Four-year monitoring of experimental green roofs: hydrological performance and vegetation evolution

Quatre années de suivi de toitures végétalisées expérimentales : performance hydrologique et évolution de la végétation

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RÉSUMÉ

Quatre toitures végétalisées expérimentales, présentant différentes configurations de stockage sous-jacent et de régulation du débit de sortie, ont été installées sur la plateforme GROOF de l'INSA Lyon, en France. La collecte de données au pas de temps de 1 minute (précipitations et autres paramètres météorologiques, stockage d'eau, débits et évapotranspiration réelle) a débuté en juin 2002. Quatre années de données (juin 2022-mai 2026) permettent d'évaluer de manière comparative les performances hydrologiques des toitures végétalisées pour diverses conditions météorologiques, ce qui contribuera à améliorer leur conception et à affiner les outils de modélisation. L'analyse des données montre qu'une partie très importante des précipitations annuelles est évapotranspirée, avec des différences selon la profondeur du substrat, le stockage de l'eau et la régulation du débit de sortie. Un premier inventaire de la végétation, après 3 ans, révèle des différences significatives entre les toitures végétalisées, avec l'apparition de nouvelles espèces favorisée par une épaisseur de substrat plus importante.

ABSTRACT

Four experimental green roofs with different configurations of underlaying storage and outflow control have been installed on the GROOF platform at INSA Lyon, France. Collecting data with a 1 min time step (rainfall and other meteorological quantities, water storage, outflow and actual evapotranspiration) started in June 2002. Four years of data (June 2022-May 2026) allow to evaluate comparatively the hydrological performance of the green roofs under various meteorological conditions, which will contribute to improve their design and to refine modelling tools. Data analysis shows that a very significant part of annual rainfall is evapotranspirated, with differences depending on substrate depths, water storage and outflow control. A first inventory of vegetation, after 3 years, reveals significant differences between the vegetated roofs, with more new species appearing when the substrate depth is higher.

KEYWORDS

Actual evapotranspiration, vegetation biodiversity, source control, urban stormwater management, vegetated roof

Biodiversité végétale, évapotranspiration réelle, gestion des eaux pluviales urbaines, ouvrage de gestion à la source, toiture végétalisée.

1 INTRODUCTION

Monitoring water fluxes in and out of green roofs is of particular importance to understand their benefits and limits for urban stormwater management, to improve their design, and to develop and refine modelling tools. However, direct monitoring of the evapotranspiration flux (ET) remains challenging (e.g. Cascone et al., 2019). This abstract describes data collection, analysis and first results from the experimental research carried out on the GROOF platform at INSA Lyon, France. Four green roofs with different substrate depths and outflow control are compared, in order to estimate their actual ET and peak flow reduction performance. Analysis of data obtained from June 2022 to September 2024 are presented in this abstract, and four years of data (June 2022 to May 2026) will be presented during the conference. In addition to hydrological performance, the evolution of the vegetation of the green roofs has been evaluated by means of an inventory of vegetation species made in June 2025. Another inventory of vegetation will be done in Spring 2026 and presented during the conference.

2 MATERIAL AND METHODS

2.1 GROOF platform

Four horizontal green roofs, provided by the company Le Prieuré, are installed on the GROOF platform (Figure 1). Their structure is shown in Figures 1a and 1b and includes i) a substrate planted with sedums, ii) a separation plate with cells filled with clay pellets, iii) an underlying storage layer (water storage capacity of 52 mm) to store water percolating from the substrate, iv) irrigation wicks allowing to transfer the water stored in the underlying storage to the above vegetation (i.e. sub-irrigation) through capillarity, and v) an outflow controller to regulate the outflow to a specified maximum value.

Figure 1. a) Scheme of the OASIS advanced green roof; b) photo of an unmounted tray; c) and d) photos in January 2023 of resp. Stromboli - 60 mm substrate and Monstro – 120 mm substrate. Adapted from Bertrand-Krajewski *et al*. (2024).

The main characteristics of the four green roofs are:

- Stromboli (STR): 60 mm substrate depth, no underlying storage and no outflow controller.
- Monstro (MOS): 120 mm substrate depth, underlying storage 52 mm with max. controlled outflow ≈ 1.54 L/s/ha = 0.56 mm/h.
- Cleo (CLE): similar to Monstro but covered with two photovoltaic panels (PV).
- Gedeon (GED): 240 mm, underlying storage 52 mm and no outflow (closed controller).

All green roofs are 3 m × 3 m (Figure 1,) and are constructed as an assembly of 40 cm × 60 cm prefabricated trays with pre-grown sedums, linked with connectors allowing the water to circulate freely between all trays (Figure 1b), and therefore creating a unique underlying storage volume.

2.2 Monitoring setup

The GROOF platform is equipped with i) two tipping bucket flowmeters: one Précis-Mécanique 10 mL bucket and one home-made 1 L bucket to measure the outflow from the green roofs (controlled outflow + overflow), ii) four Flintec SB14 strain gauges per frame to weight continuously the green roof mass, and iii) meteorological sensors (Campbell Scientific CS 215 thermometer and hygrometer, CS 03002 anemometer and anemoscope, CS 300 photovoltaic pyranometer, two raingauges : one Précis-Mécanique 3029 0.25 mm tipping bucket raingauge and one OTT HydroMet weighing raingauge, and a data acquisition and transmission system installed in a nearby shelter). Data are collected with a 2-minutes time-step till 13/03/2023 and with 1-minute time step since. All sensors have been systematically calibrated after installation and are periodically verified and re-calibrated if necessary.

2.3 Data treatment and analysis

The GROOF equipment allows to estimate the rainfall *R* (mm) received by each roof, the continuous evolution of their mass *M* (kg, converted to equivalent water depth in mm), outflow *Q* (sum of controlled outflow and overflow, mm), allowing for calculation of the actual evapotranspiration *ET* (mm), for any given time-step, from the mass balance equation: $ET = R - Q - dM/dt$.

3 RESULTS

3.1 Water balance and monthly hydrological performance

A contrasting range of rainfall conditions was observed during the monitored period: dry months in both summer and winter (1.38 mm of rainfall in July 2022, 2.44 mm in February 2023), as well as 'average' months and wet months (150 mm in October 2023; 165 mm in March 2024, 160 mm in April 2024, respectively +50%, +178% and +113% above long term averages), with an almost 50-year return period on 28/04/2024 (107 mm in 24 hours).

Figure 2 shows the hydrologic performance of the four green roofs. Monthly mean evapotranspiration (min-max) averaged respectively 77% (36%-100%), 72% (31%-100%), 73% (21%-100%), 84% (32%-100%) of precipitation for STR (60 mm substrate, no regulated outflow), CLE (120 mm substrate + PV), MOS (120 mm) and GED (240 mm). Seasonal variations were strong (average monthly ET 64%, 55%, 58%, 71% in winter, and 83%, 92%, 88% and 99% in summer, for STR, CLE, MOS, GED respectively). Not surprisingly, the roof with the thickest substrate had the best evaporative performance. These performances are in line with values found in the literature (e.g. Ladani *et al.*, 2019). 1 min data allows for event scale analysis (not shown in this abstract: peak flow attenuation, etc.). At the event scale, total outflow depth and total rainfall depth were correlated. However, there was no obvious link between rainfall intensities and outflow volumes, confirming that ability to reduce runoff peaks is not just a function of characteristics of rainfall events, but also of antecedent conditions.

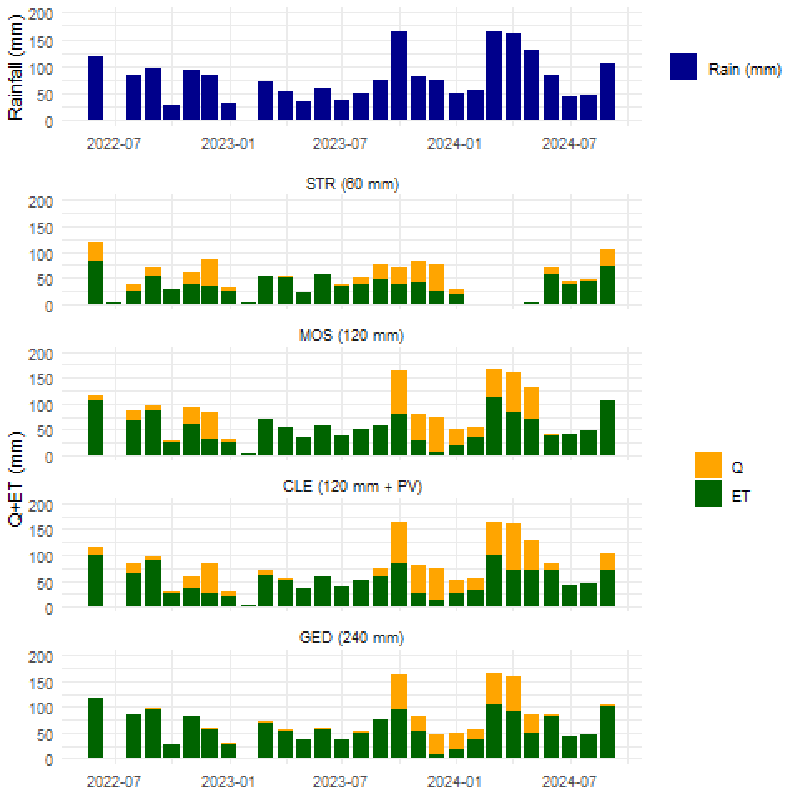

Figure 2. Monthly water balance for all four roofs (STR-MOS-CLE-GED) expressed in mm with monthly rainfall (mm), amount of water evapotranspirated (ET) in green and overflow+controlled outflow (Q) in yellow. Some monthly totals Q+ET are not equal to monthly rainfall (or data is missing) because of issues with the monitoring setup.

3.1 Inventory of vegetation

At the time of their construction in June 2022 (except GED built in January 2023), the four roofs were identically planted with the same species of sedums. The vegetation was deliberately left with no maintenance and no control. An inventory of species was done after three years in June 2025 (Table 1). On STR (thinnest substrate and no underlying storage), two of the initial six species of sedum disappeared, especially after the very dry summer 2022. On the three other roofs, with thicker substrates and underlying storage, five species of sedums are still present after three years. In addition, other species appeared and grew naturally, with eight and ten new species identified respectively on GED and CLE. The difference between MOS and CLE can be attributed to the solar panels, which generate some shade and concentrate more runoff at their feet. However, in addition to the number of species, the highest mass and density of vegetation is observed on GED: a thicker substrate with higher water retention clearly facilitates the growth of vegetation (Figure 3).

Table 1. Inventory of species on the four green roofs, June 2025.

Species	STR 60 mm	MOS 120 mm	CLE 120 mm + PV	GED 240 mm
Sedum hispanicum	X	X	X	X
Sedum album	X	X	X	X
Sedum spurium	X	X	X	
Sedum sexangulare		X	X	X
Sedum kamtschaticum		X	X	X
Sedum rupestre	X			X
Festuca sp.	X	X	X	
Alium schoenoprasum		X		X
Erigeron sumatrensis			X	X
Crepis setosa			X	X
Sonchus oleraceus			X	X
Trifolium hybridum			X	X
Bromus sp.		X		
Sonchus oleraceus		X		
Vicia hirsuta			X	
Trifolium repens			X	
Trifolium dubium			X	
Poa annua			X	
Lactuca serriola			X	
Dianthus sp.				X
Pilosella aurantiaca				X
Medicago lupulina				X

Figure 3. State of vegetation in Feb. 2025. Top to bottom: STR, MOS and GED.

4 CONCLUSIONS

Based on the first 28 months of monitoring, the mean monthly evapotranspiration represents at least 70% of the precipitation. Small to medium events (< 10 mm) are mostly entirely retained by the roofs and later evapotranspirated. This confirms green roofs perform well for stormwater management. In addition to initial sedums, new species appeared and grew naturally on the green roofs, with more diversity observed for thicker substrates and greater underlying water storage.

For the Novatech 2026 conference, data based on the four-year long monitoring will be presented, with updated evapotranspiration performance and analyses of results at lower time scales (event and daily performances, including possible overflows, not shown in this abstract). A second vegetation inventory planned in Spring 2026 will also be presented, along with data (not presented in this abstract) on birds and insects observed on the green roofs by self-triggering cameras (campaigns of Sept-Oct 2025 and Spring 2026).

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