12-2016

Parameterizing a Water-Balance Model for Predicting Stormwater Runoff from Green Roofs

Olyssa Starry
Portland State University, ostarry@pdx.edu

John Lea-Cox
University of Maryland at College Park

Andrew Ristvey
University of Maryland at College Park

Steven Cohan
University of Maryland at College Park

Parameterizing a water balance model for predicting stormwater runoff from green roofs

Olyssa Starry[1], John Lea-Cox[2], Andrew Ristvey[3], and Steve Cohan[4].

Abstract Crop coefficients (k_c) were calculated for three different species of common green roof succulents from March to November in 2011, to parameterize the FAO Penman-Monteith equation for use in a mechanistic green roof water-balance model. Seasonally averaged k_c values for each species were then used to predict plant evapotranspiration (E_T) in 2012. The adjusted FAO Penman-Monteith equation predicted total annual E_T within 3-13 mm, a substantial improvement over model predictions with k_c set to1, which over-predicted E_T by 100mm or more, depending on species. The adjusted equation was inserted in water balance models which predicted runoff within 2-13% of measured totals for 2012. This discrepancy may be explained by variability in maximum water holding capacity which is difficult for two dimensional models to predict. Nevertheless, these results provide increased confidence in the use of models to predict stormwater runoff from green roofs and evaluate performance. Monitoring multiple green roof installations with cost-effective sensor networks will increase our ability to identify the key components to enhance green roof function, reduce stormwater runoff, and inform future design.

Introduction

The design intent of many green roofs is to maximize stormwater retention, thereby reducing runoff and the burden on aging infrastructure, and decreasing the volume and concentration of pollutants to nearby waterways. The modeling process is very useful for

[1] Assistant Professor, Portland State University Honors College, PO Box 751, Portland OR 97207
[2] Professor, University of Maryland, College Park, Department of Plant Science and Landscape Architecture, 2120 Plant Sciences Building, College Park, MD 20742
[3] Senior Agent, University of Maryland Wye Research and Education Center, 124 Wye Narrows Dr., PO Box 169, Queenstown, Maryland 21658-0169
[4] Professor of Practice, University of Maryland, College Park Department of Plant Science and Landscape Architecture, 2120 Plant Sciences Building, College Park, MD 20742

evaluating the influence of various green roof elements and decisions relative to design intent (Miller, C; Roof Meadow Inc., Philadelphia, PA *pers comm*). To date, most models of stormwater retention by green roofs have been empirically constructed. Researchers and planners in the United States typically calculate how green roof implementation might affect the "curve number," or an empirically derived line representing a relationship between runoff and rainfall, for different land surfaces (USDA 1986; Carter and Rasmussen 2006; Hawkins et al. 2009; MDE 2009). The curve number relates rainfall to runoff for different land surfaces, and urban surfaces are generally assigned 0.89-0.95 depending on soil type; despite some preliminary calculations (Carter and Rasmussen 2006), it is unknown how this number might change with the addition of greenroofs to the urban landscape. Regression models have been developed to predict stormwater runoff from roofs based on storm size in places such as Belgium (Mentens 2006) and New York City (Carson et al. 2013). The challenge with empirical models is that their application is limited by the specificity of the data used to construct them (e.g. environmental and biological parameters) and they lack sensitivity to inter-rainfall event processes (Stovin et al. 2012; Nawaz et al. 2015).

In contrast, mechanistic models of the green roof water cycle switch the focus to the underlying structures and biogeochemical functions responsible for stormwater storage by these systems. Mechanistic models are usually much more flexible to a wide range of data inputs. To date, most mechanistic models of green roofs are adaptations of the Hydrus 1-3-D (Hilten et al. 2008; Palla et al. 2009) or SWMM (She and Pang 2008; Stovin 2010; Burszta-Adamiak and Mrowiec 2013) models for green roof parameters. These have proven to predict aspects of the green roof water cycle well, but they also require substantial parameterization and possibly include too much extraneous information for effective validation with all the green roof designs and materials (e.g. green roof substrates) that are currently used (Hilten et al. 2008; Burszta-Adamiak and Mrowiec 2013). An alternative modeling approach is simply to continuously estimate the water balance of the green roof system, with the added advantage of utilizing a relatively simple suite of environmental sensors which provide data to inform the stormwater prediction model on a real-time basis (Voyde 2011; Sherrard and Jacobs 2012; Starry et al., 2014a)

Because rates of plant evapotranspiration (E_T) have been directly linked to stormwater retention efficiency (Voyde et al. 2010; Starry 2013), investigating and calibrating E_T equations used in predictive models is vital to the precision and accuracy of the model outputs. A growing body of research is establishing that standard model equations can be adapted to predict E_T from green roofs with some success. Plant evapotranspiration is a major component of any water balance model, and the hardest to measure with any precision. Rezaei and Jarrett (2006) tested a number of different predictive E_T equations for green roof applications and found certain equations worked better under different environmental conditions, in greenhouse studies of *Sedum album* and *Delosperma nubigem*. Of the various equations tested (Rezaei and Jarrett 2006), four have also been used and verified by others to predict E_T from experimental mixed-species green roof modules: (a) the Penman and Penman Monteith equation (Feller 2011); (b) the FAO56 version of the Penman-Monteith equation (Hilten et al. 2008; Schneider 2011); (c) the Hargreaves-Samani equation (Hilten et al. 2008), and (d) the Thornwaite equation (Kasmin et al. 2010). These equations were also included in a study by Voyde (2011) who tested several additional equations and found the FAO56 version of the Penman-Monteith to be one of the most robust tools (the FAO24 was preferred) for predicting total E_T for green roof experiments using *D. australe* and *S. mexicanum*.

The FAO56 equations basically modify the standard Penman-Monteith equations used to predict E_T by assuming the stomatal conductance and albedo of a theoretical grass reference crop with a height of 0.12m, an albedo of 0.23, and a constant surface resistance of 70 s/m (Allen et al., 1998). This closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. The fixed surface resistance of 70 s m^{-1} implies a moderately dry soil surface resulting from about a weekly precipitation or irrigation frequency. These calculations are subsequently modified by a k_s coefficient to account for water stress, and a k_c coefficient to account for physiological adaptations of different plant species relative to the standard reference crop. A key focus of research on adapting E_T equations (originally designed for agricultural use) for green roofs has been to adjust the calculations for *less than well-watered conditions* using the k_s coefficient or similar calculations, as well as adjustments for drought-tolerance (crassulacean acid metabolism, CAM), a trait found in many successful green roof species (Butler 2011, Starry et al., 2014b). One recent study has found that the Thornwaite adjustment (Thornwaite and Mather 1955) works well with the ASCE version of the FAO56 Penman-Monteith equation (DiGiovanni et al. 2013). Another study (Sherrard and Jacobs 2012) successfully used a different adjustment to the same model (based on Guswa 2002).

Less is known about how to adjust this equation, using crop coefficients, to account for physiological and CAM adaptations by green roof plant species to drought stress. Voyde (2011) references a number of reported k_c-values from different studies globally, which we summarize and supplement in Table 1. Reported values range from 0.52 to 3.25. Preliminary model runs suggest that a change in crop coefficient from 0.5 to 1 could result in a 15-25% reduction in predicted runoff from green roofs <100mm in depth (Baraglioli et al. 2008). Some studies

(Table 1) have suggested an overall green roof k_c value is near 1 for well-watered conditions, indicating few differences in E_T rates between *Sedum* plants and cool season grasses on which the unadjusted FAO56 equations are based. At the same time, adjusting the Penman-Monteith equation for different crops is standard for predicting crop E_T in the horticultural industry; for example, the City of Riverside (1994) has even produced a manual recommending different kc values for a variety of species. Their recommendation for *Sedum rubrotinctum* was 0.25-0.35.

In fact, many green roof modeling studies appear not to consider a crop coefficient, or do not report any values; this would have the same effect of setting a k_c value to 1. Other studies recommend a single, if adjusted, k_c value over the entire year (Locatelli et al. 2014); Sherrard and Jacobs set their k_c value as a constant, but their study only covered the fall season in 2009. In the only freely available green roof modeling program, there is an option to adjust a single k_c, value for the entire model run, and pre-set values range from 0.4-0.7 for succulent and moss combinations (Raes et al. 2006). However, in the FAO guidelines, the mid-season crop coefficients for the most drought-tolerant species (pineapple) is referenced as 0.3, but is estimated to increase up to 0.5 later in the season (Allen et al. 1998). Green roof *Sedum* species might be predicted to perform similarly to pineapple, since both species utilize CAM. We found that *S. album L.* and *S. kamtschaticum* modulated CAM metabolism to varying extents with different substrate water availability over time, resulting in significantly different rates of E_T under carefully controlled environmental conditions (Starry et al., 2014b). *S. kamtschaticum* has now been reclassified as *Phedimus kamtschaticus (Fisch. & C.A.Mey.)'t Hart* (t'Hart and Eggli 1995). Most studies of crop coefficients for predicting green roof E_T to date have been conducted over short time periods, with minimal replication; these studies also lack resolution with respect to specific plant species.

The objectives of this study were to 1) determine whether seasonal and species-specific differences in E_T rates for three green roof species merit the use of different crop coefficients in the FAO56 equations for predicting plant E_T, and 2) utilize these rate limiting constants in a green roof water balance model, to evaluate model accuracy and precision for predicting stormwater runoff. In order to address these goals, we calculated k_c values for three green roof succulent species of varying growth rate and metabolism. These values were used to inform predictions of evapotranspiration and stormwater runoff using a water balance model. This model was calibrated using 2011 k_c values and verified against measured values for 2012. To our knowledge, no previous study has calibrated a green roof model using multiple platform replicates and then rigorously verified the same model with data collected in a subsequent year.

Materials and Methods.

2.1 FAO56 Penman Monteith equation and parameterization

The FAO56 equation is derived from the Penman Monteith equation (Allen et al., 1998). This equation assumes some constant parameters for a clipped grass reference crop, i.e., a surface resistance of 70s m^{-1} and an albedo value of 0.23, and is defined as:

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$ ... **Equation 1**

where E_{To} is reference evapotranspiration, R_n is net radiation at the crop surface, G is soil heat flux density, e_s is saturation vapor pressure, e_a is actual vapor pressure, r_s is the canopy surface resistance, r_a is the bulk surface aerodynamic resistance, Δ is the slope of the vapor pressure curve, γ is the psychometric constant, T is the average daily temperature and u_2 is average daily wind speed. A further adjustment is made to account for less than well-watered conditions, by introducing a water stress coefficient, k_s (Allen et al. 1998). This equation is described as:

$$k_s = \frac{TAW - D_r}{TAW - RAW} \quad \text{......}\textbf{Equation 2}$$

where, TAW is total available water, D_r is root zone depletion (mm), and RAW is water that is readily available to the plant (Allen et al. 1998). The water stress coefficient ($k_s < 1$) is then used in conjunction with a second coefficient, the crop coefficient, k_c, accounting for species-specific differences in E_T. The crop coefficient, k_c is calculated as the ratio of (ks* E_{To}) to actual E_T. For seasonal crops, different values are typically assigned throughout the year for changes in growth (primarily changes in leaf area and phenological stage of development).

Data from a study of *Sedum album* and *Phedimus kamtschaticus* in controlled experimental chamber environments (Starry et al., 2014b) was used to parameterize this equation. Wilting point, needed to estimate TAW for all species was set at 0.05 $m^3 \cdot m^{-3}$ based on these results, even though the plants did not wilt or defoliate at this very low soil moisture content, even after 14 days without watering. However, at this soil moisture content, both species had ceased to fix more carbon than they were respiring, indicating moderate to severe water stress. Total available water is defined as the difference between field capacity and wilting point (Allen et al. 1998). We define field capacity (FC) as the VWC observed after any runoff-producing event for all experimental platforms. Field capacity was adjusted continuously based on environmental parameters described in the results section below. The value of readily available water was set to equal zero (0) in equation 2. The justification for doing this is that since green roof substrates typically drain very rapidly, there are very few instances once field capacity is achieved, where one might expect E_T would not be influenced by VWC. Interestingly, by setting RAW to 0 equation 2 is simplified to the Thornwaite adjustment

(Thornwaite and Mather, 1955).

2.2 Data collection

Experimental platforms for E_T, VWC, and runoff verification:

Eighteen experimental green roof platforms (1.31 m^2 measured along interior margins) were constructed and instrumented at the University of Maryland, College Park campus from May – July, 2010 (Figure 1), located in USDA crop zone 6b. Platforms were constructed and maintained according to FLL standards (FLL, 2008). Platforms consisted of a 12mm plywood decking covered with EPDM waterproofing membrane, a protection fabric, drainage layer, filter fabric (Conservation Technology, Baltimore, MD) and a baked clay substrate (M2 Stancills, Perryville, MD). Initial bulk density of the substrate was 0.75g/mL, with 8% of particles less than 0.5mm; pH was 7.2, and organic matter content was 3.8% by mass (Pennsylvania State University, 2010). Two platforms were constructed and left as roofing membrane-only controls; these platforms were used to ensure that equipment measuring water inputs and outputs were functioning correctly and to provide some data on how standard flat roofs might perform under the conditions of this study. The remaining sixteen experimental platforms were planted with 4 replicate treatments of either *S. album*, *P. kamtschaticus*, or *S. sexangulare L.*, or left unplanted, in a completely randomized design (Starry, 2013). The unplanted platforms were used as controls in another experiment as well as in this study to determine the relationship between environmental parameters and field capacity.

All platforms drained into a gutter mounted on the lower side of each platform (Starry, 2013) that drained directly into a 40mL double-tipping rain gauge (TB-4, Hydrological Services, Lake Worth, FL). Runoff data from these rain gauges was collected at 1-minute resolution using a CR-10 data logger and two SW8A multiplexers (Campbell Scientific, Logan, UT). The logger program included an adjustment to the calibration to account for water loss during very high intensity events (Hydrological Services, Lake Worth, FL). Four substrate moisture and temperature sensors (5TM; Decagon Devices, Inc) were deployed in the center of the four quadrants of each of 16 experimental platforms. The sensors (n=16 per treatment) were positioned so that the sensor blades faced upslope, and oriented vertically (thinnest side up) to the roof surface, to minimize any interference with rainfall. Sensors were calibrated to the specific green roof substrate used and at various times throughout the study, to ascertain variations in sensor performance (Starry 2013). Evapotranspiration was calculated as the difference in average substrate moisture content each day and assumed to be negligible during rain events. Thus, E_T was not measured on rainy days in which the moisture content increased.

Environmental data collection.

All environmental and soil moisture data were logged and transmitted using radio dataloggers (EM50R; Decagon Devices Inc., Pullman WA). Air temperature and relative humidity (VP-3 sensor), wind speed (Davis cup anemometer), solar radiation (PYR, total radiation pyranometer) and rainfall (ECRN-100 tipping rain gauge) were continuously collected by a weather station at the study site during 2011 and 2012 (Starry 2013).

Sensor data was measured every minute and the 5-min averages logged by the EM50R nodes for the environmental (weather) data and the substrate moisture (5TM sensor, n=16) data for green roof species (n=4 platforms per species). Data were transmitted and downloaded via a Decagon (RM-1) radio base station in the University of Maryland, College Park (UMCP) greenhouse complex, which was connected to a dedicated computer. Data were downloaded and viewed whenever necessary using DataTrac software v.3.2 (Decagon Devices, Inc.), and from anywhere on the web using Logmein (Woburn, MA) software. More details regarding the experimental set-up and specific sensor numbers can be found in Starry 2013.

2.3 Determining k_c and Parameterizing the Water-Balance Model

For each day in 2011, k_s was calculated as per equation 2. Total available water was determined as the difference between modeled field capacity for any given day and wilting point, which was set at 5 percent VWC (based on results from Starry et al., 2014). Root zone depletion was estimated using daily averages of measured substrate moisture. Next, k_c was calculated as the ratio of (k_s* E_{To}) to actual $E_{T,}$ averaged for all platforms of the same species for any given day. Since k_c values are not well-defined for green roof species, they were estimated after estimating k_s, (Figure 3). This was done to eliminate variation due to known relationships between k_s and VWC *before* attempting to explain unknown variation due to k_c. These estimates of k_c were averaged by season during 2011 for each species, where spring was defined as 1 March – 31 May, summer as 1 June - 31 August, and fall as 1 September through 30 November.

Once E_T and associated k_c and k_s corrections were established, these values were further verified by being incorporated into a green roof water balance for 2012 to predict runoff by setting precipitation (P) equal to E_T plus change in storage, or substrate VWC, plus runoff (R) plus interception (I). We set canopy interception at 10% of total rainfall for all species, since very few measures of interception for *Sedum* species have been reported, but preliminary work suggests this is reasonable considering the structure and density of most *Sedum* canopies (Lotteau, 2006). The model was run on a daily time-step whereby the VWC from the previous time-step was used to estimate k_s. For comparison with our 2011 estimates of k_c, we also ran the model using k_c=1, the average of 2011 and 2012 k_c values (established as described above for 2011), and a constant kc value (0.38, the average of all k_cs for both years).

Results and Discussion

3.1 Field Capacity

Field capacity (FC) is key to predicting changes in storage in this model. For each experimental platform, field capacity was measured as the average VWC on the day after the end of a rain event. Previous analyses (Starry 2013) had shown that the VWC was fairly constant in the hours following a rain event regardless of planting treatment, so FC was calculated at the same time for each treatment. An empirical relationship between FC and days since the previous storm event (dpe), total daily precipitation (tdp) and average daily temperature (adt) was established by fitting a stepwise multiple regression to the 2011 data, and using this to predict FC in 2012 (Figure 2). A logistic regression (SAS, phreg) compared input variables based on their chi-squared scores. Storm size (tdp) and temperature (adt) had the highest scores (24 and 35 respectively); antecedent moisture (dpe) score was the lowest at 15. Other parameters such as storm duration were rejected from the model due to low chi squared scores (score<5). This information on field capacity was then used to calculate the k_s term in the FAO Penman Monteith equation.

3.2 Actual vs. Estimated Evapotranspiration (E_{To}).

In 2011, 1012 mm of rain were recorded. This included 304mm from tropical storm Irene during the week 8/28/11 – 09/2/15. Excluding this 'outlier' rain event, runoff totaled 474, 430, and 419mm for *S. album, P kamtschaticus,* and *S. sexangulare* platforms respectively. Differences in rates of E_T among species were also evident, though not statistically significant. In 2011, the highest total E_T at 183mm could be attributed to *S. sexangulare* compared to 147mm for *S. album* and 162mm for *P. kamtschaticus*. Figures 3(a-c) illustrate the relationship between actual E_T and estimated E_{To} for these three green roof species during 2011. The FAO56 equation consistently over-predicted rates of E_T for these three plant species. This disparity was greatest during the summer months, when predicted daily E_T rates were nearly triple measured rates.

3.3 Calculating water stress (k_s) and crop coefficients (k_c)

Our estimates of ks were above 80% for all species for a majority of the time in both 2011 and 2012. However, during times of drought, especially in early spring of 2012, we noted k_s values approaching zero for *P. kamtschticus* and *S. sexangulare* as moisture content was reaching wilting point; ks for *S. album* only approached 20% during this time due to wetter substrate presumably related to slower rates of evapotranspiration. Figure 4 shows the large variation in daily k_c estimates by species for non-rainy days in 2011. The closer the value of k_c is to 1, the greater the similarity in E_T between the species in question and the reference cool season grass (C_3 species). As can be seen in Figure 4, species-specific differences in k_c values were not easily discernible when viewed over the full year of 2011. Seasonal variation is likely explained by changes in environmental or soil-moisture conditions and whether the plant was transpiring under well-watered conditions, or was under water-stress (i.e. CAM cycling). Average seasonal k_c values are summarized by species in Table 2 for the three different green roof succulent species for 2011 and 2012. Values for k_c in 2012 were similar to those in 2011, except for k_c for *P. kamtschaticus*; this could indicate that the plants of this species were not as fully established in 2011 as we thought, or perhaps the species had a different physiological response to the environmental conditions for that year (Annandale and Stockle 1994). Our data on plant coverage for this species (Starry 2013) indicate the former explanation may be more likely. Species-specific differences were more evident as well as statistically significant in 2012.

3.4 Using ET equations to estimate VWC and the 2012 water balance:

During 2012, 676 mm of rain were recorded including 165mm during tropical storm Sandy at the end of October. Excluding this outlier rain event, runoff totaled 289, 285, and 226 mm for *S. album*, *S. sexangulare*, and *P. kamtschaticus* treatments respectively. Differences in E_T among species were significant (Starry 2013). In 2012, the highest total E_T was 184 mm for *P. kamtschaticus*, compared to180 mm for *S. sexangulare* and 138 mm for *S. album*. Despite less rain in 2012, total rates of E_T for 2011 and 2012 were similar, perhaps reflecting increased plant root density, leaf area and the associated plant water utilization.

We compared the ability of the FAO Penman Monteith equation, adjusted for a variety of k_c values, to predict E_T from green roofs in 2012. Table 3 shows how selecting different k_c values are associated with different k_c predictions and associated error for different species. For example, selecting a fixed seasonal average for k_c resulted in more error in E_T predictions for *S. album* since this species had the most seasonally variable rates of E_T. Adjusting the FAO Penman Monteith equation with 2011 crop coefficients allowed for prediction of E_T in 2012 to within 3-13 mm. Adjusting the equation with the average of 2011 and 2012 values did not improve predictions compared to just using 2011 values. These results might be different if data from more than 2 years were being compared. Slight adjustments in k_c and E_T did not have substantial impacts on the overall water balance or especially on predicted runoff. However, adjusting the k_c down from 1 resulting in significant improvement in E_T predictions for all species (Table 3). This also corresponded with substantial reduction in error runoff prediction.

Figure 5 shows the relationship between expected and predicted E_T for 2012 using average k_c values for 2011 and 2012. Perhaps due to the simplification of making seasonal k_c estimates, our calculations tend to over-predict low E_T and under-predict high E_T; this is in line with the findings of others for using the ASCE version of the Penman Monteith equation (Marasco et al. 2014). The Nash-Sutcliffe estimate comparing observed and predicting E_T for 2012 is 0.31, indicating our predictions are a substantial improvement over the dataset mean.

Figures 6a-c show the predicted runoff for (a) *P. kamtschaticus*, (b) *S. album* and (c) *S. sexangulare* using the 2012 data and 2011 k_c values. As shown, the simple water balance model predicts runoff, in the best example, to within 2%. Using the k_c values derived here, E_T was somewhat overpredicted by the model, but this had little effect on the overall water balance (Table 3). As Figure 4 suggests, the more substantial error in the model is likely attributed to errors in accurately measuring field capacity, which was not the main focus of our study. This is demonstrated (Figure 4) by the marked difference between observed and predicted VWC immediately following a rain event. The model over-predicted FC, especially during the summer months, despite our attempts to empirically adjust for this. The inability of the substrate to consistently reach FC could be explained by a hysteresis of the wetting curve for our substrate (Perelli 2014), which had a substantial clay content. This phenomenon could also be explained by a lack of low-intensity (i.e. long) saturating rainfall events, coupled with higher canopy interception, and possibly also hydrological 'channeling' and preferential stem flow (She and Pang 2008).

Conclusions:

This study clearly illustrates that once appropriate crop coefficients are established the FAO56 Penman Monteith equation, when properly parameterized, can accurately predict E_T for green roof species, and it can be adjusted to account for both variations in soil moisture and plant water use on a daily or seasonally-adjusted basis. We have identified and provided some insight into how accurate k_c-values should be estimated for different succulent species exhibiting CAM physiology, especially given that plant water use can be significantly over-estimated.   This increased precision is absolutely necessary for reflecting meaningful rates of E_T, especially when considering the multiplicative effects for predicting stormwater runoff. Long-term estimates of k_c values, accumulated over many years for different green roof plant species in different environments, along with observations about plant characteristics associated with k_c values, may ultimately yield a more generalizable k_c-value for use in this equation.

Apart from a simple direct method to more accurately predict E_T and model stormwater runoff, the simple greenroof water balance model is a tool that will enhance the way researchers can contribute to the design process (Felson et al. 2013) and assist in efforts to maximize performance in varying climates. The advantage of the simple water balance model presented here is the ease at which it can be run with relatively few easily-measured input parameters, which can be automated at a very low cost, compared with green roof installation and maintenance costs. We have shown how a water balance model can be used to predict green roof runoff with 90% precision. This is very important for us to quantify runoff from roofs where measuring runoff is difficult (in retrofit) or oftentimes impossible. In time, we may also be able to improve predictions of green roof performance at the roof scale by measuring long-term k_c values.

Perhaps the best application of models like this one is for generating new hypotheses about the green roof water cycle. We have identified a challenge with our water balance models, and an intriguing characteristic of this commercial green roof substrate, in that substrate field capacity after a storm can be highly variable depending on antecedent conditions. More complex models may need to be revisited to address this source of error in our water balance models. but this will only be possible once green roof substrate parameters are more easily defined and accurately measured utilizing techniques demonstrated by Fassman and Simcock (2012). Li and Babcock (2014) have provided a review of different models that could be used. Once sufficiently verified, a model that predicts runoff can be utilized in situations where actual rates of E_T are unknown, where measurement of runoff is difficult (e.g. in retrofit situations), and possibly even in the context of discussions about incentivizing the installation of green roofs. We suggest that until a more complex model is verified, a simple water balance model, as parameterized here, can be used to effectively estimate stormwater runoff from green roofs.

Ultimately green roof model predictions could be incorporated into larger scale watershed models that could assist in the urban planning decision-making process. The ability to quantify green roof performance at the small scale, to understand variability at the large scale, has been previously been limited by complexity and cost. With recent advances in gaining real-time information from sensor networks, this capability is now within the budgets for many green roof installations. Having models that can predict green roof efficiency and performance combined with cost-effective monitoring systems will become more important as communities become more committed to stormwater management, particularly where verification for stormwater efficiency allows trading of stormwater credits (DDOE 2015).

5. Acknowledgements:

This research was supported by funding through a United States Department of Agriculture specialty crop research initiative grant (SCRI 2009-51181-05768), and a Sigma Xi grant to Olyssa Starry. Both Emory Knoll Farms and Conservation Technology provided our plants and greenroof supplies, respectively, at a generous discount.

References:

Allen, R. G., Pereira, L.S., Raes, D., and Smith, M. (1998). "Crop evapotranspiration- Guidelines for computing crop water requirements." FAO, Rome.

Annandale, J.G., and C.O. Stockle. (1994). "Fluctuation of crop evapotranspiration coefficients with weather:a sensitivity analysis." Irrigation Science 15:1-7.

Baraglioli, A., Guillon, A., Kovacs, Y., and Senechal, C. (2008). "Studies on the quantity impacts of green roofs." 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

Burszta-Adamiak, E. and Mrowiec, M. (2013). "Modelling of green roofs' hydrologic performance using EPA's SWMM." *Water science and technology : a journal of the International Association on Water Pollution Research* 68, 36-42.

Butler, C. (2011). "Ecology and physiology of green roof plant communities." *Doctoral Dissertation*, Tufts University Department of Biology.

Carson, T.B., Marasco, D.E., Culligan, P.J., and McGillis, W.R. (2013). "Hydrological performance of extensive green roofs in New York City: observations and multi-year modeling of three full-scale systems." *Environmental Research Letters* 8, 024036.

Carter, T. and Rasmussen, R.C. (2006). "Hydrologic behavior of vegetated greenroofs." *Journal of the American Water Resources Association* October, 1261-1274.

DDOE, DC Department of Energy and Environment (2015). "Stormwater Retention Credit Trading Program." http://doee.dc.gov/src

DiGiovanni, K., (2013). "Evapotranspiration from Urban Green Spaces in a Northeast United States City." *Doctoral Dissertation.* Drexel University Department of Civil, Architectural and Environmental Engineering.

DiGiovanni, K., Montalto, F., Gaffin, S., and Rosenzweig, C. (2013). "Applicability of Classical Predictive Equations for the Estimation of Evapotranspiration from Urban Green Spaces: Green Roof Results." *Journal of Hydrologic Engineering* 18, 99-107.

Fassman, E. and Simcock, R. (2012). "Moisture Measurements as Performance Criteria for Extensive Living Roof Substrates." Journal of Environmental Engineering. 138(8), 841-851.

Feller, M. (2011). "Quantifying evapotranspiration in green infrastructure: a green roof case study." *Masters Thesis*, Villanova University, Civil and Environmental Engineering.

Felson, A.J., M. Pavao-Zuckerman, T. Carter, F. Montalto, B. Shuster,N. Springer, E. Stander, and O. Starry. (2013). "Mapping the design process for urban ecology researchers." BioScience 63(11):854-865.

FLL, Forschungsgesellschaft fuer Landschaftsentwicklung und Landschaftsbau (2008). „*Richtlinie für die Planung, Ausführung und Pflege von Dachbegrünungen*." Bonn, Eigenverlag.

Guswa, A.J., Celia, M.A., and Rodriguez-Iturbe, I. (2002). "Models of soil moisture dynamics in ecohydrology: A comparative study." *Water Resources Research* 38 (9), 1166-1180.

Hawkins, R. H., Ward,T.J., Woodward, D.E., and Van Mullem, J.A. (2009). "Curve Number Hydrology:State of the Practice. " American Society of Civil Engineers, Reston, Virginia. 106pp. ISBN 978-0-7844-1044-2.

Hilten, R.N., Lawrence, T.M., and Tollner, E.W. (2008). "Modeling stormwater runoff from green roofs with HYDRUS-1D." *Journal of Hydrology* 358, 288-293.

Kasmin, H., Stovin, V.R., and Hathway, E.A. (2010). "Towards a generic rainfall-runoff model for green roofs." *Water science and technology : a journal of the International Association on Water Pollution Research* 62, 898-905.

Lazzarin, R.M., Castellotti, F., and Busato, F. (2005). "Experimental measurements and numerical modelling of a green roof." *Energy and Buildings* 37, 1260-1267.

Li, Y., and Babcock, R.W. Jr. (2014). "Green roof hydrologic performance and modeling: a review." *Water Science and Technology*. 69(4), 727-738.

Locatelli, L., Mark, O., Mikkelsen, P.S., Arnbjerg-Nielsen, K., Bergen Jensen, M., and Binning, P.J. (2014). "Modelling of green roof hydrological performance for urban drainage applications." *Journal of Hydrology* 519, 3237-3248.

Lotteau, M. (2006). "Quantifying Interception for New Zealand Green-roofs." *Undergraduate Thesis* The University of Auckland, Department of Civil and Environmental Engineering.

Mentens, J., Raes, D. and Hermy, M. (2006). "Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?" *Landscape and Urban Planning* 77, 217-226.

Marasco, D., Hunter, B.N., Culligan, P.J., Gaffin, S.R., and McGillis, W.R. (2014), "Quantifying Evapotranspiration from Urban Green Roofs: A Comparison of Chamber Measurements with Commonly Used Predictive Methods." *Environmental Science and Technology* 48 (17), 10273-10281.

Maryland Department of the Environment (MDE) 2009. "Stormwater design manual." http://www.mde.state.md.us/Programs/WaterPrograms/SedimentandStormwater/stormwater_design/index.asp

Nawaz, R., McDonald, A., and Postoyko, S. (2015). “Hydrological performance of a full-scale extensive green roof located in a temperate climate.” *Ecological Engineering* 82, 66-80.

Palla, A., Gnecco, I., and Lanza, L.G. (2009). “Unsaturated 2D modelling of subsurface water flow in the coarse-grained porous matrix of a green roof.” *Journal of Hydrology* 379, 193-204.

Perelli, G. A. (2014). “Characterization of the Green Roof Growth Media.” *Masters Thesis* The University of Western Ontario Civil and Environmental Engineering Program.

Raes, D. Timmerman, A., Hermy, M., and Mentens, J. (2006). “GreenRoof – water balance model.” K.U.Leuven University, Faculty of Bioscience Engineering, Division of Soil and Water Management, Leuven, Belgium.

Rezaei, F. and Jarrett, A.R. (2005). “Measure and predict evapotranspiration rate from greenroof.” *Penn State College of Engineering Research Symposium*.

Schneider, D. (2011). “Quantifying Evapotranspiration from a Green Roof Analytically.” *Masters Thesis* Villanova University, Civil and Environmental Engineering.

She, N. and Pang, J. (2008). “A Deterministic Lumped Dynamic Green Roof Model.: ASCE Low Impact Development for Urban Ecosystem and Habitat Protection Proceedings, pp. 1-14, doi: 10.1061/41009(333)14.

Sherrard, J.A. and Jacobs, J.M. (2012). “Vegetated Roof Water-Balance Model: Experimental and Model Results.” *Journal of Hydrologic Engineering* 17, 858-868.

Starry, O. (2013). “The comparative effects of three sedum species on green roof stormwater retention.” *Doctoral Dissertation*, University of Maryland College Park, Department of Plant Science and Landscape Architecture.

Starry, O., Lea-Cox, J.D., Ristvey, A.G., and Cohan, S. (2014a). "Monitoring and Modeling Green Roof Performance Using Sensor Networks." *Acta Horticulturae* 1037: 663-669.

Starry, O., Lea-Cox, J.D., Kim, J., and van Iersel, M.W. (2014b). "Photosynthesis and water use by two Sedum species in green roof substrate." *Environmental and Experimental Botany* 107(2014):105-112.

Stovin, V., Vesuviano, G. and Kasmin, H. (2012). "The hydrological performance of a green roof test bed under UK climatic conditions." *Journal of Hydrology* 414-415, 148-161.

't Hart, H., Eggli, U. (1995). "Evolution and systematics of the Crassulaceae." *International Organization for Succulent Plant Study Congress 1994*, Wageningen, Netherlands, 168.

Thornthwaite, C. W. and Mather, J. R. (1955). " The Water Balance." Publications in Climatology, Drexel Institute of Technology, NJ.

USDA, United States Department of Agriculture (1986). "Urban hydrology for small watersheds." Technical Release 55.

Voyde, E., Fassman, E., Simcock, R. and Wells, J. (2010). "Quantifying Evapotranspiration rates for New Zealand green roofs." *Journal of Hydrologic Engineering* 15:395-403.

Voyde, E. (2011). "Quantifying the Complete Hydrologic Budget for an Extensive Living Roof. "*Doctoral Dissertation*, The University of Auckland Department of Civil and Environmental Engineering.

Table 1 Summary of different kc-values reported in the literature.

Kc Value	Reference	Green roof design and location	Study duration	Plant type
0.15 - 0.62	Lazzarin 2005	$1000m^2$ green roof in Vicenza, Italy	2 summers and 1 winter	*Sedum* mix
0.53	Sherrard and Jacobs 2012	Rooftop modules, NH, USA	Fall Aug-Nov	*Sedum* mix
0.85 - 1.01	Voyde 2011	Greenhouse study, Auckland, NZ (FAO-24 method used)	Simulated NZ Fall (March/April)	*S. mexicanum and D. australe*
0.59 - 0.98	DiGiovanni 2013	Single rooftop module, New York, NY	Seasonal average over 3 years	*Sedum* mix
0.80 - 1.44	Locatelli et al. 2014	3 green roof test sites in Denmark	1 year	*Sedum* mix
0.24 - 3.25	Rezai and Jarrett 2005	Greenhouse study, State College, PA, USA	6 months controlled to simulate 4 seasons	*D. nubigenum and S. album*

Table 2. Average k_c values and (standard error) for three different green roof succulent species, by season. Statistically significant differences (proc mixed) within seasons are indicated by the symbol * (p<0.01). Significant differences within species by season (p<0.01, proc mixed) are labeled with different letters.

Season	*S. album*	*P. kamtschaticus*	*S. sexangulare*
Spring 2011	0.24^{a} (0.03)	0.25^{a}(0.03)	0.36^{abc}(0.07)
Summer 2011	0.21^{a} (0.02)*	0.28^{a} (0.02)*	0.22^{b} (0.02)*
Fall 2011	0.39^{b}(0.03)	0.40^{ab}(0.04)	0.46^{ac} (0.06)
Spring 2012	0.32^{a} (0.03)*	0.58^{cd}(0.04)*	0.55^{c} (0.04)*
Summer 2012	0.25^{a} (0.02)*	0.71^{c} (0.04) *	0.36^{abc} (0.04)*
Fall 2012	0.50^{b}(0.08)	0.46^{bd} (0.03)	0.34^{ab} (0.03)

Table 3. Estimated k_c values for three different succulent species, by season in 2012, and associated effects on model predictions

Crop coefficient (k_c) used	Species	2012 E_T predicted vs (actual)	Equation relating predicted E_T to expected*	2012 Runoff (mm) predicted vs (actual)
2011	*S. album*	146 (137)	y = 0.25x + 0.58 $R^2 = 0.10$	297 (293)
	P. kamtschaticus	163 (176)	y = 0.27x + 0.58 $R^2 = 0.20$	278 (226)
	S. sexangulare	170(167)	y = 0.25x + 0.66 $R^2 = 0.14$	270 (285)
Average of 2011 and 2012	*S. album*	160 (137)	y = 0.30x + 0.61 $R^2 = 0.13$	280 (293)
	P. kamtschaticus	205 (176)	y = 0.54x + 0.56 $R^2 = 0.31$	220(226)
	S. sexangulare	185 (167)	y = 0.34x + 0.65 $R^2 = 0.17$	250(285)
Fixed seasonal average (0.38)	*S. album*	187 (137)	y = 0.29x + 0.74 $R^2 = 0.07$	245 (293)
	P. kamtschaticus	187 (176)	y = 0.42x + 0.57 $R^2 = 0.27$	245 (226)
	S. sexangulare	187 (167)	y = 0.32x + 0.68 $R^2 = 0.15$	245 (285)
k_c=1	*S. album*	275 (137)	y = 1.13x + 0.62 $R^2 = 0.18$	127 (293)
	P. kamtschaticus	275 (176)	y = 1.04x + 0.48 $R^2 = 0.31$	127 (226)
	S. sexangulare	275 (167)	y = 0.79x + 0.74 $R^2 = 0.17$	127 (285)

Note: Large storms were removed from runoff totals; E_T could only be measured on days when there was no rain.
*All correlations were significant at $p<0.01$.

Figure 1. Experimental green roof platforms

Figure 2. Relationship between predicted and observed FC: FC = 0.215 + 0.0005tdp - 0.0018dpe - 0.0021adt, (R^2=0.44, p<0.001).

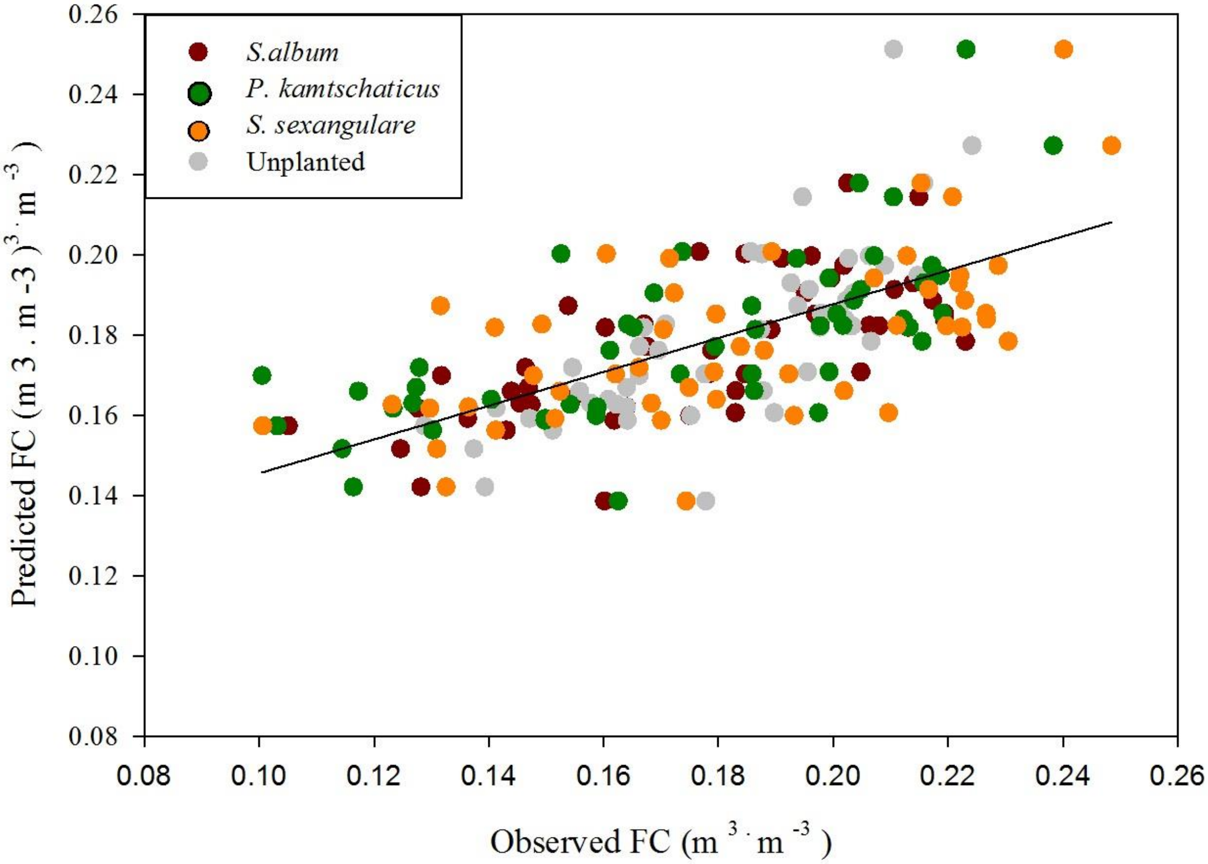


Figure 3a-c Calculated E_{T}o and actual measured E_T in 2011 for experimental green roof platforms planted with (a) *Sedum album* (b) *Phedimus kamtschaticus,* and (c) *Sedum sexangulare*

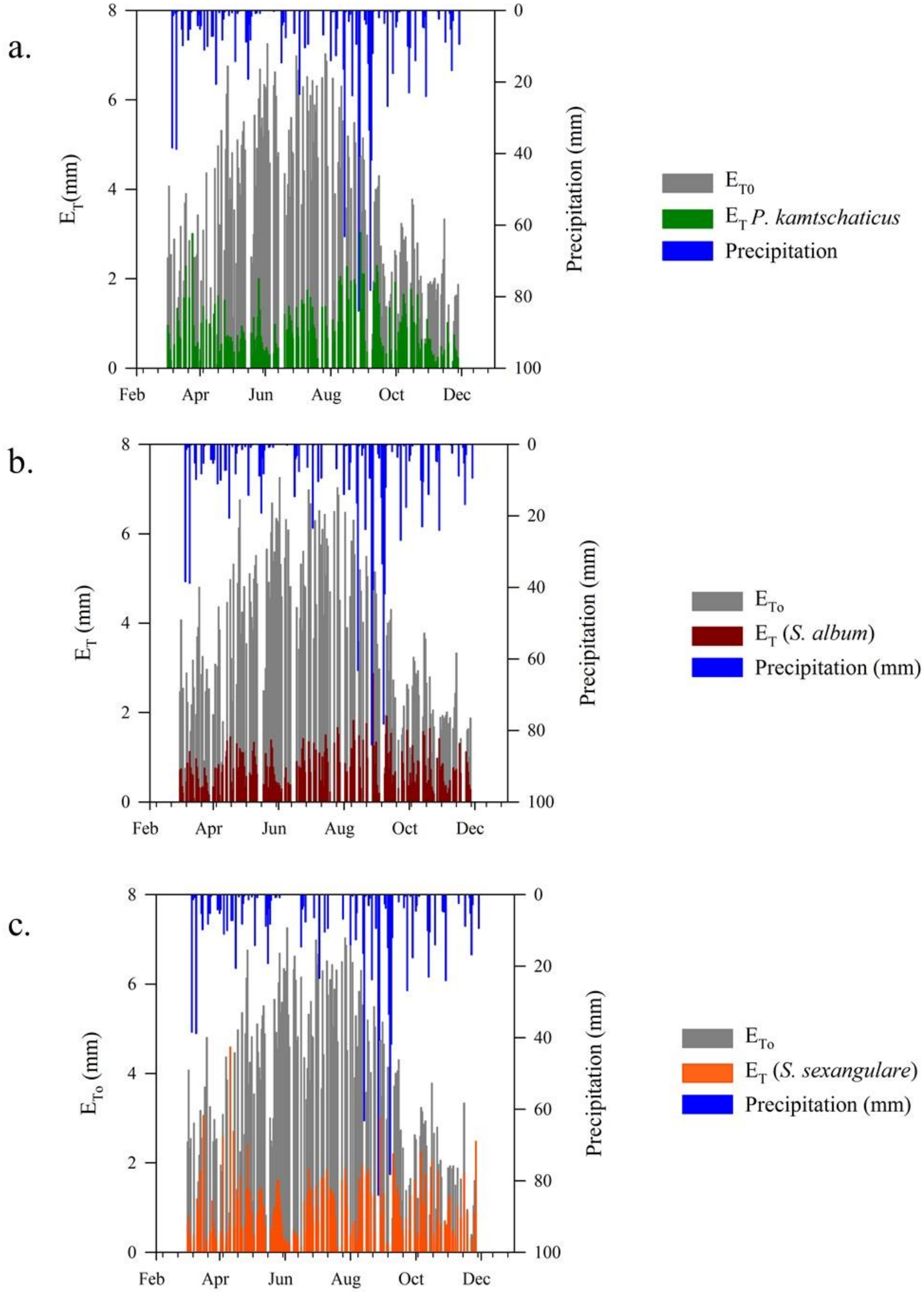
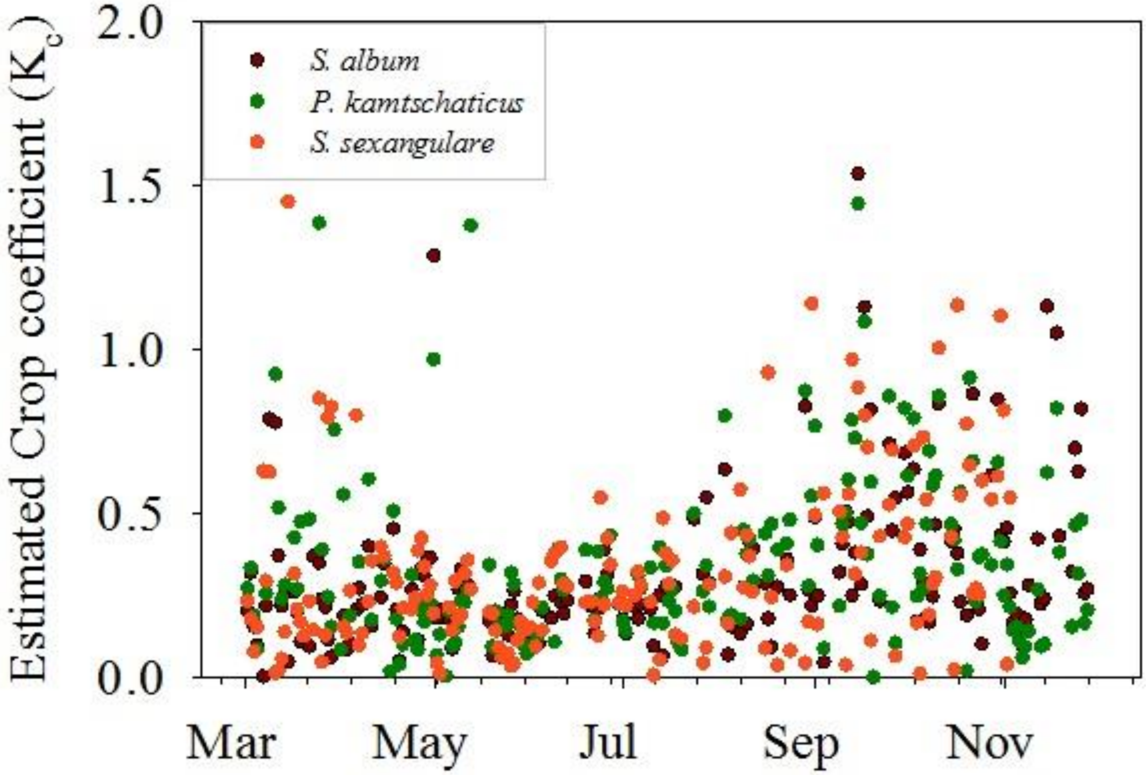


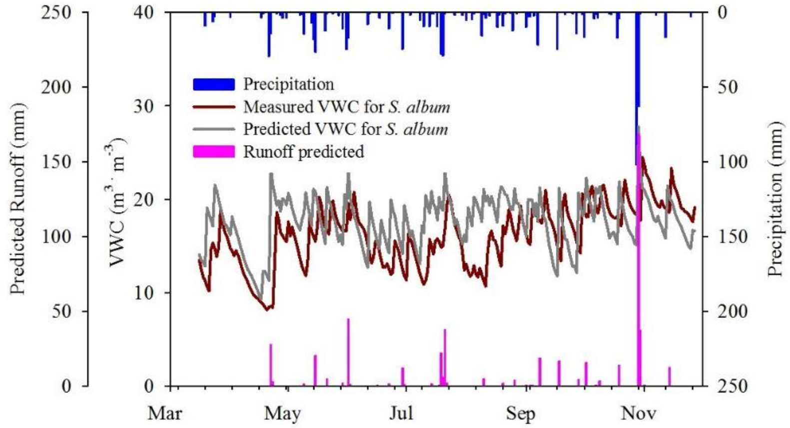
Figure 4. Estimated daily k_c values for each species for non-rainy days during 2011.



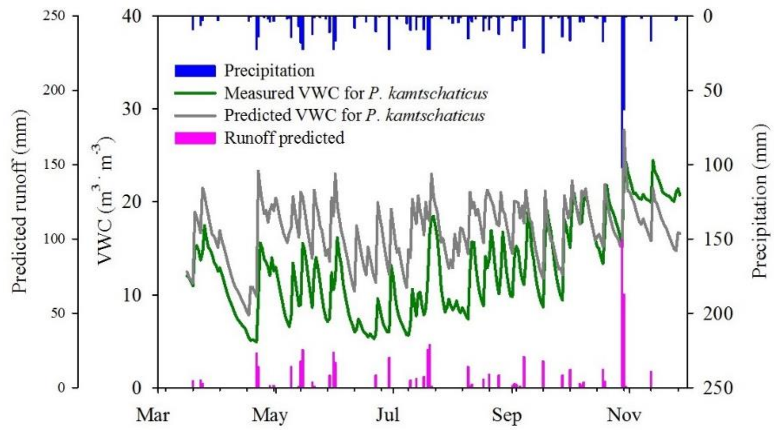
512
513

Figure 5a-c Incorporating E_T estimates into the green roof water balance model to predict stormwater runoff for (a) *S album* and (b) *P. kamtschaticus and (c) S. sexangulare.*

a.



b.



c.