Journal of Hydrology 523 (2015) 356–367

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# Parameters influencing the regeneration of a green roof's retention capacity via evapotranspiration

Simon Poë [a,*], Virginia Stovin [a], Christian Berretta [b]

[a] Department of Civil and Structural Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, United Kingdom
[b] School of Civil Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom

ARTICLE INFO

*Article history:*
Received 11 September 2014
Received in revised form 23 January 2015
Accepted 1 February 2015
Available online 7 February 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Marco Borga, Associate Editor

*Keywords:*
Evapotranspiration
Green roofs
Stormwater management
SuDS
Retention

## SUMMARY

The extent to which the finite hydrological capacity of a green roof is available for retention of a storm event largely determines the scale of its contribution as a Sustainable Drainage System (SuDS). Evapotranspiration (ET) regenerates the retention capacity at a rate that is variably influenced by climate, vegetation treatment, soil and residual moisture content. Experimental studies have been undertaken to monitor the drying cycle behaviour of 9 different extensive green roof configurations with 80 mm substrate depth. A climate-controlled chamber at the University of Sheffield replicated typical UK spring and summer diurnal cycles. The mass of each microcosm, initially at field capacity, was continuously recorded, with changes inferred to be moisture loss/gain (or ET/dew). The ranges of cumulative ET following a 28 day dry weather period (ADWP) were 0.6–1.0 mm/day in spring and 0.7–1.25 mm/day in summer. These ranges reflect the influence of configuration on ET. Cumulative ET was highest from substrates with the greatest storage capacity. Significant differences in ET existed between vegetated and non-vegetated configurations. Initially, seasonal mean ET was affected by climate. Losses were 2.0 mm/day in spring and 3.4 mm/day in summer. However, moisture availability constrained ET, which fell to 1.4 mm/day then 1.0 mm/day (with an ADWP of 7 and 14 days) in spring; compared to 1.0 mm/day and 0.5 mm/day in summer. A modelling approach, which factors Potential Evapotranspiration (PET) according to stored moisture content, predicts daily ET with very good accuracy (PBIAS = 2.0% [spring]; −0.8% [summer]).

## 1. Introduction

Green roofs reduce rainfall runoff rates due to the plant cover (by interception), the substrate (by detention and retention for evapotranspiration [ET]) and the additional storage capacity in the underlying drainage reservoir. However, the extent of the hydrological benefit that green roofs provide within the Sustainable Drainage Systems (SuDS) management train is not well-quantified. A number of green roof hydrological research programmes, typically from temperate mid-latitudes, have reported variable retention levels – with average annual retention typically between 30% and 86% (Li and Babcock, 2014) and per event retention between 0% and 100% (Berghage et al., 2007; Stovin et al., 2012). There are, however, physical factors influencing this variability.

The hydrological cycle is driven by gravitational forces and solar energy; inducing moisture vapour transfer from the earth's surface to the atmosphere via ET. The rate at which this transfer takes place is important to a green roof's response to a subsequent storm event. Voyde et al. (2010) highlighted that "green roof ET has not been well quantified or thoroughly modelled" due to the absence of experimental data to underpin the modelling of ET losses for different vegetation treatments and climatic conditions.

---

*Abbreviations:* ADWP, Antecedent Dry Weather Period; CAM, Crassulacean Acid Metabolism; ET, evapotranspiration; $ET_{CUM}$, cumulative evapotranspiration; $ET_D$, daily evapotranspiration; $ET_O$, reference evapotranspiration; $ET_{Pred}$, predicted evapotranspiration; FAO-56, FAO-56 Penman–Monteith; FLL, Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (German Landscape Research, Development and Construction Society); HLS, Heather & Lavender Substrate; LECA, Lightweight Expanded Clay Aggregate; MWHC, maximum water-holding capacity, as defined by FLL; PBIAS, Percent Bias; PET, Potential Evapotranspiration; SCS, Sedum carpet substrate; $S_{MAX}$, maximum moisture storage capacity; $SMD_t$, soil moisture deficit or retention capacity at time, $t$; SMEF, soil moisture extraction function; $S_t$, residual stored moisture content at time, $t$; $S_{VEG}$, vegetation moisture storage capacity; SuDS, Sustainable Drainage System; TB, test bed; $\theta$, volumetric water content; $\theta_{FC}$, volumetric water content at field capacity; $\theta_{PWP}$, volumetric water content at permanent wilting point; $\theta_{<PWP}$, hygroscopic volumetric water content; $\psi_m$, matric potential.

* Corresponding author. Tel.: +44 (0) 7720 883630.
*E-mail address:* poes@alumasc-exteriors.co.uk (S. Poë).

http://dx.doi.org/10.1016/j.jhydrol.2015.02.002
0022-1694/© 2015 Elsevier B.V. All rights reserved.

There are three key, but interdependent, processes involved during ET; firstly, an upward capillary flux through the soil profile towards the soil's upper horizons; secondly, evaporative losses from the surface to atmosphere; and thirdly, transpiration of soil–water by plants. Forces inducing evaporation and transpiration losses are a function of the microclimate (i.e. solar radiation, air temperature, wind, relative humidity) and of the plant's physiology. However, the rate at which these forces induce ET depends upon the soil–water characteristics of the substrate (i.e. field capacity [$\theta_{FC}$], permanent wilting point [$\theta_{PWP}$], permeability), any additional moisture storage capacity within the vegetation layer and the plant's physiological response at the prevailing moisture content (Koehler and Schmidt, 2008).

### 1.1. The importance of moisture balance to ET

The soil–water characteristics of a green roof are an important control upon ET. All drainage systems have a finite capacity to store water (or moisture). The maximum moisture storage capacity ($S_{MAX}$) of a green roof will seldom be fully available (Berghage et al., 2007; Stovin et al., 2012) due to the presence of residual stored moisture, $S_t$ (Koehler and Schmidt, 2008). During dry periods between storm events ET reduces $S_t$ and increases the retention capacity, or soil moisture deficit ($SMD_t$). ET rates are expected to decay exponentially with respect to time (Fassman and Simcock, 2011; Kasmin et al., 2010) as available moisture reduces. However, in isolation, the length of the drying cycle – or Antecedent Dry Weather Period (ADWP) – "fails to characterise the complex processes that account for the roof's residual moisture content" (Stovin et al., 2012). Moisture content has consistently been seen to depend upon soil–water characteristics and plant interactions (Berretta et al., 2014). The key moisture balance terms are shown in Fig. 1.

The terms $SMD_t$ and $S_{MAX}$ have been used as overarching indicators of moisture balance in green roof systems. However, these terms have previously typically been thought to consist only of substrate moisture. In vegetated systems, the vegetation will provide some additional moisture storage capacity. Here, $S_{MAX}$ includes both plant-available moisture in the substrate (i.e. $\theta_{FC}$ minus $\theta_{PWP}$, and therefore excluding hygroscopic moisture, $\theta_{<PWP}$) and moisture held within the vegetation itself ($S_{VEG}$). Equally, the capacity available for retention ($SMD_t$) includes the moisture deficit in both the substrate and the vegetation (i.e. $S_{MAX}$ minus $S_t$).

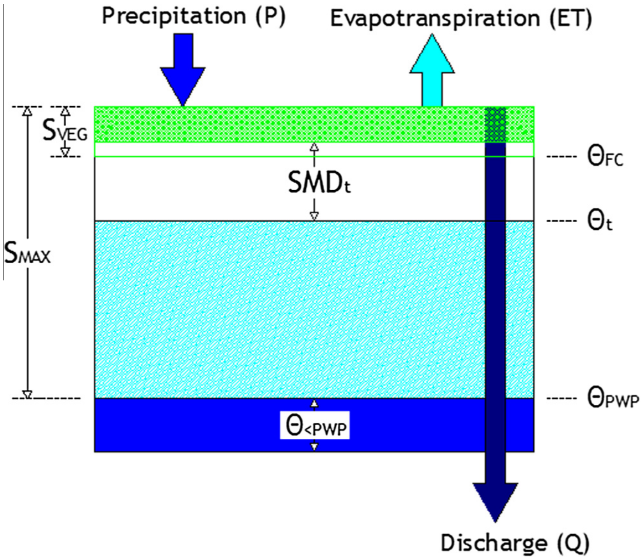

**Fig. 1.** Conceptual moisture balance retention model.

Many methods of estimating ET assume that moisture is in abundant supply (Wilson, 1990) and that, therefore, ET will not be constrained by the $SMD_t$. However, it is important to differentiate Potential Evapotranspiration (PET) from ET, as they will only be equal for the relatively short period of time when the green roof is at, or very near to, $S_{MAX}$. Thereafter, ET will be constrained by the $SMD_t$. Accordingly, any models that function on the premise that ET equals PET will typically over-predict ET losses (and underestimate runoff). The decay of ET as a proportion of PET (ET/PET) is a key modelling parameter that must account for moisture availability (Stovin et al., 2013); it is variably influenced by climatic conditions and plant and soil characteristics (Berretta et al., 2014).

### 1.2. Differences in ET due to climate

Previous research (Rezaei and Jarrett, 2006; Koehler and Schmidt, 2008; Fassman and Simcock, 2008) has identified that climatological factors (e.g. solar radiation, air temperature and relative humidity [RH]) affect ET rates; partially explaining the geographical differences in green roof retention response. Retention is typically higher in warmer conditions (Locatelli et al., 2014) and in arid or semi-arid climates, where annual average retention is typically higher (e.g. 74% in Australia according to Razzaghmanesh and Beecham, 2014) compared with temperate climates (e.g. 32–57% in Scandinavia according to Locatelli et al., 2014). Seasonal differences in ET have been identified (Rezaei and Jarrett, 2006; Koehler and Schmidt, 2008; Marasco et al., 2014), with the highest daily ET rates observed in warm summer conditions. Rezaei and Jarrett (2006) identified that ET rates from an extensive green roof (vegetated with 80% *Delosperma nubigenum* and 20% *Sedum album*) in Pennsylvania State were approximately four times greater in high summer (3.23 mm/day) compared to winter (averaging 0.79 mm/day). Koehler and Schmidt (2008) observed similar patterns in European conditions; albeit with lower winter ET of 0.1–0.5 mm/day and a greater range of summer ET (1.5–4.5 mm/day). In addition to temperature, seasonal precipitation patterns influence retention (Hakimdavar et al., 2014) with a higher incidence of intense storm events expected to result in lower retention.

### 1.3. The influence of vegetation upon ET

Plant transpiration is an important control on ET rates, accounting for between 20% and 48% of moisture lost to the atmosphere (Voyde et al., 2010). The plant's root system absorbs pore water, trans-locating it through the xylem to stomatal cavities in the leaf, where it is vapourised by solar energy. The deficit in the leaf cells creates a difference in potential between the leaves and roots, such that a suction force is transmitted back to the root (van den Honert, 1948).

Transpiration rates differ according to the plant's metabolic processes. Plants that have Crassulacean Acid Metabolism (CAM) are typically more drought tolerant than 95% of plant species (Voyde et al., 2010). Plants consume water by opening stomata. CAM plants open their stomata to metabolise at night when temperatures are cooler. Evaporative loss is therefore lower than from plants that transpire soil–water during warm daylight conditions. As such, ET from CAM plants (e.g. Sedum) tends to be controlled to a greater extent than would be the case with C3 or C4 species, e.g. Meadow Flowers, grasses (Nagase and Dunnett, 2012). Generally, previous research has focused on Sedum or other hardy, drought tolerant CAM species and hydrological differences attributable to plants with different traits are therefore not widely known. However, Fassman and Simcock (2008) reported that configurations vegetated with *Sedum mexicanum* tended to result in higher ET rates than with New Zealand Ice Plants and there is evi-