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

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

Olyssa Starry¹, John Lea-Cox², Andrew Ristvey³, and Steve Cohan⁴.

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 to 1, which over-predicted $E_T$ by 100 mm 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
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 has 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 $k_c$ 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 ET rates for three green roof species merit the use of different crop coefficients in the FAO56 equations for predicting plant ET, 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 kc 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 kc 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:

\[
ET_{0} = \frac{0.408(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)} \quad \text{... Equation 1}
\]

where \(ET_{0}\) 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, \(\Delta\) is the slope of the vapor pressure curve, \(\gamma\) 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:

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

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 ($ks \cdot E_{To}$) 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$^3$ ∙ 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. kamschaticus, 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 $k_s$ 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 ($k_s$* $E_T$) 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 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 $k_c$ value (0.38, the average of all $k_c$s 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 ks term in the FAO Penman Monteith equation.

3.2 Actual vs. Estimated Evapotranspiration (ET0)

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 ET among species were also evident, though not statistically significant.

In 2011, the highest total ET 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 $k_s$ 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. kamtschaticus* and *S. sexangulare* as moisture content was reaching wilting point; $k_s$ 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 (*C₃* 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 165 mm 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 ET among species were significant (Starry 2013). In 2012, the highest total ET was 184 mm for *P. kamtschaticus*, compared to 180 mm for *S. sexangulare* and 138 mm for *S. album*. Despite less rain in 2012, total rates of ET 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 ET from green roofs in 2012. Table 3 shows how selecting different \( k_c \) values are associated with different ET predictions and associated error for different species. For example, selecting a fixed seasonal average for \( k_c \) resulted in more error in ET predictions for *S. album* since this species had the most seasonally variable rates of ET. Adjusting the FAO Penman Monteith equation with 2011 crop coefficients allowed for prediction of ET 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 ET 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 ET 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 ET 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 ET and under-predict high ET; 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).

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

<table>
<thead>
<tr>
<th>Kc Value</th>
<th>Reference</th>
<th>Green roof design and location</th>
<th>Study duration</th>
<th>Plant type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15 - 0.62</td>
<td>Lazzarin 2005</td>
<td>1000m² green roof in Vicenza, Italy</td>
<td>2 summers and 1 winter</td>
<td>Sedum mix</td>
</tr>
<tr>
<td>0.53</td>
<td>Sherrard and Jacobs 2012</td>
<td>Rooftop modules, NH, USA</td>
<td>Fall Aug-Nov</td>
<td>Sedum mix</td>
</tr>
<tr>
<td>0.85 - 1.01</td>
<td>Voyde 2011</td>
<td>Greenhouse study, Auckland, NZ (FAO-24 method used)</td>
<td>Simulated NZ Fall (March/April)</td>
<td><em>S. mexicanum</em> and <em>D. australe</em></td>
</tr>
<tr>
<td>0.59 - 0.98</td>
<td>DiGiovanni 2013</td>
<td>Single rooftop module, New York, NY</td>
<td>Seasonal average over 3 years</td>
<td>Sedum mix</td>
</tr>
<tr>
<td>0.80 - 1.44</td>
<td>Locatelli et al. 2014</td>
<td>3 green roof test sites in Denmark</td>
<td>1 year</td>
<td>Sedum mix</td>
</tr>
<tr>
<td>0.24 - 3.25</td>
<td>Rezai and Jarrett 2005</td>
<td>Greenhouse study, State College, PA, USA</td>
<td>6 months controlled to simulate 4 seasons</td>
<td><em>D. nubigenum</em> and <em>S. album</em></td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Season</th>
<th>S. album</th>
<th>P. kamtschaticus</th>
<th>S. sexangulare</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring 2011</td>
<td>0.24$^a$ (0.03)</td>
<td>0.25$^a$ (0.03)</td>
<td>0.36$^{abc}$ (0.07)</td>
</tr>
<tr>
<td>Summer 2011</td>
<td>0.21$^a$ (0.02)*</td>
<td>0.28$^a$ (0.02)*</td>
<td>0.22$^b$ (0.02)*</td>
</tr>
<tr>
<td>Fall 2011</td>
<td>0.39$^b$ (0.03)</td>
<td>0.40$^{ab}$ (0.04)</td>
<td>0.46$^{ac}$ (0.06)</td>
</tr>
<tr>
<td>Spring 2012</td>
<td>0.32$^a$ (0.03)*</td>
<td>0.58$^{cd}$ (0.04)*</td>
<td>0.55$^c$ (0.04)*</td>
</tr>
<tr>
<td>Summer 2012</td>
<td>0.25$^a$ (0.02)*</td>
<td>0.71$^c$ (0.04) *</td>
<td>0.36$^{abc}$ (0.04)*</td>
</tr>
<tr>
<td>Fall 2012</td>
<td>0.50$^b$ (0.08)</td>
<td>0.46$^{bd}$ (0.03)</td>
<td>0.34$^{ab}$ (0.03)</td>
</tr>
</tbody>
</table>
### Table 3. Estimated $k_c$ values for three different succulent species, by season in 2012, and associated effects on model predictions

<table>
<thead>
<tr>
<th>Crop coefficient ($k_c$) used</th>
<th>Species</th>
<th>2012 $E_T$ predicted vs (actual)</th>
<th>Equation relating predicted $E_T$ to expected*</th>
<th>2012 Runoff (mm) predicted vs (actual)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>y = 0.25x + 0.58 R² = 0.10</td>
<td>297 (293)</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td><em>S. album</em></td>
<td>146 (137)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>P. kamtschaticus</em></td>
<td>163 (176)</td>
<td>y = 0.27x + 0.58 R² = 0.20</td>
<td>278 (226)</td>
</tr>
<tr>
<td></td>
<td><em>S. sexangulare</em></td>
<td>170 (167)</td>
<td>y = 0.25x + 0.66 R² = 0.14</td>
<td>270 (285)</td>
</tr>
<tr>
<td>Average of 2011 and 2012</td>
<td><em>S. album</em></td>
<td>160 (137)</td>
<td>y = 0.30x + 0.61 R² = 0.13</td>
<td>280 (293)</td>
</tr>
<tr>
<td></td>
<td><em>P. kamtschaticus</em></td>
<td>205 (176)</td>
<td>y = 0.54x + 0.56 R² = 0.31</td>
<td>220 (226)</td>
</tr>
<tr>
<td></td>
<td><em>S. sexangulare</em></td>
<td>185 (167)</td>
<td>y = 0.34x + 0.65 R² = 0.17</td>
<td>250 (285)</td>
</tr>
<tr>
<td>Fixed seasonal average (0.38)</td>
<td><em>S. album</em></td>
<td>187 (137)</td>
<td>y = 0.29x + 0.74 R² = 0.07</td>
<td>245 (293)</td>
</tr>
<tr>
<td></td>
<td><em>P. kamtschaticus</em></td>
<td>187 (176)</td>
<td>y = 0.42x + 0.57 R² = 0.27</td>
<td>245 (226)</td>
</tr>
<tr>
<td></td>
<td><em>S. sexangulare</em></td>
<td>187 (167)</td>
<td>y = 0.32x + 0.68 R² = 0.15</td>
<td>245 (285)</td>
</tr>
<tr>
<td>$k_c$=1</td>
<td><em>S. album</em></td>
<td>275 (137)</td>
<td>y = 1.13x + 0.62 R² = 0.18</td>
<td>127 (293)</td>
</tr>
<tr>
<td></td>
<td><em>P. kamtschaticus</em></td>
<td>275 (176)</td>
<td>y = 1.04x + 0.48 R² = 0.31</td>
<td>127 (226)</td>
</tr>
<tr>
<td></td>
<td><em>S. sexangulare</em></td>
<td>275 (167)</td>
<td>y = 0.79x + 0.74 R² = 0.17</td>
<td>127 (285)</td>
</tr>
</tbody>
</table>

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, (R²=0.44, p<0.001).
Figure 3a-c  Calculated $E_{T0}$ and actual measured $E_T$ in 2011 for experimental green roof platforms planted with (a) *Sedum album* (b) *Pedinus kamtschaticus*, and (c) *Sedum sexangulare*
Figure 4. Estimated daily $k_c$ values for each species for non-rainy days during 2011.
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.