DEFINING AND USING REFERENCE EVAPOTRANSPIRATION

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ABSTRACT: Values of reference evapotranspiration (ET_0) are used with crop coefficients (*KC*) for many aspects of irrigation and water resources planning and management. More than a score of methods are used for estimating ET_0. Estimated values vary widely due to the lack of standardization of the reference. Evaporation (ET) measured by lysimeters of various grasses and/or alfalfas has been used as the standard for developing estimating equations. Due to variation in the references used, some international organizations now wish to promote the use of a single equation or method to avoid the confusion caused by the current diversity. Different versions of the Penman combination equation have been proposed. The Research Center for the European Community and the ASCE Committee on Irrigation Requirements have evaluated various equations for estimating ET_0. Due to its simplicity and the accuracy of estimates, the 1985 Hargreaves et al. equation is recommended for general use. ET_0 is used in irrigation planning, design, and scheduling and for other water adequacy studies.

INTRODUCTION

Estimates of reference evapotranspiration (ET_0) and crop coefficients (*KC*) are widely used to estimate crop and vegetative water use and water requirements. These estimates are of importance for irrigation scheduling, planning, and management.

Reference evapotranspiration (ET_0) needs to be more clearly defined. Evapotranspiration (ET) of various grasses and alfalfas grown in lysimeters have been used as the standard. The ET of grasses varies with fertilization, clipping height, frequency of irrigation, grass species, cultivars within species, design of lysimeters, size and type of the buffer area, and climate and management interactions.

More than a score of equations or methods were developed from measured lysimeter ET and climatic data, and used for estimating ET_0. These have been derived and/or calibrated from the ET of various grasses of alfalfas under a variety of lysimeter designs, climates, and management conditions. Various organizations are now proposing that a specific estimating method be selected and used as the standard reference. There has been little emphasis on the evaluation or standardization of climatic data to be used with the method selected. For example, during a hot, dry month the mean temperature may be as much as 5°C higher for a dry-land site as for an irrigated site under similar conditions. This difference in temperature also influences the vapor pressure deficit. Weather data used for computing ET_0 should, therefore, be from an irrigated site. The irrigated buffer area for the weather station should be fairly large, preferably exceeding two hectares. Data should be quality-checked and instrument-calibration checked, periodically, for possible drift.

This paper makes use of good quality lysimeter and climate data from

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some European and other sites to compare the ET_0 computed using three versions of the Penman combination equation with ET_0 estimates from a simple empirical equation, which requires only measured values of maximum and minimum temperatures. The mean values of European lysimeter measured ET for 10-day periods are compared to those predicted by the ET_0 estimating methods. The seasonal variations in the relationships of ET to ET_0 were also examined. Comparisons from "Evapotranspiration" (1990) are presented. Some practical applications of ET_0 estimates are described.

Proposed References for ET_0

The International Commission for Irrigation and Drainage (ICID) and the Food and Agriculture Organization of the United Nations (FAO) have considered using the Penman-Monteith (PM) method as the standard method of computing ET_0 from climatic data, and for evaluating other methods. The Centre Commun de Recherche of the European Economic Community (1992) made a study of ET_0 equations using lysimeter ET and synoptic climatic data. Twelve equations were compared. The classical Penman was selected as the standard method. Climatic data from various sites were used to compare the Penman results with nine equations that are simpler and requires less data than the Penman combination equations. The Hargreaves et al. (1985) equation was selected as the one with results closest to the classic Penman. The Hargreaves method requires only measured values of maximum and minimum temperatures and was thus recommended for general use. The equation is

$$ET_0 = 0.0023 \times RA \times (T°\text{C} + 17.8) \times TD^{0.50} \qquad (1)$$

in which ET_0 and RA = same units of equivalent water evaporation; RA = extraterrestrial radiation; $TD = T_{mx} - T_{mi}$ (mean maximum minus mean minimum temperatures in degrees Celsius); and $T°\text{C}$ is $(T_{mx} + T_{mi})/2$. Values of RA (in mm/day) are given in Table 1 (Average temperatures of 10°C or 30°C will result in values of RA that differ from those for 20°C by less than 1.0%).

LYSIMETER ET DATA

Choisnel et al. (1992) compared measured lysimeter ET with estimated values of ET_0 for 10-day periods for six European lysimeter sites.

Three lysimeters in France were 5.0 m^2 in area, with fescue grass maintained at a height of approximately 5 cm. At Guyancourt (Latitude 48.8°N, Longitude 2.1°E, Elevation 161 m) ET measurements were weighed. In Avignon (Latitude 43.9°N, Longitude 4.9°E, Elevation 24 m) two lysimeters were measured (one by weighing, the other by drainage). At the other European sites, grass and/or site conditions were not considered comparable. Thus, only the data from these French sites are used in this study to compare estimating equations. Three versions of the Penman combination equation are compared with the Hargreaves et al. (1985) equation.

"Evapotranspiration" (1990) compares ET_0 estimates from 20 computation methods. Four of the lysimeter sites used for the comparisons of ET with ET_0—Aspendale, Australia; Davis and Lompoc, California; and Seabrook, New Jersey—are essentially perennial, rye grass, or their equivalent. The data from Davis are of particular interest because there are wide variations in climate throughout the year. The quality of the data is superior

TABLE 1. Extraterrestrial Radiation (*RA*) Expressed in Equivalent Evaporation (in mm/day)

January (1)	February (2)	March (3)	April (4)	May (5)	June (6)	July (7)	August (8)	September (9)	October (10)	November (11)	December (12)	Latitude (degrees) (13)
(*a*) Northern Hemisphere												
3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2	50
4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7	48
4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3	46
5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7	44
5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2	42
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32
8.8	10.7	13.1	15.2	16.5	17.0	16.8	15.7	13.9	11.6	9.5	8.3	30
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0

(*b*) Southern Hemisphere

17.5	14.7	10.9	7.0	4.2	3.1	3.5	5.5	8.9	12.9	16.5	18.2	50
17.6	14.9	11.2	7.5	4.7	3.5	4.0	6.0	9.3	13.2	16.6	18.2	48
17.7	15.1	11.5	7.9	5.2	4.0	4.4	6.5	9.7	13.4	16.7	18.3	46
17.8	15.3	11.9	8.4	5.7	4.4	4.9	6.9	10.2	13.7	16.7	18.3	44
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17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2	36
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17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7	24
17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5	22
17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4	20
17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1	18
16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8	16
16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6	14
16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5	12
16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2	10
16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0	8
15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7	6
15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4	4
15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1	2
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0

due to the site and its surroundings, the instruments, the management, data reduction, length of records, and availability of daily data. The ET values measured at Davis, from perennial rye grass and Alta fescue grass, are very similar and have been used as reference material for computing various sets of crop coefficients. For these reasons the ET data from Davis have sometimes been used as the standard reference for ET_0.

COMPARISONS OF ET_0 WITH ET

Three versions of the Penman combination equation were compared with the Hargreaves et al. (1985) method for three sets of lysimeter-measured ET (10-day sums) from France. The mean ET_0 in percent of lysimeter ET and coefficients of variations CV of the percentages were calculated for each ET_0 method. The methods compared are the Penman classic, Penman calibrated, Penman-Monteith, and Hargreaves. The mean percentages of 10-day ET_0, in percent of ET, for the four methods were 100, 96, 101, and 97, respectively. The mean values of CV (standard deviations in percent of mean values) were 8, 10, 9, and 10, respectively.

Some seasonal variations were observed in the 10-day percentages of ET predicted by ET_0. These variations may be associated with increasing water stress in the region in which the lysimeter was located. A particular grass has an optimum temperature range for growth. Perennial rye grass and the fescues are cool season grasses. However, low temperatures and frost may reduce growth and water use relative to radiation and temperature, during and after the colder months. The methods evaluated overestimate cool season grass ET during the first month, or months, of the growing season.

Table 2 was prepared from comparisons taken from "Evapotranspiration" (1990). Three versions of the Penman equation are compared with the Hargreaves method. In each case the peak month (mid-summer) percentage estimated is less than the seasonal average. The versions of the Penman equations used in "Evapotranspiration" (1990) are slightly different from those of Choisnel et al. (1992).

Table 2 indicates that the FAO-24-corrected Penman (Doorenbos and Pruitt 1977) gives estimates of reference crop evapotranspiration (ET_0) that

TABLE 2. Comparisons of ET_0 Estimating Methods Summarized from "Evapotranspiration" (1990)

	MONTHLY ET_0 IN % OF ET				ASEE[a] FOR DAVIS (mm/day)		
	Davis		Avenue of 4 Sites			Daily	
Method (1)	Peak month (2)	Season (3)	Peak month (4)	Season (5)	Monthly (6)	Peak month 7	Season (8)
Penman-1963	99	108	105	114	0.30	0.42	0.82
FAE-24 C. Penman	130	135	134	141	0.18	0.44	0.79
Penman-Monteith	97	106	94	104	0.32	0.41	0.71
Hargreaves et al. (1985)	102	105	96	104	0.23	0.74	0.90
Means	107	114	107	116	0.26	0.50	0.80

[a] ASEE is the adjusted standard error of estimated values comparing ET_0 estimated by the regression equation from regression through origin.

average about 30% above those of the other reference equations evaluated. However, the FAO-24 C Penman, after being corrected to the same reference value, is one of the best references for the Davis lysimeter ET values. This is indicated by the low standard errors of estimates after the regression of data through the origin (*ASEE* in Table 2).

The use of regression through the origin to adjust equations to a common reference seems justified. For the four stations used in Table 2, the average ratios of ET_0 computed to the Penman-Monteith values are: Hargreaves 1.01; Penman 1963 1.12; and FAO C Penman 1.36. The coefficients of variation of ratios are 2, 6, and 5 percent, respectively. The corrections required for these equations are not strongly influenced by climatic differences.

PRACTICAL APPLICATIONS

The use of combination equations requiring solar radiation is limited due to data availability. The World Meteorological Organization (WMO 1989) lists only 63 countries that publish data on solar radiation at the surface. For these countries 11 times as many locations publish values of maximum and minimum temperature. Therefore, (1) is recommended for general use.

The crop coefficients (*KC*) used with ET_0 from (1) should be standardized. *KC* values from several sources have been compared. The recommended *KC* values are given by Hargreaves (1990) and Hargreaves and Samani (1991).

ET_0 can be used in surface water supply studies. Hargreaves (1993) found a high degree of correlation between annual surface runoff and annual sum (S) of monthly positive values of precipitation (P) minus ET_0. The ET_0 can also be used to estimate monthly values of stream flow at a 75% probability (R_m) for ungauged watersheds. R_m correlates well with monthly values of *MAI* (moisture availability index equal to the 75% probability of assured precipitation divided by ET_0). A time delay of various time periods between rainfall and runoff provides the best correlations. The runoff from ungauged watersheds can be estimated from equations developed from similar watersheds.

Values of *MAI* are also useful in evaluating needs for surface drainage. A value of *MAI* exceeding 1.33 is an indication of the need for good, natural, or constructed surface drainage.

CONCLUSIONS

The procedure for the calculation of reference evapotranspiration (ET_0) should be standardized. Perennial rye grass or Alta fescue grass is proposed as the standard reference crop. A Penman combination equation is recommended as reference for calibrating or evaluating other methods for computing ET_0. The standardization of site conditions for collecting weather data and the quality of data used are as important as the choice of reference equation used. Crop coefficients (*KC*) need to be standardized and made appropriate for use with the reference method selected for calculating ET_0. The Hargreaves et al. (1985) equation requires only measured values of maximum and minimum temperatures, and correlates well with results from the Penman combination equations. Due to its simplicity and reliability, the Hargreaves equation is recommended for general use for computing values of ET_0. Greater emphasis should be given to the collection and publication of quality temperature data to facilitate implementation of the simple and easily used equation.

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APPENDIX II. NOTATION

The following symbols are used in this technical note:

$ASEE$ = standard error of estimate after regression through origin;
CV = coefficient of variation (standard deviation in % of mean);
DEC = declination in radians; $0.40876 \times \cos [0.0172142 \times (J + 192)]$;
DR = relative distance of sun to earth; $1.0 + 0.033 \times \cos (0.0172124J)$;
ET = evapotranspiration;
ET_0 = reference evapotranspiration;
J = Julian day (January 1 = 1); $15 + [30.5 \times (M - 1)]$;
KC = crop coefficient, multiplied by ET_0 to estimate crop ET;
LAT = Latitude in radians (1 radian = 57·2958°, negative for southern latitudes);
M = number of the month (January = 1);
MAI = moisture availability index (75% probability of assured precipitation divided by ET_0);
OM = sunset hour angle in radians for Latitude $< 55°$; $A \cos [-\tan (LAT) \times \tan (DEC)]$;
RA = extraterrestrial radiation in equivalent depth of water evaporation at 20°C;
R_m = streamflow for month m ($m = 1$ to 12) in L/s per square kilometer at 75% probability of assured runoff;

r^2 = coefficient of determination (percent of variance predicted by regression equation);
$T°C$ = mean temperature $(T_{mx} + T_{mi})/2$;
TD = $T_{mx} - T_{mi}$;
T_{mx} = mean maximum temperature in °C; and
T_{mi} = mean minimum temperature in C°.