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

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11 **ABSTRACT**

12 Evapotranspiration (ET) is a key parameter that influences the stormwater retention capacity,
13 and thus the hydrological performance, of green roofs. This paper investigates how the
14 moisture content in extensive green roofs varies during dry periods due to evapotranspiration.
15 The study is supported by 29 months continuous field monitoring of the moisture content
16 within four green roof test beds. The beds incorporated three different substrates, with three
17 being vegetated with sedum and one left unvegetated. Water content reflectometers were
18 located at three different soil depths to measure the soil moisture profile and to record
19 temporal changes in moisture content at a five-minute resolution. The moisture content
20 vertical profiles varied consistently, with slightly elevated moisture content levels being
21 recorded at the deepest substrate layer in the vegetated systems. Daily moisture loss rates
22 were influenced by both temperature and moisture content, with reduced moisture
23 loss/evapotranspiration when the soil moisture was restricted. The presence of vegetation

24 resulted in higher daily moisture loss. Finally, it is demonstrated that the observed moisture
25 content data can be accurately simulated using a hydrologic model based on water balance
26 and two conventional Potential ET models (Hargreaves and FAO56 Penman-Monteith)
27 combined with a soil moisture extraction function. Configuration-specific correction factors
28 have been proposed to account for differences between green roof systems and standard
29 reference crops.

30 **KEYWORDS**

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

33 **1 INTRODUCTION**

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

47 potential to be part of a treatment train, working in conjunction with multiple SuDS devices
48 to provide more beneficial stormwater management than any single element on its own.

49 Green roofs consist of a vegetative layer, supported by a growing medium (substrate)
50 installed above a filtration geosynthetic layer and a drainage layer. This study focuses on
51 extensive green roofs, which are characterized by thinner substrate depths (generally <
52 150 mm). Extensive green roofs have greater potential of wide-scale adoption than intensive
53 green roofs, where significant structural loading considerations restrict application. The
54 limitation of extensive type systems is that a shallower substrate has a lower, and finite,
55 stormwater retention capacity (e.g. 20 mm as observed by Stovin et al. (2012) in an 80 mm
56 substrate roof) and is more likely to experience restricted moisture conditions and plant stress
57 during prolonged dry periods. Several studies have aimed at evaluating the hydrological
58 performance of green roofs through field monitoring programmes (see Palla et al. (2010), and
59 Stovin et al. (2012) for an overview). It is evident that the roof's ability to retain stormwater
60 is highly sensitive to the initial moisture condition of the green roof system prior to a rainfall
61 event. This is controlled by the evapotranspiration (ET) process during dry periods. A better
62 understanding of the moisture content behaviour during dry periods due to ET will have
63 important implications for stormwater management and should lead to the development of
64 more accurate modelling approaches for long-term simulations. Such predictions are
65 necessary to support decision-making in stormwater management; both in terms of projecting
66 green roof performance in response to changing climatic scenarios (Stovin et al., 2013) and
67 for estimating plant stress conditions (and the consequent need for irrigation treatments).

68 Several recent research projects have focused on the measurement of ET from green roof
69 systems, and on the development of appropriate ET modelling tools. In some of the earliest
70 studies undertaken by Köhler at Neubrandenburg, Germany (Köhler, 2004) weighing
71 lysimeters were incorporated within green roof systems to quantify the water balance. More

72 recently, Berghage et al. (2007), Voyde et al. (2010) and Poë and Stovin (2012) have used
73 load cells to monitor moisture losses from green roof microcosms under controlled climatic
74 conditions. Green roof systems are typically not irrigated, and actual ET rates fall with time
75 following a rainfall event, as the available moisture becomes increasingly restricted.
76 Berghage et al. (2007) and Voyde et al. (2010) identified differences in actual ET between
77 plant species, and both proposed temporal decay relationships to model the observed
78 reductions in ET over time. However, Stovin et al. (2013) have argued that it is the substrate
79 moisture content, rather than time, that directly determines the difference between actual and
80 potential ET rates. Several authors (e.g. Rezaei, 2005; Kasmin et al., 2010) have
81 demonstrated that standard agricultural methods of predicting potential ET are transferable to
82 the prediction of observed ET rates from green roof systems, although crop/system
83 coefficients may be required to account for the non-standard vegetation and substrates.
84 Recently, some authors have used closed atmospheric chambers to quantify ET on full-scale
85 green roof installations (e.g. Coutts et al., 2013). Whilst lysimeter and surface-mounted
86 climate chamber-based experiments provide a direct measurer of total moisture loss due to
87 ET, this includes changes in the moisture content within the vegetation, and does not provide
88 a direct indication of the actual substrate moisture content, or its vertical distribution. Palla et
89 al. (2009) have demonstrated the value of direct substrate moisture content measurements for
90 the development and validation of accurate moisture flux models.

91 The moisture content behaviour during dry periods is influenced by plant species, substrate
92 characteristics and climatic conditions. Studies in the laboratory, under controlled conditions,
93 facilitate the simulation of extreme hydrological conditions that can enhance understanding
94 of key controlling parameters (Yio et al, 2013) and also underpin the development of novel
95 substrate compositions that can be optimized for water retention - for example by using
96 additives (Emilsson et al., 2012; Farrel et al., 2013). However, climatic variables cannot

97 easily been taken into consideration through laboratory studies. For this reason, the present
98 study focuses on a long-term field monitoring programme which commenced at the
99 University of Sheffield, UK in March 2011.

100 ***1.1 Objectives***

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

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

113 **2 METHODOLOGY**

114 ***2.1 The experimental setup***

115 **2.1.1 The test beds**

116 The research was conducted at the University of Sheffield's Green Roof Centre. The test site
117 is located on a fifth-floor terrace of the Sir Robert Hadfield building (53.3816, -1.4773) and
118 consists of 9 green roof test beds (TB) which vary systematically in their substrate
119 composition and vegetation options. This experiment was established in summer 2009 and

120 data have been collected since April 2010 to assess the extent to which substrate type and
121 vegetation treatment affect long-term runoff retention and detention performance (Poë et al,
122 2011). In March 2011, four of these test beds were equipped with water content
123 reflectometers for continuous moisture content measurement. This study is based on the data
124 collected from these four test beds. Each test bed is 3 m long x 1 m wide, installed to a 1.5°
125 slope. The TBs are located at a height of 1 m above the terrace roof surface (Fig. 1). The TBs
126 consist of an impervious hard plastic tray base, a drainage layer (ZinCo Floradrain FD 25-E),
127 a filter sheet (ZinCo Systemfilter SF), and one of three substrates (80 mm deep). Three test
128 beds are vegetated with Alumasc Blackdown Sedum Mat (TB1, TB2 and TB3) and the fourth
129 test bed has no vegetation (TB4¹). Sedum was chosen because it is the most commonly
130 adopted plant in green roof applications due to its tolerance to extreme temperatures, high
131 wind speeds and limited water consumption requirements (VanWoert et al., 2005). With the
132 intention of providing universally-applicable findings, two commercially-available substrates
133 manufactured by Alumasc – Heather with Lavender Substrate (HLS) (TB1 and TB4) and
134 Sedum Carpet Substrate (SCS) (TB2) – were considered alongside a bespoke substrate based
135 on the widely used Lightweight Expanded Clay Aggregate (LECA) (TB3).

136 The experimental setup includes a Campbell Scientific weather station that records hourly
137 wind speed, temperature, solar radiation, relative humidity and barometric pressure. Rainfall
138 depth was measured at one minute intervals using three 0.2 mm resolution ARG-100 tipping
139 bucket rain gauges manufactured by Environmental Measures Ltd. Runoff was measured
140 volumetrically through collection tanks equipped with a Druck Inc. PDCR 1830 pressure
141 transducers. The collection tank located under each test bed was designed for increased
142 measurement sensitivity at the beginning of each rainfall event and to avoid direct discharge
143 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.

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

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

149 **2.1.2 Moisture content measurements**

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

162 Considering the specificity of the substrates used, the 12 sensors were calibrated in the
163 laboratory using the three substrates monitored in the field (Kelleners et al., 2005; Seyfried
164 and Murdock, 2001; Western and Seyfried, 2005). Moisture content during calibration ranged
165 between 0.05 and 0.40 m³m⁻³. The actual moisture content (θ) at each calibration condition
166 was measured by drying the soil to constant weight (until change in weight was less than
167 0.5%) at 110°C from 24 to 40 hours and multiplying by the measured bulk density. The

168 temperature in the laboratory was 20°C, and the sensors were also tested at 30, 35 and 40°C.
169 It was confirmed that the effect of temperature change for higher temperatures could be
170 compensated for by applying the correction equation provided by Campbell Scientific and
171 proposed by Western and Seyfried (2005).

172 [Approximate location of Figure 1]

173 **2.1.3 Substrate characteristics**

174 HLS is a semi-intensive commercial substrate which consists of crushed bricks and pumice
175 (ZincolitPlus), enriched with organic matter including compost with fibre and clay materials
176 (Zincohum) (ZinCo GmbH). The SCS Substrate is a typical extensive green roof substrate
177 consisting of crushed bricks (Zincolit), enriched with Zincohum. The organic content in HLS
178 is greater than in SCS. The LECA-based substrate contains 80% LECA, 10% loam (John
179 Innes No. 1) and 10% compost by volume. Laboratory tests of these substrates were carried
180 out according to the *Guidelines for the Planning, Construction and Maintenance of Green*
181 *Roofing* of the German Landscape Development and Landscaping Research Society (FLL,
182 2008). The tests performed included Particle Size Distribution (PSD), apparent density (dry
183 condition and at max water capacity), total pore volume, maximum water holding capacity
184 (MWHC), permeability and organic content (Table 1). To address the uncertainty associated
185 with subsampling heterogeneous mixtures, a sample splitter was used and 3-6 replicate
186 samples were tested, depending on the analysis.

187 Soil-moisture release curves for the three substrates were determined using the pressure plate
188 extraction method (Carter, 1993; Soil Moisture Equipment Corp., 2008). The moisture
189 release curve expresses the relationship between the moisture content, θ , and the soil moisture
190 potential, ψ . The principle of this test is to gradually extract water from initially-saturated
191 samples by applying increasing pressures. The resulting curve provides important

192 information regarding the plant available water, i.e. moisture content values between MWHC
193 (field capacity) and the permanent wilting point. Field capacity defines the condition when
194 the substrate can hold no more moisture under gravity, and corresponds to 0.33 bar suction,
195 whilst the permanent wilting point defines the lower limit to plant available moisture, and
196 corresponds to 15 bar suction (Fassman and Simcock, 2012; Hillel, 1971). A 1600 Pressure
197 Plate Extractor 5 bar and a 1500F1 Pressure Plate Extractor 15 bar manufactured by Soil
198 Moisture Equipment Corporation were used for this purpose. Due to the specific
199 characteristics of the green roof substrates the standard test procedure proposed by the
200 manufacturer was slightly modified. A wet strengthened filter paper (Whatman No. 113) was
201 attached to the bottom of the sample rings to avoid collection of sample residues on the
202 ceramic plate at the end of the test. A mixture of kaolin and water was spread on the ceramic
203 plate to ensure contact between the sample and the ceramic plate.

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

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

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

234 [Approximate location of Table 1]

235 [Approximate location of Figure 2]

236 **2.2 Data analysis**

237 Data from the individual moisture content probes was examined in detail for the month of
238 May 2012. This period was selected due to the presence of several rainfall events (total
239 rainfall = 51.6 mm), and dry periods (including one selected for further analysis) and because
240 the climatic conditions recorded (high temperature and solar radiation) should enhance any

241 impact associated with the presence of vegetation. This data was used to investigate vertical
242 moisture content profiles and to confirm that the measured moisture content fluctuations were
243 consistent with the expected hydrological processes occurring in response to rainfall and dry
244 periods.

245 Individual storm events were defined as being separated by continuous dry periods of at least
246 6 hours. Five specific Dry Weather Periods (DWP) were selected from the data record for
247 detailed analysis. These were selected to give a representative range of different climatic
248 conditions and initial substrate moisture contents. Depth-averaged moisture content values
249 enabled comparisons between the four TBs to be made.

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

254 *2.3 Modelling moisture losses during dry periods in green roof systems*

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

$$258 \quad \frac{\Delta\theta}{\Delta t} = P - R - ET \quad (1)$$

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

264
$$ET_t = PET_t \cdot \frac{\theta_t}{\theta_{FC}} \quad (2)$$

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

283 The model initial moisture conditions (θ_0) were set equal to the observed data at the
284 beginning of each dry period for the three vegetated systems. The model has been
285 implemented at an hourly time step. PET was calculated using daily recorded minimum and
286 maximum temperature and relative humidity, mean daily temperature, solar radiation and
287 wind speed. Hourly PET was assumed equal to daily PET/24. It is recognised that this

288 simplification ignores the diurnal cycle, but total losses over longer periods are correctly
289 represented.

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

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

311
$$ET_t = PET_t \cdot \frac{\theta_t}{\theta_{FC}} \cdot K_s \quad (3)$$

312 3 RESULTS

313 3.1 *Characterization of the monitored dry weather periods*

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

322 Because the aim of this study was to investigate the moisture content behaviour during dry
323 periods, five DWPs were selected in which no rainfall or runoff was observed for a
324 continuous period of at least ten days. The DWPs were classified as corresponding to either
325 'cooler' or 'warmer' periods. If compared to the climatic data series 1971-2000 for Sheffield,
326 UK (source Met Office), conditions in the two cooler periods (March and April 2011)
327 correspond to typical conditions in spring with mean temperatures of 8.5 and 12.6°C.
328 Conditions during the three warmer periods (July 2013, May 2012 and July 2012) were
329 comparable to typical summer conditions in Sheffield (mean temperatures between 17.1 and
330 19.8°C).

331 The initial moisture content, θ_0 , is expected to influence moisture loss rates. For each of the
332 DWPs considered, the absolute values of θ_0 , and the ratios of θ_0 :MWHC vary between beds.
333 In TB1 and TB2, for example, a 'high' θ_0 implies θ_0 :MWHC > 0.85, medium θ_0 implies
334 θ_0 :MWHC > 0.70 and low θ_0 implies θ_0 :MWHC < 0.6. In the LECA-based substrate the
335 corresponding θ_0 and θ_0 :MWHC are lower. The two cooler periods were characterized by

336 medium and low θ_0 respectively, whilst the three warmer periods corresponded to high,
337 medium and low θ_0 . The characteristics of the selected DWPs are reported in Table 2.

338 [Approximate location of Table 2]

339 **3.2 *Moisture content fluctuations during May 2012***

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

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

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

350 Considering the vertical profile, moisture content generally increases with depth, although in
351 all four cases the differences between the top and mid-depth values are small. In the three
352 vegetated beds (TB1, TB2 and TB3), the moisture content near the bed is elevated by 10-20%
353 compared with the upper part of the profile. During rainfall events, this may be expected, due
354 to the high permeability of green roof substrates. Other studies showed that moisture
355 measurement revealed higher moisture content in the deeper layers (Palla et al., 2009).
356 Furthermore, the presence of a vertical gradient may reflect both preferential drying at the
357 surface and the effects of substrate compaction and ageing which can lead to leaching of fines
358 into the lower layers of the substrate (Morbidelli et al., 2011; 2013). However, the

359 unvegetated bed, TB4, exhibits no significant vertical gradient, suggesting that the presence
360 of vegetation and root systems contributes to the development of the vertical profile. The
361 maximum moisture content in TB1 is also consistently higher than TB4, which suggests that
362 the moisture retention effects of plant roots may have an influence on the effective field
363 capacity of a green roof system.

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

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

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

380 [Approximate location of Figure 3]

381 **3.3 *Moisture content during five selected DWPs***

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

385 As already observed in Fig. 3, it can be clearly seen that the diurnal moisture content
386 variation mirrors the hourly temperature. Between the two cooler periods of March and April
387 2011, 7 minor rainfall events with a total depth of 11.4 mm occurred. These events did not
388 alter the moisture content within the vegetated roofs, but did increase the moisture content in
389 the non-vegetated bed. This can be explained by interception by the well-established plants.

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

392 Irrespective of climatic conditions, changes in moisture content show a consistent influence
393 of substrate moisture content. This is evident when comparing the cooler periods of March
394 and April 2011 with the warmer period of May 2012. Similar behaviour is observed between
395 the vegetated HLS and SCS test beds, as expected considering the similar substrate
396 characteristics. It can be noted that at the volumetric moisture content of approximately 0.15
397 m^3m^{-3} the two curves cross over, indicating lower matric potential in the HLS. This can be
398 explained by its slightly higher porosity. When moisture conditions are restricted (see July
399 2013 in Fig. 4) the same moisture release behaviour was observed for HLS and SCS. This
400 behaviour was observed in the soil-moisture characteristic curves obtained in the pressure
401 plate extraction test (Fig. 2).

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

405 [Approximate location of Figure 4]

406 **3.4 Daily moisture loss rate**

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

409 The DWPs of March 2011 and May 2012 were characterized by similar, medium, θ_0 and
410 similar DWP duration. It may be seen that the warmer period had approximately double the
411 moisture loss rate compared with the cooler period. Specifically, mean values of 0.76, 0.81
412 and 0.79 mm/day were observed in March 2011 and 1.83, 1.44, and 1.39 mm/day in May
413 2012 respectively for HLS, SCS and LECA. Comparing the DWP of April 2011 and July
414 2013, both characterized by low θ_0 and similar duration, it may be concluded that, even in
415 this case, climatic conditions influenced the moisture loss, with mean values of 0.41, 0.28 and
416 0.13 mm/day in cooler periods and 0.76, 0.66, and 0.23 mm/day in 'warmer' periods
417 respectively for HLS, SCS and LECA.

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

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

428 consistently confirm the previous conclusions on the influence of climatic conditions and
429 initial moisture content.

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

431 It may be seen that the moisture loss rate mirrors the highly varying climatic conditions
432 within these periods. During the March 2011 period, for example, a decrease in temperature
433 and solar radiation and an increase in relative humidity between the 25th and 27th March are
434 reflected in a decrease in moisture across all TBs. This is more apparent in warmer periods
435 where high variability was observed also in the very restricted moisture conditions of July
436 2013.

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

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

450 [Approximate location of Figure 5]

451 **3.5 *Plant transpiration***

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

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

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

468 [Approximate location of Figure 6]

469 **4 COMPARISON WITH MODELLED DATA**

470 The field data presented above has established that, although substrate moisture loss is
471 strongly correlated with temperature, moisture loss rates fall when the moisture available for
472 ET is restricted. In unrestricted moisture conditions, it is reasonable to expect that a standard
473 prediction of Potential ET should provide a useful estimate of the observed moisture loss,

474 although it is important to appreciate that an ET estimate includes plant moisture losses in
475 addition to substrate moisture losses. It should also be noted that the green roof system
476 components differ in many respects from standard reference crops.

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

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

489 [Approximate location of Figure 7]

490 **4.1 Model implementation**

491 Three variants of the moisture loss model (Equations 1 to 3) were applied. Initially Equation
492 1 alone was applied, using both the 1985 Hargreaves and FAO 56 Penman-Monteith methods
493 to predict the relevant daily ET values. Subsequent iterations of the model introduced the
494 SMEF (Equation 2) and finally Equation 2 was substituted with Equation 3 to include Ks, the
495 system-specific correction factor. Appropriate coefficient values were identified using least-
496 squares optimisation. Ks values were determined for each of the vegetated test beds, for the
497 complete set of DWP data combined (Table 3). The optimisation was based on a comparison

498 between the measured and modelled moisture content data at each hourly time-step. By using
499 1985 Hargreaves method for PET the obtained Ks values were 0.68, 0.64 and 1.36,
500 respectively for HLS, SCS and LECA. Slightly different values were obtained by using FAO
501 56 Penman-Monteith method: 0.69, 0.65 and 1.36, respectively for HLS, SCS and LECA.

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

506 By failing to take into account the effects of moisture restriction on actual ET rates, the
507 simplest model (labelled Hargreaves in Fig. 8), significantly overestimates moisture loss in
508 the green roof substrates. No further analysis of this model is presented. However, it may be
509 seen that the predictions based on Hargreaves + SMEF are considerably better. Model
510 performance statistics for the PET + SMEF model evaluation are reported in Table 4 for all
511 five DWPs and for each vegetated test bed. It may be seen from this that the model predicts
512 the response in the LECA substrate satisfactorily (good to very good NSE and RSR),
513 however PBIAS was only satisfactory. In general the model underestimated the moisture
514 losses in time (PBIAS<0). This is due to the specific characteristics of the LECA, highly
515 porous substrate based on expanded clay. The model did not provide a satisfactory prediction
516 for the July 2013 DWP. This can be explained by highly-restricted moisture conditions that
517 led to the substrate becoming completely dry within 6 days. As might be expected from Fig.
518 7, the models for both HLS and SCS overestimated the moisture losses (PBIAS>0), except
519 for when the moisture content was very low. Of the two PET models, both provided similar
520 accuracy. However, in view of the fact that 1985 Hargreaves requires less input data, this
521 approach is preferable.

522 [Approximate location of Figure 8]

523 [Approximate location of Table 3]

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

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

541 [Approximate location of Table 4]

542 [Approximate location of Table 5]

543 **5 DISCUSSION**

544 **5.1 *Observed substrate characteristics***

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

561 **5.2 *Average moisture loss rate***

562 The mean values of substrate moisture loss presented in Table 2 provide a useful practical
563 indication of moisture loss rates that might be expected over periods of similar duration to the
564 observed ones (approximately 10 days) as a function of climate and of the substrate's initial
565 moisture content. For example, for the two typical brick-based substrates, loss rates of around
566 1.6 mm/day are associated with high initial moisture content levels and warmer, summer,

567 conditions. The rate is approximately halved when the initial moisture content is low and in
568 cooler, typical spring, conditions. The lowest rate, around 0.35 mm/day on average, is
569 associated with both cooler conditions and low initial moisture content. It should be noted
570 that these values are only valid for periods of similar duration; if shorter DWPs were of
571 interest, then higher mean loss rates would be expected for the same initial moisture content
572 levels.

573 **6 CONCLUSIONS**

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

582 The results showed that the moisture content vertical profile varied consistently depending on
583 the substrate characteristics and the presence of vegetation. High temporal resolution data has
584 shown diurnal fluctuations that reflect the daily temperature variations with a daily decrease
585 in the moisture content due to ET during the central warmer hours of the day. Substrate
586 specific average daily moisture loss values were derived for cooler and warmer conditions
587 and for different initial moisture content. The results showed the clear influence of the
588 moisture content on the moisture loss rate due to evapotranspiration, with lower values
589 associated with restricted moisture conditions. The daily moisture loss rate within dry
590 periods mirrored the highly variable climatic conditions, and this masked the expected

591 exponential decay in the ET rate shown in other studies. The LECA-based green roof showed
592 similar behaviour in daily moisture loss to the non-vegetated roof, with a rapid initial
593 decrease of moisture content. This behaviour may restore the green roof's retention capacity
594 more rapidly than alternative substrates, but it also increases the occurrence of plant stress
595 conditions. The presence of vegetation resulted in higher daily moisture loss after a few dry
596 days when the initial moisture conditions were medium. The presence of vegetation, if well
597 established and with good surface coverage, not only affected the rate of moisture decrease
598 through transpiration, but also prevented wetting during minor rainfall events. This has
599 important implications for the retention capacity and performance of a green roof.

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

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807 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

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

		TB1	TB2	TB3	TB4				
		Moisture Loss				T	Wind	RH	Solar
		(mm/day)				(°C)	Speed	(%)	Radiation
						(m/s)		(MJm ⁻²)	
17-29	θ_0 (m ³ m ⁻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 ³ m ⁻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 ³ m ⁻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 ³ m ⁻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 ³ m ⁻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

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

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

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849 Table 4. Quantitative statistics used for the evaluation of the hydrological model using 1985
850 Hargreaves (H) and FAO 56 Penman-Monteith (FAO56-PM). Results are reported for the
851 three vegetated test beds characterized by different substrates and for the five selected DWPs.
852 The simulations that showed *good* to *very good* performance are highlighted in bold, while
853 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	<u>0.68</u>	9.83	29.86	-21.67	0.56	2.03	<u>0.56</u>
2011	FAO56-PM	0.71	-3.14	<u>0.67</u>	10.46	30.40	-20.46	0.56	2.03	<u>0.57</u>
July	H	-0.12	0.51	<u>0.82</u>	19.21	15.38	-16.14	1.06	0.70	<u>0.42</u>
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	<u>0.88</u>	14.97	18.97	-20.24	0.48	0.63	<u>0.35</u>
2012	FAO56-PM	0.86	<u>0.74</u>	<u>0.82</u>	11.08	15.12	-26.62	0.48	<u>0.52</u>	<u>0.42</u>
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

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

		NSE			PBIAS			RSR		
		TB1	TB2	TB3	TB1	TB2	TB3	TB1	TB2	TB3
March	H	0.91	0.94	0.96	2.73	0.03	-1.53	0.30	0.25	0.19
2011	FAO56-PM	0.89	0.92	0.96	3.06	0.35	-1.13	0.30	0.29	0.19
April	H	0.85	-0.10	0.78	-6.97	14.37	0.18	0.39	1.05	0.46
2011	FAO56-PM	0.88	-0.15	0.77	-5.97	15.13	2.20	0.39	1.07	0.48
July	H	0.87	0.97	0.94	5.51	-1.62	3.59	0.37	0.17	0.24
2012	FAO56-PM	0.78	0.97	0.93	7.75	0.73	6.99	0.37	0.17	0.26
May	H	0.90	0.96	0.97	0.68	2.88	-1.43	0.31	0.21	0.16
2012	FAO56-PM	0.92	0.98	0.97	-1.95	0.33	-8.29	0.31	0.16	0.18
July	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>
2013	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

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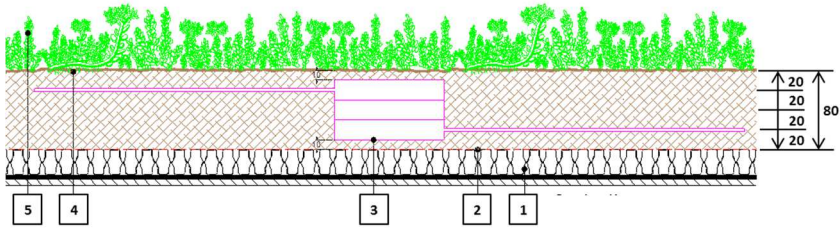
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1. Drainage layer
2. Filter sheet
3. WCR
4. Substrate
5. Vegetation



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

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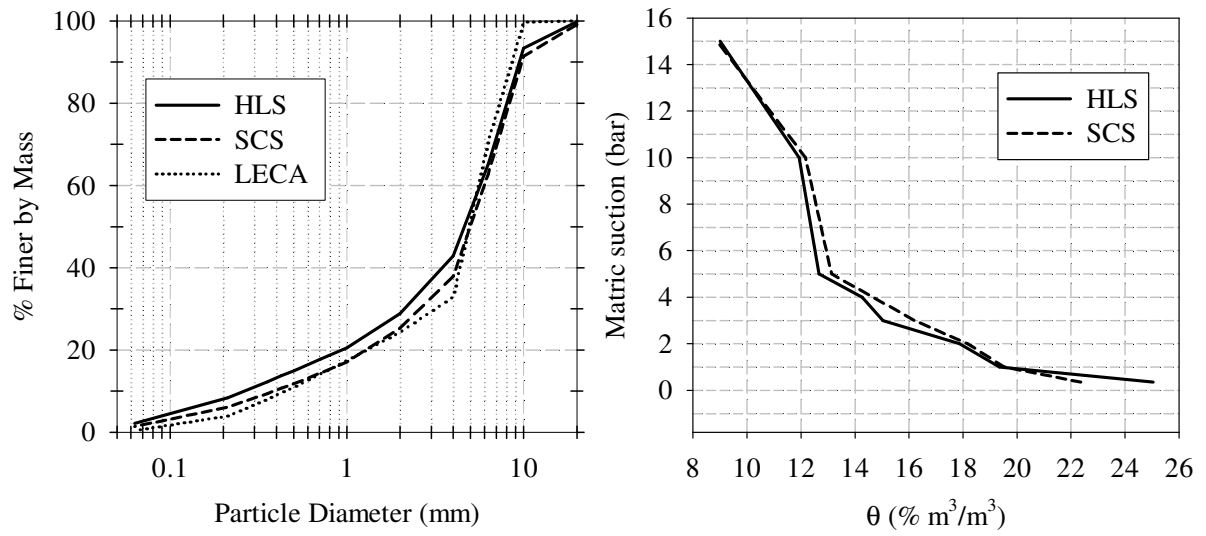
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894 Figure 2. Particle size distribution (PSD) of the three tested substrates and moisture release
 895 curves resulting from the pressure plate extraction test.

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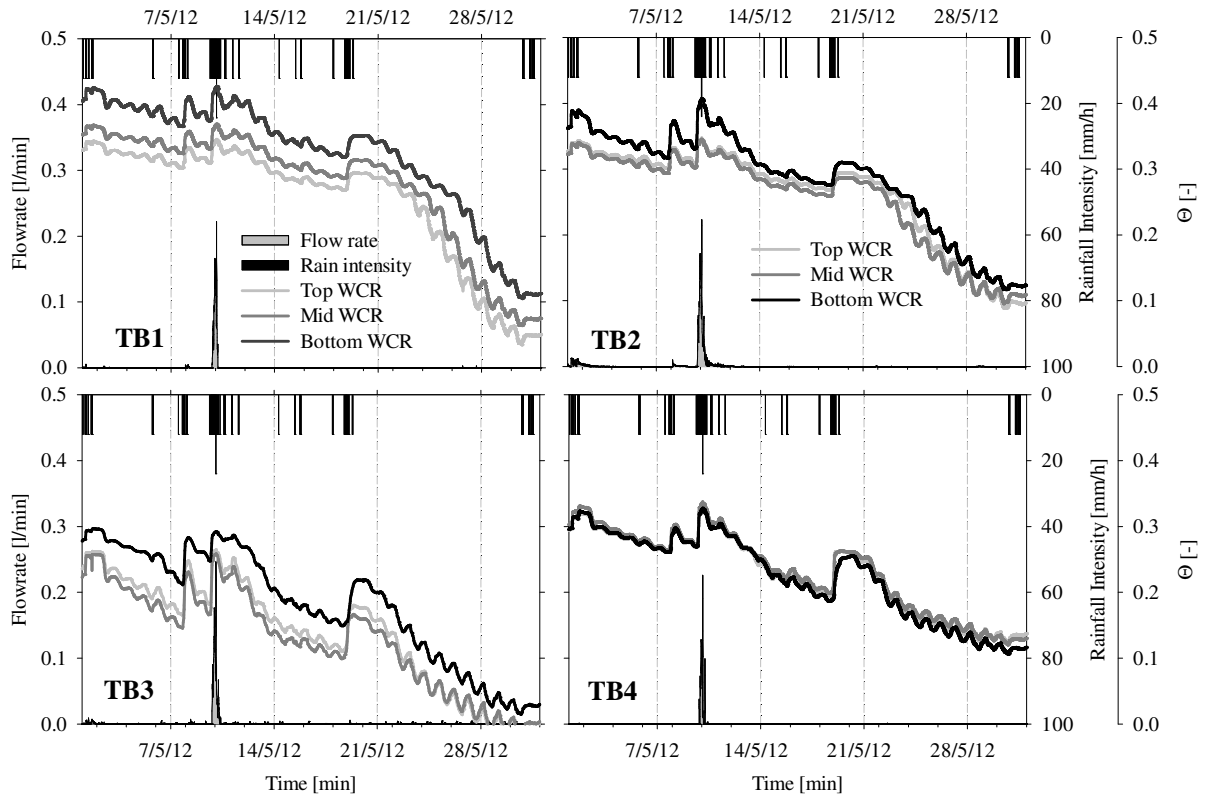
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908 Figure 3. Hydrograph, hyetograph and measured moisture content (θ) at 20 (top), 40 (mid),
 909 and 60 mm (bottom) from the surface of the tested green roof systems for the month of May
 910 2012.

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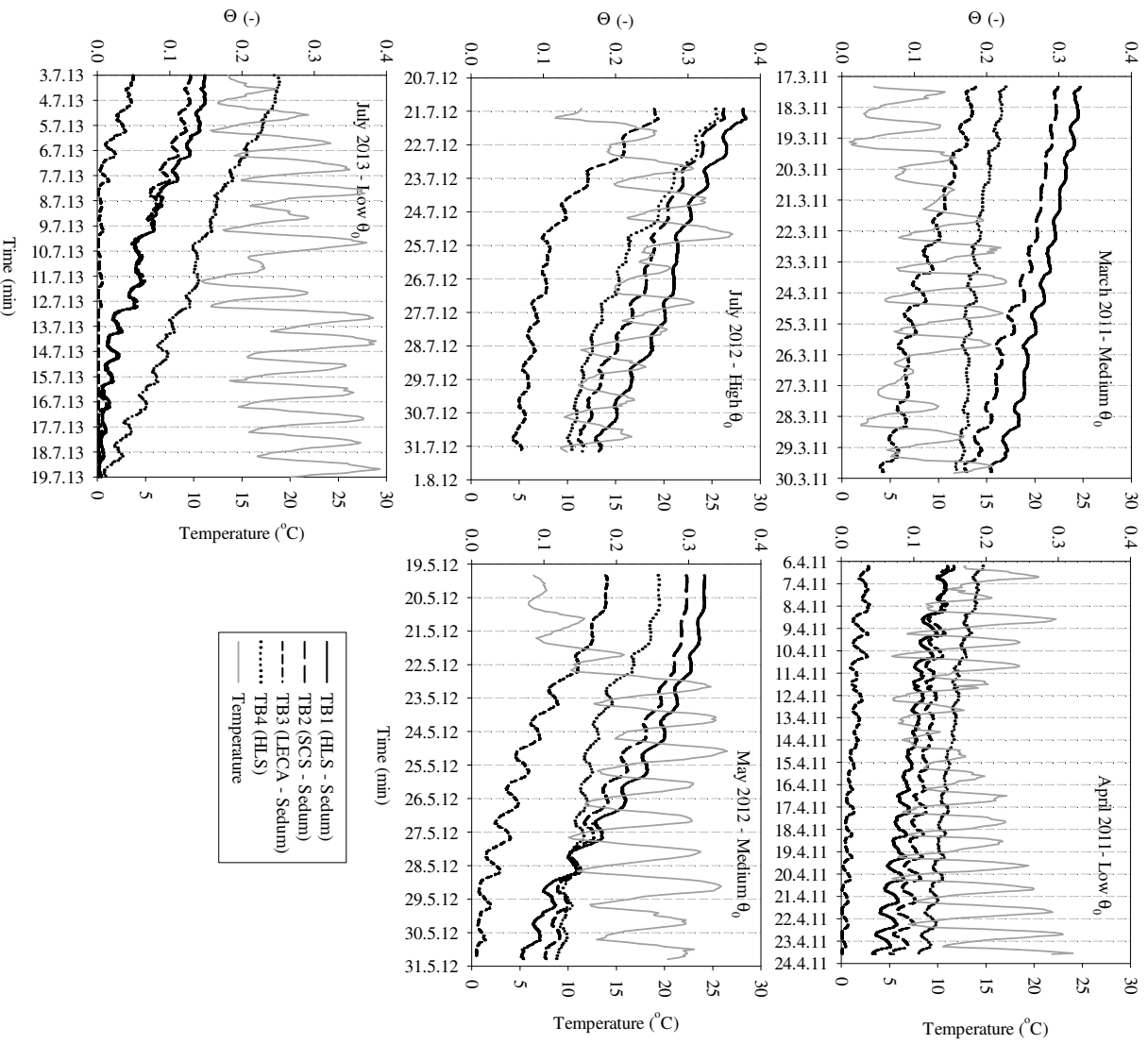
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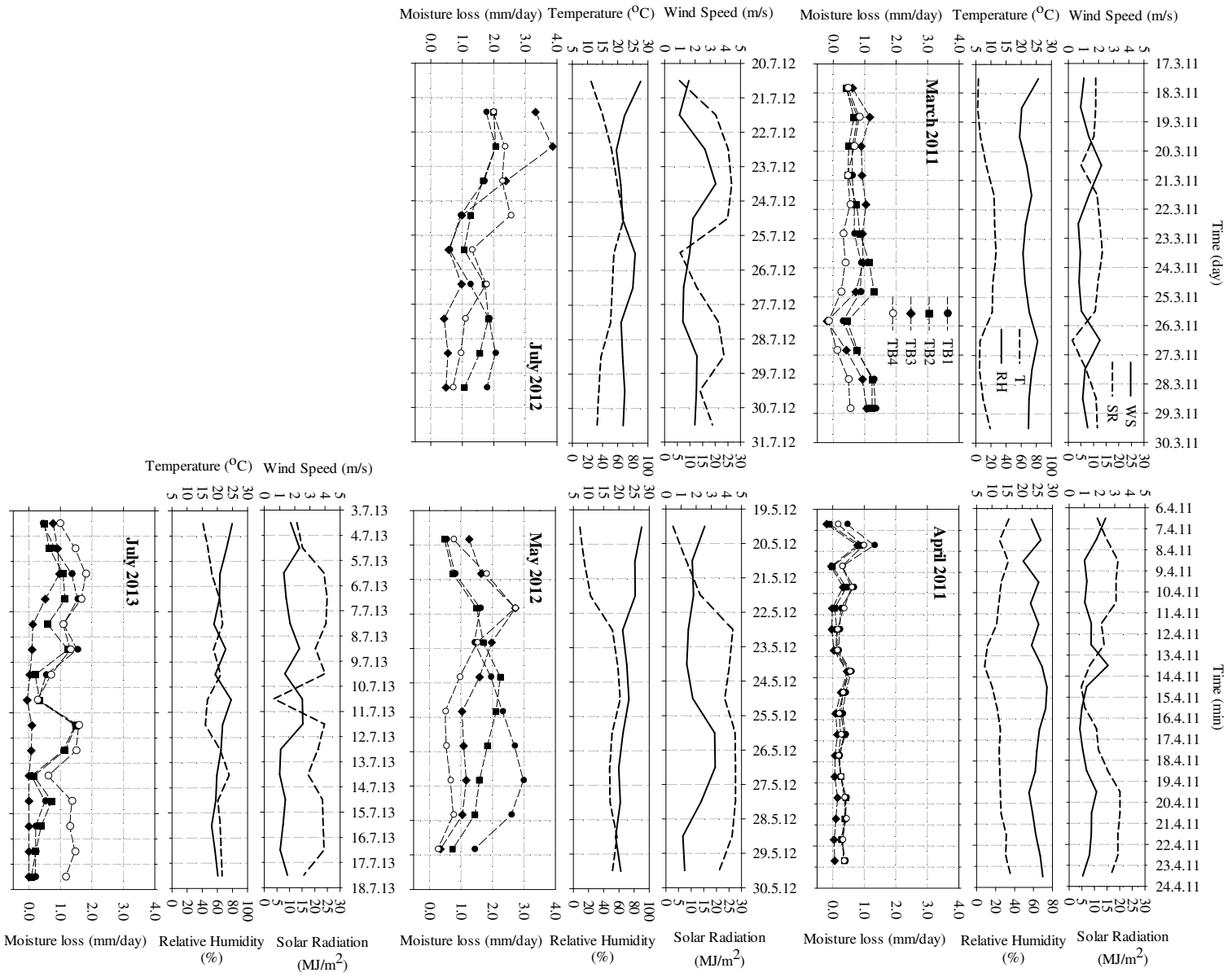
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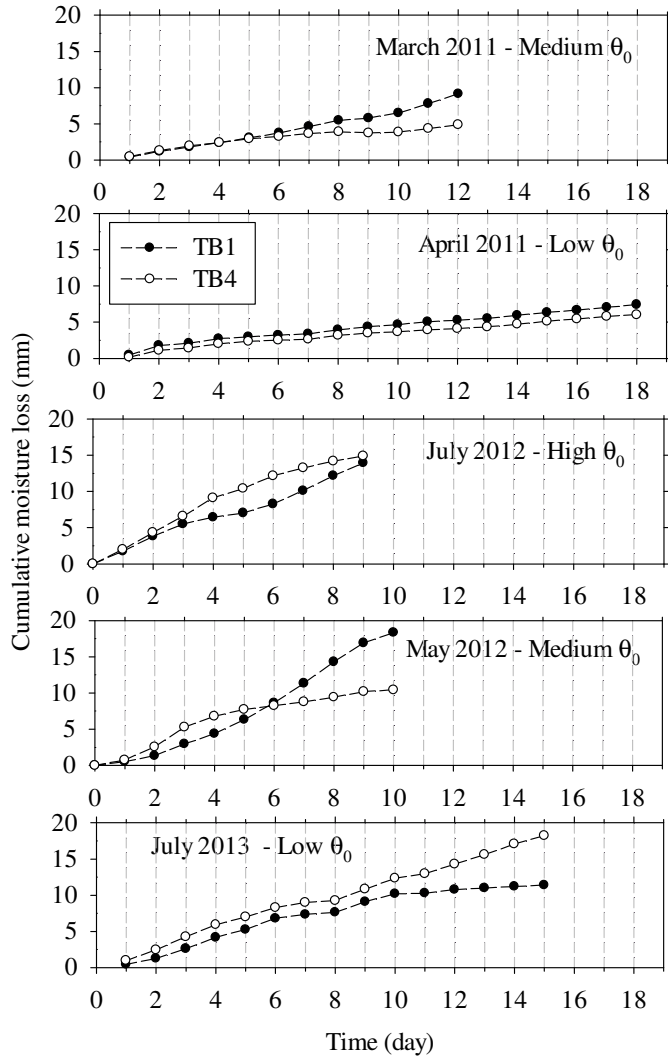
918
 919 Figure 4. Moisture content and temperature behaviour for the four tested green roof
 920 configurations and the selected DWPs.
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926 Figure 5. Moisture loss daily rate due to evapotranspiration and evaporation (TTB4) in the

927 selected DWPs for the tested green roof systems and observed climatic characteristics: daily

928 temperature (T), wind speed (WS), relative humidity (RH) and solar radiation (SR).



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

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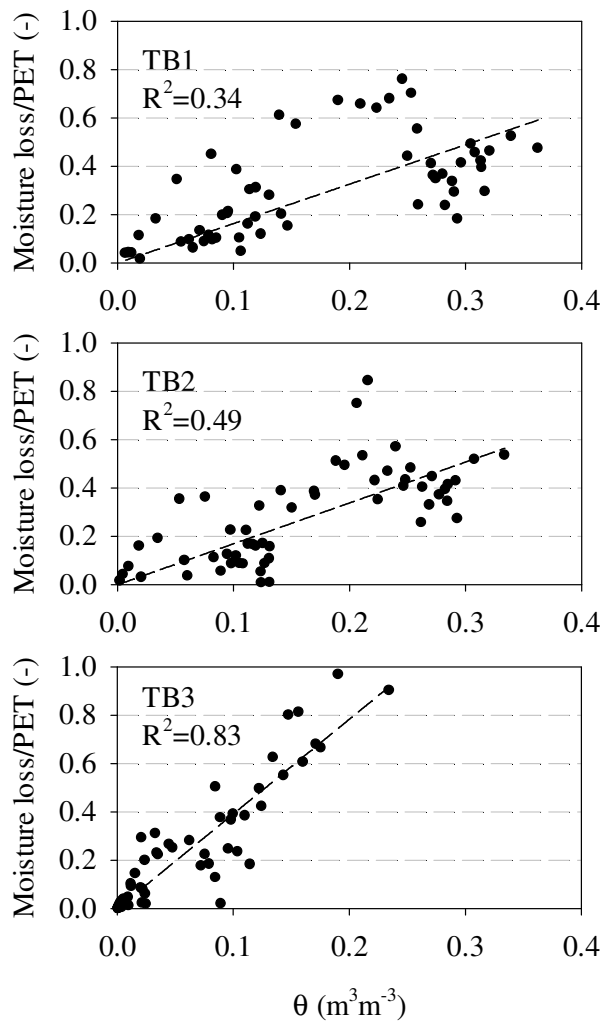
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939 Figure 7. Correlation between moisture content (θ) and the daily moisture loss rate divided by
 940 the daily PET calculated through 1985 Hargreaves method for the three vegetated systems.

941 The plots include all daily values from the five DWPs.

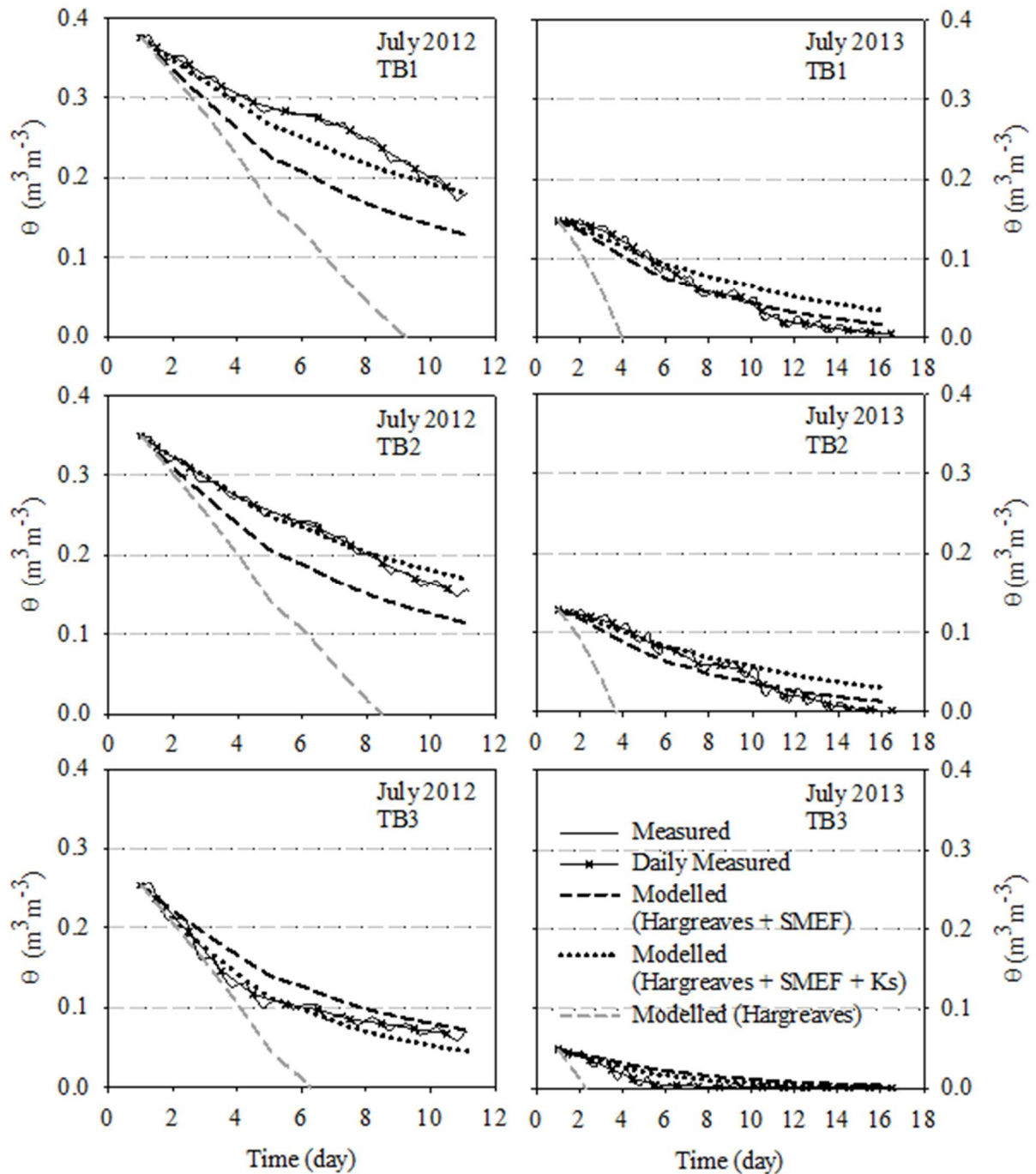
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948 Figure 8. Measured and modelled moisture losses for the three vegetated configurations (TB1
 949 –TB2 – TB3) and for the DWPs of July 2012 and 2013 which were characterized by high and
 950 low θ_0 respectively. Measured data are reported hourly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

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