A USER-FRIENDLY INTERACTIVE TOOL FOR ESTIMATING REFERENCE ET USING ASCE-EWRI STANDARDIZED PENMAN-MONTEITH EQUATION

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Keywords:	evapotranspiration, water management, irrigation scheduling
Abstract:	The Accurate daily reference evapotranspiration (ET) values are needed to estimate crop water demand for irrigation management and hydrologic modeling purposes. The Bushland Reference ET Calculator (BET) was developed to implement a user-friendly interface for calculating hourly and daily grass and alfalfa reference ET using the Java Programming Language. The calculator uses the American Society of Civil Engineers (ASCE) Standardized Reference ET equation for calculating both grass and alfalfa reference ET at hourly and daily time steps from a single set or time series of weather data. Daily reference ET can be calculated either by calculating the hourly reference ET values and summing them up or by calculating a daily value using daily statistics of the climatic data (means, maxima and minima). Graphing capabilities include line graph and scatter plot for quality assurance and quality control purposes. Descriptive statistics can be calculated for selected or all of the variables. Although the "Bushland Reference ET Calculator" was designed and developed for use mainly by producers and crop consultants to manage irrigation scheduling, it can also be used in educational training, research, and other practical applications. This paper demonstrates the use of the Bushland Reference ET Calculator that is available from the USDA-ARS Conservation and Production Research Laboratory web site to interested users at no cost.

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ABSTRACT.

The Accurate daily reference evapotranspiration (ET) values are needed to estimate crop water demand for irrigation management and hydrologic modeling purposes. The Bushland Reference ET Calculator (BET) was developed to implement a user-friendly interface for calculating hourly and daily grass and alfalfa reference ET using the Java Programming Language. The calculator uses the American Society of Civil Engineers (ASCE) Standardized Reference ET equation for calculating both grass and alfalfa reference ET at hourly and daily time steps from a single set or time series of weather data. Daily reference ET can be calculated either by calculating the hourly reference ET values and summing them up or by calculating a daily value using daily statistics of the climatic data (means, maxima and minima). Graphing capabilities include line graph and scatter plot for quality assurance and quality control purposes. Descriptive statistics can be calculated for selected or all of the variables. Although the "Bushland Reference ET Calculator" was designed and developed for use mainly by producers and crop consultants to manage irrigation scheduling, it can also be used in educational training, research, and other practical applications. This paper demonstrates the use of the Bushland Reference ET Calculator that is available from the USDA-ARS Conservation and Production Research Laboratory web site to interested users at no cost.

Keywords. *Irrigation Scheduling, Bushland Reference ET Calculator, Water Management*

INTRODUCTION

Evapotranspiration (ET) is defined as a measure of the total water consumption through evaporation from the soil and plants and transpiration by plants. In agriculture, ET is a major consumptive use of irrigation water and precipitation.

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Reliable and accurate estimates of ET or crop water use are essential to optimize irrigation management. Potential water use by a specific crop (ET_c) can be estimated by multiplying daily reference ET by an appropriate crop coefficient (K_c) derived from field measurements based on water balance methods, including lysimetry (Marek et al., 2010). Then, ET_c can be estimated by multiplying reference ET with K_c under the assumption that weather conditions for the reference crop surface are similar to (representative of) those within the surrounding region. Reference ET refers to the amount of water that would be lost to the atmosphere from a hypothetical grass or alfalfa crop grown under reference conditions: water and nutrients not limiting and the crop maintained at the reference height and full cover (Allen et al., 1998). Reference ET is attributed directly to the atmospheric water demand irrespective of crop type. Consequently, ET_{ref} can be calculated using meteorological data from solar radiation (R_s), wind speed (U_2), air temperature (T_a), and relative humidity (RH).

Prior to the reference ET concept, several equations with varying complexity and input requirements were developed to calculate what was termed as potential ET (ET_o), a closely related concept. For example, ET_o formulations proposed by Blaney and Criddle (1950), Makkink (1957), and Priestley and Taylor (1972) required only solar radiation, and that proposed by Hargreaves and Samani (1985) required only air temperature. Other methods such as Allen et al. (1998), Doorenbos and Pruitt (1977), Monteith (1965), and Penman (1948) required some combinations of parameters involving solar radiation, air temperature, humidity, and wind speed (Er-Raki et al., 2010). In the United States, in order to standardize reference ET calculation and allow for transferability of crop coefficients, the ASCE-EWRI Standardized Reference Evapotranspiration Equation (ET_{sz}) (Allen et al., 2005) was established as the benchmark equation. This equation is a simplified version of the Penman-Monteith (PM) ET equation given in ASCE Manual 70 (Jensen et al., 1990) with appropriate constants for two standardized reference crop surfaces: (1) short, smooth crop similar to clipped grass with an approximate height of 0.12 m and (2) a taller, rough agricultural crop similar to full-cover alfalfa with an approximate height of 0.50 m (Walter et al., 2000). Provision and recommendations are made for application of the equation including standardized calculations for all intermediate parameters at hourly and daily time steps. In addition, guidelines are provided for assessing integrity of weather data used for estimating reference ET and methodologies that can be used where data is limited or missing. Currently, it is one of the most widely used equations to calculate reference ET for either a short reference crop (clipped grass - ET_{os}) or a tall reference crop (alfalfa – ET_{rs}) in the United States.

The ASCE standardized reference ET (ET_{sz}) equation (Allen et al., 2005) is given as:

$$ET_{sz} = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{C_n}{T+273} u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + C_d u_2)} \quad (1)$$

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where: ET_{sz} is the standardized reference ET for grass (ET_{os}) or alfalfa (ET_{rs}) crop surfaces (mm d^{-1} for daily or mm h^{-1} for hourly time steps), R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1} for daily or MJ m^{-2} h^{-1} for hourly time steps), G is the soil heat flux density at the soil surface (MJ m^{-2} d^{-1} for daily or MJ m^{-2} h^{-1} for hourly time steps), T is the mean daily or hourly air temperature at 2-m height (^oC), u_2 is the mean daily or hourly wind speed at 2-m height (m s^{-1}), e_s is the mean hourly saturation vapor pressure (kPa) at 2-m height for hourly calculations or is calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperatures, e_a is the mean actual vapor pressure (kPa) at 2-m height, Δ is the slope of the saturation vapor pressure-temperature curve (kPa $^oC^{-1}$), γ is the psychrometric constant (kPa $^oC^{-1}$), C_n is the numerator constant that changes with reference type and calculation time step (K mm s^3 Mg^{-1} d^{-1} or K mm s^3 Mg^{-1} h^{-1}), C_d is the denominator constant that changes with reference type and calculation time step (s m^{-1}), and units for the 0.408 coefficient are m^2 mm MJ^{-1}. The values for C_n and C_d are provided in Table 1 of the manual of the ASCE standardized reference ET equation (Allen et al., 2005).

Numerous studies have been conducted to compare ET_{sz} with other widely used methods. Detail discussion on the major differences between these equations in relation to ET_{sz} is presented in the Appendix B of the ASCE-EWRI standardized reference ET equation manual (Allen et al., 2005). For example, Itenfisu et al. (2003) conducted a comparison study of commonly used reference ET equations using meteorological measurements from 49 stations in 16 states. They found that the daily ET_{os} calculated using the ET_{sz} and FAO-56 PM equations closely matched with ET_{os} calculated with the full form of ASCE-PM equation. This is expected as FAO-56 PM equation is essentially identical to procedures provided for calculating ET_{sz}, except the constant surface resistance value. In ASCE standardized reference ET equation, the value of the constant surface resistance term used for calculating ET_{os} is 70 s m^{-1} for daytime and 200 s m^{-1} for night time whereas in FAO-56 PM equation, it is 70 s m^{-1} for all time steps. They also found that daily ET_{rs} values calculated using the ET_{sz} (0.058 mm d^{-1}) had much less deviation than that with the 1982 Kimberly Penman equation (0.267 mm d^{-1}). Numerous studies (Irmak et al., 2008; Lu et al., 2005; Itenfisu et al., 2003, Xu and Singh, 2002) have indicated that accuracy of reference ET estimates vary with weather parameters used in the calculation. Irmak et al. (2008) recommended the use of ET_{sz} equation when reliable meteorological data are available.

ET_{sz} and ET_c estimates that are based on the ASCE-EWRI standardized reference ET equation are available to growers for irrigation scheduling in a few parts of the world such as California (the California Irrigation Management Information System, CIMIS, http://wwwcimis.water.ca.gov/cimis/infoEtoOverview.jsp), Nebraska (the Nebraska Agricultural Management Network, Irmak et al., 2010), Oklahoma (the Oklahoma Environmental Monitoring Network, MESONET, Liu et al., 2011), and Texas (the Texas High Plains ET (TXHPET) Network; Porter et al., 2012). Due to worsening resource constraints, availability is limited and in some cases declining. For example, the TXHPET provided ET_{ref} and ET_c

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on a daily basis to producers and crop consultants at no cost for over 20 years; however, this service was recently limited due to reductions in funding support. As a consequence, some affected producers, agronomic consultants and researchers are substituting alternative weather data sources to estimate reference ET (with less accuracy). Because the ASCE standardized PM equation is complex to use, even for experienced practitioners not to mention producers and crop consultants, ET_c estimates needed for irrigation scheduling are less reliable than desired.

Numerous reference ET calculators with user-friendly interfaces are available and discussed in the literature (Allen, 2013; Raes, 2009; Snyder and Eching, 2008). The REF-ET for Windows is one of the widely used commercial reference ET calculator developed by Allen (2013) and distributed through the Idaho Agricultural Experiment Station. Although REF-ET can be used to estimate reference ET with numerous ET formulations including the ASCE standardized PM equation and varying QA/QC procedures associated with different data formats and time-steps, it can be intimidating for producers and agronomic consultants to use as it is not intuitive. Moreover, use of this software requires proficiency in the use of spreadsheets to calculate single hourly and daily ET_{os} and/or ET_{rs}, and users should have a sufficient understanding of different ET models and input requirements. The ET_o Calculator (v3.1) by Raes (2009) uses only the FAO-PM equation for estimating ET_{ref}. Moreover, "average" producers were not the primary target audience for this software. The Hourly Reference Evapotranspiration (ET_o) Calculator (HRPM) (Snyder and Eching, 2008) calculates only ET_{os} at hourly intervals using the ASCE standardized PM equation and daily ET_{os} can be obtained by summing up the calculated hourly values. In addition, it does not have the option to calculate either ET_{rs} at any time-step or ET_{os} directly from daily average weather datasets. In 2010, the ASCE ET Steering Committee identified a need for a user-friendly ET calculator targeting advanced agricultural producers and crop consultants. There is an immediate need for a simple reference ET calculator that can be used by crop consultants and producers to estimate accurate reference ET and representative crop water use with locally available weather data for irrigation scheduling purposes, thereby assisting in implementing the latest water conservation and best management practices. Our objective was to develop a simple and user-friendly reference ET calculator to assist producers and agronomic consultants as well as researchers with minimal or no training.

MATERIALS AND METHODS

The reference ET calculator designed and developed in this study is named the "Bushland Reference ET Calculator (BET)." The BET uses the ASCE standardized PM equation (Allen et al., 2005) for calculating both ET_{os} and ET_{rs} at hourly and daily time steps. Since clear-sky solar radiation is needed for implementing the standardized equation, BET uses a more complex equation provided in Appendix D of the ASCE standardized ET manual (Allen et al., 2005).

BET was developed using the Java Programming Language for calculating both ET_{os} and ET_{rs}. It was designed to

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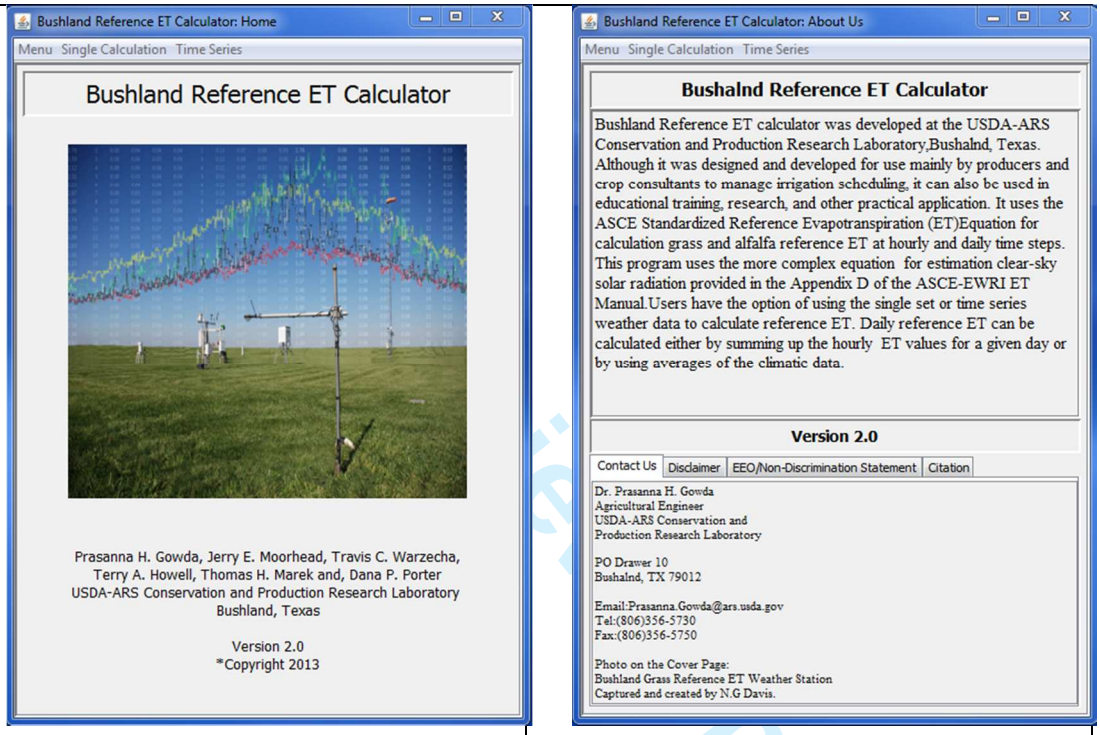
provide users with an option of using a single set of time series weather data to calculate ET_{os} and ET_{rs}. Daily ET_{os} and ET_{rs} can be calculated either by summing the hourly ET_{ref} values for a given day or by using daily averages of the climatic data. Therefore, it consists of two static and four user-friendly interactive pages. Two static informational pages provide BET version, citation, contact information for technical support, and USDA disclaimer. Figures 1(a-b) illustrate two static pages: Home page and About Us. The home page comes up on the computer screen when a user clicks on the BET software icon. It mainly gives the version of the software that the user is using for the ET_{ref} calculation. The About Us page provides a short description of the BET, developer's contact information, USDA-ARS' Disclaimer statement, and citation for the BET.



a. Home page with software version

b. About Us page

Figure 1. Static informational pages for the Bushland Reference ET Calculator (BET).

Interactive pages were designed for novice computer users to perform each of the following four tasks: (1) Hourly ET – Single Calculation, (2) Daily ET – Single Calculation, (3) Hourly and Daily ET - Time Series, and (4) Daily ET – Time Series. Efforts were made to design the interactive pages for intuitively entering the data input. Further, to ensure correct weather data are entered and submitted for calculating ET, validation controls were written into the code. When the program is executed with unreasonable, incomplete or missing data for performing a calculation, validation code resets the program and prompts the user's attention to the use by bringing up an error message box containing specific information on the erroneous input data. Also, codes were written to include and show boundary values for each of the input parameters when the mouse is moved over text boxes assigned for entering the data. An error message will be displayed

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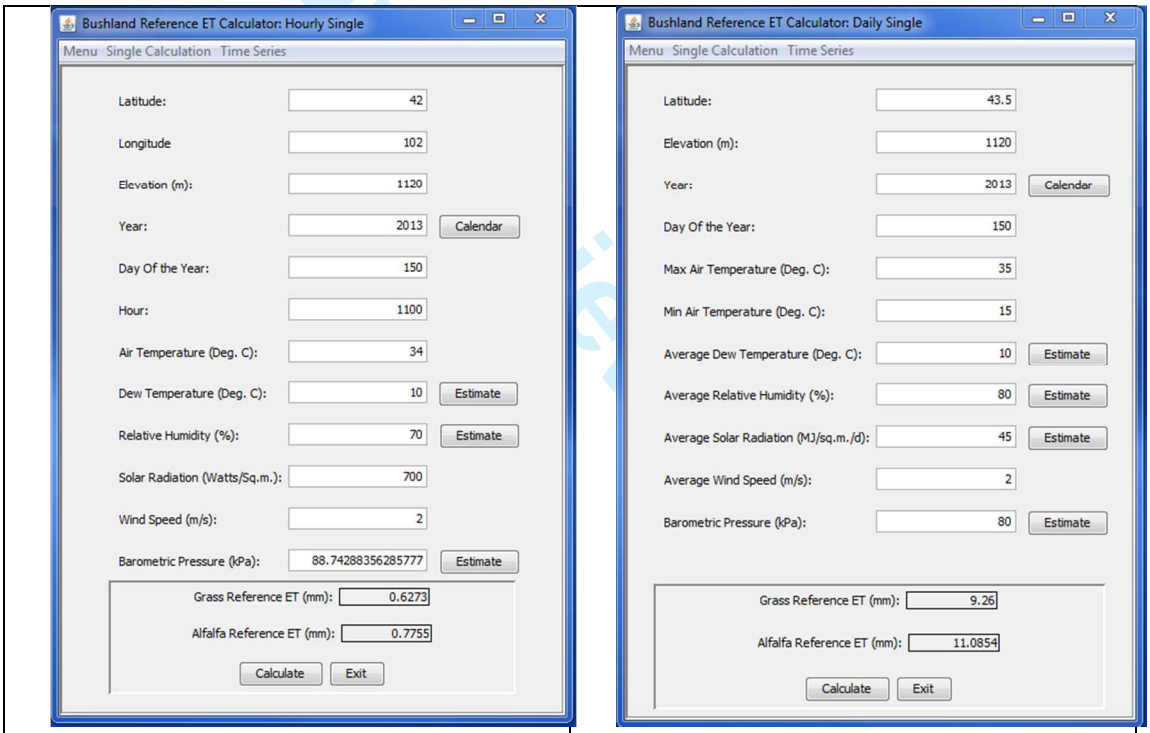
when a calculation is performed with an input value for a parameter that is outside the set boundary values.

Figure 2a illustrates an interactive page for calculating single hourly ET_{os} and ET_{rs} values. Parameters required for the single hourly calculation of ET_{os} and ET_{rs} include latitude and longitude (deg.-decimals), elevation (m), year and day of the year (DOY), hour for which ET_{ref} is to be calculated, air and dew point temperatures (deg. C), relative humidity (%), solar radiation (W m^{-2}), wind speed (m/s), and barometric pressure (kPa). Year and DOY values can be fed interactively using the Calendar button provided right next to the Year input box. If the dew point temperature value is not available, it can be calculated by clicking on the Calculate button right next to the Dew point temperature box provided the air temperature and relative humidity boxes are entered. In the case of missing relative humidity value, it can be calculated provided the air and dew point temperature boxes are entered. Barometric pressure can be calculated using the elevation data if it is not available. Equations used in the calculation of missing dew temperature, relative humidity or barometric pressure can be found in Allen et al. (2005).



a. Single hourly ET_{ref} calculation b. Single daily ET_{ref} calculation

Figure 2. Interactive pages in the Bushland Reference ET Calculator (BET) for calculating single hourly and daily ET_{ref} values.

Figure 2b illustrates an interactive page for calculating single daily ET_{os} and ET_{rs} values. Input parameters required for calculating ET_{ref} at the daily time-steps include latitude (deg.-decimals), elevation (m), year and day of the year (DOY), minimum and maximum air temperatures (deg. C), average dew point temperatures (deg. C), average relative humidity (%), average solar radiation (MJ m^{-2} d^{-1}), average wind speed (m/s), and barometric pressure (kpa). As in the case of hourly calculation, average values of dew point temperature, relative humidity, solar radiation, and barometric pressure

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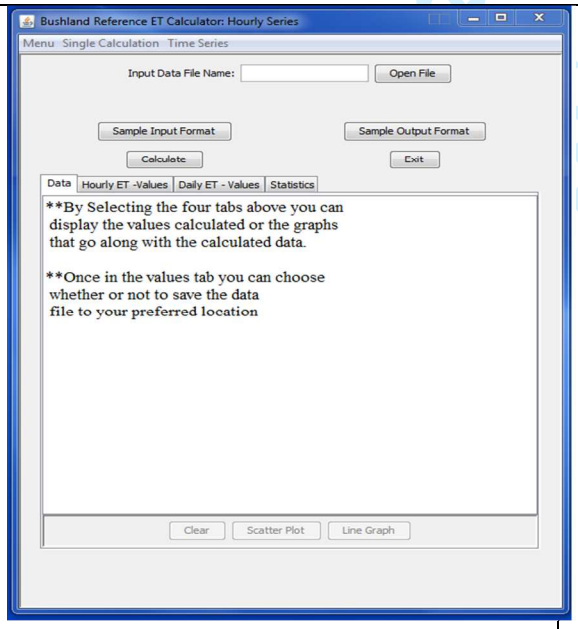
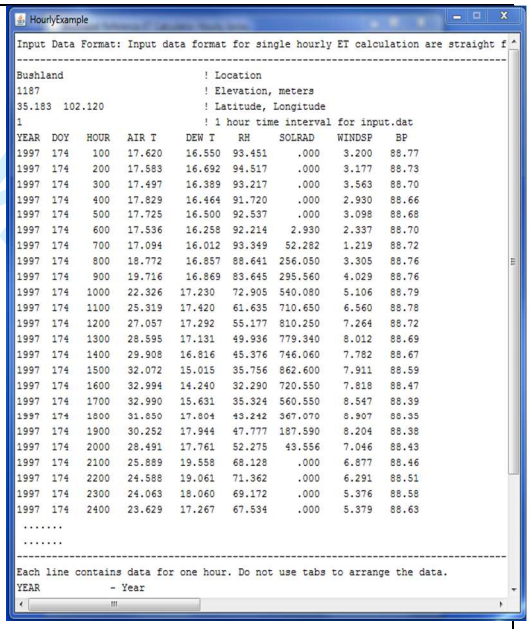
can be estimated if the measured data are not available. In case of relative humidity and dew point temperature, values cannot be calculated for both. Either relative humidity or dew point temperature must be known. A message box will appear requesting the missing data if the user tries to calculate one without entering a value for the other parameter. The user should note that the unit used for average solar radiation is different from that used in the calculation of hourly ET value.

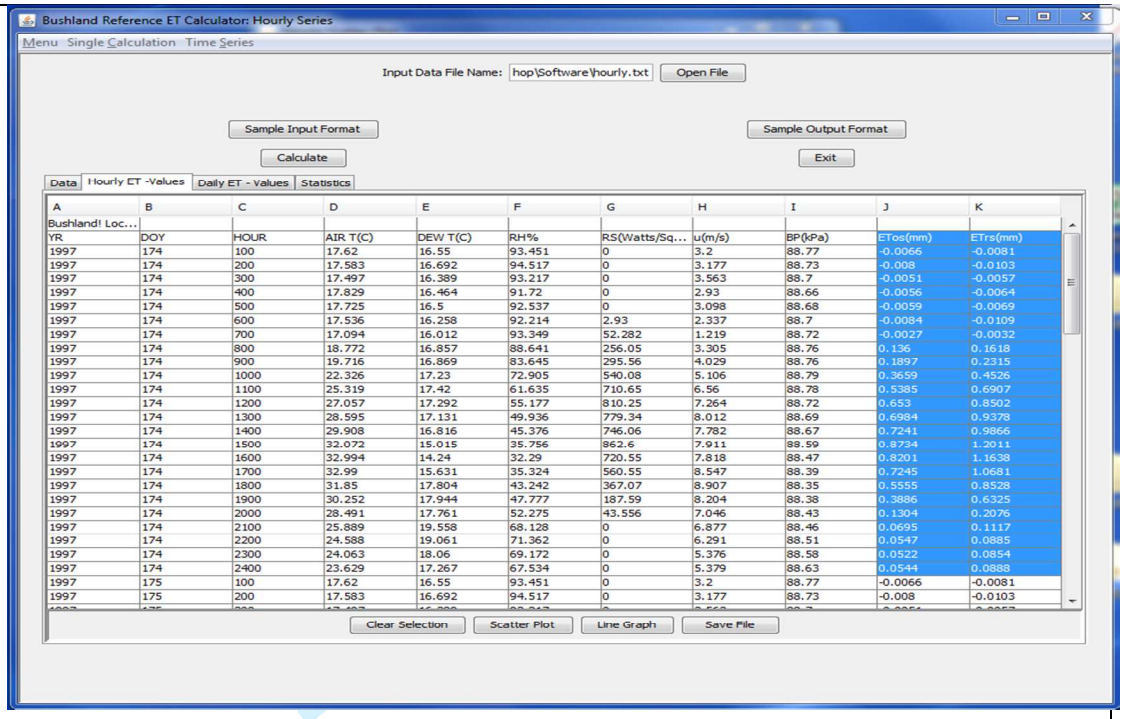
Figure 3a illustrates an interactive page for calculating hourly and daily ET using hourly time series weather data. In this interactive page, the user provides time series hourly weather data in a text file. Sample input and output files are provided for assisting the user with preparation of data files with weather data in a format required by the BET program to calculate time series hourly and daily ET. The user can view the input (Fig. 3b) and output sample files by clicking on the Sample Input Format and Sample Output Format buttons provided on the page (Fig. 3a). BET calculates daily ET values, when the input file contains hourly weather data for one or more days, by summing up hourly ET values for both grass and alfalfa reference crops. Input parameters required for calculating times series hourly and daily ET are the same as those required for calculating a single hourly ET value (Fig. 2a).



a. Hourly time series



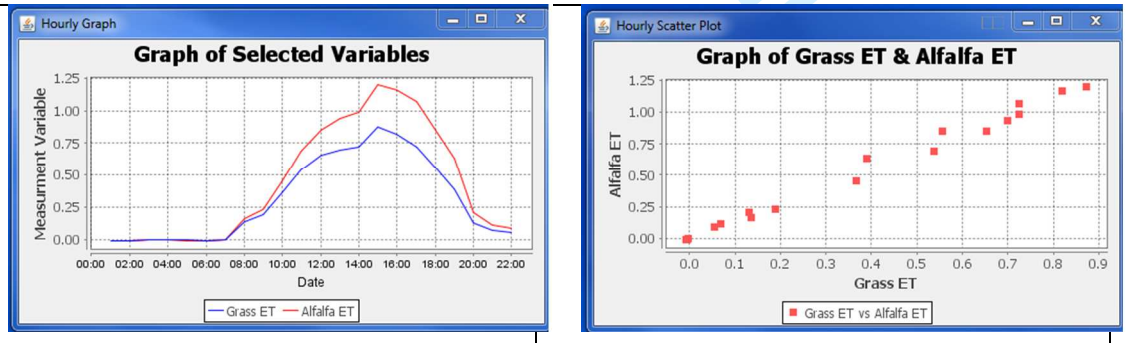
b. Sample input data format



c. Displaying hourly meteorological data and corresponding ET_{ref} for QA/QC.

Figure 3. Interactive pages for calculating hourly and daily ET_{ref} values from hourly meteorological data.

This hourly time-series page also has four tabs for displaying uploaded hourly input data as well as calculated hourly and daily ET_{os} and ET_{rs} in the built-in spreadsheet. The user can calculate eleven different statistics for each uploaded or calculated variable including mean, median, mode, and standard deviation. Figure 3c illustrates the hourly input and output in a spreadsheet format where the user can select data statistics. The user has the option of selecting one or more variables for calculating the statistics. The user can also display the variables in line graphs and scatter plots for QA/QC purposes. Figure 4(a-b) illustrates BET's graphing capabilities. The user can use these capabilities to identify outliers in the data. The interactive page for calculating daily ET_{os} and ET_{rs} is similar to that of the hourly time series page except there will be no tab for the hourly data. Data requirements for the daily ET_{ref} calculations are the same as those required for single calculations at a daily time-step.



a. Line graph b. Scatter plot

Figure 4. Plotting capabilities of the Bushland Reference ET Calculator.

APPLICATION OF BET

To demonstrate the capability of BET, ET_{os} and ET_{rs} were calculated and compared against published values. Further, a

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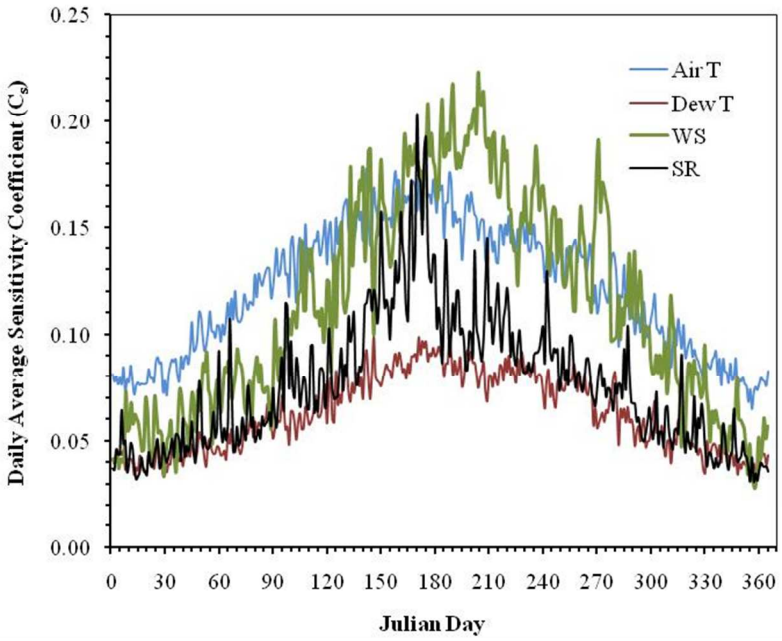
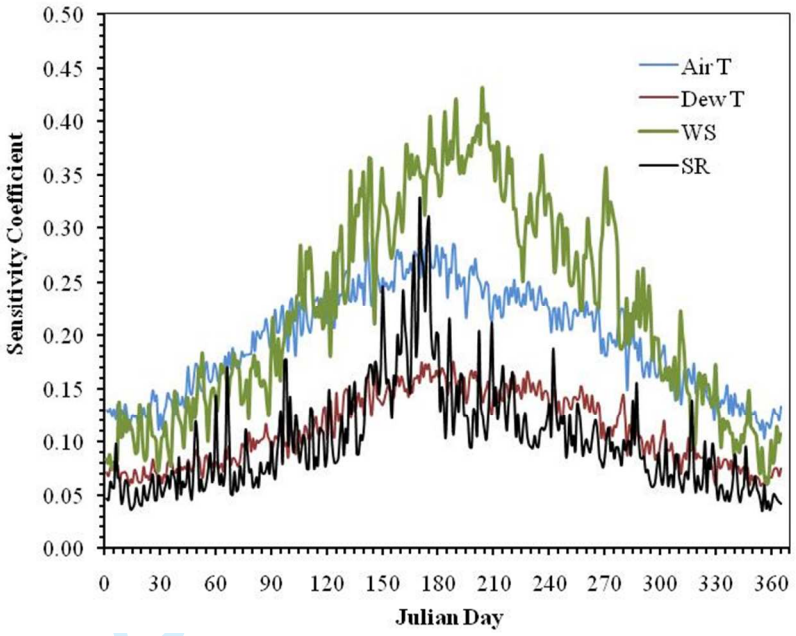
sensitivity evaluation of climate parameters on the calculation of ET_{os} and ET_{rs} was conducted using a long term climatic dataset. For this purpose, long term climatic data (1991-2008) from a weather station located at Bushland 10 miles west of Amarillo, Texas was used. This station is maintained by the TXHPET network and ASCE standardized PM equation based ET_{os} and ET_{rs} were available for this station for comparison purposes. Using the BET program, hourly ET_{os} and ET_{rs} were calculated and summed to get daily values.

To quantify the sensitivity of each climate parameter on ET_{ref}, a sensitivity coefficient (C_s) was calculated ($C_s = CH_{ETos}/CH_{CV}$; where CH_{ETos} was the change in ET_{os} with respect to climate variable, and CH_{CV} was the change in climate variable) (Irmak et al., 2006). The C_s for each climate variable was calculated by dividing the value of change in ET_{os} or ET_{rs} calculated using the BET by the amount of increase or decrease in the value of the climate input parameter. A 25 W m^{-2} increase or decrease is considered equivalent to one unit for solar radiation and one unit increase or decrease for all other variables. Finally, sensitivity coefficients for all climate parameters were compared to determine sensitivity of ET to each parameter over different cropping seasons. The higher the C_s value for a climate parameter, the more sensitive the ET calculation was to variation in that parameter.



a. Grass reference ET (ET_{os})



b. Alfalfa reference ET (ET_{rs})

Figure 5. Daily average ET_{ref} sensitivity coefficients for air temperature (Air T), dew point temperature (Dew T), wind speed (WS), and solar radiation (SR).

Calculated ET_{os} and ET_{rs} values were matched with values reported by the Texas High Plains ET Network between 1991-2008 to the fourth decimal indicating that BET program calculated both ET_{os} and ET_{rs} accurately. Figure 5(a-b) illustrates the sensitivities of ET_{os} and ET_{rs} to variations in air and dew point temperatures, wind speed, and solar radiation, respectively. Greater values of sensitivity coefficients indicate greater impact of errors in data on the calculated ET_{ref} values. Individual parameters affected ET_{os} and ET_{rs} calculations. These sensitivities were greater during the summer period corresponding to the growing season for most crops. Wind speed was found to be the most impacting parameter followed by air temperature. However, solar radiation errors also significantly affected the ET calculation, especially during the mid-summer growing period. Dew point temperature generally indicated a lower impact, yet it also showed seasonal variation with an increased sensitivity coefficient during the mid-summer growing season.

SUMMARY

Reliable and accurate estimates of crop water use or crop ET are required for improving water use efficiency in irrigated agriculture. Crop ET is calculated by multiplying the grass or alfalfa reference ET by the appropriate crop coefficient. This paper demonstrates use of the Bushland Reference ET Calculator (BET) developed and distributed, at no cost, to interested users through the USDA-ARS web site (http://www.cprl.ars.usda.gov/swmru-software-bretc.php). BET's capability was demonstrated using a long term climatic dataset from a TXHPET network station. Plotting

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capabilities were tested by plotting sample data. Although the BET was designed and developed mainly for use by progressive producers and crop consultants to manage irrigation scheduling, it can also be used in educational training, research, and other practical applications. At present, BET is made available to all PC-based operating systems. Subsequent efforts are underway to develop BET for smart phone platforms such as the iPhone and Android operating systems and further enhance capabilities of the Windows versions of the BET to include calculation of potential ET of crops using crop coefficients.

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Responses to AE and Reviewers' Comments

Associate Editor

Comments: The new user-friendly 'Calculator' for references ET at multiple time scale is very useful for many scientists, Engineers, and water users. However, I found the write up can be improved by describing more clearly the principles of reference ET. Many users are not as familiar with the history of why there are FAO ETo, Grass ETos, Alfalfa ETrs.

Response: Agreed with the AE. The introduction section is revised to give more information on different methods and principles. However, we did not any new equations that are already available (step by step) in the ASCE-EWRI manual.

Comments: Since the user can access a User's Manual, I suggest the authors discuss more of the science of reference ET, and it will be useful to provide a true application to show how the tool can be used to estimate ETref and actual ET for a cropland.

Response: There is abundant literature on the real science behind reference ET. We summarized with appropriate and selective citations for users who wants to read more. However, we made an effort to add a little more information to questions that may arise in readers' mind. The software do not calculate the actual ET. We are hoping to add that capability in the near future.

Comments: I am not very clear why the authors present the sensitivity of the two models; I was unclear how the sensitivity was conducted.

Response: The ASCE-EWRI reference ET model is used to calculate potential ET for two reference crops: grass and alfalfa. This is the reason, we presented sensitivity of two models. A case study with a real dataset is presented to demonstrate the capability of the software and importance of the accuracy of the data that is needed to estimate reference ET. A reference (Irmak et al., 2006) is provided for a more detailed step by step procedure on the sensitivity study. In addition, sensitivity methodology is also presented for ET experts.

Comments: I attached a file with editorial remarks.

Response: Summary comments (see above) made by the AE are basically derived from comments made on the manuscript. The manuscript is revised considering both summary and individual comments.

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Reviewer: 1

Comment 1: How the BET tool become more friendly than other refET tools. Are other tools not so friendly for users? Why? Add more discussions.

Response: Please see lines 114-131 for this information

Comments 2: Is the result calculated by BET different from other tool or the measurement refET? How to ensure the result correct? Discus more about the QA/QC.

Response: The Texas High Plains ET Network uses ASCE-EWRI method to estimate their reference ET values. Our values were matched to fourth decimal when we compared BET-calculated to values with historical data (1991-2008). We also compared with the testing dataset provided by the ASCE-EWRI manual (Allen et al., 2005). A line is added in the text to provide this information (Page 220-221).

Comment 3: Other modifications are remarked in the attach file.

Response: Revised the manuscript accordingly.

Reviewer: 2

Comments: Authors have done an excellent job. The tool will very helpful for irrigation scheduling and water management.

Response: Thanks.

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