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Hydrologic performance of bioretention systems with unfavourable underground conditions : complementing field monitoring with simple reservoir modelling for scenario analysis

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Highlights

- Runoff volume reduction in bioretention systems with low permeability underground
- Substituting a three-part reservoir model in lieu of unavailable or malfunctioning field monitoring.
- Scenario modelling on bottom configurations of a bioretention system.

Introduction

The bioretention system consist of shallow planted area that may include multiple layers, e.g., sunken surface, vegetated filter media, drainage and bottom storage (Osman et al., 2019), resulting in variety of possible designs and functioning. Field monitoring approaches with pilot devices are widely-applied to study the functioning of bioretention systems. In a monitoring system, the lack of specific set of sensors or their physical damage, the high uncertainty of some of them, and the influence of external factors of the system can often lead to a data gap or to difficulties in interpretation of the hydrological behaviours of the different bioretention components. In this study, a three-part reservoir model was proposed to simulate the surface ponding and bottom exfiltration behaviours of a pilot bioretention device which is facing with the issue of outflow (drain flow and overflow) measurement disruption by ground water intrusion in the bottom gravel storage. In addition, this model also shows the potential to evaluate the hydrological behaviour of bioretention systems under different bottom configuration scenarios (i.e., percolated water storage vs exfiltration) in both long-term cumulative and event-based scales.

Case study

The study case is under a large experimental project “Sense City”, which is located in the east of Paris, France. The pilot device is a cylindrical-shaped bioretention system with 7 m² of surface area. It consists of the following layers: vegetated surface, filter substrate (45-58 cm), transition (10 cm), drainage (8 cm), and gravel storage (42 cm, bottom connects to the native soil) from top to bottom. It receives stormwater runoff from an 85 m² asphalt pavement. This device was specially designed to assess runoff abstraction in bioretention cells with unfavourable underground soil conditions (clay soil), and its potential enhancement with an underground storage. It was designed to monitor influent (electromagnetic flowmeter), effluent at the underdrain and overflow outlet (tipping bucket flowmeter), surface ponding level (pressure sensor), internal water storage level (pressure sensor), as well as the media moisture at different locations and depths (3 SoilVue10 TDR soil moisture profilers). However, the outflow monitoring was continuously disrupted by an unknow water intrusion into the bottom storage layer (possibly from a perched groundwater lens). Hence, the measurements on the bottom storage depth, underdrain flow and overflow rates are unreliable.

Methodology

Model overview

The principle of the event scale water balance model is shown in Figure 1. The left part shows the hydrological process. From top to bottom, the model consists of 3 components: 1) surface ponding overflow model which calculates the volume of overflow; 2) substrate & transition module which calculates the volume of seepage; 3) bottom storage model which calculates the bottom storage level and the volume of underdrain flow and exfiltration. A list of hydrologic events which started from the beginning of rainfall and finished at the end of

seepage were distinguished as the input for the model. The inter-event water balance was used as well (only for bottom storage model).

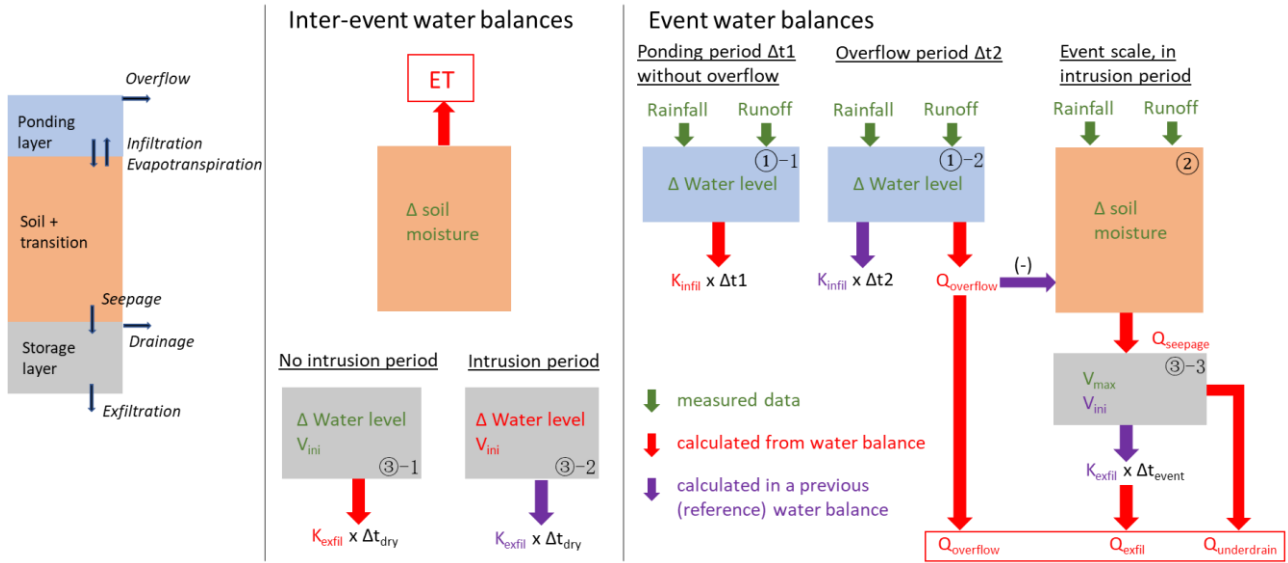


Figure 1. Schematic of the model hydrology process (left one) and the computation steps for event and inter-event water balance

Computation process – surface ponding overflow model

To assess overflow volumes, a surface reservoir model (blue box in Figure 1) is built based on reliable inflow, precipitation and surface ponding depth measurements. The model considers overflow only when the surface ponding depth exceeds the overflow level. In which the water balance (①-2) is given by:

$$Q_{runoff} + Q_{rain} = \hat{K}_{infil} \times (T_{start} - T_{end}) + \hat{Q}_{overflow}$$

Where Q_{runoff} and Q_{rain} are directly measured inflow volume and rain amount; \hat{K}_{infil} is estimated from the ponding level decrease after the overflow of each event (①-1); T_{start} and T_{end} mean the start and end time of an overflow event. Since they cannot be precisely identified from water depth measurements, a "dummy" start is introduced and the overflow volume $\hat{Q}_{overflow}$ is computed from:

$$\hat{Q}_{overflow} = Q_{runoff} + Q_{rain} - \hat{K}_{infil} \times (T_{dummy\ start} - T_{end}) - \Delta(V_{real\ start} - V_{dummy\ start})$$

Where: $\Delta(V_{real\ start} - V_{dummy\ start})$ is the water storage (level) difference of the dummy start and real start.

Computation process – substrate & transition seepage model

The substrate & transition reservoir receives measured inflow and rain volumes, from which overflow volume calculated by the surface reservoir is subtracted. Combining with the soil water storage change $\Delta Q_{soil\ water}$ that was measured by soil moisture sensor, the seepage volume $\hat{Q}_{seepage}$ that leaves from the substrate & transition part (②) can be calculated by the water balance equation:

$$\hat{Q}_{seepage} = Q_{runoff} + Q_{rain} - \hat{Q}_{overflow} - \Delta Q_{soil\ water}$$

Computation process – bottom storage model

The bottom model is based on the measurement of bottom exfiltration rate K_{exfil} (during the no-intrusion dry period ③-1) and the seepage volume $\hat{Q}_{seepage}$ from the middle substrate & transition layer (②). The calculation is separated into two steps: during the event and inter-event.

For water balance during the event (③-3), the water storage at the end V_{end} can be calculated by closing the water balance of the seepage volume, initial water storage V_{ini} and the exfiltration loss during the event $Q_{exfil\ during}$ (calculated from K_{exfil}). If V_{end} exceeds the maximum storage capacity V_{max} of the system (water level higher than the location of underdrain), the excess part becomes the volume of underdrain flow $Q_{underdrain}$; else the V_{end} remains the same.

$$\hat{Q}_{seepage} + V_{ini} = Q_{exfil\ during} + V_{end} = Q_{exfil\ during} + Q_{underdrain} + V_{max}$$

If V_{ini} is not 0, exfiltration is assumed to occur during the whole event. Otherwise, as the time of beginning of seepage is no known, exfiltration is assumed to start at the end of inflow. Yet $Q_{exfil\ during}$ is a very limited volume due to the low value of \hat{K}_{exfil} .

For water balance in between two events (③-2), the judgement is on whether the Q_{end} will be completely exfiltrated before the next event, similar to the $Q_{exfil\ during}$, the amount of exfiltration in between events

can be calculated by the time of dry period T_{dry} times K_{exfil} . Hence the initial water storage of the next event can be calculated:

$$V_{ini,next} = \max(V_{end} - T_{dry} \times K_{exfil}, 0)$$

Results and discussion

Hydrological performances of the pilot bioretention device

With the model bridging the gaps in field monitoring measurements, it becomes possible to simulate the behaviour and performance of the afore-described pilot bioretention in an “ideal” no-groundwater-intrusion scenario. From the 2021-01-01 to 2023-11-15, 363 rainfall events are identified to have impact (with measurable soil moisture change) on the bioretention device, 187 events have measured runoff volume. The cumulated water balance of the total 364 events is shown below:

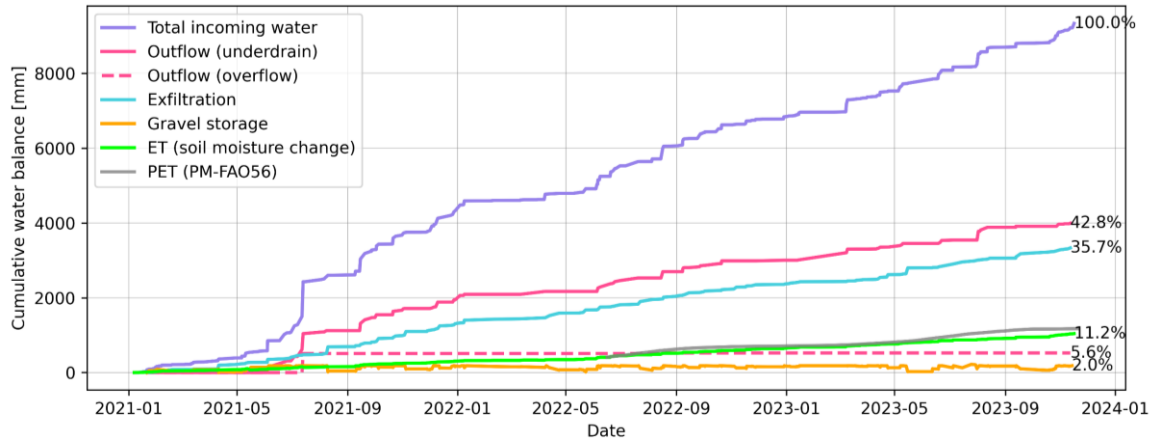


Figure 2. Cumulative water balance of the pilot bioretention over a 22 month-period (from Jan 2021 to Nov 2023); the percentage at the end of each line indicates the percentage of the regarding volume over the total income volume.

In the model calculation, all the units for water quantity are converted to mm over the bioretention surface. According to the cumulative water balance, the pilot bioretention can theoretically exfiltrate 35.7% of total incoming water over the studied period, and this although the underground soil has a very low permeability ($K_{exfil} = 0.24\text{mm/h}$) The exfiltration process is rather constant throughout the year and only interrupts during long dry periods. 48.4% of incoming water is not retained by the device (the sum of overflow and underdrain), where the dominant outflow type is underdrain flow (42.8%). The actual evapotranspiration (ET) can be estimated by the soil moisture change between the end of each event and the start of the next event. Over the period 2022-06-16 to 2023-11-15, ET estimated from the dry period soil moisture sensors change is 12.6 % lower than potential evapotranspiration (PET) calculated by FAO-56 (Allen et al., 1998) (see green and grey line in Fig. 2). The possible explanation can be 1) the initial soil moisture can impact on the ET rate (Berretta et al., 2014), therefore the PET can overestimate ET; 2) the ET during the event was ignored; 3) tiny rain events which did not generate runoff or cause significant soil moisture change are not considered.

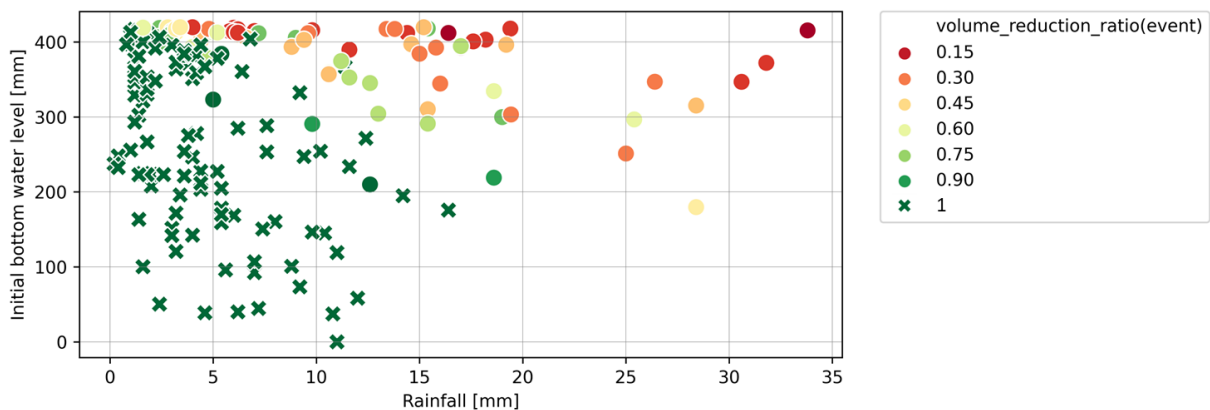


Figure 3. The relationship between rainfall, initial bottom storage level and the volume reduction ratio for each rain event (one extreme event in July 2021 is excluded in this figure due to its high rainfall).

Figure 3 shows how the initial bottom water storage level and rainfall amount can impact the volume reduction ratio of the pilot bioretention device. The greener the dot, the higher the volume reduction ratio

of the event is. The completely retained events (no outflow) are marked as crosses. As shown in Figure 3, the volume reduction ratio decreases with the initial bottom storage level and with the rainfall depth of the event. The bottom storage plays a major role in the runoff abstraction performance. When the bottom storage was nearly full (>400 mm), all the events higher than 1.6 mm generated drain flow or overflow, while the bioretention with a half empty bottom storage (200mm) could fully retain events up to 16.4 mm precipitation. As expected, the initial internal water level condition is the dominant factor for a bioretention's capability on runoff reduction.

Hydrological performance of the bioretention under other scenarios

The reservoir model allows representing more bioretention configuration scenarios by changing its setup. The following table presents the results obtained with the original configuration (S0) along with alternative settings, based on different bottom storage depths (S1 to S3) or on the lining of the drainage layer (S4).

Table 1. Hydrological performance of different design configuration scenarios (Avg. VRR-event = average event scale volume reductions, VRR-Total = total volume reduction over the sum of all events; for the 187 events with inflow volume).

Model scenarios	Avg. VRR-Event	VRR-Total	Completely retained events	Total exfiltration
S1 (620 mm gravel, unlined)	77.4%	50.3%	105/187	37.4%
S0 (420 mm gravel, unlined)	77.2%	49.3%	105/187	37.4%
S2 (220 mm gravel, unlined)	73.5%	45.4%	98/187	34.4%
S3 (20 mm gravel, unlined)	55.6%	24.5%	52/187	14.5%
S4 (no gravel, lined)	16.2%	9.9%	1/187	0.0%

Lining (scenario S4) significantly limits the volume reduction performance of the bioretention cell (total volume reduction of less than 10%). which mean that evapotranspiration alone is not an efficient mean to reduce runoff volume when the vegetated area represents only 8% on the inflow catchment. An unlined system implemented on a clay soil with even only 20 mm bottom storage can reduce by 24% the total runoff volume . This performance increases with a deeper bottom gravel storage and reaches up to 50% total volume reduction(scenario S0 to S3), however there is not much benefit to increase the storage depth above 220 mm.

Conclusions and future work

The three-part reservoir model proposed in this study allowed to fill the gaps in the field monitoring but also to simulate different bottom condition scenarios, for a better understanding of bioretention-related processes. By applying the model into a pilot bioretention device which faces the disruption from groundwater intrusion, the hydrological function of this device has been reproduced. Volume reduction ratio, drain time, total exfiltration ratio and overflow volume under different bottom configuration scenarios have been investigated. Meanwhile, few limitations remain. The current model is event-based (i.e., it does not operate at continuous time step) and thus cannot support the analysis on the dynamic performance indicators (e.g., peak flow reduction and lag time). For future work, implementation of higher resolution time step calculation is planned. Exploration on the potential of the approach for representing different types of measurement gap (e.g., reversed for use in systems with reliable underdrain measurements to obtain changes in bottom storage level) is also an interesting direction.

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