**The ROLES AND Effects of Tree Evapotranspiration AND CANOPY INTERCEPTION in Stormwater Management Systems and Strategies:**

**A REVIEW OF CURRENT LITERATURE AND PROPOSED METHODOLOGY FOR**

**QUANTIFICATION IN THE MIDS CALCULATOR APPLICATION**

**Objective 1, Task 13**

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ABSTRACT: Evapotranspiration and canopy interception by individual trees comprise a significant proportion of the hydrologic cycle. An extensive literature review was completed to evaluate and quantify the application of these values to stormwater best management practices (BMPs) and potential model inputs to the MIDS calculator. The MIDS calculator is a stormwater crediting device rather than a finely-calibrated hydrologic model and requires only coarse inputs for assignment of these credits. Due to this, recommended values generated by and inputs for the MIDS calculator are based on the Lindsey-Bassuk equation for evapotranspiration and a coarse method of generating interception capacity for individual trees. Stormwater computer models for estimation of these values are abundant and vary in type, inputs, outputs, and relative quality and precision of generated data. Recommended computer models for integrated vegetative benefits of stormwater by trees for use by MIDS are either iTree or SWAT (Soil and Water Assessment Tool).

(KEY TERMS: evapotranspiration; canopy interception; hydrologic cycle; water-balance; precipitation; trees; vegetation; surface water; groundwater; actual evapotranspiration; potential evapotranspiration; hydrologic; Penman-Monteith; Lindsey-Bassuk; “smart” technologies)

INTRODUCTION

***Magnitude of Evapotranspiration***

Evapotranspiration comprises a portion of the total net storm water volume and the losses from the effective water felt by the ground within the hydrologic cycle. This debit from the overall rainfall is a combination of 1) the gross losses attributed to vegetative uptake and use in metabolic processes associated with the movement of water from roots to leaf structures and back to the atmosphere (transpiration) and the state change of liquid water to water vapor under certain atmospheric conditions (evaporation). As it is difficult to separate these two distinct processes, they are often referred to together as “evapotranspiration,” or ET.

Evapotranspiration (ET) accounts for a large part of the pre-settlement hydrological cycle, and continues to be a large part of the hydrological cycle even in today’s landscape. Writing about the hydrological cycle in Minnesota, Baker et al (1979) write that “by far the greatest share of the precipitation is returned to the atmosphere as invisible vapor through the processs of evapotranspiration and evaporation and in the winter by sublimation.” They estimate that **75.9%** of precipitation in Minnesota is lost to evapotranspiration, 2.2 % to groundwater, 21.9% to surface runoff. They also give mean evapotranspiration and precipitation for Minnesota. For Minneapolis/St. Paul, they report mean annual precipitation of 26.82 inches based on records from 1837 to 1973. Mean evapotranspiration is between 20 and 21 inches for Hennepin County, based on the difference between precipitation and runoff. Assuming 20.5 inches of ET for Minneapolis/St.Paul yields 75.9% of precipitation being evapotranspired.

A more recent study by Sanford and Selnick (2013), based on records from 1971 to 2000, also found evapotranspiration to be a significant part of the hydrological cycle in Minnesota. They found that for most counties in Minnesota:

* Estimated fraction of precipitation lost to evapotranspiration was 0.5-.79 (5 counties on Western border at 0.79-.89)
* Estimated mean annual actual evapotranspiration was 16 inches to 23.6 inches (12.2” to 16” for 1 county along northern border)

Moreover, during the growing season, atmospheric evaporative demand exceeds precipitation in Minnesota (see Figure 13.1), meaning that if more water was available than just precipitation, evapotranspiration could even exceed precipitation during the growing season.

Figure 13.1: Monthly precipitation and evaporation in 4 major cities in the US (inches), including Minneapolis (Source: Lindsey and Bassuk 1991)

A study by Grimmond and Oke (1999) which compared the ratio of ET to precipitation (ET:P) in 7 cities with very different climates showed that:

* In many cities, ET exceeds precipitation and is sustained by irrigation from a municipal water supply.
* The hydrological importance of ET is evident from the ET:P ratios, which range from 0.7 to 3.7 for sites with precipitation. At 4 of the sites, ET:P tends to infinity because effectively there was no rain during the study periods.

An ET:P ratio of 3.7 means that ET was almost 4 times as high as the amount of rain that fell!

Many studies have found that evapotranspiration is highest when soil moisture is highest, and decreases as soil moisture decreases (e.g. Fassman, Sinclair et al 2005). Sinclair et al 2005 investigated the daily transpiration response to soil drying in five woody species and found that:

* Transpiration was unaffected by soil drying until the initial estimated transpirable soil water fraction had decreased to between 0.23 and 0.32 of that at field capacity. Beyond this point, transpiration rate declined linearly with available soil water fraction until reaching one fifth the rate observed in well watered plants. With further soil drying, the relative transpiration rates remained between 10 and 20% of that observed in well watered plants. Maintenance of transpiration at these rates with further soil drying was hypothesized to result from contributions to transpiration of water stored in plant tissues.
* Combining their results with those of studies in their literature review, the authors conclude that the sensitivity of relative transpiration rates to changes in volumetric water content is approximately constant over a wide range of plant species.

This indicates that irrigating during droughts should increase ET.

Other ways of maintaining adequate soil moisture for maximum ET, such as, for example, designing BMP’s with internal water storage also increase ET.

A study by Hinckman (2011) found that, due to more available soil moisture, a bioretention lysimeter with IWS lost twice as much water to ET as a biofiltration cell without ET.

**Implications of the above for the Minnesota Stormwater Manual and MIDS calculator are:**

* ET is a large part of the hydrological cycle, even in urban areas, and design and crediting incentives of BMP’s should aim to maximize ET.
* Directing more runoff to a BMP than just the amount of rain that falls on the BMP should increase the amount of ET in the BMP compared to ET of similar vegetation that received only the rain that falls on it. A very rough estimation from Figure 13.1 indicates that during mid-summer, vegetation should be able to evapotranspire about twice as much rain as the amount that falls directly on the BMP.
* Irrigating with runoff harvested from impervious surfaces when soil moisture falls below 0.32 of field capacity should also be encouraged to maximize ET.

ET rates vary greatly over varying temporal periods (Brutsaert and Stricker 1979 per Cheng, et al. 2011), but are mainly controlled by available water and energy. Both canopy interception and ET are quantifiable losses from the net volume of water but are disparate in their mechanism and operation in the water budget, and should be treated separately in estimation and model applications.

Zhang et al. (2001) indicate that controls on evapotranspiration rates are a combination of the following: rainfall interception, net radiation, advection, turbulent transport, total leaf (surface) area, and available water capacity. (Zhang, Dawes and Walker 2001) The authors go on to indicate that the relative importance of each aforementioned variable in quantifying ET rates is not static, and fluctuates due to climate, soil, and vegetative conditions, and later, indicates that the relative annual ET rates are higher in forested watersheds than non-forested ones. (Zhang, Dawes and Walker 2001)

Although difficult to quantify, there is an abundance of research on evapotranspiration – direct measurements, equations, and models – for different biomes around the world. Much less research appears in current literature on the evapotranpiration from individual trees, which would have direct application to individual street tree models and calculations. Even less research appears for ET rates in individual urban street trees, although the quality and sustainability of our urban canopy continues to increase within our developing cities worldwide and demand would dictate the attention to this in research, regulation, and modeling. Current projections estimate 74.4 billion trees – one-quarter of the United States’ total canopy cover – are within urban areas. (Dwyer et al. 2000, per Peper & McPherson 2003)

Lindsey and Bassuk (1991) indicate our current patterns of urban tree subsurface design and soil provision are limiting the overall growth, success, and longeivity of our urban canopy by providing insufficient soil volumes. (Lindsey and Bassuk 1991) Foster and Blaine (1978, per Day and Bassuk, 1994) indicate that the average lifespan of an urban neighborhood tree is 10 years. (Day and Bassuk 1994) Often, the design of soil provisions in tree openings are given for only slightly beyond the immediate root package on establishment, with no provision given to the biological needs of the tree at maturity. Specifically, the most significant needs provided by the soil include available moisture and nutrients. Smaller soil volumes in these tree openings offer reduced available soil moisture and do not have the capacity within the space between the soil particles to contain adequate moisture for transpirational demands. (Lindsey and Bassuk 1991).

Available soil moisture is critical to tree physiological response to increased atmospheric evaporative demand. When plant available water is abundant in the soil, tree response is to open or widen leaf stomata to increase transpiration rates to meet that demand. However, when soil moisture is limited, tree physiological response of increased moisture use to meet the rising atmospheric evaporative demand is not advantageous, as the increased moisture use could rapidly deplete the limited supply prior to the recharge of the moisture. The tree responds to limited moisture in a number of ways to conserve energy and water resources within the tree itself, including closure of the stomata, leaf rolling, leaf drop, and wilting. (Lindsey & Bassuk 1991) Therefore, defining how much soil moisture and other atmospheric conditions are necessary to achieve those rates is imperative to determining the total soil volume necessary to provide those effective ET rates.

The level of soil compaction and the resultant ability to convey intercepted surface water and air through the soil to the roots via infiltration is thought to be a complicated balance between the texture and bulk density of the soil. (Day and Bassuk 1994) There has been research done on compaction thresholds for structural support (low) and growth impedence (high) for a variety of vegetative species, and the result indicate a great variation of tolerance between species, athough the upper limit of bulk density prior to root growth limitation effects are observed is conservatively in the range of 1.21-1.40 g/cm3. (Day and Bassuk 1994) These studies generally utilize metrics to assess both density and textural character of the sample using a penetrometer – to measure resistance to penetration – and bulk density of oven-dried samples (dry mass/volume). (Day and Bassuk 1994) As plant available water in the soil is critical for establishing baselines for estimating true ET rates, this soil understanding and evaluation is critical information to management and stormwater impacts of trees, particularly in urban areas that tend to exhibit higher rates of compaction and lower soil volumes overall.

***Magnitude of Interception***

Canopy interception (INT), or the mechanical/physical removal of precipitation by individual tree leaf foliage and collective canopy, is a significant and quantifiable loss from the net precipitation contributing to surface storm water within the hydrologic water budget equation. Critical research and modeling are ongoing with respect to the magnitude of importance of interception as well as the best way to model the impact interception has on effective/net runoff. Esteemed researcher in this area, Quinfu Xiao, of the USDA Forest Service and Research Water Scientist within the Land, Air and Water Resources (LAWR) program at University of California – Davis, writes the following regarding the role and importance of understanding and quantifying interception,

 “The critical time for trees to play a role in reducing storm runoff is during and right after each storm. Both transpiration and evaporation are limited during that period of time. Thus, canopy interception will make [a] major contribution for storm runoff reduction.” (Xiao, Personal Comm. 2013)

Due to this expert indication of the importance of canopy interception, further investigation into the use of a comprehensive continuous-simulation model would be suggested to better estimate the volume and rate of stormwater lost to interception.

In his research on interception in Santa Monica’s urban forest, for example, Xiao found “Rainfall interception varied seasonally, averaging 14.8% during a 21.7 mm winter storm and 79.5% during a 20.3 mm summer storm for a large, deciduous Platanus acerifolia tree” (Xiao and McPherson 2003).

Please note that because Minnesota’s environments covered by MPCA work span the spectrum of ultra-urban to natural forest conditions, the studies included and referenced in the literature review varied in scale to understand the varying conditions that MPCA may encounter in forest assessment and quantification of interception and evapotranspiration.

IMPACT OF TREE SIZE MAGNITUDE ON STORMWATER BENEFITS

Magnitude of stormwater volume benefits increases dramatically with tree size. Since larger trees have more leaves to intercept rain, they intercept significantly more rain than small trees, with interception increasing at a faster rate than tree age. For example, a model of a hackberry tree in the Midwest estimates that interception will increase as follows with tree age (see Figure 13.2):

* a 5 year old hackberry intercepts 0.5 m3 (133 GAL) rainfall per year
* a 20 year old hackberry intercepts 5.3 m3 (1,394 GAL) rainfall per year
* a 40 year old hackberry intercepts 20.4 m3 (5,387 GAL) rainfall per year (McPherson et al, 2006).

Figure 13.2: Stormwater interception by hackberry trees versus age of tree (adapted from McPherson et al, 2006)

EVAPOTRANSPIRATION MEASUREMENT METHODS AND MODELS

*Metrics and Inputs.* Capturing the annual ET rate from catchment-area hydrologic units again exhibits a wide variation in the temporal and spatial rates, based on a complex interaction with climatic variables and catchment characteristics. (Zhang, Hickel, Dawes, Chiew, Western, & Briggs, 2004) Climatic variables include meteorological conditions of the study area, including precipitation, solar radiation, annual temperature – mean and extremes, wind speed, and humidity. (Zhang, Hickel, Dawes, Chiew, Western, & Briggs, 2004) Catchment characteristics are those dictated by the hydrologic land area unit containing the study location, including percent vegetation cover (ie. and type, soil – type, texture, and depth – character, and permeability. (Zhang, Hickel, Dawes, Chiew, Western, & Briggs, 2004)

*Approaches to Quantification.* A number of measurements methods exist for quantifying ET. Rana and Katerji (2000) indicate 3 major categories of approaches to measuring or quantifying ET rates (Rana and Katerji 2000):

1.Hydrological approaches:

(1) Soil water-balance [indirect measure]

(2) Weighing lysimeters [direct measure]

2. Micrometeorological approaches:

(3) Energy balance and Bowen ratio [indirect measure]

(4) Aerodynamic method ratio [indirect measure]

(5) Eddy covariance ratio [indirect measure]

3. Plant physiology approaches

(6) Sap flow method [direct measure]

(7) Chambers system [direct measure]

These methods may be further categorized as direct measure or indirect measure models and methodologies, as indicated above.

*Direct Evapotranspiration Measurement Methods.* Direct measures of evapotranspiration can be taken, mainly by use of soil measurements using lysimeters, laboratory measurements in a controlled environment, or by utilizing plant physiological methodologies such as sap flow or chamber systems. These direct measurement methods are often costly and require significant human resource inputs due to necessary collection of incremental data or measurements to achieve the necessary number of data points to derive a statistically-significant confidence of results. Careful consideration should be given to desired project goals, outcomes, and budgets when assessing the applicability of direct measurement methods and models to stormwater credit calculation and assignment for ET rates.

*Indirect Evapotranspiration Measurement Methods.* One method of measuring ET indirectly is via the energy balance approach at local land surface (Ward & Trimble, 2004 per Sanford & Selnick, 2012). This approach has limited transferability to the larger areas beyond the test site and requires high levels of human and economic resources to complete the measurements. With this method, hourly measurements of meteorological conditions must be taken on a small scale plot to capture the range of highly-variable ET throughout the day-night cycle. This is very limited in transferability to larger scale analyses and modeling due to the small size of plot and the relative composition and of species as a representative proxy for alternate or regional areas and ecosystems.

The eddy covariance approach is another method of indirectly assessing ET by taking meteorological readings at a specified distance above the land surface (Baldocchi et al., 2001; Mu et al, 2007 per Sanford & Selnick, 2012). The authors note that this provides an average ET value over longer time periods, but is still limited in its applicability and transferability to larger spatial extents beyond the data collection area.

If local meteorological data is available, ET can be indirectly measured using a mathematical relationship between actual ET(AET) and potential ET(PET). This indirect relational methodology is based on utilizing that local meteorological data for the site area – wind speed, relative humidity, temperature, etc. – as inputs into various models and equations to generate an estimate of PET. In these models, AET can be thought of as equivalent to PET with ample water availability. Additional local meteorological variables can be used to quantify AET as a percentage of the PET from those inputs. The regional data as a base has implication for regional comparison and studies (Ward & Trimble, 2004 per Sanford & Selnick, 2012)

A fourth approach is to measure ET via use of the water-balance approach. To note, the water-balance equation is:

The premise of this is that the hydrology of a system is conservation (no additional water is produced or lost throughout the cycle) in a specified land area or catchment. This relationship can be represented as a balanced equation relating the inputs – precipitation (P) – with the “losses” or debits – ET, streamflow (SF), etc. – to generate the total change in necessary for storage to account for the overall precipitation within the catchment, as follows:

and can be otherwise written as the following to isolate ET:

This methodology utilizes the process of elimination to isolate more-easily quantifiable variables within the water-balance equation to estimate ET. (Ward & Trimble, 2004 and Healy & Scanlon, 2010 per Sanford & Selnick, 2012) This methodology has advantages due to relative availability of hydrologic data – streamflow, soil moisture, etc. – that provide the base inputs, and can be used via remote sensing methods to provide regional and continental application of data (Cheng, Xu, Wang, & Cai, 2011; Zhang, Hickel, Dawes, Chiew, Western, & Briggs, 2004) Although relative ease of use of the equation above is high, failure to account for “other losses” could result in inaccuracies in the estimation of evapotranspirative losses and caution comprehensive analysis of losses should be applied when using this method. What is referred to in the above equation as, “other losses,” would include any other ways the overall precipitation felt by the landscape would be reduced, including but not limited to groundwater recharge, lateral translation/translatory flow in the subsurface soils and bedrock, depressional storage, and otherwise. Of particular note and suggested area for further investigation includes the groundwater losses, as stated by Xiao, “Considerable water may charge groundwater.” (Xiao (Personal Comm.) 2013) It is important to quantify all potential precipitation-reducing sources within this quantification of “other losses” in order to not overestimate the impacts of ET on the water balance.

*Capturing Meteorological Input Data.* Gathering and using meteorlogical inputs to accurately represent water use and systemic hydrologic losses are crucial to estimation as the evapotranspiration, canopy interception, and general hydrologic models all function by correlating tree response to atmospheric demand. This can either be measured directly on project site or captured remotely/indirectly using empirical datasets for a given period of record. There are a few repositories for meteorological data, including pan evaporation, temperature means, annual temperature extremes, and others – but the main one is housed at and maintained by the National Oceanographic and Atmospheric Administration, or NOAA.

*Leaf Area Index (LAI).* The total surface area associated with all the leaves in the tree’s canopy is referred to as the total leaf area. This surface area represents the boundary between the vegetation within the tree and the atmosphere outside of those contained structures. The leaf area index (LAI) is measured in leaf surface area per area of ground, and affects transpiration rates, soil moisture, and temperature. (Per Gonzales, Williams and Kaplan 2008: Chase et al., 1996; Parton et al., 1996; Pielke et al. 1998; D’Arrigo et al. 2000; Law et al. 2001; Williams 2003; Williams et al. 2008). Specific LAI for individual trees can be calculated by the following equation:

The leaf area for evergreens considered to be ½ of the needle surface, and for deciduous trees it is the single-sided surface area of of the leaves. The leaf area can be measured either by labor/time/resource-intensive direct measure of leaves within the canopy or by in situ indirect methods such as hemispheric photography or imaging models. The latter is recommended if a better estimation of LAI is desired, as it is non-destructive to trees. The total area, quality of the vegetation, and type of vegetation (needles or broad-leaves, deciduous or evergreen) affects the overall net primary productivity and photosynthetic capacity of the tree. Knowing the LAI is critical to understanding and further quantifying the effects of trees on the evapotranspirative rates and overall capacity of the tree for removal volume and rate of precipitation. For the purposes of the MIDS calculator, the importance of knowing the exact LAI for the individual tree is less important than knowing the LAI by either species or by an estimate for either deciduous or coniferous tree designation.

Current research indicates a great variation of LAIs for tree species found for the greater Minnesota vegetation by area. Gonzales et al. (2008) examined historic pollen record as compared to a simulated reconstruction over the last 21,000 years to derive a range of LAIs for the Minnesota area, finding the range to be between approximately 2.0 – 4. 5. (Gonzales, Williams and Kaplan 2008) However, this is based on a pollen record, rather than a more contemporary dataset.

For purposes of credit assignments in the calculator, we suggest using the more conservative of the contemporary datasets, using the following values for LAI:

LAI evergreen spp. = 5.47 [[1]](#footnote-1)

LAI deciduous spp. = 4.7 [[2]](#footnote-2)

We would note that there is overlap between the datasets – Breuer, Eckhardt and Frede (2003) and Scurlock, Asner and Gower (2002) – and the standard deviation is significant to provide a great variation of LAI among and within species. For a more accurate representation of actual LAI, further investigation would be recommended or site metrics taken. Please refer to the national dataset and research collected by researcher staff at the US Forest Service for the specific leaf area indices (LAIs) for different species found in the United States, as well as further tree-related research, at <http://www.fs.fed.us/psw/programs/uesd/uep/>. (Xiao, Personal Comm. 2013) Please also refer to the Discussion section on emerging methods for capturing actual or site-specific LAI values.

NOTED ISSUES WITH MEASURING AND MODELING EVAPOTRANSPIRATION

*Issues with Acquiring Data*. Evapotranspiration has been notably difficult to estimate and quantify at larger scales beyond that of an immediate or small site for a variety of factors. (Sanford & Selnick, 2012) These factors that preclude statistical confidence in the measurements of ET rates include, but are not limited to the following:

* intra-species variations in ET rates within a given sample area
* inter-species variations in ET rates within a given sample area
* intra-species leaf-area variation within a given sample area
* measurement methodology procedural or data gathering difficulties
* measurement methodology human resource requirement inputs and costs
* input data availability
* existing metrics and coefficients applicability

Although potentially costly or fraught with data-transferability complications, the relative need for quantifying this critical component of water budgets or water-balance equations outweighs the relative difficulty in data acquisition for use in some hydrologic models and studies.

*Issues with Data Transferability.* Data is often collected and analyzed to generate either a site-specific ET rate or a coefficient relating the actual ET (AET) to the potential ET (PET). This rate can then be applied to the limits of data transferability. The limits of transferability vary by equation used due to the comparability of ET rates, and the definition of those limits and parameters themselves. Continental, regional, and even large site evapotranspirative losses are difficult to assess due to complex and overlapping constraints associated with current approved and/or available technologies, data sources and datasets, project budgets, methodologies, and research or human resource requirements. Each equation or model used to generate an ET rate employs a unique range of limits of transferability, application, and output confidence; which equation or models apply to the project area, budgets, and goals should be assessed and evaluated prior to use.

SUGGESTED METHODS AND EQUATIONS FOR INCORPORATION OF EVAPOTRANSPIRATION INTO HYDROLOGIC MODELS

Significant numbers of models for generation of varying components of the hydrologic cycle have been created by public institutions, research organizations, government agencies, private organizations and companies, and others. These models exhibit a great range of scale, inputs, quality, outputs, data confidence, transferability, and coefficients used and their derivations. (Rana & Katerji, 2000) While varying greatly in their interface, the base equations utilized in the models are often similar. The water-budget equation is one of the most commonly used in models and methodologies, due to the ease of input data acquisition and period of record, data transferability to greater ecosystems for site up to continental analyses, and the ability to utilize remote sensing methods and reduce project budgets and necessary human resources. Geographic information system (GIS)-based datasets can be invaluable in generating and deriving reliable estimates of ET through available dataset for annual temperatures, annual precipitation, other meteorological conditions and trends, catchments (area units), and land cover type and quality. (Sanford and Selnick 2012) These models have the unique ability in application and overall use to water resource managers in capturing the effects of difficult to quantify conditions, such as water transportation to California’s agricultural regions that resulting in abstractedly high ET rates relative to total precipitation inputs. (Sanford & Selnick 2012)

Rana and Katerji (2000) break down potential methods for ET estimation into either analytical or empirical approaches, as follows: (Rana and Katerji 2000):

*1. Analytical approach*

*(8) Penman–Monteith model*

*2. Empirical approach*

*(9) Methods based on crop coefficient approach*

*(10) Methods based on soil water balance modeling.*

Analytical approaches, mainly by way of the Penman-Monteith equation (see below), are the most widely used methods for estimating ET. The use and applicability within the Penman-Monteith equation can be very effective for generating ET rates for land and crop areas by accounting for both the meteorological phenomena and the actual tree canopy biology and physiology. (Rana & Katerji, 2000) The tree canopy metrics and measures account for the actual capability of- and resistance within the vegetative structures - particularly the stomata – within the leaves. (Rana & Katerji, 2000)

Empirical approaches serve to estimate ET by way of a crop coefficient (Kc) as a estimated percent reduction of the overall PET being applied to the reference ET (ET0) in the following equation:

The crop coefficient (Kc) is an experimentally-derived for the given area or land type; ET0 can be determined by either a reference crop index or proxy, or a pan evaporation index. (Rana & Katerji, 2000) However, this method has been noted to have been utilized for irrigation management, and for estimating transpiration, plant available moisture or the water source for transpiration needs to be considered although it is dynamic and can be affected by irrigation (Xiao, Personal Comm. 2013).

*Penman-Monteith Transpiration Model.* The initial form of the Penman-Monteith equation was created to quantify the energy flux associated with evapotranspirative rates over a given period of time. The equation was later modified to quantify volume of water evapotranspired through the tree or other vegetation type (e.g. row corn crops), as follows:

*where:*

*ETo = water volume transpired (mm s-1)*

## Lv = Volumetric latent heat of vaporization. Energy required per water volume vaporized. (Lv = 2453 MJ m−3)

## Δ = Rate of change of saturation specific humidity with air temperature. (Pa K−1)

## Rn = net irradiance (W m-1)

*G = ground heat flux (W m-1)*

*ρa = dry air density (kg m-3)*

*cp = specific heat capacity of air (J kg-1 K-1)*

*δe = vapor pressure deficit (Pa)*

*ga = atmospheric conductance (m s-1)*

*gs = surface or stomatal conductance (m s-1)*

*γ = Psychometric constant (γ ≈ 66 Pa K-1)*

For the purposes of the MPCA crediting process, this equation is a not particularly useful, as this formula employs a large number of variables that 1) are more difficult to assess, 2) where assessment of variables is costly, or 3) are less approachable or easily understood by the standard user for purposes of generating a coarse but relatively accurate estimation of impacts from ET. For these reasons, it would be more user-friendly and applicable to the level of precision required by the MIDS Calculator to use either the Preistley-Tayor (1972) equation or the Lindsey-Bassuk (1991) equation. Both equations are examined hereafter for their qualities and merits.

*Preistly-Taylor (1972) Simplified Equation for Estimating Transpirative Losses.* The Priestly-Taylor equation is a simplified version of the Penman-Monteith equation. It has a simplified structure that only require inputs of net radiation, leaf area in the canopy, and the average daily temperature. These values are readily available or can be estimated from empirical sources for ease of use of this formula, although varying levels of scientific precision exist for the results.

*where:*

*Ea = actual evapotranspired water (mm s-1)*

##  = latent heat of vaporization. Energy required per water volume vaporized. ( = 2.45 MJ kg−1)


##  = a model coefficient per Preistley-Taylor per drying/aerodynamic conditions (1.26 is standard)


## s = slope of the saturation vapor density curve (kPa °C-1)

*G = ground or soil heat flux (MJ m-2 d-1); G=1 for daily calculations*

*Rn = net radiation* *(MJ m-2 d-1)*

*γ = Psychometric constant (γ ≈ 0.066 kPa K-1)*

For ease of use, we set the Preistley-Taylor coefficient () to 1.26 for freely-evaporating surfaces, although research indicates variation from 0.72 in forests to 1.57 in strongly-advective conditions. (Flint and Childs 1991) The ground or soil heat flux is ignored for daily calculations as the heating and cooling periods of the cycle negate themselves, and G=1. The slope of the vapor density curve (s) the relationship between saturation vapor pressure and the air temperature, as follows in the Stahgellini equation (1998):

*where:*

*s =* slope of the saturation vapor density curve (kPa °C-1)

*e* = saturation vapor pressure (kPa)

*T = air temperature (° T)*

The inputs for this would be fairly simple to acquire and input into a calculator format, but a more simple format for total tree estimation would be available for MIDS calculator inputs via the Lindsey-Bassuk equation for whole tree water use, as follows.

*Lindsey and Bassuk Single Whole Tree Water Use Equation*. Lindsey and Bassuk (1991) propose that the whole tree water use, including evaporation and transpiration losses, may be greatly simplified by use of a user-friendly equation relating the total water use to 4 measurements: 1) canopy diameter, 2) leaf area index, 3) the evaporation rate per unit time, and 4) the evaporation ratio. It is important to note that the four aforementioned inputs are taken from a given tree at a specific period in time, so it follows that the ET rate as a function of the overall estimated water use from this equation will vary throughout the life of the tree. In the case of the MIDS calculator, the total water use calculated by the Lindsey-Bassuk equation is a proxy for the ET rate. This equation is as follows:

For the purpose of the MIDS calculator, the leaf area index and canopy diameter would best be input as empirical values for the tree. The leaf area index (LAI) should be stratified by type into either 1) deciduous tree species (LAI = 4.7), or 2) evergreen tree species (5.47), per the collected research on global leaf area from 1932-2000. (Scurlock, Asner and Gower 2002)

The canopy projection area (CP) should be input by tree species for perceived tree diameter at maturity as calculated by:

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*where:*

*CP = canopy projection area (ft2)*

*d = diameter of the canopy, as measured at the dripline (ft)*

Please refer to the Tree Species List in this section of the MPCA Stormwater Manual for these values for input into the MIDS calculator.

The evaporation rate (Erate) per unit time can be calculated using a pan evaporation rate for the given area, as available at NOAA. This should be estimated into *per day* value, for later use.

The evaporation ratio (Eratio) is the equivalent that accounts for the efficiency of the leaves to transpire the available soil water or, alternately, the stomatal resistance of the canopy to transpiration and water movement. This is set based on current research at 0.20, or 20% transpiration and use of available soil moisture. (Lindsey and Bassuk, Specifying soil volumes to meet the water needs of mature urban street trees and trees in containers 1991)

Once these values are assembled, the average day between critical rainfall events or specific design storms should be evaluated. MIDS has the design storm depth set at 1.1”, so this would be the set design storm to determine a specific recurrence interval or estimated time between events of that size or greater, at minimum. This time period, in days, then can be multiplied by the rate found in the Lindsey-Bassuk equation to find the amount of soil moisture/stormwater required to both store and sustain the tree between these events.

Additionally, multiplying the value found in the Lindsey-Bassuk equatio by the total number of days in the growing season can give the total annual ET losses, per tree.

ET expert researcher Xiao noted that the Lindsey-Bassuk (1991) study and resultant equation above are not really a true estimate of ET rates, and rather an estimate for water or irrigation needs of the plant per given rainfall event recurrence interval (Xiao, Personal Comm. 2013). For the purpose of assigning stormwater credit in the MIDS calculator for the 1.1” storm event (3-day recurrence interval), this equation would provide a quick estimation of stormwater credit for ET from trees, but a better estimate would be gained by use of a digital model such as USFS’s iTree or other continuous-modeling simulators or programs that incorporate above-mentioned equations and datasets with site conditions and tree species information to provide better quantification of ET and INT rates.

CANOPY INTERCEPTION (INT)

Through the literature review, the recommendations vary widely as to different values for estimating canopy interception. There are also varying methods for quantifying interception by the tree canopy, from remotely-sensed information and models to direct measurement data-based systems. Although great variation in the methodology for quantification and calculated values of interception exist, there is no dispute in the literature that the ability of the canopy to abstract and store a significant portion of precipitation occurs with each rain event. Xiao et al. (2000) indicated that some of this variation may be due to the assumptions made in constructing each model in comparison to the actual architecture of the tree; the majority of the models fail to account for the tree architecture and prevailing wind direction in accounting for interception, and rather assume a vertical rainfall pattern with uniform (cylindrical) estimation of leaf area within the canopy (Xiao, McPherson, et al. 2000). Xiao et al. (2000) later present a refined 3-dimensional model that utilizes a cone-shaped canopy presentation of leaf surface (effective crown projection area) related to precipitation directionality (rainfall incidence angle) to better assess contact with leaves by precipitation for interception estimates. (Xiao, McPherson, et al. 2000) The model indicated a precipitation abstraction of 20.5% of total rainfall by the canopy interception, and fairly-good correlation between model predictions and field-collected data, and moreover, a new way to better account for the canopy structure and precipitation angle to generate a refined estimate of INT. This type of species- and prevailing rainfall patterns-based model is suggested for integration into future refinements of the MIDS calculator for better estimates of canopy interception.

For ease of MIDS credit assignment per the current Calculator, we would suggest assigning the simplified values of the interception capacity (Ic) as presented by Breuer et al. (2003) for deciduous and evergreen tree species:

Ic evergreen spp. = 0.087” (2.2mm)

Ic deciduous spp. = 0.043” (1.1mm)

These values were derived from historical dataset analysis and correlation for North American and European land cover types, in order to present a base for model inputs (Breuer, Eckhardt and Frede 2003) such as the MIDS calculator, as opposed to those refined values a sensitive scientific model or study would require. Although these are coarse values, they are specific to Minnesota species and datasets and represent an estimate of canopy interception as a function of total canopy projection area.

To find the total volume intercepted by the canopy of the tree at maturity, the selected species would take the canopy projection area (CP) multiplied by these values to assess the volume per storm event affect on the overall stormwater value. Although this is a coarse estimation of precipitation abstracted by canopy interception, this should provide an initial starting point for the purposes of assigning credits for INT in the current MIDS Calculator.

Please note: there is a larger dataset by species provided in the aforementioned resource. (Breuer, Eckhardt and Frede 2003) Should it be desired, the stratified list of values by species type could be used to provide a better estimate of interception capacity (Ic) in the MIDS calculator, however, for credit assignment, this seems unnecessary for a relatively more coarse quantification therein.

MODEL INTEGRATION OF ET AND INT

Through the literature review, it is noted that there are abundant models for estimation of varying parts of the vegetative-moisture relationship, spanning from general water use by trees to specific individual components. The models have varying inputs and equations used, assumptions made, and relative confidence in their results based on the outcomes desired. Current version of the MIDS calculator for trees would better integrate with a coarser estimation of stormwater abstractions from to trees rather than a finely-calibrated stormwater model, but a further discussion of the potential and how to generate a seamless model integration with the MIDS calculator is warranted for future refinements. Specific stormwater models encountered in the literature review with the capacity to accommodate these vegetative inputs are as follows:

* iTree (Hydro and other components of the model)
* IHDM (Institute of Hydrology Distributed Model);
* SWAT (Soil and Water Assessment Tool);
* Farquar equation and model
* ALEX (Atmosphere-Land Exchange model);
* VIC (Variable Infiltration Capacity model);
* BETHY (Biosphere Energy-Transfer Hydrology Scheme); and,
* WinSLAMM (Source Loading and Management Model for Windows)

Please note that this is by no means a comprehensive list, but a start of a longer list of models with vegetative capacity for stormwater benefits natively integrated into their design. Additionally, all aforementioned models have not been evaluated for use at the time of this writing, and would be suggested as a next step.

As iTree has the capacity to quantify the benefits associated with a single tree, as compared to a vegetative community or ecosystem type, this model has distinct advantages to direct quantification of the stormwater benefits in a user-friendly and spatially-distinct computer model. This program and the two – SWAT and WinSLAMM – mentioned hereafter appear to have the greatest potential for future integration of vegetative impacts from ET into a continuous model and credit assignment system.

SWAT (Soil and Water Assessment Tool) and WinSLAMM (Source Loading and Management Model for Windows) models are becoming increasingly applicable and utilized by stormwater designers, engineers, and regulatory agencies alike for quantification of water volume and rate reductions, pollution abatement, and vegetative inpacts in multiple or compound stormwater systems. These powerful modeling tools are being used by public and private industry and have growing capability to produce these compound results and parse the maximum impacts on stormwater by source areas. In particular, the ET impacts on stormwater are currently being integrated into the WinSLAMM model per Pitt et al. The methodology, sample calculations, and format for the integration of ET into the SLAMM model are outlined in the unpublished white paper found at the University of Alabama website at: <http://rpitt.eng.ua.edu/Class/StormWaterManagement/Fall%202009/Pitt_Evapo_final__copy_changes_accepted.pdf> (Pitt et al., unpublished) Please note that the methodology presented in the paper is based on a soil-based stormwater assessment for generating abstraction from stormwater volumes attributed to ET. The current methodology presented here and integrated into the MIDS Stormwater Calculator is based on this soil-based capacity when assigning stormwater credits for both trees and bioretention vegetation.

SUMMARY AND DISCUSSION

Through the literature review, the recommendations are suggested for proceeding in the credit estimation and assignment within the MIDS calculator:

1) Evapotranspiration (ET) would be to use the Lindsey-Bassuk equation for estimating and crediting trees for associated reductions in runoff.

2) Canopy interception (INT) values should be assigned by multiplying the mean values for typical tree type (Breuer, Eckhardt and Frede 2003) times the canopy area at maturity.

Values for ET and INT should be assembled and input into the MIDS calculator for current use, but it is also recommended that further integration and use may aid in calibration of the model and crediting process via inputs from outside digital standalone models such as iTree and SWAT.

There a number of areas that were discovered in the literature review process that should be mentioned for future study and integration opportunities:

*“Smart” Technologies and Applications for Total Forest Inventory and Assessment.* There are some areas for further discussion and exploration regarding the impacts trees have on stormwater. As seen in the evapotranspiration and interception equations, the impact the actual canopy leaf area, or LAI, provides has direct correlation with the treatment capacity a tree provides to the overall stormwater management system. Establishing and maintaining a good record for individual trees could be invaluable in this quantification for new, established, mature, and post-maturity trees alike. Whereas most instruments for indirect measurements of LAI employ light transmission models with varying effectiveness incorporated into dedicated commercial instruments, there is emerging research and development in “smart phone”-based applications and their capability for capturing LAIs. (Confalonieri, et al. 2013; Gong, et al. 2013) Confalonieri et al. indicate the baseline performance of their “smart” application for LAI quantification to perform at a level similar to the dedicated instruments, but requiring a larger number of reliable reference individuals or samples to calibrate the “smart” technology. (Confalonieri, et al. 2013) Although still in design development, this and other like applications could be used in conjunction with citizens’ or neighborhood-based groups to develop a Minnesota tree canopy database to derive measurements and compile information indicating tree health over time. This can have serious implications for cost-savings and prioritization of finite economic and human resources in assessing and managing the growing urban canopy as well as the preservation and assessment of the natural, exurban, and rural forested areas.

*Air-related Pollutant Removal by Trees Related to ET and Canopy Interaction.* In addition to evapotranspiration, canopy interception, and other water-related effects of trees in bioretention, there are additional benefits of these processes noted in the literature search that could add to the overall tree-related benefits that could be credited in stormwater design. Escobedo and Nowak (2008) indicate additional benefits associated with trees and the urban forest in positive effect on air quality with their work in Santiago, Chile. Results and discussion indicate these benefits include removal of atmospheric pollutants and chemicals, microclimatic temperature reduction and extremes via shading and evapotranspirative cooling, altering wind flow -pattern, fetch, and extremes, modifying boundary layer heights, and decreasing energy consumption. Additional benefits come by way of direct removal of greenhouse gases and energy production emissions. Some of the pollutants shown to be mitigated from atmospheric presence by trees include coarse dust particles (PM10), sulfur trioxide (SO3), ozone (O3), carbon monoxide (CO), and nitrogen dioxide (NO2). (Escobedo and Nowak 2009) Although not directly present in the stormwater when removed, these components often are affected by atmospheric moisture and become surface runoff pollutants such as suspended solids, acid rain, and other compounds. As seen the table below, canopy interaction and removal of these atmospheric particles prior to suspension or solution in surface water can provide important implications for water quality improvement (Escobedo and Nowak 2009). Additional information provided in the process of the research indicates little overall variation in air quality improvement by pollution mitigation during the growing season, which has significant implications for added benefits of trees for pollutant removal even during the dry season when evapotranspirative effects or other stormwater benefits may be less important.

Table 13.1 Annual Pollution Removal Rates for Santiago’s Three Subregions from July 2000 to June 2001 (Escobedo and Nowak 2009)

*“Smart” Technologies Application Development.* The development of MIDS or MPCA “Smart” applications could assist in educating the average citizen to the importance of trees and the urban canopy as it relates to the capture and processing of stormwater. Having these systems in place can increase both the awareness and approval of tree- and stormwater-related appropriations of public funds, as well as provide the base for a larger forum of discussion regarding the benefits of trees relative to global climate fluctuations and changes.

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1. Data source: Scurlock, Asner and Gower 2002 [↑](#footnote-ref-1)
2. Data source: Breuer, Eckhardt and Frede 2003 [↑](#footnote-ref-2)