Evaluation of common evapotranspiration models based on measurements from two extensive green roofs in New York City

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Abstract

Although the evapotranspiration (ET) process has historically received limited attention, it is an important factor for assessing the health and behavior of urban green spaces, including green roofs. In this study, common potential evapotranspiration (PET) models, which assume non-water-limited substrate moisture conditions, and actual evapotranspiration (AET) models, which account for water-limited substrate moisture conditions, are used to predict ET from local climate conditions at two extensive *Sedum* green roof sites in New York City (NYC); one a vegetated mat system (termed W118) and the other a built in place system (termed USPS). Results from the predictions are compared to 12,000 hours of on-site ET measurements obtained using a dynamic chamber system. Among the Hargreaves, Priestley-Taylor, Penman, and American Society of Civil Engineers Penman-Monteith PET models, results from the Priestley-Taylor model, which was developed to predict ET from a wet vegetated surface with minimal advection, best correlate with the dynamic chamber measurements ($r^2 = 0.96$ for W118, 0.82 for USPS). Nonetheless, a systematic error is seen whereby the Priestley-Taylor

model overestimates the low ET fluxes observed during the winter months and underestimates the high ET fluxes observed during the summer months. This error is only exaggerated by the inclusion of an advective ET term. To estimate green roof ET under water-limited conditions, a storage model, antecedent precipitation index (API), and advection-aridity model are applied to the Priestley-Taylor formulation to calculate AET. Results indicate that only the API model, which is based on precipitation history alone, can improve upon the Priestley-Taylor PET predictions ($r^2 = 0.96$ on W118, 0.85 on USPS). Use of a more-physically based, substrate moisture storage greatly over-estimates ET reduction during dry periods. The work provides insight into which common ET models best capture the behavior of full-scale, extensive green roofs, and points to the need for better estimates of green roof ET under climate conditions typical of NYC's winter and summer months.

Keywords

Evaporation, evapotranspiration, green roofs, stormwater management, green roof modeling, evapotranspiration modeling

1 Introduction

The expansion of green roofs and other types of urban green spaces, such as urban forests, bioswales, and green streets, is an increasingly popular strategy to counter urban land development impacts (Mayor's Office of Long-Term Planning and Sustainability, 2008). These green spaces are engineered vegetative systems primarily designed to re-introduce pre-development hydrological conditions and enhance natural processes in otherwise impervious landscapes. Urban green spaces have the potential to detain and retain stormwater, offset carbon emissions, improve air quality, reduce energy usage, and increase public space (Jim and Chen, 2009;

Marasco et al., 2014; NYC DEP, 2010; Ouldboukhithine et al., 2011; Taha et al., 1991; Voyde et al., 2010a; Wadzuk et al., 2013).

Evapotranspiration (ET) is the combined water vapor surface flux that results from evaporation and plant respiration. ET is an important factor affecting the vitality and performance of green roofs and other urban green spaces; however, the quantification of ET from these spaces has historically received limited attention (DiGiovanni et al., 2013; Grimmond and Oke, 2002; Voyde et al., 2010b). Studies of urban green spaces have shown that the ET process is directly correlated with environmental benefits related to stormwater management (Stovin et al., 2013; Wadzuk et al., 2013), urban heat island mitigation (Taha, 1997), building energy usage (Ouldboukhithine et al., 2011), carbon sequestration (Pataki et al., 2006), and air pollution (Christen and Vogt, 2004; Jim and Chen, 2009). Additionally, ET is an important parameter in many urban hydrologic (Hiltner et al., 2008; Sherrard and Jacobs, 2012; Stovin et al., 2013; Zhao et al., 2013) and energy transfer models (Lazzarin et al., 2005; Ouldboukhithine et al., 2011; Wang et al., 2013).

ET primarily results from solar energy, but is affected by vegetation properties (e.g. stomatal resistance, health, and biomass) as well as various environmental conditions, including the surface albedo, aerodynamic roughness, boundary layer humidity profile, and available substrate moisture (Allen et al., 1996; MacIvor et al., 2011; Mawdsley and Ali, 1985; Salvucci and Gentine, 2013). Because the ET process is invisible and difficult to measure directly, numerous models have been developed to predict ET from environmental data (Zhao et al., 2013).

Models developed to estimate ET, such as Hargreaves (Hargreaves and Allen, 2003), Priestley-Taylor (1972), Penman (1948), and Penman-Monteith (Monteith, 1965) generally estimate the

“potential evapotranspiration” (PET) (i.e. the energy-limited ET) or “reference evapotranspiration” (RET) (i.e. ET under typical substrate moisture conditions) over a static underlying surface, such as water, bare soil, or a “reference” vegetation. The Hargreaves and Priestley-Taylor models are based on a composite of energy and temperature data, while the Penman and Penman-Monteith models also incorporate wind and humidity measurements to estimate advective ET.

PET models neglect factors that affect the actual evapotranspiration (AET), including variations in substrate moisture availability, surface conditions, plant physiology, plant vitality, and weather (Allen et al., 1996; R. G. Allen et al., 2005; Zhao et al., 2013). When transpiration is minimal (e.g. during the winter and early spring), ET consists primarily of evaporation and is significantly correlated with substrate moisture at the surface level (R. G. Allen et al., 2005). Evaporation from bare soil can be considered “energy-limited” or “water-limited” based on the moisture availability. When evaporation is energy-limited, sufficient surface moisture is available to supply the PET demand. As surface moisture evaporates and insufficient moisture is available to meet the PET demand, evaporation becomes “water-limited”, and is affected by soil heat density, soil properties, and remaining moisture availability (R. G. Allen et al., 2005). Transpiration is a more complex process than evaporation. Even in energy-limited, or potential, conditions, transpiration is affected by sub-surface moisture, as well as the structure and vitality of substrate vegetation (Allen et al., 1996; Brutsaert, 2005). Furthermore, PET is often estimated from non-potential environmental conditions. For example, when ET drops below potential, excess energy becomes available, altering air temperature, humidity, and turbulence near the

surface (Brutsaert and Stricker, 1979), which affect PET estimates. PET calculated under these conditions is referred to as “apparent” PET (Brutsaert, 2005).

The environmental processes and conditions affecting the hydrologic cycle in urban green spaces vary from those of homogeneous, well-watered, agricultural and natural settings. Consequently, assumptions made in conventional hydrologic models may inaccurately portray the behavior and benefits of urban green spaces (Graham et al., 2004). ET in urban environments is generally lower than the surrounding natural environment and is often neglected or simplified in hydrologic models (Berthier et al., 2006; Grimmond and Oke, 2002). However, urban ET can still be a major component of the water balance, especially when urban trees and green spaces are present (Grimmond and Oke, 2002, 1991). ET from urban green spaces is affected by their unique properties, including small scale, vegetation heterogeneity, shallow substrate depths, engineered substrate properties, underlying surfaces, and uncertain moisture availability (Carson et al., 2013; DiGiovanni et al., 2013; Grimmond and Oke, 2002; Jim and Peng, 2012; Spronken-Smith et al., 2000). The increased air temperature and lower humidity of the surrounding built-up environment can enhance local and micro-scale moisture advection of urban green spaces (Spronken-Smith et al., 2000) and alter transport of heat and momentum (Taha, 1997). In addition, as described by Jim and Peng (2012), shallow extensive roof substrates can have elevated temperatures in water-limited conditions, enhancing ET.

2 Summary of AET models and Green Roof ET studies

2.1 Actual Evapotranspiration Models

AET estimation procedures generally calculate flux from PET results based on existent non-potential conditions (Brutsaert, 2005). The variation between PET and AET is primarily a

function of water availability in the soil. At substrate field capacity, AET is equal to PET; as soil moisture decreases, so does AET. Various soil moisture extraction functions (SMEFs) based on a combination of actual soil moisture, field capacity, and wilting point have been employed to relate the degree of substrate saturation to AET (Allen, 2000; DiGiovanni et al., 2013; Zhao et al., 2013).

In the absence of soil moisture data, other moisture indices and PET reduction procedures have been employed to estimate AET, including accumulated precipitation and ET deficit models (Arora, 2002; Calder et al., 1983; Grindley, 1970; Priestley and Taylor, 1972), antecedent precipitation indices (Ali and Mawdsley, 1987; Choudhury and Blanchard, 1983; Mawdsley and Ali, 1985; Westenbroek et al., 2010), the advection-aridity model (Ali and Mawdsley, 1987; Brutsaert and Stricker, 1979; Kahler and Brutsaert, 2006), water stress – surface temperature relationships (Boulet et al., 2007; Moran et al., 1994), and relative humidity profiles (Berthier et al., 2006; Salvucci and Gentine, 2013).

2.2 Studies of Green Roof ET

Green roof ET has been measured in a variety of studies in order to quantify rooftop behavior. ET is most often measured with a lysimeter (DiGiovanni et al., 2013; Ouldboukhite et al., 2012; Sherrard and Jacobs, 2012; Voyde et al., 2010b; Wadzuk et al., 2013). Results from these studies show average ET rates between 1 and 3 mm day⁻¹. Berghage et al.(2007)measured daily ET from a series of green roof test boxes within a greenhouse for approximately three weeks following irrigation and determined the presence of vegetation significantly increases ET. VanWoert et al.(2005) performed a greenhouse study of ET from *Sedum* planted test boxes with

varying substrate depths; Their results demonstrated that deeper substrates supported additional plant growth and higher ET rates.

A number of green roof studies have reported the performance of different PET models and the effects of soil moisture on ET. DiGiovanni et al. (2013) compared ET measurements from a lysimeter located on a full-scale green roof to two forms of the Penman-Monteith model and showed that the models performed well on non-water-limited days. A variation of the Thornthwaite-Mather (1955) attenuating factor was then applied to estimate AET from PET, improving predictions when substrate moisture was limited. Results from green roof test box experiments by Berghage et al. (2007), Starry et al. (2014), and Poe et al. (2015) demonstrated that substantial reductions in measured ET compared to PET generally occurred after approximately 7 days without irrigation. Lazzarin et al. (2005) employed an empirical version of the Penman model and a reduction factor based on relative humidity to predict AET. The formulation worked well in well-watered conditions, but the reduction factor was unable to account for the effects of limited water.

Jim and Peng (2012) investigated the influence of substrate moisture on green roof ET by dividing monitored days into 9 categories defined from 3 weather (sunny, cloudy, and rainy) and substrate moisture (wet, moist, and dry) types. Results show that substrate moisture had a limited influence on ET, and the primary factors correlated with measured ET were those included in common PET models. Dry substrates on sunny days demonstrated higher ET, explained by the shallow substrate allowing solar energy to heat up the entire substrate layer, increasing temperature and enhancing, rather than reducing, ET.

ET estimation techniques have been employed in a variety of studies to predict behavior and supplement green roof hydrologic and energy models. Hilten et al. (2008) were able to apply the Hargreaves model in HYDRUS 1-D (Simunek et al., 2006) to predict daily runoff from a series of green roof test boxes ($r^2 = 0.92$), after determining Monthly total ET estimates from the Hargreaves and American Society of Civil Engineers (ASCE) Penman-Monteith models were not significantly different (Hilten, 2005). Berthier et al. (2011) and Sherrard and Jacobs (2012) developed and calibrated reservoir storage models to predict runoff, incorporating daily calculations of Penman-Monteith PET. Berthier et al. used PET, while Sherrard and Jacobs incorporated a soil moisture extraction function to modify PET in water limited conditions. Sherrard and Jacobs' calibrated model was compared to data measured from a lysimeter setup and was shown to accurately predict daily storage and runoff (r^2 equal to 0.94 and 0.98, respectively) but showed reduced correlation in the prediction of ET (r^2 equal to 0.59). Stovin et al. (2013) applied average monthly estimations of PET and a soil moisture extraction function (SMEF) to better predict green roof storage and runoff. The model was used to evaluate the performance of green roofs in four different climate regions based on variations in precipitation and PET. Results show that climate variations affect rooftop hydrological performance and drought susceptibility.

This work expands upon prior studies exploring the applicability of ET models for green roof behavior, by comparing predictions from several, common PET and AET models, parameterized using local site and climate conditions, to ET measurements made at two extensive, *Sedum* green roofs located in New York City. The PET predictions are obtained using the Hargreaves, Priestley-Taylor, Penman, and American Society of Civil Engineers (ASCE) Penman-Monteith

models, which have been employed in a number of green roof ET studies (DiGiovanni et al., 2013; Hilten et al., 2008; Lazzarin et al., 2005; Wadzuk et al., 2013), while the AET predictions are derived using a storage model with a soil moisture extraction function (Stovin et al., 2013), the antecedent precipitation index, and an advection-aridity model (Ali and Mawdsley, 1987). By comparing the daily ET fluxes predicted via each model with observed values obtained from a dynamic chamber system (Marasco et al. 2014), insight is gained into the applicability of each model for green roof studies. In addition, individual model strengths and deficiencies are uncovered, together with the specific conditions under which improvements to all modeling approaches are needed.

3 Site Descriptions and Methodology

3.1 Site Descriptions and Instrumentation

Dynamic chamber measurements and environmental monitoring were conducted on two *Sedum* extensive green roofs in Manhattan, NY between January 2009 and October 2013. Table 1 summarizes the green roof characteristics. A more detailed description of the green roof sites, instrumentation, and data collection is provided by Marasco et al. (2014).

Initial dynamic chamber measurements were collected on a Columbia University residential building (termed W118), located at 423 West 118th St, Manhattan, NY for a minimum of 11 days each month between July 2009 and December 2009, with the exception of September 2009. The W118 roof system is a Xero Flor America XF301+2FL vegetated mat, which is assembled and planted before placement on the roof membrane. The system consists of 32 mm thick pre-planted and expanded shale based substrate layer that is underlain by two 6 mm thick water retention fleeces, a 19 mm non-woven polymer drainage mat, and a 0.5 mm polyethylene root barrier. The

following plant species were established on this roof: *Saxifraga granulata*, *Sedum acre*, *Sedum album*, *Sedum ellacombianum*, *Sedum hybridum* 'Czars Gold', *Sedum oregonum*, *Sedum pulchellum*, *Sedum reflexum*, *Sedum sexangulare*, *Sedum spurium* var. *coccineum*, and *Sedum stenopetalum*. Solar radiation, air temperature, relative humidity, wind speed, and precipitation data were recorded at 15-minute intervals by a Campbell Scientific CR1000 weather station from January 2009 to October 2013.

A second dynamic chamber deployment and collection of environmental data took place on the US Post Office Morgan Processing and Distribution Center green roof (termed USPS) in Manhattan, NY between April 2012 and October 2013. The USPS roof was constructed by Tecta Green using a built in place strategy where borders were set with metal brackets on the roof membrane, and a geo-composite drainage course, retention fleece, and an expanded shale based growing substrate were placed within the bounded region. The main portion of the roof was planted with the following *Sedum* species: *Sedum spurium* 'Roseum', *Sedum acre*, *Sedum album* 'Coral Carpet', *Sedum album* *murale*, *Sedum reflexum*, *Sedum sexangulare*, *Sedum reflexum* 'Blue Spruce', *Sedum grisebachii*, *Sedum kamtschaticum*, *Sedum* 'Matrona', *Sedum pluricaule* 'Rosenteppich', and *Sedum telephium* 'Autumn Joy'. In select locations, 200 mm deep berms, usually about 2 m wide and of varying lengths, were developed and sowed with the following plant species: *Achillea filipendula* 'Moonshine', *Alium schoenoprasum*, *Coreopsis vert* 'Moonbeam', *Silene caroliniana* ssp. *wherryi*, *Talinum calycinum*, and *Tradescantia ohiensis*. An Onset Hobo U30 weather station recorded air temperature, relative humidity, solar radiation, wind speed, and precipitation at 5-minute intervals from January 2012 to October 2013.

Measurements were continuous except in April 2012 and from July to September 2012, when sensors malfunctioned.

For each roof, Carson et al.(2015) measured saturated storage depth, substrate field capacity, and saturated hydraulic conductivity according to ASTM testing standards. Average values from three trials of each test were shown to match manufacturer specifications.

Table 1: Monitored green roof site characteristics

Roof Name	W118	USPS
Construction Type	Vegetated mat	Built-in-place
Year Built	2007	2009
Latitude	40°48'	40°45'
Roof Height (m)	65	45
Roof Area (m ²)	600	10,000
Substrate Depth (mm)	32	100
Saturated Storage Depth (mm)	16	51
Field Capacity (mm)	12	49
Saturated Hydraulic Conductivity (mm s ⁻¹)	0.056	0.047
Irrigation	None	None

3.2 Dynamic chamber Measurements

Dynamic chamber measurements of green roof ET, referred to as ET_{DC}, were conducted using the Licor Biosciences LI-8100 automated soil CO₂ flux system. Marasco et al.(2014) demonstrated that the dynamic chamber could be employed to measure green roof ET and that results obtained via this method were similar to reported values from other green roofs studies in temperate regions in the United States, France, and New Zealand (DiGiovanni et al., 2013; Feller, 2011; Ouldboukhitine et al., 2012; Sherrard and Jacobs, 2012; Tabares-Velasco and Srebric, 2011; Voyde et al., 2010b).

The dynamic chamber was placed at a single location on each roof, close to the center of each drainage area, where *Sedum* species and growth patterns were typical of the overall roof. Measurements occurred every 30 minutes on W118 and every 60 minutes on USPS. For each measurement, the system's chamber (volume, $V = 6850 \text{ cm}^3$ for W118, $V = 7005 \text{ cm}^3$ for USPS) encloses a section of the green roof (surface area, $S = 323.6 \text{ cm}^2$) for 5 minutes and records chamber water vapor concentration, w_c , in mmol mol^{-1} (ppt). The flux of water from the sealed green roof surface into the chamber ($\text{mol cm}^{-2} \text{ s}^{-1}$) is a measure of ET. A nonlinear regression of water vapor concentration versus time data, $t(\text{s})$, with an exponential function of the form

$$w_c(t) = w_s + (w_c(0) - w_s)e^{-K\frac{S}{V}(t-t_0)} \quad (1)$$

is performed for the first minute of measurement, excluding the first 10 seconds to allow for the system to establish steady mixing. Fitting of Equation (1) to measured values of $w_c(t)$ returns values for w_s , the saturation concentration of water vapor at the evaporative surface (mmol mol^{-1}), K , the water vapor transfer velocity (cm s^{-1}), and t_0 , when $w_c(t)$ is equal to $w_c(0)$ (s). ET is then obtained from the water vapor flux at $t = 0$, yielding

$$\text{ET} = \frac{P(0)}{RT(0)} \frac{1}{\left(1 - \frac{w_c(0)}{1000}\right)} K \left(\frac{w_s - w_c(0)}{1000}\right) \quad (2)$$

where $P(0)$ is the initial pressure (kPa), $T(0)$ is the initial temperature (K), and R is the gas constant ($8.314 \times 10^3 \text{ cm}^3 \text{ kPa K}^{-1} \text{ mol}^{-1}$). ET values from Equation (2) were converted to mm day^{-1} by assuming 18 grams of water per mol and a water density of 1 g cm^{-3} .

The dynamic chamber was laboratory calibrated with a series of 6 pan evaporation experiments. In the first 3 experiments, the pan was filled with open water, while subsequent experiments were performed using a sample of Xero Flor substrate. During each 12-hour trial, the pan was placed in the chamber. The pan was weighed every 30 minutes to measure cumulative evaporation. Chamber estimates of ET were obtained during each 5-minute automated chamber closure, programed to occur halfway between each weight measurement. Comparison of chamber and weight measurements revealed a systematic error, where the chamber recorded lower ET than measured by weight. The error is believed to be the result of variations in air turbulence and mixing, water vapor saturation in the air, and water vapor molecules adhering to the surfaces of air-lines between the system's chamber and infrared measurement sensor. A linear regression of the weight-measured ET versus the chamber estimate was able to correct this error ($r\text{-squared} = 0.95$)(Marasco et al., 2014). This correction was then applied to each field measurement. A more detailed description of the dynamic chamber methodology and calibration is provided in Marasco et al.(2014).

3.3 Potential Evapotranspiration Estimates

Four models were employed in this study to estimate baseline PET, assuming uniform, non-water-limited conditions (Table 2). These models, specifically the Hargreaves, Priestley-Taylor, Penman, and ASCE Penman-Monteith, have been used in previous green roof studies (DiGiovanni et al., 2011; Hilten, 2005; Wadzuk et al., 2013). Each model has a distinct physical basis and an assumed set of surface conditions.

Table 2: Description of PET models, physical basis, and assumed surface conditions

Model	Abbreviation	Equation #	Physical basis	Assumed Surface Conditions
Hargreaves	PET _H	(3)	Empirical model based on temperature, location, and year day	Arid/semi-arid grassland
Priestley – Taylor	PET _{PT}	(4)	Equilibrium evaporation model; empirical ET multiplier to account for advection	Wet vegetated surface with minimal advection
Penman	PET _P	(5-6)	Equilibrium evaporation model and advection term	Free water surface
ASCE Penman-Monteith	PET _{PM}	(7)	Modified Penman model; empirical constants for resistance terms	Reference vegetation, well-watered

The 1985 Hargreaves model estimates daily PET_H (mm day⁻¹) using only air temperature and location data, and is generally accurate for periods of a week or longer (Hargreaves and Allen, 2003; Hilten, 2005). The model equation is as follows

$$PET_H = 0.408(0.0023R_a(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}) \quad (3)$$

where R_a is the calculated extraterrestrial radiation, and T_{mean} , T_{max} , and T_{min} are the daily mean, maximum, and minimum air temperature (°C), respectively.

The Priestley-Taylor (1972) model is a refinement of the Slatyer-McIlroy (1961) model for PET from a wet vegetated surface with minimal advection. The Priestley-Taylor model equation for PET_{PT} (mm day⁻¹) is given by

$$PET_{PT} = 0.408 \left[\alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \right] \quad (4)$$

where R_n is the net radiation (MJ m⁻² d⁻¹), G is the soil heat flux density at the soil surface (MJ m⁻² d⁻¹), γ is the psychrometric constant (kPa °C⁻¹), Δ is the slope of the saturation vapor pressure-temperature curve (kPa °C⁻¹), and the coefficient α , which is equal to 1.26, represents the ratio

between the Slatyer-McIlroy calculated equilibrium ET and observed ET from moist, advection-free land and water surfaces (Priestley and Taylor, 1972).

The Penman (1948) model is similar to the Priestley-Taylor model, but includes an advection term. The model equation for PET_P ($mm\ day^{-1}$) is described by

$$PET_P = 0.408 \left[\frac{\Delta}{\Delta + \gamma} (R_n - G) \right] + \left[\frac{\gamma}{\Delta + \gamma} E_A \right] \quad (5)$$

$$\text{where, } E_A = 2.6(1 + 0.54u_2) (e_s - e_a) \quad (6)$$

and R_n is the net radiation ($MJ\ m^{-2}\ d^{-1}$), G is the soil heat flux density at the soil surface ($MJ\ m^{-2}\ d^{-1}$), γ is the psychrometric constant ($kPa\ ^\circ C^{-1}$), Δ is the slope of the saturation vapor pressure-temperature curve ($kPa\ ^\circ C^{-1}$), u_2 is the wind speed ($m\ s^{-1}$), e_s is the saturation vapor pressure (kPa), and e_a is the vapor pressure (kPa)

The ASCE standardized reference evapotranspiration model (i.e. ASCE Penman-Monteith model) reduces the surface and aerodynamic resistance variables in the Penman-Monteith (Monteith, 1965) equation to standard values for reference vegetation types (R. Allen et al., 2005). Here, the short reference surface (e.g. cut grasses) is used, and PET_{PM} ($mm\ day^{-1}$) is given by

$$PET_{PM} = \frac{0.408\Delta(R_n - G) + \gamma \left(\frac{C_n}{T_{mean} + 273} \right) u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (7)$$

where R_n is the net radiation ($MJ\ m^{-2}\ d^{-1}$), G is the soil heat flux density at the soil surface ($MJ\ m^{-2}\ d^{-1}$), γ is the psychrometric constant ($kPa\ ^\circ C^{-1}$), C_n is the numerator constant ($900\ K\ mm\ s^3\ Mg^{-1}\ d^{-1}$ for the daily time step), T_{mean} is the daily mean air temperature ($^\circ C$), u_2 is the wind speed ($m\ s^{-1}$), e_s is the saturation vapor pressure (kPa), e_a is the vapor pressure (kPa), Δ is the slope of the

saturation vapor pressure-temperature curve ($\text{kPa } ^\circ\text{C}^{-1}$), and C_d is the denominator constant (0.34 s m^{-1}) for short vegetation.

Table 3: Variables used in calculation of PET and AET for the daily time step

Variable	Description	Calculation Methodology
API	Antecedent Precipitation Index for calculation of API (mm)	Ali and Mawdsley (1987)
C_d	Denominator constant for short reference type (0.34 s m^{-1})	Allen et al.(2005)
C_n	Numerator constant for the short reference type and daily time step ($900 \text{ K mm s}^3 \text{ Mg}^{-1} \text{ d}^{-1}$)	Allen et al.(2005)
e_a	Mean actual vapor pressure at 1.5 to 2.5 m height (kPa)	Allen et al.(2005)
e_s	Mean saturation vapor pressure at 1.5 to 2.5 m height (kPa)	Allen et al.(2005)
G	Soil heat flux density at the soil surface for daily time step ($0 \text{ MJ m}^{-2} \text{ d}^{-1}$)	Allen et al.(2005)
K	The dimensionless recession constant for API calculation	Kohler and Linsley (1951)
P	Monitored Precipitation (mm)	Berthier et al.(2011), Stovin et al.(2013)
R_a	Calculated extraterrestrial radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$)	Allen et al.(2005)
R_n	Calculated net radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$) from monitored solar radiation data	Allen et al.(2005)
S	Substrate moisture storage depth (mm)	Berthier et al.(2011), Stovin et al.(2013)
S_{fc}	Substrate field capacity depth (mm)	Carson et al.(2015)
T_{max}	Monitored maximum daily air temperature at 1.5 to 2.5 m height ($^\circ\text{C}$)	Hargreaves and Allen (2003)
T_{mean}	Monitored mean daily air temperature at 1.5 to 2.5 m height ($^\circ\text{C}$)	Allen et al.(2005)
T_{min}	Monitored minimum daily air temperature at 1.5 to 2.5 m height ($^\circ\text{C}$)	Hargreaves and Allen (2003)
u_2	Monitored mean daily wind speed at 2 m height (m s^{-1})	Allen et al.(2005)
α	Coefficient for equilibrium ET equation to account for advection; equal to 1.26 under normal moisture conditions. Modified with API model.	Priestley and Taylor (1972), Ali and Mawdsley (1987)
β	Coefficient to calculate AET from PET when substrate moisture is limited	Zhao et al.(2013)
γ	Psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$)	Allen et al.(2005)
Δ	Slope of the saturation vapor pressure-temperature curve ($\text{kPa } ^\circ\text{C}^{-1}$)	Allen et al.(2005)

Variables in Table 3 were calculated on the daily timescale according to referenced methodologies. The variables from the ASCE Penman-Monteith specifications (R. Allen et al., 2005) were described by Marasco et al.(2014). An albedo of 0.28, similar to the ASCE reference

value of 0.23, was calculated from linear regression of upward and downward shortwave radiation measurements from USPS roof between March 2011 and June 2012 (r-squared = 0.997). The density of water (1.0 Mg m^{-3}) divided by the approximate latent heat of vaporization (2.45 MJ kg^{-1}) is 0.408, the constant term in equations (3-7).

3.4 Actual Evapotranspiration Estimates

Three models, designed to account for fluctuations in water availability, were employed to calculate AET from PET estimates (Table 4). These models include a green roof Storage Model that uses a soil moisture extraction function (SMEF), an Antecedent Precipitation Index (API) based on monitored precipitation data, and an Advection-Aridity (A-A) model parameterized by PET equations.

Table 4: Description of AET models, physical basis, and assumptions

Model	Abbreviation	Equation #	Physical basis	Assumptions
Storage Model	AET_{SM}	(8-10)	Reservoir model; rooftop storage used to account for water limitations	Storage has linear relationship to reduction in AET
Antecedent Precipitation Index (API)	AET_{API}	(11-13)	Water availability calculated empirically from precipitation on previous 28 days	Precipitation influence on ET decreases exponentially with time
Advection-Aridity (A-A)	AET_{A-A}	(14-15)	In water-limited conditions, reduction in AET equal to increase in estimated PET due to energy availability	PET_{PT} = real potential; PET_P = "apparent" potential

For the green roof Storage Model, an SMEF, of a similar form to those employed by Sherrard and Jacobs (2012), DiGiovanni et al. (2013), and Stovin et al. (2013) was incorporated as a coefficient to calculate AET from PET estimates. The dimensionless SMEF coefficient, β , which represents the ratio of AET and PET when substrate moisture is limited (Starry et al., 2014), is a function of soil moisture storage depth at the specified interval, S (mm), and the field capacity of the substrate, S_{fc} (mm) (Table 1). β is calculated on the d^{th} day as follows (Zhao et al., 2013)

$$\beta_{(d)} = \frac{S_{(d-1)}}{S_{fc}} \quad (8)$$

AET is then calculated as the following function of β and PET

$$AET_{SM(d)} = \beta_{(d)} PET_{(d)} \quad (9)$$

Because soil moisture data is not often readily available, a continuous storage model on a daily time step, similar to those developed by Berthier et al.(2011) and Stovin et al.(2013), was applied to predict soil moisture at each interval. The model calculates storage on the d^{th} day as

$$S_{(d)} = \min\{S_{fc}, S_{(d-1)} + P_{(d)} - AET_{SM(d)}\} \quad (10)$$

where P is precipitation (mm). Because AET_{SM} decreases with S , specification of a substrate wilting point or lower boundary on storage is redundant.

The Antecedent Precipitation Index (API) model is a modification of the Priestley-Taylor (1972) PET equation. The API model modifies predicted PET based on antecedent precipitation in the previous 28 days in order to account for variations in soil moisture content and predict AET in drought conditions (Ali and Mawdsley, 1987; Mawdsley and Ali, 1985). The model equation is as follows

$$AET_{API} = 0.408\alpha \left[\frac{\Delta}{\Delta + \gamma} (R_n - G) \right] \quad (11)$$

where R_n is the net radiation ($MJ\ m^{-2}\ d^{-1}$), G is the soil heat flux density at the soil surface ($MJ\ m^{-2}\ d^{-1}$), γ is the psychrometric constant ($kPa\ ^\circ C^{-1}$), Δ is the slope of the saturation vapor pressure-temperature curve ($kPa\ ^\circ C^{-1}$), and the dimensionless coefficient, α , is expressed as

$$\alpha = 0.123(\text{API}) - 0.0029(\text{API})^2 - 0.0000056(\text{API})^3, \text{ for } \text{API} \leq 20$$

$$\alpha = 1.26, \text{ for } \text{API} > 20 \quad (12)$$

with API (mm) calculated from precipitation (P) on each day (d) according to the function given by Kohler and Lindsey (1951)

$$\text{API}(d) = \sum_{t=1}^{28} K^{(t-1)} P_{(d-t)} \quad (13)$$

where K , the dimensionless recession constant, is set to 0.9 and t is limited to each of the previous 28 days ($t = 1, 2, 3, \dots, 28$) (Ali and Mawdsley, 1987; Kohler and Linsley, 1951).

The Advection-Aridity (A-A) model developed by Brutsaert and Stricker (1979) to predict AET, is based on a hypothesis developed by Bouchet (1963). Bouchet postulated that when AET is less than PET due to limited water availability, the excess energy is transferred to other components of the energy balance, which increases PET, even though AET has declined (Ali and Mawdsley, 1987; Brutsaert, 2005). The A-A model assumes that the increase in PET is exactly equal to the reduction in the AET, leading to the following equation

$$\text{AET}_{\text{A-A}} = 2\text{PET}_{\text{PT}} - \text{PET}_{\text{p}} \quad (14)$$

where Brutsaert and Stricker suggested using the Priestley-Taylor model for “apparent” PET (PET_{PT}) in non-potential conditions, and the Penman equation for the PET in non-water-limiting conditions (PET_{p}). Substituting in Equations (4) and (5) into Equation (14) gives

$$\text{AET}_{\text{A-A}} = (2\alpha - 1)0.408 \left[\frac{\Delta}{\Delta + \gamma} (R_n - G) \right] - \left[\frac{\gamma}{\Delta + \gamma} E_A \right] \quad (15)$$

for AET_{A-A} on each day, where α is the advection correction coefficient from the Priestley-Taylor model equation, R_n is the net radiation ($MJ\ m^{-2}\ d^{-1}$), G is the soil heat flux density at the soil surface ($MJ\ m^{-2}\ d^{-1}$), γ is the psychrometric constant ($kPa\ ^\circ C^{-1}$), Δ is the slope of the saturation vapor pressure-temperature curve ($kPa\ ^\circ C^{-1}$), and E_A is calculated from Equation (6).

The variables used in equations (8-15) are also provided in Table 3.

3.5 Daily data assimilation and comparison

All recorded environmental data, including 30-minute W118 dynamic chamber measurements, were averaged over each hour. For the purpose of calculating daily values, missing hourly dynamic chamber ET fluxes were estimated from a linear interpolation of the prior and following ET measurements, as long as measurements occurred within 2 hours. This procedure is similar to ET interpolation procedures performed by Stannard (1988), Vaughan et al. (2007), and Salvucci and Gentile (2013). Lower ET fluxes during nighttime resulted in increased errors (10 %) compared to daytime data (7 %), which resulted in an overall overestimation of daily ET. Days with remaining missing data were eliminated from the analysis. Additionally, while statistics are based on all concurrent PET estimates and ET_{DC} measurements; due to sensor malfunctions in 2012, the focus of the USPS trend analysis is the period between October 2012 and September 2013, where measurements were continuous.

Daily ET fluxes from the dynamic chamber (ET_{DC}) were compared to predicted values of ET (ET_P) obtained from Equations (3-15). For each ET_P , a dimensionless crop coefficient, K_c , described by

$$ET_{DC} = K_c ET_P \quad (16)$$

was determined from a least-squares linear regression of daily results for each green roof site (Allen, 2000). The coefficient K_c captures variations in *Sedum* and surface properties that alter *Sedum* ET in comparison to the reference surfaces described in Table 2 (Starry et al., 2014).

For visualization of daily time series data, a quadratic Savitzky-Golay (S-G) filter, commonly used to eliminate noise in lysimeter studies (Peters et al., 2014; Vaughan and Ayars, 2009), was applied with a span of 11 days to more clearly illustrate ET trends. This span was based on the 10-day “dekad” employed in studies of precipitation and ET trends, but adjusted for symmetrical application of the S-G filter (Moeletsi et al., 2013). The S-G method uses local least squares polynomial approximation to filter measurement results. This filter was not applied to results discussed in the text or data shown in Figure 5.

4 Analysis and Results

4.1 Precipitation and Environmental Conditions

Precipitation totals measured on W118 during July, August, and October (147, 116, and 125 mm, respectively) were similar to records from the NOAA Belvedere Castle weather station in Central Park, New York, NY between 1970 – 2012 (Figure 1(a)). Growing season (April – October) precipitation totals during the dynamic chamber deployment on USPS were less similar. In May 2012, May 2013, and June 2013, USPS received a particularly high amount of precipitation compared to the historic average (180, 203, and 265 mm, respectively). In April and August 2013 USPS received limited precipitation (43 and 71 mm, respectively) compared to historic data. During the study period, the median antecedent dry weather period (ADWP) was 1 day for both dynamic chamber deployments and ADWP never exceeded 6 days on W118 or 12 days on USPS. Furthermore, on USPS, 92% of analyzed days had an ADWP of less than 7 days.

Snowfall events occurred during dynamic chamber deployment in December 2009, and between November 2012 and March 2013, as recorded by the NOAA Central Park, NY weather station. Mean monthly temperatures were similar to historic data with exception of November 2009 (12.2 °C) and March 2012 (10.8 °C), which were considerably warmer compared to historic data (Figure 1(b)).

Figure 1: Monthly precipitation (a) and average temperature (b) from W118 in 2009, and USPS in 2012 and 2013 compared to box plots of historic data from 1970 – 2012. Rooftop data displayed for months with at least 24 days of measurements.

4.2 Measured Evapotranspiration

The two dynamic chamber deployments resulted in 12,000 hours of ET measurements. The seasonal variation in average ET flux was similar for W118 in 2009, USPS in 2012, and USPS in 2013 (Figure 2). Daily ET flux ranged from 0.022 to 6.94 mm day⁻¹ on W118 and 0.003 to 11.38 mm day⁻¹ on USPS. Average daily ET flux for the extent of the monitoring period was 1.55 mm

day⁻¹ for W118 and 1.93 day⁻¹ for USPS. As expected, the average daily ET flux between April 2013 and September 2013 on USPS was higher (3.15 mm day⁻¹) compared to October 2012 – March 2013 (0.22 mm day⁻¹), due to increased available energy. A more detailed description of the dynamic chamber results is provided by Marasco et al. (2014).

Figure 2: Monthly average ET from W118 in 2009, and USPS in 2012 and 2013 from dynamic chamber measurements.

4.3 Potential Evapotranspiration Estimates

Daily PET estimates were compared with ET_{DC} measurements from the dynamic chamber (Table 5). Monitoring resulted in 472 days of concurrent PET and dynamic chamber data. All four PET models predicted higher average ET than the dynamic chamber. This was expected as PET models do not account for reductions in ET due to water-limited conditions, which might occur after extended periods of dry weather. The Priestley-Taylor model resulted in the lowest root mean square error (RMSE) between PET estimates and ET_{DC} measurements on both W118 (0.49 mm day⁻¹) and USPS (1.27 mm day⁻¹). Crop coefficients for the Priestley-Taylor and ASCE Penman-Monteith models were approximately one (0.98 – 1.02) for both roofs, while the Hargreaves and Penman models resulted in lower crop coefficients (0.84 – 0.96). Inclusion of the crop coefficient in PET estimates appreciably improved results of the Penman model (RMSE for K_c PET_P equal to

0.83 mm day⁻¹ for W118, and 1.42 mm day⁻¹ for USPS); however, the dynamic chamber results were still most correlated with the Priestley-Taylor estimates.

Table 5: Average ET (mm day⁻¹), RMSE (mm day⁻¹), and crop coefficients of PET models compared to the dynamic chamber.

ET Method	Average ET (mm day ⁻¹)		RMSE (mm day ⁻¹)		Crop Coefficient (K_c)	
	W118	USPS	W118	USPS	W118	USPS
Dynamic Chamber	1.55	1.93	-	-	-	-
Hargreaves	1.90	2.60	0.90	1.58	0.96	0.87
Priestley-Taylor	1.61	2.28	0.49	1.27	1.02	0.98
Penman	2.27	2.72	0.95	1.49	0.84	0.85
ASCE PM	1.91	2.27	0.81	1.38	0.98	1.02

To examine how the PET models performed under non-water-limited conditions, model estimates were also compared to dynamic chamber measurements during a selection of “non-water-limited” days where ADWP did not exceed 2 days (334 out of 472 days) (Table 6). As discussed in Section 4.1, ADWP on W118 during dynamic chamber deployment did not exceed 6 days. As a result, RMSE for each of the four PET models changed only minimally, -0.03 to 0.04 mm day⁻¹, which is primarily contributed to differences between the original and “non-water-limited” data. On USPS, where more frequent dry weather occurred, RMSE was reduced 0.03 to 0.14 mm day⁻¹ across all PET models. Nonetheless, the Priestley-Taylor equation was still most correlated with dynamic chamber results, with a RMSE of 0.53 and 1.16 mm day⁻¹ on W118 and USPS respectively.

Table 6: Average ET (mm day⁻¹), RMSE (mm day⁻¹), and crop coefficients of PET models compared to the dynamic chamber considering non-water-limited days, where ADWP did not exceed 2 days.

ET Method	Average ET (mm day ⁻¹)		RMSE (mm day ⁻¹)		Crop Coefficient (K_c)	
	W118	USPS	W118	USPS	W118	USPS
Dynamic Chamber	1.64	1.97	-	-	-	-
Hargreaves	2.00	2.62	0.93	1.56	0.95	0.87
Priestley-Taylor	1.71	2.29	0.53	1.16	1.01	0.99
Penman	2.31	2.68	0.91	1.35	0.85	0.87
ASCE PM	1.95	2.25	0.78	1.26	0.99	1.03

Figure 3 displays S-G filtered daily PET and ET_{DC} for W118 in 2009 and USPS between October 2012 and September 2013. Estimates from the PET models generally followed similar trends.

PET peaked in summer, with a maximum flux of 7.16 mm day⁻¹ on USPS on June 21, 2012 (from the Penman model), and was lowest in the winter, with a minimum flux of 0.0048 mm day⁻¹ on USPS on December 10, 2012 (also from the Penman model). However, there were some particular differences in the trends of PET estimates. In winter months, the addition of the advective term in the Penman and ASCE Penman-Monteith models resulted in overestimation of ET compared to dynamic chamber and Priestley-Taylor fluxes. The empirical Hargreaves model was generally comparable to the radiation based transfer equations (4-7), with the exception of a few periods where it overestimated PET (e.g. May 17 to May 27, 2013 on USPS).

Figure 3: 11-day S-G filtered daily dynamic chamber ET (ET_{DC}) results from (a) W118 in 2009 and (b) USPS between October 2012 and September 2013 compared to PET estimates.

PET patterns generally mimicked those of the measured dynamic chamber ET; however, because PET equations do not account for moisture variability, they tended to over-predict ET during drought and under-predict during periods of heavy precipitation. PET estimates were considerably higher than dynamic chamber measurements in April, May, and September 2013. For each of these periods, limited precipitation was recorded in the preceding month, resulting in limited substrate moisture and increased substrate surface resistance, and consequently, reduced

measured ET. Conversely, the PET equations under-predicted the magnitude of ET throughout June and July 2013, where both antecedent precipitation and available energy were elevated. This behavior is supported by the findings of Spronken-Smith et al.(2000)and Jim and Peng (2012) who demonstrated that the unique conditions of green spaces in urban environments can increase the actual ET in relation to estimated potential.

4.4 Actual Evapotranspiration Estimates

AET was calculated for each method and compared to dynamic chamber measurements (Table 7). The Priestley-Taylor model was used to calculate PET for input in the storage model as it had the strongest correlation with dynamic chamber ET measurements and was used by Ali and Mawdsley (1987) for the API and A-A models. As expected, all AET models showed reduced ET compared to the Priestley-Taylor model; however, only the API model showed an improvement in RMSE. Average ET estimates from the storage and the A-A models were lower than dynamic chamber results for both W118 and USPS. The API model resulted in the lowest root mean square errors (RMSE) between ET predictions and dynamic chamber measurements on both W118 (0.48 mm day⁻¹) and USPS (1.19 mm day⁻¹). Crop coefficients for the AET models all exceeded one; however, coefficients for API model were near unity with K_c values of 1.03 and 1.04 for W118 and USPS, respectively.

Table 7: Average ET (mm day⁻¹), RMSE (mm day⁻¹), and crop coefficients of AET models compared to the dynamic chamber.

ET Method	Average ET (mm day ⁻¹)		RMSE (mm day ⁻¹)		Crop Coefficient (K_c)	
	W118	USPS	W118	USPS	W118	USPS
Dynamic Chamber	1.55	1.93	-	-	-	-
Storage Model	0.97	1.66	1.50	1.62	1.45	1.28
API	1.59	2.17	0.48	1.19	1.03	1.04
Advection-Aridity	0.93	1.82	0.88	1.32	1.09	1.10

Figure 4 displays S-G filtered daily AET estimates and dynamic chamber measured ET from W118 in 2009 and USPS between October 2012 and September 2013. In the winter, early spring and late fall, all models show similar trends, although the A-A model predicted lower ET values than the other two models. During late spring, summer and early fall, however, the Storage model predicted significantly lower ET values than the other two models, as well as the dynamic chamber, and also exhibited greater fluctuations in daily ET. API results on W118 were very similar to Priestley-Taylor estimates. During chamber deployment on W118, precipitation was fairly regular (Figure 1(a)) and α hardly deviated from 1.26. Reductions in α mainly occurred in cooler months where energy available for ET was minimal (minimum $\alpha = 0.89$ on November 30, 2009). The API estimated AET showed more significant reductions compared to Priestley-Taylor results on USPS (minimum $\alpha = 0.41$ on May 8, 2013). Reduced values of α corresponded with periods where precipitation in the preceding month was limited, including April, May, and September 2013. AET estimates from the A-A model did not capture reductions in ET compared to potential corresponding with water-stressed conditions during the summer months. However, on USPS, the A-A formulation of the transfer equations better reflected the seasonal variation of dynamic chamber ET.

Figure 4: 11-day S-G filtered daily dynamic chamber ET (ET_{DC}) results from (a) W118 in 2009 and (b) USPS between October 2012 and September 2013 compared to AET estimates.

5 Discussion

5.1 Evapotranspiration behavior

The comparison of estimates from the four PET models with ET measurements from the dynamic chamber system, revealed that the Priestley-Taylor model was most effective at predicting ET at the studied green roof sites (RMSE = 0.49 on W118, 1.27 on USPS). Although there were variations in the magnitude of ET, fluctuations in PET_{PT} estimates mimicked those of the

dynamic chamber measurements (Figure 3). Crop coefficients based on linear regression of Priestley-Taylor and dynamic chamber fluxes were approximately one ($K_C = 1.02$ for W118, 0.98 for USPS). However, a systematic error was seen on USPS, where the Priestley-Taylor model multiplied by K_C over-predicted ET at lower fluxes and under-predicted ET at higher fluxes (Figure 5(a)). AllPET model overestimated ET in the winter on both rooftops, as the equations do not consider factors which limit winter PET, including decreased vegetation productivity, higher albedo of snow-covered surfaces (0.40 – 0.90), or increased ET resistance of frozen substrates (Allen et al., 1998).

Figure 5: Scatter plot of daily dynamic chamber ET (ET_{DC}) results from W118 and USPS compared to (a) Priestley-Taylor (PET_{PT}) and (b) APT (AET_{API}) estimates, corrected with crop coefficients, K_c .

In June and July 2013 dynamic chamber ET measurements exceeded PET estimates, thought to be the result of elevated surface temperature and more frequent precipitation during this period. Maximum daily surface temperatures, measured by the dynamic chamber, exceeded maximum daily air temperatures in the summer, resulting in increased energy availability for ET (Jim and Peng, 2012). Application of the Hargreaves equation (Equation (3)) with surface temperature

values showed maximum PET fluxes similar to dynamic chamber measurements in June and July 2013 (Figure 6). Additionally, frequent precipitation in May and June 2013 is believed to have enhanced *Sedum* productivity and transpiration, as well as replenish surface moisture, reducing surface resistance for evaporation (R. G. Allen et al., 2005).

Figure 6: 11-day S-G filtered daily dynamic chamber ET (ET_{DC}) results from USPS in 2013 compared to Hargreaves estimates (PET_{HG}) based on air temperature (T_{Air}) and surface temperature ($T_{Surface}$).

In addition to seasonal variations between ET_{DC} and PET estimates, the PET models over-predicted ET during periods of limited water availability, observed through precipitation data, predicted storage, and API calculations (Figure 3(b)). Analysis of the storage, API, and A-A AET models revealed that only the API model was able to improve the prediction of measured ET (RMSE = 0.48 on W118, 1.19 on USPS) compared to the Priestley-Taylor model. The API model, multiplied by crop coefficient K_C , corrected many overestimations visible in predicted $K_C PET_{PT}$ (Figure 5(b)). For W118 in 2009 and USPS in 2012, precipitation was frequent enough that API AET estimates were nearly equal to Priestley-Taylor PET estimates. However, on USPS in May and September 2013, API AET results were comparatively lower, which corresponded to the behavior of measured ET. During drought periods, the day where the API coefficient, α , first

decreased varied with respect to when dynamic chamber ET began to deviate from PET; however, the overall behavior was similar (Figure 4(b)). As expected, when a significant precipitation event occurred both the API and dynamic chamber fluxes returned to potential values.

The SMEF used in the storage model reduced PET during periods of dry weather (Crago and Brutsaert, 1992), however the magnitude of these reductions was overestimated. This storage model does not account for processes that increase water availability, including depression storage, interception, vegetation storage, temporary detention, and ponding water, or factors that alter ET fluxes, including the location of moisture in the substrate, non-potential environmental conditions, and transpiration. It is also important to note that reductions in dynamic chamber ET measurements compared to PET estimates were delayed with respect to the storage model, which supports the idea that there is a range of storage depths where ET is still energy limited, and only when storage crosses that threshold, does AET decline in comparison to PET (R. G. Allen et al., 2005).

5.2 Model Sensitivity

The crop coefficients determined for the Priestley-Taylor, ASCE Penman-Monteith, and API models were between 0.98 and 1.04, indicating that calibration of these models based on the scalar crop coefficient, K_c , does not considerably improve the model. The remaining variance is sensitive to other conditions on the roof or the relationship between PET model variables.

The storage model was shown to underestimate ET in summer months when ET fluxes were elevated. Increased ET fluxes deplete water storage and consequentially the coefficient β used to predict AET in Equation (9) is reduced. Modification of Equation (8) for β for specifying a storage

depth threshold where ET becomes water-limited did not considerably improve the model, as higher PET values deplete storage depth faster. As discussed by DiGiovanni et al.(2013), the model is sensitive to storage depth; however, increasing storage depth in this analysis resulted in ET overestimation during the water-limited period on USPS in May 2013.

The coefficients for the cubic α function (Equation (12)) and variables in the API formulation (Equation (13)) were analyzed to determine AET_{API} sensitivity. The following variables were analyzed within the given ranges: (1) the decay coefficient, K (0.80-0.95), (2) input antecedent precipitation days (5-50 days), (3) maximum daily precipitation input (5-104 mm), and (4) the maximum API for α calculation (5-50 mm). The standard API formulation results ($K_c AET_{API}$) along with two variations of the method are displayed in Figure 7. In the first modification ($AET_{API} - \text{Fitted } \alpha$), a cubic regression of α and $ET_{DC} (K_c PET_{PT})^{-1}$ was performed to determine coefficients for Equation (12), where all $ET_{DC} (K_c PET_{PT})^{-1}$ ratios associated with API greater than the maximum API (i.e. 20 mm) were set to unity. In the second model ($AET_{API} - \text{Modified, Fitted } \alpha$), in addition to regression of α , K was set to 0.95, max API was set to 10 mm, and 15 antecedent precipitation days were used in the analysis. The modified API formulation showed increased significance of correlation between the API and $ET_{DC} (K_c PET_{PT})^{-1}$ ($p = 2.8 \times 10^{-68}$), compared to the original API ($p = 7.4 \times 10^{-23}$). However, the analysis revealed that AET_{API} results are particularly insensitive to these adjustments, with adjusted models having nominal effects on AET_{API} behavior and RMSE (Figure 7).

Figure 7: 11-day S-G filtered daily dynamic chamber ET (ET_{DC}) results from USPS in 2013 compared to the original API values (AET_{API}), an API model with modified α ($AET_{API} - \text{Fitted } \alpha$), and an API model with fitted α , K of 0.95, and a max API of 10, calculated from 15 antecedent precipitation days ($AET_{API} - \text{Modified, Fitted } \alpha$).

The A-A equation (15) can be considered a form of the Penman equation (5) with different coefficients for the radiation and advective terms. The major distinction between models is that for the A-A model, Brutsaert and Stricker (1979) assumed that advective term was negatively correlated with actual ET. Multi-variate linear regression of the separated terms of Equation (5) in the following form

$$ET_{DC} = C(1)0.408 \left[\frac{\Delta}{\Delta + \gamma} (R_n - G) \right] + C(2) \left[\frac{\gamma}{\Delta + \gamma} E_A \right] \quad (17)$$

revealed coefficients of a similar form to the A-A model, with $C(1) = 1.34$ and $C(2) = -0.09$ on W118, and $C(1) = 1.47$ and $C(2) = -0.50$ on USPS for a minimized error between modeled and measured ET. This approach improved correlation slightly (RMSE = 0.48 on W118, 1.26 on USPS) compared to the Priestley-Taylor model with a crop coefficient (RMSE = 0.49 on W118, 1.28 on USPS) and showed that a form of the A-A model may be useful for estimating seasonal variations in PET resulting from differences in crop coefficients (Allen et al., 1998).

5.3 Evapotranspiration behavior compared to other studies

Studies of certain agricultural (Ali and Mawdsley, 1987; Salvucci and Gentine, 2013), natural (Kahler and Brutsaert, 2006), and green roof (Sherrard and Jacobs, 2012; Wadzuk et al., 2013) sites show a systematic error where predictive algorithms overestimate lower ET fluxes and underestimate higher ET fluxes, similar to results from USPS, particularly in 2013 (Figure 5). In many studies (Ali and Mawdsley, 1987; Kahler and Brutsaert, 2006; Salvucci and Gentine, 2013; Sherrard and Jacobs, 2012), a water availability algorithm was included, but it did not account for this error.

Water limitations affect actual ET and alter PET estimates. Studies of green roof ET have reported that estimates from predictive equations are more correlated with measured ET during years with frequent precipitation (Lazzarin et al., 2005; Wadzuk et al., 2013) or when considering only non-water-limited days in the analysis (DiGiovanni et al., 2013). In this study, ET measurements on W118 and USPS in 2012 (Figure 5(a)) more closely matched Priestley-Taylor model results than USPS in 2013, which received irregular precipitation. Additionally, when considering only non-water-limited days on USPS, RMSE for Priestley-Taylor results compared to dynamic chamber measurements was reduced.

5.4 Application of ET models for green roof hydrologic and energy models

ET estimation techniques are important for quantifying green roof benefits and supplementing green roof hydrologic and energy models. PET models provide an acceptable estimation of overall ET behavior in normal moisture conditions. The Priestley-Taylor model showed the strongest correlation with measured ET on both W118 and USPS, with the crop coefficient, K_c , approximately equal to one. Nonetheless, the Priestley-Taylor model overestimated ET in winter

months on both roofs where limited plant productivity, snow reflectance, and the resistance of ET from frozen surfaces is thought to limit ET (Allen et al., 1998). The Priestley-Taylor model excludes an advection term that further increased ET estimates from the Penman and ASCE Penman-Monteith models in the winter, when surface resistance is increased and energy available for ET is limited. However, empirical analysis of the Penman equation on both W118 and USPS showed that a PET model with a negative coefficient for the advection term was more correlated with ET_{DC} , similar to the theory of the A-A model. Additionally, since each PET model cannot account for water availability or non-potential conditions affecting PET estimates, correlation is reduced when substrate moisture is limited.

AET models attempt to correct PET models in order to account for variations in water availability. The API model proved to be a straightforward and practical method to account for water availability when calculating AET. Although the method is empirical, it is insensitive to changes to its formulation and unaffected by preceding ET fluxes, water storage, or site conditions. The method was able to predict AET during significant dry periods during the study, such as during May and September 2013 on USPS, where measured ET was most limited. During normal precipitation conditions, such as most of the dynamic chamber deployment on W118, AET_{API} was simply equal to PET_{PT} . Although the storage model has a more physical basis than the other AET calculation procedures, it is highly sensitive to rooftop water storage and environmental conditions that can affect ET. This sensitivity resulted in significant underestimations of ET during the summer, when ET fluxes were high and storage was depleted quickly. However, if a designer is only interested in estimating runoff for a precipitation event, a

storage model may be sufficient, as seen by results from Berthier et al.(2011)and Sherrard and Jacobs (2012).

6 Concluding remarks

Because the unique properties of green roofs (including the small scale, vegetation heterogeneity, shallow substrate depth, underlying impervious layers, and uncertain moisture availability) can affect the ET flux (DiGiovanni et al., 2013; Grimmond and Oke, 2002; Jim and Peng, 2012; Spronken-Smith et al., 2000); it is important to validate predictive ET models against measured ET data at green roof sites. For measurements undertaken at the so-called W118 and USPS extensive, *Sedum* green roofs in New York City, it was shown that the Priestley-Taylor model was more effective than the Hargreaves, Penman, and ASCE Penman-Monteith Potential Evapotranspiration (PET) models for predicting ET when assuming uniform moisture conditions. This result supports the applicability of the Priestley-Taylor model for calculating PET in green roof hydrologic models (Sherrard and Jacobs, 2012; Stovin et al., 2013) and energy models (Lazzarin et al., 2005; Ouldboukhitine et al., 2011) under conditions similar to those of this study.

Analysis of the storage, Antecedent Precipitation Index (API), and Advection-Aridity (A-A) models for estimating actual Evapotranspiration (AET), revealed that only the API model, originally applied by Mawdsley and Ali (1985) at agricultural sites, was able to improve the Priestley-Taylor prediction of measured ET under water-limited conditions. Nonetheless, in general, even with the API model corrections to the Priestley-Taylor AET model, observed ET values were generally overestimated for the low fluxes that occur during winter months and underestimated for the high fluxes that occur during summer months. This fact points to the need

for improved modeling of green roof ET processes under climate conditions typical of NYC's winter and summer months.

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References

- Ali, M.F., Mawdsley, J.A., 1987. Comparison of two recent models for estimating actual evapotranspiration using only regularly recorded data. *J. Hydrol.* 93, 257–276.
doi:10.1016/0022-1694(87)90099-0
- Allen, R., Walter, I.A., Elliott, R., Howell, T., Itenfisu, D., Jensen, M. (Eds.), 2005. *The ASCE Standardized Reference Evapotranspiration Equation*. Reston, VA.
- Allen, R., 2000. Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study. *J. Hydrol.* 229, 27–41. doi:10.1016/S0022-1694(99)00194-8
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. *Crop Evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56*. Rome, IT.
- Allen, R.G., Pruitt, W.O., Businger, J.A., Fritschen, L.J., Jensen, M.E., Quinn, F.H., 1996. Evaporation and Transpiration, in: *Hydrology Handbook*. American Society of Civil Engineers, New York, NY, pp. 125–252. doi:10.1061/9780784401385
- Allen, R.G., Pruitt, W.O., Raes, D., Smith, M., Pereira, L.S., 2005. Estimating Evaporation from Bare Soil and the Crop Coefficient for the Initial Period Using Common Soils Information. *J. Irrig. Drain. Eng.* 131, 14–23. doi:10.1061/(ASCE)0733-9437(2005)131:1(14)
- Arora, V.K., 2002. The use of the aridity index to assess climate change effect on annual runoff. *J. Hydrol.* 265, 164–177. doi:10.1016/S0022-1694(02)00101-4
- Berghage, R.D., Jarrett, A., Beattie, D., Kelley, K., Husain, S., Rezai, F., Long, B., Negassi, A., Cameron, R., Hunt, W., 2007. *Quantifying Evaporation and Transpirational Water Losses*

from Green Roofs and Green Roof Media Capacity for Neutralizing Acid Rain, ...
Resources Capacity

- Berthier, E., Dupont, S., Mestayer, P.G., Andrieu, H., 2006. Comparison of two evapotranspiration schemes on a sub-urban site. *J. Hydrol.* 328, 635–646.
doi:10.1016/j.jhydrol.2006.01.007
- Berthier, E., Ramier, D., Gouvello, B. De, 2011. Simulation of green roof hydrological behavior with a reservoir model, in: 2nd International Conference on Urban Drainage. Porto Alegre, Brazil, pp. 10–15.
- Bouchet, R., 1963. Evapotranspiration réelle et potentielle, signification climatique. *IAHS Publ* 62, 134–142.
- Boulet, G., Chehbouni, a., Gentine, P., Duchemin, B., Ezzahar, J., Hadria, R., 2007. Monitoring water stress using time series of observed to unstressed surface temperature difference. *Agric. For. Meteorol.* 146, 159–172. doi:10.1016/j.agrformet.2007.05.012
- Brutsaert, W., 2005. *Hydrology: An Introduction*, 6th ed. Cambridge University Press, Cambridge, UK.
- Brutsaert, W., Stricker, H., 1979. An advection-aridity approach to estimate actual regional evapotranspiration. *Water Resour. Res.* 15, 443–450. doi:10.1029/WR015i002p00443
- Calder, I.R., Harding, R.J., Rosier, P.T.W., 1983. An objective assessment of soil-moisture deficit models. *J. Hydrol.* 60, 329–355. doi:10.1016/0022-1694(83)90030-6
- Carson, T.B., Keeley, M., Marasco, D.E., McGillis, W.R., Culligan, P.J., 2015. Assessing methods for predicting green roof rainfall capture: A comparison between full-scale

- observations and four hydrologic models. *Urban Water J.* In press.
doi:10.1080/1573062X.2015.1056742
- Carson, T.B., Marasco, D.E., Culligan, P.J., McGillis, W.R., 2013. Hydrological performance of extensive green roofs in New York City: observations and multi-year modeling of three full-scale systems. *Environ. Res. Lett.* 8, 024036. doi:10.1088/1748-9326/8/2/024036
- Choudhury, B.J., Blanchard, B.J., 1983. Simulating soil water recession coefficients for agricultural watersheds. *J. Am. Water Resour. Assoc.* 19, 241–247. doi:10.1111/j.1752-1688.1983.tb05321.x
- Christen, A., Vogt, R., 2004. Energy and radiation balance of a central European city. *Int. J. Climatol.* 24, 1395–1421. doi:10.1002/joc.1074
- Crago, R.D., Brutsaert, W., 1992. A comparison of several evaporation equations. *Water Resour. Res.* 28, 951–954. doi:10.1029/91WR03149
- DiGiovanni, K., Gaffin, S.R., Montalto, F., Rosenzweig, C., 2011. The Applicability of Classical Predictive Equations for the Estimation of Evapotranspiration from Urban Green Spaces: Green Roof Results, in: *World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability*. ASCE, pp. 783–792.
- DiGiovanni, K., Montalto, F., Gaffin, S., Rosenzweig, C., 2013. Applicability of Classical Predictive Equations for the Estimation of Evapotranspiration from Urban Green Spaces: Green Roof Results. *J. Hydrol. Eng.* 18, 99–107. doi:10.1061/(ASCE)HE.1943-5584.0000572
- Feller, M.M., 2011. Quantifying Evapotranspiration in Green Infrastructure: a Green Roof Case Study. Villanova University.

- Graham, P., Maclean, L., Medina, D., 2004. The role of water balance modelling in the transition to low impact development. *Water Qual. Res. ...* 39, 331–342.
- Grimmond, C.S.B., Oke, T.R., 2002. Turbulent Heat Fluxes in Urban Areas: Observations and a Local-Scale Urban Meteorological Parameterization Scheme (LUMPS). *J. Appl. Meteorol.* 41, 792–810. doi:10.1175/1520-0450(2002)041<0792:THFIUA>2.0.CO;2
- Grimmond, C.S.B., Oke, T.R., 1991. An evapotranspiration-interception model for urban areas. *Water Resour. Res.* 27, 1739–1755. doi:10.1029/91WR00557
- Grindley, J., 1970. Estimation and mapping of evaporation. *World Water Balanc.* 200–213.
- Hargreaves, G.H., Allen, R.G., 2003. History and Evaluation of Hargreaves Evapotranspiration Equation. *J. Irrig. Drain. Eng.* 129, 53–63. doi:10.1061/(ASCE)0733-9437(2003)129:1(53)
- Hiltner, R.N., 2005. An Analysis of the Energetics and Stormwater Mediation Potential of Greenroofs. University of Georgia.
- Hiltner, R.N., Lawrence, T.M., Tollner, E.W., 2008. Modeling stormwater runoff from green roofs with HYDRUS-1D. *J. Hydrol.* 358, 288–293. doi:10.1016/j.jhydrol.2008.06.010
- Jim, C.Y., Chen, W.Y., 2009. Ecosystem services and valuation of urban forests in China. *Cities* 26, 187–194. doi:10.1016/j.cities.2009.03.003
- Jim, C.Y., Peng, L.L.H., 2012. Substrate moisture effect on water balance and thermal regime of a tropical extensive green roof. *Ecol. Eng.* 47, 9–23. doi:10.1016/j.ecoleng.2012.06.020
- Kahler, D.M., Brutsaert, W., 2006. Complementary relationship between daily evaporation in the environment and pan evaporation. *Water Resour. Res.* 42, n/a–n/a. doi:10.1029/2005WR004541

- Kohler, M.A., Linsley, R.K., 1951. Research Paper No. 34 - Predicting the runoff from storm rainfall. Washington, DC.
- Lazzarin, R., Castellotti, F., Busato, F., 2005. Experimental measurements and numerical modelling of a green roof. *Energy Build.* 37, 1260–1267. doi:10.1016/j.enbuild.2005.02.001
- MacIvor, J.S., Ranalli, M.A., Lundholm, J.T., 2011. Performance of dryland and wetland plant species on extensive green roofs. *Ann. Bot.* 107, 671–679. doi:10.1093/aob/mcr007
- Marasco, D.E., Hunter, B.N., Culligan, P.J., Gaffin, S.R., McGillis, W.R., 2014. Quantifying Evapotranspiration from Urban Green Roofs: A Comparison of Chamber Measurements with Commonly Used Predictive Methods. *Environ. Sci. Technol.* 48, 10273–10281. doi:10.1021/es501699h
- Mawdsley, J.A., Ali, M.F., 1985. Estimating Nonpotential Evapotranspiration by Means of the Equilibrium Evaporation Concept. *Water Resour. Res.* 21, 383–391. doi:10.1029/WR021i003p00383
- Mayor's Office of Long-Term Planning and Sustainability, 2008. Sustainable Stormwater Management Plan. New York.
- Moeletsi, M.E., Walker, S., Hamandawana, H., 2013. Comparison of the Hargreaves and Samani equation and the Thornthwaite equation for estimating dekadal evapotranspiration in the Free State Province, South Africa. *Phys. Chem. Earth, Parts A/B/C* 66, 4–15. doi:10.1016/j.pce.2013.08.003
- Monteith, J.L., 1965. Evaporation and environment. *Symp. Soc. Exp. Biol.* 19, 205–34.

- Moran, M., Clarke, T., Inoue, Y., Vidal, A., 1994. Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. *Remote Sens. Environ.* 49, 246–263. doi:10.1016/0034-4257(94)90020-5
- NYC DEP, 2010. NYC Green Infrastructure Plan. New York, NY.
- Ouldboukhité, S.-E., Belarbi, R., Djedjig, R., 2012. Characterization of green roof components: Measurements of thermal and hydrological properties. *Build. Environ.* 56, 78–85. doi:10.1016/j.buildenv.2012.02.024
- Ouldboukhité, S.-E., Belarbi, R., Jaffal, I., Trabelsi, A., 2011. Assessment of green roof thermal behavior: A coupled heat and mass transfer model. *Build. Environ.* 46, 2624–2631. doi:10.1016/j.buildenv.2011.06.021
- Pataki, D.E., Alig, R.J., Fung, a. S., Golubiewski, N.E., Kennedy, C. a., Mcpherson, E.G., Nowak, D.J., Pouyat, R. V., Romero Lankao, P., 2006. Urban ecosystems and the North American carbon cycle. *Glob. Chang. Biol.* 12, 2092–2102. doi:10.1111/j.1365-2486.2006.01242.x
- Penman, H.L., 1948. Natural Evaporation from Open Water, Bare Soil and Grass. *Proc. R. Soc. A Math. Phys. Eng. Sci.* 193, 120–145. doi:10.1098/rspa.1948.0037
- Peters, A., Nehls, T., Schonsky, H., Wessolek, G., 2014. Separating precipitation and evapotranspiration from noise – a new filter routine for high-resolution lysimeter data. *Hydrol. Earth Syst. Sci.* 18, 1189–1198. doi:10.5194/hess-18-1189-2014
- Poë, S., Stovin, V., Berretta, C., 2015. Parameters influencing the regeneration of a green roof's retention capacity via evapotranspiration. *J. Hydrol.* 523, 356–367. doi:10.1016/j.jhydrol.2015.02.002

- Priestley, C.H.B., Taylor, R.J., 1972. On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters. *Mon. Weather Rev.* 100, 81–92. doi:10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2
- Salvucci, G.D., Gentile, P., 2013. Emergent relation between surface vapor conductance and relative humidity profiles yields evaporation rates from weather data. *Proc. Natl. Acad. Sci. U. S. A.* 110, 6287–91. doi:10.1073/pnas.1215844110
- Sherrard, J.A., Jacobs, J.M., 2012. Vegetated Roof Water-Balance Model: Experimental and Model Results. *J. Hydrol. Eng.* 17, 858–868. doi:10.1061/(ASCE)HE.1943-5584.0000531
- Simunek, J., Genuchten, M. Van, Sejna, M., 2006. The HYDRUS software package for simulating the two-and three-dimensional movement of water, heat, and multiple solutes in variably-saturated media, Technical manual.
- Slatyer, R.O., McIlroy, I.C., 1961. *Practical Microclimatology*. UNESCO, Australia.
- Spronken-Smith, R.A., Oke, T.R., Lowry, W.P., 2000. Advection and the surface energy balance across an irrigated urban park. *Int. J. Climatol.* 20, 1033–1047. doi:10.1002/1097-0088(200007)20:9<1033::AID-JOC508>3.0.CO;2-U
- Stannard, D.I., 1988. Use of a hemispherical chamber for measurement of evapotranspiration. Denver, CO.
- Starry, O., Lea-Cox, J.D., Kim, J., van Iersel, M.W., 2014. Photosynthesis and water use by two *Sedum* species in green roof substrate. *Environ. Exp. Bot.* 107, 105–112. doi:10.1016/j.envexpbot.2014.05.014
- Stovin, V., Poë, S., Berretta, C., 2013. A modelling study of long term green roof retention performance. *J. Environ. Manage.* 131, 206–15. doi:10.1016/j.jenvman.2013.09.026

- Tabares-Velasco, P.C., Srebric, J., 2011. Experimental quantification of heat and mass transfer process through vegetated roof samples in a new laboratory setup. *Int. J. Heat Mass Transf.* 54, 5149–5162. doi:10.1016/j.ijheatmasstransfer.2011.08.034
- Taha, H., 1997. Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. *Energy Build.* 25, 99–103. doi:10.1016/S0378-7788(96)00999-1
- Taha, H., Akbari, H., Rosenfeld, A., 1991. Heat island and oasis effects of vegetative canopies: Micro-meteorological field-measurements. *Theor. Appl. Climatol.* 44, 123–138. doi:10.1007/BF00867999
- Thornthwaite, C.W., Mather, J.R., 1955. The Water Balance, in: *Publications in Climatology*. Drexel Institute of Climatology, Centerton, NJ, pp. 1–104.
- VanWoert, N.D., Rowe, D.B., Andresen, J.A., Rugh, C.L., Xiao, L., 2005. Watering regime and green roof substrate design affect Sedum plant growth. *HortScience* 40, 659–664.
- Vaughan, P.J., Ayars, J.E., 2009. Noise Reduction Methods for Weighing Lysimeters. *J. Irrig. Drain. Eng.* 135, 235–240. doi:10.1061/(ASCE)0733-9437(2009)135:2(235)
- Vaughan, P.J., Trout, T.J., Ayars, J.E., 2007. A processing method for weighing lysimeter data and comparison to micrometeorological ETo predictions. *Agric. Water Manag.* 88, 141–146. doi:10.1016/j.agwat.2006.10.008
- Voyde, E., Fassman, E., Simcock, R., 2010a. Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. *J. Hydrol.* 394, 384–395. doi:10.1016/j.jhydrol.2010.09.013

- Voyde, E., Fassman, E., Simcock, R., Wells, J., 2010b. Quantifying Evapotranspiration Rates for New Zealand Green Roofs. *J. Hydrol. Eng.* 15, 395–403. doi:10.1061/(ASCE)HE.1943-5584.0000141
- Wadzuk, B.M., Schneider, D., Feller, M., Traver, R.G., 2013. Evapotranspiration from a Green-Roof Storm-Water Control Measure. *J. Irrig. Drain. Eng.* 139, 995–1003. doi:10.1061/(ASCE)IR.1943-4774.0000643
- Wang, Z.-H., Bou-Zeid, E., Smith, J. a., 2013. A coupled energy transport and hydrological model for urban canopies evaluated using a wireless sensor network. *Q. J. R. Meteorol. Soc.* 139, 1643–1657. doi:10.1002/qj.2032
- Westenbroek, S., Kelson, V., Dripps, W., 2010. SWB — A Modified Thornthwaite-Mather Soil-Water- Balance Code for Estimating Groundwater Recharge. Reston, VA.
- Zhao, L., Xia, J., Xu, C., Wang, Z., Sobkowiak, L., Long, C., 2013. Evapotranspiration estimation methods in hydrological models. *J. Geogr. Sci.* 23, 359–369. doi:10.1007/s11442-013-1015-9