the IWS cell has 63% more ET than non-IWS cell with both sandy substrate. Compared to these weight-lysimeter studies, the difference on ET between JdB1 and JdB2 seems overly large, the reason could be that the common periods were only selected from the dry periods instead of the entire period.

- Event-scale performance

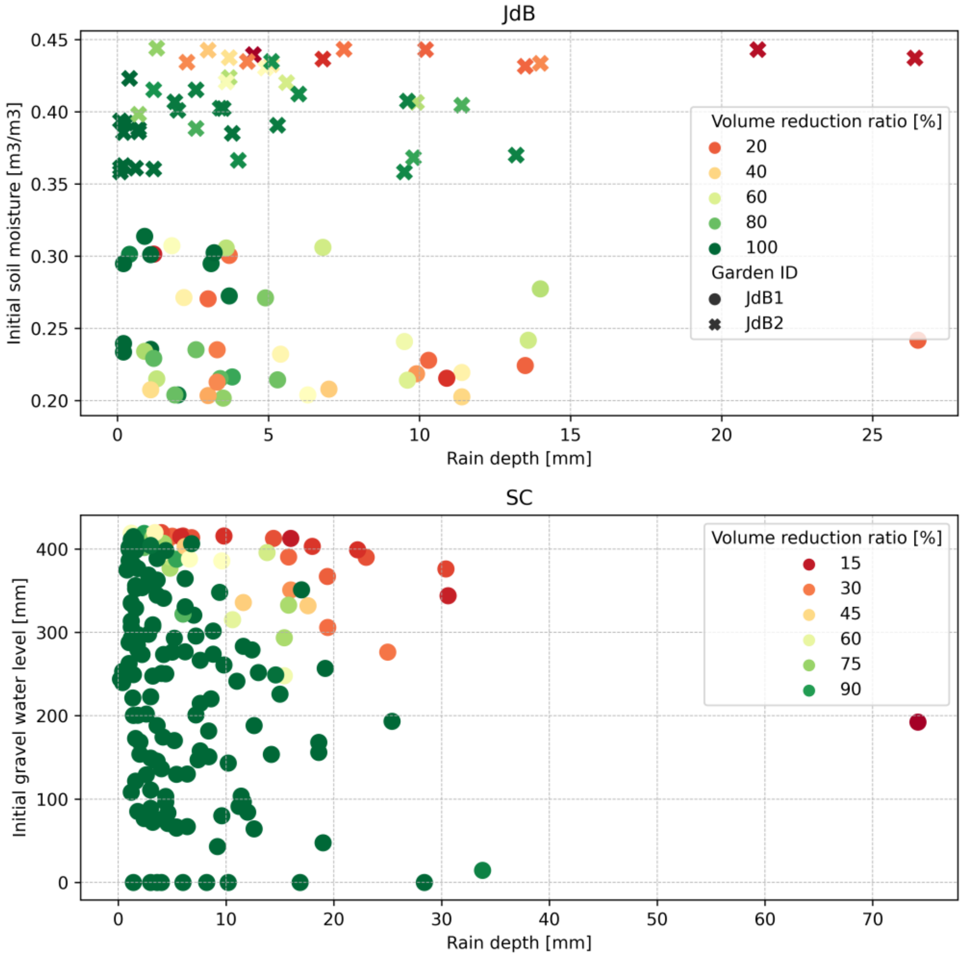

Figure 5: Event-scale volume reduction ratio related to different initial average soil moisture over the whole substrate layer (left: JdB) and different bottom gravel water level (right: SC)

Figure 8 shows how the event-based volume reduction from the different cells varies depending on rainfall depth and initial conditions. Expectably, higher rain depths lead to lower VRR for all three cells. Overall, JdB1 shows significantly lower initial water contents than JdB2. For JdB2 and SC, volume reduction efficiency tends to be higher under dry initial conditions (i.e., low soil water content or a low water level in the gravel layer), which are associated with higher storage capacity. Surprisingly, this is not the case for JdB1, where water content does not show a clear influence on volume reduction. This situation may result from the possible preferential flow caused by cracks, as identified along the wall close to the inflow through a tracer experiment in 2024-07 (conducted by E. Berthier, Cerema), although other locations might also be affected. Those cracks may have formed as a result of the shrinkage of the silty substrate during the dry periods. They allow the water to reach quickly and directly the underdrain flow with limited control from the substrate media. This interpretation in terms of preferential flow is also consistent with the generally lower volume reduction efficiency from JdB1 compared to JdB2 (although this lower volume reduction efficiency may also be explained by the possible clogging issue at the JdB2 outlet). In this case, higher initial water content can help achieve a more even distribution of water on and in the substrate. The presence of an IWS (JdB2) can prevent this drying out of the soil, and hence avoid soil cracks to form and create preferential flows.

- Scenario analysis

For SC, the reservoir model used to reconstruct hydrological processes allows testing alternatives scenarios regarding the extension of the gravel storage layer and underlying soil permeability. The following table (Table 3) presents the results obtained with the original configuration (S0) along with alternative settings, based on different bottom storage depths (S1, S2, S3) or on the lining of the drainage layer (S4).

Table 3: Hydrological performance of different design configuration scenarios for SC bioretention.

Model scenarios	Avg. VRR-Event	VRR-Total	Completely retained events	Total exfiltration
S1 (620 mm IWS, unlined)	87%	66%	136/185	51.5%
S0 (420 mm IWS, unlined)	85%	62%	128/185	49.3%
S2 (220 mm IWS, unlined)	82%	55%	118/185	43.5%
S3 (20 mm IWS, unlined)	61%	27%	59/185	15.9%
S4 (no IWS, lined)	22%	11%	2/185	0.0%

Lining (scenario S4) significantly limits the volume reduction performance of the bioretention cell (total volume reduction is only 11%), which means for soil and hydraulic loading conditions in SC, the ET alone is not an efficient mean to reduce runoff volume. An unlined system implemented on a low permeability clay underlying soil can still reduce by 27% the total runoff volume by applying a 20 mm very thin bottom storage. This performance can increase if a deeper bottom gravel storage is applied, however, since 220 mm of IWS already encountered for 55% of VRR-Total, there is not much benefit to increase the storage depth when it is above 220 mm (for instance from 220 mm to 420 mm, the VRR-Total only increase 7% more).

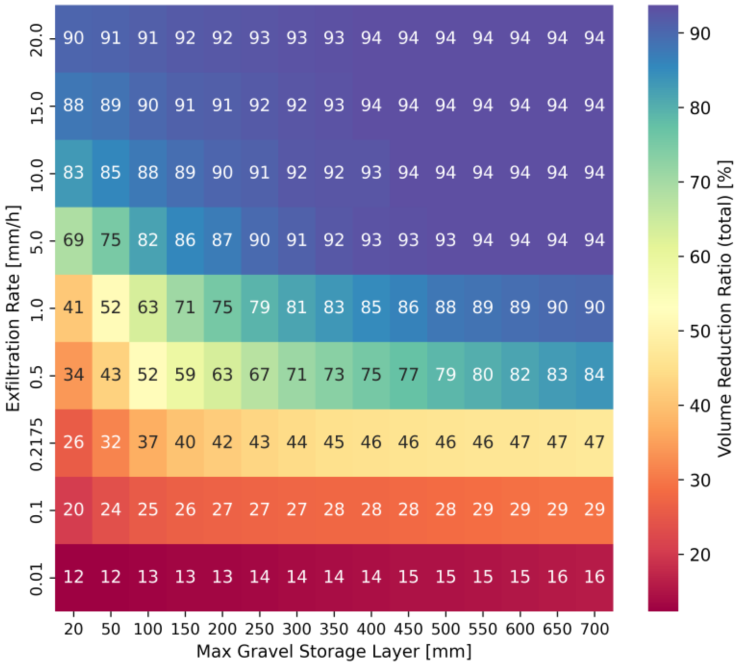

Figure 6: Heatmap of different max gravel storage layer thickness and bottom exfiltration rate impact on VRR-Total for SC bioretention (the number in each square: VRR-Total under a certain scenario)

By applying grid search on bottom gravel storage layer thickness and exfiltration rate of underlying soil, a VRR heatmap can be generated (see Figure 6). As shown in Figure 6, higher bottom exfiltration rate and higher gravel storage layer thickness can provide higher volume reduction ratio, but the benefit from extending gravel layer thickness largely depends on the bottom exfiltration rate. For high exfiltration rates, significant volume reduction can be achieved with a minimal storage layer thickness. For the lowest permeability settings, increasing the gravel storage thickness cannot compensate for the limited exfiltration rates.

3. Model representing

- <u>Dynamic of soil moisture change and drought resilience</u>

Figure 7 presents the average soil moisture over the substrate and transition layer for both simulated and monitored results. The simulations can be grouped according to corresponding bottom boundary conditions. Each group contains curves that represent different sets of hydrodynamic parameter inputs for substrate and transition layer. Note that some of parameter sets did not allow the model to converge, thus the number of curves under each group is different. To show the details of the changes in the curves more clearly, only part of the results (four months) is shown in Figure 7.

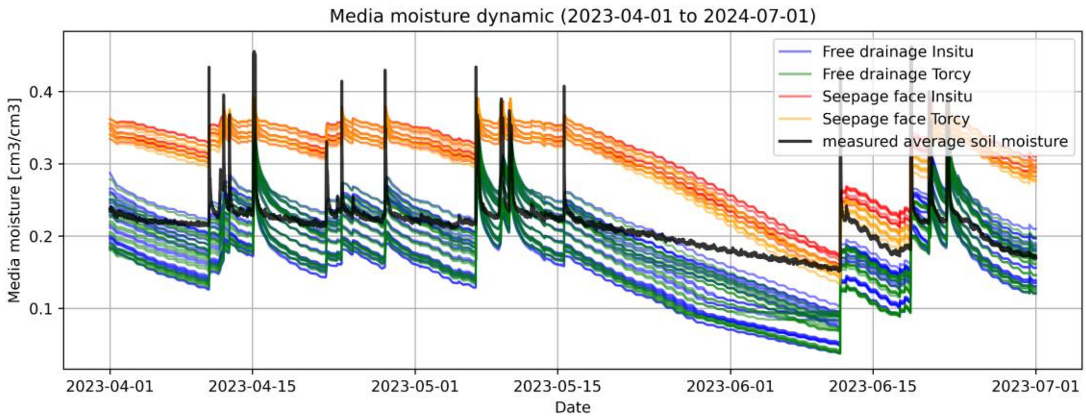

Figure 7: The dynamic of average soil water content in different simulations for Step1 (period: 2023-04-01 to 2023-07-01)

According to Figure 7, simulations with free drainage (blue) and seepage face (red) bottom boundary conditions lead to significantly different mean soil water content. Soil water content during dry weather periods is much higher for seepage face simulations compared to both field measurements and free drainage simulations. The decrease of soil storage after each rain event shows different trends depending on the two bottom boundary conditions. For seepage face, the fast decrease of water content immediately after a rain event (associated with drainage) interrupts after a few hours at relatively high-water contents. For free drainage, this initial stage persists for a longer period until reaching lower water content values. Hence, seepage face leads to an important overestimation of ET during long dry periods (as shown by the significant difference in decreasing slope between measured and modelled soil water content) and free drainage leads to water stress conditions that do not exist in reality. The impact of soil hydrodynamic parameters is also important. When combined with seepage face bottom boundary condition, BEST infiltration test parameter sets lead to near saturated storage (the top two red curve). In half of the cases with BEST parameters, simulations fail to converge due to a full saturation of the soil profile (that cannot be handled by HYDRUS-1D), a behaviour that is in any case not consistent with field observations.

- Model robustness on ET and vBot

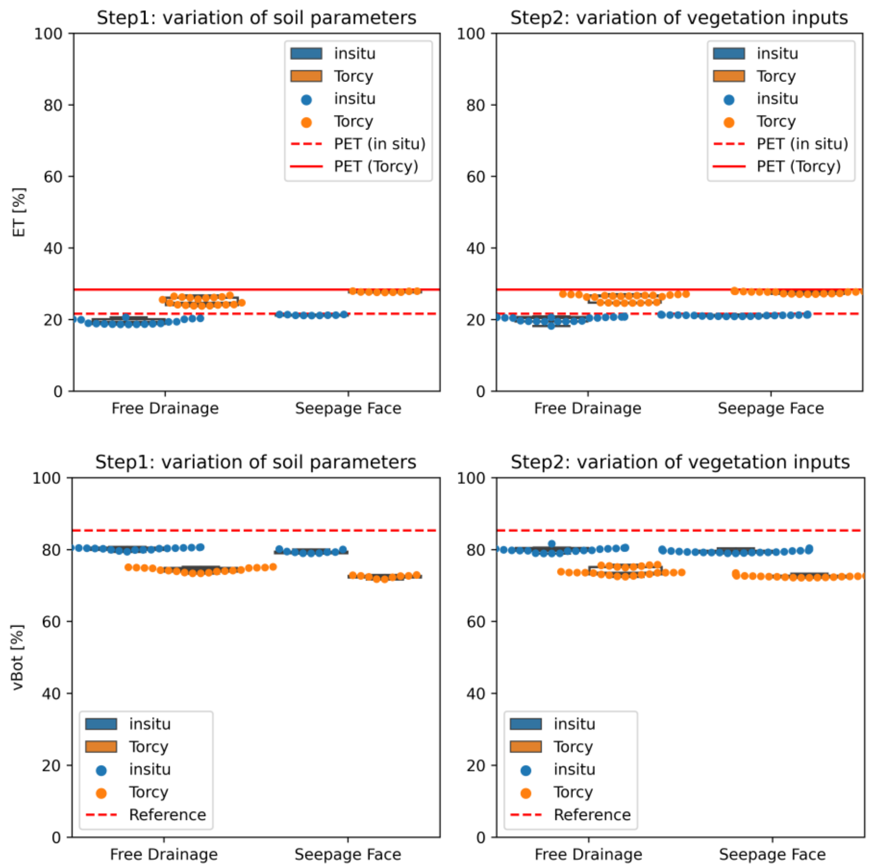

Figure 8: Evapotranspiration (upper row) and vBot (lower row) ratio for Step1 and Step2

According to Figure 8, when focusing on the long-term performance, this model allows for a good estimation of exfiltration and ET total fluxes (results are close to their corresponding references), which leads to the fact that the sensitivity of vBot and ET is very low for soil hydraulic parameters and vegetation parameters. Combining the large variation in the substrate moisture among different boundary conditions and soil parameters (as shown previously in Figure 7), model is accurate so assess hydrological performance but not to assess plant water stress conditions. However, considering the HLR (13) of the selected prototype, the modelled system is not well representative for drought conditions, further scenarios (e.g., with lower HLR) are necessary to test.

CONCLUSIONS

This action focused under the main objective of elucidating the impacts of various bioretention design characteristics on their hydrological performance, with special focuses on their ability to limit runoff volumes and potential for restoring components of the natural water balance that have been altered by urbanisation (e.g., infiltration, ET). The Part I of the work was based on a thorough literature review, which focused on the hydrological behaviour and performance of bioretention systems worldwide. This review attempted to estimate the linkages between the design and local context of a bioretention system and its hydrological performance. The Part II of this work involved experiments on three bioretention cell prototypes (JdB1, JdB2 and SC) in Paris region. This experiment part included continuous hydrological monitoring and field/lab investigations. Based on corresponding data and results, aspects of bioretention system behaviours that were underrepresented in the current literature, were explored and completed, especially the case of unfavourable underground conditions. Thus, based on Part I and Part II, the findings regarding to the different aspects of bioretention implications can be summarised as follows:

1) Soil characteristics:
   The choice of substrate media is always challenging; coarse media have high conductivity but poor water retention, whereas fine media have good water retention ability but low conductivity. This study tested two different types of media, a conventional engineered media (sandy loam) and a less commonly used fine media (silt loam). As shown in the study, the sandy loam was well suited for vegetation growth and water requirement, possibly due to the relatively high clay and silt component in the chosen sandy loam media which may have improved water retention. Also, the higher HLR and the capillary barrier observed in the substrate-transition interface also helped to maintain the substrate moisture. On the other hand, the finer media in JdB supported nicely the vegetation growth under a low HLR, but it also caused problems such as clogging and cracks for the cell without IWS, and sometimes prolonged surface ponding for the cell with IWS. While an increased proportion of clay generally leads to increased adsorption capacity for the treatment of micropollutants, such soil is also very likely to emit colloids (clay particles) in the percolation water and thus are at risk of increased pollutant transfer to the underground or drainage.
2) Internal water storage:
   For an unlined system but with low permeability underground, even a small IWS can improve runoff volume reduction (for example in SC reservoir scenario, a 22 cm of bottom water storage can increase total volume reduction from 11% to 55% compared to a lined case). However, it is needed for a survey of local underground conditions, and ensure the level of the drain is above possible saturation level of surrounding soils. For a lined system with an IWS configurated to maintain permanent saturation at the bottom of the substrate, it allows better water distribution within the substrate (avoids preferential flow due to soil shrinking) and increased ET. To achieve these benefits, it is important to consider whether the outlet height allows the water in the IWS to reach the bottom of the substrate or whether the HLR provides enough water to maintain the IWS level at the substrate bottom. Otherwise, adjusting the substrate media depth may be necessary to ensure that roots can extend into the IWS (but in this case it won't help much for wetting the substrate).
3) Hydraulic loading ratio:
   The ratio between the receiving catchment and the bioretention surface (i.e., HLR) is directly linked to the system water balance. To promote ET, lower HLR should be preferred. For the studied systems, the high HLR (>10) in SC led to lower ET ratio and a large fraction of water

cannot be extracted. Finer substrate might be considered as another way to promote ET by ensuring soil moisture under lower HLR. In any case, it is worth noting that, due to the limitation of ET by PET, ET alone is unlikely to provide sufficient volume control to meet current stormwater management targets under the climate considered - unless considering HLR ratios approaching one. In this case, it is necessary to be careful on the surface size of a bioretention system, when a low HLR is applied to a larger bioretention surface, it may result in an uneven distribution of incoming water. This can leave parts of the cell dry, making them less favourable for supporting ET.

Lastly, one prototype (i.e., the SC bioretention cell) has been modelled with the physical-based model HYDRUS-1D (Part III). Model's robustness, more specifically the validity of calculated performance indicators, was assessed to better understand its applicability for simulating other design scenarios. In reality, the system is far more complex than how it is represented in the model due to factors such as media and vegetation heterogeneity. Thus, the modelling part of this research was primarily focused on assessing the model's robustness under these various uncertain input types (e.g., different boundary conditions, media hydraulic parameters, PET and vegetation characteristics). This study examined the extent to which the results of such a model can be relied upon, considering the uncertainties and knowledge gaps inherent in bioretention implementation. This last part of work indicates that:

1) compared to the field monitoring result, the modelling approach is overall good at representing cumulative flux in water balance (i.e., ET, exfiltration and drainage), but not robust at representing the moisture variation at different depths in the substrate media.

2) for water balance (flux) simulation, only bottom boundary conditions and PET inputs have visible impact. The impact of media hydraulic parameters and vegetation characteristics (i.e., root uptake model, root distribution and SCF) is almost neglectable.

3) for media moisture variation simulation, the most sensible factors are bottom boundary conditions and media hydraulic parameters, while PET and vegetation characteristics have limited impacts. Thus, considering the knowledge on bottom boundary condition and soil hydraulic parameters are commonly very limited, this modelling approach can be used on water balance flux (e.g., drainage) evaluation, but still needs further testing before extending to other design scenarios (e.g., lower HLR), especially for ET and media moisture evaluation.

4) for vegetation's role in the bioretention cell, according to modelling results, differences in vegetation characteristics (e.g., root density distribution, root uptake model and SCF) showed neglectable impacts on the bioretention water balance performance. To enhance ET and ensure healthy long-term vegetation development, it is nevertheless valuable to further explore plant selection strategies, which includes considering their ability to extract water within the soil profile and their tolerance to water stress. In another words, optimizing plant selection to better match with predicted water content variations in the whole soil profile could also be interesting to investigate.

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