

## Vegetation and internal water storage enhance stormwater control via increased evapotranspiration in bioretention mesocosms

### Rôle de la végétation et du stockage interne sur l'évapotranspiration dans les biofiltres

Jurijs Kondratenko<sup>1</sup>, Margit Kõiv-Vainik<sup>1,2</sup>, Floris C. Boogaard<sup>1,3</sup>, Luca Adami<sup>1,4</sup>, Jānis Rubulis<sup>1</sup>

<sup>1</sup> Water Systems and Biotechnology Institute, Riga Technical University - [jurijs.kondratenko@rtu.lv](mailto:jurijs.kondratenko@rtu.lv), [janis.rubulis@rtu.lv](mailto:janis.rubulis@rtu.lv)

<sup>2</sup> Department of Geography, Institute of Ecology and Earth Sciences, University of Tartu - [margit.koiv.vainik@ut.ee](mailto:margit.koiv.vainik@ut.ee)

<sup>3</sup> Research Centre for Built Environment NoorderRuimte, Hanze University of Applied Sciences Groningen - [f.c.boogaard@pl.hanze.nl](mailto:f.c.boogaard@pl.hanze.nl)

<sup>4</sup> Department of Civil, Environmental and Mechanical Engineering, University of Trento - [luca.adami@unitn.it](mailto:luca.adami@unitn.it)

## RÉSUMÉ

Cette étude a évalué l'effet combiné de la végétation et du stockage interne d'eau (SIE) sur la dynamique de l'ET dans des mésocosmes de biorétention. Douze mésocosmes ont été installés en conditions estivales extérieures selon quatre configurations : planté/drainage libre (PF), planté/SIE (PI), non planté/drainage libre (UF) et non planté/SIE (UI). L'ET a été déterminée par bilan massique à partir de pesées périodiques, tandis que l'humidité du sol a été suivie à trois profondeurs par capteurs. Les résultats ont montré que la végétation constituait le principal facteur de contrôle de l'ET, doublant presque la perte d'eau cumulée par rapport aux systèmes non végétalisés (~500 mm pour PI contre ~200 mm pour UI). Le SIE a renforcé l'ET en maintenant l'humidité de la zone racinaire, particulièrement en période sèche. Les coefficients culturaux ont atteint 3,0 à 3,5 en fin d'été pour PI, traduisant une forte capacité de restauration du stockage par la végétation. Ces résultats mettent en évidence le rôle du SIE comme amélioration de conception efficace pour une gestion des eaux pluviales plus résiliente face aux changements climatiques.

## ABSTRACT

This study evaluated the combined effect of vegetation and internal water storage (IWS) on evapotranspiration (ET) dynamics in bioretention mesocosms. Twelve mesocosms were arranged under outdoor summer conditions in four configurations: planted/free-drainage (PF), planted/IWS (PI), unplanted/free-drainage (UF), and unplanted/IWS (UI). ET was determined by mass balance from periodic weighing, while soil moisture was monitored at three depths using sensors. Results showed that vegetation was the dominant control of ET, nearly doubling cumulative water loss compared to the unvegetated systems (~500 mm in PI compared with ~200 mm in UI). IWS further amplified ET by maintaining root-zone moisture, particularly during dry periods. Crop coefficients reached 3.0–3.5 in late summer for PI, demonstrating strong plant-driven recovery of retention capacity. The findings highlight IWS as an effective design enhancement for climate-resilient stormwater control.

## KEYWORDS

Bioretention, Evapotranspiration (ET), Internal water storage (IWS), *Salix integra*, Soil moisture dynamics, Urban blue-green infrastructure

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## 1 INTRODUCTION

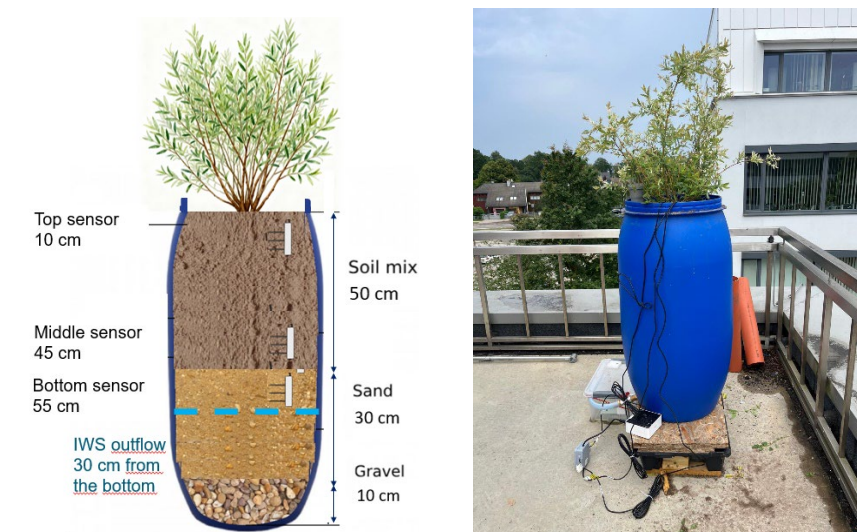
Bioretention systems are widely implemented as nature-based solutions for urban stormwater management, helping reduce runoff, mitigate flooding, and support groundwater recharge (Huang et al 2025, Boogaard et al 2025). These systems are one of the most widely used nature-based solutions for stormwater management (Boogaard & Kondratenko, 2024). However, their design has traditionally focused on infiltration, paying less attention to evapotranspiration (ET), which is important not only for the recovery of the hydraulic capacity of the system, but also for local water retention and mitigating the urban heat island effect.

ET is a major water balance component in bioretention, supporting plant growth and returning 30–90% of captured rainfall back to the atmosphere (Ouédraogo et al., 2022). Its magnitude depends strongly on soil moisture availability and functional traits of the vegetation. In shallow engineered substrates, declining moisture rapidly limits plant transpiration, which is reflected in highly variable crop coefficients ( $K_c \approx 0.65\text{--}2.91$  in temperate climates (De Ville et al. 2024). Internal water storage (IWS) has been shown to sustain root-zone moisture and enhance ET between storm events. While vegetation is the primary driver of ET, its effectiveness is constrained by the hydrological design of bioretention systems — particularly drainage configuration and moisture retention. Yet the combined effect of vegetation and IWS on ET under controlled stormwater regimes remains insufficiently quantified.

This study addresses this knowledge gap by evaluating how vegetation and IWS jointly influence ET dynamics in replicated mesocosm-scale bioretention systems under outdoor conditions, providing insights relevant for climate-resilient system design.

## 2 MATERIALS AND METHODS

Twelve cylindrical 150 L mesocosms were used to evaluate the influence of vegetation and IWS on ET in bioretention systems. The units were placed on elevated platforms to allow periodic weighing for mass-balance ET estimation. Each mesocosm consisted of a three-layer substrate profile representative of bioretention design: 10 cm gravel at the base, 30 cm sand, and 50 cm loamy soil mix made of sifted topsoil, compost, and sand. Layers were installed uniformly to ensure consistency across replicates. Drainage was provided through a single bottom outlet with a controllable valve system. In IWS treatments, the drainage outlet height was elevated through a transparent riser pipe assembly, creating a perched water table at 30 cm above the base setting. *Salix integra* ‘Hakuro-nishiki’ saplings were planted in the vegetated treatments. Four treatments were established: planted/free drainage (PF), planted/IWS (PI), unplanted/free drainage (UF), and unplanted/IWS (UI), with three replicates per treatment. Mesocosms were placed outdoors (June–September) on a flat rooftop, with randomized locations to minimize environmental bias. Rainfall events were simulated according to local precipitation patterns derived from meteorological station data, assuming contributing area 10 times the top area of the mesocosm. Water was applied evenly over the soil surface using a showerhead watering can.



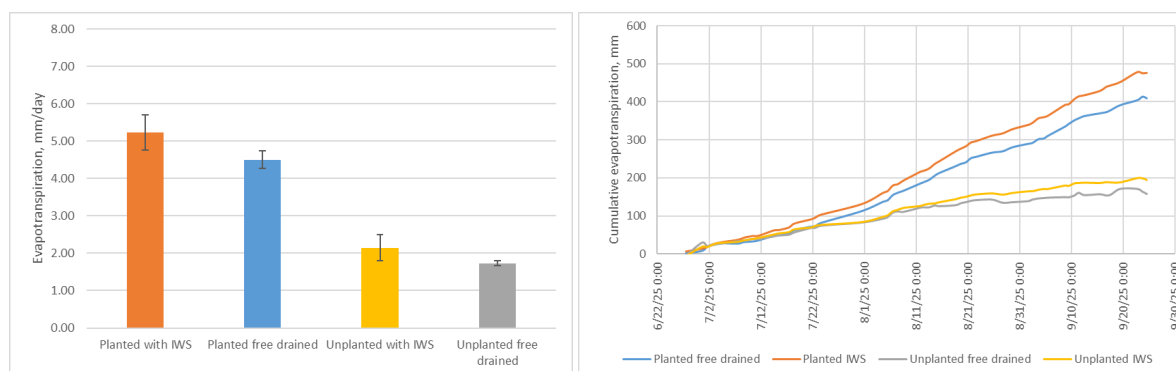
**Figure 1.** Schematic (a) and photograph (b) of bioretention mesocosms.

ET was calculated using a mass-balance approach based on periodic weighing, subtracting observed drainage outflow where applicable. Overflow volumes from drainage were collected and measured during each watering cycle. Soil moisture (volumetric water content), electric conductivity and temperature were logged using TEROS 12 sensors installed at three depths: 10 cm (topsoil root-active zone), 4 cm above the soil–sand interface (transition zone), and 4 cm below the interface (sand layer). One replicate of each treatment additionally included a TEROS 21 water-potential sensors at corresponding depths. Sensor placement and calibration were standardized across mesocosms to ensure cross-treatment comparability.

Meteorological parameters (air temperature, relative humidity, wind speed, and solar radiation) were monitored to characterize atmospheric drivers of ET and calculate reference evapotranspiration  $ET_0$ . ET datasets were aggregated into daily and cumulative time series and analyzed across experimental periods to evaluate vegetation effects, IWS influence, and the interaction between soil moisture availability and ET behaviour. Differences among treatments were interpreted in the context of designed water retention conditions and observed climatic variability.

### 3 RESULTS AND CONCLUSIONS

The highest ET occurred in the planted mesocosms with IWS, reaching approximately 5.2 mm/day (Fig. 2a). This demonstrates that vegetation combined with sustained water availability substantially enhances water loss through evapotranspiration. Planted mesocosms without IWS maintained a high ET rate (~4.5 mm/day), though slightly less compared to IWS units, indicating occasional moisture limitations between watering or rainfall events. Unplanted mesocosms showed considerably lower ET: about 2.1 mm/day with IWS and 1.7 mm/day without IWS, confirming that transpiration from vegetation is the dominant contributor to total ET. Meanwhile, differences between planted and unplanted treatments as well as between free-drained and IWS-equipped mesocosms are statistically significant.

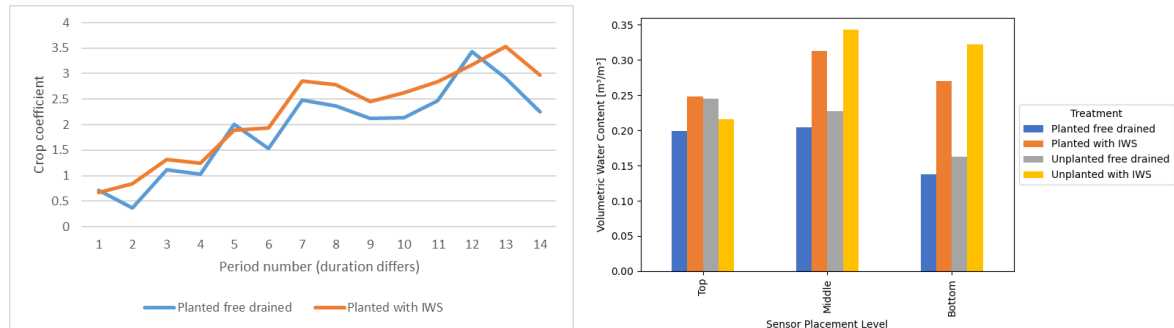


**Figure 2.** The average daily evapotranspiration (ET) (a) and the cumulative ET dynamics under outdoor conditions for four mesocosm types (b).

The cumulative ET curves (Fig. 2b) show a clear separation between planted and unplanted mesocosms, as well as a strong enhancement from IWS. From early July through late September, the planted treatments exhibited the highest cumulative ET, with PI outperforming PF throughout the experiment. By late September, PI reached approximately 480–500 mm, while PF accumulated around 420 mm. In contrast, unplanted treatments showed substantially reduced ET. UI gradually reached roughly 200 mm, while UF remained the lowest, around 160–180 mm. The difference between planted and unplanted systems progressively increased over time, especially during prolonged dry periods in August and September. Overall, the results demonstrate that vegetation was the dominant driver of water loss, nearly doubling cumulative ET compared to unvegetated systems, while IWS further enhanced ET by sustaining root-zone moisture between watering or rainfall events. The combination of plants and IWS therefore yielded the greatest and most continuous storage recovery potential in bioretention under outdoor summer conditions.

The crop coefficient ( $K_c$ ) determined as  $ET/ET_0$  increased progressively over the outdoor experiment, reflecting plant growth and the strengthening role of transpiration throughout the summer (Fig. 3a). In both treatments,  $K_c$  values started below 1.0 during the initial establishment period and consistently rose above 2.0 as vegetation

developed. Across most analysis periods, PI exhibited higher  $K_c$  values compared to the PF. Peaks of 3.0–3.5 were observed in late summer, indicating strong plant-driven ET even under drying atmospheric conditions. The persistent difference between PI and PF suggests that IWS sustained root-zone moisture, enabling higher transpiration rates when free-drained systems experienced intermittent water stress. Overall, IWS improved plant water availability, resulting in enhanced ET efficiency relative to reference ET — particularly during later growth stages and prolonged dry intervals.



**Figure 3.** Crop coefficient dynamics in planted bioretention mesocosms with and without IWS (a) and average volumetric water content at three substrate depths for four bioretention mesocosm types under outdoor conditions (b).

Soil moisture distributions differed clearly among mesocosm types and depths (Fig. 3b). The planted treatments with IWS (PI) consistently maintained the highest volumetric water content across all three monitored depths, followed by the unplanted IWS treatment (UI). In contrast, free-drained treatments (PF and UF) showed lower moisture availability, especially in the bottom layer, where rapid drainage led to the driest conditions. In the topsoil (10 cm), moisture levels were moderate and relatively similar between treatments, indicating that this layer experienced frequent drying and rewetting driven by atmospheric conditions (Fig. 3b). Differences became more pronounced deeper in the profile: the middle sensor, in both IWS treatments, showed visibly greater retained moisture, reflecting the influence of the controlled water table. At the bottom sensor, the contrast was strongest—PI and UI maintained substantially higher water contents than PF and UF, demonstrating effective moisture storage and upward availability for root uptake. Overall, internal water storage increased root-zone hydration, particularly in deeper layers, which supports the higher ET observed in vegetated IWS systems.

The results are of importance for stakeholders in (inter)national cities that implement, maintain, and monitor biofiltration. Knowledge of ET, vegetation and water balance related to long-term performance enables urban planners to implement the most appropriate stormwater management strategies [Boogaard & Kondratenko, 2024]. Similar research with the same equipment is planned in Italy and The Netherlands to set the research results in a bigger perspective and should be available in 2026.

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