A NEW PROCEDURE FOR ESTIMATING REFERENCE EVAPOTRANSPIRATION IN ARIZONA

Introduction

The Arizona Meteorological Network (AZMET) has provided daily values of reference evapotranspiration (ETo) for a number of southern Arizona locations for more than 15 years. ETo is a computed meteorological parameter that provides an estimate of environmental evaporative demand and serves as a critical input variable for most scientifically based irrigation scheduling systems. ETo is also used to estimate evaporation from water bodies and evapotranspiration (ET) from rain-fed ecosystems.

While there is general agreement among agronomists, irrigation engineers and meteorologists that ETo is a useful environmental parameter, there has been less agreement on how to compute ETo. And all too often the computational procedure for ETo varies from region to region and sometimes within a region. Use of multiple ETo computation procedures within a region can generate biases in ETo that result from the computation process, not any true differences in environmental evaporative demand. Figure 1 provides graphic evidence of this computational bias by presenting the total ETo for Tucson in 1996 as computed using the published ETo procedures for the public weather networks operating in Arizona (Brown, 1998), California (Snyder and Pruitt, 1985), and New Mexico (Sammis, 1996). It is important to note that the same meteorological data were used to generate the ETo data in Figure 1; only the computational procedures differed. These results provide clear evidence that lack of a standardized computational procedure for ETo can lead to confusion and perhaps serious mistakes when one is involved in activities such as irrigation scheduling, estimating consumptive use of vegetation, water rights litigation (especially across state lines), and development of crop coefficients (adjustment factors that convert ETo to crop ET).

Over the past decade, scientists have recognized the problems and frustrations associated with non-standardized ETo computation and have formed national and international committees to address this issue. The American Society of Civil Engineers (ASCE) developed

Figure 1. Reference ET (ETo) for Tucson for calendar year 1996 as computed using the published procedures for the public weather networks in Arizona, California, and New Mexico.

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a special Task Committee (TC) in 1999 to develop a standardized procedure for computing ETo. The ASCE TC has issued its recommendations (Walter et al., 2004) which are to be published in 2005. AZMET participated in the ASCE TC and began generating ETo values using this ASCE Standardized ETo procedure in 2003. The purpose of this report is to first review the computation procedure recommended by the ASCE TC; second, provide specifics on the computation procedure AZMET will employ; and third, summarize how the new standardized ETo procedure and the original AZMET ETo (EToa) procedure compare across months and locations.

**Standardized Reference Evapotranspiration Definition**

The ASCE TC defined reference evapotranspiration as “the ET rate from a uniform surface of dense actively growing vegetation having specified height and surface resistance (to transfer of water vapor), not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation.” This definition leaves open the option of having more than one reference surface (differing height and surface resistance) and reflects the view of the TC that standardized computation procedures were necessary for two reference surfaces: 1) a short crop similar to clipped grass and 2) a tall crop similar to full-cover alfalfa. The recommended abbreviations for ETo computed for the short and tall crops using the standardized procedures are ETos and ETrs, respectively (see Table 1 for list of ET abbreviations used in this report).

The need to have procedures for two reference surfaces reflects the history of ET research in the U.S. Two crops — cool-season grass and alfalfa — have been used as reference surfaces for ET estimation for several decades. The TC recommendations allow users with a strong preference for one reference surface or another to continue using their preferred surface. An important reason for recommending two surfaces pertains to crop coefficients (Kcs) — the adjustment factors used to convert ETo to estimates of ET for a specific type of vegetation. Kcs will differ for the two reference surfaces since alfalfa typically uses more water than grass when both are grown under reference conditions. Over the past 30+ years, Kcs have been developed for use with ETo computed for both grass and alfalfa reference surfaces. The TC recommendation to allow for two reference surfaces allows local users to continue using the Kcs and reference surface they are most comfortable with.

<table>
<thead>
<tr>
<th>ABBREVIATION</th>
<th>EXPLANATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ET</td>
<td>Evapotranspiration</td>
</tr>
<tr>
<td>ETo</td>
<td>Reference Evapotranspiration in general</td>
</tr>
<tr>
<td>ETc</td>
<td>Evapotranspiration of a particular crop or vegetation type</td>
</tr>
<tr>
<td>ETos</td>
<td>Standardized Reference Evapotranspiration for Short Reference Crop</td>
</tr>
<tr>
<td>ETrs</td>
<td>Standardized Reference Evapotranspiration for Tall Reference Crop</td>
</tr>
<tr>
<td>ETsz</td>
<td>Standardized Reference Evapotranspiration in general</td>
</tr>
<tr>
<td>EToa</td>
<td>Reference Evapotranspiration as computed by AZMET in past years</td>
</tr>
</tbody>
</table>

Table 1. Abbreviations related to evapotranspiration that are contained in this report.

**Generalized Form of Standardized Equation**

The ASCE TC standardized procedure for computing reference evapotranspiration is based on the Penman-Monteith Equation and more specifically on simplifying the version of the Penman Monteith Equation recommended by ASCE (Jensen et al., 1990). The recommended general computation procedure is provided below:

\[
ETsz = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_r}{T + 273} (e_s - e_a)}{\Delta + \gamma (1 + C_{aTc})}
\]

Where:

- ETsz = standardized reference crop evapotranspiration (mm d\(^{-1}\) or mm h\(^{-1}\))
- \(\Delta\) = slope of the saturation vapor pressure-temperature curve (kPa °C\(^{-1}\))
- \(R_n\) = Calculated net radiation at the crop surface (MJ m\(^{-2}\) d\(^{-1}\) or MJ m\(^{-2}\) h\(^{-1}\))
- \(G\) = Soil heat flux density at the soil surface (MJ m\(^{2}\) d\(^{-1}\) or MJ m\(^{2}\) h\(^{-1}\))

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\[ \gamma = \text{psychrometer constant (kPa °C}^{-1} \]

\[ C_n = \text{numerator constant that changes with reference type and calculation time step} \]

\[ T = \text{mean daily air temperature measured at 1.5 to 2.5 m above ground level (°C)} \]

\[ U_2 = \text{mean daily wind speed wind speed measured at 2 m above ground level (m s}^{-1} \]

\[ e_s = \text{saturation vapor pressure measured at 1.5 to 2.5 m above ground level (kPa)} \]

\[ e_a = \text{mean actual vapor pressure measured at 1.5 to 2.5 m above ground level (kPa)} \]

\[ C_d = \text{denominator constant that changes with reference type and calculation time step} \]

Equation 1 represents a generalized equation that can, with appropriate use of constants, handle different reference surfaces; different computational time steps; and slight variation in the measurement height of certain meteorological measurements. Note that standardized reference ET when described in this generalized form is given the abbreviation ETsz.

**Standardized Equation To Be Used By AZMET**

AZMET will utilize the standardized procedure for a short reference crop computed using a daily computational time step. The appropriate equation for this version of the standardized procedure is provided below:

\[
ETos = \frac{0.408\Delta R_n + \gamma}{T + 273} \frac{900}{\Delta + \gamma (1 + 0.34U_2)} u_2 (e_s - e_a) \tag{2}
\]

Where:

\[ ETos = \text{standardized reference crop evapotranspiration for a short crop in mm d}^{-1} \]

\[ \Delta = \text{slope of the saturation vapor pressure-temperature curve (kPa °C}^{-1} \]

\[ R_n = \text{Calculated net radiation at the crop surface in MJ m}^{-2} \text{d}^{-1} \]

\[ \gamma = \text{psychrometer constant (kPa °C}^{-1} \]

\[ T = \text{mean daily air temperature measured at 1.5 m above ground level (°C)} \]

\[ U_2 = \text{mean daily wind speed measured at 2 m above ground level (m s}^{-1} \]

\[ e_s = \text{saturation vapor pressure measured at 1.5 m above ground level (kPa)} \]

\[ e_a = \text{mean actual vapor pressure measured at 1.5 m above ground level (kPa)} \]

A comparison of Eqs. 1 and 2 reveal some significant differences. One notable difference is the change in abbreviation for reference ET. The ASCE task force recommended using the abbreviation ETos for short crop standardized reference ET. Another important difference among the two equations is that the numerator and denominator constants in Eq. 1 are set equal to 900 and 0.34, respectively which represent the appropriate constants for the short reference crop and daily computational time step. Finally, one will notice that Eq. 2 no longer contains the soil heat flux variable (G in Eq. 1). Soil heat flux is typically very small over a period of 24 hours (heat that flows into soil in day is lost back to the surface at night) and thus is set equal to zero in the standardized equation when the daily computation time step is used.

The reason AZMET chose to use reference ET computed for a short reference crop is to provide continuity with past AZMET ETo data. AZMET has used a 0.08-0.15 m tall cool season grass as its ET reference surface since the inception of the network in 1987.

The time step for ETsz computation was another factor addressed by the ASCE TC. Time step refers to the time interval over which the ETsz computation is made. The TC recommended standardized procedures for two computational time steps — hourly and daily. The daily computational time step has been used for many decades, in part because most older meteorological data sets consisted of daily summaries. The advent of automated weather stations in the late 1970s led to an increase in the number of hourly data sets that could be used to compute ETo. Past research suggests the ETo computation is more accurate when the computation time step is hourly as opposed to daily or longer (Tanner and Pelton, 1960, Van Bavel, 1966), particularly in regions where meteorological conditions vary in an asymmetric manner each day (e.g., coastal locations with fog or sea breeze; certain mountain areas subject to sudden changes in wind or cloudiness each day). One of the objectives of the TC was to recommend a standardized procedure where the computational time step did not greatly impact the resulting ETsz value. The TC did conduct an evaluation of the impact of time step on the resulting ETsz value (Itenfisu et al., 2000). The evaluation found that ETsz computed using the hourly and daily time step was generally within 2% across a large number of locations (including Arizona).

AZMET chose to use the daily time step computation model for the following reasons: 1) meteorological conditions in Arizona do not generally exhibit serious asymmetric tendencies over the course of a day; 2) daily
Comparison of Standardized Reference ET with Original AZMET ETo

A logical question for users of ETo data would be how does the new standardized procedure (ETos) compare with the original AZMET ETo (EToa) data. To answer this question, AZMET computed daily ETos for the period 1 January 1998 through 31 December 2001 (4 years), then compared the monthly, seasonal, and annual totals of ETos against similar totals of EToa for locations presently served by AZMET weather stations.

ETos and EToa were highly correlated across all locations served by AZMET. The data presented in Figure 2 are representative of the general relationship between ETos and EToa. While ETos and EToa are highly correlated, values of ETos generally run lower than EToa. This lower bias of ETos is clearly evident in Tables 2 and 3 that present monthly, seasonal, and annual totals of ETos and EToa for all locations presently served by AZMET weather stations. Also included in Tables 2 and 3 are ratios of ETos to EToa for the various time scales.

Annual totals of ETos were 3-17% lower than similar totals of EToa depending on location (Table 3). The lowest ratios of ETos to EToa occur where wind flow is generally low (e.g., Waddell, Phoenix Encanto, and Phoenix Greenway). The highest ratios occur at locations exhibiting fairly high wind speeds (e.g., Marana, Parker).

The monthly and seasonal ratios presented in Tables 2 and 3 reveal that the lower bias of ETos (relative to EToa) is not constant over time. Higher ratios typically occur during windy months and months with higher dew point temperatures (e.g., summer monsoon months). Lower ratios commonly occur when dew point and wind flow are low.

Converting Past EToa to ETos

Long time users of AZMET data may have databases and spreadsheets that contain values of EToa generated in past years. Users interested in converting EToa data into reliable estimates of ETos may use the ratios presented in Tables 2 & 3. The simple conversion process uses the following equation:

$$ \text{ETos} = \text{Ratio} \times \text{EToa} $$

Data Required To Compute ETos

Both meteorological and non-meteorological data are required for the computation of ETos. The required meteorological data include: 1) daily solar radiation (MJ m\(^{-2}\) d\(^{-1}\)), 2) mean daily vapor pressure (kPa), 3) mean daily wind speed (m s\(^{-1}\)), and 4) maximum and minimum air temperature for the day (°C). All of the required meteorological data are collected by AZMET weather stations. Required non-meteorological data consist of elevation above sea level and latitude for the locations providing the meteorological data (AZMET weather station locations).

The meteorological data required for computation of ETos must be converted into the specific variables required in Eq. 2. Multiple procedures are available for making these required conversions. The ASCE TC reviewed many of the recommended conversion procedures and made recommendations on the best procedures to use based on the kind and quality of available meteorological data. The specific procedures and/or equations employed by AZMET to generate these required variables are presented in the Appendix to this report.

meteorological data are easier to estimate than hourly data when data are missing due to instrument failure or station maintenance; and 3) AZMET questions the accuracy of nighttime net radiation (R\(_n\)) estimates required to estimate ETos on an hourly timescale.
Table 2. Mean monthly values of reference evapotranspiration for all AZMET station sites for the period 1998-2001 computed using the ASCE standardized (ETos) and original AZMET (EToa) computation procedures. Monthly ratios of ETos to EToa are provided in columns labeled “Ratio.”

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>JANUARY</th>
<th>FEBRUARY</th>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ETos</td>
<td>EToa</td>
<td>Ratio</td>
<td>ETos</td>
<td>EToa</td>
<td>Ratio</td>
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<tr>
<td>Aguila</td>
<td>72.6</td>
<td>80.5</td>
<td>0.90</td>
<td>77.8</td>
<td>90.1</td>
<td>0.86</td>
</tr>
<tr>
<td>Buckeye</td>
<td>74.3</td>
<td>83.8</td>
<td>0.89</td>
<td>84.7</td>
<td>96.1</td>
<td>0.88</td>
</tr>
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<td>Bonita</td>
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<td>79.0</td>
<td>0.88</td>
<td>82.8</td>
<td>94.2</td>
<td>0.88</td>
</tr>
<tr>
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<td>73.5</td>
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<td>0.94</td>
<td>82.2</td>
<td>90.4</td>
<td>0.91</td>
</tr>
<tr>
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<td>81.1</td>
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<td>0.93</td>
<td>87.3</td>
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<td>80.9</td>
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Table 2 continued. Mean monthly values of reference evapotranspiration for all AZMET station sites for the period 1998-2001 computed using the ASCE standardized (ETos) and original AZMET (EToa) computation procedures. Monthly ratios of ETos to EToa are provided in columns labeled “Ratio.”

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>JULY</th>
<th>AUGUST</th>
<th>SEPTEMBER</th>
<th>OCTOBER</th>
<th>NOVEMBER</th>
<th>DECEMBER</th>
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<td></td>
<td>ETos (mm)</td>
<td>EToa (mm)</td>
<td>Ratio</td>
<td>ETos (mm)</td>
<td>EToa (mm)</td>
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Table 3. Seasonal and annual means of reference evapotranspiration for all active AZMET monitoring sites for the period 1998-2001 as computed using the ASCE standardized (ETos) and original AZMET (EToa) procedures. Ratios of ETos to EToa are provided in columns labeled “Ratio.”

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>WINTER (Dec. - Feb.)</th>
<th>SPRING (Mar. - May)</th>
<th>SUMMER (Jun. - Aug.)</th>
<th>FALL (Sep. - Nov.)</th>
<th>ANNUAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ETos (mm)</td>
<td>EToa (mm)</td>
<td>Ratio</td>
<td>ETos (mm)</td>
<td>EToa (mm)</td>
</tr>
<tr>
<td>Aguila</td>
<td>225.9</td>
<td>252.9</td>
<td>0.89</td>
<td>538.1</td>
<td>618.7</td>
</tr>
<tr>
<td>Buckeye</td>
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<td>259.2</td>
<td>0.89</td>
<td>554.7</td>
<td>628.7</td>
</tr>
<tr>
<td>Bonita</td>
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<td>250.3</td>
<td>0.87</td>
<td>516.6</td>
<td>600.4</td>
</tr>
<tr>
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<td>227.6</td>
<td>244.2</td>
<td>0.93</td>
<td>546.5</td>
<td>607.3</td>
</tr>
<tr>
<td>Eby</td>
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<td>241.4</td>
<td>0.89</td>
<td>540.8</td>
<td>626.4</td>
</tr>
<tr>
<td>Harquahala</td>
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<td>242.9</td>
<td>0.86</td>
<td>512.2</td>
<td>599.3</td>
</tr>
<tr>
<td>Litchfield Pk.</td>
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<td>233.1</td>
<td>0.88</td>
<td>539.3</td>
<td>616.9</td>
</tr>
<tr>
<td>Maricopa</td>
<td>202.2</td>
<td>228.3</td>
<td>0.89</td>
<td>545.0</td>
<td>610.2</td>
</tr>
<tr>
<td>Marana</td>
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<td>275.4</td>
<td>0.99</td>
<td>580.9</td>
<td>637.8</td>
</tr>
<tr>
<td>Mohave Val.</td>
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<td>281.4</td>
<td>0.92</td>
<td>595.4</td>
<td>658.1</td>
</tr>
<tr>
<td>Paloma</td>
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<td>247.4</td>
<td>0.92</td>
<td>539.0</td>
<td>609.3</td>
</tr>
<tr>
<td>Parker</td>
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<td>250.7</td>
<td>0.91</td>
<td>590.6</td>
<td>645.5</td>
</tr>
<tr>
<td>Phoenix Encanto</td>
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<td>208.0</td>
<td>0.83</td>
<td>475.3</td>
<td>565.9</td>
</tr>
<tr>
<td>Phoenix Greenway</td>
<td>163.5</td>
<td>219.7</td>
<td>0.74</td>
<td>463.6</td>
<td>562.4</td>
</tr>
<tr>
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<td>211.1</td>
<td>0.92</td>
<td>492.7</td>
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</tr>
<tr>
<td>Roll</td>
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<td>0.82</td>
<td>525.7</td>
<td>610.0</td>
</tr>
<tr>
<td>Safford</td>
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<td>0.93</td>
<td>577.2</td>
<td>642.7</td>
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<tr>
<td>Tucson</td>
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<td>0.85</td>
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<tr>
<td>Waddell</td>
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<td>591.7</td>
</tr>
<tr>
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<td>0.83</td>
<td>515.7</td>
<td>602.3</td>
</tr>
<tr>
<td>Yuma N. Gila</td>
<td>226.4</td>
<td>264.0</td>
<td>0.86</td>
<td>509.5</td>
<td>590.0</td>
</tr>
<tr>
<td>Yuma Valley</td>
<td>263.4</td>
<td>295.7</td>
<td>0.89</td>
<td>546.9</td>
<td>620.7</td>
</tr>
</tbody>
</table>
where \textbf{Ratio} represents the appropriate annual, seasonal or monthly ratio from Tables 2 and 3. Annual ratios should be used only to adjust annual totals of \( \text{EToa} \). Monthly ratios provide the best means of converting short term data sets (e.g., daily, weekly or monthly totals of \( \text{EToa} \)). \textit{Users wishing to obtain actual computed values of \( \text{ETos} \) for past years should contact AZMET. As part of the move to adopt \( \text{ETos} \), AZMET will generate \( \text{ETos} \) for its entire database which extends back to 1987 at some locations.}

\section*{Crop Coefficients and \( \text{ETos} \)}

Crop coefficients (Kcs) are used to convert ETo data into estimates of crop evapotranspiration (ETc). The simple conversion procedure is as follows:

\[ \text{ETc} = Kc \times \text{ETo} \]  
\[ (4) \]

It is important to note that Kcs need to be matched to the ETo procedure in order to obtain reliable estimates of ETc from Eq. 4. To help clarify this point, suppose one has a turf Kc of 0.75 that is appropriate for use with AZMET ETo (EToa). To obtain an estimate of turf water use in Tucson for May one would multiply the Kc (0.75) times the May EToa value for Tucson (258.1 mm from Table 2):

\[ \text{ETc} = Kc \times \text{EToa} \]

\[ \text{ETc} = 0.75 \times 258.1 \text{ mm} \]

\[ \text{ETc} = 193.6 \text{ mm (7.62")} \]

If, however, this same Kc is erroneously applied to values of \( \text{ETos} \), the same May turf water use estimate in Tucson would be:

\[ \text{ETc} = Kc \times \text{ETos} \]

\[ \text{ETc} = 0.75 \times 224.3 \text{ mm} \]

\[ \text{ETc} = 168.2 \text{ mm (6.62")} \]

or 25.4 mm (1.0”) less than the correct value. It is clear from this example that failure to match Kcs with ETo procedure can lead to significant errors when estimating water use from vegetation.

Very few Kcs have been validated for use with \( \text{ETos} \) in Arizona with the notable exception of turfgrass (Brown and Kopec, 2000). While a number of research studies are presently underway (University of Arizona and USDA-ARS) that should provide validated Kcs for a number of Arizona crops in the near future, individuals interested in applying Kcs to \( \text{ETos} \) must either use published Kcs developed in another location, or adjust existing AZMET Kcs. A good place to locate Kcs for use with \( \text{ETos} \) is the publication entitled \textit{Crop Evapotranspiration: Guidelines for computing crop water requirements} which is listed in the Reference section of this report.

Adjusting AZMET Kcs is a simple process that requires the use of the ratio data in Tables 2 and 3:

\[ Kc_{\text{os}} = Kc_{\text{az}} / \text{Ratio} \]  
\[ (5) \]

where \( Kc_{\text{os}} \) and \( Kc_{\text{az}} \) are the crop coefficient values appropriate for use with \( \text{ETos} \) and \( \text{EToa} \), respectively; and \textbf{Ratio} is the ratio of \( \text{ETos} \) to \( \text{EToa} \) provided in Tables 2 and 3. In the previous example pertaining to turfgrass water use for Tucson in May, one would correct the Kc \( \text{az} \) value of 0.75 by dividing by the May ratio presented in Table 2 (0.87):

\[ Kc_{\text{os}} = 0.75 / 0.87 = 0.86 \]

Seasonal ratios of \( \text{ETos} \) to \( \text{EToa} \) are provided in Table 3 to assist with adjusting Kc \( \text{az} \) for row crops. For example, AZMET has recommended using a Kc of 1.12 for full cover cotton when using \( \text{EToa} \). The process of adjusting this Kc for use with \( \text{ETos} \) at Maricopa would proceed as follows:

\[ Kc_{\text{os}} = 1.12 / 0.97 = 1.15 \]

The value of 0.97 is the summer ratio for Maricopa (see Table 3).

On a practical note it is important to recognize that existing Kc \( \text{az} \) values will require only minor adjustments (if any) when used during the summer months. Larger adjustments will be required in winter where the ratios of \( \text{ETos} \) to \( \text{EToa} \) are generally much less than 1.0.

\section*{References}


Appendix

The procedures and equations used to compute the variables presented in Equation 2 are described in this Appendix. The variables are presented in the order they are encountered in Eq. 2.

Δ: Slope of Saturation Vapor Pressure vs. Temperature Relationship

The slope of the saturation vapor pressure versus temperature relationship, \( \Delta \text{ (kPa °C}^{-1} \) is computed using:

\[
\Delta = 2503 \exp((17.27T)/(T + 237.3))/(T + 237.3)^2 \quad (A1)
\]

where \( T \) is the mean temperature for the day (°C).

Rn: Net Radiation

Net radiation is the net amount of radiant energy available at the surface for evaporating water. Rn includes both short and long wave radiation and is computed using:

\[
R_n = R_{ns} - R_{nl} \quad (A2)
\]

where \( R_{ns} = \) net shortwave radiation (MJ m\(^{-2}\) d\(^{-1}\)) defined as positive in the downward direction (toward earth) and \( R_{nl} = \) net longwave radiation (MJ m\(^{-2}\) d\(^{-1}\)) defined as positive in the upward direction (toward sky).

Net shortwave radiation (Rns) is computed as the difference between incoming and reflected shortwave radiation:

\[
R_{ns} = R_s - \alpha R_s = (1 - \alpha)R_s \quad (A3)
\]

where \( \alpha = \) albedo or canopy reflection coefficient which is fixed at 0.23 and \( R_s = \) incoming solar radiation (MJ m\(^{-2}\) d\(^{-1}\)).

Net longwave radiation (Rnl) is the difference between upward longwave radiation (Rlu) and downward longwave radiation from the sky (Rld):

\[
R_{nl} = R_{lu} - R_{ld} \quad (A4)
\]

The daily value of Rnl is computed using:

\[
R_{nl} = \sigma[(T_k^{max} + T_k^{min})/2]^{0.34-0.14 \sqrt{ea}}[1.35(R_s/R_{so}) - 0.35] \quad (A5)
\]

where \( R_{nl} = \) net long-wave radiation in MJ m\(^{-2}\) d\(^{-1}\), \( \sigma = \) the Stefan-Boltzman constant \([= 4.901 \times 10^\text{9} \text{MJ K}^{-4} \text{m}^{-2} \text{d}^{-1}]\), \( T_k^{max} = \) the maximum absolute temperature for the day (K), \( T_k^{min} = \) the minimum absolute temperatures for the day (K), \( ea = \) the actual vapor pressure (kPa), \( R_s = \) solar radiation (MJ m\(^{-2}\) d\(^{-1}\)), and \( R_{so} = \) solar radiation (MJ m\(^{-2}\) d\(^{-1}\)). The ratio \( R_s/R_{so} \) indicates the relative level of cloudiness must be limited to 0.3 < \( R_s/R_{so} < 1.0 \). \( R_s/R_{so} \) values <0.30 are set = 0.30; \( R_s/R_{so} \) values > 1.0 are set = 1.0.
Clear sky solar radiation (Rso) is computed using:

\[
Rso = (0.75 + 2 \times 10^{-5} z)Ra \quad (A6)
\]

where \( z \) is the elevation above sea level (m) and Ra is extraterrestrial radiation (MJ m\(^{-2}\) d\(^{-1}\)).

Extraterrestrial radiation is computed from earth-sun geometry using:

\[
Ra = \frac{24}{\pi} Gsc \ dr \ast [\cos(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \sin(\omega_s)] \quad (A7)
\]

where Gsc is the solar constant \([= 4.92 \text{ MJ m}^{-2} \text{ h}^{-1}]\), \( dr \) is relative distance factor (between the earth and sun), \( \omega_s \) is sunset hour angle (radians), \( \phi \) is the latitude (radians), and \( \delta \) solar declination (radians).

The relative distance factor is computed using:

\[
dr = 1 + 0.033 \cos(2\pi J/365) \quad (A8)
\]

where \( J \) is the day of the year (1 = 1 January; 365 = 31 December).

The solar declination angle is computed using:

\[
\delta = 0.409 \sin((2\pi J/365) - 1.39) \quad (A9)
\]

The sunset angle is computed using:

\[
\omega_s = \arccos[-\tan(\phi) \tan(\delta)] \quad (A10)
\]

\( \gamma \): *Psychrometer Constant*

The psychrometer constant, \( \gamma \) (kPa °C\(^{-1}\)), is computed using:

\[
\gamma = 0.000665 \ P \quad (A11)
\]

where \( P \) is the atmospheric pressure at the weather station site. Atmospheric pressure (kPa) is computed from the elevation of the weather station site:

\[
P = 101.3 \ ((293 - 0.0065 z) / 293)^{5.26} \quad (A12)
\]

where \( z \) is the elevation of the weather station above mean sea level (m).

**T: Mean Air Temperature**

Mean air temperature (°C) is calculated as the mean of the daily maximum and daily minimum air temperature:

\[
T = (Tmax + Tmin)/2 \quad (A13)
\]
where Tmax and Tmin are the maximum and minimum air temperatures (°C) as obtained from the weather station data logger.

**U₂: Wind Speed**
The standardized equation requires the mean daily wind speed measured at 2 m above ground level (agl). Because AZMET measures wind speed at 3 m agl, wind speed is adjusted to an equivalent value at 2 m agl using the following:

\[
U_2 = U_3 \left( \frac{4.87}{\ln(67.8 \text{ zw} - 5.42)} \right) \quad (A14)
\]

where \( U_3 \) is the wind speed measured at 3 m agl and zw is the height of the wind speed measurement (3 m).

**\( \varepsilon_\text{s} \): Saturation Vapor Pressure**
Saturation vapor pressure is computed using:

\[
\varepsilon_s = \frac{(\varepsilon_s(T_{\text{max}}) + \varepsilon_s(T_{\text{min}}))}{2} \quad (A15)
\]

where \( \varepsilon_s(T_{\text{max}}) \) and \( \varepsilon_s(T_{\text{min}}) \) are the saturation vapor pressures (kPa) computed using the maximum and minimum air temperatures, respectively. Saturation vapor pressure is computed using the following:

\[
\varepsilon_s = 0.6108 \exp\left(\frac{17.27T_{\text{ex}}}{T_{\text{ex}} + 237.3}\right) \quad (A16)
\]

where \( T_{\text{ex}} \) is either \( T_{\text{max}} \) or \( T_{\text{min}} \) (°C).

**\( \varepsilon_a \): Actual Vapor Pressure**
The mean actual vapor pressure for the day is computed by the weather station datalogger using simultaneous measurements of relative humidity (RH; %) and air temperature (Ta; °C) using:

\[
\varepsilon_a = \frac{(RH/100) [0.6108 \exp((17.27Ta) / (Ta + 237.3))]}{0.6108 \exp((17.27Ta) / (Ta + 237.3))} \quad (A17)
\]

Values of \( \varepsilon_a \) are computed by the datalogger every 10 s and averaged for the day.