Closing the Water Budget in an Experimental Urban Watershed: A Comparative Assessment of Methods for Estimating Evapotranspiration

Prepared for the Hixon Center for Urban Ecology, Yale University

Leana Weissberg

ABSTRACT

Three methods for the measurement of evapotranspiration were tested for quantitative agreement and ease of implementation at the Yale Experimental Watershed on the Yale University campus. Methods were employed over the course of the 2016 growing season (July – October, 2016) and included a micrometeorological heat budget (Penman FAO 24 model), pan evaporation, and soil moisture profiles. Penman FAO 24 and pan evaporation showed a modest linear relationship in a multiple linear regression model accounting for seasonality. However, inter-method variability, calculated as the root mean square error, typically showed better agreement between pan evaporation and soil moisture profiles. The use of a micrometeorological heat budget was the most cost-effective and feasible method tested for the measurement of urban evapotranspiration. Quantifying this crucial water budget component in urban environments could incentivize urban design that either reduces runoff or increases storage on the landscape, depending on the requirements of the climate in question.

Closing the Water Budget in an Experimental Urban Watershed: A Comparative Assessment of Methods for Estimating Evapotranspiration

Leana Weissberg
Yale School of Forestry and Environmental Studies
December 12, 2016

1. Project Summary

1.1. Overview

My research compared three methods for measuring evapotranspiration (ET) in urban environments. ET, the combined water vapor flux lost via evaporation and transpiration, was independently measured with micrometeorological, plant physiological, and hydrological methods. These techniques utilize various environmental data (*i.e.* climatic variables, vegetative water use, and soil moisture) to obtain ET values. While the chosen methods are not novel, they have mostly been applied to the study of water use for irrigated crops and not to the more complicated mix of land use and land cover (LULC) characteristic of urban environments. Research was conducted at the Yale Experimental Watershed (YEW) located on the Yale University campus. Active data collection took place from June through October 2016.

1.2. Intellectual Merits

Quantifying ET in urban environments presents unique challenges. Large fractions of impermeable surface and heterogeneity in LULC may complicate the application of traditional methods that rely upon plant physiology, meteorology, or relatively intact hydrological systems to produce estimates. Understanding urban ET is, however, incredibly important. A more complete picture of the urban water cycle can inform storm water management, decreasing the need for gray infrastructure in cities with abundant storm water. Conversely, in water-stressed cities, storm water may become an increasingly critical resource. In such a case, improving ET estimates may help managers conserve this resource. The aim of this comprehensive comparison of the suitability of ET measurement methods was to increase the ease of application for urban resource managers.

2. Introduction

ET has been described as "the weakest point in the study of the urban water balance"[1] and accounts for roughly 64% of the global atmospheric return of terrestrial precipitation.[2] Though it is one of the most important terms in any water budget, accurate measurements are difficult to produce. Theoretically, ET estimates can be obtained by difference using a simplified mass-balance equation:

$$\text{ET} = \text{Precipitation} - \text{Runoff} - \text{Infiltration} \qquad (1)$$

However, if the remaining terms are not well known (especially runoff and infiltration), compounding inaccuracies will lead to an unreliable estimate. Additionally, ET is frequently necessary to predict runoff (i.e. stream flow). Therefore, estimating ET by difference is often not possible.

Challenges to quantifying urban ET include: large, impermeable surfaces with high rates of evaporation after rainfall; artificial removal of storm water runoff by water conveyance infrastructure; obstruction of instrumentation by tall buildings; and preferential "sight" of impervious surfaces by remote sensing.[3] In urban environments, pervious, vegetated areas serve to increase water retention and infiltration on the landscape. They also increase recreational opportunities, decrease soil erosion, improve surface drainage and air quality, and buffer the urban heat island effect.[4] By allowing for water infiltration, these vegetated areas reduce combined sewer overflows and pollution and nutrient loading to receiving waters. They can also help cities avoid costly storm sewer separation.

3. Background

ET (measured in mm or mm/time) is comprised of evaporation and transpiration. Evaporation is the process of water vaporization and loss to the atmosphere (*i.e.* pavement, vegetation, water bodies, etc.). Transpiration is the vaporization of water by a plant, resulting in a loss of water vapor through the leaf's stomata.[5] Evaporation and transpiration occur simultaneously and are both dependent upon solar radiation, air temperature, relative humidity, and wind speed; transpiration rates also vary between plants,[5] and evaporation rates vary depending on the land cover. The broad factors influencing evapotranspiration are related to micrometeorological, plant, and soil dynamics.[6] Micrometeorological and soil dynamics were directly observed in this study.

In urban areas, low impact development (LID), such as green roofs, pervious pavement, and constructed wetlands, provides an environmental and social benefit by decreasing runoff and combined sewer overflows.[7] Combined sewers are common in many cities, including New Haven. These systems convey municipal waste in combination with storm water runoff to waste water treatment plants. When storm water runoff exceeds the relatively small capacity of the combined sewer, combined sewer overflows (CSOs) occur, discharging raw sewage to receiving water bodies.[7] CSOs may occur as the result of storms which provide as little as 30 mm of precipitation and are a major factor in the pollution of US rivers, lakes and estuaries. The cost of CSO abatement has been estimated by the United States Environmental Protection Agency at more than $44 billion.[7] Understanding urban ET and the urban water cycle will help land managers make more informed decisions about land use and land cover, and may incentivize investment in LID or other means to reduce CSO events and resulting pollution.

4. Objectives, Goals, and Hypotheses

4.1. Objectives

Objectives of the project were three-fold. First and foremost was the production of independent measurements of ET (mm/day) for the 2016-growing season at the YEW, using the following methods:

a. Micrometeorological: Penman FAO 24 model heat budget
b. Hydrological: Soil moisture profiles
c. Physical: Pan evaporation

Pan evaporation is typically employed as a measure of reference evaporation. Therefore, the second objective was to evaluate the micrometeorological and hydrological methods based on their agreement with estimates of pan evaporation. The final objective was to evaluate the qualitative feasibility of the tested methods based on the following criteria:

a. Cost
b. Data intensity
c. Ease and reliability

4.2. Research Question

Of the aforementioned ET measurement methods (Section 4.1):

1. Which is most accurate, as judged by quantitative agreement with pan evaporation estimates?
2. Which is most feasible for implementation in urban environments?

4.3. Hypothesis

H_0: There will be no significant difference in the ET estimates produced by the chosen methods.

H_1: I expect the Penman FAO 24 model to agree most closely with the pan evaporation estimate, as they both are influenced only by climatic, and not other environmental, factors. Soil moisture will likely be the least feasible for implementation in the urban environment, both due to the expense and fragility of instrumentation, as well as the issue of representativeness in urban areas with very high percentages of impervious cover.

5. Methods

5.1. Site Description

This study was conducted within the 20-acre YEW, at the center of which is a 5.5-acre woodland. The YEW also encompasses streets, parking lots, grassed areas, and residential and campus buildings. A small, ephemeral stream flows through the woodland. Students from the Hixon Center for Urban Ecology's intern program have conducted preliminary research of site hydrology, soils, vegetation, and plant and animal communities over the past three years. This research has resulted in the quantification of impervious areas, delineation of the surface water watershed, evaluations of existing conveyance infrastructure, and a complete tree census.

The watershed is 74% pervious area (26% impervious). 54% of precipitation landing on the YEW is estimated to become storm water drainage.[8] The YEW is included in the Yale Office of Sustainability's Stormwater Management Plan (Plan), which calls for disconnecting a number of nearby residential downspouts from storm drains, which will increase inflow to the YEW. An ET estimate that precedes downspout disconnection allows for the creation of a baseline water budget. Existing monitoring equipment at the YEW includes a meteorological station, water quality meters, V notch weir stream gauges, shallow piezometers, and 12 groundwater wells in two transects. Most devices are connected to continuous data loggers, which are accessible in real time via the Internet. ET at this site (and in Connecticut generally) is highly seasonal, ranging from <2 mm/month to >80 mm/month during the peak-growing season.[9] ET is considered to be very low in the winter months.

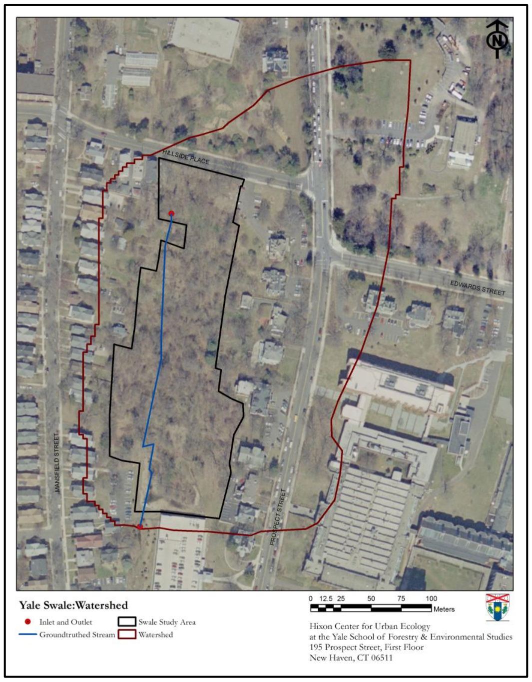

Fig. 1 Map of the YEW with watershed (red), study area (black), and ephemeral stream (blue) highlighted (copied from Hixon Center for Urban Ecology 2013).

5.2. Measuring Reference Evaporation

As previously stated, ET measurements derived from the chosen methods will be compared for agreement with reference evaporation. One of the most commonly employed, and simplest, means for estimating ET is a Class A evaporation pan. The U.S. Class A pan measures 1.21 m in diameter (with a water surface area of 1.15 m), and 0.25 m in height.[10] Evaporation from this open, circular pan provides a useful estimate of water vapor flux from water bodies and vegetated land surfaces,[11] and is typically related to evapotranspiration via a pan coefficient:

$$ET_0 = K_p E_{pan} \tag{2}$$

where ET_0 is reference evapotranspiration (mm/day); K_p is the pan coefficient; and E_{pan} is pan evaporation (mm/day).[12] However, because the pan coefficient is typically used to determine irrigation requirements of agricultural crops, only raw measurements of depth of water evaporated per day were taken.

The evaporation pan was placed directly adjacent to the YEW's meteorological station, in the northwest portion of the woodlot. A wooden platform was constructed for the evaporation pan, reducing heat convection from the underlying ground surface. The platform is located 15 cm above the ground, as recommended by the Food and Agriculture Organization of the United Nations (UN FAO).[12]

Rather than measuring depth evaporated from the pan itself, an attempt was made to automate pan refill and incorporate a data logger for consistent, and numerous measurements. To this end, a float valve was installed on the inner rim of the pan and connected with PVC tubing to a 4-gallon carboy reservoir. When water levels in the pan fell below 14.6 cm, the shifting angle of the float valve facilitated automatic refill from the carboy.

The evaporation pan was visited on a near-daily basis for the period of study, with refill occurring as necessary to the 4-gallon mark (38.4 cm). A Solinst level logger contained within the carboy measured the depth of water evaporated from the reservoir. The level logger senses both barometric and water pressure. The water level is estimated, with 0.1 cm resolution, at 5-minute intervals by subtracting the barometric from the total pressure.[13]

On September 2, 2016 a 4x4 hardware cloth screen was installed over the pan to reduce the introduction of leaf litter and to prevent animal interference with water levels. The screen covers approximately 22% of the surface area of the pan, reducing solar radiation and wind speed, and increasing humidity. These conditions should decrease the rates of evaporation from the pan surface and were accounted for in data analysis (Section 5.5a).

5.3. Micrometeorological Method: Penman FAO 24 model

The FAO 24 Penman method is a variant of the Penman equation, developed in 1948 and considered the most rigorous of the micrometeorological heat budget models for the estimation of ET.[14] In 1965, the Penman equation was modified by Monteith, adding a canopy resistance term.[14] The Penman-Monteith equation measures ET defined as the

> "rate of evapotranspiration from a hypothetic crop with an assumed crop height (12 cm) and a fixed canopy resistance (70 s m^{-1}) and albedo (0.23) which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water."[15]

The FAO 24 method is one of four recommended for the measurement of ET by the UN FAO in a 1977 report and is defined as the

> "rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water."[15]

The Penman FAO 24 modification utilizes the following input variables, obtained from the site meteorological station and include:

a. Air temperature (°F)
b. Barometric pressure (in. Hg)
c. Relative humidity (%)
d. Solar radiation (W/m^2)
e. Wind speed (mph)

These measured values were used in the following equations:

$$\text{Sun: } \frac{\frac{(\Delta * R_n)}{\lambda * (\Delta + \Upsilon)}}{24} \qquad (3)$$

$$\text{Wind: } \frac{\frac{\Upsilon * 6.43 * (1 + 0.536 * W_{S}) * VP}{\lambda * (\Delta + \Upsilon)}}{24} \qquad (4)$$

where:

Δ is the slope of the saturation vapor pressure-temperature curve (kPa/K); R_n is net radiation (MJ/m^2d); λ is the latent heat of vaporization (MJ/kg); γ is the psychrometric constant (kPa/K); W_s is wind speed (m/s); and VP is the vapor pressure deficit (kPa).[16]

Twenty-four is a divisor in both functions because they are calculated on the hour. The sun function returns positive values when net irradiation, calculated as re-emitted long wave radiation subtracted from incoming short wave radiation (MJ/m^2d), is greater than zero. The wind function returns non-zero values regardless of broad environmental conditions. Total ET is calculated as the sum of both functions.

5.4. Hydrological Method: Soil Moisture

Soil moisture measurements are indirect estimates of ET, which are determined by difference from the soil water balance equation

$$\Delta S = P + I + W - ET - R - D \tag{5}$$

where ΔS is change in soil water storage; P is precipitation; I is irrigation; W is capillary rise; R is surface runoff; and D is drainage.[4] In this study, ET was not separated from drainage. Runoff is considered minimal during the period of research due to low levels of precipitation, insufficient for the production of stream flow.

Soil moisture was measured with a Sentek EnviroScan soil moisture probe. The probe is equipped with six sensors, which measure soil moisture in their surroundings at multiple depths (10 cm, 20 cm, 30 cm, 40 cm, 60 cm and 100 cm). Measurements apply within a zone 10 cm vertically and 5-10 cm laterally.[3] In order to measure soil moisture, the sensors use capacitance, which varies with water content.[3]

The soil moisture probe was utilized at three sites within the YEW and recorded measurements at 30-minute intervals, with averages stored every 60 minutes. All data were stored on a Campbell Scientific CR200X datalogger. The soil moisture probe was moved between access tubes, allowing for a broader characterization of site topography and edaphic conditions.

5.5. Obtaining Estimates

5.5.a. Pan Evaporation

The Solinst level logger measured water levels within the carboy every five minutes, producing a great deal of noise. Of note is the tendency for logged values to increase between instances of reservoir refill. For this reason, hours-long sections of the data were averaged to produce a more reliable ET estimate.

To calculate daily ET, a two-hour average was taken each day around the noon hour, i.e. between 11:00 and 13:00, consisting of 24 data points. The absolute difference between successive days' average water level at 12:00 was taken. To relate this difference of water level in the carboy to difference in the pan by relative surface areas, the absolute daily difference was divided by the ratio of the squared radius of the pan to the squared radius of the carboy ($R^2/r^2 = 19.1$). Precipitation, measured at the adjacent Davis Instruments meteorological station, was included in these calculations as a sum added to average daily water levels on those days with rainfall.

For days in which the carboy was refilled, a two-hour average was taken of the water level before and after refill. These values were included in the daily calculation so as not to artificially inflate daily differences.

As stated previously, the screen installed in September 2016 decreased evaporative demand over the surface of the pan. A corrective factor was applied to daily estimated rates from the date of install through the end of the study. The corrective factor (12.8%) is based on a study comparing rates of evaporation from an un-screened and a screened pan in the semi-humid climate of South Carolina over the course of two summers (1973 and 1974).[11]

5.5.b. Penman FAO 24 Model

Hourly measurements of the aforementioned meteorological data (barometric pressure, temperature, wind speed, relative humidity, and solar radiation), collected from the Davis Instruments meteorological station, were used to calculate hourly estimates of ET (mm/hour). Daily estimates were taken as the sum of all values between consecutive noon hours.

Transmission between the meteorological station and receiving console was poor during the summer months. For the month of July, when transmission issues were most pronounced, estimates are made for any day with at least 50% of possible records. For all other months, estimates are made for any day with at least 75% of all possible records, with the majority of days having full records.

Calculated values are a sum of the wind and sun functions, as detailed in Section 5.3. Though the wind function accounts for a higher percentage of non-zero values, the sun function accounts for a greater proportion of total ET. Hourly calculated values of ET were summed to produce daily estimates.

Though only the wind function contributes to total ET overnight, the proportion of total ET attributable to the sun function was of a consistently greater magnitude over the course of the study period. This is due to the preeminence of R_n as an energy input in the evaporative process.[17] For this reason, it is likely that the two functions never contribute equally to total ET, though the relative importance of the sun function does decrease seasonally.

5.5.c. Soil Moisture

Hourly soil moisture values were recorded for the period from mid-July through October 2016. A factory calibration converts the raw capacitance-based measurement (scaled frequency) to volumetric water content (mm H_2O/100 mm soil) for each 10 cm increment along the probe, represented by a sensor. Because each sensor samples an area of soil in its surroundings to a depth of 10 cm, the volumetric water content measurement is taken as a raw depth (mm H_2O).

Though the data resolution is on the hourly scale, it is more likely that soil moisture values vary on a scale approaching a day. To produce a daily estimate, differences were taken at the 12:00 hour for each measured depth. Precipitation was then subtracted from this change in storage, as in equation 5.

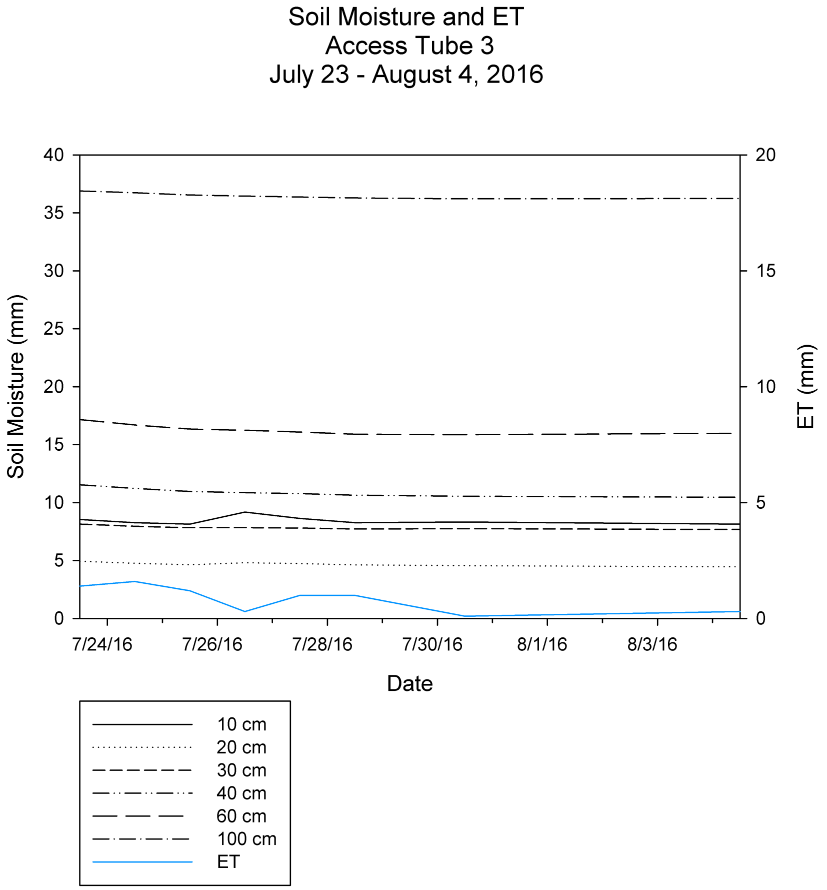

Fig. 2 Example soil moisture and ET curves for a dry period.

5.5.d. Davis Instruments Console Estimate

An ET estimate produced by the Davis Instruments meteorological station console was included in analysis as an additional point of comparison. The raw data used in this estimate is also derived from the Davis Instruments VantagePro2 meteorological station, which records meteorological values each half hour. ET estimates are produced each half hour and reported in inches. Hourly data were summed over the period of each day and converted to mm for ease of comparison with other methods.

The equation employed by Davis Instruments is as follows and is another variant of the Penman-Monteith heat budget[18]

$$ET_0 = \frac{\Delta}{\Delta + \gamma} * \frac{R_n}{\lambda} + \left(1 - \frac{\Delta}{\Delta + \gamma}\right) * (e_a - e_d) * F \tag{6}$$

where:
ET_0 is the hourly potential ET; Δ is the slope of the saturation vapor pressure curve (units not specified); γ is the psychrometric constant (units not specified); R_n is the average net radiation over the hour (W/m^2); $e_a - e_d$ is the vapor pressure deficit (kPa); WS is the wind speed; and F is the wind function:

$F_{day} = 0.030 + 0.0576 * WS$

$F_{night} = 0.125 + 0.0439 * WS$

Of significance is the difference in the calculation of R_n between the above Penman equation and the Davis Instruments estimate. The estimate produced by the Davis Instruments console includes estimates of albedo and cloud cover, which are absent from the FAO 24 model.[18] This difference is especially critical as the sun function accounts for a greater proportion of total ET throughout the course of the study. This is due to the preeminence of R_n as an energy input in the evaporative process.[17] Furthermore, constants included in the wind function, as well as the calculation of the vapor pressure deficit, differ between models.[18]

5.6. Data Analysis

The table below summarizes monthly ET estimates by method. Missing data are interpolated to produce these estimates, increasing their uncertainty. The Penman FAO 24 consistently produces significantly higher estimates than all other methods, and pan evaporation almost always produces the lowest monthly estimates. There is no agreement between methods as to the month with the highest ET rates. Interestingly, October is the month with the greatest ET as predicted by the soil moisture method. However, this is likely due to the presence of two days in October with high estimated ET, at least some of which may be attributable to drainage (discussed further in Section 6 and depicted below in Figure 3).

Table 1. Monthly ET estimates by method.

Method	Jul (mm)	Aug (mm)	Sep (mm)	Oct (mm)
Penman	165.5	150.1	93.8	60.9
Pan	29.9	23.9	37.3	28.5
Soil Moisture	47.2	42.1	34.5	53.4
Met Station	46.4	84.3	59	41.8

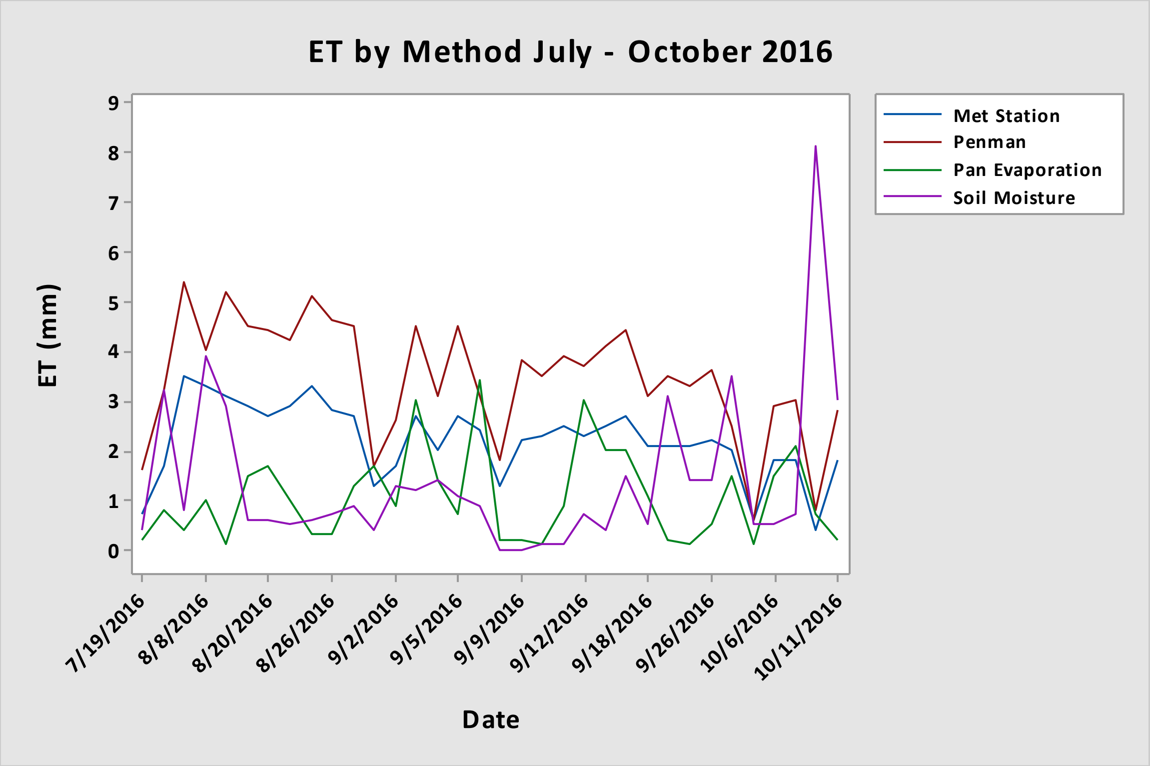

Fig. 3 ET rates for all methods (July – October, 2016), excluding missing values.

To better characterize agreement of each method with pan evaporation, I performed linear regression analyses using the statistical software Minitab. All predictors were considered statistically significant at α= 0.05. The most powerful model was one that predicted Penman FAO 24 ET estimates using pan evaporation ET and month, as well as an indicator variable for one outlier, which was a relatively low estimate for the Penman equation (1.1 mm). Taken together, these predictors account for 62.64% of the variation in ET estimates derived by the Penman FAO 24 model.

```
Model Summary

       S    R-sq    R-sq(adj)  R-sq(pred)
0.839629  62.64%      58.60%           *

Coefficients
Term                Coef  SE Coef  T-Value  P-Value   VIF
Constant           4.578    0.270    16.94    0.000
Pan Evaporation    0.286    0.134     2.14    0.039  1.03
```

```
Month_o
  1           -2.821    0.447    -6.31    0.000  1.25
Month_s
  1           -1.762    0.301    -5.86    0.000  1.30
Outlier 29
  1           -2.031    0.857    -2.37    0.023  1.02
```

Pan evaporation was not a significant predictor of either the meteorological station or soil moisture ET estimates. To better understand the degree of variability between methods, I calculated the root mean square error (RMSE) both over the course of the study and by month for each method, designating pan evaporation as the "standard."[19]

$$\sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{7}$$

Where P_i is the predicted value (pan evaporation) and O_i is the observed value (each respective method of comparison.[19] The RMSE is measured on the same scale as the data itself (mm/day), with a magnitude relative to that of the data.

Table 2. Total and monthly RMSE values for methods comparisons.

Methods	Total RMSE	Jul RMSE	Aug RMSE	Sep RMSE	Oct RMSE
Pan/Penman	2.8	NA	4.1	2.2	1.4
Pan/Met	1.5	1.3	2.3	1.3	0.8
Pan/Soil	1.9	1.8	1.5	1.4	3.6
Penman/Met	1.3	2.1	1.8	1.2	0.7

Overall RMSE is lowest for the meteorological station estimate vs. pan evaporation. This comparison also has among the lowest monthly RMSE values in October (0.8 mm/day). Interestingly, the one method that showed a linear relationship with pan evaporation, Penman FAO 24, has the highest overall RMSE and the highest RMSE for a single month (August).

Soil moisture has a relatively low overall RMSE and low monthly values, save the RMSE for October. As stated previously, there were two precipitation events in the month of October after which high values of ET were calculated, though it is possible that some of the loss attributed to ET was actually free drainage. As a point of comparison, RMSE was calculated for the Penman FAO 24 vs. meteorological station estimates, as both tend to agree well over the course of the study and are the methods with the greatest similarities. Though the overall RMSE is lowest for this comparison, some individual months still show relatively high variability between methods.

To further examine pan evaporation estimates in their own right, I sought to predict water loss from the carboy with meteorological variables that dictate evaporation rates. To this end, I utilized hourly data from the YEW's meteorological station, specifically:

atmospheric pressure (kPa), temperature (°C), relative humidity (%), wind speed (m/s), irradiance (MJ/m^2d), and vapor pressure deficit (kPa). These are the variables included in the Penman-Monteith equation. This type of analysis was performed for the months of July and August, only.

I began by trying to relate successive differences in the carboy level to these variables. To prepare the data, I used five-minute logger data and worked backwards from the end of each month, adding the amount of refill at each relevant point, increasing over the course of the month. This essentially created one downward trend of the carboy level. To reduce the noise created by five-minute measurements, I again created hourly averages around the half-hour. Final data for July is depicted below.

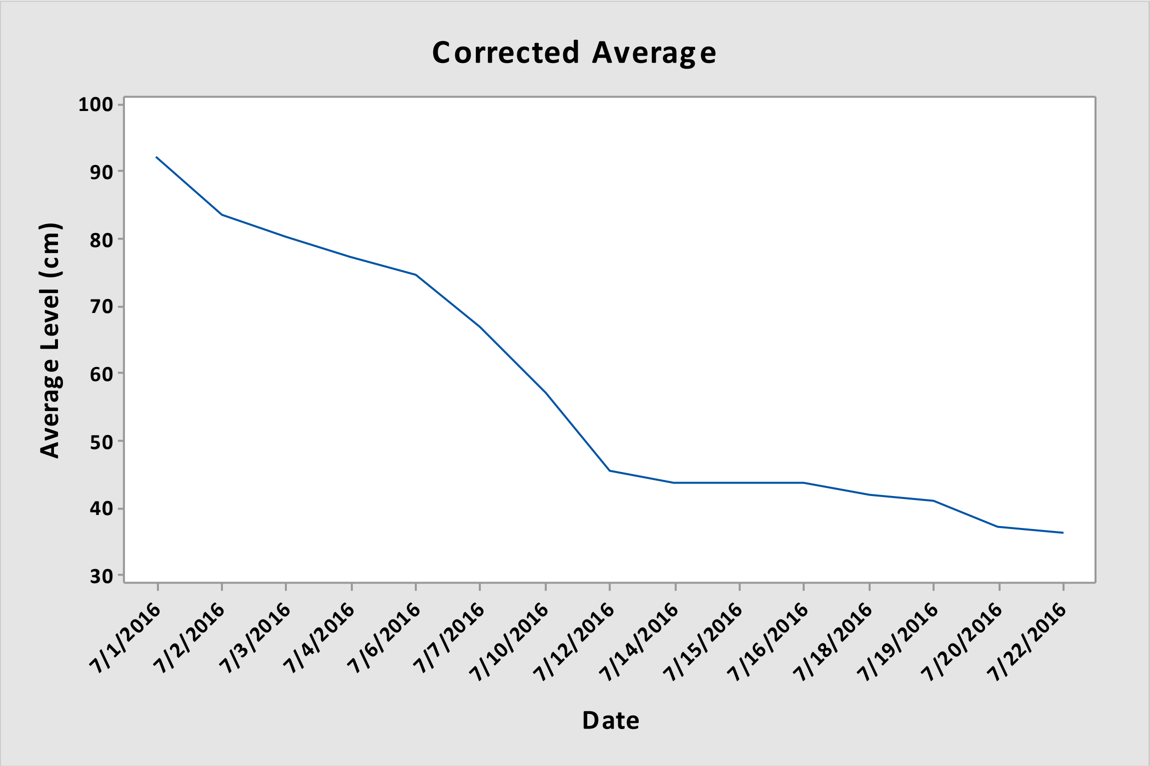

Fig. 4   Singular downward trend carboy data for the month of July 2016.

Successive differences were only predicted by meteorological variables (relative humidity and vapor pressure deficit) for the month of August and with indicator variables for nine outliers. The accounted for outliers are all either data points with positive differences, likely attributable to noise in the 5-minute data, or data points occurring after excerpted data, where the difference from the preceding point is unusually large.

```
Model Summary

       S     R-sq    R-sq(adj)  R-sq(pred)
0.313849   79.23%     78.53%            *
```

```
Coefficients
Term             Coef  SE Coef  T-Value  P-Value    VIF
Constant        1.065    0.467     2.28    0.023
Rel Hum      -0.01153  0.00486    -2.37    0.018  16.75
VP Deficit     -0.346    0.125    -2.77    0.006  16.98
Outlier 39
  1             1.690    0.314     5.38    0.000   1.00
Outlier 87
  1             1.637    0.316     5.18    0.000   1.01
Outlier 133
  1            -2.835    0.315    -9.01    0.000   1.00
Outlier 149
  1            -3.233    0.314   -10.28    0.000   1.00
Outlier 306
  1            -8.976    0.324   -27.68    0.000   1.06
Outlier 313
  1            -1.692    0.316    -5.36    0.000   1.01
Outlier 324
  1            -2.520    0.314    -8.02    0.000   1.00
Outlier 32
  1             1.566    0.314     4.98    0.000   1.00
Outlier 33
  1            -1.421    0.315    -4.51    0.000   1.01
```

Though this model explains 79.23% of the variability in differences in carboy level, there is significant multi-collinearity between the meteorological variables included in the model.

5.7. Feasibility Assessments

Table 3. Implementation and repair costs by method.

Method	Description	Cost
Penman FAO 24	Station, Console, Repeater, WeatherLink	$1,048.00
Pan Evaporation	Pan, Carboy, Data logger	$2,188
Soil Moisture	Probe, Data Acquisition, Probe Repair	$2,805.80

The above costs reflect both the infrastructure required for each measurement method, as well as costs of equipment repair incurred over the course of the study period, if any. Penman FAO 24 is clearly the most cost effective method, with the inclusion of the WeatherLink software connection allowing for long-term storage of meteorological data. Additionally, as the console provides its own Penman-Monteith derived ET estimate, the cost of acquiring the meteorological station provides a point of comparison for any meteorological heat budget constructed from the available data.

Though pan evaporation would appear to be the simplest form of data collection, the costs of the pan itself, as well as the level logger, are quite substantial. These costs also do not include those associated with the building of the platform or of the installed screen. Costs could be significantly reduced by eliminating the level logger and manually measuring the depth to water in the pan at the same time each day prior to refill to a standard height. This method would require a greater time investment over the course of the study but may significantly decrease the time associated with data analysis.

Soil moisture is also relatively expensive, though, as in this study, one probe can be used to gather data for multiple locations, a limitation not easily overcome using the other methods. Some minor costs are excluded from this calculation, including the PVC pipe access tube that must be installed for use. Soil moisture was the only method tested that required equipment repair over the course of the study. Though relatively minimal compared to infrastructure costs ($162.30), the soil moisture probe is somewhat fragile and may need to be repaired, especially if used for long-term studies.

5.7.a. Pan Evaporation

Throughout the course of the summer wildlife and residents interfered with the regular operations of the evaporation pan. Camera traps were installed to verify the use of the evaporation pan by raccoons, likely displacing water in the pan and initiating refill from the carboy. Interference typically occurred over night or in the early morning during periods with low atmospheric evaporative demand. On multiple occasions, the tubing connecting the float valve to the reservoir was also forcibly removed, causing the carboy to drain and terminating data collection until the reservoir was found to be empty and refilled. This interference motivated the installation of the screen, which limited tampering with research equipment but increases the complexity of data analysis.

Though precipitation was accounted for in pan evaporation estimates, it is possible that the data contains artifacts related to rainfall. If, for example, heavy rains occur sufficient to submerge the float valve for days following a precipitation event, the effect of the storm is only accounted for on the actual day of precipitation input, and not those that follow.

Overall, data intensity was the greatest for this method. To safeguard against interference, the pan needed to be visited on a near-daily basis. Furthermore, noise in the level logger data requires the use of careful notes to either confirm or eliminate the suspicion of interference during periods of dramatic decreases in level. Finally, five-minute data is likely too fine a resolution to detect meaningful changes in level, and significantly intensified data analysis.

5.7.b. Penman FAO 24 Model

During peak leaf-out reception between the Davis Instruments weather station and the station console was intermittent. Data from the month of July was most severely impacted by poor reception, limiting data collection during this month. On July 21, 2016 a wireless repeater was installed.

Intensity of data analysis was considered to be minimal with this method. All data can be downloaded from Davis' WeatherLink software and analyzed in Excel. No repairs to field equipment were required over the course of the study period.

5.7.c. Soil Moisture Profiles

Data analysis and field deployment for this method are minimal. However, absent a complete understanding of soil properties, especially textural class and rooting depth, ET estimates are somewhat crude. For example, according to daily differences, ET occasionally spikes on days following precipitation. It is, however, plausible that some of the daily difference in soil moisture attributed to ET is actually drainage, especially in coarser-grained soils.

Furthermore, though it is possible to calibrate the Sentek EnviroScan probe to site soils, the process requires significant time and labor, especially in the case of field calibrations. As in this study, the Sentek EnviroScan probe is often used with its factory calibration, which should return reasonable values of *relative* VWC over a wide range of soil textures.[20] Some studies indicate that the use of the factory calibration leads to an overestimate in VWC, which may inflate ET estimates derived from daily differences.[21]

Logistical concerns with the implementation of this method include increased uncertainty introduced by the use of factory calibration or increased cost and labor expenditure associated with site-specific calibration. Furthermore, soil properties change considerably over relatively short distances, decreasing the applicability of values extrapolated to an entire urban landscape. Finally, as previously mentioned, many cities have limited soil cover, or may have heavily compacted soil with altered rates of infiltration and, thereby, ET. In this case, a physical estimate may be less accurate than one based upon climatic variables.

6. Future Analysis and Concluding Remarks

My data analysis shows that, of the tested methods, the Penman FAO 24 model relates best to pan evaporation, though only in a linear regression model which includes "month" as a categorical variable. Furthermore, the FAO 24-pan evaporation RMSE is consistently higher than any other tested method. According to the total RMSE, the meteorological station relates best to pan evaporation, though there are individual months in which the meteorological station-pan evaporation RMSE exceeds the soil moisture-pan evaporation error.

The absence of a linear relationship between pan evaporation and the other tested methods (soil moisture and meteorological station) likely results from a number of factors, including:

1. A considerable volume of data was unusable due to interference with the pan
2. Though rain was accounted for in pan evaporation estimates, it is possible that the data contains artifacts (i.e. the pan level may have been increased over a number of days, though it is only explicitly considered on the day of rainfall)
3. Inaccuracies surrounding the calculation of soil moisture ET, specifically with regards to partitioning ET and drainage

There do seem to be some relationships between successive differences of the carboy and meteorological variables, at least for a subset of the data. Analyzing the remainder of the data through the end of November 2016 should show whether this pattern bears out over the course of the study.

In future experiments, estimates of soil moisture ET could be improved by better knowledge of soil properties. Specifically, soil texture, field capacity and rooting depth will influence the amount of soil water available for ET vs. drainage. Large outliers currently exist in the soil moisture data set on days following precipitation and likely incorrectly attribute some free drainage to ET.

Pan evaporation estimates could be improved by keeping equipment modifications installed over the course of the study that successfully deterred wildlife interference (i.e. attaching the float valve tubing to the carboy with super glue and installing a screen over the pan). Finally, drilling a hole in the side of the evaporation pan slightly higher than the refill line could remove artifacts from the data by allowing rainfall to drain. This modification may result in higher pan evaporation ET estimates, bringing this method more in line with historic pan evaporation data from the surrounding area.[22]

While infrastructural and knowledge-based improvements could refine future pan evaporation and soil moisture measurements, for budgeting purposes, a measurement of growing season ET could reasonably be made from the meteorological heat budgets produced over the course of this study. However, the tendency for the Penman FAO 24 model to overestimate ET when compared with the Penman-Monteith model has been shown in previous studies,[15] justifying either the use of the meteorological station derived estimate, or a re-calculation of ET values for the course of the study using the Penman-Monteith equation. Furthermore, it should be noted that the definition of ET in either model attempts to capture behavior in a cropped, and not a wooded, landscape. It may be useful to seek meteorological heat budgets that are designed specifically for forested landscapes to compare estimates.

Storm water separation is costly, and represents a significant financial burden to many older cities. Reducing these costs can be achieved through the promotion of natural water fluxes and increased use of green infrastructure. Understanding urban ET is critical to the development of sound management principles in this realm. Though a clear “best” method did not become evident through the course of this analysis, a meteorological heat budget using local climatic data was the most cost-effective, the least data intensive, and required the smallest investment of time and human resources. Therefore, this method may serve as an easy baseline method for estimating ET. Other advantages of this method are that it does not rely upon relatively intact soils, open grassy or cropped areas, and is not particularly sensitive to interference or vandalism.

Utilizing this method, especially over a longer time span, may help to close the water budget in an urban environment. Calculating the heat budget in two areas within the city with drastically different LULC could also be illuminating and, if capable of demonstrating higher rates of ET in more vegetated areas, may be a compelling argument for investing in LID. Such an investment could lead to reductions in water inputs to the urban system, decreasing the pressure on storm water systems, and facilitating both water savings and declines in overland flow runoff and pollutant export.

REFERENCES

1. Grimmond C.S.B. and Oke T.R. 1991. An evapotranspiration-interception model for urban areas. *Water Resources Research* 27: 1739-1755.
2. Sumner D.M. and Jacobs J.M. 2005. Utility of Penman-Monteith, Priestley-Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. *Journal of Hydrology* 308: 81-104.
3. Trout K. and Ross M. 2006. Estimating Evapotranspiration in urban environments. *Urban Groundwater Management and Sustainability,* 157-168.
4. Nouri H., Beecham S., Kazemi F., Hassanli A.M. 2012. A review of ET measurement techniques for estimating the water requirements of urban landscape vegetation. *Urban Water Journal* 10: 247-259.
5. Zotarelli L., Dukes M.D., Romero C.C., Migliaccio K.W., Morgan K.T. 2010. Step by step calculation of the Penman-Monteith evapotranspiration (FAO-56 method). *University of Florida IFAS Extension.*
6. Al-Kaisi M., Brun L.J., Enz J.W. 1989. Transpiration and evapotranspiration from maize as related to leaf area index. *Agricultural and Forest Meteorology* 48: 111-116.
7. Montalto F., Behr C., Alfredo K., Wolf M., Arye M., Walsh M. 2007. Rapid assessment of the cost-effectiveness of low impact development for CSO control. *Landscape and Urban Planning* 82: 117-131.
8. Brooks S. and Sarsfield R. 2012. Initial assessment of the Yale Swale.
9. Bhandaram U., Jaeckel D., Kuhn C. 2014. Yale Swale assessment report 2013-2014.
10. Linacre E.T. 1994. Estimating U.S. Class A pan evaporation from few climate data. *Water International* 19: 5-14.
11. Campbell R.B. and Phene C.J. 1976. Estimating potential evapotranspiration from screened pan evaporation. *Agricultural Meteorology* 16: 343-352.
12. Food and Agriculture Organization of the United Nations. 2016. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Corporate Document Repository.
13. Solinst. 2001. User guide levelogger series - software version 4.2.
14. Stannard D.I. 1993. Comparison of Penman-Monteith, Shuttleworth-Wallace, and Modified Priestley-Taylor evapotranspiration models for wildland vegetation in semiarid rangeland. *Water Resources Research* 29: 1379-1392.
15. Chiew F.H.S., Kamaladas N.N., Malano H.M., McMahon T.A. 1995. Penman-Monteith, FAO-24 reference crop evapotranspiration and class-A pan data in Australia. *Agricultural Water Management* 28: 9-21.
16. Singh V.P. and Yadava R.N. *Watershed Hydrology.* Mumbai: Allied Publishers Private Limited, 2003. Online, p. 68-69.
17. Hobbins M.T., Ramírez J.A., Brown T.C. 2004. Trends in pan evaporation and actual evapotranspiration across the conterminous U.S.: Paradoxical or complementary? *Geophysical Research Letters* 31L13503.
18. Davis Instruments. 2006. Derived variables in Davis weather products.
19. Hossein T., Grismer M.E., Trajkovic S. 2011. Comparative analysis of 31 reference evapotranspiration methods under humid conditions. *Irrigation Science* 31: 107-117.
20. Sentek Pty Ltd. 2001-2011. Calibration manual for Sentek soil moisture sensors version 2.0.

21. Jabro J.D., Leib B.G., Jabro A.D. 2005. Estimating soil water content using site-specific calibration of capacitance measurements from Sentek Enviroscan systems. *Applied Engineering in Agriculture* 21: 393-399.
22. National Oceanic and Atmospheric Administration National Weather Service. 1982. Mean monthly, seasonal, and annual pan evaporation for the United States. NOAA Technical Report NWS 34.

Advisor Signature

12/13/16

Dr. Gaboury Benoit, Date