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Case Study on the Accuracy and Cost/Effectiveness in Simulating Reference Evapotranspiration in West-Central Florida

Michael Grant Exner-Kittridge, M.ASCE1; and Mark Cable Rains2

Abstract: The objective of this study was to conduct an accuracy and cost/effectiveness analysis of various reference evapotranspiration (ET₀) estimation equations that rely solely upon the collection of meteorological data. A meteorological station was established in an open grassland near Ft. Meade, Florida. The ASCE Penman-Monteith (PM) equation (full ASCE-PM equation) was set as the standard to which nine variants of five equations were compared. The number of parameters that had to be measured for each equation ranged from five (full ASCE-PM equation) to one (Hargreaves equation). ET₀ was calculated on daily time steps. A variant of the ASCE-PM equation with solar radiation, wind speed, relative humidity, and temperature measured and the Simple equation with only solar radiation measured were most accurate and cost/effective. The most accurate and cost/effective alternative equations were those in which some of the less-important energy and mass-transfer terms were omitted and/or calculated from less-expensive instrumentation. The Simple equation instrumentation required only 33% of the cost of the full ASCE-PM, while only reducing the effectiveness by ~10%. With the Simple equation’s minimal data requirements and superior accuracy and cost/effectiveness, the Simple equation could be a viable tool for the estimation of ET₀ in situations where funding is limited.

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Author keywords: Cost/effectiveness; Evapotranspiration; Hydrologic cycle; Meteorology.

ET: Primary Outflow in Terrestrial Water Budgets

Annual evapotranspiration (ET) is ~65% of the annual precipitation on global land surfaces (Trenberth et al. 2007), while annual ET is ~75% of the annual precipitation in peninsular Florida (Bidlake et al. 1996). Unfortunately, ET cannot be directly measured and must therefore be indirectly measured or calculated. Because ET fluxes are so large, small errors in indirect measurement or calculation can result in large errors in projections. Therefore, water managers need accurate yet cost/ effective methods to indirectly measure or calculate ET. This is particularly true in developing countries where populations are large, money is scarce, and accurate yet cost/effective methods are critical for such basic needs as irrigation scheduling and/or water-supply forecasting.

Evaporation requires energy to vaporize the water and mass-transfer mechanisms to transfer water vapor from the saturated surface to the atmosphere (Penman 1948). The energy available to vaporize water comes mainly from net radiation. The saturated vapor is then transported from the saturated surface layer to the atmosphere mainly by advection by wind and to a lesser extent by diffusion down vapor pressure gradients.

Penman (1948) developed the first equation for calculating ET by combining energy and mass-transfer terms in the first so-called combination equation. Monteith (1965) later modified this equation by introducing empirical coefficients for canopy and aerodynamic resistance. However, the Penman-Monteith (PM) equation requires physical measurements of the vegetation in the calculation of the canopy and aerodynamic resistance terms. Physical measurements of vegetation can be difficult to obtain if the site is remote, the vegetation changes seasonally, and/or the vegetation is structurally complex.

This led to the development of numerous empirically derived equations that calculate potential ET (PET) from a variety of land covers using only meteorological parameters as variables (e.g., Priestley and Taylor 1972, Hargreaves and Samani 1982, Hargreaves and Allen 2003, and Abtew 1996). PET, though inconsistently defined in the literature, is typically defined as the amount of ET from a uniform short crop surface with soil water at field capacity (Irmak and Hanam 2003). Problems arose because PET equations were calibrated to different land covers in different regions, so it was difficult to compare results between studies and/or to calculate actual ET for specific conditions (Winter and Rosenberry 1995). Consequently, reference ET (ET₀) was introduced and further developed to mean the ET from a “hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23” in which “the reference surface closely resembles an extensive surface of
green, well-watered grass of uniform height, actively growing and completely shading the ground.” (Guidelines for prediction of crop water requirements.” 1977; Allen et al. 1994a,b; Hargreaves 1994; Allen et al. 1998; The ASCE standardized reference evapotranspiration equation 2005). With this standardized approach, it is now easier to compare results between studies and/or to calculate actual ET for specific conditions.

The United Nations Food and Agriculture Organization (FAO) developed the first ET₀ equation, modifying the PM equation to the more general FAO PM equation (“Guidelines for prediction of crop water requirements.” 1977). This basic approach has been updated on numerous occasions, with the ASCE making the most recent modifications (The ASCE standardized reference evapotranspiration equation 2005). This basic approach has been tested, with ET₀ from the FAO PM equation having been shown to closely approximate ET₀ from lysimeters in a variety of climates around the world (Ventura et al. 1999). Therefore, this basic approach has become the standard method for calculating operational estimates of ET₀ around the world.

The ASCE PM equation (hereafter referred to as the ASCE-PM equation) requires the measurement or estimation of energy terms (i.e., net radiation, soil heat flux density, and temperature) and mass-transfer terms (i.e., wind speed and humidity). However, complete data sets are not always available, and complete instrumentation sets cannot always be afforded. In these cases, ET₀ can be estimated by (1) calculating ET₀ using the ASCE-PM equation with some calculated or estimated meteorological parameters (e.g., The ASCE standardized reference evapotranspiration equation 2005) or (2) calculating or estimating ET₀ using one of the numerous other ET₀ or empirically derived PET equations (e.g., Priestley and Taylor 1972, Hargreaves and Samani 1982, 1985, Hargreaves and Allen 2003, and Abtew 1996). Though these approaches provide cost savings, they may also reduce accuracy.

The objective of this study is to conduct accuracy and cost/effectiveness analyses of the calculation or estimation of ET₀. To do so, we set the full ASCE-PM equation as the standard and evaluate the accuracy and cost/effectiveness of alternative equations on daily time steps. Though the full ASCE-PM equation is the most accurate method, we hypothesize that alternative equations can be accurate and cost/effective if some of the less-important energy and mass-transfer terms were omitted and/or calculated from less-expensive instrumentation.

Materials and Methods

Site Description: Location and Hydrogeological Setting

The study site is located near Ft. Meade in Polk County, Fla. (81°51’54.0” W, 27°41’09.6” N) (Fig. 1). The site is nearly level to undulating with a slight topographic gradient from north to south. Above ~0.5 m (~1.6 ft) in depth is a subangular blocky, clay-rich surface layer with abundant desiccation cracks and other macropores associated with bioturbation such as burrows and root channels. Below ~0.5 m (~1.6 ft) in depth is a massive, clay-rich sublayer that is saturated below ~1.0–2.5 m (~3.3–8.2 ft) (Murphy et al. 2008). There are several closed-basin depressions that pond water seasonally.

Climate

The climate at the study area is subtropical with warm, relatively dry winters and hot, relatively wet summers (Fig. 2). Summer rainfall is due to frequent, local convective thunderstorms, while winter rainfall is due to infrequent cold fronts. Mean (± standard deviation) annual temperature is 23.2°C ± 0.57°C (73.8°F ± 1.0°F) (Southeast Regional Climate Center data for Bartow, Fla. for calendar years 1986–2006). Mean (± standard deviation) annual precipitation is 1,375 mm ± 244 mm (54.13 in. ± 9.60 in.), with ~58% falling during the four primary wet-season months of June–September (Southeast Regional Climate Center data for Bartow, Fla. for calendar years 1892–2006). During the course of the study, conditions were slightly cooler and drier than normal, with mean annual temperature and annual precipitation in Bartow being 22.0°C (71.6°F) and 952 mm (37.48 in.), respectively, and mean annual temperature and annual precipitation at the study site being 21.8°C (71.2°F) and 883 mm (34.76 in.).

Vegetation

On ~65% of the study site, the predominant vegetation is the invasive Cogon Grass [Imperata cylindrica (L.) Raeuschel]. On the remaining ~35% of the study site, the predominant veg-

Fig. 2. Mean monthly temperature and precipitation for the study site
etation is mixed hardwoods including the invasive Earleaf Acacia (Acacia auriculiformis A. Cunn. Ex. Benth.) in the uplands and the native Coastal Plain Willow (Salix caroliniana Michx.) in the closed-basin depressions that pond seasonally. The meteorological station is surrounded by Cogon Grass ~1 m (~3.3 ft) in height; fetches to ~60 m (~200 ft) in all directions.

**Instrumentation and Measurement**

Instrumentation included a meteorological station with which precipitation, solar radiation, temperature, relative humidity, and wind speed and direction were measured at a height of 2 m (6.6 ft) and soil heat flux plates, thermocouples, and water-content reflectometers with which soil heat flux density was calculated (Table 1). Soil heat flux density was calculated using standard procedures (Campbell Scientific, Inc. 2003), using unpublished soil data from the study site (Aidee Cirra unpublished data). Data were collected hourly and summarized daily during calendar year 2006. The 38 days of missing data due to equipment failure were replaced by using least-squares regression with data from the Florida Automated Weather Network Station located ~55 km (~34 mi) away in Balm, Fla. as independent variables and data from the study site as the dependent variables.

**ETo Equations**

ETo was calculated on daily time steps using a total of 10 versions of five equations; five versions of the ASCE-PM equation (The ASCE standardized reference evapotranspiration equation 2005), two versions of the Priestley-Taylor equation (Priestley and Taylor 1972), the Radiation/Tmax equation (Abtew 1996), the Simple equation (Abtew 1996), and the Hargreaves equation (Hargreaves and Samani 1982, 1985; Hargreaves and Allen 2003). The ASCE-PM and Hargreaves equations were developed to calculate ETo. The other equations were originally developed to calculate some form of PET, though many are frequently used to estimate ETo (e.g., Jacobs and Satti 2001).

The various versions of the ASCE-PM and Priestley-Taylor equations differed in the variables that were measured and the variables that were parameterized using standard procedures detailed in The ASCE standardized reference evapotranspiration equation (2005) (Table 2). Net radiation Rs is difficult to measure because it is sensitive to variations in land cover, and net radiometers are also difficult to calibrate and maintain (The ASCE

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### Table 1. Meteorological Parameters and Instrumentation Used in This Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil heat flux density</td>
<td>G</td>
<td>REBS soil heat flux plates (HFT3-L50)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TCAV-L averaging soil thermocouples (TCAV-L20)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CS6155 water-content reflectometer (CS615-L20)</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>Rs</td>
<td>Apogee PYR-P pyranometer (CS300-L11)</td>
</tr>
<tr>
<td>Wind speed</td>
<td>U</td>
<td>Met One anemometer (014A-L11)</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>Vaisala temperature/RH probe (HMP45C-L11)</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>Vaisala temperature/RH probe (HMP45C-L11)</td>
</tr>
</tbody>
</table>

---

### Table 2. Versions of the ASCE-PM and Priestley-Taylor Equations Evaluated in This Study

<table>
<thead>
<tr>
<th>Equation</th>
<th>Variables measured</th>
<th>Variables parameterized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full ASCE-PM</td>
<td>Rs, G, U, RH, T</td>
<td>Rs, g, G, U, RH</td>
</tr>
<tr>
<td>ASCE-PM (Rs, G, T)</td>
<td>Rs, G, T</td>
<td>Rs, G, U, RH</td>
</tr>
<tr>
<td>ASCE-PM (Rs, U, RH, T)</td>
<td>Rs, U, RH, T</td>
<td>Rs, G, U, RH</td>
</tr>
<tr>
<td>ASCE-PM (T)</td>
<td>T</td>
<td>Rs, G, U, RH</td>
</tr>
<tr>
<td>Full Priestley-Taylor</td>
<td>Rs, G, T</td>
<td>Rs, G, U, RH</td>
</tr>
<tr>
<td>Priestley-Taylor (Rs, T)</td>
<td>Rs, T</td>
<td>Rs, G, U, RH</td>
</tr>
</tbody>
</table>

Note: Parameterization of variables follows standard procedures as detailed in Allen et al. (2005).

---

standardized reference evapotranspiration equation 2005). Therefore, Rs was calculated from solar radiation Rs, as per the recommendations of and using the procedures detailed in The ASCE standardized reference evapotranspiration equation (2005). This calculated Rs was used in all ETo equations, including in the full ASCE-PM. For equations in which relative humidity was required, actual vapor pressure (e) was calculated by averaging e over the daily period using hourly measurements of humidity (i.e., Method 1). For equations in which relative humidity was not required, e was calculated from daily minimum air temperature (i.e., Method 8).

The ASCE-PM equation is

\[
ET_o = \frac{0.408(\Delta (R_s - G)) + \gamma \frac{900}{T + 273} U_2 (e_i - e_o)}{\Delta + \gamma (1 + 0.34 U_2)}
\]

where \(ET_o\) = reference ET (mm day\(^{-1}\)); \(\Delta\) = slope vapor pressure curve (kPa °C\(^{-1}\)); \(R_s\) = net radiation (MJ m\(^{-2}\) day\(^{-1}\)); \(G\) = soil heat flux density (MJ m\(^{-2}\) day\(^{-1}\)); \(\gamma\) = psychrometric constant (kPa °C\(^{-1}\)); \(T\) = mean daily temperature (°C); \(U_2\) = wind speed at 2-m height (m s\(^{-1}\)); \(e_i\) = mean saturation vapor pressure (kPa); and \(e_o\) = actual vapor pressure (kPa). The Priestley-Taylor equation is

\[
ET_o = \frac{\Delta}{\Delta + \gamma}(R_s - G)
\]

where all terms are as previously defined. The Radiation/Tmax equation is

\[
ET_o = \frac{1}{\lambda} \frac{R_s T_{\text{max}}}{56}
\]

where \(T_{\text{max}}\) = maximum daily temperature (°C); \(\lambda\) = latent heat of vaporization of water (2.45 MJ kg\(^{-1}\)); and all other terms are as previously defined. The Simple equation is

\[
ET_o = 0.52 \frac{R_s}{\lambda}
\]

where all terms are as previously defined. Last, the Hargreaves equation is

\[
ET_o = 0.0023R_s \left( \frac{T_{\text{max}} + T_{\text{min}}}{2} + 17.8 \right) (T_{\text{max}} - T_{\text{min}})^{0.5}
\]

where \(R_s\) = extraterrestrial radiation (MJ m\(^{-2}\) day\(^{-1}\)); \(T_{\text{min}}\) = minimum daily temperature (°C); and all other terms are as previously defined. Extraterrestrial radiation \(R_s\) is calculated as
where \( G_c = \) solar constant \((0.0820 \text{ MJ m}^{-2} \text{ min}^{-1})\); \( d_r = \) inverse relative earth-sun distance; \( w_s = \) sunset hour angle \((\text{rad})\); \( \varphi = \) latitude \((\text{rad})\); and \( \delta = \) solar declination \((\text{rad})\). The inverse relative earth-sun distance \( d_r \), the sunset hour angle \( w_s \), and the solar declination \( \delta \) are calculated as

\[
d_r = 1 + 0.033 \cos \left( \frac{2 \pi}{365} J \right)
\]

\[
w_s = \arccos \left( -\tan(\varphi) \tan(\delta) \right)
\]

\[
\delta = 0.409 \sin \left( \frac{2 \pi}{365} J - 1.39 \right)
\]

where \( J = \) Julian day and all other terms are as previously defined.

**ET\(_o\) Analysis**

The accuracy of daily ET\(_o\) calculated or estimated with the alternative equations was assessed with linear least-squares regression and the standard error of estimate (SEE), with daily ET\(_o\) calculated with the full ASCE-PM equation as the independent variable, and daily ET\(_o\) calculated or estimated with the alternative equations as the dependent variables. Seasonal bias was assessed by calculating the monthly mean percent differences between daily ET\(_o\) calculated with the full ASCE-PM equation and daily ET\(_o\) calculated or estimated with the alternative equations.

The effectiveness of daily ET\(_o\) calculated or estimated with the alternative equations was calculated as

\[
\text{Effectiveness} = \frac{\sum X_n [Y_n - \bar{Y}_n]}{n_{\text{total}}}
\]

where \( X_n = \) daily ET\(_o\) calculated with the full ASCE-PM equation for day \( n \); \( Y_n = \) daily ET\(_o\) calculated with the alternative equations for day \( n \); and \( n_{\text{total}} = \) total number of days \((i.e., 365 \text{ days})\).

Costs for all instrumentation, including mounting and enclosure hardware, were quoted by Campbell Scientific, Inc. in March 2007. All costs were converted to cost ratios for the cost/effectiveness calculation. The cost of the instrumentation necessary to calculate or estimate ET\(_o\) with an alternative equation was divided by the cost of the instrumentation necessary to calculate ET\(_o\) with the full ASCE-PM equation. Labor costs were assumed to be the same for each approach as they all require similar installation and maintenance. The cost/effectiveness ratio was calculated as

\[
\text{Cost/Effectiveness} = \frac{\text{Cost}_{\text{Alt}} - \text{Cost}_{\text{ASCE-PM}}}{\text{Effectiveness}_{\text{Alt}} - \text{Effectiveness}_{\text{ASCE-PM}}}
\]

where the subscript “Alt” refers to a given alternative equation and the subscript “FASCE-PM” refers to the full ASCE-PM equation.

**Results and Discussion**

**ET\(_o\) with the Full ASCE-PM Equation**

Mean \((\pm \text{standard deviation})\) daily ET\(_o\) for calendar year 2006 was \(4.10 \text{ mm} \pm 1.12 \text{ mm} \) \((0.16 \text{ in.} \pm 0.04 \text{ in.})\). Total annual ET\(_o\) for calendar year 2006 was \(1,496 \text{ mm} \). ET\(_o\) was strongly seasonal (Fig. 3). ET\(_o\) was lowest in December, when mean \((\pm \text{standard deviation})\) daily ET\(_o\) was \(2.58 \text{ mm} \pm 0.90 \text{ mm} \) \((0.10 \text{ in.} \pm 0.04 \text{ in.})\), and highest in April, when mean \((\pm \text{standard deviation})\) daily ET\(_o\) was \(5.48 \text{ mm} \pm 0.47 \text{ mm} \) \((0.22 \text{ in.} \pm 0.02 \text{ in.})\).

**Accuracy**

Least-squares regressions indicated that some of the alternative equations were better than others at providing accurate estimates of daily ET\(_o\) (Fig. 4). Slopes ranged from 0.88 to 1.25, \(R^2\) ranged from 0.57 to 0.96, and SEE ranged from 0.21 to 0.67 mm/d. The most accurate alternative equations were the ASCE-PM \((R_s, U, RH, T)\) and the Simple equations. Both had slopes near 1.00, and the ASCE P-M \((R_s, U, RH, T)\) equation had the highest \(R^2\) and lowest SEE (0.96 and 0.22 mm/d, respectively), while the Simple equation had the second-highest \(R^2\) and second-lowest SEE (0.87 and 0.40 mm/d, respectively). The least accurate alternative equation was the Hargreaves equation, with a slope of 0.92, the lowest \(R^2\) and highest SEE (0.57 and 0.67 mm/d, respectively).

**Seasonality**

Comparisons of monthly ET\(_o\) indicated that some of the alternative equations show little or no seasonal bias with respect to the full ASCE-PM equations, while other alternative equations showed marked seasonal bias with respect to the full ASCE-PM equation (Table 3). The ASCE-PM \((R_s, G, T)\) and Simple equations largely lacked a seasonal bias. The other alternative equations showed marked seasonal bias, overestimating ET\(_o\) during the hot, relatively warm summer months and underestimating ET\(_o\) during the warm, windy, and relatively dry winter months.
Table 3. Percent Difference between the Mean Daily ET, Calculated with the Given Alternative Equation for the Given Month with respect to the Mean Daily ET, Calculated with the Full ASCE-PM Equation for the Given Month

<table>
<thead>
<tr>
<th>Equation</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASCE-PM ((R_s, G, T))</td>
<td>-2.22</td>
<td>2.65</td>
<td>-4.71</td>
<td>-6.56</td>
<td>7.03</td>
<td>0.36</td>
<td>6.13</td>
<td>6.92</td>
<td>7.16</td>
<td>1.73</td>
<td>-0.15</td>
<td>-0.51</td>
</tr>
<tr>
<td>ASCE-PM ((R_s, U, RH, T))</td>
<td>-5.42</td>
<td>-6.03</td>
<td>-1.40</td>
<td>1.95</td>
<td>4.49</td>
<td>7.70</td>
<td>8.51</td>
<td>9.41</td>
<td>8.69</td>
<td>2.63</td>
<td>-5.54</td>
<td>-2.99</td>
</tr>
<tr>
<td>ASCE-PM ((R_s, T))</td>
<td>-7.20</td>
<td>-3.38</td>
<td>-4.88</td>
<td>-3.13</td>
<td>10.04</td>
<td>8.60</td>
<td>15.45</td>
<td>17.69</td>
<td>16.73</td>
<td>5.66</td>
<td>3.00</td>
<td>0.99</td>
</tr>
<tr>
<td>ASCE-PM ((T))</td>
<td>4.44</td>
<td>12.44</td>
<td>8.80</td>
<td>12.94</td>
<td>31.90</td>
<td>24.50</td>
<td>42.70</td>
<td>41.33</td>
<td>36.85</td>
<td>18.61</td>
<td>13.15</td>
<td>7.57</td>
</tr>
<tr>
<td>Priestley-Taylor ((R_s, G, T))</td>
<td>-31.49</td>
<td>-19.47</td>
<td>-17.77</td>
<td>-16.27</td>
<td>-0.28</td>
<td>3.33</td>
<td>-4.73</td>
<td>-5.82</td>
<td>-9.75</td>
<td>-20.32</td>
<td>-31.55</td>
<td>-32.91</td>
</tr>
<tr>
<td>Simple ((R_s))</td>
<td>-4.93</td>
<td>0.28</td>
<td>0.75</td>
<td>-4.13</td>
<td>5.11</td>
<td>4.54</td>
<td>0.58</td>
<td>5.52</td>
<td>6.41</td>
<td>-1.78</td>
<td>-1.87</td>
<td>-11.86</td>
</tr>
<tr>
<td>Hargreaves ((T))</td>
<td>-18.45</td>
<td>-10.59</td>
<td>-10.17</td>
<td>-4.20</td>
<td>15.33</td>
<td>16.56</td>
<td>26.34</td>
<td>24.38</td>
<td>18.73</td>
<td>-2.08</td>
<td>-8.90</td>
<td>-8.75</td>
</tr>
</tbody>
</table>
Table 4. Cost/Effectiveness for the Full ASCE-PM and Alternative Equations

<table>
<thead>
<tr>
<th>Equation</th>
<th>Parameters</th>
<th>Cost ($)</th>
<th>Cost ratio</th>
<th>Effectiveness</th>
<th>Cost/effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASCE-PM</td>
<td>( R_s, G, U, RH, T )</td>
<td>5,620</td>
<td>1.00</td>
<td>1.00</td>
<td>N/A</td>
</tr>
<tr>
<td>ASCE-PM</td>
<td>( R_s, G, T )</td>
<td>4,317</td>
<td>0.77</td>
<td>0.90</td>
<td>2.25</td>
</tr>
<tr>
<td>ASCE-PM</td>
<td>( R_s, U, RH, T )</td>
<td>3,867</td>
<td>0.69</td>
<td>0.94</td>
<td>4.94</td>
</tr>
<tr>
<td>ASCE-PM</td>
<td>( R_s, T )</td>
<td>2,038</td>
<td>0.36</td>
<td>0.87</td>
<td>4.77</td>
</tr>
<tr>
<td>ASCE-PM</td>
<td>( T )</td>
<td>1,657</td>
<td>0.29</td>
<td>0.72</td>
<td>2.49</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>( R_s, G, T )</td>
<td>4,317</td>
<td>0.77</td>
<td>0.83</td>
<td>1.34</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>( R_s, T )</td>
<td>2,038</td>
<td>0.36</td>
<td>0.82</td>
<td>3.51</td>
</tr>
<tr>
<td>Radiation/( T_{\text{max}} )</td>
<td>( R_s, T )</td>
<td>2,038</td>
<td>0.36</td>
<td>0.83</td>
<td>3.71</td>
</tr>
<tr>
<td>Simple</td>
<td>( R_s )</td>
<td>1,848</td>
<td>0.33</td>
<td>0.89</td>
<td>5.92</td>
</tr>
<tr>
<td>Hargreaves</td>
<td>( T )</td>
<td>1,657</td>
<td>0.29</td>
<td>0.81</td>
<td>3.62</td>
</tr>
</tbody>
</table>

Cost/Effectiveness

Three alternative equations were most cost/effective at providing accurate estimates of daily \( \text{ET}_o \) (Table 4, Fig. 5). The most cost/effective alternative equations were the Simple, ASCE-PM \( (R_s, U, RH, T) \), and the ASCE-PM \( (R_s, T) \) equations with cost/effectiveness values of 5.92, 4.94, and 4.77 respectively. The remaining alternative equations had cost/effectiveness values of \( \approx 3.71 \). The least cost/effective alternative equation was the full Priestley-Taylor equation with a cost/effectiveness value of 1.34.

\( \text{ET}_o \) and Actual \( \text{ET} \)

The \( \text{ET}_o \) values calculated in this study are comparable to \( \text{ET}_o \) values calculated for a variety of land covers in peninsular Florida (Jacobs and Satti 2001; Sumner and Jacobs 2005) and to the actual evaporation calculated for lakes and estuaries in peninsular Florida (Sacks et al. 1994; Lee and Swancar 1997; Swancar et al. 2000; Sumner and Belaineh 2005). Actual ET can be calculated by multiplying \( \text{ET}_o \) by a crop coefficient \( (K_c) \). \( K_c \) are available, though most are for agricultural land covers and vary only on seasonal time scales (e.g., “Guidelines for prediction of crop water requirements.” 1977; Allen et al. 1998; The ASCE standardized reference evapotranspiration equation 2005). If concurrently collected data are available for a typical year, then \( K_c \) can be calculated by dividing actual ET calculated with lysimeter or eddy-flux data by \( \text{ET}_o \) calculated with meteorological station data. If done on daily or monthly time steps, then curves can fit the \( K_c \) versus day or month data and used to calculate a generic daily- or monthly-varying \( K_c \) for use in similar environments and in similar years. Murphy et al. (2008) used this approach to calculate actual ET at the study site. In a similar environment near the study site, actual ET was estimated by eddy correlation, and \( \text{ET}_o \) was calculated by the full ASCE-PM equation (D. Sumner, unpublished data). Data were used to calculate a generic daily-varying \( K_c \) which was subsequently used to convert \( \text{ET}_o \) to actual ET on the study site. Using this approach, Murphy et al. (2008) found that actual ET for the study site was 1,073 mm/year (42.24 in/year), which is comparable to the actual ET calculated for dry prairies in peninsular Florida (Bidlake et al. 1996).

Accuracy and Seasonal Biases

There are numerous equations commonly used to provide operational estimates of \( \text{ET}_o \) (e.g., Jacobs and Satti 2001). However, these equations vary in their accuracy and their seasonal biases in peninsular Florida (Jacobs and Satti 2001) and across the 48 contiguous states (Jensen et al. 1990). In two locations in northeast Florida and one location in north-central Florida, Jacobs and Satti (2001) found that a variety of temperature-based, radiation-based, and combination equations performed well, typically differing by less than 5% from a previous version of the ASCE-PM equation (Jensen et al. 1990), which they chose to serve as their reference standard. However, they noted some seasonal biases in temperature-based and, to a lesser extent, radiation-based methods, with some equations overestimating \( \text{ET}_o \) in summer and underestimating \( \text{ET}_o \) in winter.

With respect to overall accuracy, the ASCE-PM \( (R_s, U, RH, T) \) and the Simple equations were most accurate. Others were less accurate, with the Hargreaves equation being the least accurate [Figs. 4(a–i)]. One source of error may be that many equations commonly used to provide operational estimates of \( \text{ET}_o \) were originally calibrated to provide PET from a particular reference crop rather than \( \text{ET}_o \) from the standard reference crop. However, many of the particular reference crops had characteristics similar to the standard reference crop, i.e., they were well-watered grasses of uniform height which were actively growing and fully covering the ground surface. Therefore, many equations originally calibrated to calculate PET from a particular reference crop (e.g., Hargreaves and Samani 1982) have more recently been redefined to calculate \( \text{ET}_o \) from the standard reference crop (e.g., Hargreaves and Samani 1985; Hargreaves and Allen 2003).

The less-accurate alternative equations tended to show a seasonal bias from the full ASCE-PM equation, overestimating \( \text{ET}_o \) during the hot, relatively wet summer months and underestimating \( \text{ET}_o \) during the warm, windy, and relatively dry winter.

Fig. 5. Cost/effectiveness of all of the \( \text{ET}_o \) equations with the optimum cost/effectiveness line
months. This is similar to the findings of Jacobs and Satti (2001). In peninsular Florida, summer temperatures are high, but days are generally cloudy and humid, while winter temperatures are moderate, but days are generally sunny and subhumid. Therefore, alternative equations that use \( T \) without satisfactory energy and/or mass-transfer terms may tend to overestimate \( ET_o \) in the summer and underestimate \( ET_o \) in the winter. This kind of seasonal bias was evident in the alternative equations that only require \( T \) or both \( R_s \) and \( T \), such as the ASCE-PM \((R_s, T)\), ASCE-PM \((T)\), Priestley-Taylor \((R_s, T)\), Radiation/\( T_{max} \), and Hargreaves equations. Conversely, this kind of seasonal bias was not evident in the Simple equation which requires only \( R_s \).

In peninsular Florida, all of the equations, including the full ASCE-PM equation, show an inherent seasonal bias from actual ET related to the position of the water table in natural environments. For a fully wet reference grass surface, actual ET and \( ET_o \) are essentially equal. As the surface dries, the lack of water causes actual ET to decrease, while \( ET_o \) remains unaffected. The result in peninsular Florida is that \( ET_o \) peaks in the late dry season when solar radiation intensity is high and cloud cover is at a minimum before the rainy season, while actual ET peaks in the middle of the wet season when temperatures are highest and water tables are at or near the ground surface (Murphy et al. 2008). Regardless of which \( ET_o \) equation is used, this inherent seasonal bias must be corrected through the application of a temporally varying \( K_s \) that shifts peak ET from the late dry season to the middle of the wet season (e.g., Murphy et al. 2008).

**Summary and Limitations**

The Simple, ASCE-PM \((R_s, U, RH, T)\) and ASCE-PM \((R_s, T)\) equations were most cost/effective. Others were less cost/effective, with the full Priestley-Taylor equation being the least cost/effective. An optimum cost/effectiveness line can be drawn through the alternative equations with the highest cost/effectiveness ratios from the full ASCE-PM signifying that \( ET_o \) instrumentation with a specific cost ratio should be expected to obtain a corresponding effectiveness near the optimum cost/effectiveness line (Fig. 5).

ET is dominated by energy rather than mass-transfer terms (Priestley and Taylor 1972). Incoming energy terms are either \( R_s \) or \( R_p \), depending upon the equation. Additionally, \( R_s \) can be accurately estimated from \( R_s \) (Frischen 1967; *The ASCE standardized reference evapotranspiration equation* 2005). In this analysis, 77% of the cost of the instrumentation was for the measurement of all of the other parameters other than for the measurement of \( R_s \). Therefore, the most cost/effective alternative equations tended to be those in which less-important energy and mass-transfer terms were omitted and/or calculated from less-expensive instrumentation. Perhaps the best example is the Simple equation, which only requires a single coefficient and \( R_s \), and which proved to be an accurate and highly cost/effective alternative equation.

**Conclusions**

There are numerous equations commonly used to provide operational estimates of \( ET_o \). The ASCE-PM equation is becoming the standard in the United States (*The ASCE standardized reference evapotranspiration equation* 2005). The tendency may be to believe that the most accurate and cost/effective alternative equations are those that are the most complex. This was not the case at our study area. Rather, the most accurate and cost/effective alternative equations tend to be those in which mass-transfer terms are omitted and/or calculated from less-expensive and less-complex instrumentation. Perhaps the best example is the Simple equation, which only requires a single coefficient and \( R_s \), and which proved to be an accurate and highly cost/effective alternative equation.

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