Published paper

Stovin, V, Poe, S and Berretta, C (2013) *A modelling study of long term green roof retention performance*. Journal of Environmental Management, 131. 206 - 215.
http://dx.doi.org/10.1016/j.jenvman.2013.09.026

A Modelling Study of Long Term Green Roof Retention Performance

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Abstract

This paper outlines the development of a conceptual hydrological flux model for the long term continuous simulation of runoff and drought risk for green roof systems. A green roof's retention capacity depends upon its physical configuration, but it is also strongly influenced by local climatic controls, including the rainfall characteristics and the restoration of retention capacity associated with evapotranspiration during dry weather periods. The model includes a function that links evapotranspiration rates to substrate moisture content, and is validated against observed runoff data. The model's application to typical extensive green roof configurations is demonstrated with reference to four UK locations characterised by contrasting climatic regimes, using 30-year rainfall time-series inputs at hourly simulation time steps. It is shown that retention performance is dependent upon local climatic conditions. Volumetric retention ranges from 0.19 (cool, wet climate) to 0.59 (warm, dry climate). Per event retention is also considered, and it is demonstrated that retention performance decreases significantly when high return period events are considered in isolation. For example, in Sheffield the median per-event retention is 1.00 (many small events), but the median retention for events exceeding a 1 in 1 yr return period threshold is only 0.10. The simulation tool also provides useful information about the likelihood of drought periods, for which irrigation may be required. A sensitivity study suggests that green roofs with reduced moisture-holding capacity and/or low evapotranspiration rates will tend to offer reduced levels of retention, whilst high moisture-holding capacity and low evapotranspiration rates offer the strongest drought resistance.

Keywords

Evapotranspiration; Green roof; Stormwater management; Retention; Return period.

1 Introduction

Stormwater runoff from urban roofs makes a significant contribution to sewerage-derived flooding and urban water quality problems. In most developed cities, roofs may account for approximately 40-50% of the impermeable urban surface area (Dunnett and Kingsbury, 2004). Any technique that reduces the rate and volume of roof runoff has the potential to contribute to improved stormwater management.

In the UK, the Environment Agency and the Scottish Environment Protection Agency promote the use of Sustainable Drainage Systems (SuDS) for the management of surface water runoff (Woods-Ballard *et al.*, 2007). SuDS include, amongst others, green roofs, soakaways, swales, rain gardens, infiltration basins and ponds. Because of their reliance on natural catchment processes (i.e. infiltration, attenuation, conveyance, storage and biological treatment) these techniques are seen to constitute a 'more sustainable' approach to stormwater management compared with conventional buried piped drainage systems. The SuDS approach goes beyond the need to control the quantity of runoff, aiming also to improve urban water quality and provide amenity. Green roofs have the potential to achieve these three aims simultaneously. In addition to the quantity-quality-amenity SuDS 'triangle', the SuDS philosophy also embraces two other important concepts. The first is that rainfall is generally best controlled as close to the source as possible. The second is the concept of a treatment train, where multiple SuDS devices may be combined to provide more robust and beneficial stormwater management than any single element can achieve on its own. Internationally the terms BMPs (Best Management Practices), LID (Low Impact Development), WSUD (Water Sensitive Urban Design) and GI (Green Infrastructure) refer to similar concepts.

Understanding the hydrological performance characteristics of the different technical components is key to the successful development and implementation of SuDS-type approaches. Green roofs have received a particularly high level of interest in recent years, and the literature includes many reports on the hydrological performance of both test beds and full scale roof installations; see Palla *et al.* (2010) and Stovin *et al.* (2012) for an overview.

Practical, field-based, studies are invaluable for providing real experiential data on system performance. They also help to establish an understanding of key controlling processes and parameters, and provide valuable validation data to underpin the development of modelling tools. However, these studies are generally limited by the specific nature of their individual configuration details and climatic setting. In many cases the observational records are relatively short (less than two years' duration), which makes it difficult to draw meaningful conclusions about performance. Furthermore, few studies have specifically addressed the drainage engineer's need for information on performance during extreme rainfall events, such as those with 1 in 5, 10, 30 or 100 year return periods. Stovin *et al.* (2012) argued for the development of generic process-based modelling tools to address this need.

The objective of the present paper is to develop – and demonstrate the value of – a generic modelling approach to understanding the influence of both climate and roof configuration on the long-term retention performance characteristics of green roof systems. The model is intended to provide a tool for practitioners, regulators and policy-makers requiring objective, quantitative, performance data to inform the development of stormwater management strategies. In addition, data regarding the likelihood of drought periods will help to inform green roof designers and installers about the location-specific viability of alternative green roof configurations, including choices with respect to substrate type and depth, plant species and the need to incorporate provision for irrigation.

The research described in this paper comprises three stages: i) model development; ii) model validation and iii) model application. It should be noted that the focus here is specifically on retention performance (i.e. volumetric control); detention (temporal delay) is addressed separately (see for example, Jarrett and Berghage, 2008; Kasmin *et al.*, 2010; Yio *et al.*, 2012; Vesuviano *et al.*, 2012).

2 Material and methods

2.1 Conceptual Hydrological Flux Model

Extensive green roofs typically consist of a vegetative layer, supported by lightweight growing media (substrate) overlying a drainage layer. Figure 1 presents the conceptual model of substrate moisture flux. The substrate's maximum water-holding capacity (WHC_{max}) defines the condition when the substrate can hold no more moisture under gravity (i.e. field capacity). The moisture content at any given time will lie somewhere between field capacity and a minimum practical moisture content, which may vary in response to ambient conditions. This minimum moisture content may be considered to define the depth of non-plant-available moisture, or the permanent wilting point (PWP). Standard laboratory tests exist for the determination of field capacity in green roof substrates (FLL, 2008). The PWP depends upon the plant species as well as the substrate, but it is generally assumed to correspond to the moisture held at 1,500 kPa in a pressure-plate extraction test (Hillel, 1971; Fassman and Simcock, 2012). The difference between WHC_{max} and PWP determines the maximum stormwater retention (or storage) capacity of the green roof (S_{max}), which is clearly finite. The value of S_{max} will depend on green roof configuration. However, empirical data presented by Stovin *et al.* (2012) suggest a typical value for S_{max} on an extensive green roof with 80 mm substrate of 20 mm.

[Approximate location of Figure 1]

In a rainfall event, the substrate will retain rainfall (P (for precipitation)) until the point when field capacity is reached. If further moisture is added to the system, runoff (R) will occur. In reality, due to substrate heterogeneity, runoff may be initiated slightly before field capacity is reached; this may have a minor impact on the timing of runoff (detention), but can be neglected in the context of the present retention model. It should be noted that, as green roof substrates typically have very high hydraulic conductivities, surface runoff is not expected to occur. The excess runoff will drain vertically down through the substrate and leave the roof via the underlying drainage layer, where it will be temporarily detained before becoming runoff.

Between rainfall events the roof's storage capacity will be restored via evapotranspiration (ET). Evapotranspiration rates vary seasonally and daily depending upon meteorological conditions, plant species and condition, as well as the substrate's moisture content. The prediction of ET rates for green roofs is discussed further in section 2.1.1.

The hydrological processes outlined above are widely understood (e.g. Miller, 2003; Bengtsson *et al.*, 2005; Jarrett and Berghage, 2008; Palla *et al.,* 2010; and Stovin *et al.*, 2012). Furthermore, Jarrett and Berghage (2008) and Kasmin *et al.* (2010) have both demonstrated that implementations of this type of substrate moisture flux model, when combined with storage routing to represent detention, can accurately simulate observed runoff quantities and temporal runoff profiles associated with specific green roof test beds. Input data requirements for this type of model are the rainfall time series, suitable evapotranspiration rates, an estimate of the roof's maximum retention capacity and relevant storage routing parameters. Here, particular attention is paid to the ET rate, which is considered to by the key parameter in green roof retention performance modelling.

2.1.1 Modelling ET rates in green roof systems

The term Potential Evapotranspiration (PET) refers to the expected rate of evapotranspiration associated with a crop under well-watered conditions. If access to soil moisture becomes restricted, actual ET rates fall below the PET. In the hydrological and agricultural science literature, many alternative PET formulae have been proposed (Oudin *et al.*, 2005; Zhao *et al.*, 2013). These are often categorised into temperature-based approaches, energy-based approaches or combination approaches, and have varying levels of input data requirements. These formulae typically permit the estimation of daily or monthly ET rates. The formulae have generally been developed for reference crops (such as short grass or cereals), and may require the use of crop coefficients (K_c) to represent non-standard types of vegetation.

The Penman-Monteith equations have been compared favourably to monitored green roof evapotranspiration (Rezaei, 2005). However, Oudin *et al.* (2005) undertook a detailed review of PET calculation methods for input into lumped rainfall-runoff models, concluding that very simple models relying only on extraterrestrial radiation and mean daily temperature are as efficient as more complex models such as the Penman model and its variants. The temperature-based Thornthwaite model was also shown to perform well.

Kasmin *et al*. (2010) suggested that a modified form of the Thornthwaite formula led to modelled runoff results that were comparable with monitored green roof runoff. The Thornthwaite equation requires only the local temperature profile in order to estimate ET for short close set vegetation with an adequate water supply (Wilson, 1990). PET for the particular month with average temperature, t_n (°C) is given by (Wilson, 1990):

$$PET = 16\left(\frac{T}{12}\right)\left(\frac{D}{30}\right)\left(\frac{10t_n}{J}\right)^a \text{ mm per month;} \tag{1}$$

$$J = \sum_{1}^{12} j \text{ (for the 12 months);} \tag{2}$$

$$j = \left(\frac{t_n}{5}\right)^{1.514} \tag{3}$$

D is number of days in the month, T is average number of hours between sunrise and sunset in the month; a = $(6.75 \times 10^{-7})J^3 - (7.71 \times 10^{-5})J^2 + (1.792 \times 10^{-2})J + 0.492$; J is the yearly 'heat index'; and j is the monthly 'heat index'.

Green roof systems are typically not irrigated, and actual ET rates fall with time during dry weather following a rainfall event, as the available moisture becomes increasingly restricted. Work undertaken at Pennsylvania State University (Rezaei, 2005; Berghage *et al.,* 2007) recognised that the prediction of green roof retention performance requires accurate input data relating to ET under both well-watered and moisture-stressed conditions. They conducted greenhouse trials to establish ET rates from both planted and unplanted green roof substrates. The results showed that moisture losses were greater in vegetated plots, and that loss rates tended to decrease exponentially as water availability became limited. Berghage *et al.*, (2007) proposed three ET decay relationships corresponding to three alternative plant species (B1: *Sedum spurium*; B2: *Delosperma nubigenum*; and B3: *Sedum sexangulare*). Similarly, Voyde *et al.* (2010a) undertook greenhouse trials in Auckland to establish time-based ET decay relationships for two different plant varieties (V1: *Sedum mexicanum*; V2: *Disphyma australe*). The corresponding temporal ET decay rate models are presented in Figure 2a. Preliminary findings from research undertaken in controlled climate chambers by the current authors (Poë and Stovin, 2012) has also confirmed that the actual ET rate declines exponentially with time as the amount of available moisture becomes restricted. In addition to the effects of plant species and climate, it has also been shown that substrate physical characteristics influence ET rates, and that ET rates generally follow a diurnal cycle.

[Approximate location of Figure 2]

Zhao *et al.* (2013) provide an extensive summary of methods for estimating actual ET under conditions of restricted moisture availability. These are referred to as Soil Moisture Extraction Function (SMEF) models. The basic form of the SMEF method describes ET as a function of PET multiplied by the ratio of actual moisture content to the field capacity of the substrate. In accordance with the description of the conceptual hydrological flux model presented in Section 2.1, it may be suggested that S_{max} should replace the field capacity term in the denominator, which leads to a temporal decay model in the form:

$$ET_t = PET_t \times \frac{S_{t-1}}{S_{max}} \tag{4}$$

In Figure 2b, the values of PET and S_{max} have been adjusted to demonstrate the feasibility of fitting the generalised relationship to the specific green roof ET data sets described above. Although both sets of experiments were conducted under greenhouse conditions and with comparable substrate depths (70-80 mm), other aspects of the experimental studies are less directly comparable. The tests reported by Berghage *et al.* (2007) were conducted at higher temperatures, using larger trays and with different substrate compositions compared with Voyde *et al.* (2010a). Other climatic influences such as humidity, wind speed, light levels and plant species and condition will also have influenced the findings. Nonetheless, Figure 2b clearly demonstrates the feasibility of using Equation 4 to represent the temporal exponential decay that typically occurs in observed ET rates. Curve no. 1 models the V2 data set exactly, whilst curve no. 3 provides a reasonable approximation of B3. The differences in fitted S_{max} values suggest that the substrate used in the Voyde *et al*. (2010a) experiments had a significantly greater moisture retention capacity compared with that used by Berghage *et al*. (2007). Curve no. 2 illustrates the form of the relationship for an intermediate parameter set.

The intention here is to identify a practical and generic modelling approach with application to 'typical' extensive green roof systems, although there is clearly a need for further research to refine the predictive value of the model in response to specific plant, substrate or other climatic factors. Zhao *et al.* (2013) list eighteen variations on the basic SMEF method, which may improve predictive capabilities. However, Figure 2b confirms that the basic SMEF method is acceptable for the present purpose.

Kasmin *et al.* (2010), assumed that ET was constant but equal to 0.75 x PET. The total depth of moisture removed from the substrate over 6-7 days using this constant value would be approximately equivalent to that modelled using the SMEF method. This suggests that the unmodified Thornthwaite-derived PET values used by Kasmin *et al.* (2010) could have resulted in reasonable predictions if they had been combined with a more physically realistic SMEF model.

While there is a need to further refine PET and actual ET prediction methods for green roof systems, the evidence presented above supports a generic modelling approach based on the use of the Thornthwaite formula to predict PET and the application of the basic SMEF model to account for the decay in ET that occurs in response to restricted substrate moisture.

2.1.2 Model implementation

At each timestep, t, actual ET is modelled as a function of PET and substrate moisture content, S, using Equation 4. Runoff is calculated depending on ET, the rainfall depth, P and S:

$$R_t = \begin{cases} 0, & S_{t-1} + P_t - ET_t \leq S_{max} \\ P_t - (S_{max} - S_{t-1}) - ET_t, & S_{t-1} + P_t - ET_t > S_{max} \end{cases} \tag{5}$$

Substrate moisture content is then updated:

$$S_t = \begin{cases} S_{t-1} + P_t - ET_t, & S_{t-1} + P_t - ET_t \leq S_{max} \\ S_{max}, & S_{t-1} + P_t - ET_t > S_{max} \end{cases} \tag{6}$$

The model has been implemented at an hourly time step. A sub-daily time-step is required to characterise the system's performance in response to individual storm events that are typically shorter in duration than one day. Note that, although in reality ET rates vary according to a diurnal cycle, this is neglected in the model. The hourly PET value is assumed to be a constant hourly rate equivalent to the relevant monthly Thornthwaite PET rate. This simplifying assumption is justified by an appreciation that ET rates are low (in the order of 0.1 mm/hr) compared with storm event rainfall intensities (1-10 mm/hr). It is the cumulative effect of ET over several days prior to a storm event that impacts on the green roof's runoff retention performance.

The model has been implemented in MATLAB (2007). It should be noted that – perhaps contrary to expectations – this process-based continuous simulation approach does not require excessive computational resources. It takes less than 10 seconds to process a 30-year hourly rainfall time-series on a standard computer (Intel Core 2 Duo, 2.4 GHz, Windows 7).

2.2 Retention Model Validation

Stovin *et al.* (2012) presented findings from a continuously-monitored extensive green roof test bed located in Sheffield, UK. The present model has been validated against the first complete year (2007) of this data set. PET values were calculated from the relevant historical monthly temperature data. Figure 3a confirms that the model is capable of reproducing the observed cumulative runoff profile. Overall, the cumulative annual runoff is overpredicted by 1.3 %, and the predicted hourly runoff models the monitored data with a Nash-Sutcliffe Model Efficiency (NSME) of 0.770. Figure 3b demonstrates that the predicted runoff depths in each of the 163 individual storm events were reproduced with a high degree of accuracy (NSME = 0.956).

Of note here is that the model's accuracy appears to show no deterioration for the larger rainfall events, which are of particular interest for flood risk assessment. The maximum absolute model error is defined by the system's finite storage capacity, S_{max} (in this case 20 mm). This implies that the maximum possible percentage error on runoff depth decreases as the rainfall depth increases, falling to within 20% for events of 100 mm or more.

[Approximate location of Figure 3]

2.3 Model Application

2.3.1 Input Climate Data

To provide an assessment of the way in which climate impacts upon green roof retention performance, four UK locations with contrasting climates have been selected. Mean temperatures in the UK vary on a North-South gradient, with highest mean temperatures of over 11°C in the South-East and lowest (<4°C) in central Scotland. Rainfall varies on a predominantly West-East gradient from > 3000 mm per annum in the West down to less than 600 mm per annum in the East. The country may be approximately classified into four quadrants: NW – cool and very wet; NE – cool and moderately dry; SW – warm and wet; SE – hot and dry. Each of the four locations (Figure 4) has been selected to represent one of these four quadrants, although it should be appreciated that there are considerable climatic variations (due to altitude, distance from the coast and urban effects, for example) within each quadrant, such that findings from specific locations should not necessarily be assumed to apply across the entire quadrant. Sheffield is characterised by a temperate climate, and is representative of much of central England and the NE quadrant. The East Midlands was chosen to represent a warm, dry climate characteristic of the SE; Cornwall in the SW is wet and warm, whilst NW Scotland is cool and very wet.

[Approximate location of Figure 4]

As highlighted in Section 2.1.2, the model requires input climate data at an hourly resolution to capture the runoff retention responses to individual short-duration rainfall events. It is also important that the input data time-series is sufficiently long to include extreme events and to enable return period analysis (e.g. 10-30 years). In many locations these requirements may be met by historical records. However, the model is intended to be used to plan for future stormwater management requirements, in which case projected climate data may be more relevant. The model's application is illustrated here with reference to the UK Climate Projections (UKCP09, http://ukclimateprojections.defra.gov.uk/). UKCP09 uses global climatic modelling and assumptions about future greenhouse gas emissions to generate probabilistic climate change projections at a 25 km grid spatial resolution. The data is focussed on the UK, and is publicly available. UKCP09 incorporates a Weather Generator, which is a downscaling tool that can be used to generate statistically plausible daily and hourly time-series of key weather variables at a 5 km spatial resolution. The Weather Generator is based around a stochastic model that simulates future rainfall sequences. Other weather variables are derived from the rainfall states. Statistical measures within the Weather Generator are then modified according to the UKCP09 probabilistic projections. For each location, 100 30-year time series were generated, assuming medium emissions and centred on the 2050s. The stochastic nature of weather predictions is such that the Weather Generator produces – and recommends the use of – a minimum of 100 30-year time series for each specific scenario. However, as the purpose here is to illustrate the utility of the continuous simulation approach and not to produce statistically valid predictions for the four locations, only the first 30-year time-series from each set has been analysed. It is important to note that the objective here is simply to source credible long time series climate data, with which to illustrate the influence of representative, contrasting, climate characteristics on the retention performance of green roof systems. It is not our intention to discuss the validity of the climate projections or to provide a detailed review of specific climate change impacts at particular locations.

Figure 4 presents the climatic characteristics for each location, as derived from the first 30-year UKCP09 time series in each Weather Generator output. The greatest contrast in climate is evident in the total rainfall data; mean annual total rainfall depths are 2708, 1365, 838 and 496 mm for NW Scotland, Cornwall, Sheffield and the East Midlands respectively. In terms of temperature, Cornwall exhibits the smallest annual variability and is characterised by mild winters and a warm spring. The East Midlands experiences high summer temperatures which often lead to drought/water stressed conditions. PET rates were derived from the climate profile in UKCP09 data set, using the Thornthwaite formula. Daylight hours were determined for the 15th day of each month for 2013 using timeanddate.com. The PET rates are broadly similar, with a reduced seasonal range evident in the predictions for Cornwall, and the highest values evident under summer conditions in the East Midlands.

2.3.2 Data Analysis and Interpretation

Taking as input the hourly rainfall time-series and the monthly PET rates presented in Figure 4, hourly runoff values have been determined based on the conceptual water balance-based retention model described in Equations 4 to 6. ET was predicted at each time-step based on PET and the current level of moisture available in the substrate moisture store. The only assumptions made were that the moisture store had a maximum retention capacity of 20 mm (Stovin *et al.*, 2012) and that the initial moisture content at start of the 30-year simulation was 50% of S_{max}.

Total volumetric retention was calculated from (rainfall-runoff)/rainfall. The rainfall and runoff records were separated into individual events based on a 6-hour Antecedent Dry Weather Period (ADWP) threshold. Retention has also been determined on a per event basis. As highlighted by Stovin *et al.* (2012), it is important to distinguish between routine and 'significant' events. 'Significant' events were defined here as those having an expected return period of greater than 1 year. This was determined as the T = 1.1 year event from a Gumbel distribution fitted to the annual maximum storm depth series. The storm events were not sub-divided by storm duration. Consequently, the maximum storm depths are generally associated with long duration (> 24 hour) events. The depths associated with, for example, 1 year return periods of 1 hour's duration would be considerably smaller.

Although warmer, drier climates are expected to generate better retention performance, it must also be anticipated that these climates may lead to greater incidence of drought stress and/or the requirement for irrigation. An estimate of this risk has been made by counting the number and duration of periods for which the substrate moisture level fell to within 1 mm of the PWP.

In addition to the detailed investigation of climatic controls, the final set of simulations aimed to assess the influence of roof configuration on retention performance under constant climatic conditions. The Sheffield climate condition was chosen for this sensitivity analysis, and variations in the moisture retention capacity (S_{max} = 40 mm, 5 mm) and crop coefficients (K_c = 0.5, 2) were simulated. The variations in moisture holding capacity represent a roof with a deeper/shallower substrate, or one in which the substrate's physical composition leads to greater or lesser retention. The variation on K_c is intended to reflect differences in plant species and/or plant condition. Irrigation was not included in any of the simulations.

3 Results

3.1 Overall Retention

Table 1 highlights the total rainfall, total runoff, volumetric retention, and the per event retention performance for all events and for the 'significant' events.

[Approximate location of Table 1]

Figure 5 presents the first years' cumulative rainfall and runoff profiles from the full 30-year time series. Not surprisingly, the greatest proportional retention is observed at the hottest, driest, location, the East Midlands, Figure 5d. No runoff is evident for an extended period of over 130 days during the summer months, which indicates drought risk and/or the need for irrigation. 59% of the rainfall was retained overall. In contrast, the same roof configuration in NW Scotland retains only 19% of the total rainfall, although it should be noted that in absolute terms (Table 1) this location results in the highest possible absolute retention, 1.8 times greater than the East Midlands. Ample year-round moisture availability in NW Scotland leads to ET losses at, or close to, the PET level for a substantial proportion of the time. For Sheffield, the overall retention of 40% is comparable with the observed performance shown in Figure 3, although it is a little lower than the overall retention figure of 50.2% reported by Stovin *et al*. (2012). This may indicate the influence of climate change, but it should also be recalled that the data reported by Stovin *et al.* (2012) only spanned a 29-month period, whilst the simulated data corresponds to only one of the 100 30-year Weather Generator series that should be considered for robust future predictions. As with the East Midlands case, there is some indication of drought risk during the summer months. In Cornwall (Figure 5c), the higher rainfall and warmer conditions combine to generate similar retention performance to the Sheffield condition, albeit with reduced risk of drought.

[Approximate location of Figure 5]

3.2 Per-event retention

In addition to the overall volumetric retention, Figure 6 presents the per-event data, both for all the events and for the significant events from the full 30-year time series.

[Approximate location of Figure 6]

When all events are considered together, the mean and median per-event retention exceed the overall volumetric retention for all four locations. This is because the full rainfall time-series contain many events less than 1.0 mm in depth. The complete retention of very many small events leads to apparently excellent per event retention performance, and – in the cases of Sheffield and the East Midlands – means that the median retention is 1.0. This should be interpreted as meaning that a lot of very small, insignificant, events are fully retained.

When only the significant events are considered, mean and median retention values fall well below the overall volumetric retention. For example, in the East Midlands, overall volumetric retention of 59% may be compared with a median per event retention of only 23% (i.e. less than half) in significant events (mean 35%). The median values are typically lower than the mean values for the significant events due to a small number of high retention events skewing the distributions.

The reduced retention associated with significant events is not surprising, as the green roof system has a finite storage capacity and is inherently able to retain a greater proportion of a smaller rainfall. In this case the maximum possible retention was assumed to be 20 mm, which is lower than the significant events threshold in all four locations. In Scotland, a retention capacity of 20 mm corresponds to only one fifth of the 1 year return period maximum storm depth.

Figure 7 presents the depth-frequency curves for rainfall and runoff. The runoff curve lies slightly below the rainfall curve, with the difference between them never exceeding the roof's 20 mm finite retention capacity. The largest proportional reduction is associated with the East Midlands data set, where rainfall depths are significantly lower than at the other three locations. The same relationship between the runoff and rainfall depth-frequency curves is also evident in the New Zealand field data set presented by Voyde *et al*. (2010b), although in that case the largest rainfall event observed was less than 60 mm.

[Approximate location of Figure 7]

Although only the 1 in 1 year rainfall depth threshold has been considered here, drainage engineers often require information concerning more extreme events, such as those with return periods of 5, 10, 30 or 100 years. It is feasible to use the same approach adopted here to derive mean and median retention characteristics for these larger events and/or for specific shorter duration events. However, it should also be evident that a simple estimate of the best-case scenario may be obtained by assuming that the retention depth equals S_{max}, whilst a worst-case estimate would be to assume runoff depth equals rainfall depth. As the depth of the design storm increases, so the proportion that may be retained by a given roof decreases.

3.3 Drought stress

Table 2 (upper portion) summarises the drought stress parameters extracted from the four simulation records. As suggested above, the records for Sheffield and the East Midlands both indicate that periods in which the substrate may be expected to be at, or close to, the permanent wilting point occurred relatively frequently (> twice per annum on average), whereas such occurrences are rare for the two wetter Western locations. Mean durations of drought are highest in the East Midlands (200 hours, or > 8 days), and the data suggests that the roof would be exposed to drought conditions for 8% of time overall. This is likely to restrict the range of species that may be supported in this type of climate without irrigation interventions and/or the use of a deeper substrate.

[Approximate location of Table 2]

3.4 Sensitivity to substrate and plant characteristics

Figure 8 and Table 2 (lower portion) demonstrate how retention performance and drought resistance respectively are affected by roof configuration variables. As might be expected, roofs with reduced moisture-holding capacity retain less than deeper/more retentive substrates. Similarly, higher K_c values (e.g. due to more vigorous plants) will lead to enhanced retention. Doubling the maximum retention capacity from 20 to 40 mm has limited effect on the overall volumetric retention, but increases mean retention in significant events from 16 to 24%. Changing PET through the application of crop coefficients has greater impact on overall volumetric retention.

Halving S_{max} or doubling K_c both cause the number of drought periods to increase approximately four-fold compared with the base-case Sheffield data. The maximum drought duration also increases. Increasing S_{max} or decreasing K_c reduces the number of drought periods to practically zero.

[Approximate location of Figure 8]

4 Discussion

The continuous simulation approach allows the long-term retention performance characteristics of green roof systems to be derived, assuming that suitable hourly rainfall time-series are available. Importantly, the approach enables per-event and per-significant event retention to be assessed in addition to overall volumetric performance. Clearly the threshold for significant events may be adjusted to meet local requirements. The method can also be applied to gain an understanding of potential drought risks or irrigation requirements.

The model reflects widely-accepted hydrological principles, including the dependency of actual ET rates on the substrate moisture content. The model concepts are readily transferable to commercial urban drainage and SuDS modelling tools. Implementation of the model at smaller time steps (1 to 10 minutes) and the inclusion of a suitable detention modelling approach (e.g. Kasmin *et al.*, 2010) would enable the runoff delay effects to also be represented.

This study has highlighted the important link between ET and the green roof's retention capacity. Relatively simple assumptions have been used to evaluate ET, specifically the monthly Thornthwaite formula for PET in combination with the basic SMEF model. Although it has been demonstrated that these assumptions lead to perfectly reasonable predictions for a 'typical' extensive green roof, there is clearly a need to further refine this aspect of the model to reflect differences in ET associated with different plants and/or substrates. Similarly, although the value for S_{max} assumed here is considered to provide a reasonable estimate for a typical extensive green roof system, its value will depend upon substrate characteristics (depth and retention/release properties).

5 Conclusions

A hydrological flux model has been developed to predict the long-term volumetric and storm event runoff retention performance of a typical extensive (shallow) green roof system. A green roof's capacity to retain rainfall depends upon evapotranspiration (ET) in the period prior to a storm event. Previous experimental studies have shown that green roof ET rates fall significantly below potential ET rates during dry periods, as the moisture available within the substrate is depleted. The model includes a soil moisture extraction function (Equation 4) which enables ET to be predicted from PET as a function of substrate moisture content. PET is estimated using the Thornthwaite temperature-based formula. However, green roof plants and substrates differ from the agricultural reference crops typically used to develop PET models, and it is recognised that further work is required to refine both the PET and SMEF models to better reflect the processes occurring within specific green roof configurations.

The model has been validated against one year's rainfall-runoff data monitored on a green roof test bed in Sheffield, UK. The model marginally overpredicted cumulative annual runoff (+1.3%), and the modelled hourly runoff predicted the monitored data with a Nash-Sutcliffe Model Efficiency (NSME) of 0.770. Predicted runoff depths for individual storm events were reproduced with a high degree of accuracy (NSME = 0.956). The model's accuracy does not deteriorate for the larger rainfall events, which are of particular interest for flood risk assessment.

The model has been applied to 30-year hourly climate projections corresponding to four UK locations characterised by contrasting climatic regimes. Retention performance and susceptibility to drought vary markedly in response to climatic variations. Overall volumetric retention ranges from 0.19 (cool, wet climate) to 0.59 (warm, dry climate). The median retention in significant events ranged from 3.2 to 23.1%, whereas the frequency of drought periods ranged from 0.1 to 3.6 per annum. This highlights the importance of undertaking long duration, location-specific, analysis to assess the viability and effectiveness of any planned green roof implementation.

The long time series permit storm events to be classified according to return period, and it has been shown that retention performance in events with return periods of greater than one year is lower than in routine events at all locations. A green roof's finite retention capacity limits the reliance that should be placed on green roofs for controlling runoff during the extreme events that are responsible for urban flooding. It is not appropriate to assume that a fixed runoff coefficient can be applied to estimate storm runoff. Consistent with the SuDS philosophy, complementary control devices (e.g. swales, ponds, soakaways) will need to be placed downstream from green roofs to ensure complete protection from extreme events.

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Figure Captions:

Fig. 1. Conceptual model of moisture flux within the green roof substrate layer.

Fig. 2. Models for actual evapotranspiration (ET). B1, B2 and B3 refer to the temporal decay models proposed by Berghage et al. (2007) for three different plant species. V1 and V2 refer to the temporal decay models proposed by Voyde et al. (2010a) for two different plant species. The curves in b) correspond to Equation (4).

Fig. 3. Runoff prediction validation against monitored data from the Sheffield test bed for 2007.

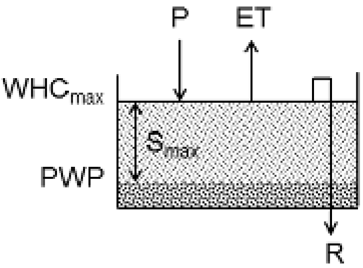
Fig. 4. UK map and monthly climate profiles (UKCP09) for the four locations.

Fig. 5. Cumulative rainfall and runoff profiles for year 1 of the analysed 30-year time series.

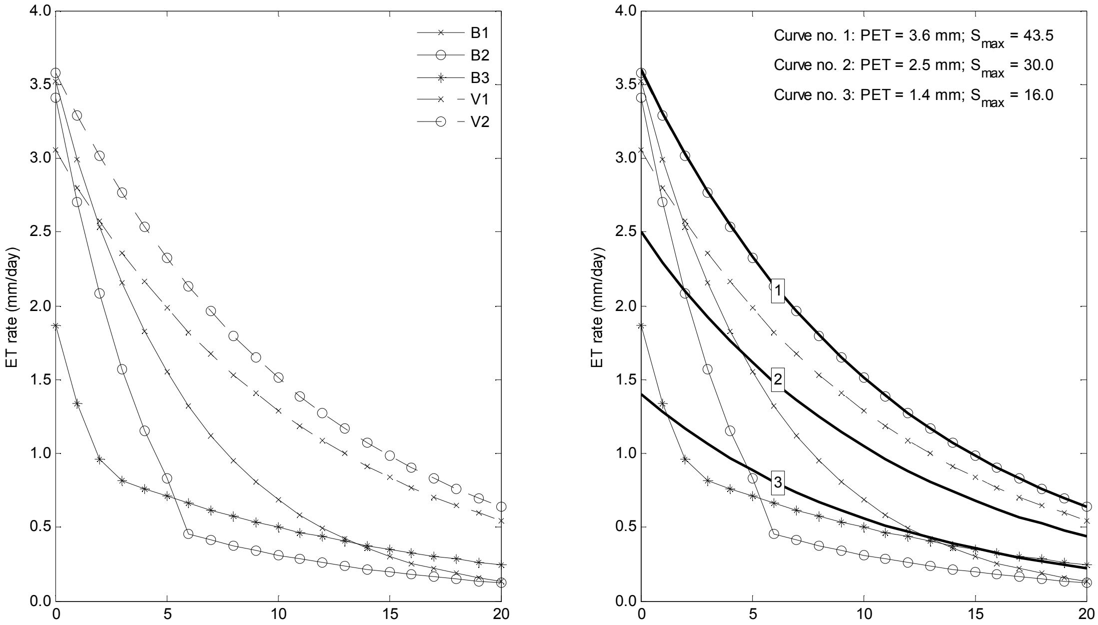
Fig. 6. Retention characteristics.

Fig. 7. Rainfall-runoff depth-frequency distributions for the selected UK locations.

Fig. 8. Sensitivity analysis on the hydrological moisture flux model.

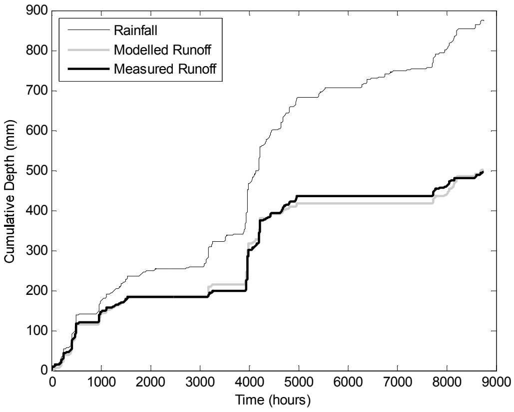


P – Precipitation (mm/hr)
ET – Evapotranspiration (mm/hr)
R – Runoff (subsurface) (mm/hr)
WHC$_{max}$ – Maximum water holding capacity (mm)
(equivalent to field capacity)
PWP – Permanent wilting point
S$_{max}$ – Maximum substrate retention capacity (mm)

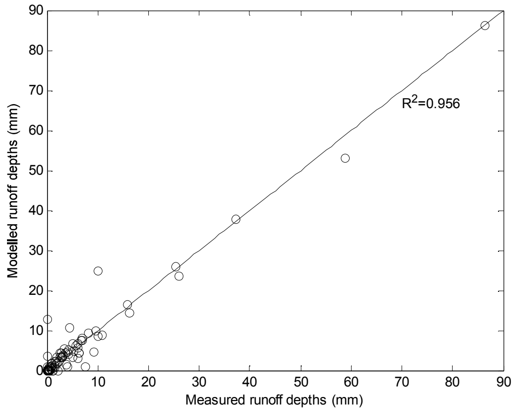


a) Experimental ET dacay curves

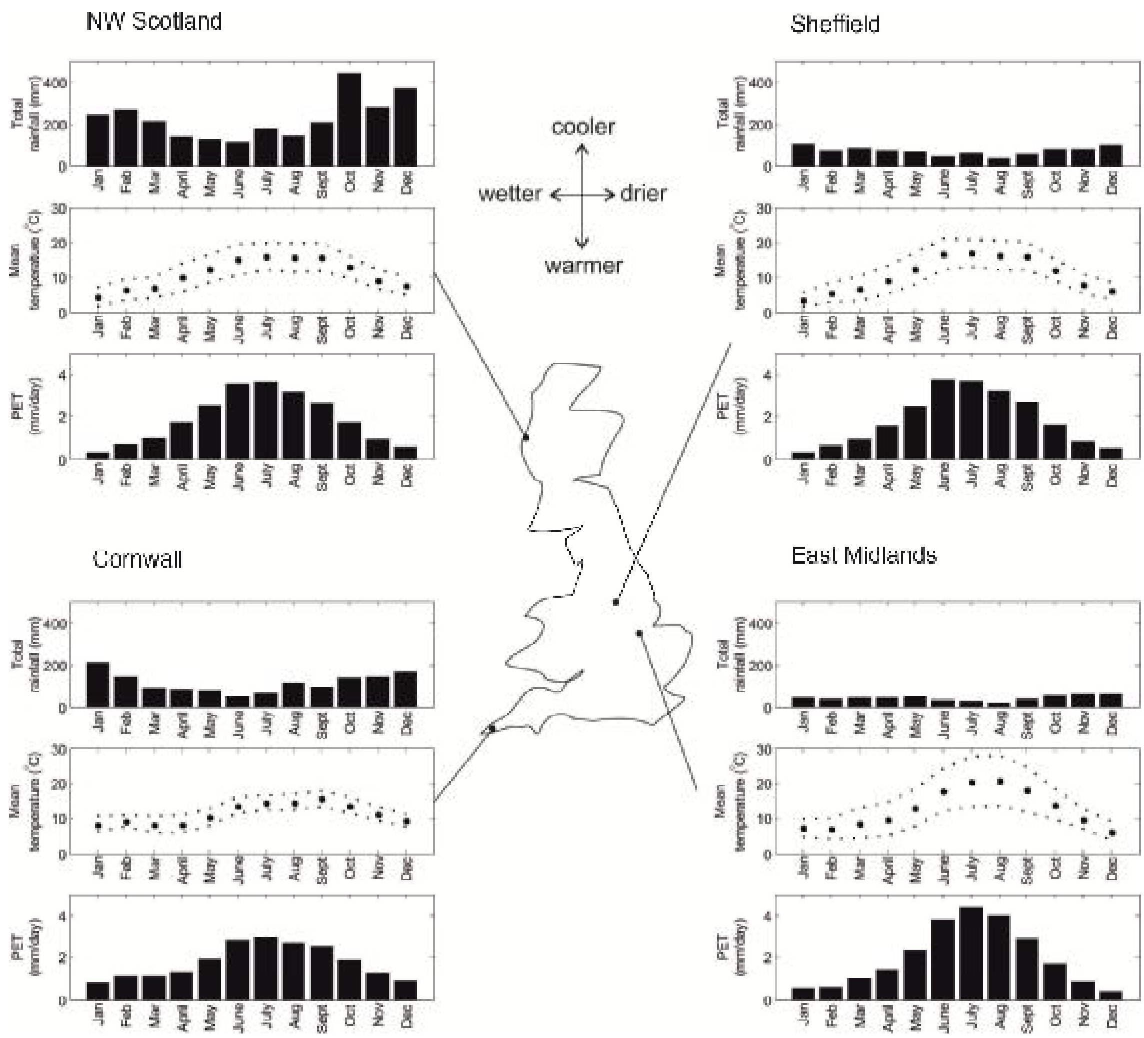
b) Fitted SMEF models



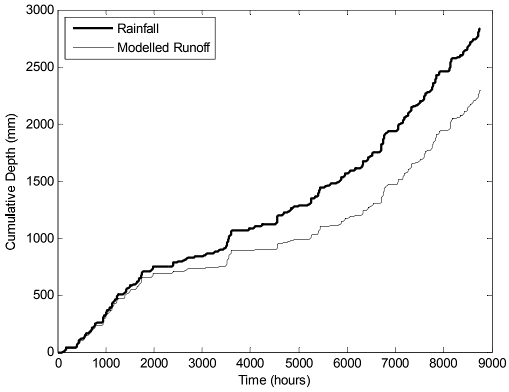
a) Cumulative rainfall and runoff depths



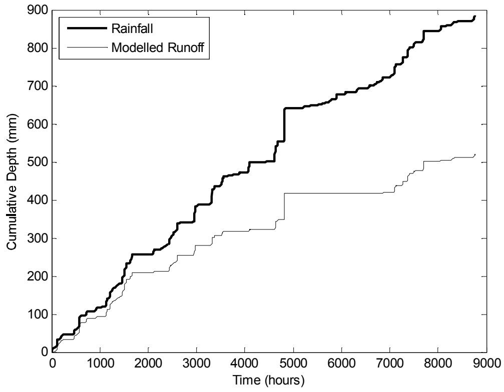
b) Runoff depths for all 163 events



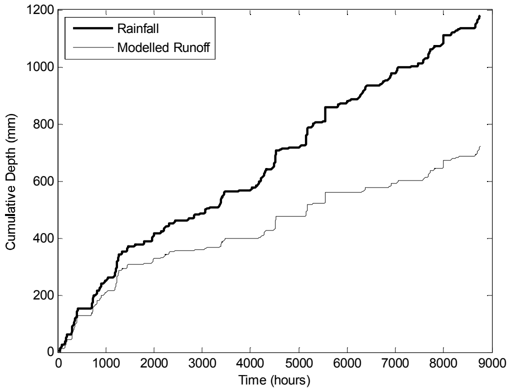
NW Scotland
Sheffield
Cornwall
East Midlands
cooler
wetter
drier
warmer
Total rainfall (mm)
Mean temperature (°C)
PET (mm/day)
Jan
Feb
Mar
April
May
June
July
Aug
Sept
Oct
Nov
Dec



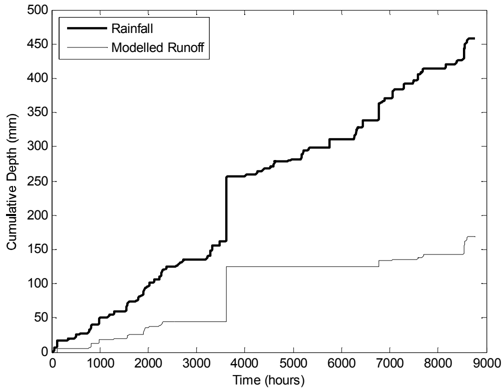
a) NW Scotland



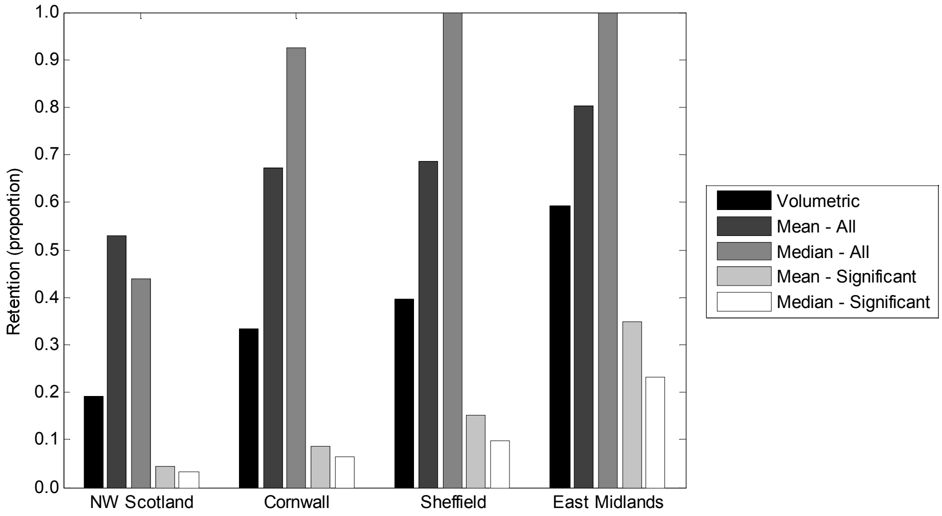
b) Sheffield

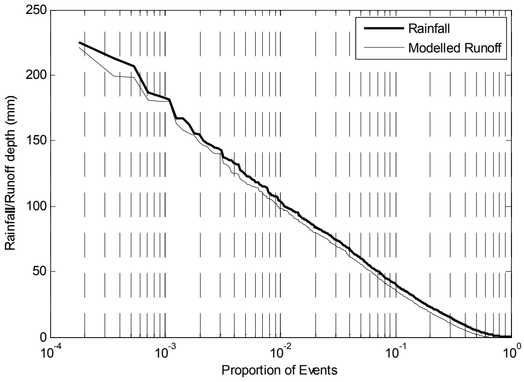


c) Cornwall

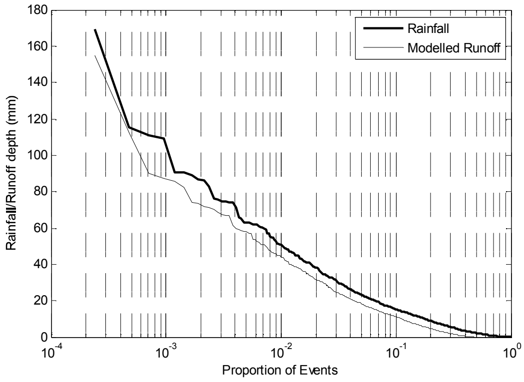


d) East Midlands

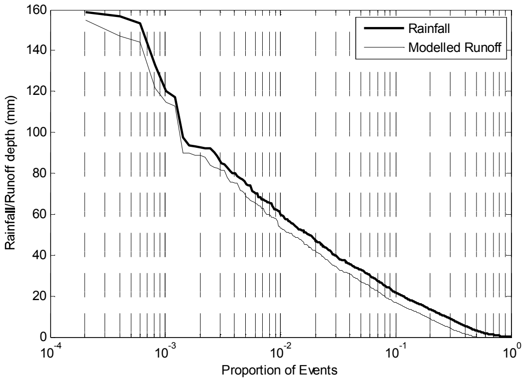

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Retention (proportion)
NW Scotland
Cornwall
Sheffield
East Midlands
Volumetric
Mean - All
Median - All
Mean - Significant
Median - Significant



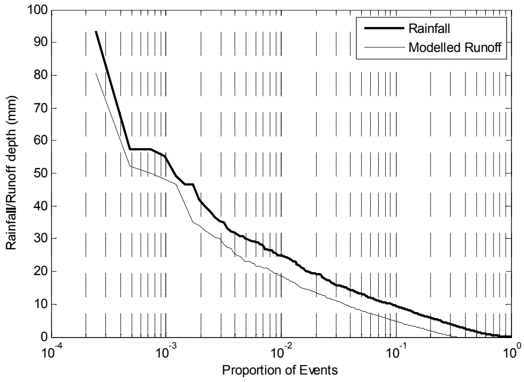
a) NW Scotland



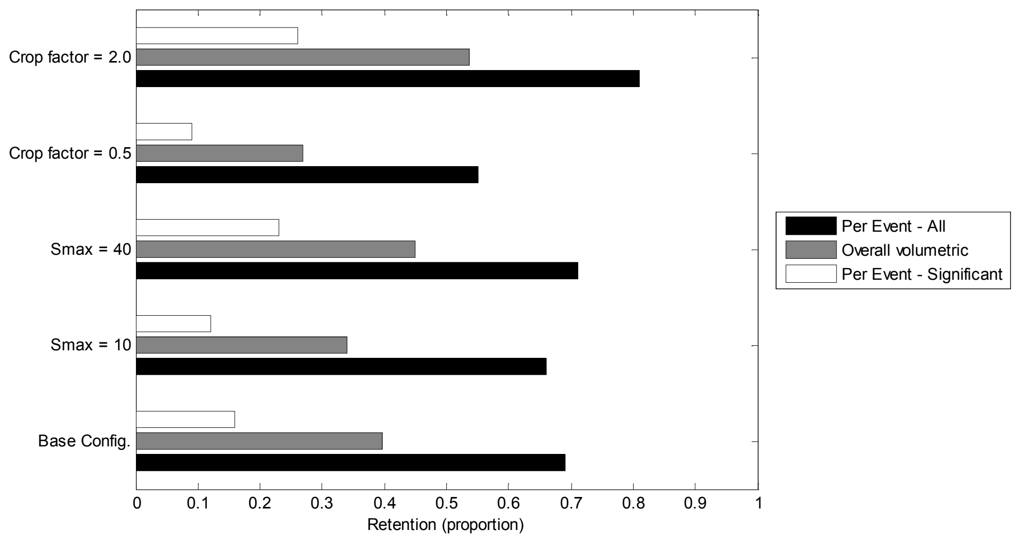
b) Sheffield



c) Cornwall



d) East Midlands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Smax = 40
Smax = 10
Base Config.
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Retention (proportion)
Per Event - All
Overall volumetric
Per Event - Significant

Table 1 Retention performance characteristics

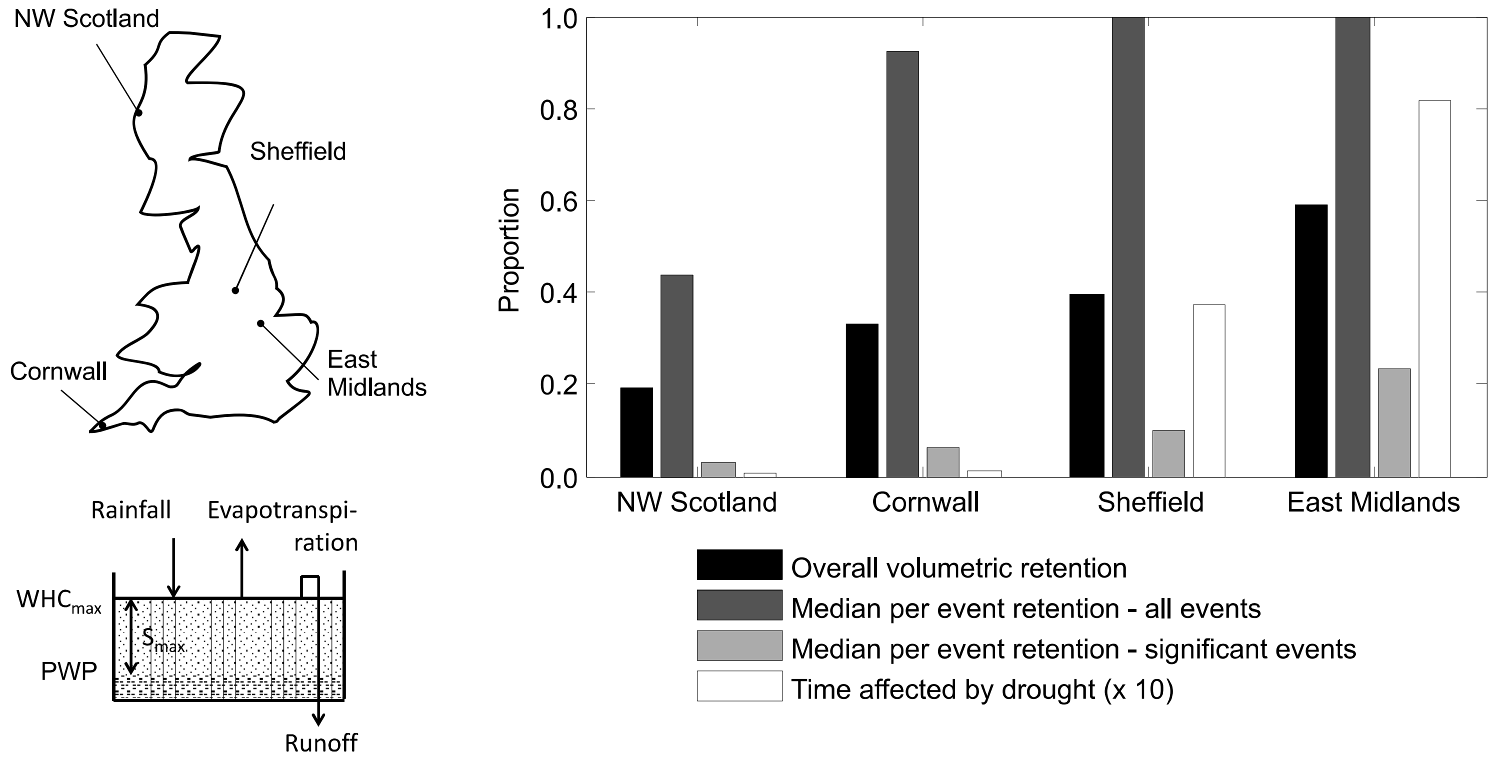
	units	NW Scotland	Cornwall	Sheffield	East Midlands
Total rain	(mm)	81,251	40,947	25,153	14,869
Mean annual rainfall	(mm)	2,708	1,365	838	496
Total runoff	(mm)	65,642	27,334	15,172	6,076
Retained depth	(mm)	15,609	13,613	9,981	8,793
No. events	(-)	5,607	4,932	4,216	4,111
Volumetric retention	(-)	0.192	0.333	0.397	0.591
Mean per event retention	(-)	0.531	0.672	0.687	0.802
Median per event retention	(-)	0.439	0.925	1.00	1.00
Minimum per event ret.	(-)	0.005	0.023	0.008	0.013
Maximum per event ret.	(-)	1.00	1.00	1.00	1.00
1 in 1 yr threshold depth[a]	(mm)	100	55.7	42.7	17.5
Mean ret. significant[a] events	(-)	0.044	0.086	0.152	0.349
Median ret. sig. events	(-)	0.032	0.063	0.098	0.231
Min. ret. sig. events	(-)	0.005	0.027	0.008	0.013
Max. ret. sig. events	(-)	0.238	0.294	0.470	1.00

[a]significant events are defined as those having an expected return period of greater than 1 year, determined as the T= 1.1 yr event from a Gumbel distribution fitted to the annual maximum rainfall depth series. These depths are typically associated with long duration rainfall events (> 24 hours).

Table 2 Drought stress indicators as a function of location and configuration

	No. drought stress events (-)	**Mean duration** (hours)	**Median duration** (hours)	**Max duration** (hours)	**Min duration** (hours)	**Prop. Time affected** (-)
Location:						
NW Scotland	3	68.3	40	135	30	0.0008
Cornwall	5	72.4	56	193	14	0.0014
Sheffield	65	150	88	630	2	0.0371
East Midlands	107	200	144	900	1	0.0815
Configuration[a]:						
Reduced S_{max}	279	124	78	720	1	0.1319
Increased S_{max}	7	48.4	12	134	4	0.0013
Red. Crop factor	9	73	38	215	13	0.0025
Inc. Crop factor	251	125	77	720	1	0.1194

[a]Variations on substrate and plant species all based on the Sheffield climatic input


NW Scotland
Sheffield
Cornwall
East
Midlands
Rainfall
Evapotranspi-
ration
WHC$_{max}$
S_{max}
PWP
Runoff
Proportion
1.0
0.8
0.6
0.4
0.2
0.0
NW Scotland
Cornwall
Sheffield
East Midlands
Overall volumetric retention
Median per event retention - all events
Median per event retention - significant events
Time affected by drought (x 10)