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Moisture content behaviour in extensive green roofs during dry periods: The influence of vegetation and substrate characteristics

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ABSTRACT

Evapotranspiration (ET) is a key parameter that influences the stormwater retention capacity, and thus the hydrological performance, of green roofs. This paper investigates how the moisture content in extensive green roofs varies during dry periods due to evapotranspiration. The study is supported by 29 months continuous field monitoring of the moisture content within four green roof test beds. The beds incorporated three different substrates, with three being vegetated with sedum and one left unvegetated. Water content reflectometers were located at three different soil depths to measure the soil moisture profile and to record temporal changes in moisture content at a five-minute resolution. The moisture content vertical profiles varied consistently, with slightly elevated moisture content levels being recorded at the deepest substrate layer in the vegetated systems. Daily moisture loss rates were influenced by both temperature and moisture content, with reduced moisture loss/evapotranspiration when the soil moisture was restricted. The presence of vegetation resulted in higher daily moisture loss. Finally, it is demonstrated that the observed moisture content data can be accurately simulated using a hydrologic model based on water balance and two conventional Potential ET models (Hargreaves and FAO56 Penman-Monteith) combined with a soil moisture extraction function. Configuration-specific correction factors have been proposed to account for differences between green roof systems and standard reference crops.

KEYWORDS

Moisture content; Evapotranspiration; Green roof; Stormwater management; Retention; Substrate

1 INTRODUCTION

Recent trends of urbanization and climate change pose important challenges in urban areas, including the increased risk of flooding (due to drainage system surcharge) and pollution (due to Combined Sewer Overflows and diffuse pollution). It is recognised that more resilient stormwater management infrastructure is required, with Sustainable Drainage Systems (SuDS) (and similar concepts worldwide) aiming to restore pre-development hydrological conditions. Emerging concepts like Water Sensitive Urban Design are driving researchers and practitioners to investigate ‘green infrastructure’ that, by including vegetation, can also provide benefits to the ecosystem (e.g. mitigating heat islands, promoting biodiversity, enhancing water quality). SuDS include green roofs, swales, rain gardens, wet ponds, and infiltration basins. Green roofs have the potential to deliver significant stormwater management benefits, especially in dense urban cores where space is limited. Roof spaces account for approximately 40-50% of the impervious urban surface area (Dunnett and Kingsbury, 2004), and in view of the relative simplicity of installation, green roofs have the potential to be part of a treatment train, working in conjunction with multiple SuDS devices to provide more beneficial stormwater management than any single element on its own.

Green roofs consist of a vegetative layer, supported by a growing medium (substrate) installed above a filtration geosynthetic layer and a drainage layer. This study focuses on extensive green roofs, which are characterized by thinner substrate depths (generally < 150 mm). Extensive green roofs have greater potential of wide-scale adoption than intensive green roofs, where significant structural loading considerations restrict application. The limitation of extensive type systems is that a shallower substrate has a lower, and finite, stormwater retention capacity (e.g. 20 mm as observed by Stovin et al. (2012) in an 80 mm substrate roof) and is more likely to experience restricted moisture conditions and plant stress during prolonged dry periods. Several studies have aimed at evaluating the hydrological performance of green roofs through field monitoring programmes (see Palla et al. (2010), and Stovin et al. (2012) for an overview). It is evident that the roof's ability to retain stormwater is highly sensitive to the initial moisture condition of the green roof system prior to a rainfall event. This is controlled by the evapotranspiration (ET) process during dry periods. A better understanding of the moisture content behaviour during dry periods due to ET will have important implications for stormwater management and should lead to the development of more accurate modelling approaches for long-term simulations. Such predictions are necessary to support decision-making in stormwater management; both in terms of projecting green roof performance in response to changing climatic scenarios (Stovin et al., 2013) and for estimating plant stress conditions (and the consequent need for irrigation treatments).

Several recent research projects have focused on the measurement of ET from green roof systems, and on the development of appropriate ET modelling tools. In some of the earliest studies undertaken by Köhler at Neubrandenburg, Germany (Köhler, 2004) weighing lysimeters were incorporated within green roof systems to quantify the water balance. More recently, Berghage et al. (2007), Voyde et al. (2010) and Poë and Stovin (2012) have used load cells to monitor moisture losses from green roof microcosms under controlled climatic conditions. Green roof systems are typically not irrigated, and actual ET rates fall with time following a rainfall event, as the available moisture becomes increasingly restricted. Berghage et al. (2007) and Voyde et al. (2010) identified differences in actual ET between plant species, and both proposed temporal decay relationships to model the observed reductions in ET over time. However, Stovin et al. (2013) have argued that it is the substrate moisture content, rather than time, that directly determines the difference between actual and potential ET rates. Several authors (e.g. Rezaei, 2005; Kasmin et al., 2010) have demonstrated that standard agricultural methods of predicting potential ET are transferable to the prediction of observed ET rates from green roof systems, although crop/system coefficients may be required to account for the non-standard vegetation and substrates. Recently, some authors have used closed atmospheric chambers to quantify ET on full-scale green roof installations (e.g. Coutts et al., 2013). Whilst lysimeter and surface-mounted climate chamber-based experiments provide a direct measurer of total moisture loss due to ET, this includes changes in the moisture content within the vegetation, and does not provide a direct indication of the actual substrate moisture content, or its vertical distribution. Palla et al. (2009) have demonstrated the value of direct substrate moisture content measurements for the development and validation of accurate moisture flux models.

The moisture content behaviour during dry periods is influenced by plant species, substrate characteristics and climatic conditions. Studies in the laboratory, under controlled conditions, facilitate the simulation of extreme hydrological conditions that can enhance understanding of key controlling parameters (Yio et al, 2013) and also underpin the development of novel substrate compositions that can be optimized for water retention - for example by using additives (Emilsson et al., 2012; Farrel et al., 2013). However, climatic variables cannot easily been taken into consideration through laboratory studies. For this reason, the present study focuses on a long-term field monitoring programme which commenced at the University of Sheffield, UK in March 2011.

1.1 Objectives

The main objective of the research was to utilise new moisture content data from four green roof test beds collected over 29 months continuous field monitoring to understand the hydrological processes occurring within green roof systems during dry periods. In particular, the analysis focused on the vertical moisture content profile and the behaviour of moisture content with respect to time. It was expected that the temporal changes in substrate moisture content would relate to climatic conditions and to the initial moisture content, as well as to the substrate physical characteristics and the presence of vegetation.

An additional objective was to investigate the possibility of simulating the temporal changes in moisture content using a hydrologic model based on water balance, an estimate of Potential ET and a soil moisture extraction function. The final objective was to assess whether correction factors would be required to account for the differences between green roof systems and standard reference crops and soils.

2 METHODOLOGY

2.1 The experimental setup

2.1.1 The test beds

The research was conducted at the University of Sheffield's Green Roof Centre. The test site is located on a fifth-floor terrace of the Sir Robert Hadfield building (53.3816, -1.4773) and consists of 9 green roof test beds (TB) which vary systematically in their substrate composition and vegetation options. This experiment was established in summer 2009 and data have been collected since April 2010 to assess the extent to which substrate type and vegetation treatment affect long-term runoff retention and detention performance (Poë et al, 2011). In March 2011, four of these test beds were equipped with water content reflectometers for continuous moisture content measurement. This study is based on the data collected from these four test beds. Each test bed is 3 m long x 1 m wide, installed to a 1.5° slope. The TBs are located at a height of 1 m above the terrace roof surface (Fig. 1). The TBs consist of an impervious hard plastic tray base, a drainage layer (ZinCo Floradrain FD 25-E), a filter sheet (ZinCo Systemfilter SF), and one of three substrates (80 mm deep). Three test beds are vegetated with Alumasc Blackdown Sedum Mat (TB1, TB2 and TB3) and the fourth test bed has no vegetation (TB4[1]). Sedum was chosen because it is the most commonly adopted plant in green roof applications due to its tolerance to extreme temperatures, high wind speeds and limited water consumption requirements (VanWoert et al., 2005). With the intention of providing universally-applicable findings, two commercially-available substrates manufactured by Alumasc – Heather with Lavender Substrate (HLS) (TB1 and TB4) and Sedum Carpet Substrate (SCS) (TB2) – were considered alongside a bespoke substrate based on the widely used Lightweight Expanded Clay Aggregate (LECA) (TB3).

The experimental setup includes a Campbell Scientific weather station that records hourly wind speed, temperature, solar radiation, relative humidity and barometric pressure. Rainfall depth was measured at one minute intervals using three 0.2 mm resolution ARG-100 tipping bucket rain gauges manufactured by Environmental Measures Ltd. Runoff was measured volumetrically through collection tanks equipped with a Druck Inc. PDCR 1830 pressure transducers. The collection tank located under each test bed was designed for increased measurement sensitivity at the beginning of each rainfall event and to avoid direct discharge on the sensor. The pressure transducers were calibrated on site. A solenoid electronic valve

[1] This test bed is TB7 in the full test set presented in Poë et al. (2011). However, it is referred to as TB4 here as only four of the beds were instrumented for moisture content measurements.

empties the tank when maximum capacity is reached and every day at 14:00. Runoff is recorded at 1 minute intervals. Data are recorded through a Campbell Scientific CR3000 data logger.

During this monitoring programme the sedum vegetation was well established with good surface coverage.

2.1.2 Moisture content measurements

Water content reflectometers were located at three different soil depths to measure the soil moisture profile and behaviour in the four test beds. The sensors used were Campbell Scientific CS616 Water Content Reflectometer (Campbell Scientific Inc., 2006). The probes were installed horizontally at the centre of each test bed and the rods were located at 20 mm (bottom), 40 mm (mid) and 60 mm (top) above the drainage layer and filter sheet (as shown in Fig. 1). Considering the proximity of the probes in each test bed, the rods of the mid and top probes were installed at 90° and 180° respectively from the lower one, in order to avoid distortion of the measurement reading taken by the enabled probe. The orientation of each probe was pre-determined to ensure that the wires did not interfere with the accuracy of the measurements from nearby probes. Furthermore, to avoid inter-probe interference, the probes are differentially-enabled, with each of the four sub-scans measuring three probes in different test beds. Moisture content measurements were recorded at 5 minute intervals.

Considering the specificity of the substrates used, the 12 sensors were calibrated in the laboratory using the three substrates monitored in the field (Kelleners et al., 2005; Seyfried and Murdock, 2001; Western and Seyfried, 2005). Moisture content during calibration ranged between 0.05 and 0.40 m^3m^{-3}. The actual moisture content (θ) at each calibration condition was measured by drying the soil to constant weight (until change in weight was less than 0.5%) at 110°C from 24 to 40 hours and multiplying by the measured bulk density. The temperature in the laboratory was 20°C, and the sensors were also tested at 30, 35 and 40°C. It was confirmed that the effect of temperature change for higher temperatures could be compensated for by applying the correction equation provided by Campbell Scientific and proposed by Western and Seyfried (2005).

[Approximate location of Figure 1]

2.1.3 Substrate characteristics

HLS is a semi-intensive commercial substrate which consists of crushed bricks and pumice (ZincolitPlus), enriched with organic matter including compost with fibre and clay materials (Zincohum) (ZinCo GmbH). The SCS Substrate is a typical extensive green roof substrate consisting of crushed bricks (Zincolit), enriched with Zincohum. The organic content in HLS is greater than in SCS. The LECA-based substrate contains 80% LECA, 10% loam (John Innes No. 1) and 10% compost by volume. Laboratory tests of these substrates were carried out according to the *Guidelines for the Planning, Construction and Maintenance of Green Roofing* of the German Landscape Development and Landscaping Research Society (FLL, 2008). The tests performed included Particle Size Distribution (PSD), apparent density (dry condition and at max water capacity), total pore volume, maximum water holding capacity (MWHC), permeability and organic content (Table 1). To address the uncertainty associated with subsampling heterogeneous mixtures, a sample splitter was used and 3-6 replicate samples were tested, depending on the analysis.

Soil-moisture release curves for the three substrates were determined using the pressure plate extraction method (Carter, 1993; Soil Moisture Equipment Corp., 2008). The moisture release curve expresses the relationship between the moisture content, θ, and the soil moisture potential, ψ. The principle of this test is to gradually extract water from initially-saturated samples by applying increasing pressures. The resulting curve provides important information regarding the plant available water, i.e. moisture content values between MWHC (field capacity) and the permanent wilting point. Field capacity defines the condition when the substrate can hold no more moisture under gravity, and corresponds to 0.33 bar suction, whilst the permanent wilting point defines the lower limit to plant available moisture, and corresponds to 15 bar suction (Fassman and Simcock, 2012; Hillel, 1971). A 1600 Pressure Plate Extractor 5 bar and a 1500F1 Pressure Plate Extractor 15 bar manufactured by Soil Moisture Equipment Corporation were used for this purpose. Due to the specific characteristics of the green roof substrates the standard test procedure proposed by the manufacturer was slightly modified. A wet strengthened filter paper (Whatman No. 113) was attached to the bottom of the sample rings to avoid collection of sample residues on the ceramic plate at the end of the test. A mixture of kaolin and water was spread on the ceramic plate to ensure contact between the sample and the ceramic plate.

The physical characteristics of the substrates are reported in Table 1, while the PSD and moisture release curve are shown in Fig. 2. To address the uncertainty of testing substrates consisting of heterogeneous mixtures of different materials, tests were conducted using different batches of substrates. It was observed that individual batches of each specific material provided different results. Often the raw materials composing the substrates are sourced by different suppliers, resulting in material characteristics per batch that vary from the nominal expected values. For this reason, the results presented in this paper refer to the specific batches used in the field installation.

In general the three substrates, although different in composition and material, have similar PSD curves, albeit with HLS characterized by a higher proportion of finer particles. The similarities are not surprising considering that the three substrates were developed according to the FLL guidelines, which restrict the range of permissible granulometric distributions. The MWHC of HLS from the laboratory test is 41.2 %, slightly higher than the SCS and

LECA substrates due to its higher organic content and finer gradation. While HLS and SCS have similar characteristics, the LECA is a lightweight, low density substrate characterized by higher porosity and higher organic content. The moisture release curve obtained through the pressure extraction test did not provide meaningful results for the LECA, as the characteristics of the material proved to be unsuitable for the test. The HLS and SCS substrates have similar moisture release curves, consistent with their soil characteristics. The wilting point is reached at 9.0 and 8.9 % volumetric moisture content respectively for HLS and SCS. A slight deviation in moisture release is shown when the volumetric moisture content falls below 18%, with lower moisture release from the SCS substrate below this datum. When moisture conditions are restricted, below 11% moisture content, the same moisture release behaviour was observed for the two substrates. The MWHC values obtained from this test were lower than the values resulting from FLL tests (25.0 and 22.4 % volumetric moisture content respectively for HLS and SCS). It is possible that the sieving procedure needed for the preparation of the sample affected the test at low pressure (i.e. field capacity). Also, the smaller volume of sample required for this test could lead to errors due to subsampling and/or boundary effects. In this sense the MWHC obtained through the FLL test are more representative of the characteristics of the substrates.

[Approximate location of Table 1]

[Approximate location of Figure 2]

2.2 Data analysis

Data from the individual moisture content probes was examined in detail for the month of May 2012. This period was selected due to the presence of several rainfall events (total rainfall = 51.6 mm), and dry periods (including one selected for further analysis) and because the climatic conditions recorded (high temperature and solar radiation) should enhance any impact associated with the presence of vegetation. This data was used to investigate vertical moisture content profiles and to confirm that the measured moisture content fluctuations were consistent with the expected hydrological processes occurring in response to rainfall and dry periods.

Individual storm events were defined as being separated by continuous dry periods of at least 6 hours. Five specific Dry Weather Periods (DWP) were selected from the data record for detailed analysis. These were selected to give a representative range of different climatic conditions and initial substrate moisture contents. Depth-averaged moisture content values enabled comparisons between the four TBs to be made.

The daily moisture loss, during DWP, was calculated as the difference of the average daily moisture content of two consecutive days. Mean and median daily loss rates were calculated over the full duration of each of the five DWPs, and moisture loss with respect to time was also considered.

2.3 Modelling moisture losses during dry periods in green roof systems

The water balance equation (Equation 1) was used to simulate the moisture content behaviour during dry periods. Given the present focus on dry weather periods, precipitation (P) and runoff (R) are assumed to be zero, and it is assumed that the moisture loss is solely due to ET:

$$\frac{\Delta\theta}{\Delta t} = P - R - ET \qquad (1)$$

ET is calculated using the basic form of the Soil Moisture Extraction Function (SMEF) model (Zhao et al., 2013) that estimates actual ET under conditions of restricted moisture availability. The basic form of the SMEF method (Equation 2) describes ET at a generic time t as a function of potential evapotranspiration (PET) at the time t multiplied by the ratio of actual moisture content (θ_t) to the moisture content at field capacity (θ_{FC}):

$$ET_t = PET_t \cdot \frac{\theta_t}{\theta_{FC}} \qquad (2)$$

This method was used by Stovin et al. (2013) to simulate ET in a hydrological flux model developed for long term simulation of green roof systems and was validated against data monitored on a green roof test bed in Sheffield, UK with similar characteristics to the one used in this study. PET refers to the expected ET rate associated with a reference crop under well watered conditions. Oudin et al. (2005) and Zhao et al. (2013) report many PET formulae proposed in the hydrological and agricultural science literature. Two PET models were used in this study: a temperature based equation that requires limited input data, 1985 Hargreaves equation (Hargreaves and Samani, 1985) and the energy balance-aerodynamic FAO-56 Penman Monteith equation (Allen et al., 1998). The Hargreaves method estimates daily grass reference PET from climatic conditions (temperature) and extraterrestrial radiation calculated as a function of latitude and day of the year. The method of Hargreaves and Samani best estimated daily ET among empirical models based only on temperature (Allen et al., 1998; Hargreaves and Allen, 2003; Itenfisu et al., 2003; Jensen et al., 1990). The FAO-56 Penman-Monteith model is the model recommended by FAO and the World Meteorological Organization (WMO) to estimate reference PET from a grass surface (Allen et al., 1998). This method has been shown to provide a better prediction amongst other methods for green roofs (Hilten, 2005). These methods and equations are described in Jensen et al. (1990).

The model initial moisture conditions (θ_0) were set equal to the observed data at the beginning of each dry period for the three vegetated systems. The model has been implemented at an hourly time step. PET was calculated using daily recorded minimum and maximum temperature and relative humidity, mean daily temperature, solar radiation and wind speed. Hourly PET was assumed equal to daily PET/24. It is recognised that this simplification ignores the diurnal cycle, but total losses over longer periods are correctly represented.

The model results were evaluated through graphical techniques and three quantitative statistics: Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS) and the ratio of the root square error to the standard deviation of measured data (RSR) as recommended by Moriasi et al. (2007). NSE is a normalized statistic expressing the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970). PBIAS represents the deviation of the simulated data from the observed values, the optimal value being 0.0 and positive and negative values indicating model underestimation or overestimation bias respectively (Gupta et al., 1999). The RSR includes a commonly used error index statistic and it is normalized by a scaling factor that allows comparison with different parameters (Moriasi et al., 2007; Singh et al, 2004). Model simulation can be judged *good* or *very good*, respectively if $0.65<\mathrm{NSE}\leq0.75$ or $0.75<\mathrm{NSE}\leq 1.00$ and $0.50< \mathrm{RSR} \leq 0.60$ or $0.00<\mathrm{RSR}\leq0.50$ irrespective of the parameter or constituent analysed. A recommendation for PBIAS $< \pm$ 10% for *very good* performance and $\pm10\leq\mathrm{PBIAS}<\pm$ 15% for *good* performance is provided for streamflow data. The same model performance ratings were applied here.

The same model evaluation method was used to propose green roof system factors (Ks) specific for the configurations tested, as described by equation 3. This coefficient takes into consideration the specificity of green roof substrates and the difference between the tested sedum vegetation and the reference grass crop in the PET models used. When accounting for differences in vegetation, this factor is often referred to as the crop coefficient. Coefficients were derived by using the method of least squares.

$$ET_t = PET_t \cdot \frac{\theta_t}{\theta_{FC}} \cdot K_s \qquad (3)$$

3 RESULTS

3.1 *Characterization of the monitored dry weather periods*

The 29 months rainfall record contained 641 rainfall events and DWPs. Of these events, 32 can be considered significant, being characterized by a return period greater than 1 year (Stovin et al., 2012). The probability density function of the corresponding DWPs showed that 10 % of the DWPs were greater than 4 days. The mean and median DWP values were respectively 39.8 and 20.5 hours, and the maximum value was 18.4 days. The climate in Sheffield is generally temperate with an average 824.7 mm of rain per year (source MET office data series 1971-2000). A detailed analysis of Sheffield's climate is reported in Stovin et al. (2012).

Because the aim of this study was to investigate the moisture content behaviour during dry periods, five DWPs were selected in which no rainfall or runoff was observed for a continuous period of at least ten days. The DWPs were classified as corresponding to either 'cooler' or 'warmer' periods. If compared to the climatic data series 1971-2000 for Sheffield, UK (source Met Office), conditions in the two cooler periods (March and April 2011) correspond to typical conditions in spring with mean temperatures of 8.5 and 12.6°C. Conditions during the three warmer periods (July 2013, May 2012 and July 2012) were comparable to typical summer conditions in Sheffield (mean temperatures between 17.1 and 19.8°C).

The initial moisture content, θ_0, is expected to influence moisture loss rates. For each of the DWPs considered, the absolute values of θ_0, and the ratios of θ_0:MWHC vary between beds. In TB1 and TB2, for example, a 'high' θ_0 implies θ_0:MWHC > 0.85, medium θ_0 implies θ_0:MWHC > 0.70 and low θ_0 implies θ_0:MWHC < 0.6. In the LECA-based substrate the corresponding θ_0 and θ_0:MWHC are lower. The two cooler periods were characterized by medium and low θ_0 respectively, whilst the three warmer periods corresponded to high, medium and low θ_0. The characteristics of the selected DWPs are reported in Table 2.

[Approximate location of Table 2]

3.2 Moisture content fluctuations during May 2012

Fig. 3 shows the temporal variations in moisture content at 20, 40, and 60 mm depth from the substrate surface during the month of May 2012 for the four tested green roof configurations. The rainfall hyetograph and runoff hydrograph are reported in the same figure.

In general it may be seen that the substrate moisture content decreases during dry periods, and that moisture levels are restored to their maximum value (i.e. field capacity) during the larger rainfall events, which also result in runoff. Some of the smaller rainfall events result in increases in the substrate moisture content, but are insufficient to restore moisture to field capacity or to generate runoff from the green roof.

The data show consistent behaviour during dry and wet periods and provide confidence in the quality of the moisture measurements through calibrated water content reflectometers.

Considering the vertical profile, moisture content generally increases with depth, although in all four cases the differences between the top and mid-depth values are small. In the three vegetated beds (TB1, TB2 and TB3), the moisture content near the bed is elevated by 10-20% compared with the upper part of the profile. During rainfall events, this may be expected, due to the high permeability of green roof substrates. Other studies showed that moisture measurement revealed higher moisture content in the deeper layers (Palla et al., 2009). Furthermore, the presence of a vertical gradient may reflect both preferential drying at the surface and the effects of substrate compaction and ageing which can lead to leaching of fines into the lower layers of the substrate (Morbidelli et al., 2011; 2013). However, the unvegetated bed, TB4, exhibits no significant vertical gradient, suggesting that the presence of vegetation and root systems contributes to the development of the vertical profile. The maximum moisture content in TB1 is also consistently higher than TB4, which suggests that the moisture retention effects of plant roots may have an influence on the effective field capacity of a green roof system.

It may be noted that substrate characteristics affect the moisture content vertical profile. The HLS and LECA result in a higher moisture content gradient compared with the SCS, probably due to their higher organic content. The difference between the moisture content in the bottom layer and the layers above is most pronounced for the LECA. This may reflect the LECA's high proportion of similarly-sized large particles combined with a relatively high proportion of fines. The higher porosity of the LECA also results in more rapid variation of the moisture content during drying and wetting cycles.

The data presented in Fig. 3 suggests that, although vertical profiles clearly exist, the temporal changes in moisture content are extremely consistent throughout the substrate depth. For this type of extensive (shallow), green roof system, this justifies the use of a depth-averaged moisture content value for each bed in subsequent analysis.

Regular diurnal fluctuations are evident throughout the substrate depth. The daily fluctuation corresponds to temperature variations, with a daily decrease of the moisture content during the central warmer hours of the day reflecting typical ET daily cycles (Poë and Stovin, 2012; Voyde et al., 2010a). There is some evidence of moisture gain during the early hours of the day, which is believed to result from condensation.

[Approximate location of Figure 3]

3.3 Moisture content during five selected DWPs

In Fig. 4 the depth-averaged moisture content of the four test beds is plotted together with the hourly temperature for the five DWPs characterized by different initial moisture conditions and temperature.

As already observed in Fig. 3, it can be clearly seen that the diurnal moisture content variation mirrors the hourly temperature. Between the two cooler periods of March and April 2011, 7 minor rainfall events with a total depth of 11.4 mm occurred. These events did not alter the moisture content within the vegetated roofs, but did increase the moisture content in the non-vegetated bed. This can be explained by interception by the well-established plants.

The rate of moisture loss is similar for the vegetated beds, while it is lower for the non-vegetated one, thus showing the role of plant transpiration.

Irrespective of climatic conditions, changes in moisture content show a consistent influence of substrate moisture content. This is evident when comparing the cooler periods of March and April 2011 with the warmer period of May 2012. Similar behaviour is observed between the vegetated HLS and SCS test beds, as expected considering the similar substrate characteristics. It can be noted that at the volumetric moisture content of approximately 0.15 m^3m^{-3} the two curves cross over, indicating lower matric potential in the HLS. This can be explained by its slightly higher porosity. When moisture conditions are restricted (see July 2013 in Fig. 4) the same moisture release behaviour was observed for HLS and SCS. This behaviour was observed in the soil-moisture characteristic curves obtained in the pressure plate extraction test (Fig. 2).

In the vegetated test beds, it is clear that the soil characteristics influence the initial moisture content, with higher MWHC corresponding to higher θ_0 consistently in the order HLS > SCS >> LECA.

[Approximate location of Figure 4]

3.4 Daily moisture loss rate

The mean, median and standard deviation of the daily moisture loss and climatic conditions observed for each DWP are reported in Table 2.

The DWPs of March 2011 and May 2012 were characterized by similar, medium, θ_0 and similar DWP duration. It may be seen that the warmer period had approximately double the moisture loss rate compared with the cooler period. Specifically, mean values of 0.76, 0.81 and 0.79 mm/day were observed in March 2011 and 1.83, 1.44, and 1.39 mm/day in May 2012 respectively for HLS, SCS and LECA. Comparing the DWP of April 2011 and July 2013, both characterized by low θ_0 and similar duration, it may be concluded that, even in this case, climatic conditions influenced the moisture loss, with mean values of 0.41, 0.28 and 0.13 mm/day in cooler periods and 0.76, 0.66, and 0.23 mm/day in 'warmer' periods respectively for HLS, SCS and LECA.

Moisture loss data from the three warmer DWPs confirm the strong influence of moisture content on the moisture loss rate. The DWPs are characterized by very similar climatic conditions, but the resulting average moisture loss values - showing July 2012 > May 2012 > July 2013 for the vegetated test beds - depend only on θ_0.

The DWP of July 2013 lasted 16 days and, as shown by the lower median values of moisture loss especially for LECA, high moisture stress conditions occurred. Plant stress was observed after 11 days in HLS and SCS and after 5 days for LECA. If only the days in which the moisture content was higher than 0.02 m^3m^{-3} are considered, the resulting average moisture loss values were 1.02, 0.84, and 0.79 mm/day, with standard deviation of 0.47, 0.44 and 0.20 respectively for HLS, SCS and LECA. These results, if compared with the other DWPs, consistently confirm the previous conclusions on the influence of climatic conditions and initial moisture content.

In Fig. 5 the daily moisture loss rates are plotted together with daily climatic data.

It may be seen that the moisture loss rate mirrors the highly varying climatic conditions within these periods. During the March 2011 period, for example, a decrease in temperature and solar radiation and an increase in relative humidity between the 25th and 27th March are reflected in a decrease in moisture across all TBs. This is more apparent in warmer periods where high variability was observed also in the very restricted moisture conditions of July 2013.

LECA and the non-vegetated HLS generally showed the highest initial moisture loss. This was expected due to the higher porosity of LECA and the lack of vegetation respectively. However, after the first days of the DWPs, the highest moisture losses were recorded in the vegetated HLS and SCS, with the peak rates observed in May 2012 due to the higher temperature, solar radiation and wind speed recorded by the end of month.

A decrease in the moisture loss with time was observed in warmer periods or in moisture restricted conditions. However, here the effect of moisture restrictions is largely masked by the variability of climatic conditions and less evident than results from other experimental studies (Berghage et al., 2007; Voyde et al., 2010) and in the laboratory in more controlled conditions (Poë and Stovin, 2012). In the event of March 2011 the daily moisture loss did not show any decrease because the moisture availability remained high and the climate was temperate. It can be noted also that the differences among green roof configurations are more apparent in the warmer periods.

[Approximate location of Figure 5]

3.5 *Plant transpiration*

In Fig. 6 the cumulative moisture loss over time is plotted for the five DWPs for TB1 and TB4, which are characterized by the same substrate and respectively with and without vegetation. Similar moisture loss rates were observed at the beginning of each DWP. The effect of plant transpiration is more evident after a few dry days when the level of initial moisture content was medium to low (May 2012 and March 2011). In March 2011, higher moisture losses occurred in TB1 after the 6th dry day due to transpiration, even when temperatures fell (Fig. 5).

In non-restricted moisture content conditions, similar moisture losses were observed in both beds at the end of the 10 day DWP in July 2012. Earlier in this DWP, higher moisture loss rates were observed in the unvegetated bed. This suggests that whilst the planted beds may be better at conserving moisture and resisting drought, these beds will have a lower retention capacity for stormwater runoff compared with an unvegetated system.

In low initial moisture content conditions, the effect of plant transpiration is not evident and similar moisture loss rates were observed until the plant stressed conditions and wilting point were approached at the 11th day of July 2013 (see Figure 4). In this case, evaporation was higher in TB4 due to the higher initial moisture content (see Table 2).

[Approximate location of Figure 6]

4 COMPARISON WITH MODELLED DATA

The field data presented above has established that, although substrate moisture loss is strongly correlated with temperature, moisture loss rates fall when the moisture available for ET is restricted. In unrestricted moisture conditions, it is reasonable to expect that a standard prediction of Potential ET should provide a useful estimate of the observed moisture loss, although it is important to appreciate that an ET estimate includes plant moisture losses in addition to substrate moisture losses. It should also be noted that the green roof system components differ in many respects from standard reference crops.

Figure 7 clearly shows that the observed daily moisture loss rates are dependent upon the available soil moisture. Rather than show the absolute moisture loss rates, which are strongly influenced by fluctuations in climate, the observed values are plotted relative to the PET value calculated with the 1985 Hargreaves method. Although the data are scattered, there is a clear trend in each case, confirming that moisture loss (and by implication ET) is controlled by moisture availability. The linear relationship confirms that a SMEF in the form of Equation 2 is suitable for this type of data.

For TB3 (LECA), the moisture loss in unrestricted conditions is approximately equal to the predicted PET. However, for the HLS and SCS substrates, PET in unrestricted moisture conditions does not provide a good estimate of the daily moisture loss, overestimating the observed values, and the results suggest that it may be appropriate to apply a system-specific correction factor.

[Approximate location of Figure 7]

4.1 Model implementation

Three variants of the moisture loss model (Equations 1 to 3) were applied. Initially Equation 1 alone was applied, using both the 1985 Hargreaves and FAO 56 Penman-Monteith methods to predict the relevant daily ET values. Subsequent iterations of the model introduced the SMEF (Equation 2) and finally Equation 2 was substituted with Equation 3 to include Ks, the system-specific correction factor. Appropriate coefficient values were identified using least-squares optimisation. Ks values were determined for each of the vegetated test beds, for the complete set of DWP data combined (Table 3). The optimisation was based on a comparison between the measured and modelled moisture content data at each hourly time-step. By using 1985 Hargreaves method for PET the obtained Ks values were 0.68, 0.64 and 1.36, respectively for HLS, SCS and LECA. Slightly different values were obtained by using FAO 56 Penman-Monteith method: 0.69, 0.65 and 1.36, respectively for HLS, SCS and LECA.

Fig. 8 compares the three model implementations with measured data corresponding to two 'warmer' DWPs, July 2012 and July 2013. These DWPs were characterized by high and low θ_0 respectively. Differences between the two PET estimates were not found to be significant; for clarity only the results based on the Hargreaves method are included in the figure.

By failing to take into account the effects of moisture restriction on actual ET rates, the simplest model (labelled Hargreaves in Fig. 8), significantly overestimates moisture loss in the green roof substrates. No further analysis of this model is presented. However, it may be seen that the predictions based on Hargreaves + SMEF are considerably better. Model performance statistics for the PET + SMEF model evaluation are reported in Table 4 for all five DWPs and for each vegetated test bed. It may be seen from this that the model predicts the response in the LECA substrate satisfactorily (good to very good NSE and RSR), however PBIAS was only satisfactory. In general the model underestimated the moisture losses in time (PBIAS<0). This is due to the specific characteristics of the LECA, highly porous substrate based on expanded clay. The model did not provide a satisfactory prediction for the July 2013 DWP. This can be explained by highly-restricted moisture conditions that led to the substrate becoming completely dry within 6 days. As might be expected from Fig. 7, the models for both HLS and SCS overestimated the moisture losses (PBIAS>0), except for when the moisture content was very low. Of the two PET models, both provided similar accuracy. However, in view of the fact that 1985 Hargreaves requires less input data, this approach is preferable.

[Approximate location of Figure 8]

[Approximate location of Table 3]

Ks was introduced in the final implementation of the moisture loss model. The single ‘all data’ substrate-specific Ks values have been applied in Fig. 8. The derived Ks values led to significant improvements in the model performance, as shown in Fig. 8 and Table 5. It is therefore proposed to use the 1985 Hargreaves method for PET together with a SMEF function and Ks values of 0.68, 0.64, and 1.36 to estimate moisture losses in green roof characterized by HLS, SCS and LECA substrates respectively and sedum vegetation.

Ks values were determined also for individual DWPs (Table 3) and revealed a high level of consistency across all five DWPs. Although noticeably different values were observed for the exceptionally-dry DWP of July 2013, such extreme moisture-stressed conditions are relatively rare, and any uncertainties in their estimation are not critical for stormwater management applications. However, this may suggest that further refinement of the model is required to fully-capture the moisture content behaviour in highly moisture-stressed conditions. The selected DWPs are limited in number and it is not possible to say whether the differences in optimised Ks values for different events on the same test bed reflect real changes in substrate or vegetation or whether they are compensating for errors or uncertainties in the prediction of PET. Nonetheless, the derived system-specific Ks values clearly provide an improvement in the overall performance of the ET predictions.

[Approximate location of Table 4]

[Approximate location of Table 5]

5 DISCUSSION

5.1 Observed substrate characteristics

The apparent field capacity observed in the moisture content data should correspond to the MWHC obtained through FLL laboratory tests. Fig. 3 confirms that similar values were obtained, although moisture levels in the unvegetated bed are lower than expected. It has also been observed that in warmer spring and summer periods, when the rainfall event is characterized by a longer previous DWP, the apparent field capacity is reduced relative to MWHC. This can be explained by the fact that the FLL tests are performed on pre-saturated substrate and do not take into consideration the presence of the plant root system that influences the substrate structure or the fact that dry substrates require wetting before their full moisture retention capacity is restored. Compaction of the substrate in the field can also lead to different behaviour during wetting and drying cycles and the possibility of preferential paths for runoff. Furthermore, the organic material is subject to decomposition and probably compaction in time, thus changing the substrate structure and behaviour. Similar issues were discussed by Fassman and Simcock (2012), and further research is required to properly establish the relationships between the FLL-derived MWHC, the pF curve-derived MWHC and actual values of moisture content observed in operational and aging vegetated green roof systems.

5.2 Average moisture loss rate

The mean values of substrate moisture loss presented in Table 2 provide a useful practical indication of moisture loss rates that might be expected over periods of similar duration to the observed ones (approximately 10 days) as a function of climate and of the substrate's initial moisture content. For example, for the two typical brick-based substrates, loss rates of around 1.6 mm/day are associated with high initial moisture content levels and warmer, summer, conditions. The rate is approximately halved when the initial moisture content is low and in cooler, typical spring, conditions. The lowest rate, around 0.35 mm/day on average, is associated with both cooler conditions and low initial moisture content. It should be noted that these values are only valid for periods of similar duration; if shorter DWPs were of interest, then higher mean loss rates would be expected for the same initial moisture content levels.

6 CONCLUSIONS

With the purpose of investigating the hydrological processes within green roof systems a comparative long term field monitoring programme has been carried out at the University of Sheffield (UK) since March 2011. This paper focused on the moisture content behaviour in extensive green roofs during dry periods due to evapotranspiration. The study is supported by 29 months continuous monitoring of the moisture content of four green roof test beds characterized by different soil characteristics and with and without vegetation. Water content reflectometers located at three different soil depths were used to measure the soil moisture profile and to record temporal changes in moisture content at a five-minute resolution.

The results showed that the moisture content vertical profile varied consistently depending on the substrate characteristics and the presence of vegetation. High temporal resolution data has shown diurnal fluctuations that reflect the daily temperature variations with a daily decrease in the moisture content due to ET during the central warmer hours of the day. Substrate specific average daily moisture loss values were derived for cooler and warmer conditions and for different initial moisture content. The results showed the clear influence of the moisture content on the moisture loss rate due to evapotranspiration, with lower values associated with restricted moisture conditions. The daily moisture loss rate within dry periods mirrored the highly variable climatic conditions, and this masked the expected exponential decay in the ET rate shown in other studies. The LECA-based green roof showed similar behaviour in daily moisture loss to the non-vegetated roof, with a rapid initial decrease of moisture content. This behaviour may restore the green roof’s retention capacity more rapidly than alternative substrates, but it also increases the occurrence of plant stress conditions. The presence of vegetation resulted in higher daily moisture loss after a few dry days when the initial moisture conditions were medium. The presence of vegetation, if well established and with good surface coverage, not only affected the rate of moisture decrease through transpiration, but also prevented wetting during minor rainfall events. This has important implications for the retention capacity and performance of a green roof.

Finally, the observed data have been compared with simulated moisture content using a hydrologic model based on water balance and two Potential ET models (Hargreaves and FAO56 Penman-Monteith) combined with a soil moisture extraction function. The results confirmed the need to apply a soil moisture extraction function. Further improvements in model performance were achieved through the application of configuration-specific correction factors derived from the observed data. These factors account for differences between green roof system substrate characteristics and standard reference crops. The two PET models used did not show significant difference, thus suggesting that 1985 Hargreaves method is preferable due to its more limited data input requirements.

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Table 1. Substrate characteristics according to FLL testing method.

		HLS		SCS		LECA	
		Mean	**St. Dev.**	**Mean**	**St. Dev.**	**Mean**	**St. Dev.**
Particle Size < 0.063mm	(%)	2.1	1.4	1.4	0.3	0.4	0.0
d_{50}	(mm)	4.7	0.7	5.2	0.3	5.0	0.1
Dry Density	(g/cm^3)	0.95	0.04	1.06	0.05	0.41	0.00
Wet Density	(g/cm^3)	1.36	0.02	1.45	0.07	0.76	0.02
Total Pore Volume	(%)	63.8	1.6	59.8	2.0	84.8	0.0
MWHC (field capacity)	(%)	41.2	2.3	39.1	2.1	35.0	1.6
Air content at MWHC	(%)	22.6	0.8	20.7	4.1	49.8	1.5
Organic Content	(%)	3.8	0.1	2.3	0.5	6.0	0.3

Table 2. Selected DWPs climatic characteristics and initial moisture content conditions (θ_0) together with mean, median and standard deviation of the daily moisture loss measured in each TB.

		TB1	TB2	TB3	TB4	T (ºC)	Wind Speed (m/s)	RH (%)	Solar Radiation (MJm^{-2})
		Moisture Loss (mm/day)							
17-29	θ_0 (m^3m^{-3})	0.33	0.30	0.18	0.23				
March 11	Median	0.70	0.75	0.92	0.46	8.5	1.0	69.4	10.9
[12 days]	Mean	0.76	0.81	0.79	0.41	8.5	1.2	69.2	9.8
	St.Dev	0.31	0.34	0.37	0.26	2.3	0.5	7.4	3.3
6-23	θ_0 (m^3m^{-3})	0.16	0.15	0.04	0.20				
April 2011	Median	0.39	0.27	0.07	0.31	12.7	1.2	64.4	15.1
[17 days]	Mean	0.41	0.28	0.13	0.34	12.6	1.4	63.4	14.5
	St.Dev	0.27	0.22	0.22	0.21	2.3	0.5	6.6	4.9
20-31	θ_0 (m^3m^{-3})	0.38	0.35	0.25	0.34				
July 2012	Median	1.75	1.66	0.97	1.75	17.6	1.9	67.3	20.2
[11 days]	Mean	1.55	1.58	1.50	1.65	17.1	1.9	68.8	19.3
	St.Dev	0.51	0.38	1.33	0.67	2.9	0.7	7.3	6.55
19-31	θ_0 (m^3m^{-3})	0.32	0.30	0.18	0.26				
May 2012	Median	1.78	1.54	1.22	0.76	17.8	1.8	65.3	24.3
[12 days]	Mean	1.83	1.44	1.39	1.04	16.0	1.9	68.9	20.5
	St.Dev	0.82	0.60	0.64	0.75	4.5	0.8	10.6	8.4
3-19	θ_0 (m^3m^{-3})	0.15	0.13	0.05	0.24				
Jul 2013	Median	0.54	0.59	0.07	1.31	20.9	1.4	61.6	22.1
[16 days]	Mean	0.76	0.66	0.23	1.21	19.8	1.7	65.7	19.5
	St.Dev	0.54	0.46	0.36	0.42	2.5	0.5	8.2	5.7

Table 3. System-specific correction factor (Ks) derived from the observed and simulated data through hydrological model using 1985 Hargreaves (H) and FAO 56 Penman-Monteith (FAO56-PM). Results are reported for the three vegetated test beds and for the five selected DWPs together with the values derived by using the complete set of DWP data.

		Ks (-)		
		TB1	TB2	TB3
March 2011	H	0.59	0.67	1.41
	FAO56-PM	0.60	0.68	1.41
April 2011	H	0.77	0.38	1.32
	FAO56-PM	0.78	0.39	1.30
July 2012	H	0.58	0.68	1.29
	FAO56-PM	0.55	0.64	1.22
May 2012	H	0.72	0.62	1.41
	FAO56-PM	0.78	0.67	1.58
July 2013	H	1.01	0.91	2.47
	FAO56-PM	1.12	1.01	2.77
All data	H	0.68	0.64	1.36
	FAO56-PM	0.69	0.65	1.36

Table 4. Quantitative statistics used for the evaluation of the hydrological model using 1985 Hargreaves (H) and FAO 56 Penman-Monteith (FAO56-PM). Results are reported for the three vegetated test beds characterized by different substrates and for the five selected DWPs. The simulations that showed *good* to *very good* performance are highlighted in bold, while the underlined values represent the single *good* to *very good* statistic.

		NSE			PBIAS			RSR		
		TB1	TB2	TB3	TB1	TB2	TB3	TB1	TB2	TB3
March	H	-0.06	0.50	**0.75**	10.86	9.74	**-13.18**	1.03	0.71	**0.50**
2011	FAO56-PM	-0.05	0.49	**0.74**	10.94	9.82	**-13.03**	1.03	0.72	**0.51**
April	H	**0.69**	-3.13	0.68	**9.83**	29.86	-21.67	**0.56**	2.03	0.56
2011	FAO56-PM	**0.71**	-3.14	0.67	**10.46**	30.40	-20.46	**0.56**	2.03	0.57
July	H	-0.12	0.51	0.82	19.21	15.38	-16.14	1.06	0.70	0.42
2012	FAO56-PM	-0.36	0.36	**0.88**	21.17	17.50	**-12.97**	1.06	0.80	**0.35**
May	H	**0.76**	0.60	0.88	**14.97**	18.97	-20.24	**0.48**	0.63	0.35
2012	FAO56-PM	**0.86**	0.74	0.82	**11.08**	15.12	-26.62	**0.48**	0.52	0.42
July	H	**0.93**	**0.90**	0.35	**1.36**	**6.99**	-102.17	**0.26**	**0.31**	0.81
2013	FAO56-PM	**0.92**	**0.91**	0.18	**-5.98**	**-0.09**	-118.54	**0.26**	**0.31**	0.91

Table 5. Quantitative statistics used for the evaluation of the hydrological model using 1985 Hargreaves (H) and FAO 56 Penman-Monteith (FAO56-PM) and applying the system-specific factor (Ks) derived by using the whole set of data. The simulations that showed *good* to *very good* performance are highlighted in bold, while the underlined values represent the single *good* to *very good* statistic.

		NSE			PBIAS			RSR		
		TB1	TB2	TB3	TB1	TB2	TB3	TB1	TB2	TB3
March 2011	H	**0.91**	**0.94**	**0.96**	**2.73**	**0.03**	**-1.53**	**0.30**	**0.25**	**0.19**
	FAO56-PM	**0.89**	**0.92**	**0.96**	**3.06**	**0.35**	**-1.13**	**0.30**	**0.29**	**0.19**
April 2011	H	**0.85**	**-0.10**	**0.78**	**-6.97**	**14.37**	**0.18**	**0.39**	**1.05**	**0.46**
	FAO56-PM	**0.88**	**-0.15**	**0.77**	**-5.97**	**15.13**	**2.20**	**0.39**	**1.07**	**0.48**
July 2012	H	**0.87**	**0.97**	**0.94**	**5.51**	**-1.62**	**3.59**	**0.37**	**0.17**	**0.24**
	FAO56-PM	**0.78**	**0.97**	**0.93**	**7.75**	**0.73**	**6.99**	**0.37**	**0.17**	**0.26**
May 2012	H	**0.90**	**0.96**	**0.97**	**0.68**	**2.88**	**-1.43**	**0.31**	**0.21**	**0.16**
	FAO56-PM	**0.92**	**0.98**	**0.97**	**-1.95**	**0.33**	**-8.29**	**0.31**	**0.16**	**0.18**
July 2013	H	<u>0.79</u>	<u>0.80</u>	<u>0.70</u>	-23.70	-21.06	-59.85	<u>0.46</u>	<u>0.45</u>	<u>0.54</u>
	FAO56-PM	<u>0.71</u>	<u>0.72</u>	<u>0.61</u>	-29.86	-27.07	-74.02	<u>0.46</u>	<u>0.53</u>	0.63

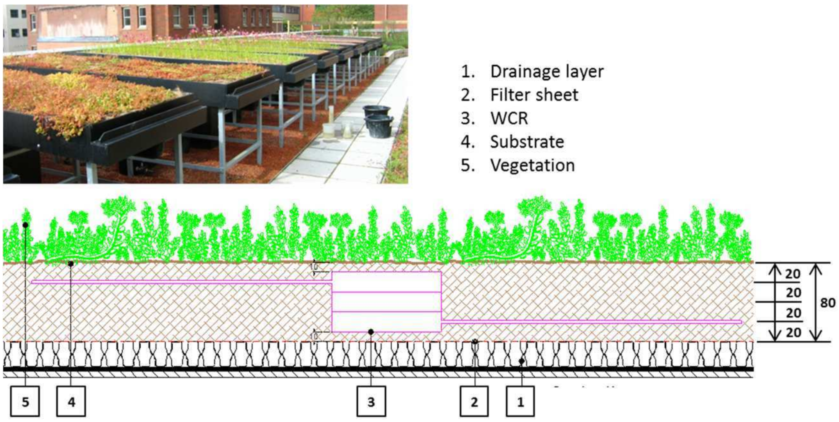

Figure 1. The experimental site at the University of Sheffield, UK and section view of the green roof test bed with the water content reflectometers (WCR) location within the substrate.

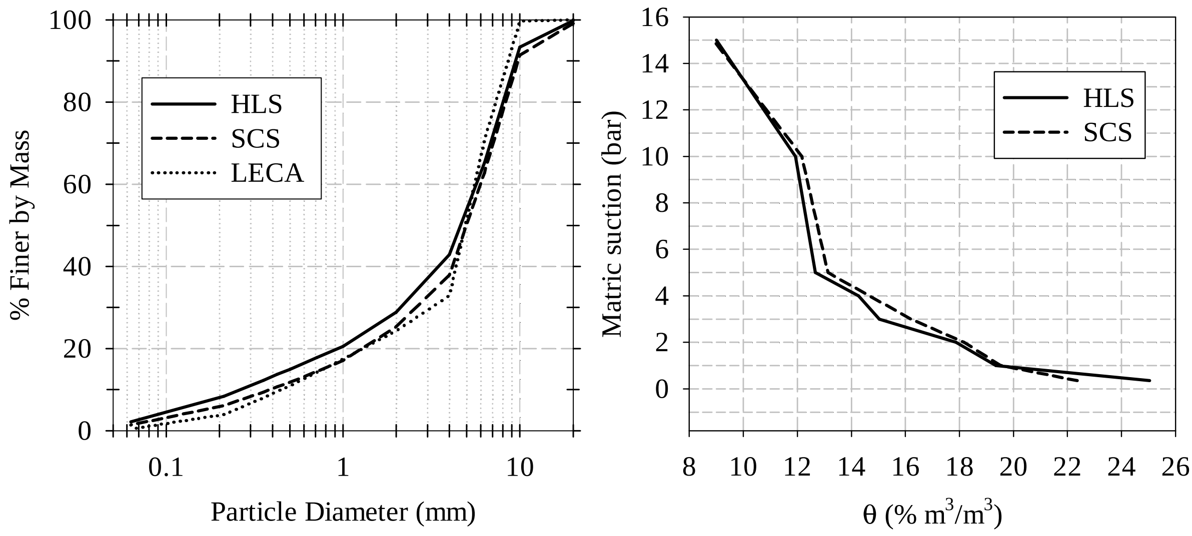

Figure 2. Particle size distribution (PSD) of the three tested substrates and moisture release curves resulting from the pressure plate extraction test.

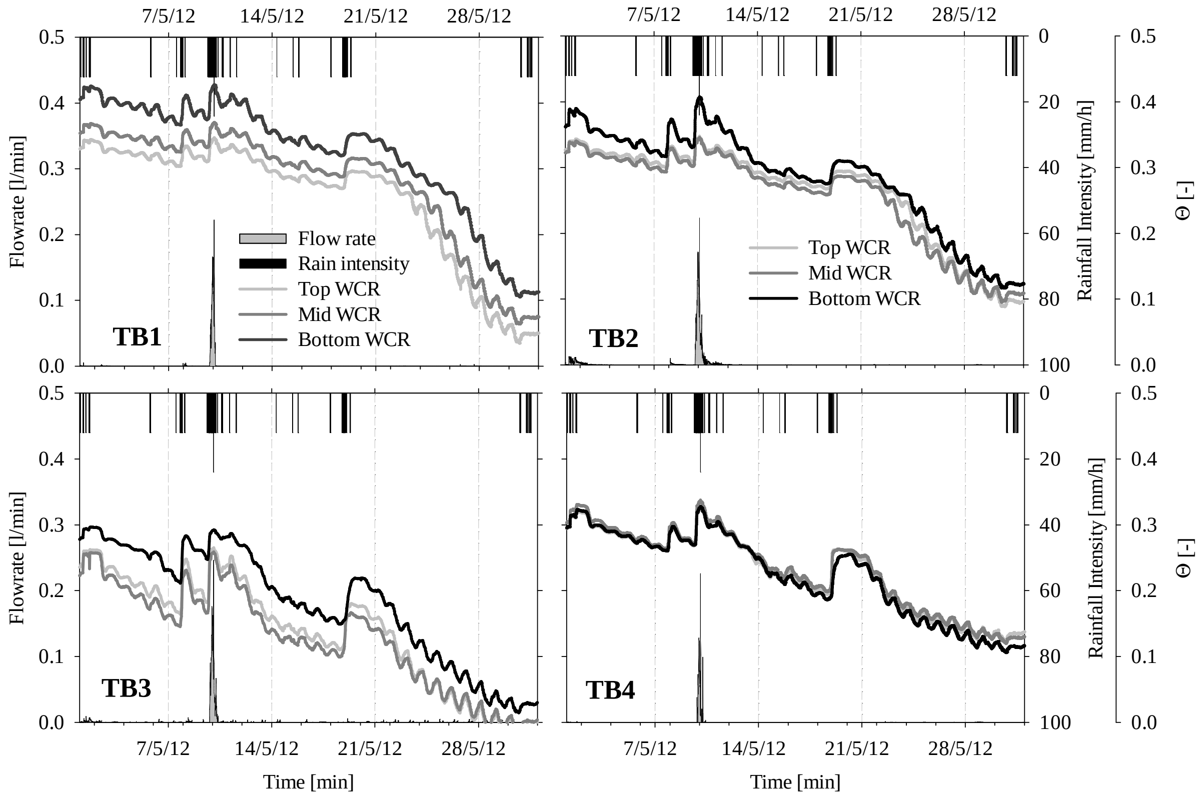

Figure 3. Hydrograph, hyetograph and measured moisture content (θ) at 20 (top), 40 (mid), and 60 mm (bottom) from the surface of the tested green roof systems for the month of May 2012.

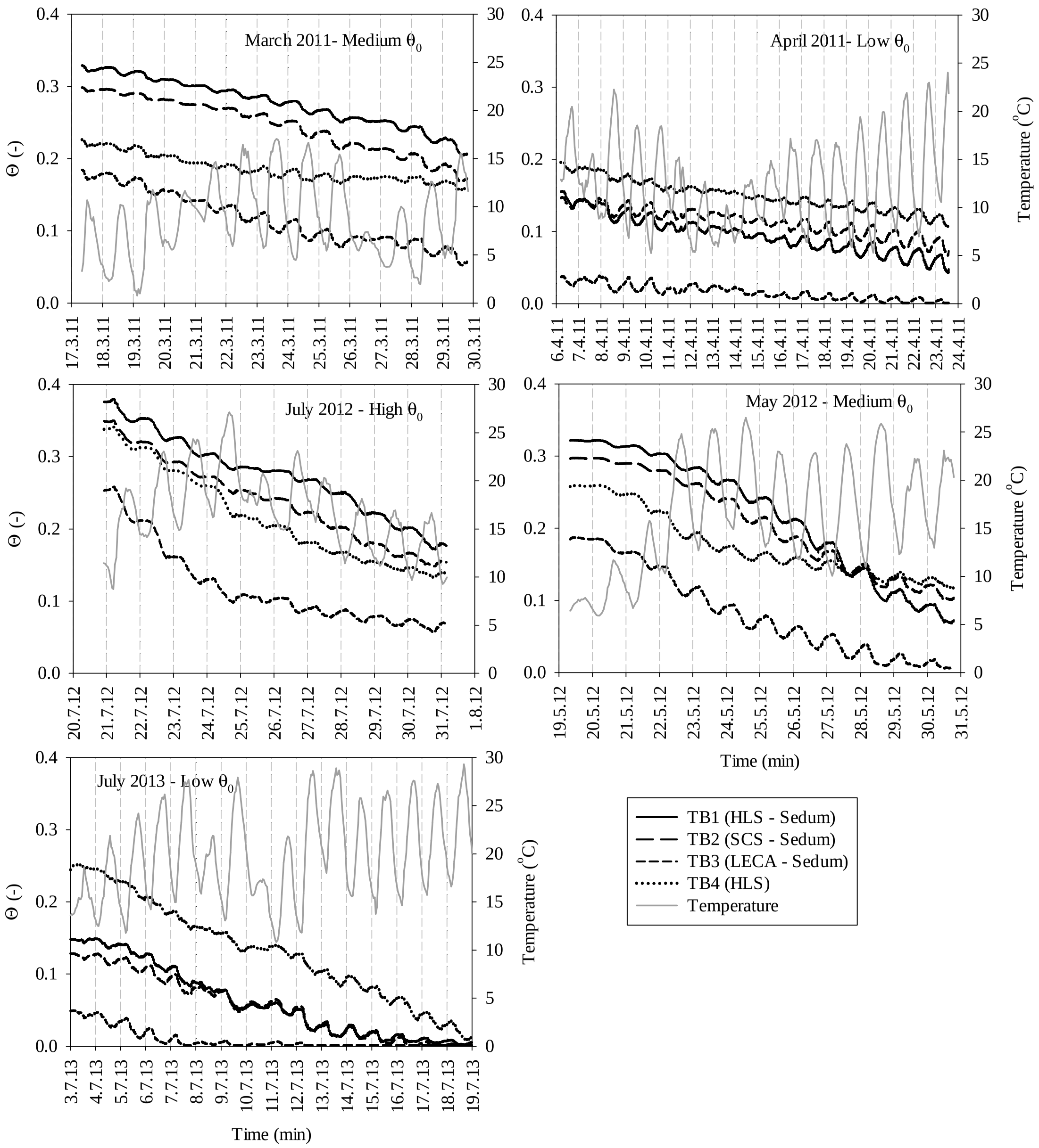

Figure 4. Moisture content and temperature behaviour for the four tested green roof configurations and the selected DWPs.

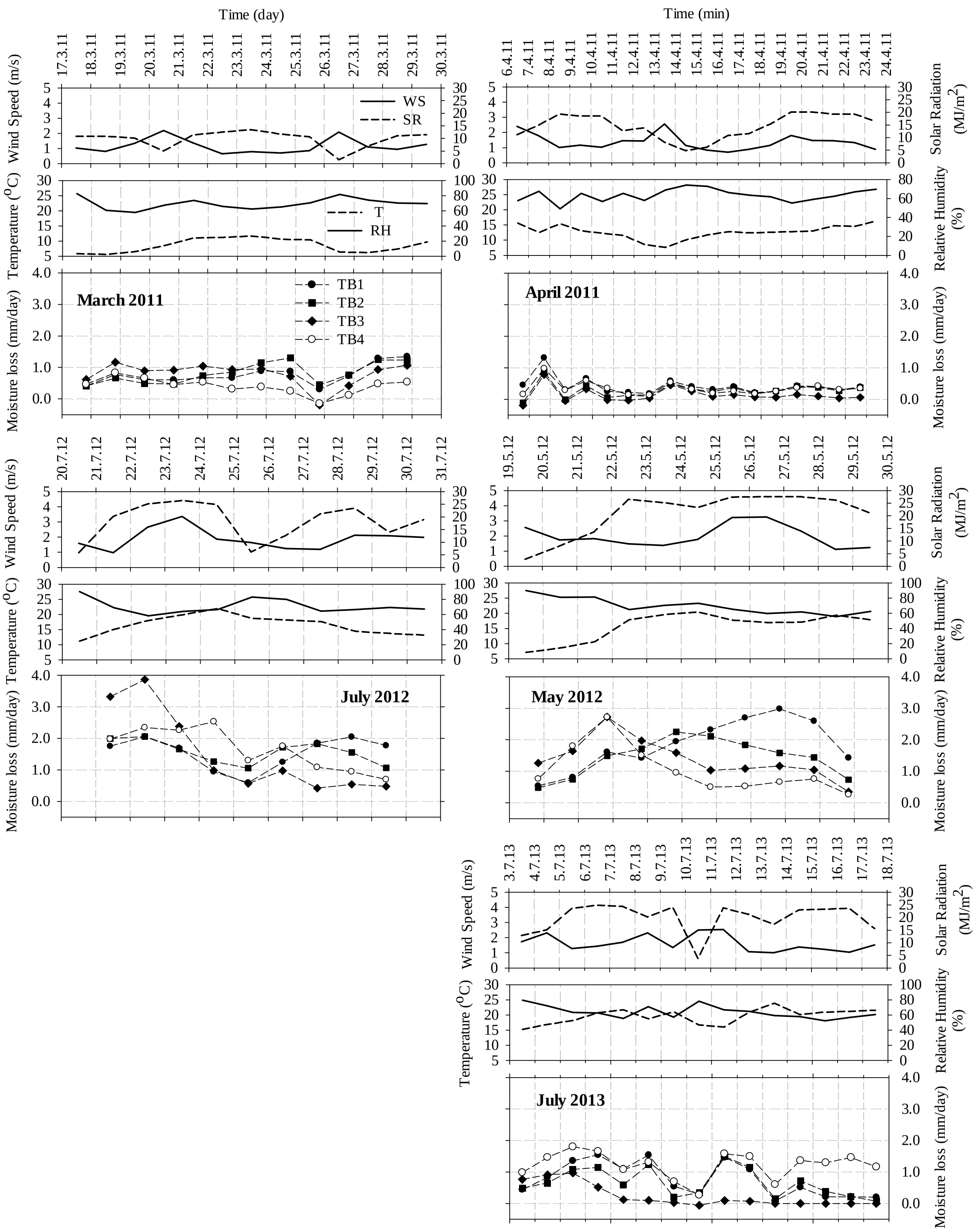

Figure 5. Moisture loss daily rate due to evapotranspiration and evaporation (TB4) in the selected DWPs for the tested green roof systems and observed climatic characteristics: daily temperature (T), wind speed (WS), relative humidity (RH) and solar radiation (SR).

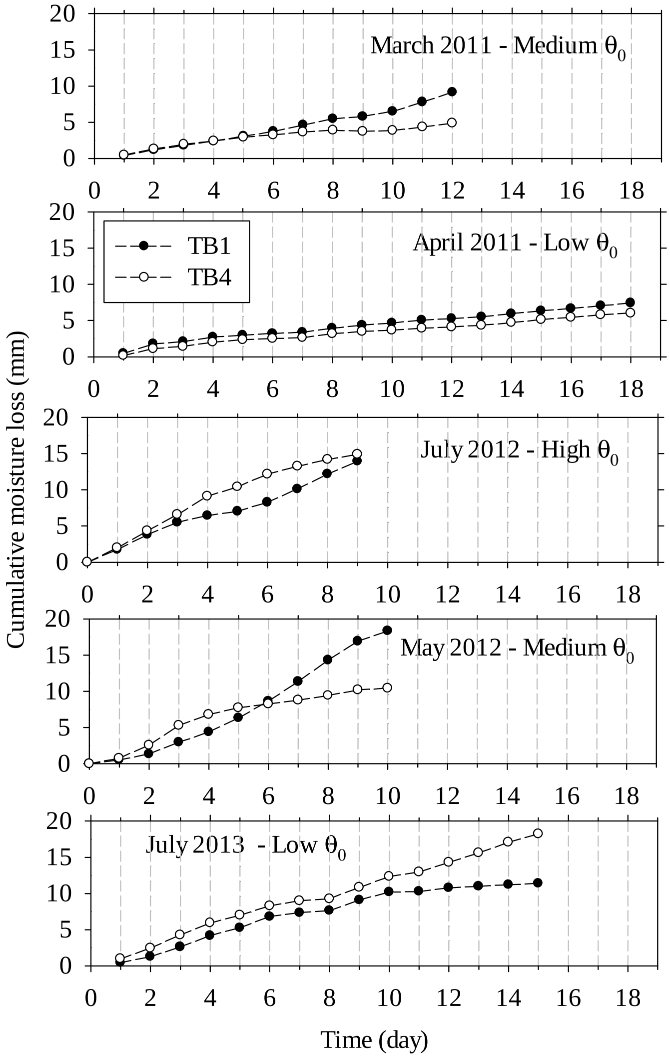

Figure 6. Cumulative moisture loss due to evapotranspiration (TB1 – HLS vegetated) and evaporation (TB4 – HLS non-vegetated) for the selected DWPs in Sheffield, UK.

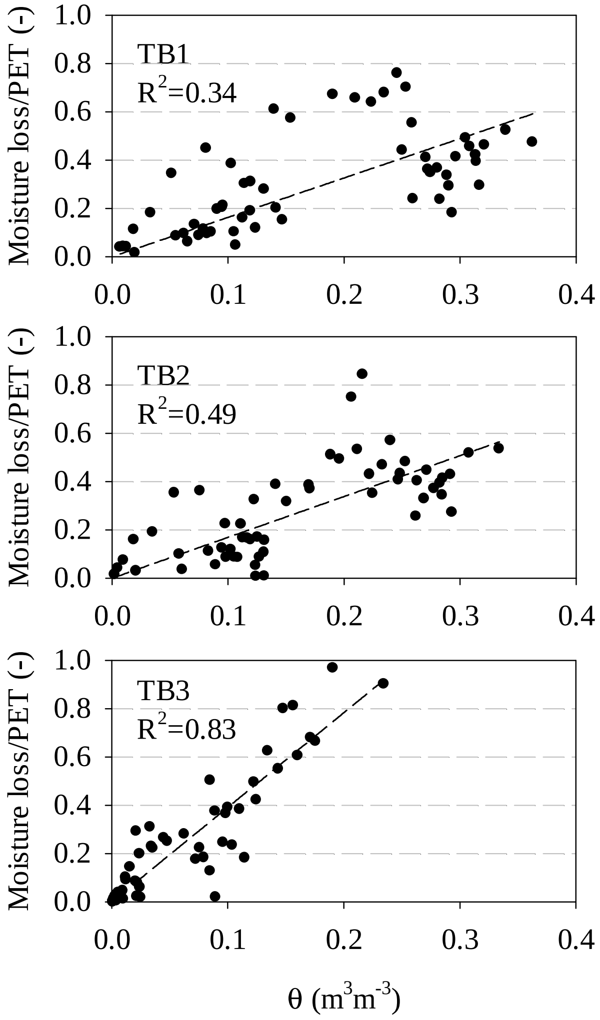

Figure 7. Correlation between moisture content (θ) and the daily moisture loss rate divided by the daily PET calculated through 1985 Hargreaves method for the three vegetated systems. The plots include all daily values from the five DWPs.

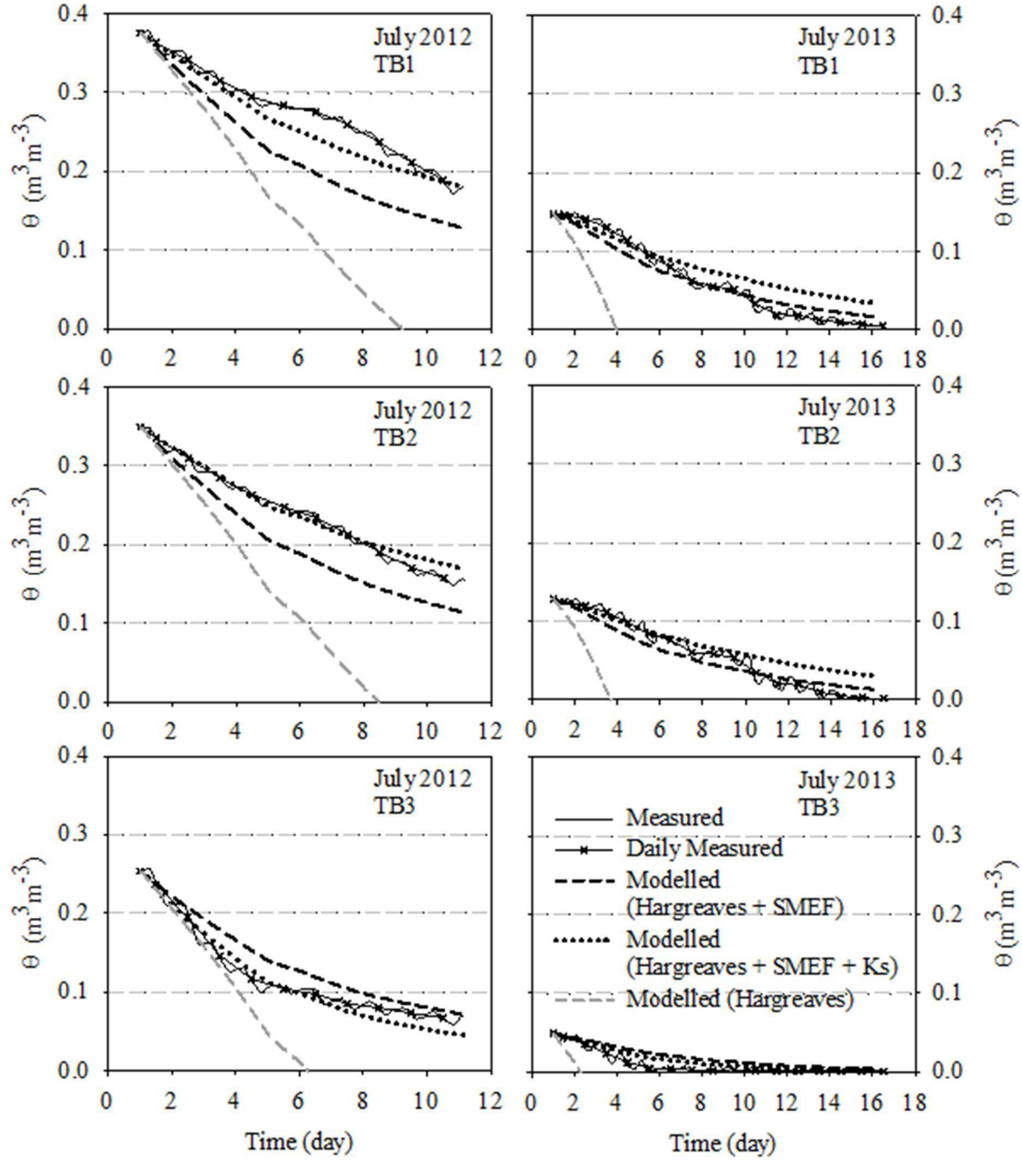

Figure 8. Measured and modelled moisture losses for the three vegetated configurations (TB1 –TB2 – TB3) and for the DWPs of July 2012 and 2013 which were characterized by high and low θ_0 respectively. Measured data are reported hourly and daily.