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History and Evaluation of Hargreaves Evapotranspiration Equation

George H. Hargreaves, F.ASCE,[1] and Richard G. Allen[2]

Abstract: A brief history of development of the 1985 Hargreaves equation and its comparison to evapotranspiration (ET) predicted by the Food and Agricultural Organization of the United Nations (FAO) Penman-Monteith method are described to provide background and information helpful in selecting an appropriate reference ET equation under various data situations. Early efforts in irrigation water requirement computations in California and other arid and semiarid regions required the development of simplified ET equations for use with limited weather data. Several initial efforts were directed towards improving the usefulness of pan evaporation for estimating irrigation water requirements. Similarity with climates of other countries allowed developments in California to be extended overseas. Criticism of empirical methods by H. L. Penman and others encouraged the search for a robust and practical method that was based on readily available climatic data for computing potential evapotranspiration or reference crop evapotranspiration (ET_o). One of these efforts ultimately culminated in the 1985 Hargreaves ET_o method. The 1985 Hargreaves ET_o method requires only measured temperature data, is simple, and appears to be less impacted than Penman-type methods when data are collected from arid or semiarid, nonirrigated sites. For irrigated sites, the Hargreaves 1985 ET_o method produces values for periods of five or more days that compare favorably with those of the FAO Penman-Monteith and California Irrigation Management Information Services (CIMIS) Penman methods. The Hargreaves ET_o predicted 0.97 of lysimeter measured ET_o at Kimberly, Idaho after adjustment of lysimeter data for differences in surface conductance from the FAO Penman-Monteith definition. Monthly ET_o by the 1985 Hargreaves equation compares closely with ET_o calculated using a simplified, ‘‘reduced-set’’ Penman-Monteith that requires air temperature data only.

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Introduction

A study sponsored by the United Nations and the World Bank indicates that irrigated agriculture will need to provide 70% of the world's increased food requirements in 2025 (Anonymous 2000). Postel (1999) indicates that food production levels needed in 2025 could require up to 2,000 cubic kilometers (1,600 million acre-ft) of additional water for irrigation.

Water management and crop yields can be improved by means of increased use of reliable methods for estimating crop evapotranspiration (ET). More than a score of methods have been proposed and used over the past 50 years. Various international agencies are attempting to develop a consensus with respect to the best and most appropriate methods to use for routine calculation of ET_o (Smith et al. 1991; Allen et al. 1994b, IWMI, 1997, 2000; New et al., unpublished, 2001). This paper presents some background and abbreviated history of development of the Hargreaves equation for predicting ET_o for use in planning and managing irrigation developments and contrasts this method to other commonly used approaches.

California—Initial Efforts

Most of California's agricultural regions are classified as having very arid, arid, or semiarid climates. Consequently, the availability and use of water for irrigation determines the agricultural potential. In spite of the arid climate, California's agricultural production ranks first in the United States. Experience gained in California on water management and irrigation requirements have had a large influence on the development and use of irrigation in other regions of the world.

By about 1938, F. J. Veihmeyer of the University of California had compiled considerable data and information on crop evapotranspiration (ET_c). The predominant method for measuring ET_c was gravimetric soil water content sampling using a driven soil tube to take samples of the known volume. In the southern San Joaquin Valley, a highly successful scheduling service used this information, combined with measurements of soil moisture depletion, to schedule irrigation. Measured values of ET_c were related to Class A Pan evaporation (E_p) for corresponding stages of crop growth. This kind of information proved so useful to farmers that the Division of Water Resources of the State of California published E_p data from seven agroclimatic field stations in the Central Valley (State of California 1945). At about this same time, the U.S. Weather Bureau began to regularly publish E_p values collected from agricultural regions.

In 1947, the Branch of Operation and Maintenance of the Sacramento Office of the U.S. Bureau of Reclamation sponsored a

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program of field research intended to measure values of ET_c for additional crops. The Blaney-Criddle method (Blaney and Criddle 1945) was then the most widely used procedure by the Bureau for estimating seasonal consumptive water use. However, the Blaney-Criddle method provided unreliable predictions of consumptive use during peak demand periods.

That same year, the Bureau contacted Veihmeyer for suggestions and data on crop water requirements. Veihmeyer recommended the use of the published E_p values and the measured ET_c. Hargreaves (1948) was asked by the Bureau of Reclamation to prepare a manual on using E_p and ET_c in the planning and design phases of the Central Valley Project. Monthly values of ET_c for 29 crops at Davis were published and monthly consumptive use factors were given for 14 locations. These factors were derived from measured or estimated ratios of monthly E_p at the location to the E_p at Davis. For locations where measured values of E_p from a well-watered site were not available, a simple method was used, based on differences in temperatures and in relative humidity readings at noon between the location and Davis. This approach was successful in predicting ET_c for a number of locations within the Central Valley and for peak demand periods.

During the period 1948–1950, experience gained in California was used to calculate the irrigation requirements for the rehabilitation of facilities in Greece following World War II and for the design of new projects. The method for estimating E_p and the crop coefficients derived in California provided useful estimates due to the similarity in climate.

Haiti

In 1951, the Institute of Inter-American Affairs (a predecessor of USAID) assisted in the rehabilitation of irrigation projects and on the development of new projects in Haiti, including the large Artibonite multipurpose project. Studies from Puerto Rico, Jamaica, and the Dominican Republic provided gravimetrically derived information on crop water use for sugar cane and bananas. These locations had climates similar to those in Haiti.

Climatic data, including air temperature and relative humidity, were available for various locations in Haiti. These data were used to estimate values of E_p and crop coefficients from California were applied for some crops. An attempt was made to use the Blaney-Criddle f factor to transfer crop-use information from California, however, results did not appear to be reasonable, considering the aridity of the Haitian climate. During the 1960s, Food and Agricultural Organization of the United Nations (FAO) supervised the collection of grass ET data and E_p from a lysimeter site located within a large irrigated area near Damien. A regression was made between lysimeter data and the f factor. Although grass ET and E_p data correlated well with the f factor, the slope and intercept were substantially different from those found for Davis, Calif. It was concluded that the Blaney-Criddle method could not be directly transferred from California to the Caribbean. Jensen (1966) later showed that the crop factors for the Blaney-Criddle equations contained a substantial climatic component that would impede spatial transfer.

The computations of the water requirements for Haiti were forwarded to H. L. Penman in England for his review and comment. Penman's review contained very strong criticism of empirical methods and a lecture on the value of physically sound computations. Penman probably was not fully aware of the paucity of adequate and reliable data in the developing countries. However, his encouragement and advice were well taken, and they stimulated further development of more transferable methods.

Developments in 1960s and 1970s

During the 1960s and 1970s, many attempts to estimate crop evapotranspiration were based upon measured or estimated E_p, modifications to the Blaney-Criddle (1945) method, or on versions of or simplifications to a method developed by J. E. Christiansen. A version of the Christiansen (1968) equation can be written

$$\mathrm{ET}_o = 0.385 R_s \;\; \mathrm{CT} \;\; \mathrm{CH} \;\; \mathrm{CW} \tag{1}$$

where R_s = global solar radiation at the surface; ET_o and R_s are in the same units of water evaporation; and CT, CH, and CW are coefficients for temperature, relative humidity, and wind run, respectively. The coefficients vary with climate, and were adjusted to be as near to 1.0 as practical for average conditions. This minimized the error when data were missing.

In 1975, eight years of daily cool season grass (Alta fescue) evapotranspiration (ET_g) and weather data from precision weighing lysimeters operated at Davis, Calif. (Latitude 38°, Elevation 18 m) by W. O. Pruitt (unpublished, 1975) were obtained by Hargreaves (1975) and were recorded onto computer cards. The ET_g data represented ET_o for a clipped grass surface between 8 and 15 cm height and were collected during all months of the year ($n = 2{,}901$ days). Regressions were made using measured ET_g as a function of a large number of combinations of weather data and versus various ET estimating methods. For a five-day time step, temperature in degrees Fahrenheit (TF) times R_s predicted 94% of the variance in measured ET. The equation subsequently published by Hargreaves (1975) is

$$\mathrm{ET}_o = 0.0075 \;\; R_s \;\; \mathrm{TF} \tag{2}$$

where ET_o and R_s = the same units of water evaporation. For temperature in degrees Celsius (TC) the equation is written

$$\mathrm{ET}_o = 0.0135 \;\; R_s \;\; (\mathrm{TC} + 17.8) \tag{3}$$

It is worthy to note that Eq. (2) was originally presented to predict what was then referred to as potential ET (ET_p). The ET_p term is no longer recommended due to the difficulty in definition. The Davis ET data set represented grass reference ET_o. The ET_o term was introduced later by Doorenbos and Pruitt (1977).

Attempts were made to add a correction for wind velocity (U_2) and for relative humidity (RH). Five-day time step ratios of $\mathrm{ET}_o/\mathrm{ET}_g$ were regressed as a function of U_2. Wind explained only 10% of the variance in the ratios and RH explained only nine percent of the variance. Therefore, these terms were left out of the ET_o equation to foster simplicity and to reduce the data requirement.

Analysis of the climate data from Davis, Calif. and a review of the literature resulted in the conclusion by Hargreaves (1977) that R_s could be computed from extraterrestrial radiation (R_a) and the percentage of possible sunshine (S) similar to the approach of Angstom (1924). S is the measured sunshine hours times 100 divided by the number of possible sunshine hours. The equation with R_s and R_a in the same units (Hargreaves 1977) is

$$R_S = 0.075 R_a \;\; S^{0.50} \tag{4}$$

The use of Eq. (4) was seriously limited by the paucity of data for S. Therefore, for Central America, an average relationship between S and relative humidity (RH) was derived (Hargreaves 1977)

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$$S = 12.5 \ (100 - \mathrm{RH})^{0.50} \qquad (5)$$

in which RH = mean monthly relative humidity. Eq. (5) was less consistent than desired. Efforts continued to find a better method for estimating S.

Eq. (3) was developed for use principally with monthly climate data and for evaluating the adequacy of rainfall for rain-fed agricultural production. Hargreaves and Samani (1986) used R_s data from Lof et al. (1966) and climate data furnished by the National Weather Service to compare various precipitation probabilities with ET_o computed using Eq. (3). Rainfall probabilities ET_o and a monthly moisture adequacy index (MAI) were additionally computed for 2,147 worldwide locations contained in the Utah State University World Water for Agriculture data base (Hargreaves and Samani 1986).

Wu (1997) compared Eq. (3) with Penman (1963), Jensen-Haise (1963) and Priestley-Taylor (1972) ET_o equations for daily calculations of ET_o using data collected over a three year period at the CTAHR Waimenalo Research station in Hawaii. Excellent correlations were found for all four ET_o models when a seven-day or longer moving average of daily readings was used. Wu concluded that Eq. (3) could be used to estimate ET_o as accurately as the more complicated Penman model in Hawaii when seven-day temperature averages are used and was therefore sufficiently accurate for use in irrigation water management and scheduling.

1985 Hargreaves ET_o Equation

A comparison by the senior writer in the early 1980s of sunshine data with air temperature data from U.S. weather stations and from locations in various countries indicated that values of S averaged about five times those of the daily temperature range (TR) in degrees Celsius ($\mathrm{TR} = T_{\max} - T_{\min}$; where $T_{\max}$ is the mean daily maximum temperature and $T_{\min}$ is the mean daily minimum temperature). Hargreaves (1981) and Hargreaves and Samani (1982) proposed the predictive form

$$R_s = K_{\mathrm{RS}} \ R_a \ \mathrm{TR}^{0.50} \qquad (6)$$

where K_{RS} = empirical coefficient fitted to R_s/R_a versus TR data. In general, values for K_{RS} increased slightly with increasing temperature. Hargreaves (1983) found a value of 0.16 using climatic data from the Senegal River Basin. Eq. (6) was adopted in FAO-56 (Allen et al. 1998) for predicting R_s when data are missing or of questionable integrity and was the basis for a self-calibrating method for predicting R_s (Allen 1997). Eq. (6) has served as the initial basis for prediction methods by Bristow and Campbell (1984), Kimball et al. (1997) and Thornton et al. (2000).

Combining Eqs. (3) and (6) and using $K_{\mathrm{RS}} = 0.16$, Hargreaves (1983) and Hargreaves et al. (1985) obtained the equation

$$\mathrm{ET}_o = 0.0022 \ R_a \ (\mathrm{TC} + 17.8) \ \mathrm{TR}^{0.50} \qquad (7)$$

However, for months of peak demand, Hargreaves and Samani (1985) recommended that the coefficient be increased to 0.0023. This adjustment resulted in the so-called 1985 Hargreaves equation

$$\mathrm{ET}_o = 0.0023 \ R_a \ (\mathrm{TC} + 17.8) \ \mathrm{TR}^{0.50} \qquad (8)$$

The 1985 Hargreaves method is often used to provide ET_o predictions for weekly or longer periods for use in regional planning, reservoir operation studies, canal design capacities, regional requirements for irrigation and/or drainage, potentials for rain-fed agricultural production, and, under some situations, for irrigation scheduling. The attractiveness of the method is its simplicity, reliability, minimum data requirements, ease of computation, and low impact by weather station aridity. Eq. (8) has been widely used in the U.S. and globally to predict ET_o in data short situations, for example, when only air temperature data are available. Many irrigation and water resources studies have used Eq. (8) to produce historical time series of ET_o using historical air temperature data. Eq. (8) was used by IWMI (1997) to calculate ET_o for ten-day and monthly time steps for incorporation into the 1997 version of the IWMI World Climate Atlas. The World Water and Climate Atlas is available on the Internet at *www.iwmi.org* or at *www.cgiar.org*. Some of the uses of the Atlas are described by Hargreaves and Merkley (1998).

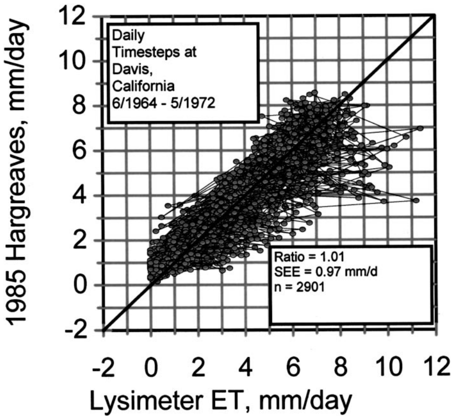

Fig. 1. Daily ET_o calculated over eight-year period at Davis, Calif. using 1985 Hargreaves method versus ET from Alta fescue measured by lysimeter (data from W. O. Pruitt)

Evaluation of 1985 Hargreaves Equation

Various studies have compared Eq. (8) against measured ET_o or against ET_o predicted by some other ET_o method. Jensen et al. (1990) evaluated 20 reference ET methods and compared against lysimeter measurements at 11 locations. The 1985 Hargreaves method ranked highest of all methods that required only air temperature data. Standard error of estimate (SEE) was 0.9 $\mathrm{mm\,d^{-1}}$ for Eq. (8) compared against monthly lysimeter data. This compared to 0.6 $\mathrm{mm\,d^{-1}}$ for the Penman (1963) method and 0.4 $\mathrm{mm\,d^{-1}}$ for the ASCE Penman-Monteith method as defined in Jensen et al. (1990). Seasonal ET_o predicted by Eq. (8) averaged 91% of measured ET for locations in arid climates and 125% of measured ET for locations classified as humid.

Jensen et al. (1997) used monthly data from the six grassed lysimeters from the Jensen et al. (1990) report to compare ET_o from the 1985 Hargreaves equation and ET_o from the FAO Penman-Monteith (FAO-PM) method as defined in Allen et al. (1998). The SEE for Eq. (8) for the reduced data set was 0.34 $\mathrm{mm\,day^{-1}}$ with $r^2 = 0.94$ for monthly estimates. The SEE for the FAO-PM was 0.32 $\mathrm{mm\,day^{-1}}$ with $r^2 = 0.96$.

Fig. 1 shows a plot of daily ET_o by Eq. (8) versus daily grass lysimeter data measured during the period June, 1964–May, 1972 at Davis, Calif. ($n = 2{,}901$ with 21 days missing data). The grass at Davis during this period was clipped Alta fescue and measurements were made by W.O. Pruitt of the University of California at Davis. Grass height was maintained between 8 and 15 cm. The mean daily lysimeter ET during the period was 3.62

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mm and the mean daily estimate by Eq. (8) was 3.66 mm [ratio of Eq. (8) to lysimeter$=1.01$]. The SEE for Eq. (8) was 0.97 mm day^{-1}. These statistics compare to a mean and SEE for the FAO-PM method of 3.60 and 0.70 mm d^{-1}, respectively. ET$_o$ by Eq. (8) followed a 1:1 relationship to lysimeter measurements during all portions of the calendar. Underprediction of ET$_o$ for about 100 days (3% of total days) was caused by high winds.

The FAO-PM has been used as a comparison basis for other ET$_o$ methods. A study by Allen (1995) for FAO compared estimates of monthly ET$_o$ from Eq. (8) with the FAO-PM equation for more than 3,000 weather stations worldwide ($n=39{,}024$) and found good agreement between the two methods over a wide range of climates (monthly $T_{\max}$ ranged from -22 to 46°C, averaging 26°C, $T_{\min}$ ranged from -38 to 35°C, averaging 15°C, vapor pressure ranged from 0.04 to 3.8 kPa, averaging 1.7 kPa, wind at 2 m height ranged from 0.1 to 11.4 m s^{-1}, averaging 1.8 m s^{-1}, and R_s ranged from 1.4 to 31 MJ m^{-2} d^{-1}, averaging 17 MJ m^{-2} day^{-1}). The root-mean-square difference (RMSD) between the two methods averaged 0.65 mm day^{-1} (15%) for monthly estimates under well-watered conditions (defined as when monthly $P/\mathrm{ET}_o>0.5$ for the previous two months, where P is monthly precipitation in the same units as ET$_o$). The ratio of Hargreaves ET$_o$ to FAO-PM averaged 1.02 over the 39,024 data observations. The RMSD parameter is similar in calculation to SEE ($\mathrm{RMSD}=[\Sigma(X-Y)^2/n]^{0.5}$) and is used when comparing two estimates rather than comparing an estimate with a measurement as with the SEE.

Figs. 2–4 illustrate the relatively close relationship between ET$_o$ from Eq. (8) and from the FAO-PM method, using weather data collected in Kimberly, Idaho. The RMSD between the two methods was 0.70 mm day^{-1} for all days in a 25 year record from 1966–1990 ($n=9{,}075$, with 55 missing days) with the ratio of Eq. (8) to the FAO-PM over all months and years equal to 0.92. For the April–October growing season, the RMSD was 0.62 mm day^{-1} and the ratio was 0.95. ET$_o$ for Eq. (8) and the FAO-PM averaged 2.9 and 3.2 mm day^{-1} over the 25 year period (January to December) and ET$_o$ during the peak month of July averaged 6.1 mm day^{-1} for both methods. The agreement among daily estimates is considered to be quite good, considering that Eq. (8) used only air temperature data and considering the sometimes large fluctuations in wind speed from day to day in the Kimberly data set. Agreement between the two methods is even closer when five-day average ET$_o$ is compared (Fig. 3), where RMSD$=0.47$ mm day^{-1}. Trends in predicted ET$_o$ during the calendar year are quite similar between the two methods in the Kimberly climate. These RMSD values compare to an SEE for the FAO-PM method versus grass ET measured by lysimeter at Kimberly (Wright et al. 2000) of 0.80 mm day^{-1}, and a ratio of ET$_o$ by the FAO-PM to ET from the lysimeter$=0.89$ prior to adjustment for the differences in surface resistance between lysimeter and FAO-PM. This adjustment is described in a following section on the reduced form of the FAO-PM equation.

Itenfisu et al. (2000) compared common ET$_o$ methods at 48 locations in 16 states spanning Washington to New York and California to Florida. The 1985 Hargreaves Eq. (8), using daily weather data, predicted within 10% of the FAO-PM method for 60% of the stations evaluated and predicted 10% or higher than the FAO-PM equation for 33% of the stations and 10% or lower than the FAO-PM equation for 7% of the locations. Data represented annual periods. On average, Eq. (8) predicted 6% higher than the FAO-PM method and the RMSD between the two methods for daily data averaged 0.9 mm day^{-1} which is equivalent to 23% of mean average ET$_o$ over all locations. Longer calculation time steps were not evaluated.

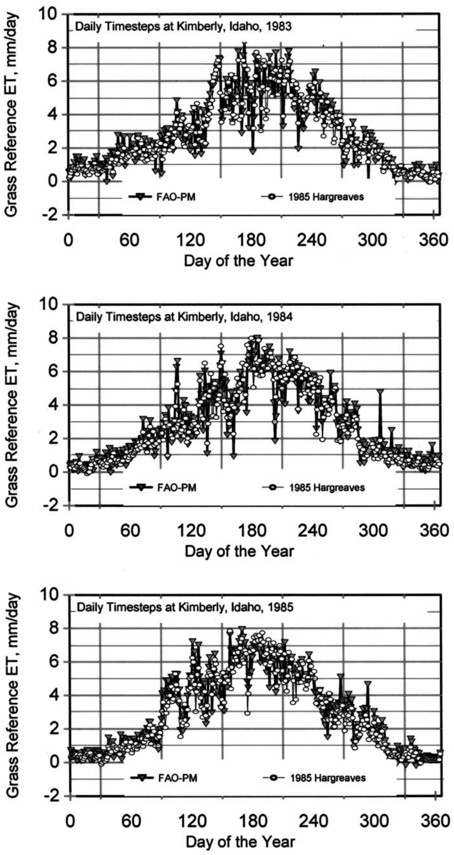

Fig. 2. Comparison of daily ET$_o$ calculated for three years at Kimberly, Idaho using 1985 Hargreaves method and FAO-Penman-Monteith method

Attempts to Improve 1985 Hargreaves Equation

The 1985 Hargreaves equation has a minimum weather data requirement, using only maximum and minimum air temperature. The equation self compensates for the lack of R_s and humidity data required by the Penman and Penman-Monteith methods. The parameter TR (temperature range) in Eq. (8) implicitly accounts for effects of cloudiness in that TR generally decreases with increasing cloudiness. In addition, TR correlates with relative humidity and vapor pressure deficit and is inversely influenced by wind run. Although influenced by frontal weather systems, average values for five or more days compare favorably with Penman-Monteith derived ET$_o$ for well-watered sites.

There is an interaction between wind and humidity on ET. However, due to the variability found in ratios of ET$_o$/ET$_g$ using Eq. (8) for different grasses and climatic conditions, attempts to correct Eq. (8) for differences in wind and/or aridity were not fruitful. In these studies, the influence of U_2 on ratios of predicted ET$_o$/ET$_g$ was found to be insignificant for monthly lysimeter data from Damien in Haiti and for five-day averages from Davis, Calif.

Allen (1993) developed a wind function for Eq. (8) by comparing against the FAO-PM equation using mean annual monthly data from 3,000 CLIMWAT sites (Smith 1993) and using daily data from Davis, Calif. Allen found slight improvement to

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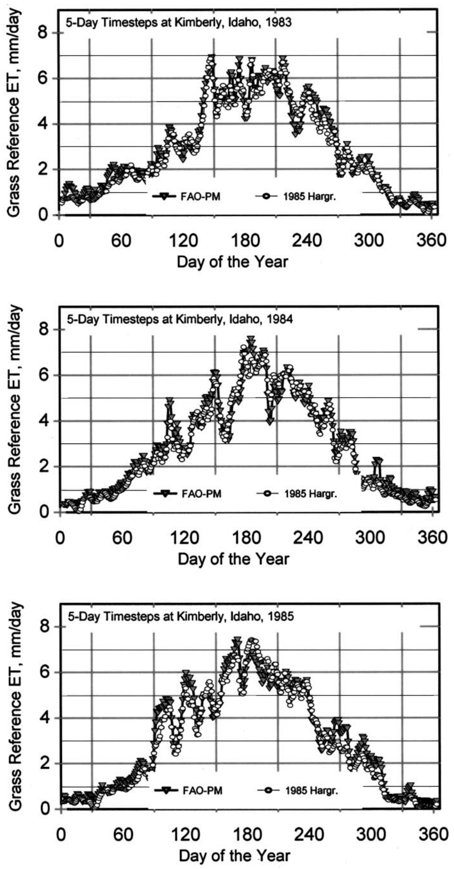

Fig. 3. Comparison of five-day ET_o calculated for three years at Kimberly, Idaho using 1985 Hargreaves method and FAO-Penman-Monteith method

Eq. (8) when wind speed was included as a parameter, but concluded that the impact was insufficient to warrant the inclusion of wind speed as a standard practice. Salazar (personal communication, 1990) also developed a wind function for the 1985 Hargreaves equation for use in scheduling irrigations in the San Luis valley of Colorado.

Allen (1993) attempted to improve on the coefficients and general form of Eq. (8) using measured monthly ET data reported in ASCE Manual 70 and the daily lysimeter data from Davis, Calif. Derived coefficients and functions were compared with estimates by the FAO-PM at 3,000 CLIMWAT sites. Allen found the general form of Eq. (8) to be universally applicable, with a wide range of coefficients in the equation providing similar predictive accuracy. The exponent on TR in Eq. (8) could range from 0.2 to 0.9 in calibrations with little loss or gain in accuracy when commensurate changes were made to the primary equation coefficient. Similarly, the mean air temperature offset (17.8°C) could be varied widely with no loss or gain in prediction accuracy when commensurate changes were made to other coefficients. The ‘‘best’’ equation developed by Allen (1993) having the same form as Eq. (8) was

$$\mathrm{ET}_o = 0.0029\ R_a\ (\mathrm{TC}+20)\ \mathrm{TR}^{0.4} \tag{9}$$

with $r^2=0.96$ and $\mathrm{SEE}=0.93\ \mathrm{mm\,day}^{-1}$ for the daily Davis data set (1964–1972). These statistics compared to $r^2=0.95$ and $\mathrm{SEE}=0.98\ \mathrm{mm\,day}^{-1}$ for Eq. (8). Results were similar for the monthly CLIMWAT data set where the calibration basis was the FAO-PM. Allen concluded that the gain in prediction improvement of Eq. (9) over Eq. (8) was not significant and that the original coefficients of Hargreaves et al. (1985) [i.e., Eq. (8)] could be utilized in practice. Allen (1993) reported other forms similar to Eq. (8), but which included exponents on all terms. However, none had substantial improvement over Eq. (8).

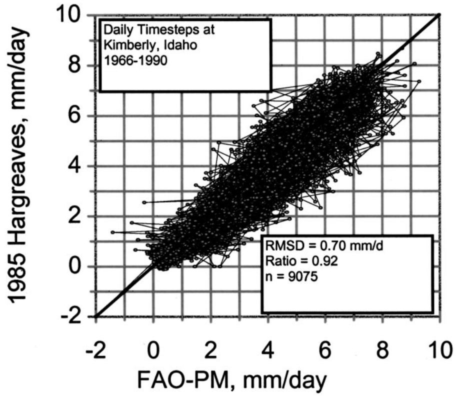

Fig. 4. Daily ET_o calculated over 25-year period at Kimberly, Idaho using 1985 Hargreaves method versus ET_o by FAO-Penman-Monteith method

Droogers and Allen (2002) explored recalibration of coefficients and exponents in Eq. (8) using mean monthly ET_o from nearly all land areas on the globe. Data were assembled on an approximately 16 km grid derived from the IWMI climate data base (IWMI 2000) and the FAO-PM equation was used as the calibration basis. Approximately 56,000 weather stations were used to develop the IWMI data base (New et al., unpublished, 2001). Surprisingly, no substantial improvement over coefficients used in Eq. (8) was found. Only the inclusion of mean monthly precipitation in the equation was found to improve predictions, where the RMSD was reduced by about 15% relative to the FAO-PM. However, Droogers and Allen concluded that monthly precipitation served as a surrogate for station dryness and may have only adjusted Eq. (8) to force the equation to predict aridity biases that can plague the combination equation (see sections following).

Comparison With the Penman-Monteith Equation Including Simplified Forms

Penman (1948) published the radiation-aerodynamic combination equation to predict evaporation from open water, bare soil, and grass (turf). Various modifications of the Penman equation have been widely used to estimate ET_o and for scheduling irrigations. The modifications include the FAO-24 Penman (Doorenbos and Pruitt 1977), the Penman-Monteith (Monteith 1965; Jensen et al. 1990, Allen et al. 1998), the California Irrigation Management Information Service (CIMIS) equation (Pruitt and Doorenbos 1977) and others.

One advantage of Eq. (8) relative to the combination equation, which is often overlooked, is the reduced data requirement. In Eq. (8), only maximum and minimum air temperatures are required. This is advantageous in regions where solar radiation, humidity, and wind data are lacking or are of low or questionable quality. Generally, air temperature can be measured with less error and by less trained individuals than can the other three parameters required by combination equations. Eq. (8) can be calibrated against combination equations where data are available to produce a ‘‘regionally’’ calibrated temperature equation (Allen et al. 1996).

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Droogers and Allen (2002) investigated the impact of data error on Eq. (8) and the FAO-PM using all land masses in the IWMI climate database. They found Eq. (8) to have smaller RMSD, using the full FAO-PM as a basis, than the FAO-PM method with introduced error in measured solar radiation, humidity, and wind speed of approximately 25%. These errors represented the maximum expected error (95% confidence) for weather data sets typical of developing regions of the globe.

Reduced Set Penman-Monteith Equation

The FAO Penman-Monteith equation (Smith et al. 1991, Allen et al. 1998) has an assumed crop height, surface resistance, and albedo closely resembling the conditions of clipped Alta fescue grass in the weighing lysimeters at Davis, Calif. The FAO-PM method requires solar radiation, wind speed, humidity, and air temperature measurements. In data short situations, the FAO-56 publication suggests that the FAO-PM method can be applied with a minimum of maximum and minimum air temperature data. In these instances, solar radiation is predicted using various procedures, including Eq. (7). For a site that is well watered, there are generally only small differences between dew-point temperature and minimum temperature (Allen et al. 1998). Therefore, dew-point temperature is predicted based on minimum daily air temperature. Wind speed is obtained from monthly or annual means for the region.

Campbell Scientific, Inc. of Logan, Utah, a worldwide distributor of automated weather stations, has described an application of the FAO-PM method that requires only measured values of maximum and minimum temperature and solar radiation, following recommendations by Allen et al. (1996) and by FAO-56. The development of the ''reduced set'' PM method was intended to reduce the cost of required weather measurement equipment. Christiansen and Worlton (1998) have demonstrated this particular reduced set PM method, when used with data from well-watered sites, to produce ET_o values that are not significantly different from those from the FAO-PM for multiday periods.

Allen (1995) evaluated the FAO-56 reduced-set FAO-PM and Eq. (8) using mean annual monthly data from the 3,000 stations in the FAO CLIMWAT data base, with the full FAO-PM serving as the comparative basis. The FAO-56 reduced set FAO-PM was based on measured $T_{\max}$ and $T_{\min}$ only, with solar radiation and dew-point temperature predicted following FAO-56 and wind speed at 2 m height predicted as $2\ \mathrm{m\,s^{-1}}$. Allen (1995) found little difference in mean monthly ET_o using the reduced set FAO-PM method as compared to using Eq. (8). Since the comparator basis was the FAO-PM equation with all weather parameters measured, results were statistically heavily biased toward the reduced set FAO-PM computations.

Allen et al. (1996) compared Eq. (8), with the FAO-56 reduced-set FAO-PM, and the full ASCE-PM method for daily and five-day average data at Eaton, Colorado and using monthly data from Davis, Calif. Eq. (8) functioned as well as or better than the reduced-set PM in reproducing the ASCE-PM ET_o estimates. Annandale et al. (2001) evaluated the FAO-56 reduced-set FAO-PM for three locations in South Africa and recommended its use in data short situations and where maintenance of sensors and associated data integrity are at risk.

Comparison With Lysimeter Measurements at Kimberly

The surface resistance parameter r_s in the FAO-PM was fixed at $70\ \mathrm{s\,m^{-1}}$ by FAO-56 to represent the mean surface characteristic of the clipped alta fescue grass that was grown by Pruitt on the Davis, Calif. lysimeters. Wright et al. (2000) compared the FAO-PM and other combination methods to a clipped grass crop grown by Wright (1996) on a weighing lysimeter system near Kimberly, Idaho. The Kimberly grass was a 'Fawn' tall fescue clipped to maintain the height between 0.09 and 0.18 m, averaging 0.12 m (Wright et al. 2000). This fescue was noted to be a very lush, leafy grass with dense, erect leaves, so that the effective leaf area was greater than that of the Alta fescue grown by Pruitt at Davis. Wright et al. (2000) found ET from the Fawn fescue at Kimberly to average about 11% greater than ET_o predicted by FAO-PM. A value for r_s of approximately $30\ \mathrm{s\,m^{-1}}$ was required in the PM method to satisfactorily reproduce lysimeter measurements, when roughness commensurate with a 0.12 m height was assumed. Larger roughness values, commensurate with a 0.18 m height, were explored by Wright et al. (2000) to account for effects of taller surrounding crops on aerodynamic transport across the lysimeter. With the larger roughness, an r_s of $50\ \mathrm{s\,m^{-1}}$ explained lysimeter ET measurements. The $30\ \mathrm{s\,m^{-1}}$ r_s associated with use of a 0.12 m mean height implies that 100% of the leaf area of the clipped Fawn fescue grass was effective in transpiration, whereas the FAO-56 definition of reference ET_o presumes that only 50% of the leaf area is effective (Allen et al. 1989, 1994a, 1998).

Daily measured ET data from the Kimberly lysimeter system evaluated by Wright et al. (2000) were compared against Eq. (8) and the FAO-PM equation for 63 days from the period May–September, 1991. Prior to comparison with the ET_o methods, the Kimberly grass data were adjusted to the $r_s = 70\ \mathrm{s\,m^{-1}}$ definition for ET_o employed by FAO-56 by multiplying lysimeter measurements by the ratio of $\text{ASCE-PM}_{70}/\text{ASCE-PM}_{30}$ where the ASCE-PM is the ASCE full-form PM equation (Jensen et al. 1990) applied using $r_s = 70$ and using $30\ \mathrm{s\,m^{-1}}$. The $r_s = 70\ \mathrm{s\,m^{-1}}$ represents the FAO-PM definition for ET_o and the $r_s = 30\ \mathrm{s\,m^{-1}}$ represents r_s required to reproduce the measured ET for the lysimeter vegetation. All other parameters and calculations in the ASCE-PM were identical to those used in the FAO-PM. The impact of applying the $\text{ASCE-PM}_{70}/\text{ASCE-PM}_{30}$ ratio was to reduce lysimeter measured ET by an average 11% to reflect the type and characteristics of the grass in the Davis lysimeter.

Daily ET_o by Eq. (8) is plotted against the adjusted lysimeter ET in Fig. 5. ET_o by Eq. (8) averaged 0.97 of adjusted lysimeter measurements, with $\text{SEE} = 0.94\ \mathrm{mm\,d^{-1}}$ $(n = 63)$. Daily ET_o by the FAO-PM is plotted against adjusted lysimeter ET in Fig. 6, where estimated ET_o averaged 1.01 of adjusted lysimeter measurements, with $\text{SEE} = 0.37\ \mathrm{mm\,d^{-1}}$. Daily ET_o by the FAO-56 reduced set FAO-PM is plotted in Fig. 7 against adjusted lysimeter ET, where only measured $T_{\max}$ and $T_{\min}$ were used. R_s was computed using Eq. (7), dew-point temperature was predicted as $T_{\min} - 3°\mathrm{C}$, and $U_2 = 2\ \mathrm{m\,s^{-1}}$. The ratio of estimates to adjusted lysimeter measurements was 0.98 and the SEE was $0.94\ \mathrm{mm\,d^{-1}}$.

The fit of the FAO-56 daily ET_o against the adjusted lysimeter ET is considered to be very good, with data following a strong 1:1 line against lysimeter measurements. ET_o by Eq. (8) and by the reduced set FAO-PM had more scatter, day to day, but tended along the 1:1 line. The similarity in estimates by Eq. (8) and the reduced set FAO-PM are remarkable, considering the FAO-PM uses a calculation of net radiation and partitions the ET_o estimate into the radiation and aerodynamic terms of the combination equation.

Five-day average ET_o by Eq. (8) and by the reduced form FAO-PM are plotted against five-day adjusted lysimeter measure-

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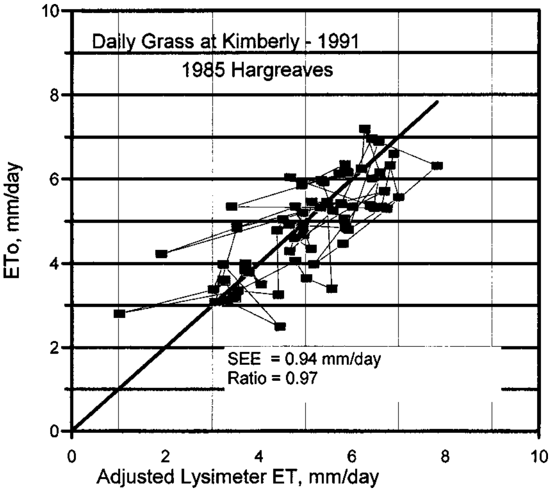

Fig. 5. Daily ET_o by Eq. (8) versus lysimeter measured ET for clipped grass at Kimberly, Idaho during 1991 following adjustment for surface resistance different from FAO-PM (Data from J. L. Wright)

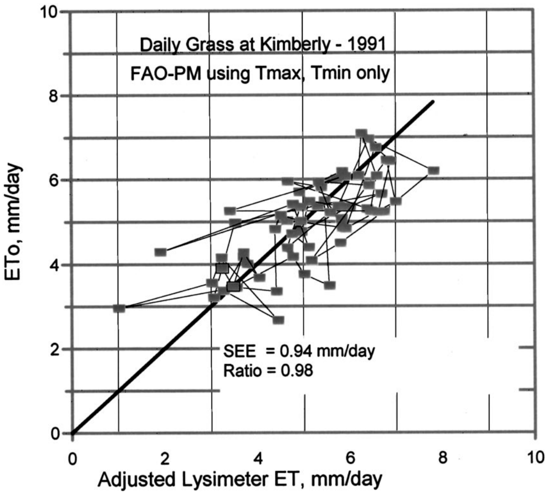

Fig. 7. Daily ET_o by the FAO-56 reduced set FAO-PM versus lysimeter measured ET for clipped grass at Kimberly, Idaho during 1991, following adjustment for surface resistance different from FAO-PM (Data from J. L. Wright)

ments in Figs. 8 and 9. The SEE for each equation was about 0.5 mm d^{-1}. Again, estimates by the two methods are nearly indistinguishable.

Comparisons in Imperial Valley, Calif.

The primary method for computing ET_o in California is with the CIMIS Penman method, which is applied hourly (Snyder and Pruitt 1985). The CIMIS ET_o equation is routinely applied by CIMIS (California Irrigation Management Information System) at more than 100 stations. Records of CIMIS ET_o date to 1984 in the Imperial Valley of California and provide an opportunity to compare estimates by Eq. (8) with those by CIMIS long term.

Monthly ET_o over the 15 year period from 1985–1999 are presented in Fig. 10, where Eq. (8) was applied to monthly air temperature data from a national weather station near Brawley, Calif., and hourly ET_o data from CIMIS were summed monthly and averaged over three CIMIS stations in Imperial Valley (Calipatria, Seeley, and Meloland). On average, Eq. (8) predicted only 1% lower than CIMIS ET_o, with RMSD for monthly estimates equal to 13 mm month^{-1}, which is 9% of average monthly ET_o. Fig. 11 shows annual sums of ET_o by Eq. (8), by CIMIS Penman, and by the FAO-56 reduced set FAO-PM for the 15 year period. Annual ET_o by Eq. (8) averaged 1% below the CIMIS Penman and annual ET_o by the reduced set FAO-PM averaged 2% below the CIMIS Penman. One important difference among methods is the standard deviation of ET_o among years. The CIMIS Penman ET_o had roughly twice the standard deviation as for the two simplified methods and is likely more representative of true conditions. The reduced weather data inputs (e.g., only air temperature) for Eq. (8) and the reduced set FAO-PM caused variance of the predicted ET_o population to reduce. This

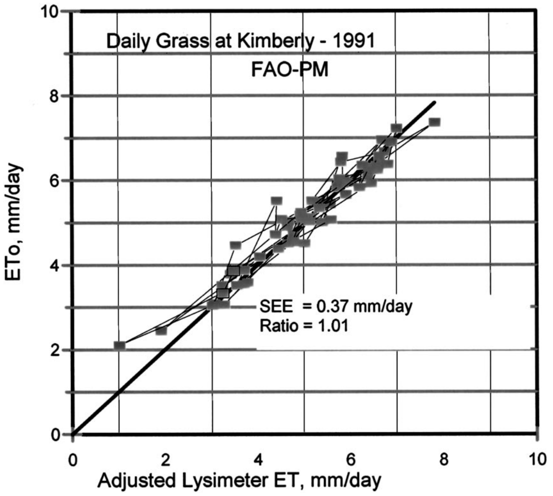

Fig. 6. Daily ET_o by the FAO-PM versus lysimeter measured ET for clipped grass at Kimberly, Idaho during 1991, following adjustment for surface resistance different from FAO-PM (Data from J. L. Wright)

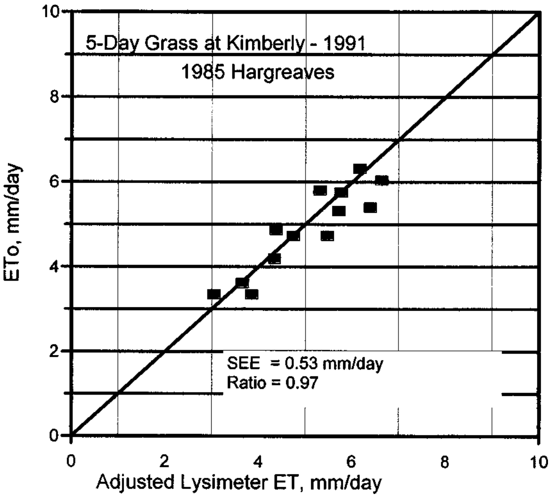

Fig. 8. Five-day ET_o by Eq. (8) versus five-day lysimeter measured ET for clipped grass at Kimberly, Idaho during 1991, following adjustment for surface resistance different from FAO-PM (Data from J. L. Wright)

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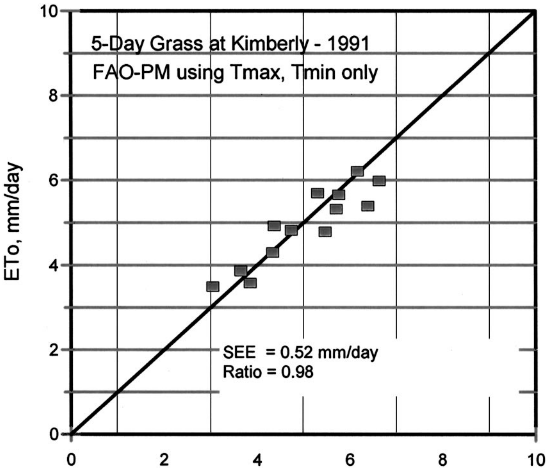

Fig. 9. Five-day ET_o by the FAO-56 reduced set FAO-PM versus five-day lysimeter measured ET for clipped grass at Kimberly, Idaho during 1991, following adjustment for surface resistance different from FAO-PM (data from J. L. Wright)

same amount of reduction in population variance was noted by Allen and Pruitt (1986) for air temperature methods applied to Idaho stations.

Monthly ET_o by Eq. (8) is compared against the FAO-56 reduced set FAO-PM equation for a 75 year record for Brawley, Calif. in Fig. 12. The relationship between the two methods is linear with a ratio of 1.03 and $\text{RMSD} = 7\ \text{mm month}^{-1}$ (4%). There is a slight, but noticeable departure in relationship between the two methods depending on the time of year. The upper sequence of data points (above the 1:1 line) in Fig. 12 occurred during January–June and the lower sequence (below the 1:1 line) occurred during July–December. This phenomenon reflects a slight seasonal trend in the relationship between the methods.

It appears that the 1985 Hargreaves method and the ''reduced set'' FAO-PM method, applied using only maximum and minimum air temperature, provide comparable estimates over a relatively wide range of climates. An advantage of using the FAO-PM is that measured data for R_s, humidity, or wind speed can be placed into the equation as they become available, or that specific calibrations for these parameters can be developed outside of the equation. The advantage of Eq. (8) is its simplicity.

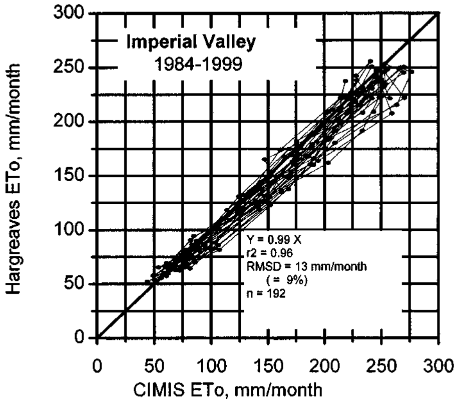

Fig. 10. Monthly ET_o predicted by Eq. (8) using weather data from Brawley, Calif. versus monthly ET_o by the CIMIS Penman (average of three CIMIS stations)

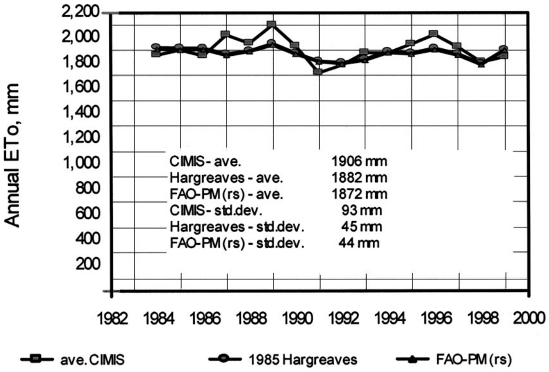

Fig. 11. Annual ET_o predicted for Imperial Valley, Calif. by CIMIS Penman, 1985 Hargreaves equation, and by FAO-56 reduced set FAO-PM

Response of ET_o Estimates to Weather Station Aridity

When a large area in an arid or semiarid climate is irrigated, generally daytime air temperatures are lowered, humidity is increased, vapor pressure deficit is decreased, and wind run is decreased (Burman et al. 1975; Allen et al. 1983, 1996). These impacts are caused by the conversion of available energy into ET and the effects of boundary-layer stability on wind speed. The Penman and Penman-Monteith equations have, as their foundation, the presumption of a steady-state, equilibrium aerodynamic connection between the evaporating surface and the boundary layer above. The combination equations presume that the evaporation condition at the surface has a feedback effect on temperature and humidity at reference height. Therefore, the equations should only be applied using weather data collected from adequately watered sites. The FAO Penman-Monteith and the similar ASCE standardized Penman-Monteith (EWRI 2001) methods have become an accepted transfer benchmark for standardizing and developing crop coefficients. However, these methods can be impacted by the use of weather data collected from ''nonreference'' (i.e., poorly watered) sites (Jensen et al. 1997; Temesgen et al. 1999). Screening and adjustment of humidity data should be implemented, for example, following Allen (1996) and Allen et al. (1998).

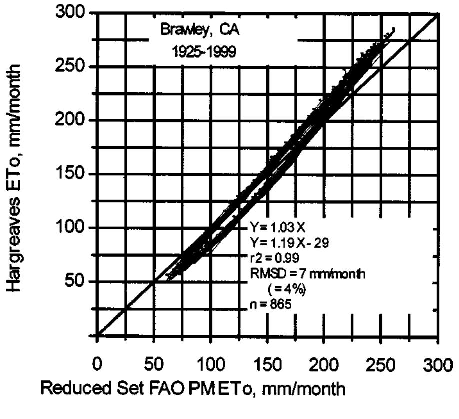

Fig. 12. Monthly ET_o by 1985 Hargreaves equation versus monthly ET_o by the FAO-56 reduced set FAO-PM for 75 years of air temperature data from Brawley, Calif.

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An example of the impact of local aridity on ET_o in an extremely dry environment was observed in a study near Parker, Arizona by Brown (personal communication, 2001) where two weather stations were installed in adjacent 15-ha fields. One field contained irrigated alfalfa and the other, fallow ground. Weather data collected from each station were used to estimate ET_o using the ASCE-PM equation. Monthly totals of ET_o computed using weather data from the fallow station data set exceeded similar ET_o totals computed using weather data from the alfalfa data set by 18–26% during months of June through September (EWRI 2001, Fig. D-8). The weather station in the alfalfa field correctly sensed the transformed weather conditions created by the local irrigated environment. ET_o estimates from these data therefore represent the true ET_o for the Arizona environment. The larger ET_o estimates from the arid weather data represent an overestimation of true reference ET. Appendix D of the EWRI (2001) report places strong emphasis on evaluation and possibly adjustment of humidity data from arid locations before use in an ET_o equation.

Meyer et al. (1989) used climate data from several locations in the Midwest and a Penman equation to evaluate error in ET_o computations caused by error in the climate data. They concluded that error in wind measurement had the smallest impact on ET_o. Error in temperature measurement caused three times as much error as that for wind and error in solar radiation and relative humidity data caused four to five times the effect as error from wind run. Ley et al. (1994a, b) conducted a similar analysis in the Northwest U.S. and found similar results. Ley et al. also evaluated the impact of local station environment on RH and T data.

Allen (1995), Temesgen (1996), and Jensen et al. (1997) found the temperature bias caused by weather station aridity to increase with decreasing precipitation (P). They divided P by ET_o to create a normalized scalar depicting relative availability of soil water in a region for transpiration. Jensen et al. (1997) found a correction to temperature data based on P/ET_o to produce estimates of ET_o with the combination equation that compared well with ET_o from well-watered locations. However, the aridity correction failed to improve the use of Eq. (8) in many regions of Utah.

Hargreaves et al. (1997) and Temesgen et al. (1999) compared ET_o values from the FAO-PM with those from Eq. (8) for paired weather stations (one irrigated and the other dry in the same arid or semiarid climate). They found ET_o predicted by Eq. (8) to be significantly less impacted by the station aridity than was ET_o by FAO-PM. Droogers and Allen (2002) found similar behavior in comparing the two methods using IWMI climatic data base data for the Sahara region of Africa. Temesgen et al. (1999) selected 580 nonirrigated weather stations from the CLIMWAT data base (Smith 1993) that were considered to have high-quality weather data. Locations included weather sites in France, Spain, Italy, Egypt, Sudan, India, Pakistan, Bolivia, and Peru. Of the 580 sites, 418 were in arid climates and 162 were in humid climates. Adjustments were made to the temperature and humidity data to simulate well-watered conditions at each site by comparing $T_{\min}$ and dew-point temperature. Differences in ET_o computed from the original data and those computed from the adjusted data were considered to be caused by an aridity bias. The average ET_o bias in the FAO-PM was about 20% for the arid locations and 10% for those classed as humid. For Eq. (8), the average biases were 10% for arid locations and 5% for the humid sites.

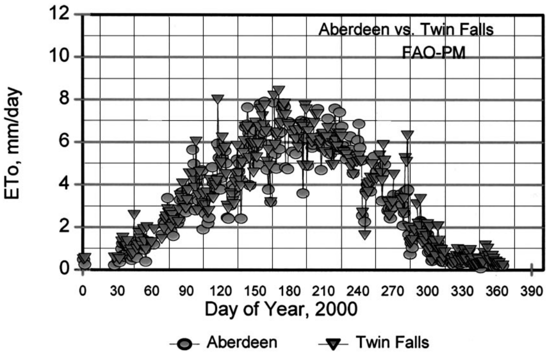

Fig. 14. Daily ET_o at Aberdeen irrigated site and at Twin Falls irrigated site during 2000 using FAO-PM

A final illustration of the lower impact of weather station aridity on Eq. (8) as compared to the FAO-PM is provided in Figs. 13–16, where daily ET_o by the two methods is compared for Potter Butte, Idaho, a dry station surrounded by 50 km of desert, for Aberdeen, Idaho, an irrigated station in an irrigated region, and for Twin Falls, Idaho (near Kimberly), an irrigated station in an irrigated region. Potter Butte is located 60 km northeast of Twin Falls and Aberdeen is located 120 km east of Twin Falls. Even though Potter Butte is half the distance from Twin Falls as Aberdeen, the ET_o predicted by FAO-PM is much greater than that for Twin Falls, whereas ET_o predicted by FAO-PM for Aberdeen is similar to that for Twin Falls (ratio of Potter Butte to Twin Falls was 1.18 and ratio of Aberdeen to Twin Falls was 0.95). The higher ET_o predicted for Potter Butte was due to lower dew-point temperature (average 3°C lower from April–October) caused by the desert conditions. If the area surrounding Potter

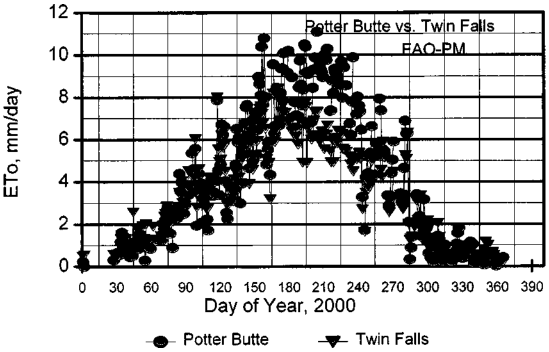

Fig. 13. Daily ET_o at Potter Butte desert site and at Twin Falls irrigated site during 2000 using FAO-PM

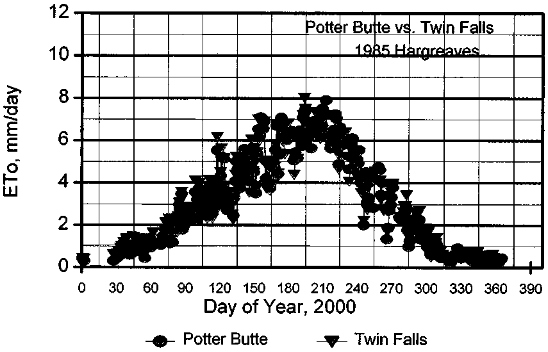

Fig. 15. Daily ET_o at Potter Butte desert site and at Twin Falls irrigated site during 2000 using Eq. (8)

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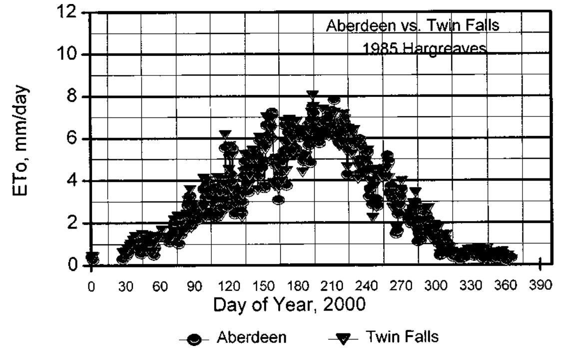

Fig. 16. Daily ET_o at Aberdeen irrigated site at Twin Falls irrigated site during 2000 using Eq. (8)

Butte were irrigated, the ET_o would be expected to be similar to that at Twin Falls and Aberdeen. In contrast, the ET_o estimated by Eq. (8) at Potter Butte compared closely to that at both Twin Falls and Aberdeen, (the ratio of Potter Butte to Twin Falls was 1.00 and the ratio of Aberdeen to Twin Falls was 0.98) indicating little impact or bias caused by the aridity of the air temperature data at Potter Butte on estimates by Eq. (8).

Summary and Conclusions

The Hargreaves ET_o equations and methods were developed primarily for purposes of irrigation planning and design. The FAO Penman-Monteith equation with crop height, surface resistance, and albedo standardized to represent ET from a clipped, cool season grass similar to Alta fescue provides an accepted benchmark for comparing ET_o methods. The method has been endorsed by FAO and is considered to be one of the more physically sound methods. The climatic data used with the FAO-PM should be from a standardized, well-watered site, since ET_o estimated by the combination method is impacted by data aridity (EWRI 2001).

The 1985 Hargreaves method predicted ET_o that was 0.97 of lysimeter measured ET_o at Kimberly, Idaho after the adjustment of lysimeter data for differences in surface conductance according to the FAO Penman-Monteith definition. The method predicted 1.01 of lysimeter ET at Davis where it was developed. The Hargreaves equation predicted annual ET_o in the Imperial Valley of California that averaged 0.99 of that predicted by the CIMIS Penman method over a 15-year period.

The selection of the preferred ET_o method should be based on the time step required, site aridity, equipment costs, and operation and maintenance requirements, quality of the weather data available, and the required simplicity of computations. Where equipment cost is a consideration, where data quality is questionable, or where historical data are missing, both the reduced set FAO-PM or the 1985 Hargreaves are recommended, since the two methods are surprisingly equivalent over a wide range of climates. When the weather data site is not located within a large, well-watered area, the 1985 Hargreaves method will generally have less aridity-bias impact in the estimate of ET_o as compared to the combination equations. Daily estimates by the Hargreaves equations are subject to error caused by the influence of the temperature range caused by the movement of weather fronts and by large variations in wind speed or cloud cover. Therefore, the Hargreaves methods are recommended for use with five-day or longer time steps.

Acknowledgments

Lysimeter measurements by Professor William O. Pruitt, Emeritus, University California, Davis, and by Dr. James L. Wright, USDA-ARS, Kimberly, Idaho were provided to this study. The tremendous value of these precision measurements and the meticulous care and investment by these two researchers is gratefully acknowledged.

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