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Modelling bioretention systems: does physical-based mean robust?

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Abstract

This study aims to test the robustness of a physical based bioretention cell model, given the inaccuracies inherent to our knowledge of the systems' hydrodynamic. Field monitoring data on a pilot bioretention cell is compared to HYDRUS 1D modelling results for a range of possible soil properties and bottom condition scenarios. The uncertainties in the hydrodynamic properties of the filtration and transition medias as well as the bottom boundary conditions (BCs) are found to significantly affect modelling results for water content dynamics in the filtration media but have limited impact on the long-term water balance of the system.

Highlights

- The model is robust for long-term volume reduction/groundwater recharge.
- It is not robust for soil water storage dynamics, and thus assessing resilience to climate extremes
- Field survey of soil hydrodynamic parameters does not mean better fitted/converging model.

Introduction

Bioretention systems are widely used today as a part of sustainable urban drainage systems, to restore a more natural water balance in urbanised area. Corresponding benefits include reducing the runoff volume, mitigating urban heat island by evapotranspiration (ET), recharging groundwater by exfiltration. Modelling is a common tool to evaluate the hydrological performance of a bioretention system. To determine the model input parameters, the common practice is calibrating or tuning from the observations, which is often used in research applications (where hydrological monitoring data is available). Another approach is to test sets of plausible parameters based on the knowledge on system's characteristics, which is more consistent with real world applications (where hydrological monitoring data are typically not available). However, in real practice, detailed knowledge of all the properties/characteristics of the modelled bioretention systems (detailed geometry, soil and vegetation properties, underground conditions, etc.) is rarely available. Even when field measurements are available, they might not be completely representative of the system due to spatial heterogeneity. Whether these incomplete/limited data compromise the assessment of the system performance or not remains questionable. In this study, the impact of different levels of knowledge on soil hydrodynamic properties and bottom boundary condition (BC) on the hydrological behaviour of an experimental bioretention cell modelled with a physical based approach (in HYDRUS 1D) was analysed. The sensitivity of modelling results to these uncertain modelling input parameters was assessed from both the fitting goodness and a range of hydrological performance indicators.

Methodology

Study case

This study is based on a pilot cylindrical-shaped bioretention device located within a large experimental facility "Sense City", in the East of Paris, France. The device has 7 m2 of surface area and receives stormwater runoff from an 85 m2 asphalt pavement, thus the hydraulic loading ratio (total receiving surface over the infiltration surface) equals to 13. The system consists of the following layers from top to down: vegetated surface depression (max ponding depth 25 cm; ponding volume equivalent to 14.6 cm over the whole bioretention surface), filtration media (45-58 cm), transition (10 cm), drainage (8 cm), and bottom storage (42 cm, bottom connects to the native clay soil). Influent, effluent at the underdrain and overflow outlet, surface ponding level, internal water storage level, as well as the media moisture at different locations and depths were monitored during the studied period (Huang et al., 2024).

Conceptualisation of the selected bioretention cell in the model

The pilot bioretention cell was modelled with HYDRUS 1D. Due to its very coarse nature, the gravel layer used cannot be well represented in HYDRUS-1D. Thus, only the surface ponding layer (14.6 cm), filtration layer (48 cm) and transition layer (10 cm) of the selected case were modelled in HYDRUS 1D. A complementary reservoir model was used to represent the hydrological behaviour of drainage and bottom gravel layers (Huang et al., 2024) and obtain the volume of exfiltration and drainage. Note that the uncertainty that may arise from the parameterization of the reservoir model (especially the exfiltration loss term) was not considered in this abstract.

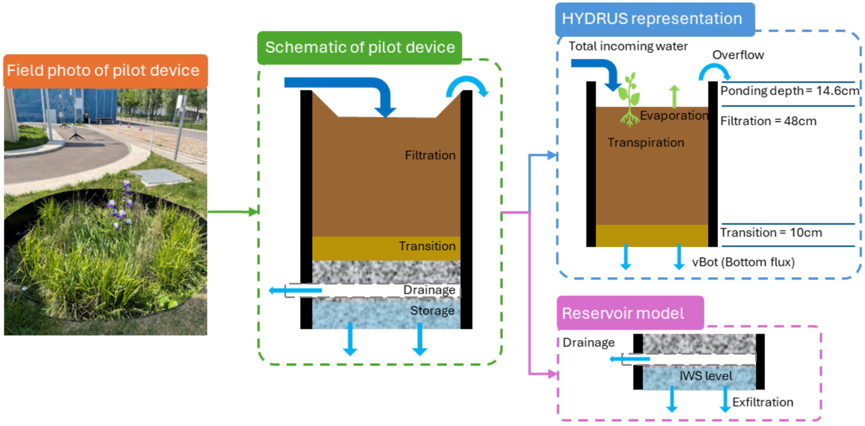

Figure 1. Schematic and model representation of the pilot bioretention

Uncertain HYDRUS inputs for sensitivity analysis

Aside from shape parameters mentioned in Figure 1, other input variables required by the model are often hard to obtain through direct observation. To evaluate the impact of those uncertain variables, a sensitivity analysis was conducted by applying a range of different input variables. To model water fluxes in the vadose zone, soil hydrodynamic parameters are needed. In HYDRUS, the Van Genuchten laws are used to describe both retention curve and soil hydraulic conductivity curve. Several approaches can be applied, depending on available data, to assess the parameters of these laws. They can be predicted with the Rosetta pedotransfer function, based only on the soil type information (sandy loam for filtration layer and sand for transition layer in this case), or based on grain size distribution, or on both grain size and bulk density (Zhang & Schaap, 2017). Soil hydrodynamic parameters can also be estimated based on field investigations such as BEST-infiltration tests (Lassabatere et al., 2013). 14 sets of parameters (the 3 levels of Rosetta predictions + 11 Best-infiltration field measurements) for filtration and 3 sets of transition parameters (Rosetta predictions) were used for sensitivity analysis. 2 different bottom BCs were selected. Normally, as atmospheric pressure condition is expected at the bottom of a transition layer connected to gravel layer with large difference on particle size, the bottom BC should be a seepage face. However, during the operation of bioretention system, some sand from the transition layer might have migrated into the gravel layer, and thus the bottom BC could become similar to a free drainage condition.

Simulation inputs and hydrological performance indicators

All simulations were started from 2022-11-01 to 2024-01-01 with 1 min time step inputs, include measured inflow plus direct rainfall as incoming water, and potential evapotranspiration (PET) was calculated with in-situ measured climate data and PM-FAO56 equation (Allen et al., 1998). Outputs were selected for the period of 2023-01-01 to 2024-01-01, without the first 2 months stabilising the initial soil moisture condition. The following hydrologic performance indicators were used for HYDRUS and reservoir model outputs:

- ET [%]: $\frac{ET}{V_{total\ incoming}}$, calculated by HYDRUS.
- vBot [%]: $\frac{V_{flux\ flow\ through\ transition\ layer}}{V_{total\ incoming}}$, calculated by HYDRUS.
- Soil water content [cm^3/cm^3]: average water content filtration and transition layer, calculated by HYDRUS.
- Exfiltration [%]: $\frac{V_{recharge\ into\ surround\ soil}}{V_{total\ incoming}}$, calculated by reservoir model.
- Drainage [%]: $1 - \frac{V_{underdrain}}{V_{total\ incoming}}$, calculated by reservoir model.
- Drought period [%]: $\frac{T_{soil\ moisture<0.2\ at\ 15\ cm\ depth}}{T_{total}}$, $T_{soil\ moisture}$ <0.2 indicates the period when the soil moisture at 15 cm depth is lower than 0.2 cm^3/cm^3, calculated from HYDRUS output

Results and discussions

Robustness of water balance assessment

To minimize the impact of initial bottom gravel storage, the performance comparison between monitored results and simulated results was chosen to start after a long dry period in February 2023, thus ensuring near-zero initial gravel storage level for both simulations and observations. In Figure 2, the left three subplots are direct outputs from HYDRUS, while the right two subplots are recalculated exfiltration and underdrain flow by using the reservoir model and vBot from HYDRUS. Reference values, derived from the observations (as detailed in Huang et al, (2024)), is provided for exfiltration and drainage, except for ET where reference is PET. When considering the long-term water balance, the differences brought by bottom BCs are not significant. vBot from HYDRUS can be seen as drainage volume if the bioretention was lined. In the case of a bottom storage with a low permeability underlying soil, the drainage volume calculated with the reservoir model shows a smaller difference between simulation and reference. The only large difference between the two BCs is on the proportion of drought periods (period in which soil water content is lower than 0.2 at 15 cm): the latter has huge difference, even so associated total ETs seem relatively close. To discuss this difference, the dynamic of soil water content change is necessary.

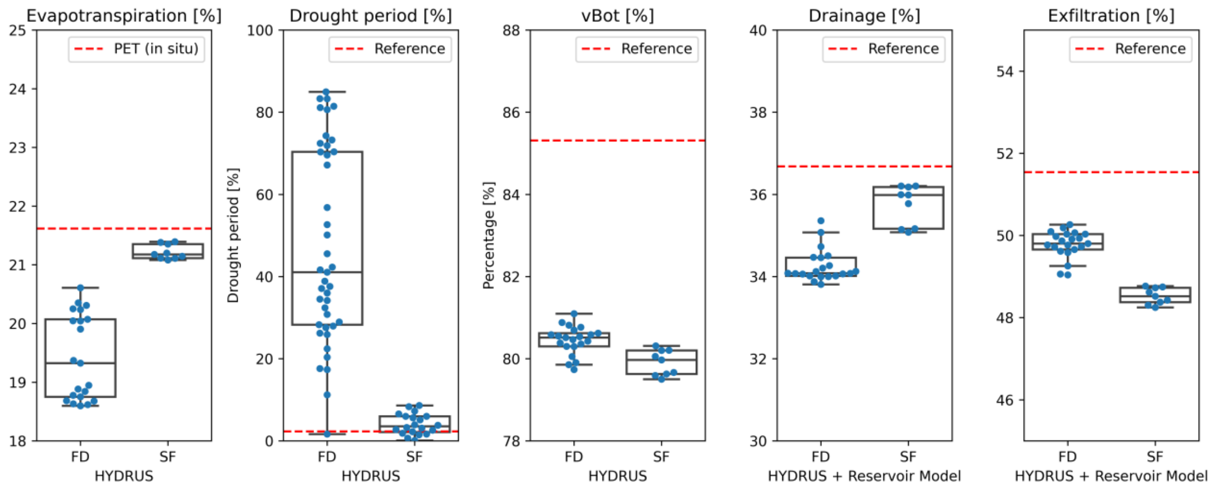

Figure 2. Performance indicators provided by HYDRUS and HYDRUS + Reservoir model (FD: free drainage, SF: seepage face). Each dot represents the result of one simulation (1 input set)

Dynamic of soil moisture change

As shown in Figure 3, the simulations can be grouped according to corresponding bottom BCs. Each group contains curves that represent a set of hydrodynamic parameter inputs for filtration 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 3.

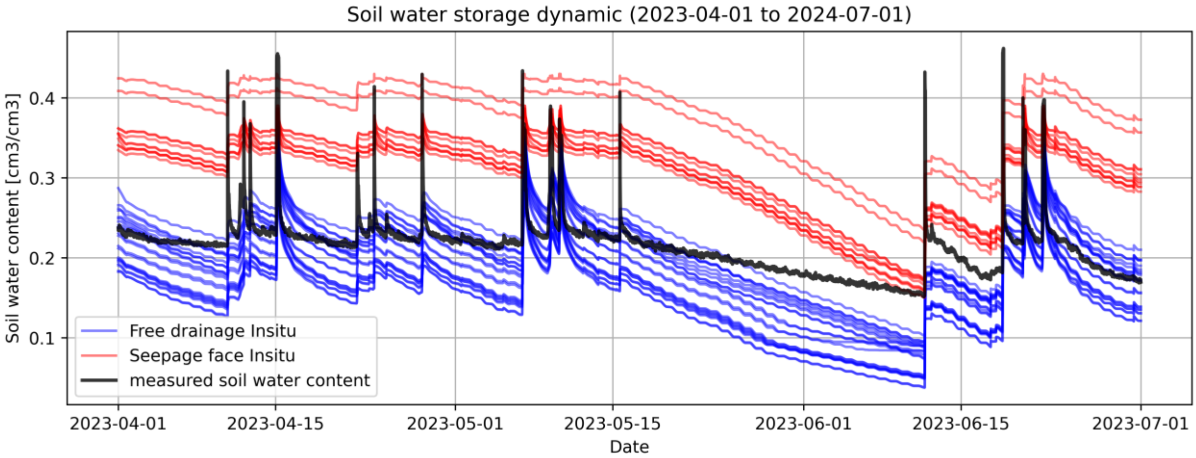

Figure 3. The dynamic of average soil water content in different simulations (period: 2023-04-01 to 2023-07-01)

According to Figure 3, simulations with free drainage (blue) and seepage face (red) bottom BCs 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 boundaries. 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 significantly lower water content values. Hence, during long dry periods, seepage face leads to an important overestimation of ET (difference in slope between measured and modelled) 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 BC, BEST infiltration test parameter leads 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.

Conclusions and future work

Based on the sensitivity analysis, the following conclusions can be drawn: 1) models under the two BCs are quite robust for assessing long-term water balance such as volume reduction and groundwater recharge, but results are not reliable for assessing ET under continuously dry periods or plant ecophysiology influenced by drought stress and water logging; 2) detailed knowledge (e.g., field measured media parameters) did not provide more accurate model compare to simple knowledge (e.g., Rosetta). However, it is noteworthy that in the current result, ET and soil water storage variation represent only a limited fraction of the total incoming water (due to the hydraulic loading ratio of the selected case). Hence, even the simulated storage variation and ET are not always well represented, there impact on the long-term water balance is still not significant. For future work, further evaluations will be conducted on two aspects: 1) different vegetation parameters (e.g., surface coverage fraction for the aerial part, root distribution profile and root uptake model) for their impact on model results; 2) representing systems with different hydraulic loading ratios.

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