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# Monitoring hydrologic performance and evapotranspiration of four experimental green roofs: first results after 16 months

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## Highlights

- A dedicated experimental platform has been installed and equipped to estimate green roofs evapotranspiration and hydrologic performance.
- Four green roofs with different substrate depths are monitored since June 2022.
- First results show the importance of substrate depth in hydrologic performance.

## Introduction

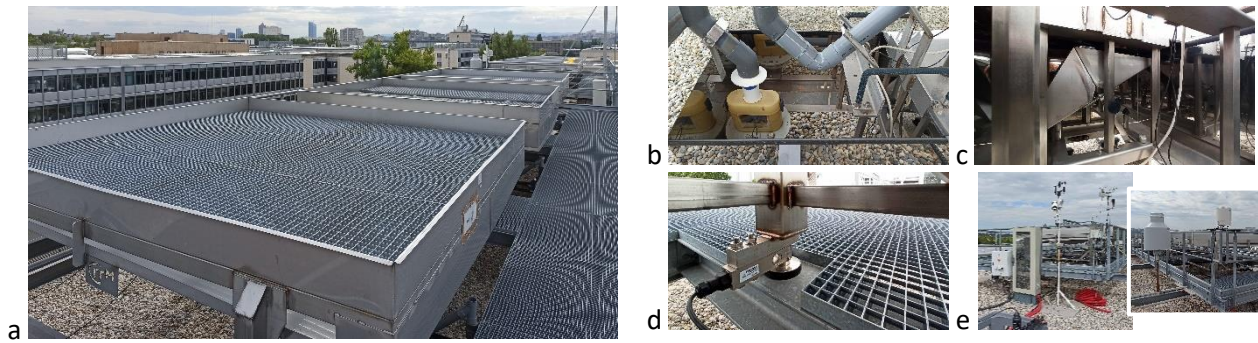
Monitoring actual evapotranspiration (ET) of green roofs is of particular importance to estimate their hydrologic performance, to improve their design, and to develop and refine modelling tools. However, monitoring ET remains difficult (e.g. Cascone *et al.*, 2019). This abstract describes new experimental research carried out on the GROOF platform to compare the performances of four green roofs and to estimate their actual ET. The monitoring campaign started in May 2022 and will last at least two years. Some results obtained after 16 months (June 2022-Sep 2023) are presented in this abstract.

## Material and methods

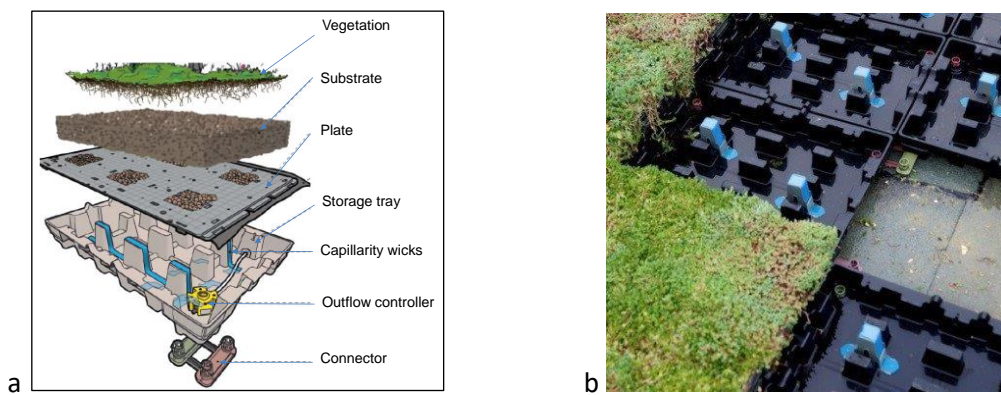
The GROOF (Green ROOF Facility) platform is dedicated to testing and evaluating the behaviour and the hydrologic performance of pilot green roofs (Figure 1a). It includes six frames of 9 m<sup>2</sup> (3 m × 3 m), equipped with i) two tipping bucket flowmeters: one Précis-Mécanique 10 mL bucket and one home-made 1 L bucket to measure the outflow (Figure 1b&c), and ii) four Flintec SB14 strain gauges (Figure 1d) per frame to continuously weight the green roof mass. The platform is also equipped with 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 shelter (Figure 1e). Data are collected with a 1-minute time step. All sensors have been systematically calibrated after installation and are periodically verified and re-calibrated if necessary.

Four advanced horizontal green roofs provided by the French company Le Prieuré are installed on the GROOF platform. They are based on the structure shown in Figure 2: i) a substrate planted with sedums, ii) a separation plate with cells filled with clay pellets, iii) an underlying storage layer filled with water coming from the substrate, iv) irrigation wicks allowing to transfer the water stored in the underlying storage to the above vegetation (i.e. sub-irrigation), v) an outflow controller to regulate the outflow to a given maximum value. The underlying storage capacity is equal to 52 mm. The four experimental green roofs names, substrate thickness, and particularities are the following ones: 1) Stromboli, 60 mm, no underlying storage; 2) Monstro, 120 mm, underlying max. regulated outflow  $\approx 1.54$  L/s/ha = 0.56 mm/h; 3) Cleo, similar to Monstro but covered with two photovoltaic panels (PV); and 4) Gedeon, 240 mm, underlying storage without outflow, i.e. only evapotranspiration and overflow. Cleo allows evaluating the possible influence of PV on green roof performance. The 3 m × 3 m roofs (see Figure 3) are built as an assembly of 40 cm × 60 cm trays with pre-grown sedums, linked with connectors allowing the water to circulate freely between all trays (Figure 2, detail), and therefore creating a unique underlying storage volume. In early 2024, the green roofs will be additionally equipped with Watermark soil moisture sensors (3 to 9 sensors per roof depending on

the substrate depth) which are currently individually calibrated under controlled laboratory conditions before installation.



**Figure 1.** The GROOF platform: a) general view, b) Précis-Mécanique 10 mL tipping bucket flow meter, c) home-made 1 L tipping bucket flowmeter, d) Flintec SB 14 strain gauge, and e) Campbell Scientific meteorological sensors (air temperature, air humidity, wind speed and direction, pyranometer), Précis-Mécanique tipping bucket rain gauge, OTT weighing rain gauge and data acquisition and transmission shelter.



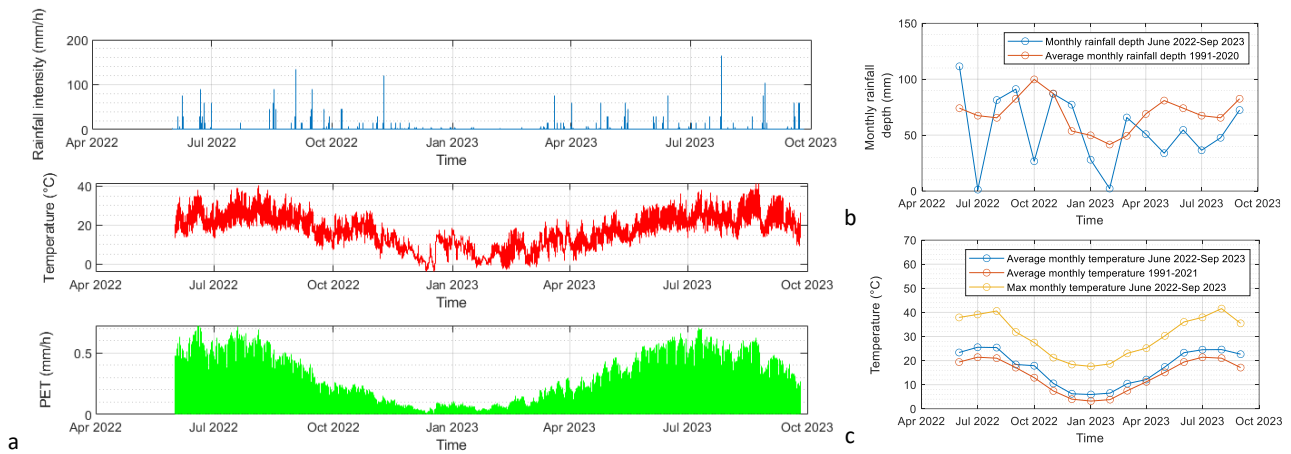
**Figure 2.** a) Scheme of the OASIS advanced green roof, and b) photo of trays with and without the upper vegetated layer.



**Figure 3.** Photos of a) Stromboli - 60 mm substrate, b) Monstro - 120 mm substrate, and c) Gedeon - 240 mm substrate under installation phase with naturally grown vegetation before upper trays with sedums are installed (January 2023).

## Results and discussion

Rainfall intensity, air temperature, and potential evapotranspiration (PET) estimated from the Oudin formula (Oudin *et al.*, 2005) are shown on Figure 4a. Total rainfall depth and PET (Figure 4a top and middle) during the June 2022-Sep 2023 campaign are respectively equal to 868 mm and 1414 mm. Compared to average monthly rainfall depths from the reference period 1991-2020 (Meteo France, 2023), the June 2022-Sep 2023 campaign shows a significant 22% rainfall deficit: 868 mm compared to 1110 mm for theoretical average precipitation during the same period (Figure 4b). The green roofs have therefore received less rain than during average months. Average monthly temperatures are also compared between the June 2022-Sep 2023 campaign and the reference period 1991-2021 (Climate Data, 2023). Average temperatures are systematically higher during the campaign (Figure 4c), with a mean difference of +3.2°C. Maximum monthly temperatures are, on average, 13°C above mean monthly temperatures measured during the campaign, with peaks greater than 40°C in Aug 2022 and Aug 2023. Such high temperatures tend to increase evaporation and therefore ET. However, the observed high temperatures combined with low rainfall depths is critical for the vegetation, which may suffer from strong hydric stress and transpire less, and creates a chance of evaluating the influence of the vegetation in the roof performance. PET (Figure 4a bottom) shows typical annual pattern, with high values in 2022 and 2023 summer periods.



**Figure 4.** Meteorological time series - a) from top to bottom: rainfall intensity (mm/h), temperature (°C), and Oudin PET (mm/h) from 01 June 2022 to 25 Sep 2023; b) comparison of monthly rainfall depth (mm) for June 2022-Sep 2023 and reference period 1991-2020; c) comparison of average monthly temperature (°C) for June 2022-Sep 2023 and reference period 1991-2021, along with maximum monthly temperature for June 2022-Sep 2023.

Compared to previous experiments (Arias *et al.*, 2019), the novelty is that GROOF allows to measure continuously the mass of each green roof, which is used to estimate the actual evapotranspiration from the mass balance equation:

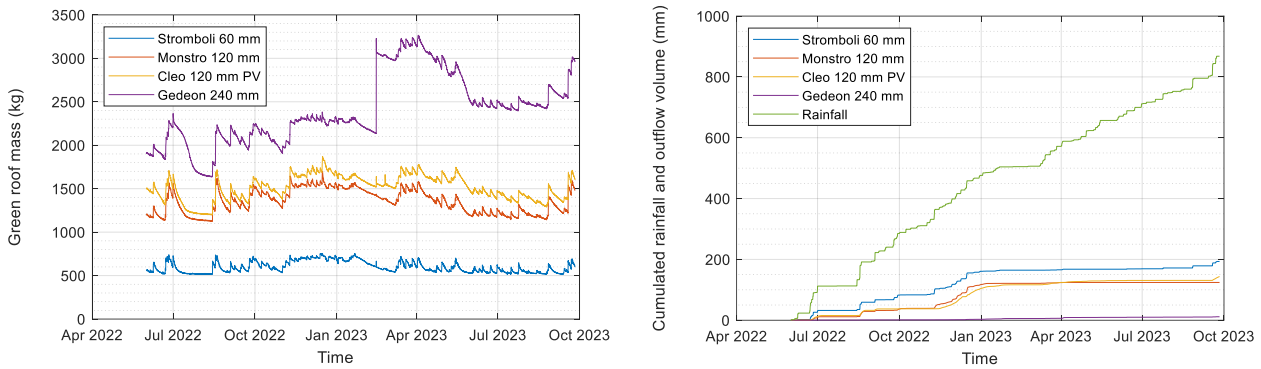
$$\frac{dM}{dt} = I - Q - ET \quad \text{Eq. 1}$$

with  $dM/dt$  the variation of the roof mass during  $dt$  (mm/h), and  $I$  the rainfall intensity (mm/h),  $Q$  the roof total outflow (mm/h) and  $ET$  the actual evapotranspiration (mm/h) during  $dt$ .

Figure 5 left shows the mass of the four green roofs during the June 2022-Sep 2023 campaign. Stromboli, Monstro and Cleo were fully installed from June 2022. Gedeon substrate was only partly installed in June 2022, without upper trays with vegetation. The installation was delayed to due additional checking to verify that the building supporting GROOF could accept a mass heavier than initially planned. Gedeon was terminated on 14 Feb 2023, as is clearly visible on Figure 6 with a sudden increase of mass from 2134 kg to 3074 kg. This delay allows to evaluate the green roof performance without vegetation and a substrate thickness temporarily lower than 240 mm.

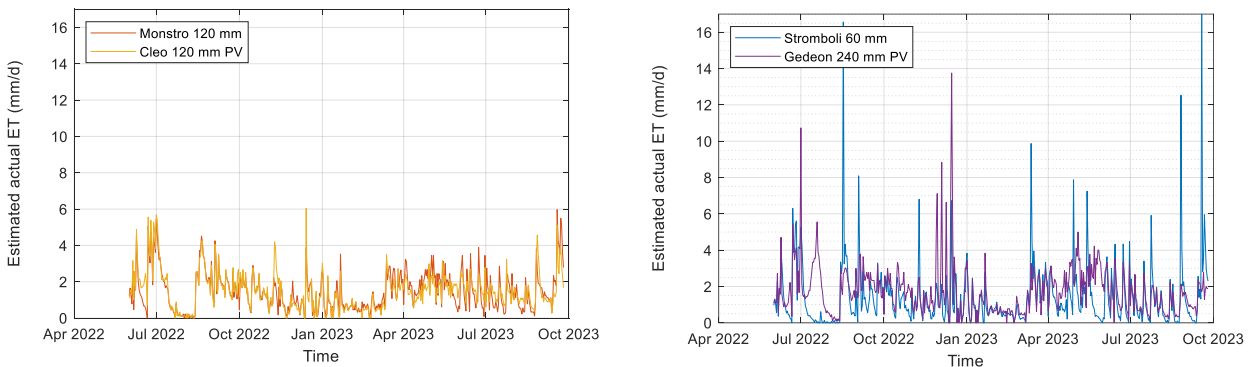
The mass of each roof increases during rainfall events. By neglecting  $ET$  during rainfall events, the variation of the green roof mass corresponds accurately to the rainfall depth measured by the raingauges when green roof outflow is accounted for. During dry periods between storm events, the green roof mass decreases. The decrease rate is higher when there is some outflow shortly after a rainfall event, and lower when there is no more significant outflow and only  $ET$ . In theory, the decrease in mass is then equal to the mass of water evapotranspired from the green roofs. As expected, the outflow is also higher during intense and strong rainfall events, as the system as a higher probability to become saturated.

Cumulated rainfall depth and green roof outflow volumes are shown in Figure 5 right. During the June 2022-Sep 2023 campaign, the total rainfall depth is 868 mm, and the total outflow volumes, expressed in mm, for Stromboli, Monstro, Cleo and Gedeon are respectively 193 mm, 124 mm, 144 mm, and 11 mm. The global performances, corresponding to both  $ET$  (major part) and retention in the roof structure (minor part) compared to rainfall depth, are respectively equal to 78%, 86%, 83% and 99%. As expected, the performance increases with the substrate depth. At first glance, photovoltaic panels (PV) do not lead to a significantly lower global performance. However, visual observations (not shown here) reveals that the vegetation under PV is less developed and tends to shrink. A more detailed comparative analysis of Monstro and Cleo performances and of their evolution during the campaign and at rainfall event scale is in progress. Gedeon (240 mm substrate) is very close to a “zero discharge” global performance. A more detailed analysis will be carried out to evaluate if the vegetation layer, installed only on 14 Feb 2023, plays a significant role or not in the global performance compared to the previous period.



**Figure 5.** Left: green roof mass, right: cumulated rainfall depth and green roof outflow volumes, both for June 2022-Sep 2023.

The actual ET is estimated at daily time step from Eq. 1, based on measurements of rainfall, outflow, and roof mass at 1 minute. Results are shown on Figure 6. During the June 2022-Sep 2023 campaign, the total estimated ET depths for Stromboli, Monstro, Cleo and Gedeon are respectively 676 mm, 715 mm, 721 mm, and 843 mm (errors in mass balances are below 4%). These values correspond respectively to 48%, 51%, 51% and 60% of the total Oudin PET over the same period (1414 mm). Calculations are also done with Penman-Monteith PET estimates (not shown here) based on local meteorological measurements. A few ET peaks for Stromboli and Gedeon appear to be linked with high intensity rainfalls and deserve further analysis.



**Figure 6.** Estimated actual ET for June 2022-Sep 2023. Left: Monstro and Cleo; right: Stromboli and Gedeon.

## Conclusions and future work

The four experimental green roofs have a retention + evapotranspiration global performance ranging from 78% to 99%. Total estimated actual ET ranges from 48 to 60% of the Oudin PET. The conference presentation will present two years of monitoring results with more details, in particular further analysis of the estimated ET at event and month scales. It will also include the very rainy period that started in mid-October 2023 and how it affects the green roof performance. Further work will include model testing and calibration based on the experimental data.

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