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Determinants of the evapotranspiration flux from an experimental green roof: analysis based on observations using water balance method

Déterminants du flux d'évapotranspiration d'une toiture végétalisée expérimentale : analyse à partir d'observations par la méthode du bilan hydrologique

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RÉSUMÉ

L'évapotranspiration est un processus important dans les ouvrages végétalisés de gestion des eaux pluviales dont l'objectif n'est pas seulement de réduire le ruissellement urbain mais aussi de favoriser un rafraîchissement et/ou une restauration d'un bilan hydrologique plus proche du milieu naturel. Cependant, son évaluation sur ces ouvrages et particulièrement sur les toitures végétalisées reste parfois difficile et/ou méconnue. Des estimations d'évapotranspiration par bilan hydrologique ont été effectuées dans différents compartiments d'une toiture végétalisée expérimentale du Cerema (Trappes, Ile de France, France). Les résultats obtenus montrent que pendant les jours secs (sans pluie), les valeurs d'évapotranspiration évaluées sont entre 0,8 et 2 mm par jour (quantile de 90 %) en fonction des configurations. L'épaisseur du substrat est un facteur déterminant qui augmente l'évapotranspiration (cumul d'évapotranspiration des périodes communes, 341 jours : 101 mm vs 257 mm respectivement pour 3 et 15 cm de substrat). Le type de substrat (322 jours, 280 mm vs 243 mm respectivement pour un substrat intensif et extensif) et le type de végétation (311 jours, sedums vs graminées, de 226 mm et 212 mm respectivement) restent des facteurs qui ont un impact sur l'évapotranspiration des toitures végétalisées.

ABSTRACT

Evapotranspiration is an important process in green infrastructure systems that aims not only to reduce urban runoff but also to promote cooling and/or restoration of a hydrological balance closer to the natural system. However, its evaluation on these structures and particularly on green roofs remains sometimes difficult and/or unknown. Estimates of evapotranspiration by hydrological balance were performed in different plots of an experimental green roof (Trappes, France). Results show that, during dry days (without rain), the assessed evapotranspiration values are around 0.8 to 2 mm per day (90% quantile) depending on the plots. The thickness of the substrate is a major factor that increases evapotranspiration (cumulative evapotranspiration for common periods, 341 days: 101 mm vs 257 mm respectively for 3 and 15 cm of substrate). The types of substrates (322 days, 280 mm vs. 243 mm respectively for intensive and extensive substrate) and vegetation (311 days, sedums vs. grasses, of 226 mm and 212 mm respectively) were also found to affect evapotranspiration from green roofs.

KEYWORDS

Evapotranspiration, green roofs, observation, stormwater

1. INTRODUCTION

Green roofs (GRs) belong to the family of green infrastructure systems GIS (infiltration ditches, roofs, rain gardens, permeable parking lots, etc.) used to manage urban stormwater and reduce the impact of climate change (Ferrans et al., 2022). The contribution of green roofs to stormwater management is well documented in the literature. In several cities in Europe (Sweden, Belgium and Germany) and the USA, Palla et al. (2010), by analysing experimental studies, reported that runoff retention of GRs varies between 40% and 80% of the total rainfall on a yearly basis. Such performance depends on factors such as rainfall intensity, substrate thickness, climate, vegetation and season (Zheng et al., 2021). If the ability of GRs to reduce runoff is widely studied, the process by which they perform is poorly addressed. Indeed, during rain, a part of the water is intercepted by the vegetation and the other part arrives in the pores of the roof substrate, and it is the evapotranspiration (ET) process (transpiration and evaporation) which restores the storage capacity of these pores.

In this study, a particular attention is paid to the ET process on GRs and two main objectives are pursued: i) assessment of the ET by water balance from the available measurement database and ii) evaluate the determinants of the ET.

2. MATERIALS AND METHODS

The experimental setup is an extensive green roof installed in the Cerema site at Trappes in Paris metropolitan area (France, Figure 1). The roof was divided into six 35 m² (7x5 m) vegetated plots which differ from four design parameters: the vegetation cover (sedum and/or grass), the substrate thickness (3 cm or 15 cm), and the nature of the substrate (intensive or extensive), as well as the type of drainage layer (expanded polystyrene or pozzolan). More details on the experimental set-up can be found in Gromaire et al. (2013). A rain gauge and tipping buckets are used to measure respectively rainfall and drainage at the gutter outlet of each plot. For each plot, sensors were used to monitor water content (EC5 and HS10 capacitive sensor, Decagon) at different depths in the substrate. The data set was acquired at a 1-minute time step over a period of several years from July 2011 to July 2018.



Figure 1: experimental green roof. (1): the weather station and (2): the rain gauge. The green box (3) at the foot of the building contains the tipping buckets for measuring the drainage from the gutters. The symbols are defined by G: Grass, S: Sedum, E: Extensive substrate, I: Intensive substrate, 15 cm or 3 cm for substrate thickness, Y: expanded polystyrene drainage layer, Z: pozzolan drainage layer and, N: bare substrate.

ET is assessed at daily intervals for each plot by a water balance approach:

$$ET = P - D - d\theta \text{ (in mm)} \quad (1)$$

where P, D, and $d\theta$ are respectively the rainfall, the drainage, and the water storage variations in the green roof substrate estimated with the water content sensors.

The estimates focused on the non-rainy days (957 days). These periods are appropriate for the ET impact study considering that they are favourable for ET and also because of the reduction of the number of variables involved in the ET estimation (therefore less uncertainty).

3. RESULTS AND DISCUSSION

Figure 1 illustrates the estimated daily ETs on the different plots for the seven (7) years of processed data, only 49-55% of non-rainy days depending on the plot (SE3Y: 55%, SE15Y: 47%, GE15Y: 51%, GI15Y: 49% and NE3Y: 54%) were validated and used for ET estimation. These data represent significantly the summer (38% to 42%) and spring (29% to 40%) seasons rather than the autumn (1 to 15%) and winter (12 to 19%) where few days are rainless.

The ET annual dynamics are illustrated with daily values around 0.8 to 3 mm per day (90% quantile) in spring and summer, and low values in winter and autumn. These results are consistent with pilot studies (lysimeters mimicking green roofs) conducted in Europe and the USA reporting estimated daily ETs between 0.5 and 10 mm for temperate climates (Ebrahimian et al., 2019). The observed seasonality of ET is related to atmospheric factors such as solar radiation, wind speed, air humidity and air temperature. The assessed ETs are significantly higher than the potential evapotranspiration of grass (ETP MF) evaluated by the Meteo-France formula (Vannier and Braud, 2012) generally used for the study (models, ET estimations) of these structures.

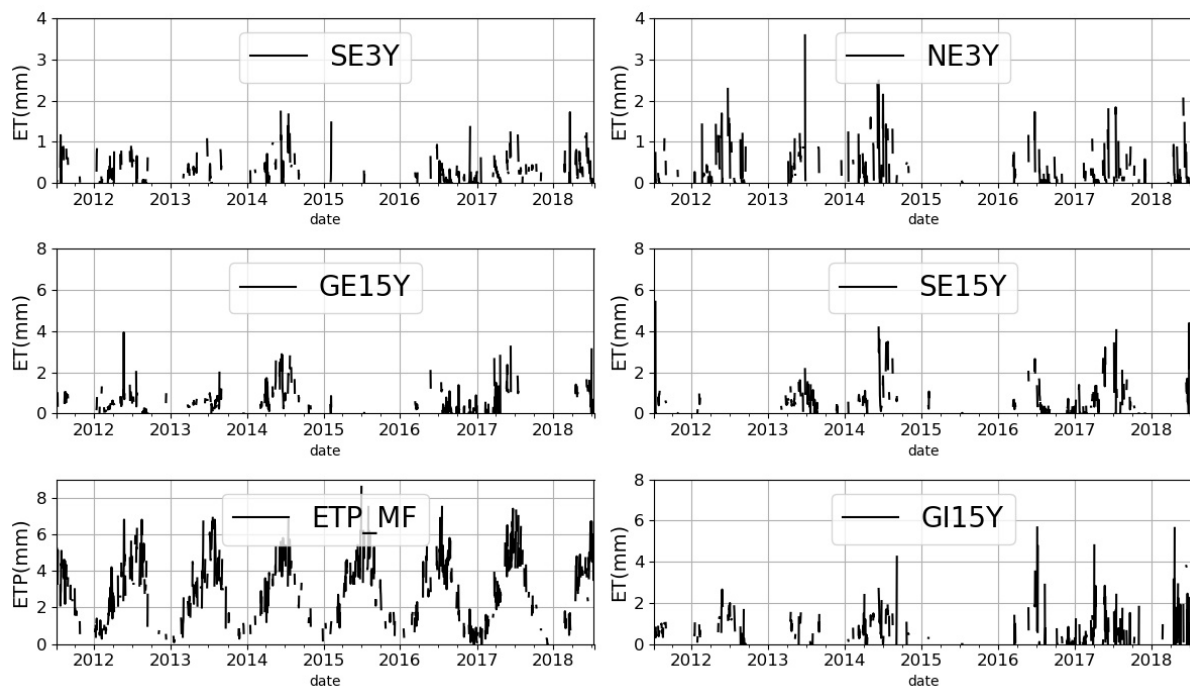


Figure 2: Daily evapotranspiration for the five plots of the green roof from July 8, 2011 to July 14, 2018, and a comparison with the potential evapotranspiration ETP_MF of a grass (Meteo-France).

The impact of substrate (thickness and type) and vegetation (sedum or grass) was also evaluated by comparing the common ETs values of the different plots two by two (Table 1). Results show a small inverse impact of the presence of vegetation when compared to bare soil, for substrates of 3 cm (SE3Y and NE3Y have respectively total accumulations of 145 mm and 158 mm). The type of vegetation – sedum or grass – which is compared for the 15 cm substrate, also have an impact (respectively 226 and 212 mm). For the same type of vegetation (sedum in our case), the thicker the substrate, the higher the evapotranspiration (SE3Y and SE15Y have respectively total accumulations of 103.5 mm and 258 mm). These last observations indicate the importance of the water stock available for ET.

In an experimental laboratory study of various green roof plots in the UK for 28 dry days in spring and summer, Poë et al. (2015) also show higher ET rates for bare substrates compared to sedum or meadow flower plots. These observations occur most frequently just after rainfall and can be sustained for many days before the ET of the bare plot to decrease significantly compared to the ET of the vegetated plots. In addition, Heusinger and Weber (2022) by evaluating the energy balance on an extensive green roof at Berlin Brandenburg Airport, Germany, show the importance of maintaining moist green roof substrates (water content minimum of 11%) to support higher latent heat flux (then, evapotranspiration) and thus good local cooling. The impact of the type of vegetation, under the same climate, is quite contrasted in the literature. Contrary to our case between sedums and grasses, Poë et al. (2015) do not

observe significant differences between the ET of sedum and meadow flowers. Under the same UK climatic conditions (in a greenhouse), Kemp et al. (2019) showed that herbaceous plants such as stachys and Salvia with 15 cm of peat based compost give more ET (up to 72% water retention due to ET) than commonly used species of sedums (46% retention due to ET) and then show that other species can be promoted in green roof engineering.

Table 1: Comparison of ET on different green roof configurations based on dry days (i.e., no rain, 957 days) from July 2011 to July 2018 (2053 days). "std" in the table refers to standard deviation.

Determinants		Number of common valid days	Daily Evapotranspiration (mm/d) (Descriptive statistics)						Cumulative ET on common valid days (mm)
			Mean	Std	Max	Percentiles			
						25%	50%	90%	
Substrate thickness	SE15Y	341	0.8	0.8	4.4	0.2	0.5	2	257
	SE3Y		0.3	0.3	2	0.07	0.2	0.7	101
Type of substrate	GE15Y	322	0.8	0.7	4	0.2	0.6	1.6	243
	G15Y		0.9	1	5.6	0.14	0.6	2	280
Type of vegetation	SE15Y	311	0.7	0.8	5.4	0.2	0.5	1.5	226
	GE15Y		0.7	0.6	3	0.2	0.5	1.7	212
Presence/absence of vegetation	SE3Y	417	0.4	0.3	1.8	0.1	0.3	0.8	145
	NE3Y		0.4	0.5	3.6	0.02	0.2	1	158

4. CONCLUSION

The estimated ETs values of green roofs on dry days are around 0.8 to 2 mm per day (90% quantile) depending on the plots. They can reach 1.8 to 5.6 mm per day under optimal conditions. However, these values are still lower than the potential ET generally used for the study of these structures. The design and the assessment of the hydrological/thermal performance of green roofs need to take into account the limitation of the available water storage which is one of the most important factors influencing ET. In standard conditions, the cooling efficiency of green roofs in summer or spring is probably limited by the low water content of the substrate. Increase of the substrate thickness, introduction of a water storage and/or irrigation of the roof are possible options to ensure good hydrological and/or thermal performance of green roofs.

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