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Parameters Influencing the Regeneration of a Green Roof's

Retention Capacity via Evapotranspiration

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ABSTRACT

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

1 to be moisture loss/gain (or ET/dew). The ranges of cumulative ET following a 28 day dry
2 weather period (ADWP) were 0.6-1.0 mm/day in spring and 0.7-1.25 mm/day in summer.
3 These ranges reflect the influence of configuration on ET. Cumulative ET was highest from
4 substrates with the greatest storage capacity. Significant differences in ET existed between
5 vegetated and non-vegetated configurations. Initially, seasonal mean ET was affected by
6 climate. Losses were 2.0 mm/day in spring and 3.4 mm/day in summer. However, moisture
7 availability constrained ET, which fell to 1.4 mm/day then 1.0 mm/day (with an ADWP of 7
8 and 14 days) in spring; compared to 1.0 mm/day and 0.5 mm/day in summer. A modelling
9 approach, which factors potential evapotranspiration (PET) according to stored moisture
10 content, predicts daily ET with very good accuracy (PBIAS = 2.0% [spring]; -0.8% [summer]).

11 **KEY WORDS:** Evapotranspiration, Green Roofs, Stormwater Management, SuDS, Retention

12 **ABBREVIATIONS**

13	ADWP	Antecedent Dry Weather Period
14	CAM	Crassulacean Acid Metabolism
15	ET	Evapotranspiration
16	ET _{CUM}	Cumulative Evapotranspiration
17	ET _D	Daily Evapotranspiration
18	ET _O	Reference Evapotranspiration
19	ET _{Pred}	Predicted Evapotranspiration
20	FAO-56	FAO-56 Penman-Monteith

1	FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (German
2		Landscape Research, Development and Construction Society)
3	HLS	Heather & Lavender Substrate
4	LECA	Lightweight Expanded Clay Aggregate
5	MWHC	Maximum Water-Holding Capacity, as defined by FLL
6	PBIAS	Percent Bias
7	PET	Potential Evapotranspiration
8	SCS	Sedum Carpet Substrate
9	S_{MAX}	Maximum moisture storage capacity
10	SMD_t	Soil Moisture Deficit or retention capacity at time, t
11	SMEF	Soil Moisture Extraction Function
12	S_t	Residual stored moisture content at time, t
13	S_{VEG}	Vegetation moisture storage capacity
14	SuDS	Sustainable Drainage System
15	TB	Test bed
16	θ	Volumetric water content
17	θ_{FC}	Volumetric water content at field capacity
18	θ_{PWP}	Volumetric water content at permanent wilting point

1 $\theta_{<PWP}$ Hygroscopic volumetric water content

2 Ψ_m Matric potential

3 **1 INTRODUCTION**

4 Green roofs reduce rainfall runoff rates due to the plant cover (by interception), the substrate
5 (by detention and retention for evapotranspiration [ET]) and the additional storage capacity in
6 the underlying drainage reservoir. However, the extent of the hydrological benefit that green
7 roofs provide within the Sustainable Drainage Systems (SuDS) management train is not well-
8 quantified. A number of green roof hydrological research programmes, typically from
9 temperate mid-latitudes, have reported variable retention levels – with average annual retention
10 typically between 30 and 86% (Li & Babcock, 2014) and per event retention between 0 and
11 100% (Berghage *et al.*, 2007, Stovin *et al.*, 2012). There are, however, physical factors
12 influencing this variability.

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

19 There are three key, but interdependent, processes involved during ET; firstly, an upward
20 capillary flux through the soil profile towards the soil’s upper horizons; secondly, evaporative
21 losses from the surface to atmosphere; and thirdly, transpiration of soil-water by plants. Forces
22 inducing evaporation and transpiration losses are a function of the microclimate (i.e. solar

1 radiation, air temperature, wind, relative humidity) and of the plant's physiology. However, the
2 rate at which these forces induce ET depends upon the soil-water characteristics of the substrate
3 (i.e. field capacity [θ_{FC}], permanent wilting point [θ_{PWP}], permeability), any additional moisture
4 storage capacity within the vegetation layer and the plant's physiological response at the
5 prevailing moisture content (Koehler & Schmidt, 2008).

6 **1.1 The importance of moisture balance to ET**

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

19 [Approximate location of Figure 1]

20 The terms SMD_t and S_{MAX} have been used as overarching indicators of moisture balance in
21 green roof systems. However, these terms have previously typically been thought to consist
22 only of substrate moisture. In vegetated systems, the vegetation will provide some additional
23 moisture storage capacity. Here, S_{MAX} includes both plant-available moisture in the substrate

1 (i.e. θ_{FC} minus θ_{PWP} , and therefore excluding hygroscopic moisture, $\theta_{<PWP}$) and moisture held
2 within the vegetation itself (S_{VEG}). Equally, the capacity available for retention (SMD_t)
3 includes the moisture deficit in both the substrate and the vegetation (i.e. S_{MAX} minus S_t).
4 Many methods of estimating ET assume that moisture is in abundant supply (Wilson, 1990)
5 and that, therefore, ET will not be constrained by the SMD_t . However, it is important to
6 differentiate Potential Evapotranspiration (PET) from ET, as they will only be equal for the
7 relatively short period of time when the green roof is at, or very near to, S_{MAX} . Thereafter, ET
8 will be constrained by the SMD_t . Accordingly, any models that function on the premise that
9 ET equals PET will typically over-predict ET losses (and underestimate runoff). The decay of
10 ET as a proportion of PET (ET/PET) is a key modelling parameter that must account for
11 moisture availability (Stovin *et al.*, 2013); it is variably influenced by climatic conditions and
12 plant and soil characteristics (Berretta *et al.*, 2014).

13 **1.2 Differences in ET due to climate**

14 Previous research (Rezaei & Jarrett, 2006; Koehler & Schmidt, 2008; Fassman & Simcock,
15 2008) has identified that climatological factors (e.g. solar radiation, air temperature and relative
16 humidity [RH]) affect ET rates; partially explaining the geographical differences in green roof
17 retention response. Retention is typically higher in warmer conditions (Locatelli *et al.*, 2014)
18 and in arid or semi-arid climates, where annual average retention is typically higher (e.g. 74%
19 in Australia according to Razzaghmanesh & Beecham, 2014) compared with temperate
20 climates (e.g. 32-57% in Scandinavia according to Locatelli *et al.*, 2014). Seasonal differences
21 in ET have been identified (Rezaei & Jarrett, 2006; Koehler & Schmidt, 2008; Marasco *et al.*,
22 2014), with the highest daily ET rates observed in warm summer conditions. Rezaei & Jarrett
23 (2006) identified that ET rates from an extensive green roof (vegetated with 80% *Delosperma*

1 *nubigenum* and 20% *Sedum album*) in Pennsylvania State were approximately four times
2 greater in high summer (3.23 mm/day) compared to winter (averaging 0.79 mm/day). Koehler
3 & Schmidt (2008) observed similar patterns in European conditions; albeit with lower winter
4 ET of 0.1-0.5 mm/day and a greater range of summer ET (1.5-4.5 mm/day). In addition to
5 temperature, seasonal precipitation patterns influence retention (Hakimdavar *et al.*, 2014) with
6 a higher incidence of intense storm events expected to result in lower retention.

7 ***1.3 The influence of vegetation upon ET***

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

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

1 there is evidence that Sedum-vegetated configurations reduced runoff to a significantly greater
2 extent than equivalent configurations with a mix of ‘Meadow Flowers’ (Poë *et al.*, 2011). This
3 evidence contradicts the expectation that retention would be lower in CAM (Sedum) species
4 due to reduced ET rates. This could reflect the greater capacity for interception by the dense
5 Sedum foliage and/or the fact that certain Sedum species may have the ability to switch their
6 metabolism to CAM only under drought conditions (Sayed, 2001).

7 ***1.4 The effect of substrate characteristics upon ET***

8 The soil-water characteristics of a substrate are typically recognised as a key influence in the
9 system’s capacity to store rainfall (Palla *et al.*, 2010). The structure and texture of a substrate
10 governs its field capacity, permanent wilting point (Beattie & Berghage, 2004) and retention
11 and release characteristics (Manning, 1987; Miller, 2003). Adsorption of water molecules to
12 soil particles and cohesive forces between water molecules create negative (matric) pressure in
13 the soil-water. Matric pressure (ψ_m) is the driving force for soil-water fluxes in unsaturated
14 flow. When ψ_m is in equilibrium with gravitational forces, the substrate is at θ_{FC} . ψ_m is lower
15 in large pores than in small pores due to the greater distance between soil particles (Hillel,
16 1998). The granulometric distribution of the substrate will therefore govern the relationship
17 between θ and ψ_m .

18 This paper presents data from an experimental study, under laboratory-controlled conditions,
19 at the University of Sheffield, aimed at identifying the drying cycle behaviour of nine different
20 green roof configurations (with combinations of three characterised substrates and three typical
21 planting options) that were subjected to diurnal cycles representative of UK spring and summer
22 conditions. Responses are analysed for measurable physical influences; an important step
23 towards the development of predictive models of ET and stormwater retention. Observed

1 results will then be compared to ET that has been predicted using a simple moisture balance
2 model.

3 **2 MATERIALS AND METHODS**

4 **2.1 *Experimental Set-up***

5 An experimental set-up was established to continuously monitor mass balance changes
6 (inferred as changes in moisture, i.e. ET) from nine different green roof configurations,
7 comprising combinations of three substrates (to a settled depth of 80 mm, in accordance with
8 the Green Roof Code of Best Practice for the UK [GRO, 2014]) and three vegetation
9 treatments. A filtration membrane prevented the loss of fine particles from the substrate. A
10 drainage layer (with zero storage capacity) facilitated drainage to field capacity. Microcosms
11 of each configuration were established in polypropylene trays with internal dimensions of
12 237 x 237 x 120 mm (a size that was compatible with the capacity of the load cell and
13 platform). Tray bases were perforated for drainage of gravitational water prior to the trials. 25
14 x 6 mm Ø holes (providing a nominal drainage capacity of 0.1 litres per second) were set on a
15 60 mm grid, with a row of holes centred 5 mm from the tray's upstand. Each microcosm was
16 placed on to load cells within a Conviron BDW40 plant growth chamber at the University of
17 Sheffield's Department of Animal & Plant Sciences (see Figure 2a & 2b). Starting at S_{MAX} , no
18 irrigation was applied throughout the trials. Typical diurnal cycles were replicated for UK
19 spring and summer conditions. The former is of interest as, in spring, vegetation exits winter
20 dormancy and starts to transpire soil-water, whereas summer conditions will have greater ET
21 and drought stress due to the longer dry periods with higher temperatures. From a stormwater
22 management perspective, summer conditions are of particular interest as the long dry periods
23 may be interspersed with intense storm events.

1 [Approximate location of Figure 2]

2 Six trials were scheduled to take place between the 7th April and the 25th August 2011. First,
3 the spring condition was replicated three times on a sequential basis; followed by three
4 replications under summer conditions. The third test under each climatic condition trialled for
5 28 days; the other two ran for 14 days. A mechanical failure within the chamber during the first
6 spring trial led to its abortion and replacement by a fourth spring trial. The three replicate
7 summer trials followed on from the spring trials. Each microcosm was established in triplicate,
8 avoiding its employment in more than one trial per climatic condition and ensuring the health
9 of the vegetation at the start of the trial. The decision to employ only three replicates for each
10 test was informed by the following factors. The tests were intended to provide a preliminary
11 assessment of the relative importance, and interactions between, several controlling variables,
12 i.e. substrate, vegetation and climatic conditions. As only 10 load cells were available, replicate
13 tests had to be run consecutively in the climate chamber, such that the full series of tests for
14 each season required a minimum of 8 weeks. Although the climate chambers provided climatic
15 control irrespective of the absolute date or season, the experimental timings also needed to be
16 matched to the relevant external seasons to capture any effects due to the plants' seasonal
17 growth cycle and to avoid any risk of shocking the plants by rapidly transferring them between
18 contrasting climatic conditions.

19 **2.2 Trial configurations**

20 Microcosms were established to replicate each of the nine test bed (TB) configurations that
21 have been the subject of on-going complementary field research trials (Poë *et al.*, 2011;
22 Berretta *et al.*, 2014). Microcosms for a tenth configuration were trialled but results are not
23 reported here.

1 2.2.1 *Vegetation treatments*

2 Vegetation options were applied to each substrate to replicate the three most typical UK
3 extensive green roof types:

- 4 1. Sedum Carpet (Sedum) – a pre-cultivated mat, from Blackdown Greenroofs,
5 comprising Sedum species that are ideally suited to green roofs (Monterusso *et al.*,
6 2005) due to the high rate of survival without irrigation (Cook-Patton & Bauerle, 2012).
7 Applied on TB1, TB2 and TB3;
- 8 2. Meadow Flower (MF) – a treatment comprising a broader mix of species, including
9 flowers, grasses and succulents, that can benefit biodiversity (Benvenuti, 2014) – an
10 important driver for green roofs in the UK. The higher biomass and larger roots of
11 Meadow Flower, relative to Sedum, is expected to result in poorer drought tolerance
12 (Lu *et al.*, 2014). Added to TB4, TB5 and TB6; and
- 13 3. Non-vegetated (NV) – microcosms with a bare soil surface are often referred to as
14 “brown roofs” in the UK. The intention is for the roof to self-colonise with local native
15 flora and fauna over time. However, in the interim, non-vegetated roofs are
16 characterised by a reduced surface area from which evaporation can occur and the
17 absence of plant transpiration. Here, this treatment represents a basis against which the
18 contribution of the vegetation to ET can be evaluated. Relevant to TB7, TB8 and TB9.

19 2.2.2 *Substrate types*

20 Three substrates were trialled. Each substrate has different soil-water characteristics. These are
21 broadly as reported in Berretta *et al.* (2014) with only minor differences in the sample sets.

- 1 1. Alumasc ZinCo Sedum Substrate (SCS) – a commercial extensive substrate with few
2 fine particles (1.9% < 0.063 mm), median particle diameter (d_{50}) of 5.1 mm and low
3 organic content (2.3%). Used on TB2, TB5 and TB8;
- 4 2. Alumasc ZinCo Heather & Lavender Substrate (HLS) – a commercial semi-intensive
5 mix with a greater proportion of fines than SCS (2.7% < 0.063 mm), higher organic
6 content (3.8%) and the lowest median particle diameter ($d_{50} = 4.1$ mm). Used on TB1,
7 TB4 and TB7;
- 8 3. A mix based on Lightweight Expanded Clay Aggregate (LECA) with a mean particle
9 diameter (d_{50}) of 5.0 mm, but a high proportion of large particles (66.6% in excess of 4
10 mm) and voids (such that air content at field capacity is 49.8%). Used on TB3, TB6 and
11 TB9.

12 Figure 3 shows the particle size distribution of each substrate and includes the acceptable limits
13 for an extensive green roof substrate (FLL, 2008). All three substrates are almost wholly
14 composed of sand and gravel sized particles, with minimal silt content. The composition of
15 SCS and LECA falls marginally outside FLL limits due to the low proportion of fine particles.
16 HLS has the greatest proportion of fine particles, with 32% of particles less than 2 mm in
17 diameter (i.e. sand); 9% of this can be classified as ‘fine’ sands. SCS (27%) and LECA (22%)
18 contain smaller proportions of sand particles and have a greater fraction of larger particles.
19 58% of LECA is composed of particles between 4 and 8 mm in diameter; compared to 40% of
20 SCS and 35% of HLS.

21 [Approximate location of Figure 3]

22 Both vegetation treatments were grown to establishment in late winter and early spring within
23 a climate-controlled glasshouse. Meadow Flower did not establish well on the LECA substrate.

1 No microcosms were therefore suitable for testing during the first completed spring trial. As
2 such, only two data records were obtained for TB6 under spring conditions.

3 **2.3 Data collection methods**

4 The nine microcosms were submersed in water for 2 hours, drained to field capacity over a
5 further period of 2 hours and placed on to calibrated RLS010 single-point compression load
6 cells (with a safe working capacity of 10 kg). The allocation of configurations to load cells was
7 randomly selected for each replication. The signal (in mV) was amplified and recorded on an
8 hourly basis by a Modular 600 multi-channel signal conditioning and datalogging unit. Prior
9 to the experiments, each load cell was tuned to a low of zero and a full scale value, at 10 kg, of
10 9.775 volts. The signal was then recorded for each cell at 2 kg intervals up to 10 kg, enabling
11 the signal to be converted to mass (in kg) using simple linear regression equations with high
12 accuracy ($R^2=1$) for each load cell. The published maximum linearity error of the load cell
13 (0.02% of full scale value, equivalent to 0.032 mm of moisture) was checked experimentally;
14 apparently identifying greater linearity errors ranging between 0.05 - 0.21% and 0.07 - 0.18%
15 in the spring and summer trials respectively. However, the mean linearity error of every load
16 cell was 0.00%. It is therefore expected that the higher-than-anticipated errors were attributable
17 to manual or rounding-up errors from the visual display on the datalogger during the calibration
18 exercise. Changes in mass from each microcosm were inferred to be moisture loss/gain in
19 mm/m^2 . The chamber's climatic data was captured via a separate, central logging system.

20 **2.4 Controlled condition settings**

21 Target climatic settings were derived from hourly temperature and RH data, as recorded by a
22 Met Office weather station in Sheffield (NGR: 4339E 3873N; Altitude of 131 m) during 2009,
23 this being the first year in which hourly weather station data was published.

1 For trials in spring conditions, the diurnal temperature range was 5.06 to 9.75 °C, with a mean
2 daily temperature of 7.13 °C and mean RH of 81.43% (ranging from 75.5% to 87.18%). For
3 summer trials, the diurnal temperature range was 13.76 to 19.84 °C. Mean daily temperature
4 was 16.72 °C and mean RH was 75.96% (ranging between 70.44 and 83.59%).

5 The lighting system provided a daylight source. 16 Metal Halide and Tungsten Halogen
6 incandescent lamps and 16 Phillips Halogen A Pro lamps provided lighting with an intensity
7 of 1000 $\mu\text{mol}/\text{m}^2/\text{s}$ (at a distance of 1 m) when turned on to replicate daylight hours. Daylight
8 hours were derived from sunrise and sunset data recorded in Sheffield, via the US Naval
9 Observatory website (accessed 2010). For spring trials, lights were switched on for 12 hours
10 each day (between 07:00 and 19:00). For summer trials, lighting was switched on for 17 hours
11 per day; between 05:00 and 22:00.

12 The capacity of the climate chamber to generate wind was limited to a vertical airflow of up to
13 24 l/s. Airflow was uniformly dispensed into the chamber via plenums and out via exhausts.
14 Based upon a floor area of 1.6 m^2 , this air exchange equates to 15 $\text{l}/\text{s}/\text{m}^2$ and therefore a wind
15 speed of 0.015 m/s. Whilst this is sufficient to maintain uniform plant canopy temperatures and
16 disturb the boundary layer of water on the plants' leaf surface, these settings are lower than
17 typical mean wind speeds (e.g. at an elevation of 10 metres in Sheffield [Grid reference: SK
18 34867 87326], estimated average wind speed is 3.7 m/s (Renew-Reuse-Recycle website,
19 accessed 2010). As windier conditions would be expected to induce higher ET, measurements
20 are expected to be on the conservative side. Spatial patterns of air flow within the chamber
21 were not monitored, although it is acknowledged that they are unlikely to have been particularly
22 uniform. The random distribution of microcosms for each test was intended to mitigate against
23 any bias that this may have introduced.

1 2.5 *Data analysis and interpretation*

2 2.5.1 *ET values*

3 The term ET is employed here to encompass moisture loss from both vegetated and non-
4 vegetated configurations. Transpiration only occurs from vegetated treatments. ET from non-
5 vegetated configurations therefore results solely from evaporation. Several ET values are
6 analysed and discussed here:

- 7 1) Configuration-mean ET: established for each of the nine configurations by taking the
8 mean of the values derived from the 3 trial replications under each climatic regime.
9 Given the heterogeneous nature of green roof substrates and vegetation, some variation
10 in the individual loss rates was expected. Considering the cumulative loss over the first
11 14 days of the trial, the mean standard deviation over the 18 different test configurations
12 was 7.3%, ranging from 0.5 to 19.2%. The smallest variations occurred on the non-
13 vegetated configurations and the largest variations were generally associated with the
14 spring tests. Figure 4 shows the individual loss profiles for the three replicate tests for
15 spring and summer associated with the Sedum on HLS configuration (TB1), which had
16 a 14-day variation of 6.9% (10.5% in spring and 3.3% in summer), and is therefore
17 typical of the full test set. When ADWP>14 days, ET is derived from the single 28-day
18 long replication;
- 19 2) Vegetation- and substrate-mean ET: a mean of the nine values covering the three
20 configurations with the relevant vegetation treatment or substrate.
- 21 3) Seasonal-mean ET: mean ET from all nine configurations for each climatic condition.

22 References will be made to daily (ET_D) and cumulative ET (ET_{CUM}). ET_D was calculated as
23 the sum of hourly ET data over each 24 hour interval. ET_{CUM} was simply derived by summing

1 ET_D measured up to the time interval in question. The statistical significance of configuration
2 and climatic factors to ET_{CUM} was evaluated using Kruskal-Wallis and Mann-Whitney U tests
3 at ADWPs of 3, 7, 14, 21 and 28 days.

4 [Approximate location of Figure 4]

5 2.5.2 *Moisture balance values*

6 Residual stored moisture content, S_t , is an important influence upon ET. S_t is calculated as
7 S_{MAX} minus SMD_t and will therefore vary depending upon antecedent ET occurring during the
8 ADWP. There is no established protocol for determining the S_{MAX} of a vegetated configuration.
9 It was not appropriate to start trials with an oven-dry substrate, due to the plants' requirements
10 for water. The adopted method is predicated on an assumption that the maximum moisture
11 storage capacity that can practicably be regenerated via ET under UK atmospheric conditions
12 is equal to the known moisture loss (i.e. ET_{CUM}) at Day 28 of summer trial conditions, when
13 wilting was clearly observed. Residual moisture after this time was considered to be
14 hygroscopic moisture ($\theta_{<PWP}$). $\theta_{<PWP}$ was measured through the post-test, destructive oven
15 drying of the substrate only configurations. To validate this approach, values of θ_{FC} for non-
16 vegetated configurations were derived (through summation of ET_{CUM} and $\theta_{<PWP}$) and compared
17 to related values obtained during substrate characterisation tests (see Table 1).

18 [Approximate location of Table 1]

19 Pressure plate tests established θ for ψ_m values of 33 kPa and 1500 kPa - values that define
20 field capacity and permanent wilting point (and therefore plant-available moisture) in soil
21 science (Richards & Weaver, 1944). No meaningful results could be ascertained for LECA.
22 For HLS and SCS, at $\psi_m = 33$ kPa, θ is lower than both maximum water-holding capacity

1 (MWHC) and the derived values of θ_{FC} . At $\psi_m = 1500$ kPa, θ is higher than $\theta_{<PWP}$. According
2 to these test results, θ available to plants would be 14.0 and 13.5% for HLS and SCS
3 respectively; values that are significantly lower than observed ET_{CUM} (or S_{MAX}). However, this
4 conventional scientific definition of field capacity may not be wholly applicable to green roof
5 substrates. Green roofs are multi-layered structures that differ from natural soils with
6 homogeneous textures. The highly porous and heterogeneous composition of green roof
7 substrates is such that moisture is apparently retained at ψ_m lower than 33 kPa; being readily
8 available between 10 and 100 kPa (Fassman & Simcock, 2011). MWHC is determined at
9 atmospheric pressure (following FLL protocol). The differences between MWHC and θ at ψ_m
10 = 1500 kPa of 31.2% (HLS) and 30.2% (SCS) are comparable to the respective derived S_{MAX}
11 values. From a stormwater management perspective, S_{MAX} is a more relevant moisture storage
12 term than the absolute values of field capacity and permanent wilting point; representing the
13 proportion of the retention capacity that can be regenerated between storm events.

14 **2.6 Modelling ET losses**

15 The experimental data will be used to evaluate the simple moisture balance model that was
16 proposed by Stovin *et al.* (2013). This accounts for climatic factors (in the calculation of PET)
17 and moisture content (through consideration of S_{MAX} and S_i) to predict ET (ET_{Pred}).

18 There is no single universally-adopted approach for calculating PET; with several methods
19 widely adopted, including Priestley-Taylor, Hargreaves, Thornthwaite and Penman-Monteith.
20 There is a significant body of literature evaluating the suitability of each method (Zhao *et al.*,
21 2013; Tabari *et al.*, 2011; Voyde, 2011; Oudin *et al.*, 2005). The FAO-56 Penman-Monteith
22 (FAO-56) approach – recommended in the FAO Irrigation and Drainage Paper # 56 (Allen *et*
23 *al.*, 1998) – is adopted here due to its physical basis. The FAO-56 approach predicts PET on

1 the basis of atmospheric conditions, and assumes that the grass is actively growing and has
2 abundant plant-available water. This approach was also adopted by Locatelli *et al.* (2014). It
3 should be noted however that Stovin *et al.* (2013) demonstrated that the simpler Thornthwaite
4 PET model, when combined with a moisture content factor, could provide good predictions
5 compared with measured data, whilst Berretta *et al.* (2014) confirmed that the precise choice
6 of PET model may be of less importance than the need to ensure that moisture restriction effects
7 are properly accounted for.

8 A balancing factor will then be applied to reflect the fact that ET is not always equal to PET.
9 Zhao *et al.* (2013) present numerous soil moisture extraction functions (SMEFs) that factor
10 PET and obtain a more realistic forecast of ET as moisture availability changes. The SMEFs
11 considered by Zhao *et al.* (2013) all factored PET by an equation that included θ_t as a proportion
12 of θ_{FC} . However, here, S_{MAX} is considered instead of θ_{FC} . It is expected that this is a more
13 relevant parameter, as $\theta_{<PWP}$ will not typically be released through ET. This moisture balancing
14 factor is consistent with the approach adopted by Stovin *et al.* (2013); taken as the ratio of
15 available, S_t , to maximum storage, S_{MAX} ; such that:

$$ET_{Pred} = \frac{S_t}{S_{MAX}} \times PET \quad \text{Equation 1}$$

16 It is envisaged that this generic model might subsequently be refined to account for the subtler
17 variations associated with different vegetation and substrate configurations. However, at this
18 preliminary stage, it is appropriate to demonstrate the model's validity using the seasonal-mean
19 data averaged across all nine configurations.

1 3 RESULTS

2 Configuration-mean ET trends are presented here and analysed (in Section 4) to identify the
3 underlying physical trends. A Kruskal-Wallis test identified that seasonal differences in
4 configuration-mean ET_{CUM} are significant ($p=0.05$) at all ADWPs; 3 days ($p=0.0003$), 7 days
5 ($p=0.001$), 14 days ($p=0.004$), 21 days ($p=0.009$) and 28 days ($p=0.024$). It is therefore
6 pertinent to consider the responses of configurations to each climatic regime separately. Figure
7 5 shows the configuration-mean ET_{CUM} for the spring and summer test series.

8 [Approximate location of Figure 5]

9 Overall, cumulative ET losses were greater in summer (19-35 mm) compared with spring (17-
10 29 mm). In both climatic regimes the maximum ET_{CUM} was associated with TB4 (Meadow
11 Flower on HLS), and the minimum was associated with TB9 (non-vegetated LECA). After 14
12 days in summer twice as much moisture had been removed from TB4 than TB9 (33 mm as
13 opposed to 16 mm). In general the 28-day ET_{CUM} was highest for configurations vegetated with
14 Meadow Flower and lowest for non-vegetated microcosms, although initial ET rates for non-
15 vegetated microcosms were amongst the highest observed. Although the variations with respect
16 to vegetation treatment appeared to be more pronounced than the effects of substrate type,
17 systematic differences with respect to substrate were also evident, with the LECA-based
18 configurations generally exhibiting the lowest ET rates and HLS-based configurations the
19 highest. Variations due to substrate type were least evident with the Sedum vegetation, and
20 most apparent with non-vegetated microcosms.

21 Figure 6 shows configuration-mean ET_D over the preceding 7 days for ADWPs of 7, 14, 21
22 and 28 days. Every three groups of columns correspond to a vegetation treatment. These plots

1 reinforce the observations made above, with relatively high ET losses from non-vegetated
2 configurations (TB7, TB8 and TB9) over the initial 7 days being exceeded by the vegetated
3 systems in the later stages of the trials. Within each group the consistent behaviour between
4 the three substrate types was readily apparent; losses were consistently greatest from HLS (TBs
5 1, 4 and 7) and least from LECA (TBs 3, 6 and 9). It is also clear that for several of the
6 configurations, losses after 14 days in summer conditions were reduced to zero or close to zero.
7 Indeed, a net moisture gain was observed in TB6 when ADWP exceeds 21 days.

8 [Approximate location of Figure 6]

9 In all cases there was an observable decrease in ET rate with time. This phenomenon has been
10 widely reported elsewhere (Voyde *et al.*, 2010; Stovin *et al.*, 2013, Berghage *et al.*, 2007). This
11 effect was particularly pronounced in non-vegetated configurations, and also evident in the
12 Meadow Flower configurations in summer. Initial ET rates were of the order of 1.5 mm/day in
13 spring and 2.5 mm/day in summer. In contrast, ET rates during the final seven days dropped to
14 below 0.5 mm/day.

15 Statistical analysis of the 3, 7, 14, 21 and 28 day cumulative ET values showed that differences
16 as a result of vegetation treatment were generally only significant ($P = 0.05$) when contrasting
17 ET from vegetated and non-vegetated configurations. No statistical differences existed
18 between Sedum and Meadow Flower.

19 In view of the significant influence that moisture constraints have upon ET rates when ADWP
20 exceeds 14 days, it is pertinent to assess the variations in ET_{CUM} as a function of configuration
21 and season after an ADWP of 14 days (see Table 2).

22 [Approximate location of Table 2]

1 Seasonal-mean ET_{CUM} is greater in summer (24.7 mm) than in spring (17.4 mm) after an
2 ADWP of 14 days. This is consistent with the phenomenon of warmer conditions inducing
3 greater ψ (leading to higher ET). The higher standard deviation (σ) in summer (5.1 mm)
4 compared to spring (2.8 mm) is expected due to (a) the lower absolute seasonal-mean ET_{CUM}
5 in spring and (b) the greater influence that the range of S_{MAX} values has upon ET_{CUM} following
6 high antecedent ET in summer. Comparing the spring and summer losses over the first 14 days,
7 the seasonal difference in substrate-mean ET_{CUM} is greatest with HLS (9 mm), compared with
8 SCS (6.1 mm) and LECA (7 mm). The seasonal differences are far greater in the vegetated
9 configurations (around 10 mm) compared with non-vegetated configurations (2 mm). The
10 small σ of 0.6 mm for Sedum in spring indicates a lesser reliance of Sedum's transpiration rates
11 upon substrate soil-water characteristics; particularly in cooler climatic conditions. However,
12 in summer, as ET_{CUM} from Sedum-vegetated configurations exceeds ET from non-vegetated
13 configurations, σ also increases to 3.0 mm. Here, the differences in configuration specific S_{MAX}
14 lead to greater contrasts in ET_{CUM} between LECA and HLS. The variance in substrate-mean
15 ET_{CUM} is greatest from HLS, where low ET_{CUM} from Sedum contrasts with high ET from
16 Meadow Flower and non-vegetated configurations. Variance is further increased in summer,
17 as the low ET_{CUM} from non-vegetated configurations contrasts with the very high ET_{CUM} from
18 Meadow Flower.

19 **4 DISCUSSION**

20 The key physical parameters that influence ET - climate, moisture content and configuration
21 (i.e. vegetation and substrate) - will now be considered.

1 **4.1 The influence of climate upon ET**

2 Conceptually, the climate can be considered to be a source of potential energy that acts upon
3 the green roof to extract moisture via ET. Assuming abundant and constant S_t , summer
4 conditions would be expected to induce ET at higher rates than during the cooler spring
5 conditions. ET is directly related to temperature. Higher temperatures will lead to higher
6 absolute cumulative losses as a greater proportion of the moisture that is held with higher ψ_m
7 in the small pores of a substrate can be removed under increased levels of heat energy. In
8 spring, the lower source of energy generated in the cooler conditions is often not sufficient to
9 break the bonds that act to retain moisture in the substrate to the same extent as observed under
10 summer conditions.

11 The physical characteristics of each configuration govern its moisture retention behaviour,
12 affecting the level of resistance to the extraction of moisture from within. However, on average,
13 once S_t fell to approximately one quarter of S_{MAX} , moisture appeared to be held too tightly for
14 ET to occur during spring conditions, as S_t remained relatively high, even after an ADWP of
15 28 days. Summer conditions were often sufficient to induce ET until S_t reached less than 10%
16 of its S_{MAX} , emptying moisture from a higher proportion of the substrate's pores. The
17 influences of climate and S_t are therefore intrinsically linked, as warm conditions generally
18 induce faster initial losses; but in so doing, decrease S_t which then leads to lower subsequent
19 ET losses.

20 Under constant climatic conditions, PET should remain constant. However, ET appears to fall
21 relative to PET even at short ADWPs (see Figure 7). It is hypothesised that this almost instant
22 decline can be attributed to a combination of short-rooted vegetation and highly porous
23 substrates.

1 [Approximate location of Figure 7]

2 Seasonal-mean ET_D was greater in summer conditions than in spring for ADWPs of up to 12
3 days; such that seasonal-mean ET_{CUM} was 7.6 mm greater in summer by this time. However,
4 at longer ADWPs, ET appeared to have been constrained by the lower S_t that results from high
5 antecedent rates of ET. Summer ET_D subsequently fell below spring rates (in many cases
6 approaching zero). Lower antecedent ET in spring resulted in more sustained, consistent ET_D ;
7 contrasting with the exponential decay in ET observed in summer trials.

8 The influence of season upon ET_D was most apparent when moisture availability was abundant
9 (i.e. at short ADWPs). Median ET_D in summer fell from 3.4 mm to 1.9 mm over 7 days, then
10 to 0.5 mm, 0.3 mm and 0.2 mm after 14, 21 and 28 days respectively. In spring, initial median
11 ET_D of 2.0 mm was then consistently maintained at approximately 1.2 mm between day 2 and
12 day 12, before falling to 0.7 mm after 21 days and 0.3 mm after 28 days.

13 Seasonal climate differences were significant to ET; most notably when moisture availability
14 was not constrained by high antecedent moisture losses. In general terms the decay of ET over
15 time reflects the effects of reduced moisture availability.

16 **4.2 *The effect of moisture content upon ET***

17 S_t had an underlying influence upon ET rates. Highest ET was recorded at the highest values
18 of S_t ; the lowest when S_t was low. In most cases, this decline in ET occurred simultaneously
19 with a reduction in moisture availability, as evidenced by the contrasts of rapidly declining ET_D
20 during summer and the more consistent reduction in ET_D in spring. By considering ET/PET ,
21 and expressing moisture availability as a ratio of residual, S_t , to maximum storage, S_{MAX} , the
22 constraints imposed upon ET by moisture availability can be seen (see Figure 8).

1 [Approximate location of Figure 8]

2 In all instances, ET reduced as S_t fell. A best-fit regression line ($R^2=0.73$) with a gradient of
3 0.89 reflects a relatively linear reduction in ET/PET as S_t/S_{MAX} fell. ET/PET in summer fell
4 largely above the best-fit line. Certain configurations (e.g. TB1) were also seen to have non-
5 linear relationships between ET/PET and S_t/S_{MAX} .

6 The importance of moisture availability to ET_D is also apparent in Figure 9; comparing ET over
7 a mean diurnal cycle when moisture was abundant (i.e. week 1) with conditions when moisture
8 availability was constrained (i.e. week 4).

9 [Approximate location of Figure 9]

10 ET_D was highest when moisture was abundantly available, with seasonal-mean ET of
11 1.5 mm/day in spring and 2.3 mm/day in summer. In moisture-constrained conditions, ET_D of
12 between 0.2 and 0.3 mm/day was measured; albeit actual ET of 0.8 mm was observed during
13 the day when moisture gains of 0.5 mm were taken into account. Moisture gain was most
14 pronounced in the conditions where moisture was most constrained (i.e. in week 4 of summer).
15 This is consistent with the fact that the highly negative pressures within a dry soil will create a
16 vapour pressure gradient that would typically lead the moisture from the relatively humid air
17 above to be drawn into the soil matrix.

18 The distinct change in ET as a result of reducing moisture availability highlights the importance
19 of including moisture content as a key parameter in any modelling approach.

1 **4.3 The effects of green roof configuration**

2 **4.3.1 Vegetation treatment**

3 The incorporation of vegetation will typically provide some level of additional moisture storage
4 capacity (Morgan *et al.*, 2013). ET losses will be positively influenced by plant transpiration
5 but negatively affected by reduced evaporation relative to bare soil surfaces (Nagase &
6 Dunnett, 2012). On average, the addition of vegetation increased 28-day ET_{CUM} by 17% in
7 spring and 23% in summer. The incremental effect of adding Sedum was greatest in summer
8 (26%) than in spring (10%), with additional losses in summer ranging between 7.2 mm
9 (representing 22% of ET_{CUM}) and 9.5 mm (33%) compared to the equivalent non-vegetated
10 configuration. The higher figure was witnessed from the LECA substrate, which has the highest
11 permeability. It is believed that the greater incremental effect of adding Sedum into LECA can
12 be attributed to the binding effect of the roots penetrating this highly porous substrate. The
13 incremental effect of Sedum on HLS and SCS was lower – 7.8 mm and 7.2 mm respectively.
14 Vegetating with Meadow Flower led to an increase in 28-day ET_{CUM} of 25% in spring and 21%
15 in summer. The substrate type was an influence; particularly in summer when the increment
16 ranged between 3.5 mm or 12% (SCS) and 7.7 mm or 29% (LECA). Adding Meadow Flower
17 to HLS increased ET_{CUM} by 7.7 mm.

18 However, any incremental effect of vegetation upon ET will vary as a function of the
19 substrate's soil-water characteristics, ADWP and climatic conditions. Figure 10 presents
20 vegetation-mean ET_D over each of the 4 weeks.

21 [Approximate location of Figure 10]

1 Initially, the addition of vegetation had a detrimental impact on ET. The duration of this lag
2 varied seasonally and by vegetation treatment. However, vegetation ultimately made a positive
3 net contribution to ET_{CUM} . In spring, this contribution was positive after 12 days (with Meadow
4 Flower) or 20 days (for Sedum), ultimately increasing ET_{CUM} by 6 mm and 2 mm respectively.
5 In summer, the net contribution to ET by vegetation was evident at an earlier stage – after 4
6 and 6 days for Meadow Flower and Sedum respectively – and to a much greater degree. ET_{CUM}
7 increased by as much as 9 mm (after 14 days) through the addition of Meadow Flower
8 (subsequently reducing below 6 mm after 28 days due to permanent wilting of the vegetation)
9 or 9.5 mm when Sedum was added.

10 It was expected that the Sedum vegetation would improve the hydrological response of the
11 green roof (compared to both Meadow Flower and non-vegetated configurations), due to its
12 extensive (90-95%) plant coverage and to its Crassulacean Acid Metabolism (CAM). However,
13 Sedum's tendency to regulate transpiration actually restrained ET losses in certain
14 circumstances. In spring, vegetation-mean ET_D from Sedum was lower than from Meadow
15 Flower at virtually all stages. This was also the case for the first two weeks under summer
16 conditions. This is consistent with the findings of Farrell *et al.* (2012), who identified slower
17 ET from Sedum (compared to C3 plants) over an initial 20 day period. Sedum species typically
18 have relatively shallow fibrous roots, whereas grasses and forbs tend to have larger root and
19 shoot biomass that can be conducive to more effective moisture retention (Nagase & Dunnett,
20 2012). However, the CAM photosynthesis and leaf succulence of Sedum ensure stronger
21 drought tolerance (MacIvor & Lundholm, 2011) compared to grasses and forbs (Lu *et al.*,
22 2014). The seasonal differences in ET_{CUM} for Sedum were the greatest of the tested vegetation
23 treatments; as low, regulated ET in spring contrasts with faster ET and subsequent exponential
24 decay in summer. Unlike other vegetation treatments, ET losses were observed from Sedum

1 for more prolonged periods, even after long summer ADWPs. Yet there were no observations
2 of higher transpiration from Sedum during night conditions; a trait that is often associated with
3 CAM plants. Differences in ET rates attributable to substrate were marginal when Sedum was
4 the chosen vegetation treatment.

5 The different transpiration rates of Meadow Flower, compared with Sedum, were most
6 apparent in summer. Generally high ET was measured for an initial 7 day period, as vegetation-
7 mean ET_D from Meadow Flower exceeded ET_D from Sedum in both spring (1.4 versus
8 1.25 mm/day) and summer (2.7 versus 2.4 mm/day). However, an almost linear decline in
9 vegetation-mean ET_D from Meadow Flower towards zero by Day 14 (with virtually no
10 subsequent ET thereafter) supports a hypothesis that the fast initial transpiration of Meadow
11 Flower leads to ET_D that is constrained by a configuration's S_{MAX} at longer ADWPs. The
12 highest ET_{CUM} (of 34.7 mm) was measured from the substrate with the greatest θ_{FC} (i.e. HLS).
13 Yet all plant-available moisture appeared to have been consumed; as confirmed by
14 observations of permanent wilting.

15 Three key trends distinguish patterns of ET for non-vegetated configurations from their
16 vegetated equivalents:

- 17 a) Faster initial rates of ET, as ET_{CUM} exceeded ET_{CUM} from Sedum and Meadow Flower
18 configurations for 12, 15 and 10 days (for HLS, SCS and LECA respectively) in spring
19 and for 3, 6 and 1 day in summer;
- 20 b) Lower ET_{CUM} after 28 days; and
- 21 c) Smaller seasonal ET differentials.

1 In spring, vegetation-mean ET_D from non-vegetated configurations was as high as 2.8 mm/day.
2 Vegetation-mean ET_D over the first week was 1.8 mm/day and continued to fall in the second
3 week (to a mean of 0.7 mm/day), averaging just 0.15 mm/day in the fourth week. As a result,
4 ET_{CUM} was limited to between 17.3 and 22.9 mm after 28 days. In summer, higher ET rates of
5 up to 4.2 mm/day were observed, but declined instantly towards zero by Day 14. Generally,
6 the faster decay in ET from non-vegetated configurations (relative to vegetated configurations)
7 can be attributed to a lower albedo (i.e. the absence of a plant cover that would otherwise serve
8 to moderate evaporation from a highly porous, dark, bare substrate surface) and to the lower
9 S_{MAX} . The smaller seasonal increase in ET_{CUM} from non-vegetated configurations reflects (a)
10 the constraints imposed on ET by low S_{MAX} , and (b) the greater plant transpiration in warm
11 conditions.

12 The vegetation treatments trialled here were relatively young. Further root development as the
13 vegetation ages would be expected to change the organic content and porosity of the substrate
14 (Berndtsson, 2010). A more developed root distribution, filling a higher proportion of large
15 voids in the substrate, would act to increase moisture retention capacity (Nagase & Dunnett,
16 2012).

17 4.3.2 *Substrate*

18 ET varied as a function of a substrate's soil-water characteristics; both in vegetated and non-
19 vegetated configurations. Figure 11 presents substrate-mean ET_D over each of the 4 weeks.

20 [Approximate location of Figure 11]

21 Substrate type appeared to influence ET less than vegetation treatment. However, in both
22 climatic regimes and at all ADWPs, substrate-mean ET_D generally reflected the substrate's θ_{FC}

1 with substrate-mean ET_D greatest from HLS configurations and least from LECA. The extent
2 to which a substrate's θ_{FC} affected ET_{CUM} varied according to the climate. In spring, the range
3 of substrate-mean ET_{CUM} was lower (22-25 mm) than in summer (25-33 mm). The seasonal
4 increase in substrate-mean ET_{CUM} was greater from HLS (8 mm) than SCS (4 mm) after 28
5 days. This indicates that, in warm conditions, higher θ_{FC} will generally facilitate higher ET_{CUM} .
6 A greater proportion of the moisture that is held with higher ψ_m in the small pores of HLS can
7 be removed via ET with the greater heat energy that is generated in warmer climatic conditions.
8 Yet, in cooler conditions, a substrate's S_{MAX} is unlikely to be fully depleted via ET and other
9 characteristics, such as permeability, will influence the rate of ET.

10 HLS is the substrate with the greatest θ_{FC} , yet also the highest proportion of fines (and lowest
11 permeability). SCS has a lower θ_{FC} . Yet, substrate-mean ET_{CUM} was virtually identical
12 (24 mm) from both substrates after 28 days in spring. This is consistent with a hypothesis that
13 the lower heat energy in spring can induce slower moisture balance changes (particularly in the
14 substrate's smaller pores, where moisture is retained with greater tenacity). In cooler climates,
15 no discernible increase in ET is therefore likely to result from substrates with high θ_{FC} and low
16 permeability (e.g. HLS) compared to substrates with lower θ_{FC} and higher permeability (e.g.
17 SCS). Indeed, despite the low θ_{FC} and very high permeability of LECA, substrate-mean ET_{CUM}
18 was only marginally lower than from SCS in spring. However, in warm conditions that are
19 conducive to high PET, a lower S_{MAX} would be expected to constrain ET, as was evident from
20 the small seasonal difference in substrate-mean ET_{CUM} of 3 mm measured with LECA after 28
21 days.

1 **4.4 Summary of key influences**

2 Overall, moisture content is a very important influence upon ET. ET will be greatest when
3 moisture availability is high, but will almost instantly fall below PET when available moisture
4 is less than S_{MAX} . A configuration's S_{MAX} varies according to vegetation treatment and
5 substrate type. The rate at which the retention capacity is generated will be affected,
6 significantly, by the climate (with warmer temperatures inducing greater initial rates of ET)
7 and by the response of the vegetation treatment to the ambient conditions.

8 **4.5 Model Application**

9 Significant differences in the cumulative ET profiles were evident in Figure 5, and the paper
10 has highlighted the relative importance of vegetation and substrate characteristics in
11 determining these differences. Notwithstanding these influences, all nine configurations clearly
12 respond similarly to two critical driving forces, the PET rate (i.e. the seasonal influence) and
13 the available soil moisture. In all configurations, reductions in actual ET were clearly evident
14 when moisture became restricted. Here the experimental data is used to validate the simple
15 two-part ET model presented in section 2.6. The model predicts actual ET from an estimate of
16 PET and the application of a moisture balancing factor.

17 The FAO-56 PET calculation was used to estimate ET for a reference crop (green grass) of
18 uniform height (0.12 m), surface resistance (70 s/m) and albedo (0.23) in response to
19 climatological factors, i.e. radiation, air temperature, relative humidity and wind speed.
20 Factoring in the chamber's climatic settings, reference PET, ET_0 , was calculated to be
21 1.8 mm/day and 4.5 mm/day for spring and summer conditions respectively. A SMEF (see
22 Equation 1) was then applied. The model was implemented at hourly/daily time intervals, with
23 the actual substrate moisture content being continuously updated.

1 PET, seasonal-mean ET_{CUM} and ET_{Pred} are presented for both spring and summer in Figure 12.

2 [Approximate location of Figure 12]

3 Here, the improved accuracy achieved by applying a SMEF to factor PET is immediately
4 apparent. The use of PET alone would result in significant errors (e.g. a near 50%
5 overestimation of ET after 7 days in summer). A Percent Bias (PBIAS) metric was applied to
6 quantify the accuracy of ET_{Pred} based on the average tendency of modelled values to be larger
7 or smaller than observed values. Optimum PBIAS is zero. Positive values reflect an over-
8 prediction in the modelled ET value and negative values are calculated where the model under-
9 predicts ET. A very good prediction would have PBIAS of less than or equal to +/-10%. For
10 spring, PBIAS values were 0.6% (ET_{CUM}) and 2.0% (ET_D). For summer, PBIAS values were
11 6.1% (ET_{CUM}) and -0.8% (ET_D). ET_{CUM} was therefore predicted with very good accuracy. In
12 summer, initially, ET_{Pred} was over-predicted (with a peak error of 3 mm after 4 days). However,
13 this over-prediction is gradually eroded so that $ET=ET_{Pred}$ from day 23 onwards. In spring,
14 ET_{Pred} was virtually identical to ET at all stages of the trial.

15 **5 CONCLUSIONS**

- 16 • Trials under controlled conditions concluded that statistically significant differences in
17 ET from green roofs can be attributed to climatic differences and, in certain conditions,
18 to vegetation treatment and substrate.
- 19 • ET was higher in warmer summer conditions than in lower spring temperatures.
20 Seasonal differences in ET were significant. As ADWP increased, statistical
21 significance fell slightly.

- 1 • Moisture content is a critical influence upon ET rates and retention capacity. A factor
2 must be applied to PET to reflect a decay in ET with falling moisture availability.
- 3 • Significant differences in ET existed between vegetated and non-vegetated
4 configurations, particularly after long ADWPs (28 days).
- 5 • No significant differences in ET were identified between systems vegetated with Sedum
6 and Meadow Flower. However, practical differences were observed (e.g. the permanent
7 wilting of Meadow Flower after an ADWP of 14 days in summer).
- 8 • Substrates with high θ_{FC} led to the greatest ET_{CUM} in most circumstances.
- 9 • Differences in a substrate's soil-water characteristics can have a significant influence
10 upon ET (e.g. LECA vs HLS). However, where soil-water characteristics are relatively
11 similar (e.g. HLS vs SCS), differences were not significant.
- 12 • ET can be predicted with very good accuracy by a simplistic model that accounts for
13 climate (with a PET calculation) and moisture balance (using a SMEF).

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1 Table 1: Soil-water characteristics of the trialled substrates

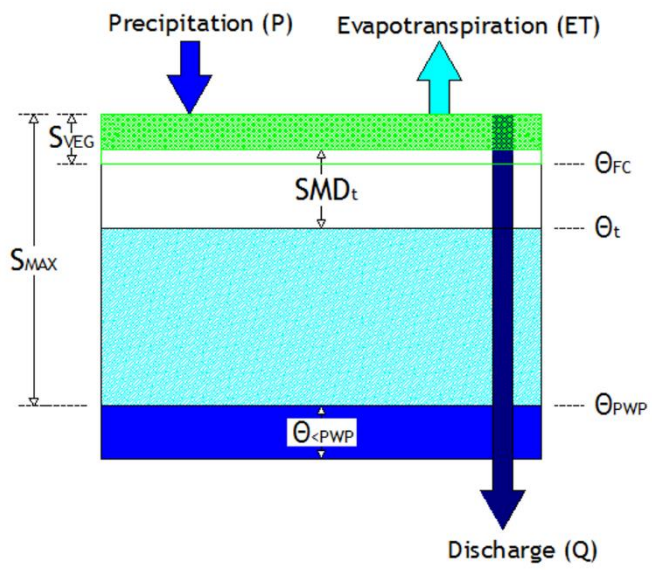
		HLS	SCS	LECA
$\theta_{<PWP}$	(% m ³ /m ³)	6.6	2.9	2.1
S_{MAX}	(% m ³ /m ³)	33.7	31.5	24.2
θ_{FC}	(% m ³ /m ³)	40.3	34.3	26.3
Permeability	(mm/min)	2.41	14.8	33
MWHC	(% m ³ /m ³)	41.2	39.1	35
θ [$\psi_m = 33$ kPa]	(% m ³ /m ³)	25	22.4	-
θ [$\psi_m = 1500$ kPa]	(% m ³ /m ³)	9	8.9	-

2

1 Table 2: Mean ET_{CUM} after a 14 day ADWP, by vegetation treatment and substrate

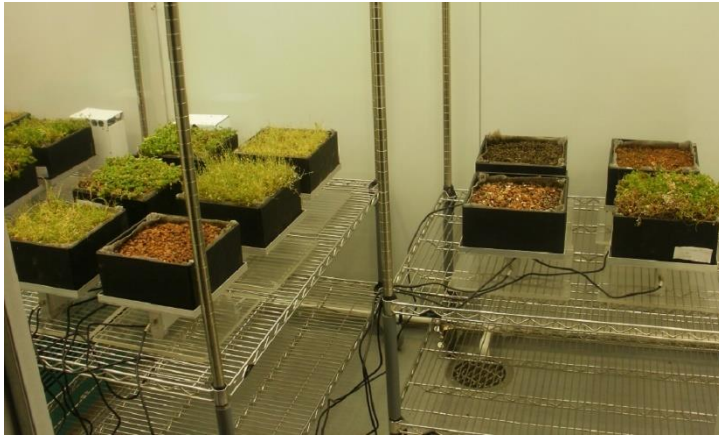
		Vegetation:	<i>Sedum</i>	<i>Meadow Flower</i>	<i>Non- Vegetated</i>	Mean	Std Dev (σ)
Spring ET_{CUM} (mm)	Substrate	HLS	15.8	21.8	20.5	19.4	3.2
		SCS	15.9	18.9	19.2	18	1.8
		LECA	14.8	15.7	13.7	14.7	1.0
	Mean		15.5	18.8	17.8	17.4	-
	Std Dev (σ)		0.6	3.1	3.6	-	2.8
Summer ET_{CUM} (mm)	Substrate	HLS	28.8	33.2	23	28.4	5.1
		SCS	23.7	27.8	20.9	24.1	3.5
		LECA	23.5	26.3	15.4	21.7	5.7
	Mean		25.4	29.1	19.8	24.7	-
	Std Dev (σ)		3.0	3.6	3.9	-	5.1

2



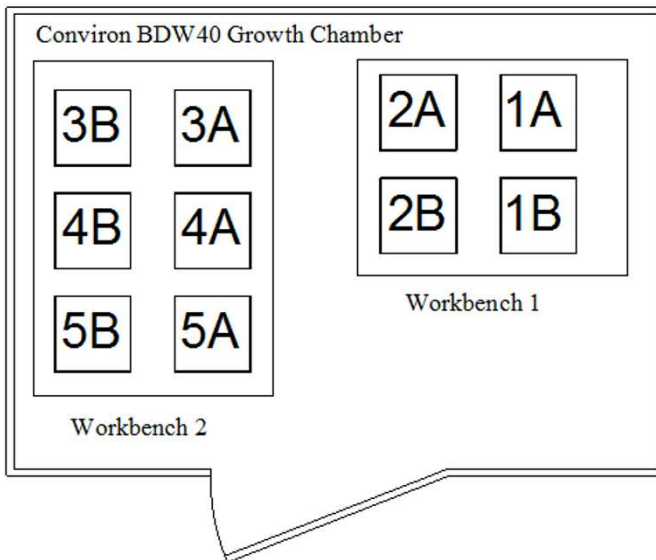
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2 Figure 1: Conceptual Moisture Balance Retention Model



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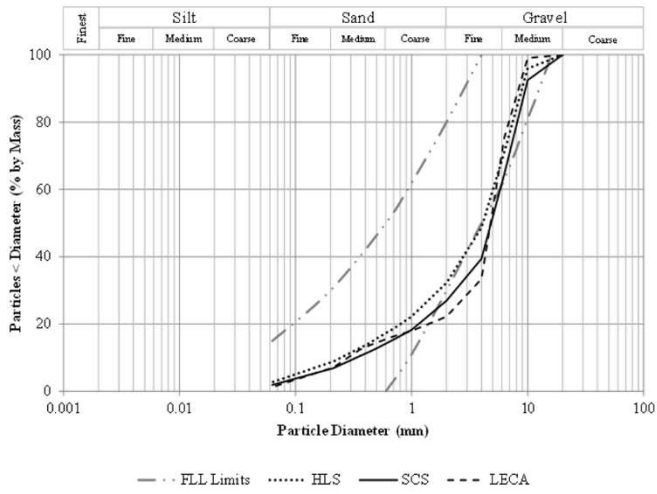
2 (a) Photograph



3

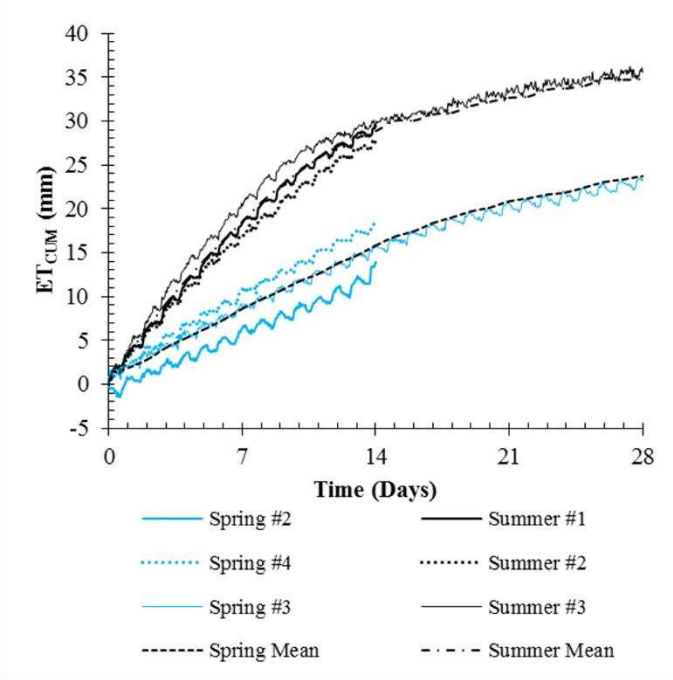
4 (b) Plan drawing

5 Figure 2: Microcosms in Climate-Controlled Chamber



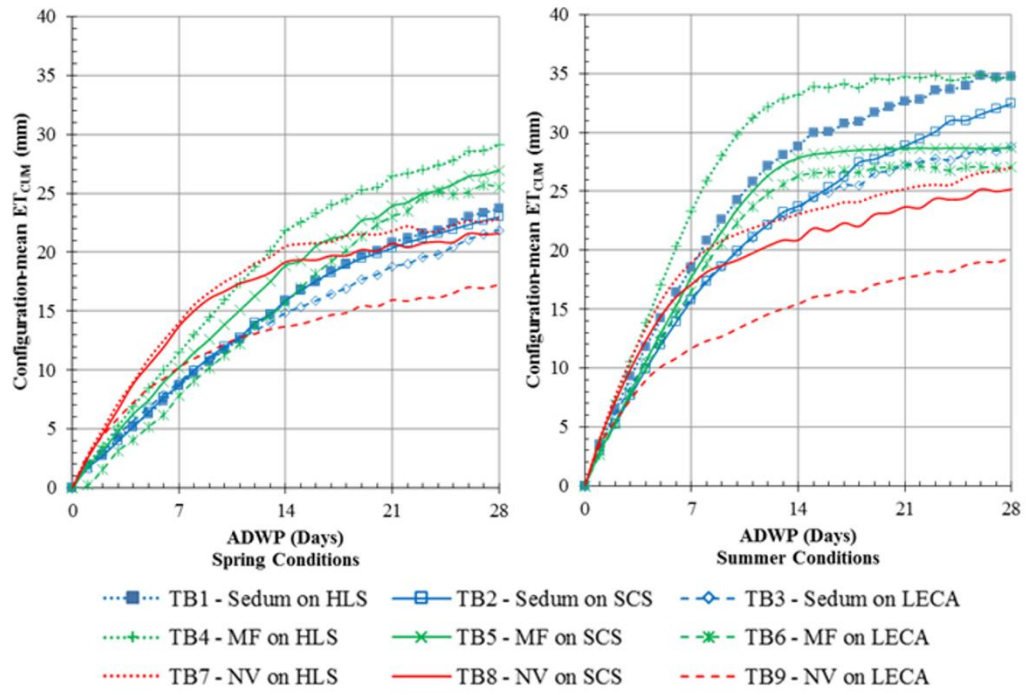
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2 Figure 3: Particle size distributions of HLS, SCS and LECA



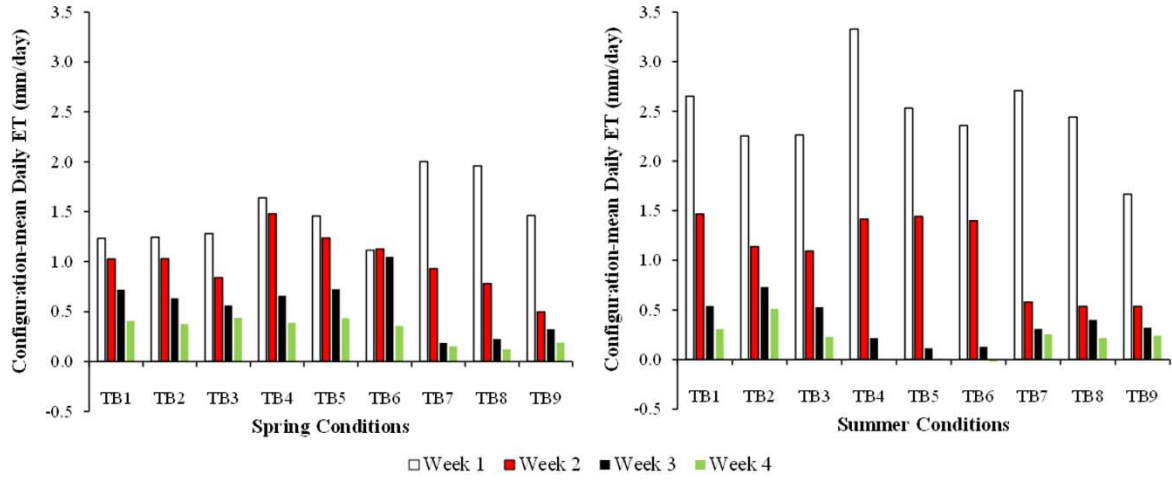
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2 Figure 4: ET_{CUM} for Sedum on HLS (6 replications)



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2 Figure 5: Configuration-mean ET_{CUM}



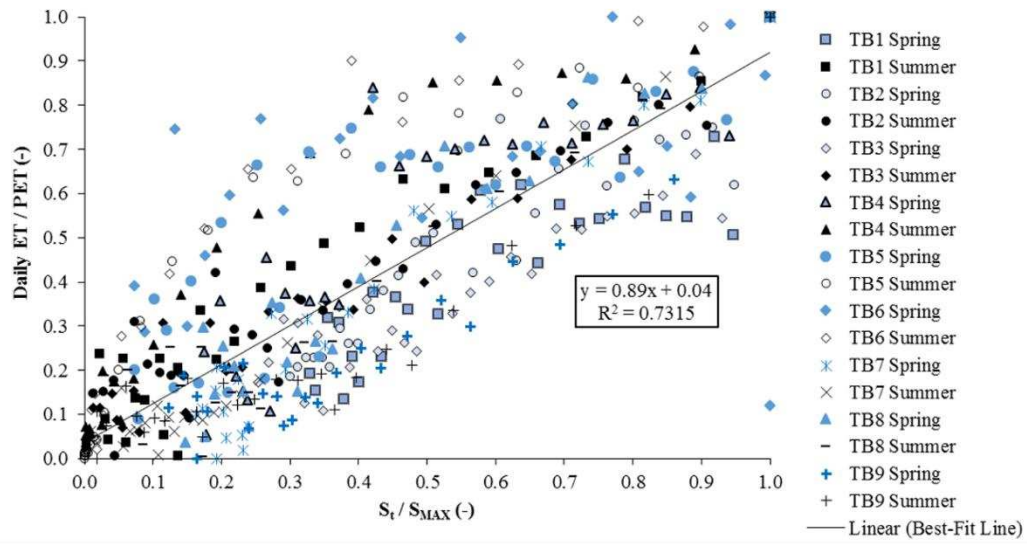
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2 Figure 6: Configuration-mean ET_D



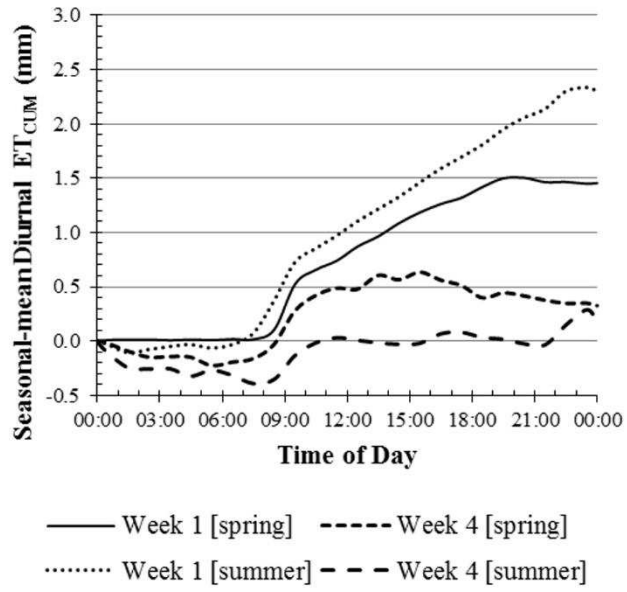
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2 Figure 7: Seasonal-mean ET_D



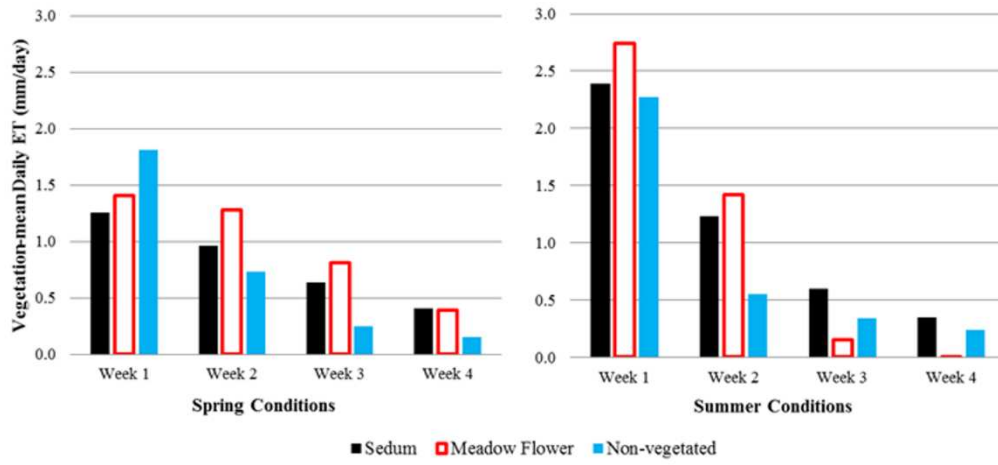
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2 Figure 8: ET/PET versus S_t / S_{MAX}



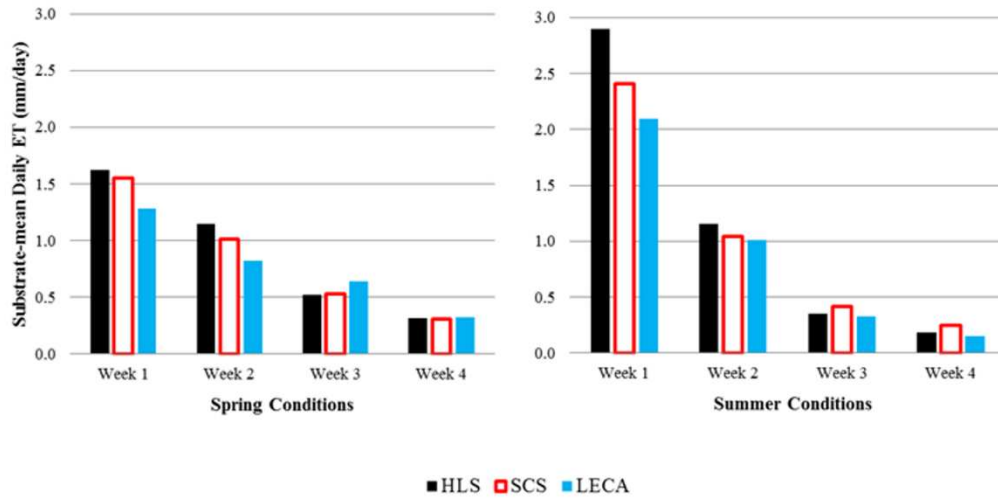
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2 Figure 9: Mean Diurnal ET_{CUM}



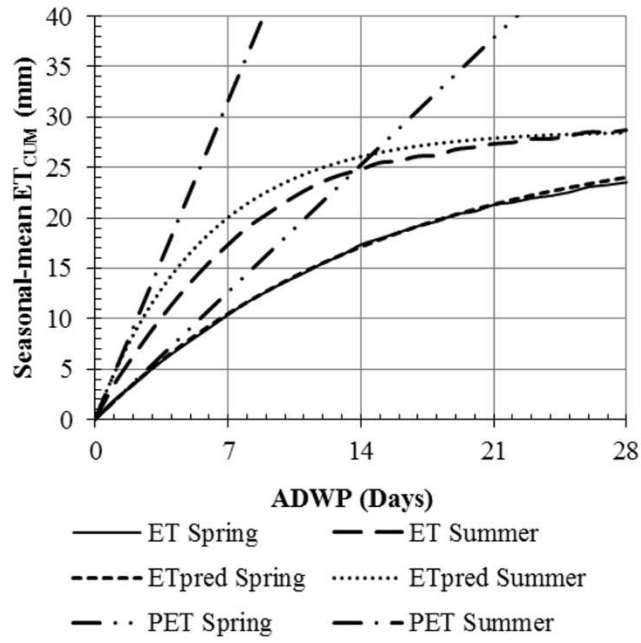
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2 Figure 10: Vegetation-mean ET_D



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2 Figure 11: Substrate-mean ET_D



1

2 Figure 12: Observed versus predicted ET using FAO-56 PET calculation and SMEF