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Tinghao Huang, Jérémie Sage, Didier Techer, Marie-Christine Gromaire. Hydrologic performance of bioretention cells -Preliminary results from a pilot device Performance. Novatech 2023 - 11th International conference on urban water, Jul 2023, Lyon, France. hal-04081738

HAL Id: hal-04081738

<https://enpc.hal.science/hal-04081738>

Submitted on 25 Apr 2023

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Hydrologic performance of bioretention cells - Preliminary results from a pilot device

Performance hydrologique des cellules de biorétention - Résultats préliminaires d'un ouvrage pilote

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RÉSUMÉ

Un ouvrage de biorétention expérimental, comportant une couche de stockage souterrain en gravier pour améliorer l'exfiltration vers le sol argileux sous-jacent, a été mis en place dans la mini ville climatique Sense-City (France). Le dispositif pilote est entièrement équipé de capteurs permettant de mesurer les flux entrant et sortant, l'humidité du sol et les paramètres météorologiques. L'étude comprend l'évaluation de l'incertitude de mesure des capteurs et une analyse du bilan hydrique cumulé sur 5 mois (16/6/2022 – 22/11/2022). Les premiers résultats indiquent un pourcentage comparativement élevé d'évapotranspiration (40%) et plus limité d'exfiltration (20%) pendant la période estivale (16/6 – 25/9), tandis que plus tard durant la période pluvieuse d'automne (25/9-22/11) une intrusion d'eau souterraine dans le fond de l'ouvrage est mise en évidence. L'évaluation des incertitudes de mesure met en évidence une forte incertitude des mesures de teneur en eau du sol, dont l'incidence sur les bilans volumiques devra être évaluée à l'avenir.

ABSTRACT

A pilot bioretention cell with a deep underground storage layer to enhance exfiltration into the underlying clay soil was set up in Sense-City climatic mini city (France). The pilot system is fully equipped with sensors for inflow, outflow, soil moisture and meteorological monitoring. The study involves the uncertainty evaluations of sensors and a 5-month cumulative water balance analysis (16/06/2022 – 22/11/2022). The preliminary results indicate that during the relatively dry summer period (16/06-25/09), the bioretention cell provided a comparatively high percentage of evapotranspiration (40%) and more limited exfiltration (19%), while later in the wet autumn (25/09-22/11), some evidence might suggest groundwater intrusion into the storage/drainage layer at the bottom. Uncertainty evaluations showed high uncertainties on soil water contain measurements, whose impact on the water balance need to be further analysed.

KEYWORDS

bioretention, evapotranspiration, exfiltration, monitoring, water balance

1 INTRODUCTION

Bioretention is a sustainable solution for urban runoff management. It has multiple functionalities due to its ability to retain stormwater, delay flow peaks and improve water balance, but also to its potential to retain pollutants, reduce local temperatures and provide landscape amenities. The design of bioretention can significantly vary depending on location and design objectives. Although a great amount of studies has been conducted, some absences remain: 1. The effect of design parameters remains partially understood especially when infiltration is not the dominant process. 2. The local context (climate, geological conditions) of the Paris region (Western Europe) is less represented in the overall conducted studies (Sprakman et al., 2020). In this study, the functioning of a fully monitored experimental bioretention cell, implemented in a low-permeability subsoil, is investigated.

2 MATERIALS AND METHODS

2.1 Experimental setup

The experimental bioretention cell is located at Champs-sur-Marne (France) within Sense-City equipment (a 400 m² city model equipped with various sensors and a movable climate chamber). The system consists of an 85 m² asphalt pavement catchment area and a 7 m² circular bioretention cell. The site was built at the end of 2019 and was completed progressively until 11/03/2022. Weekly maintenance was done to remove the upper part of weeds during the growing season (April to September) of 2022. The observation period (with full sensor equipped) has started since 16/06/2022 and is still ongoing till the present.

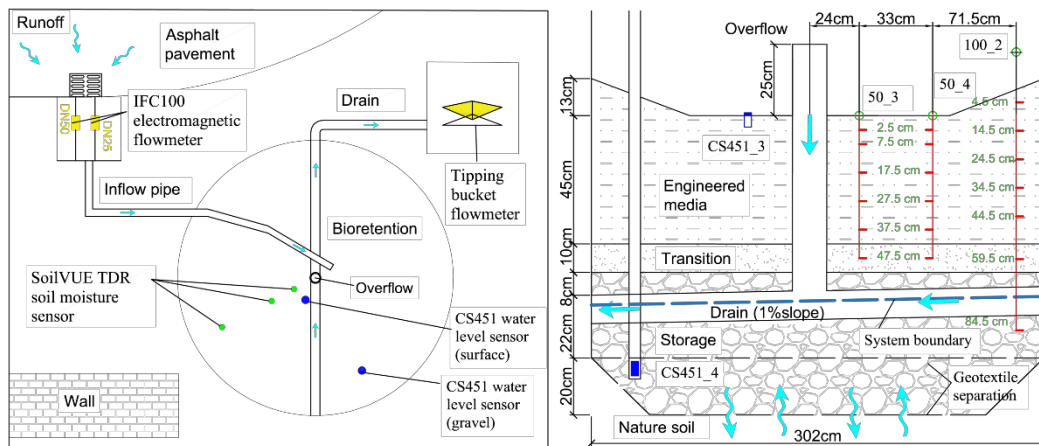


Figure 1: Sense City bioretention cell and sensors setup

The Sense City bioretention cell consists of 3 layers: 45-58 cm topsoil (silty-sandy engineered media with 24 mm/h saturated hydraulic conductivity), 10 cm transition layer (sand) and 55 cm bottom storage layer (gravel). The cell is lined vertically, the bottom is set on natural low-permeable clay soil with a geotextile separation, which allows slow exfiltration. An overflow pipe rises 25cm above the lowest point of the bioretention cell surface and is connected to a horizontal perforated drain situated in the upper part of the gravel layer (the perforation is at the top one-third). The deep gravel depth below the level of the drain slots (approximately 40 cm) was aimed at improving exfiltration into the underlying soil. The inlet flow is directed to the centre of the cell by a pipe, a stone slab was placed at the end of the pipe to prevent erosion at the inflow point. The perforated part of the drain (blue line in Figure 1) is considered the system's lower boundary during the water balance analysis.

As shown in Figure 1, the Sense City bioretention cell is equipped with different types of sensors. These sensors correspond to different physical measurements, including the inflow rate and volume (2 parallel electromagnetic flowmeters Krohne OPTIFLUX-25 for inflow, DN25 for small flow and DN50 for big flow), outflow volume (1 tipping bucket flowmeter for outflow, Précis Mécanique 2x1 L), soil water content (3 TDR soil moisture profile sensors, Campbell SoilVUE50), water level (2 pressure sensors for the surface ponding level and the gravel water level, Campbell CS451). These sensors are connected to a data logger and data are transmitted and stored via Wi-Fi and local storage respectively. Besides, there are two meteorological stations very next to the bioretention cell, one is located 6 m above the ground on a wall (Vaisala WXT536), and the other is placed on the catchment pavement, around 3 m above the ground (Campbell ClimaVUE50). These two meteorological stations are continuously measuring air

pressure, air temperature, wind direction and speed, solar flux, and precipitation. There is also a tipping bucket rain gauge 1 m above the ground (Précis Mécanique 2x0.2mm). Meteorological stations, electromagnetic flowmeters and water level sensors collect data with a time step of 1 minute, soil moisture sensors collect data every 15 minutes, and the tipping bucket rain gauge and flowmeter do not have a fixed collecting time step, they record an exact time to the second every time there is a tip.

2.2 Methods

2.2.1 Sensor measurement uncertainty evaluation

The uncertainties of sensors were evaluated from the following lab tests and field experiments:

- Water level measurements with the pressor sensor were controlled in the lab, in a Perspex column. 33 to 59 sensor measurements were repeated for each water level tested. The 8 water levels reached from 29.8 mm to 500 mm.
- Electromagnetic flowmeter: a water tube based on Mariotte's bottle principle was used to inject adjustable constant flow to be compared with the one measured by the electromagnetic flowmeters. 3 to 205 sensor measurements were taken during each simulated flow rate depending on the tested flow rate. The 8 simulated flow rates reached from 0.03 L/min to 2.4 L/min.
- Soil sampling test: 15 soil core samples were collected in the field with 100 cm³ calibrated cylinders at different depths next to the sensors. The water content of the soil cores was determined in the lab by subsequent weighting/drying/weighting. 1 or 2 sensor readings were associated to each soil sample. The soil moisture ranged from 0.092 m³/m³ to 0.276 m³/m³.

For each sensor type, a linear regression was drawn between reference test values and sensor measurements. The prediction interval of each regression was calculated based on (Shalizi, 2015), with a confidence interval of 95%. The prediction uncertainties of the regression are ± 1.7 mm for the water level sensor in the gravel, ± 0.044 L/min for the inflow electromagnetic flowmeter and ± 0.0692 m³/m³ for the volumetric water content. While uncertainty of water level and flow are limited, the last value on water content is very high compared to the measurement range.

2.2.2 PET estimation and water balance calculation

The total water balance equation is as follows:

$$V_{inflow} + \sum P_{direct} \cdot A = V_{outflow} + V_{exchange} + \sum ET \cdot A + \Delta V_{soil\ water}$$

Where: V_{inflow} = the total inflow volume through the flowmeter (L); A = Surface area of the bioretention cell (m²); P_{direct} = direct rainfall onto the bioretention cell surface (mm); $V_{outflow}$ = the total outflow volume measured by the tipping bucket flowmeter(L); $\Delta V_{soil\ water}$ = the estimated soil water storage volume change between the two dates; $V_{exchange}$ = the exchange volume at the lower boundary of the considered system (positive for exfiltration, negative for groundwater intrusion) (L); $\sum ET$ = cumulation of the estimated daily evapotranspiration ET (mm).

In this study, ET was approximated by potential evapotranspiration (PET), which can lead to an overestimation if the soil water content is limiting. PET was estimated by the meteorological station data at a daily time step. The most commonly used method is the FAO56 Penman-Monteith equation (Allen et al., 1998). The calculation was based on an open-source Python package namely PyET (Vremec & Collenteur, 2021). However, it has been reported by a local study in Paris that the PM FAO56 underestimated the PET compared to the actual ET measured by rain garden lysimeters with internal water storage layer (Ouédraogo et al., 2022).

3 RESULTS AND DISCUSSIONS

Figure 2 plots the long-term water balance in the Sense City bioretention cell from 16/06/2022 to 22/11/2022. The green line represents the total inflow ($V_{inflow} + \sum P_{direct} \cdot A$). The blue line represents the measured outflow ($V_{outflow}$). The black line is accumulated PET ($\sum PET \cdot A$) estimated by the FAO56-PM method. The purple line does a simple calculation of $V_{inflow} + \sum P_{direct} \cdot A - V_{outflow}$. According to Equation 2, the red dot line represented $V_{exchange}$, the volume of water exchanged between the bioretention system and the surrounding soil.

Based on the trend of the red line, the study period can be divided into three parts. Period 1 (16/06 to

14/08) is the summer period, and the red line shows a more pronounced downward trend during the dry period, which indicates that the estimated soil water storage change is less than the estimated ET. As no external water intrusion is likely to happen during this period, this probably means that PET slightly overestimates ET during this dry period (71.8 mm total precipitation, 44% outflow, 58% ET, -3% exfiltration). For period 2 (15/08 to 25/09), the red line shows a clear positive value with an increasing trend, representing the presence of a large amount of exfiltration from the system (36.2 mm total precipitation, 38% outflow, 24% ET, 36% exfiltration). During periods 1 and 2 (40% outflow, 40% ET, 19% exfiltration over the whole two periods), some inflow events do not produce any outflow, probably due to the role of the dry soil and gravel layer, which eventually leads to ET and exfiltration. Period 3 (26/09 to 22/11) shows abnormal functioning with an anomalous increase in outflow even several times greater than inflow volume. This evidence points to the system receiving external, unmeasured water in period 3. The results of the water balance hence suggest that during the rain events in the wet season, there were intrusions from the groundwater. A possible explanation is the formation of a shallow (and temporary) saturated lens below the system.

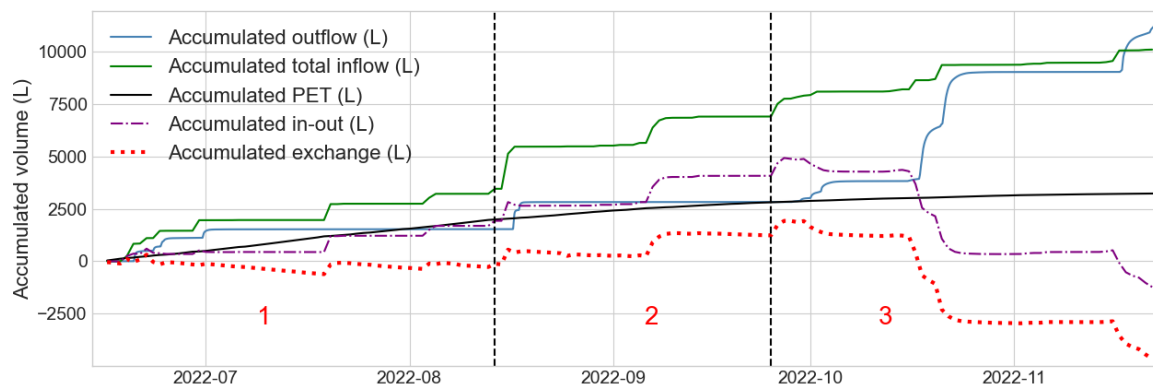


Figure 2: Water balance from June 2022 to November 2022

4 CONCLUSION

The cumulative water balance over 5 months indicates high evapotranspiration rates during the 2022 summer period (40%), associated with a more limited exfiltration flux (19%), while autumn 2022 has yielded the existence of important water intrusions from the surrounding soil into the bioretention cell during rainy periods. However, a longer-term successive observation is needed to confirm this seasonal performance pattern change. Moreover, uncertainty evaluations showed very high uncertainty in soil water content measurements. The effect of this uncertainty on the calculated water balance has not been analysed yet and needs further developments. In order to improve the water balance calculation and to improve the analysis of exchanged water between the bioretention cell and the underlying soil, a water level sensor was installed in the gravel storage layer in November 2022 and 2 piezometers will be installed next year as well for the perched lens groundwater depth monitoring. In addition, event-based water balances are being analysed and an algorithm to systematically distinguish whether runoff events are independent is being designed and tested.

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ACKNOWLEDGEMENT

This research was carried out under the OPUR research program (<https://leesu.univ-paris-est.fr/opur/>). The authors gratefully acknowledge OPUR partners and especially the municipality of Paris, for their financial support, as well as Sense-City partners for technical support and data management.