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VARIATION WITHIN MEASURED AND ESTIMATED CONSUMPTIVE USE REQUIREMENTS

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Abstract

Statistical analyses of alfalfa water use measured at Kimberly, Idaho indicate that a modified Penman combination equation and the FAO-Blaney-Criddle with daily or monthly weather data replicate underlying population variances reasonably well, with the combination method being about 30% low. Statistics generated using the SCS-Blaney-Criddle or the FAO-Blaney-Criddle where only air temperature is available on a daily or monthly basis indicate that variances calculated from estimates by these equations are much less than variances of the underlying population (measured values). Standard deviations or variances of estimated ET values should be adjusted based on lysimeter measurements before probability tables or frequency analyses are generated.

Introduction

Design engineers in the fields of irrigation, wastewater treatment, hydrology, hydropower, and planners involved in river regulation and policy making frequently need to consider probabilities of occurrence and time variations of consumptive use requirements of irrigated crops. Variation within daily, weekly, monthly and seasonal consumptive use requirements necessitates the use of statistics and frequency analyses for predicting probabilities of occurrence and risk levels for proper design and operation of irrigation and drainage systems and for efficient use of energy and water resources. The potential evaporative demand placed on an agricultural environment is a function of dryness, temperature and mixing of air (wind) above the crop, and radiative flux of energy between the crop and surrounding environment. Use of humidity, temperature, wind and radiation parameters to describe evapotranspiration (ET) can account for a large part of the variation within consumptive use, depending on the sensitivity and completeness of the mathematical equation used. However, statistics describing consumptive use estimated by many methods, especially single parameter methods such as temperature or radiation equations, may require some

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form of statistical adjustment to represent real occurrences.

Lysimeter Measurement of Water Use

Precision weighing lysimeters provide a means for direct measurement of evaporative loss of water from soil and crop surfaces without soil or crop disturbance and without the need to account for upward or downward movement of soil water. Two precision weighing lysimeters were installed at the USDA Snake River Conservation Research Center at Kimberly, Idaho during 1968 and 1971 by Wright (1983). The design of these lysimeters is similar to that of Ritchie and Burnett (1968). Dimensions of the lysimeters are 1.83 meters square by 1.22 meters deep. Both lysimeters were installed at the centers of fields of sufficient size to insure adequate fetch. Soil moisture was maintained at levels suitable for maximum growth and crops were managed to provide representative cover conditions. Ranger alfalfa (*Medicago sativa* L., Ranger) a tall, upright variety, was seeded in lysimeter 1 during 1968. A good, healthy stand resulted, which was managed during 1969, 1970 and 1971. The lysimeter was harvested manually when fields were cut three times per season. The lysimters and management have been described in detail by Wright (1983). Lysimeter weights were recorded at 20 minute intervals. The alfalfa fields generally began to show green shoots in early April and rapid growth began by mid-April. Canopy regrowth tended to reach full cover about 20 days after each harvest.

Evapotranspiration Methods

The use of a reference ET to define a standard or potential against which ET by crops can be compared has merit, in that ET by the reference crop can be measured and duplicated between locations and climates for local calibration. Alfalfa provides a good reference in that it has a long growing season and provides sufficient canopy thickness to absorb solar radiation above ground surface. Alfalfa also has low leaf resistance to water vapor diffusion and a large root system, especially compared to grass. This minimizes the effects of high climatic demands and decreasing soil moisture on reference ET. Consumptive use for other agricultural crops is commonly calculated by multiplying a time-dependent coefficient times the reference ET value (Wright,1982).

Wright Combination Method

A calibrated and validated form of the combination equation, hereafter referred to as the Wright ET method (Wright, 1982; Burman et al, 1980) for brevity, is a modification of the original Penman combination method (Penman, 1948). Although the structure of the Wright equation is unchanged from the Penman, major revisions have occurred in calculating necessary equation requirements, such as net radiation, mean vapor pressure deficit and soil heat flux. In addition, the Wright method incorporates time dependent coefficients in the wind function term of the combination equation to compensate for varying day lengths and regional advection in semiarid regions. Alfalfa lysimeter data from the 1969-1971 period was used to calibrate the wind function coefficients. Days during which the crop was at full cover were used. Standard errors of daily estimates by the equation were found to be less than 0.8 millimeter per day (Wright and Jensen, 1978).

FAO-Blaney-Criddle Method

The FAO-Blaney-Criddle (FAO-BC) Method is suggested for areas where weather measurements include air temperature only. The FAO-BC with elevation correction, as suggested by Pruitt (Doorenbos and Pruitt, 1977), representing mean grass reference ET over a given month, is expressed as:

$$ET_o = (a+b[p(0.46T+8.13)])(1.+0.1E/1000.) \quad \text{mm/day} \qquad (1)$$

where: ET_o = grass reference evapotranspiration in mm/day for the time period considered
T = mean daily temperature in degrees Celsius
p = mean daily percentage of total annual daytime hours for given date and latitude
a,b = adjustment factors which depend on minimum daily relative humidity, percent sunshine hours and daytime wind
E = elevation of station in meters

Measurements of minimum daily relative humidity, percent sunshine hours (solar radiation) and daytime wind speed (7am - 7pm) must be obtained for each time period estimated. These secondary parameters can be estimated using long term, regional averages, if short term, actual measurements are not available (Doorenbos and Pruitt, 1977). However, method accuracy and sensitivity to changes in atmospheric conditions is decreased.

Coefficients which adjust the FAO-BC grass reference to an alfalfa reference (ET_r) and which also provide a local calibration of the equation to Idaho provide good estimates of ET_r when compared to the Wright method (Allen and Brockway, 1983b).

SCS-Blaney-Criddle Method

The SCS-Blaney-Criddle (SCS-BC or Technical Release 21) is unlike other ET methods evaluated in that it does not predict ET by a specific reference crop. Rather, ET for any crop must be calculated with special coefficients presented by the SCS (1967). These coefficients are not the same as coefficients used with an alfalfa or grass reference ET method. The SCS-BC equation is of the form:

$$U = K_t K_c (tp)/100 \qquad (2)$$

where: U = the monthly consumptive use of a crop in inches
K_t = a climatic coefficient related to mean air temperature
K_t = 0.173t-0.314, where t is mean air temperature in Fahrenheit
K_c = coefficient reflecting the growth stage of a specific crop Values for K_c can be selected from curves presented in Technical Release 21 (SCS, 1967)
t = mean air temperature in degrees Fahrenheit
p = the monthly percentage of daylight hours in the month Values of p are tabulated in Technical Release 21.

The p in equation 2 is the same as that used in the FAO-Blaney-Criddle. The SCS-BC has been widely used during the last fifteen years for state consumptive use bulletins and in water rights adjudication processes.

Variability of Lysimeter Measured and Estimated Water Use

The daily ET of an agricultural crop varies according to time of season, crop status, and daily fluctuations in the evaporative power of the atmosphere. Daily ET by the Ranger alfalfa crop as measured by lysimeter during periods of full cover (20 cm of top growth) is shown in Figure 1 for the 1969, 1970, and 1971 seasons. Daily alfalfa reference ET estimated using the Wright method for this same period is shown in Figure 2. Comparison of Figures 1 and 2 indicates that the populations are distributed in similar manner. Sparsity of data points during late June and early July are due to cutting effects.

Daily water use by an alfalfa reference crop estimated using the Wright method for all days during April through October for the 14-year period 1965-1978 is shown in Figure 3. Monthly statistics describing daily values are listed in Table 1 for the three data sets pictured in Figures 1, 2, and 3. Values of skewness and distribution of data points from Table 1 and Figures 1,2, and 3 indicate that both measured and estimated daily ET are normally distributed. Negative values of skewness during many months are not of sufficient magnitude to justify use of a lognormal distribution. Because of the goodness of fit of the normal distribution, use of more elastic, three-parameter distributions such as the Pearson, Gumbel, Weibull or gamma is not justified. Use of the normal distribution to desribe the data populations allows for straight forward calculation of frequency and exceedence levels. The lack of a zero bound in the normal distribution poses no real problem in application. Shape of the normal distribution can be modified by increasing or decreasing the calculated variance or standard deviation.

Standard deviations and computed coefficients of variation of daily estimates of ET_r by Wright during 1969-1971 are about 15-20% less than the respective parameters of daily measurements during the same period (Table 1). Monthly means of the fourteen year estimates are greater than three year measurements during May, June and July, and are less during other months, indicating some among-years variation in evaporative demands. This would explain some of the increase in standard deviation for the fourteen year period. Coefficients of variation are very similar between lysimeter measurements during the three year period and reference ET estimated during the fourteen year period.

Monthly means and means plus or minus one standard deviation are included in Figure 4 for daily measured and estimated ET during full-cover periods during the 1969-1971 period. Comparison of lysimeter measurements and ET_r calculations during the three year period would indicate that standard deviations of ET_r estimated using the Wright method could be adjusted upward by 16-20% to more closely model daily variation in lysimter measurements.

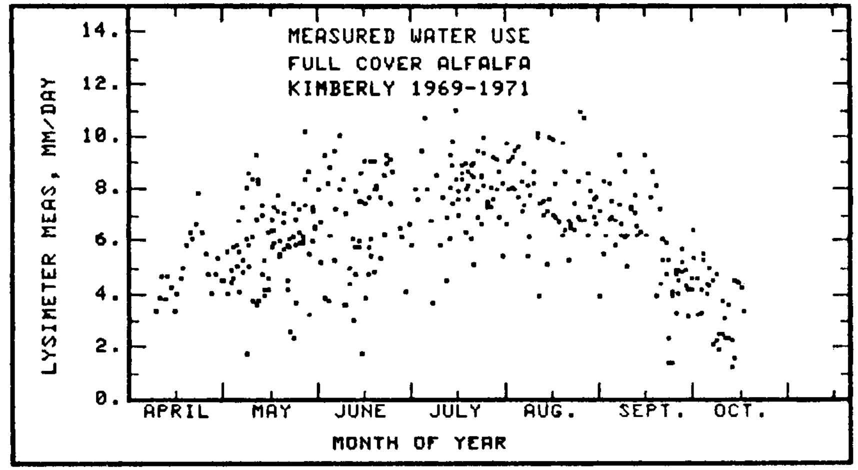

Figure 1. Measured daily water use by established Ranger variety alfalfa during periods of full cover at Kimberly, Idaho during 1969-1971.

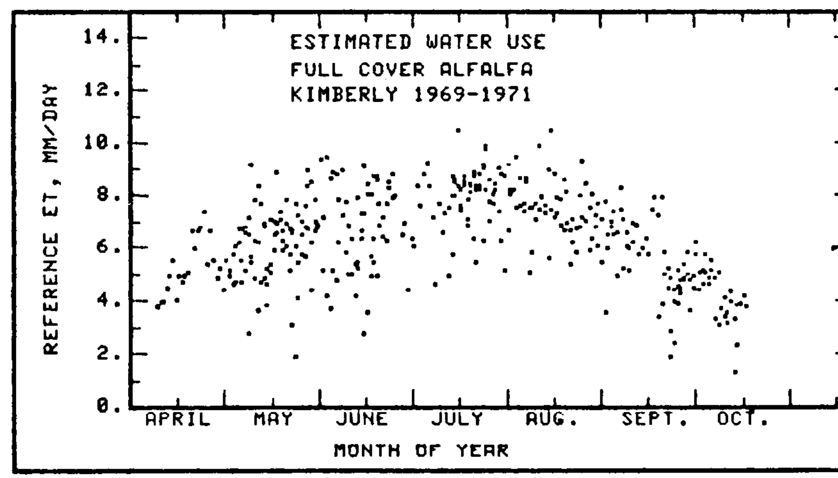

Figure 2. Calculated daily reference evapotranspiration using the Wright method during periods of full alfalfa cover at Kimberly, Idaho during 1969-1971.

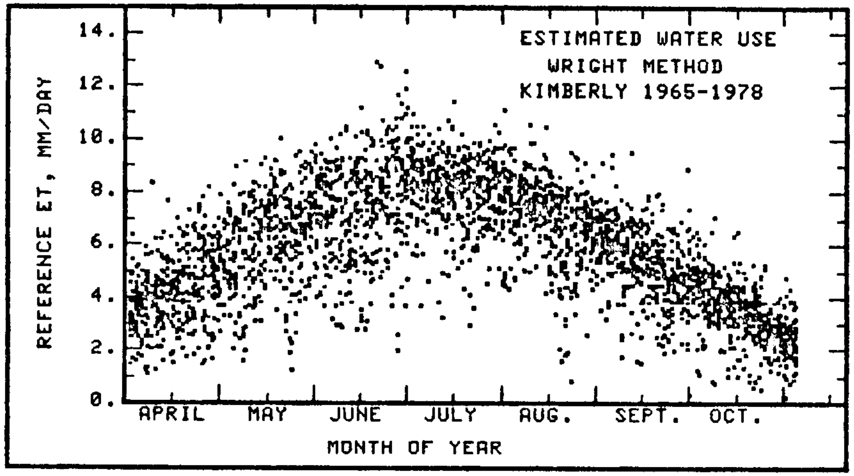

Figure 3. Calculated daily alfalfa reference evapotranspiration using the Wright method for all days during 1965-1978 at Kimberly, Idaho.

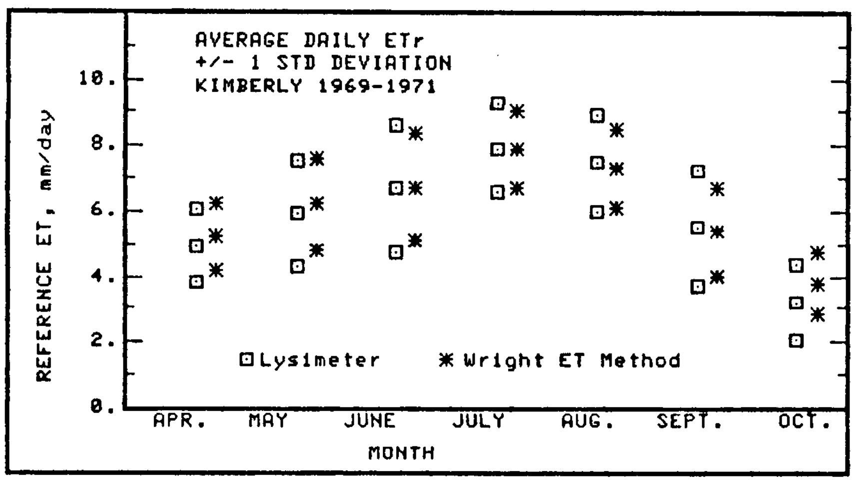

Figure 4. Lysimeter-measured and calculated mean daily evapotranspiration and mean daily ET plus or minus one standard deviation for full-cover days during 1969-1971 at Kimberly, Idaho.

Variability of ET_r Estimated Using Wright, FAO-BC and SCS-BC

Monthly alfalfa reference ET for the fourteen year period was calculated using the Wright and FAO-BC methods and ET by alfalfa hay (with cutting effects included) was calculated using the SCS-BC. The Wright method was applied on a daily basis and summed over monthly periods. The FAO-BC and SCS-BC methods were applied using monthly averages of weather data.

The FAO-BC method was applied in two manners. In the first manner, temperature, minimum relative humidity, percent sunshine hours and daytime wind speed were made available on a monthly basis for each year of record (FAO-BC short term). In the second manner of application, only temperature was supplied on a monthly basis for each year of record (FAO-BC long term). The three secondary parameters of humidity, sunshine and wind were supplied as fourteen year averages for each month. This type of application (long-term) will generally be the case when estimating consumptive use requirements in areas with minimal weather records. The FAO-BC long term application is essentially a single-parameter ET method. In both applications of the FAO-BC method an elevation correction and monthly alfalfa/grass reference ratios were used, resulting in estimates of alfalfa reference ET. Development of monthly reference ratios and elevation adjustment for the FAO-BC is discussed by Allen and Brockway (1983a; 1983b).

Statistics generated from fourteen years of monthly estimates are included in Table 2 for the method applications. Variance (square of standard deviation) of the estimates is markedly decreased when a single-parameter ET method is used (FAO-BC long term and SCS-BC). Standard deviations of monthly estimates by the FAO-BC with short term data were greater than Wright for most months. Means were similar for Wright and FAO-BC short term and long term applications. Distributions of ET estimated with the single-parameter methods were positively skewed, especially during June, as a result of sporadic, high temperature months during the period of record. Skewness during June results from typically rainy, cool periods during that month, with occasional years with little cloudiness and high temperatures.

Statistics contained in Table 1 describe variation within daily ET and statistics listed in Table 2 represent variation within monthly ET. Therefore, standard deviations from the two tables can not be directly compared. Because lysimeter information was not available for complete months due to cutting effects, and due to the lack of a long period of record (3 years), direct comparison with monthly statistics was precluded. To allow for a comparison between estimated and measured ET, "apparent" ratios of standard deviations of estimated to standard deviations of measured alfalfa reference were calculated as shown in Table 3. These ratios were calculated by multiplying ratios of standard deviations of daily Wright estimates for 1969-1971 (Table 1) to standard deviations of daily lysimeter measurements for 1969-1971 by ratios of standard deviations of monthly estimates calculated by the appropriate method during the fourteen year period to standard deviations of monthly calculatations by Wright during the fourteen year period (see Table 3).

Table 1. Statistical analyses of lysimeter measured and calculated daily ET of Ranger variety alfalfa during periods of full cover and reference ET calculated using fourteen years of weather record.

	Full Cover Days, only													
	Lysimeter Measurements 1969-1971 (millimeters/day)				Calculated ET_r 1969-1971 (millimeters/day)					Calculated ET_r 1965-1978 (millimeters/day)				
Mo	#n	Mean	St.Dv	Skew	CV*	Mean	St.Dv	Skew	CV	#n	Mean	St.Dv	Skew	CV
4	23	4.96	1.11	.79	.22	5.24	1.01	.47	.19	420	4.20	1.37	.21	.32
5	84	5.93	1.59	-.11	.27	6.21	1.41	-.37	.23	434	6.21	1.63	-.40	.26
6	58	6.69	1.94	-.43	.29	6.72	1.64	-.38	.24	420	7.54	1.86	-.37	.25
7	65	7.93	1.36	-.64	.17	7.88	1.15	-.87	.15	434	7.99	1.31	-.90	.16
8	62	7.46	1.48	.19	.20	7.28	1.20	-.16	.16	434	6.84	1.43	-.77	.21
9	60	5.52	1.75	-.03	.32	5.39	1.34	-.11	.25	420	5.12	1.39	-.21	.27
10	23	3.23	1.16	-.10	.36	3.83	.95	-.64	.25	434	3.19	1.14	.05	.36

* CV = Coefficient of variation (standard deviation/mean).
ET_r was calculated using the Wright method on a daily basis.

Table 2. Statistics describing monthly alfalfa reference ET estimated using the Wright, FAO-BC and SCS-BC methods with monthly weather data at Kimberly, Idaho, 1965-1978.

Wright-1982					FAO-BC with long term data				
Month	Mean	St.Dv.	Skew	C.V.	Month	Mean	St.Dv.	Skew	C.V.
4	4.20	.70	.25	.167	4	4.19	.46	.02	.109
5	6.21	.65	-.46	.104	5	6.20	.45	.18	.072
6	7.54	.75	-.11	.100	6	7.56	.33	1.27	.043
7	7.99	.42	.22	.053	7	8.03	.22	.55	.028
8	6.84	.69	-.47	.101	8	6.79	.40	.12	.059
9	5.12	.54	.61	.106	9	5.11	.44	.07	.087
10	3.19	.31	-.58	.097	10	3.20	.28	-.08	.088

FAO-BC with short term data					SCS-BC with alfalfa hay coef.				
Month	Mean	St.Dv.	Skew	C.V.	Month	Mean	St.Dv.	Skew	C.V.
4	4.26	.95	.36	.222	4	1.62	.30	.32	.182
5	6.20	.91	-.30	.147	5	3.13	.39	.30	.125
6	7.43	.82	.51	.110	6	4.79	.38	1.25	.080
7	8.02	.40	.38	.050	7	5.82	.30	.65	.051
8	6.81	.79	-.48	.117	8	4.79	.48	.21	.100
9	5.10	.67	.44	.131	9	2.85	.39	.19	.135
10	3.21	.51	.45	.160	10	1.42	.16	.08	.114

According to "apparent" ratios of standard deviations in Table 3, variances of monthly estimates by the FAO-BC using short term (actual year) weather data exceed variances of measured ET during the months April, May and October. Variances of FAO-BC short estimates during June and August and September are closer to measured variances than are estimates calculated using the Wright method. However, the Wright method appears to be more consistant in variability of water use estimates than the FAO-BC, as compared to lysimeter estimates.

Comparison of estimates by the FAO-BC with long term data and SCS-BC methods to lysimeter-measured values indicates that standard deviations calculated from equation estimates are only 50 percent as large as standard deviations of actual recorded use. These results are significant in that water resource system designs and frequency tables based on statistics generated from estimates by single-paramter consumptive use methods may be in error, compared to probabilities of real occurrence. Because apparent ratios of standard deviation for the FAO-BC with long term data and the SCS-BC are consistantly low during all months, standard deviations of estimates using these methods at Kimberly, Idaho should be about doubled to more reasonably describe variance of true underlying populations of crop water use. Monthly means and means plus or minus one standard deviation for the Wright, SCS-BC and two applications of the FAO-BC are included in Figure 5. Values for the SCS-BC fall below the other two methods primarily due to the effect of the SCS alfalfa hay coefficient. Seasonal alfalfa reference ET is typically about 20% greater than ET by alfalfa harvested for hay due to cutting effects (Wright, 1982). Statistics describing monthly alfalfa hay water use as estimated using the Wright combination method are included in Allen and Brockway (1983b).

Frequency distribution of Reference ET

Frequency levels of occurrence were calculated for one day and thirty day periods of alfalfa reference ET calculated using the Wright method at Kimberly, Idaho for 1965-1978. Results of these frequency analyses are shown in Figures 6 and 7. These figures illustrate the large decrease in variability of water use as the time period is increased, as was also shown previously (Wright and Jensen, 1972).

Summary and Conclusions

Statistics generated from crop water use estimated using mathematical equations may not describe real variations within the underlying population. This is due primarily to the absence in the equations of all environmental factors contributing to evapotranspiration. Statistical analyses of lysimeter-measured water use by alfalfa at Kimberly, Idaho indicate that variances of daily estimates of ET calculated using a modified Penman combination method are only 70% as large as variances of lysimeter-measured values (standard deviations are reduced by 16%). Use of a single-parameter equation, such as the SCS-Blaney-Criddle or FAO-Blaney-Criddle with average values of wind, solar radiation and humdity, results in variances of estimates which are only 25% of measured water use

Table 3. Apparent ratios of standard deviations of estimated to standard deviations of measured alfalfa reference ET.

Month	Wright /Lys (mm/d)	FAOBC-ST /Lys (mm/d)	FAOBC-LT /Lys (mm/d)	SCSBC /Lys (mm/d)
4	.91*	1.23**	.59**	.38**
5	.89	1.25	.61	.54
6	.85	.92	.37	.43
7	.85	.80	.45	.60
8	.81	.93	.47	.56
9	.76	.93	.62	.54
10	.82	1.35	.74	.43

* Calculated from Table 1.

** Apparent ratio of standard deviation of estimated to standard deviation of measured calculated as:

SD[Wright]/SD[Lys] X SD[Method]/SD[Wright]

(full cover) (14 years monthly data)
(three year period)

where SD = Calculated Standard Deviation.

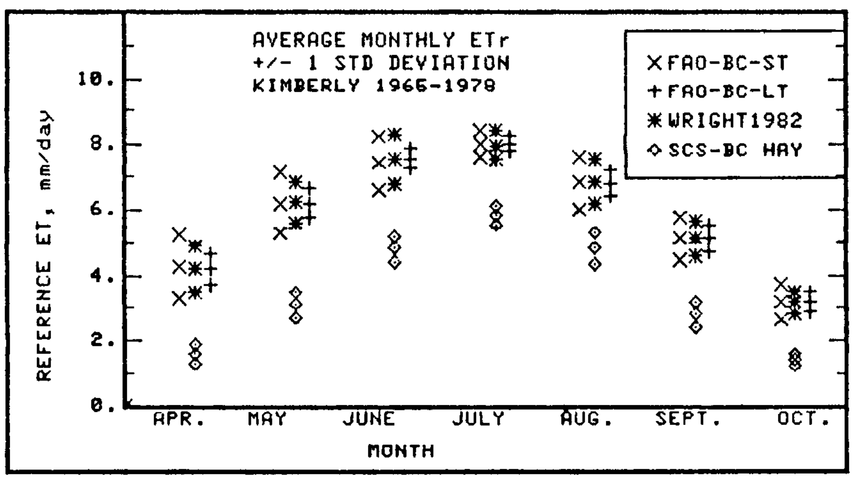

Figure 5. Calculated mean monthly alfalfa reference evapotranspiration plus or minus one standard deviation for monthly periods at Kimberly, Idaho during 1965-1978.

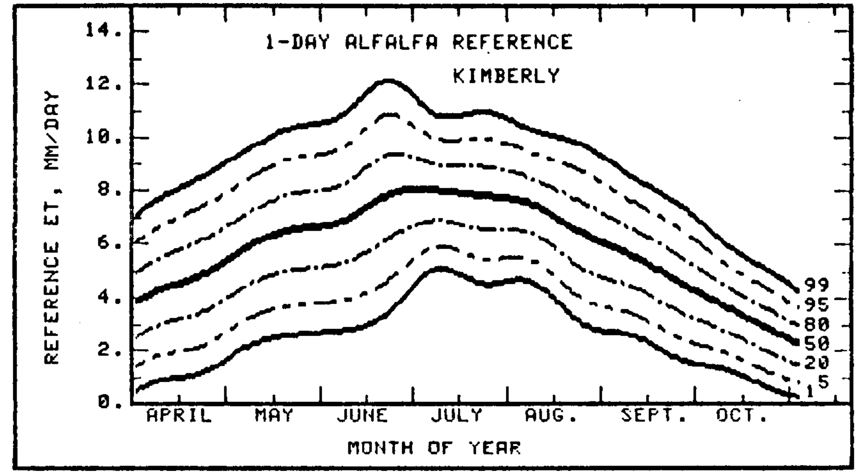

Figure 6. Frequency curves of daily estimates of alfalfa reference ET calculated using the Wright method for Kimberly, Idaho during 1965-1978.

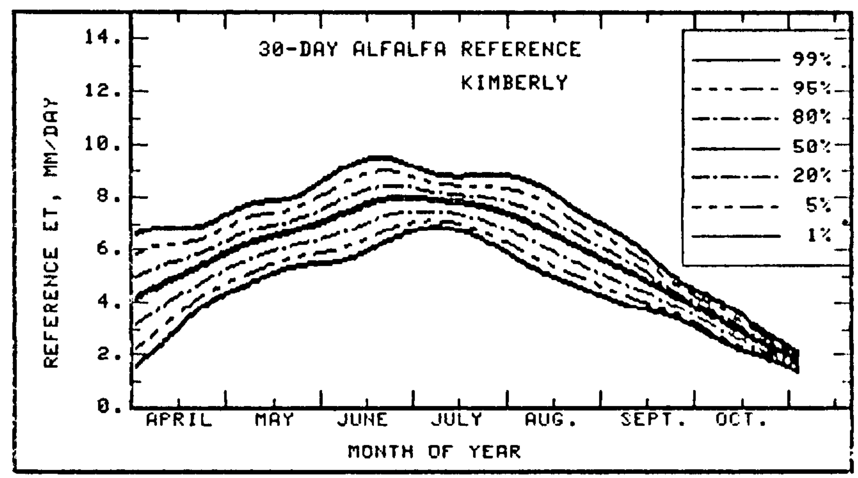

Figure 7. Frequency curves of thirty-day estimates of alfalfa reference ET calculated using the Wright method for Kimberly, Idaho during 1965-1978.

(standard deviations are 50% of actual). Results indicate that frequency analyses and probability tables generated using statistics describing estimated ET values will often result in an underestimation of the variation in daily and monthly consumptive use experienced by field crops. Estimated statistics should be adjusted according to comparisions made with lysimeter-measured values. Both measured ET and ET estimated using the modified Penman method were found to be normally distributed about the mean.

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