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CONSUMPTIVE USE COMPUTATIONS

FROM

EVAPORATION PAN DATA

(A Method of Calculating Irrigation Requirements.
for Irrigation Project Studies)

by

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United States Agency for International Development

Bogotá, Colombia

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CONSUMPTIVE USE COMPUTATIONS FROM EVAPORATION PAN DATA

by

George H. Hargreaves [1]

SYNOPSIS

The needs for improved methods of calculating irrigation requirements are described. The history of the development of evaporation and evapotranspiration (consumptive use) formulas is briefly given. New and improved evaporation formulas are presented and developed. The basis for formula improvement and for the formulas presented consists of large quantities of computer analysis of data. Ratios of evapotranspiration to Class A pan evaporation (Et/Ep) are studied for a large number of crops. Crops are grouped together into eight crop groups having similar consumptive use and irrigation requirements. Consumptive use coefficients for each of these groups are presented by 5 percent increments of the crop growing season or vegetative cycle. A formula is presented for converting consumptive use to irrigation requirements by allowing for a suitable irrigation efficiency and for utilizable rainfall

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INTRODUCTION

Agrarian reform and increased irrigation planning and construction, increasing uses of water for agriculture and other purposes make it necessary that improved methods be used for computing irrigation requirements and consumptive use and evapotranspiration requirements. Irrigation requirements need to be defined for canal design, for computing storage requirements and for planning the operation of projects.

The relationship of evaporation to consumptive use or evapotranspiration has long been recognized. Evaporation data or computations are necessary for reservoir operation studies and water use studies.

Fortunately recent developments make computations much easier. Al-Barrak[2] reviewed the literature on methods and formulas for estimating both evaporation and evapotranspiration and developed computer programs for 12 formulas for evaporation and 15 formulas for evapotranspiration.

This paper presents a method of computing irrigation requirements based upon Class A type evaporation pan data. Formulas

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2 Al-Barrak, Ala H., 1964, Evaporation and Evapotranspiration in Central Iraq., Master of Science thesis, Utah Water Research Laboratory, Utah State University, Logan, Utah.

are presented for computing evaporation equivalent to Class A pan data. These formulas use climatic data and include one that can be used from temperature data alone. More complicated formulas are presented requiring the availability of fairly complete climatic data.

HISTORICAL

As early as 1798 Dalton developed an evaporation formula. During the last 35 years numerous authors have derived formulas for computing evaporation from climatic data. The better known of these include Rohwer(1931), Meyer (1942), Blaney and Morin (1942), Penman (1948), Hargreaves (1956), Christiansen Patil (1961), Mathison (1963), and the Christiansen Mehta formula (1965). The Blaney-Morin[3] formula deserves special mention. It can be written: $Et \text{ or } Ep = K \left[(T \cdot P)/100\right](114 - H)$ (1)

where Et is consumptive use or evapotranspiration, Ep is Class A pan evaporation, T is the mean temperature in ^{o}F, P is the percentage of the annual daytime hours for the period considered, H is the mean relative humidity and K is an experimentally determined factor. This formula became the basis for later studies

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3 Blaney, H.F. and K.V. Morin, 1942, Evaporation and Consumptive Use of Water, Emperical Formulas, Trans., Am. Geophys. Union., 23, 76-83.

and other widely used formulas

In 1942 Lowery and Johnson developed a formula for relating use of water by crops to climatic data. Others of the better known formulas for computing consumptive use or evapotranspiration include those by Thornthwaite (1948), Penman (1948), Blaney-Criddle (1950), Hargreaves (1956), and Grassi (1964). These formulas are largely based upon the relationship of pan evaporation to evapotranspiration. Some of the formulas have been developed from previous research plus thousands of monthly evaporation data and thousands of evapotranspiration records. This paper attempts to utilize previous studies and formulas in such a manner as to provide the engineer and agriculturalist with formulas that can be applied in almost any set of circumstances.

EVAPORATION FORMULAS

A useful formula requiring a minimum of data can be expressed as follows: $Ep = D\,(13.5 - 0.135\,Hn)\,T$ (2)

in which Ep is Class A pan evaporation in mm., D is a monthly daytime coefficient as indicated in Table 1, Hn is the mean monthly relative humidity at noon or at 1300 hours and T is the mean monthly temperature in ^{o}centigrade. This equation produces results typical

TABLE 1

MONTHLY DAYTIME COEFFICIENTS

Latitude North	Jan.	Feb.	Mar.	Apr.	May	June
40°	0.81	0.81	1.00	1.07	1.20	1.21
38°	0.82	0.81	1.00	1.07	1.19	1.19
36°	0.84	0.82	1.00	1.06	1.12	1.18
34°	0.85	0.83	1.00	1.06	1.17	1.16
32°	0.86	0.84	1.00	1.05	1.16	1.15
30°	0.88	0.84	1.01	1.05	1.14	1.14
28°	0.89	0.84	1.01	1.04	1.14	1.13
26°	0.90	0.13	1.01	1.04	1.12	1.12
24°	0.91	0.86	1.01	1.03	1.12	1.10
22°	0.93	0.87	1.01	1.03	1.11	1.10
20°	0.93	0.87	0.98	1.02	1.10	1.08
18°	0.95	0.87	1.01	1.02	1.09	1.08
16°	0.95	0.88	1.01	1.01	1.08	1.08
14°	0.85	0.89	1.01	1.01	1.07	1.05
12°	0.97	0.89	1.01	1.01	1.06	1.04
10°	0.97	0.89	1.01	1.01	1.06	1.03
8°	0.98	0.89	1.01	0.41	1.05	1.02
6°	0.98	0.90	1.01	1.01	1.05	1.02
4°	0.98	0.91	1.02	1.00	1.04	1.01
2°	1.01	0.91	1.02	0.99	1.02	0.99
0°	1.02	0.92	1.02	1.00	1.02	0.99

Table 1. Continued

Latitude North	July	Aug.	Sep.	Oct.	Nov.	Dec.
40°	1.24	1.15	1.01	0.93	0.81	0.78
38°	1.21	1.14	1.01	0.94	0.82	0.80
36°	1.20	1.13	1.00	0.94	0.83	0.81
34°	1.19	1.12	1.00	0.95	0.84	0.83
32°	1.17	1.11	1.00	0.95	0.85	0.85
30°	1.16	1.11	1.00	0.96	0.86	0.86
28°	1.15	1.10	1.00	0.96	0.87	0.87
26°	1.14	1.09	1.00	0.97	0.88	0.88
24°	1.13	1.09	1.00	0.97	0.89	0.90
22°	1.12	1.08	1.00	0.98	0.90	0.91
20°	1.11	1.07	1.00	0.98	0.91	0.96
18°	1.10	1.06	0.99	0.99	0.92	0.94
16°	1.09	1.06	0.99	0.99	0.93	0.95
14°	1.08	1.05	0.99	0.99	0.94	0.96
12°	1.07	1.05	0.99	0.99	0.94	0.97
10°	1.06	1.05	0.99	0.99	0.95	0.97
8°	1.05	1.04	0.99	0.99	0.95	0.97
6°	1.05	1.04	0.99	1.01	0.95	0.98
4°	1.04	1.04	0.99	1.01	0.95	0.98
2°	1.02	1.02	0.98	1.02	0.98	1.01
0°	1.02	1.02	0.98	1.02	0.99	1.02

Table 1. Continued

Latitude South	Jan.	Feb.	Mar.	Apr.	May	June
0°	1.02	0.92	1.02	0.99	1.02	0.99
2°	1.03	0.93	1.02	0.98	1.01	0.98
4°	1.04	0.93	1.02	0.98	1.01	0.97
6°	1.05	0.94	1.02	0.97	1.00	0.96
8°	1.05	0.94	1.02	0.97	0.99	0.95
10°	1.06	1.05	1.02	0.97	0.98	0.94
12°	1.07	0.95	1.02	0.97	0.98	0.93
14°	1.08	0.96	1.02	0.96	0.97	0.92
16°	1.09	0.96	1.03	0.96	0.96	0.91
18°	1.10	0.97	1.03	0.96	0.96	0.90
20°	1.11	0.97	1.03	0.95	0.94	0.89
22°	1.12	0.97	1.03	0.95	0.93	0.88
24°	1.13	0.98	1.03	1.06	0.91	0.87
26°	1.14	0.99	0.96	0.94	0.91	0.85
28°	1.15	1.00	1.03	0.93	0.90	0.83
30°	1.16	1.00	1.04	0.93	0.89	0.83
32°	1.17	1.00	1.04	0.92	0.89	0.82
34°	1.19	1.01	1.04	0.92	0.88	0.81
36°	1.21	1.02	1.04	0.91	0.85	0.79
38°	1.22	1.03	1.04	0.91	0.84	0.78
40°	1.23	1.04	1.04	0.90	0.84	0.76
42°	1.25	1.05	1.05	0.90	0.82	0.74
44°	1.26	1.06	1.05	0.89	0.81	0.72
46°	1.28	1.07	1.05	0.89	0.79	0.70
48°	1.30	1.08	1.05	0.88	0.77	0.68
50°	1.32	1.09	1.05	0.87	0.76	0.66

Table 1. Continued

Latitude South	July	Aug.	Sep.	Oct.	Nov.	Dec.
0°	1.02	1.02	0.98	1.02	0.99	1.02
2°	1.01	1.01	0.98	1.14	0.99	1.03
4°	0.98	1.01	0.98	1.03	1.00	1.04
6°	0.98	1.00	0.98	1.03	1.11	1.05
8°	0.98	1.00	0.98	1.03	1.02	1.06
10°	0.97	0.99	0.98	1.04	1.02	1.07
12°	0.97	0.99	0.98	1.04	1.03	1.07
14°	0.85	0.98	0.98	1.04	1.04	1.08
16°	0.95	0.98	0.98	1.05	1.05	1.10
18°	0.95	1.07	0.98	1.06	1.06	1.11
20°	0.93	0.97	0.98	1.06	1.06	1.12
22°	0.93	0.96	0.98	1.06	1.07	1.13
24°	0.91	0.96	0.97	1.07	1.08	1.14
26°	0.90	0.94	0.97	1.07	1.09	1.15
28°	0.89	0.94	0.97	1.08	1.10	1.17
30°	0.88	0.94	0.97	1.08	1.11	1.18
32°	0.86	0.93	0.97	1.08	1.12	1.18
34°	0.85	0.92	0.97	1.09	1.13	1.20
36°	0.84	0.91	0.97	1.10	1.02	1.23
38°	0.82	0.90	0.97	1.10	1.15	1.24
40°	0.81	0.90	0.96	1.11	1.16	1.25
42°	0.79	0.89	0.96	1.11	1.17	1.27
44°	0.77	0.88	0.96	1.12	1.19	1.29
46°	0.76	0.87	0.96	1.13	1.20	1.31
48°	0.74	0.85	0.96	1.14	1.22	1.33
50°	0.72	0.84	0.95	1.14	1.24	1.36

of evaporation from a pan located in an irrigated area.

One of the problems encountered in using equation 2 has been the difficulties encountered in locating published data for noon humidity. In order to overcome this Al-Barrak[2] developed a formula for converting mean humidity for a 24 hour period to mean humidity at noon. This formula has been compared with data from Thailand and Colombia and somewhat modified. The revised formula can be written as follows:

$$Hn = 1+0.4H + 0.005H^2 \qquad (3)$$

in which Hn is mean humidity at noon or mean humidity at 1300 hours and H is mean humidity for a 24 hour period. Either daily values or monthly averages may be converted.

Unfortunately humidity data are not always available. Several authors have used temperature differences as a substitute for humidity data. Mathison[4] plotted relative humidity against temperature difference. The line of best fit can be expressed by the equation: $H = 109.3 - 3.53\,(\Delta T)$ (4)

in which H is mean relative humidity in percent and ΔT is

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4 Mathison, Kenneth José, 1963, The Use of Climatological and Related Factors for Estimating Evaporation, Master of Science thesis, Univ. Research Project. U - 193, Utah State University, Logan, Utah.

maximum temperature minus minimum temperature,

$\Delta T = T\ (max) - T\ (min)$, in ^{o}centigrade.

By using formulas 2, 3 and 4 evaporation can be calculated from temperature data and latitude.

With additional climatic data the accuracy of equation 2 can be substantially increased. The equation is based upon an average wind movement of 100 km. per day. Evaporation increases or decreases about 9 percent with each 50 km. per day increase or decrease in the wind. Where wind data are available it is recommended that this correction be applied.

Equation 2 is based upon conditions of approximately 60 percent sunshine. Where the sunshine is materially different from this the following corrections are proposed:

Percent Sunshine:	30	40	50	60	70	80	90
Correction in percent:	-14	-8	-4	0	+4	+11	+20

The percent sunshine can be calculated from cloud cover, scale 0 to 8. Palayasoot[5] developed the following formula:

$$S = 74.5 + 9.5C - 2.0C^2 \qquad (5)$$

in which S is the percent sunshine and C is cloud cover, scale 0-8.

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5 Palayasoot, Paitoon, 1965, Estimation of Pan Evaporation and Potential Evapotranspiration of Rice in the Central Plain of Thailand by Using Various Formulas based on Climatological Data, Master of Science thesis Utah State University, Logan, Utah.

Formula 2 is based upon data from locations with an average elevation of 500 feet, say 150 meters. Evaporation increases with elevation. Formula 2 can be corrected for elevation by increasing the calculated values by 1.0 percent for each 100 meter increase in elevation up to 1300 meters and by 0.7 percent for each 100 meter increase above elevation 1300 meters.

Christiansen and Mehta[6] have made a very detailed analysis of more than 3,650 months of pan evaporation data from 23 U.S. States and from Nigeria, Peru, Panama, Puerto Rico, and Canada. As a result of computer analysis they derived a formula for computing evaporation from a standard U.S. Weather Bureau Class A pan as follows:

$$Ep = K\,R\,C_T\,C_W\,C_H\,C_S\,C_E\,C_M \qquad (6)$$

in which Ep is Class A pan evaporation in inches, K = 0.4677, R is the radiation as given in Table 3.

$C_T = 0.1532 + 0.00874T + 0.0000546T^2$ (Table 4).

$C_W = 0.790 + 0.0037W - 0.00000333W^2$ (Table 5).

$C_E = 0.9654 + 0.0362E - 0.0016E^2$ (Table 8).

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6 Christiansen, J.E. and Mehta, Ashwen D., 1965, Estimation of Pan Evaporation from Climatological Data, Utah Water Research Laboratory, Utah State University, Logan, Utah.

$C_H = 1.202 - 0.00353\ H - 0.0000381\ H^2$ (Table 6).

$C_S = 0.402 + 0.019\ S - 0.0028\ S^2 + 0.0000017\ S^3$ (Table 7).

C_M is the monthly coefficient as given in Table 2.

Application of the formula

The formula looks impractical because of the time needed to calculate the coefficients. This is solved by the use of several tables which give the coefficient and the logarithm of the coefficient for each of the factors.

To show just how the formula can be applied, the following example, based on the same climatic data as was used by Patil[7] is presented by Christiansen and Mehta[6].

Station: Lodi, California

Year: 1951

Month: June

Factor	Value	Coefficient	Logarithm
K	0.4677		-0.3300
R (Table 3)	19.83		1.2973
Temperature, °F	67.7	0.995	-0.0021
Wind mpd	74.6	1.048	0.0202

7 Patil, B. B., 1962, A New Formula for the Evaluation of Evaporation. Master of Science thesis, Utah State University - Library, Logan, Utah, (Unpublished).

Factor	Value	Coefficient	Logarithm
Humidity, %	42.5	0.985	-0.0029
Sunshine, %	96	1.15	0.0605
Elevation, feet	40	0.967	-0.0146
Monthly coefficient (Table 2)		1.00	0.0000
Sum of logarithm			1.0284
Estimated evaporation (antilog)			10.68
Actual evaporation			10.02

Table 2. Monthly coefficients by groups

Group	Latitude Range	Months of Record	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
	South													
1	12	34	1.24	1.23	1.25	1.24	1.21	1.22	1.33	1.34	1.26	1.20	1.16	1.17
	North													
2	4 - 13	127	0.93	0.96	0.96	1.00	0.93	0.94	0.90	0.90	0.92	0.93	0.96	0.95
3	18 - 22	140	1.10	1.08	1.05	1.05	1.04	1.025	1.04	1.03	1.05	1.06	1.065	1.10
4	26 - 34	688	1.10	1.05	1.00	0.94	0.90	0.94	0.95	0.98	1.00	1.05	1.14	1.19
5	31 - 34	638	0.95	1.00	1.02	1.02	0.99	0.98	1.00	0.98	0.98	1.00	1.00	1.00
6	33	120	0.96	1.00	1.02	1.05	1.05	1.07	1.05	1.07	1.05	1.10	1.10	1.05
7	34 - 37	205	1.04	1.05	1.05	1.08	1.09	1.09	1.12	1.18	1.23	1.25	1.27	1.18
8	38 - 40	421	0.88	0.85	0.95	1.00	1.00	1.00	0.99	1.03	1.04	1.03	0.97	0.89
9	38 - 42	99	---	---	---	0.92	0.90	0.90	0.90	0.95	0.98	1.05	---	---
10	38 - 39	115	---	---	---	1.20	1.15	1.08	1.10	1.10	1.13	1.20	1.33	---
11	38 - 41	125	---	1.15	1.10	0.90	0.88	0.85	0.84	0.83	0.87	1.04	1.04	---
12	40 - 42	325	---	---	0.85	0.85	0.84	0.84	0.83	0.88	0.92	0.94	---	---
13	42 - 45	213	0.75	0.77	0.85	0.93	0.94	0.97	1.00	1.03	0.95	0.90	0.80	0.70
14	45 - 49	168	---	---	---	0.97	0.90	0.88	0.90	1.00	1.00	0.98	---	---
15	46 - 48	130	---	0.65	0.75	0.75	0.80	0.80	0.85	0.87	0.85	0.80	0.75	---
16	43 - 62	100	---	---	---	1.18	1.13	1.08	1.05	1.05	1.10	1.15	---	---

Table 3. Solar radiation, R, at top of atmosphere. Expressed as equivalent evaporation at 20° C.*

Latitude	Jan.	Feb.**	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
North						inches						
60	1.76	3.93	8.53	13.28	18.05	19.51	19.12	15.39	10.23	5.68	2.27	1.19
50	4.59	6.65	11.27	15.12	19.01	19.80	19.72	16.91	12.48	8.70	5.15	3.80
45	6.05	7.99	12.53	15.89	19.34	19.88	19.90	17.52	13.51	10.12	6.60	5.21
40	7.53	9.29	13.69	16.56	19.57	19.89	20.00	18.02	14.45	10.44	8.03	6.67
35	9.03	10.54	14.74	17.12	19.69	19.80	20.00	18.41	15.29	12.66	9.45	8.16
30	10.52	11.72	15.68	17.57	19.70	19.60	19.90	18.68	16.02	13.78	10.80	9.66
25	11.97	12.82	16.50	17.90	19.59	19.28	19.68	18.82	16.63	14.80	12.10	11.15
20	13.35	13.83	17.20	18.10	19.35	18.84	19.34	18.83	17.11	15.74	13.34	12.61
15	14.63	14.74	17.77	18.16	18.98	18.29	18.87	18.70	17.45	16.60	14.50	14.03
10	15.81	15.54	18.20	18.07	18.48	17.63	18.27	18.44	17.65	17.36	15.57	15.36
5	16.88	16.22	18.49	17.85	17.86	16.86	17.55	18.05	17.72	17.98	16.53	16.59
Equator	17.84	16.78	18.63	17.50	17.12	15.99	16.71	17.53	17.67	18.42	17.37	17.70
South												
5	18.68	17.23	18.62	17.03	16.27	15.02	15.77	16.88	17.46	18.68	18.09	18.67
10	19.40	17.58	18.47	16.43	15.32	13.95	14.73	16.10	17.15	18.80	18.70	19.51
15	20.02	17.72	18.19	15.71	14.27	12.79	13.60	15.20	16.70	18.80	19.19	20.23
20	20.52	17.84	17.79	14.87	13.12	11.57	12.39	14.20	16.12	18.70	19.55	20.73
25	20.90	17.84	17.27	13.92	11.89	10.29	11.11	13.17	15.42	18.50	19.77	21.21
30	21.14	17.70	16.63	12.86	10.58	8.95	9.77	12.00	14.61	18.18	19.85	21.56
35	21.28	17.42	15.84	11.70	9.21	7.57	8.38	10.77	13.70	17.72	19.81	21.78
40	21.22	17.00	14.92	10.56	7.80	6.19	6.96	9.49	12.59	17.11	19.66	21.86
50	20.88	15.76	12.68	8.00	5.09	3.59	4.16	6.28	10.31	15.44	19.07	21.65

* Computed from data by Napier Shaw (1942).
** February computed for average of 28.25 days.

Table 4. Temperature, coefficient of temperature and Log C

T	T	C_T	Log C_T	T	T	C_T	Log C_T
°F	°C	-----	-----	°F	°C	-----	-----
35	1.67	.526	-.2790	70	21.11	1.033	.0138
36	2.22	.539	-.2687	71	21.67	1.049	.0207
37	2.78	.551	-.2585	72	22.22	1.066	.0275
38	3.33	.564	-.2485	73	22.78	1.082	.0343
39	3.89	.577	-.2387	74	23.33	1.099	.0409
40	4.44	.590	-.2290	75	23.89	1.116	.0475
41	5.00	.603	-.2194	76	24.44	1.133	.0541
42	5.56	.617	-.2099	77	25.00	1.150	.0606
43	6.11	.630	-.2006	78	25.56	1.167	.0671
44	6.67	.643	-.1914	79	26.11	1.184	.0735
45	7.22	.657	-.1824	80	26.67	1.202	.0798
46	7.78	.671	-.1734	81	27.22	1.219	.0861
47	8.33	.685	-.1645	82	27.78	1.237	.0923
48	8.89	.699	-.1558	83	28.33	1.255	.0985
49	9.44	.713	-.1471	84	28.89	1.273	.1047
50	10.00	.727	-.1386	85	29.44	1.291	.1107
51	10.56	.741	-.1302	86	30.00	1.309	.1168
52	11.11	.755	-.1218	87	30.56	1.327	.1228
53	11.67	.770	-.1136	88	31.11	1.345	.1287
54	12.22	.784	-.1054	89	31.67	1.364	.1346
55	12.78	.799	-.0974	90	32.22	1.382	.1405
56	13.33	.814	-.0894	91	32.78	1.401	.1463
57	13.89	.829	-.0815	92	33.33	1.419	.1520
58	14.44	.844	-.0737	93	33.89	1.438	.1578
59	15.00	.859	-.0660	94	34.44	1.457	.1635
60	15.56	.874	-.0584	95	35.00	1.476	.1691
61	16.11	.890	-.0508	96	35.56	1.495	.1747
62	16.67	.905	-.0433	97	36.11	1.515	.1803
63	17.22	.921	-.0359	98	36.67	1.534	.1858
64	17.78	.936	-.0286	99	37.22	1.554	.1913
65	18.33	.952	-.0213	100	37.78	1.573	.1967
66	18.89	.968	-.0141	101	38.33	1.593	.2022
67	19.44	.984	-.0070	102	38.89	1.613	.2075
68	20.00	1.000	.0000	103	39.44	1.633	.2128
69	20.56	1.016	.0070	104	40.00	1.653	.2181

Table 4. Continued

T	T	C_T	Log C_T
°F	°C	-----	-----
105	40.56	1.673	.2234
106	41.11	1.693	.2286
107	41.67	1.713	.2338
108	42.22	1.734	.2390
109	42.78	1.755	.2441
110	43.33	1.775	.2492
111	43.89	1.796	.2543
112	44.44	1.817	.2593
113	45.00	1.838	.2643
114	45.56	1.859	.2693
115	46.11	1.880	.2742
116	46.67	1.902	.2791
117	47.22	1.923	.2840
118	47.78	1.945	.2888
119	48.33	1.966	.2936
120	48.89	1.988	.2984

Table 5. Wind, coefficient of wind, and Log C_W

W	W	C_W	Log C_W	W	W	C_W	Log C_W
mi/day	km/day	-----	---	mi/day	km/day	---	---
0	0.00	.790	-.1023				
5	8.05	.808	-.0923	155	249.45	1.283	.1083
10	16.09	.827	-.0826	160	257.50	1.297	.1128
15	24.14	.845	-.0732	165	265.54	1.310	.1172
20	32.19	.863	-.0641	170	273.59	1.323	.1214
25	40.23	.880	-.0553	175	281.64	1.336	.1256
30	48.28	.898	-.0467	180	289.68	1.348	.1297
35	56.33	.915	-.0383	185	297.73	1.361	.1337
40	64.37	.933	-.0302	190	305.78	1.373	.1375
45	72.42	.950	-.0223	195	313.82	1.385	.1414
50	80.47	.967	-.0147	200	321.87	1.397	.1451
55	88.51	.983	-.0072	205	329.92	1.409	.1487
60	96.56	1.000	.0000	210	337.96	1.420	.1523
65	104.61	1.016	.0070	215	346.01	1.432	.1558
70	112.65	1.033	.0139	220	354.06	1.443	.1592
75	120.70	1.049	.0206	225	362.10	1.454	.1625
80	128.75	1.065	.0272	230	370.15	1.465	.1657
85	136.79	1.080	.0336	235	378.20	1.476	.1689
90	144.84	1.096	.0398	240	386.24	1.486	.1603
95	152.89	1.111	.0459	245	394.29	1.497	.1751
100	160.94	1.127	.0518	250	402.34	1.507	.1780
105	168.98	1.142	.0575	255	410.38	1.517	.1809
110	177.03	1.157	.0632	260	418.43	1.527	.1837
115	185.08	1.171	.0687	265	426.48	1.547	.1865
120	193.12	1.186	.0740	270	434.52	1.546	.1892
125	201.17	1.200	.0793	275	442.57	1.556	.1919
130	209.22	1.215	.0844	280	450.62	1.565	.1944
135	217.26	1.229	.0894	285	458.66	1.574	.1969
140	225.31	1.243	.0943	290	466.71	1.583	.1994
145	233.36	1.256	.0991	295	474.76	1.592	.2018
150	241.40	1.270	.1038	300	482.81	1.600	.2042

Table 6. Relative humidity, coefficient of humidity, and Log C_H

H	C_H	Log C_H	H	C_H	Log C_H
%	---	---	%	---	---
0	1.202	.0799			
1	1.198	.0786	36	1.026	.0110
2	1.195	.0773	37	1.019	.0083
3	1.191	.0759	38	1.013	.0055
4	1.187	.0745	39	1.006	.0028
5	1.183	.0731	40	1.000	.0000
6	1.179	.0717	41	.993	-.0030
7	1.175	.0702	42	.987	-.0059
8	1.171	.0687	43	.980	-.0089
9	1.167	.0671	44	.973	-.0119
10	1.163	.0655	45	.966	-.0150
11	1.159	.0639	46	.959	-.0182
12	1.154	.0623	47	.952	-.0214
13	1.150	.0606	48	.945	-.0247
14	1.145	.0588	49	.938	-.0280
15	1.140	.0571	50	.930	-.0314
16	1.136	.0553	51	.923	-.0349
17	1.131	.0535	52	.915	-.0384
18	1.126	.0516	53	.908	-.0420
19	1.121	.0497	54	.900	-.0456
20	1.116	.0477	55	.893	-.0493
21	1.111	.0457	56	.885	-.0531
22	1.106	.0437	57	.877	-.0570
23	1.101	.0417	58	.869	-.0609
24	1.095	.0395	59	.861	-.0649
25	1.090	.0374	60	.853	-.0690
26	1.084	.0352	61	.845	-.0732
27	1.079	.0330	62	.837	-.0774
28	1.073	.0307	63	.828	-.0818
29	1.068	.0284	64	.820	-.0862
30	1.062	.0260	65	.812	-.0907
31	1.056	.0236	66	.803	-.0953
32	1.050	.0212	67	.794	-.0999
33	1.044	.0187	68	.786	-.1047
34	1.038	.0162	69	.777	-.1096
35	1.032	.0136	70	.768	-.1145

Table 6. Continued

H	C_H	Log C_H
%	----	----
71	.759	-.1196
72	.750	-.1247
73	.741	-.1300
74	.732	-.1354
75	.723	-.1409
76	.714	-.1465
77	.704	-.1522
78	.695	-.1581
79	.685	-.1641
80	.676	-.1702
81	.666	-.1765
82	.656	-.1829
83	.647	-.1894
84	.637	-.1961
85	.627	-.2030
86	.617	-.2100
87	.607	-.2172
88	.596	-.2245
89	.586	-.2321
90	.576	-.2398
91	.565	-.2477
92	.555	-.2559
93	.544	-.2643
94	.534	-.2728
95	.523	-.2817
96	.512	-.2907
97	.501	-.3001
98	.490	-.3097
99	.479	-.3196
100	.468	-.3298

Table 7. Sunshine percentage, coefficient of sunshine, and log C_S

S	C_S	Log C_S	S	C_S	Log C_S
%	----	-----	%	----	----
0	.402	-.3958			
1	.421	-.3760	36	.802	-.0956
2	.439	-.3576	37	.808	-.0927
3	.457	-.3405	38	.813	-.0899
4	.474	-.3245	39	.818	-.0872
5	.490	-.3096	40	.823	-.0847
6	.506	-.2956	41	.827	-.0823
7	.522	-.2825	42	.832	-.0799
8	.537	-.2700	43	.836	-.0776
9	.552	-.2584	44	.841	-.0753
10	.566	-.2474	45	.845	-.0732
11	.579	-.2370	46	.849	-.0711
12	.593	-.2272	47	.853	-.0691
13	.605	-.2179	48	.857	-.0671
14	.618	-.2091	49	.861	-.0651
15	.630	-.2008	50	.865	-.0632
16	.641	-.1929	51	.868	-.0614
17	.652	-.1854	52	.872	-.0595
18	.663	-.1783	53	.876	-.0577
19	.674	-.1715	54	.879	-.0559
20	.684	-.1652	55	.883	-.0541
21	.693	-.1590	56	.886	-.0523
22	.703	-.1533	57	.890	-.0506
23	.712	-.1477	58	.894	-.0488
24	.720	-.1425	59	.897	-.0470
25	.729	-.1375	60	.901	-.0451
26	.737	-.1327	61	.905	-.0433
27	.744	-.1282	62	.909	-.0415
28	.752	-.1239	63	.913	-.0397
29	.759	-.1197	64	.917	-.0377
30	.766	-.1158	65	.921	-.0358
31	.773	-.1120	66	.925	-.0338
32	.779	-.1084	67	.929	-.0318
33	.785	-.1050	68	.934	-.0297
34	.791	-.1017	69	.938	-.0276
35	.797	-.0986	70	.943	-.0254

Table 7. Continued

S	C_S	Log C_S
%	----	----
71	.943	-.0232
72	.953	-.0209
73	.958	-.0185
74	.964	-.0161
75	.969	-.0136
76	.975	-.0110
77	.981	-.0083
78	.987	-.0056
79	.994	-.0027
80	1.000	.0002
81	1.007	.0032
82	1.015	.0063
83	1.022	.0095
84	1.030	.0128
85	1.038	.0162
86	1.046	.0197
87	1.055	.0233
88	1.064	.0270
89	1.074	.0308
90	1.083	.0347
91	1.093	.0388
92	1.104	.0429
93	1.115	.0472
94	1.126	.0515
95	1.138	.0558
96	1.150	.0540
97	1.162	.0652
98	1.175	.0700
99	1.188	.0749
100	1.202	.0799

Table 8. Elevation, coefficient of elevation, and log C_E

Elev. E 1000 feet	Elev. meters	C_E	Log C_E	Elev. E 1000 feet	Elev. meters	C_E	Log C_E
.0	0	.965	-.0153				
.1	30	.969	-.0137	3.6	1097	1.075	.0313
.2	61	.973	-.0121	3.7	1128	1.077	.0323
.3	91	.976	-.0106	3.8	1158	1.080	.0333
.4	122	.980	-.0089	3.9	1189	1.082	.0343
.5	152	.983	-.0074	4.0	1219	1.085	.0352
.6	183	.987	-.0059	4.1	1250	1.087	.0362
.7	213	.990	-.0044	4.2	1280	1.089	.0371
.8	244	.993	-.0029	4.3	1311	1.091	.0380
.9	274	.997	-.0014	4.4	1341	1.094	.0389
1.0	305	1.000	.0000	4.5	1372	1.096	.0397
1.1	335	1.003	.0014	4.6	1402	1.098	.0406
1.2	366	1.007	.0028	4.7	1433	1.100	.0414
1.3	396	1.010	.0042	4.8	1463	1.102	.0422
1.4	427	1.013	.0056	4.9	1494	1.104	.0431
1.5	457	1.016	.0069	5.0	1524	1.106	.0439
1.6	488	1.019	.0082	5.1	1554	1.108	.0446
1.7	518	1.022	.0095	5.2	1585	1.110	.0454
1.8	549	1.025	.0109	5.3	1615	1.112	.0462
1.9	579	1.028	.0121	5.4	1646	1.114	.0469
2.0	610	1.031	.0134	5.5	1676	1.116	.0476
2.1	640	1.034	.0146	5.6	1707	1.118	.0484
2.2	671	1.037	.0158	5.7	1737	1.120	.0491
2.3	701	1.040	.0171	5.8	1768	1.122	.0498
2.4	732	1.043	.0183	5.9	1798	1.123	.0505
2.5	762	1.046	.0194	6.0	1829	1.125	.0511
2.6	792	1.049	.0206	6.1	1859	1.127	.0518
2.7	823	1.051	.0218	6.2	1890	1.128	.0524
2.8	853	1.054	.0229	6.3	1920	1.130	.0530
2.9	884	1.057	.0240	6.4	1951	1.132	.0536
3.0	914	1.060	.0251	6.5	1981	1.133	.0542
3.1	945	1.062	.0262	6.6	2012	1.135	.0548
3.2	975	1.065	.0272	6.7	2042	1.136	.0554
3.3	1006	1.067	.0283	6.8	2073	1.138	.0559
3.4	1036	1.070	.0293	6.9	2103	1.139	.0565
3.5	1067	1.073	.0304	7.0	2134	1.140	.0570

Table 8. Continued

Elev. E	Elev.	C_E	Log C_E
1000 feet	meters		
7.1	2164	1.142	.0575
7.2	2195	1.143	.0580
7.3	2225	1.144	.0585
7.4	2256	1.146	.0590
7.5	2286	1.147	.0595
7.6	2316	1.148	.0599
7.7	2347	1.149	.0604
7.8	2377	1.150	.0608
7.9	2408	1.152	.0612
8.0	2438	1.153	.0616
8.1	2469	1.154	.0620
8.2	2499	1.155	.0624
8.3	2530	1.156	.0628
8.4	2560	1.157	.0631
8.5	2591	1.158	.0635
8.6	2621	1.158	.0638
8.7	2652	1.159	.0641
8.8	2682	1.160	.0644
8.9	2713	1.161	.0647
9.0	2743	1.162	.0650
9.1	2774	1.162	.0653
9.2	2804	1.163	.0655
9.3	2835	1.164	.0658
9.4	2865	1.164	.0660
9.5	2896	1.165	.0662
9.6	2926	1.165	.0664
9.7	2957	1.166	.0667
9.8	2987	1.166	.0668
9.9	3018	1.167	.0670
10.0	3048	1.167	.0672
10.1	3078	1.168	.0673
10.2	3109	1.168	.0674
10.3	3139	1.169	.0676
10.4	3170	1.169	.0677
10.5	3200	1.169	.0678

Palayasoot[5] computed pan evaporation by equation 2 and by an equation similar to equation 6. He then computed monthly coefficients (C_m) for pan evaporation and compared equation 2 and equation 6. Equation 2 was used without correction for differences in sunshine or wind. Values of C_m are given for equation 2 in Figure 1 and for the Palayasoot formula in Figure 2. It is obvious that the simpler equation (equation 2) contains larger errors in computed monthly values but will on the average indicate approximately the same evaporation or irrigation requirements. When used with corrections for wind, sunshine and elevation this simple equation gives results exceeding the limits of required accuracy for engineering design.

As will be demonstrated later evaporation and evapotranspiration do not correlate as well during conditions where advection is high. Under these conditions (hot dry windy climate) formula 2 may somewhat under estimate evaporation but will still provide a dependable index of irrigation requirements.

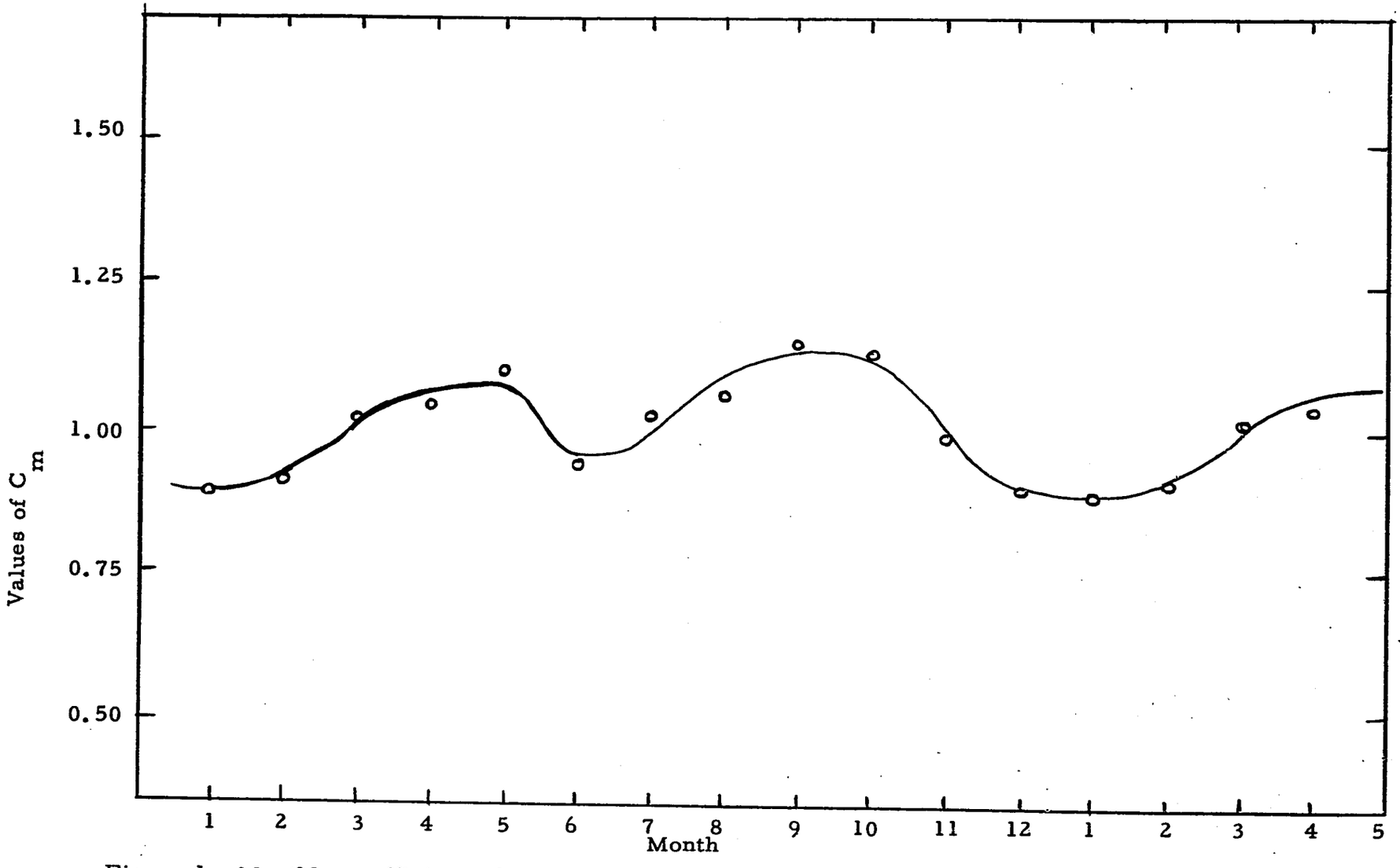

Figure 1. Monthly coefficients for pan evaporation by Hargreaves formula (equation 2)

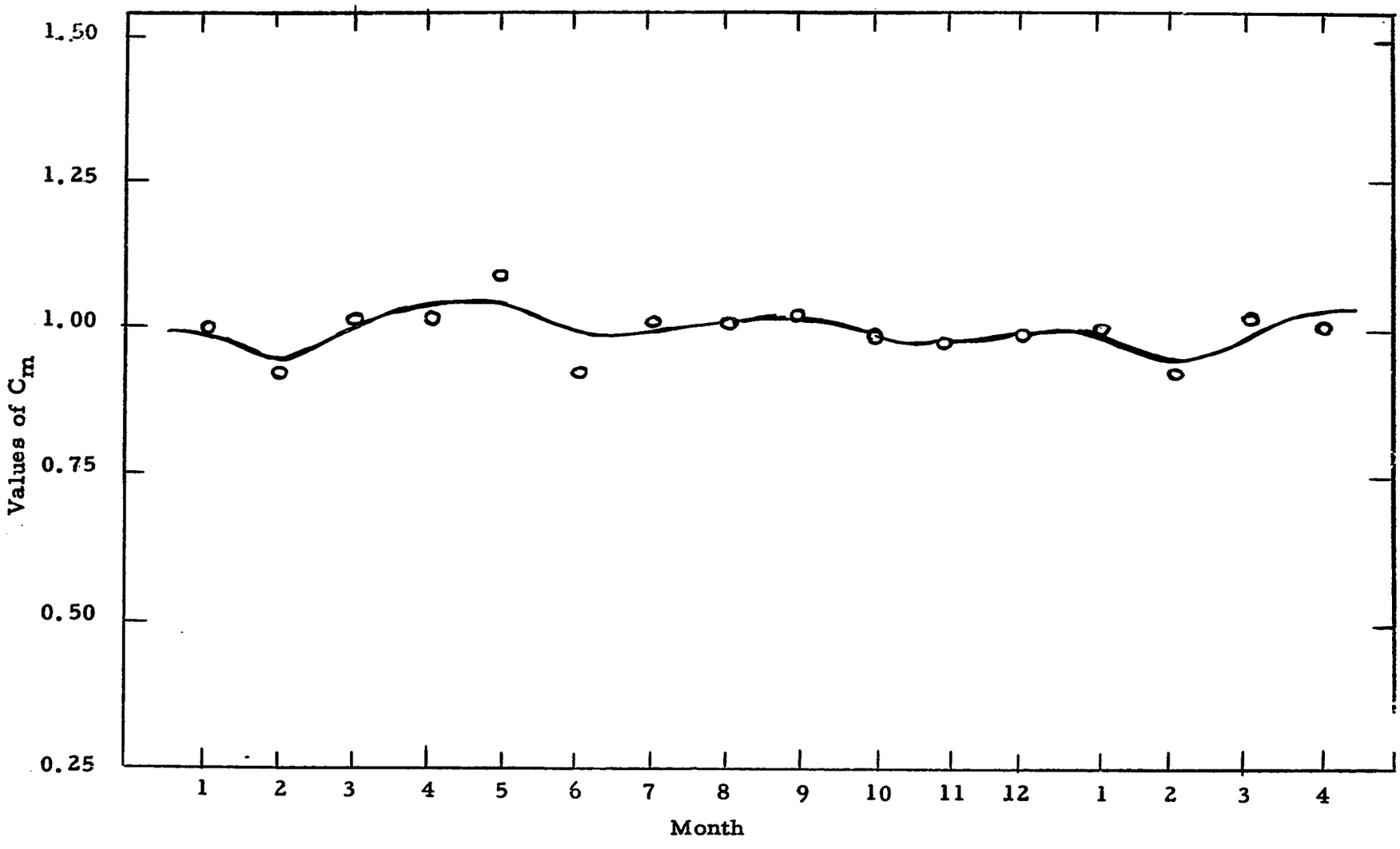

Figure 2. Monthly coefficients for pan evaporation by Palayasoot formula

EVAPOTRANSPIRATION COMPUTATIONS

The relationship of evapotranspiration to pan evaporation has long been used in the computation of irrigation requirements. This relationship formed the basis for the Blaney-Morin[3] equation the Hargreaves[8] formula and the Grassi[9] formulas. In the Central Valley of California Hargreaves [10] used evaporation data for transferring consumptive use measurements from one location and applying them to another. Pruitt[11] found a high degree of correlation between evapotranspiration by ladino clover and pan evaporation. Correlation coefficients ranged from .972 to .995. The work at Davis, California with rye grass grown on a weighing lysimeter shows a good correlation with evapotranspiration. In

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8 Hargreaves, G. H. 1956, Irrigation Requirements Based on Climatic Data, Paper 1105, Journal of the Irrigation and Drainage Div., Amer. Soc. Civil Engrs. Vol. 82 No. IR-3.

9 Grassi, Carlos Julian, Estimation of Evapotranspiration from Climatic Formulas, Master of Science thesis, Proj. EC-33g, Utah State University, Logan, Utah.

10 Hargreaves, G. H. 1948, Irrigation Requirement Data for Central Valley Crops, U.S. Department of Interior, Bureau of Reclamation, Sacramento, California.

11 Pruitt, W. O. 1960, Relation of Consumptive Use of Water to Climate, Trans. Amer. Soc. Agr. Engrs., Vol. 3, No. 1.

this work Pruitt[12] found that on high advection days, or days of strong dry north winds evaporation sometimes increased by 300 to 500 percent but evapotranspiration increased in the range of 50 to 100 percent.

Formula 2 is based upon data from areas where low advection prevailed and is considered typical of evaporation from a Class A pan located in an irrigated area. Pruitt found that, by using an evaporation pan located in a large irrigated grass field as a standard, evaporation was increased by 11 percent for a pan located in a 48 foot fetch of irrigated grass and by 25 percent for a pan located in a dry land area. In comparing measured pan evaporation with computed evaporation, differences in pan exposure must be taken into account.

Anderson[13] developed crop curves relating ratios of Et/Ep (Evapotranspiration divided by Class A pan evaporation) to percent of active plant growing period. Grassi[9] developed formulas for

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12 Pruitt, W. O. 1960, Correlation of Climatological data with Water Requirements of Crops. Annual Report. Dept. of Irrigation, University of California, Davis, California.

13 Anderson, Bruce H. 1963, A Method of Estimating Evapotranspiration for Use in Determining Water Requirements of an Irrigation Project, Doctor of Engineering thesis, University of California, Davis, California.

computing evapotranspiration (Et) which included factors for crop cover and for the vegetative cycle. The Grassi formulas contain a crop factor, F, which takes into consideration other anatomical and physiological characteristics of the crop species. The Grassi crop factors are as follows:

Crop	F	Crop	F
Alfalfa	1.09	Winter Wheat	1.10
Beans	0.98	Apples with Cover Crop	1.27
Corn	1.00	Dates with Cover Crop	1.07
Cotton	1.08	Dates with Grape fruit	0.99
Oats	0.89	Grapes	0.61
Potatoes	1.02	Grape fruit	0.62
Grain Sorghum	1.16	Lemons	0.52
Sugar Beets	1.00	Oranges	0.51

Anderson[13] obtained evapotranspiration data from several sources for eight crops and plotted the ratio of evapotranspiration to pan evaporation (Et/Ep) as a percent of the crop growing season. From these data a mean curve was developed. Since the curves were similar for the various crops a mean curve was

developed showing the percent of maximum ratio of evapotranspiration to pan evaporation as a function of the percent of the crop growing season(%Max Et/Ep and %CV). The crops used and the maximum ratios for Et/Ep were the following:

Crop	Max. Et/Ep	Crop	Max. Et/Ep
Peaches	0.74	Beans	0.85
Plums	0.70	Cotton	0.82
Walnuts	0.74	Sugar Beets	0.78
Citrus	0.56	Tomatoes	0.75

A comparison was made of Et/Ep ratios for all available data. These data included those reported by Anderson[13], by Blaney and Harris[14], by Palayasoot[5], by Grassi[9], and by Hargreaves[8]. Data from Palmira, Colombia[15], and from several other sources were also evaluated. An attempt was made to group the similar crops together. Et/Ep ratios were plotted against vegetative cycle percentage for individual crops. Smooth curves of approximate best fit were drawn. Although experimental data give a wide variation in results general conclusions can be drawn by eliminating unusually low or unusually high values. Three types

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14 Blaney H. F. and Harris, Karl, 1951, Consumptive Use and Irrigation Requirements of Crops in Arizona, USDA, Soil Cons. Serv., Washington, D. C.

15 Unpublished data furnished by Dr. Angel Ibarra (Caicedo).

of curves were obtained. These are:

a. The fairly flat curve with not much change from month to month in the Et/Ep ratios.

b. A fairly even bell type curve which gave maximum Et/Ep ratios when from 50 to 60 percent of the crop vegetative cycle had been completed.

c. A curve similar to the bell type but with maximum Et/Ep ratios occuring when 75 to 80 percent of the crop growing season had been completed.

Similar crops are grouped together into crop groups as follows:

Crop Group A: These crops have a modal grouping of maximum Et/Ep ratios in the range of 0.75 to 1.15. In this study a value of 1.00 is used. The more important crops include: beans, corn, cotton, potatoes, sugar beets, grain sorghum, peas and tomatoes.

Crop Group B: This group consists of the deciduous fruits and include: dates, olives, peaches, plums and walnuts. The maximum Et/Ep ratio is about 0.75.

Crop Group C: The crops include melons, onions, carrots, hops, grapes and almonds with a maximum Et/Ep ratio of about 0.60.

Crop Group D: The maximum Et/Ep ratio is about 0.90 and usually occurs at about 75 to 80 percent completion of the crop vegetative cycle. The crops included are asparagus, barley, celery, flax, oats and wheat.

Crop Group E: These crops have fairly flat curves. Ratios of Et/Ep range from 0.70 to 1.20. The usual or modal group ratio is about 1.00. The crops include pangola pasture, trenza pasture, orchard with cover crop, bananas and plantain.

Crop Group F: This group includes the citrus crops: oranges, lemons and grapefruit. The Et/Ep ratios are fairly constant throughout the year and average about 0.60.

Crop Group G: Group G includes sugar cane and alfalfa.

Rice: The Et/Ep ratios present a fairly flat curve. A maximum value of 1.10 and a minimum of 0.80 is proposed as representative of average conditions.

Table 9 gives evapotranspiration coefficients, K, for computing evapotranspiration (Et) from either computed or measured evaporation (Ep).

Table 9. Crop Consumptive Use Coefficients

Percent of Crop Growing Season	Consumptive Use (Evapotranspiration) Coefficients, K, to be Multiplied by Class A Pan Evaporation or Calculated Ep.							
	Group A	Group B	Group C	Group D	Group E	Group F	Group G	Rice
0	0	0	0	0	0	0	0	0
5	0.20	0.15	0.12	0.08	1.00	0.60	0.55	0.90
10	0.36	0.27	0.22	0.15	1.00	0.60	0.60	0.92
15	0.50	0.38	0.30	0.19	1.00	0.60	0.65	0.95
20	0.64	0.48	0.38	0.27	1.00	0.60	0.70	0.98
25	0.75	0.56	0.45	0.33	1.00	0.60	0.75	1.00
30	0.84	0.63	0.50	0.40	1.00	0.60	0.80	1.03
35	0.92	0.69	0.55	0.46	1.00	0.60	0.85	1.06
40	0.97	0.73	0.58	0.52	1.00	0.60	0.90	1.08
45	0.99	0.74	0.60	0.58	1.00	0.60	0.95	1.10
50	1.00	0.75	0.60	0.65	1.00	0.60	1.00	1.10
55	1.00	0.75	0.60	0.71	1.00	0.60	1.00	1.10
60	0.99	0.74	0.60	0.77	1.00	0.60	1.00	1.10
65	0.96	0.72	0.58	0.82	1.00	0.60	0.95	1.10
70	0.91	0.68	0.55	0.88	1.00	0.60	0.90	1.05
75	0.85	0.64	0.51	0.90	1.00	0.60	0.85	1.00
80	0.75	0.56	0.45	0.90	1.00	0.60	0.80	0.95
85	0.60	0.45	0.36	0.80	1.00	0.60	0.75	0.90
90	0.46	0.35	0.28	0.70	1.00	0.60	0.70	0.85
95	0.28	0.21	0.17	0.60	1.00	0.60	0.55	0.80
100	0	0	0	0	0	0	0	0

IRRIGATION REQUIREMENTS

In order to convert evapotranspiration to irrigation requirements it is necessary to determine the utilizable rainfall and the irrigation efficiency. Most methods of computing utilizable rainfall are difficult to use or unreliable. It is much simpler and probably about as accurate to assume that irrigation efficiencies as applied to water deliveries also can be applied to total rainfall.

Irrigation efficiencies should not fall below 60 percent and rarely exceed about 80 percent. Irrigation requirements at 60 percent efficiency can be expressed by the formula:

$$(Et/0.60) - P = IR \qquad (7)$$

in which Et is the evapotranspiration for the period, P is the total precipitation and IR is the irrigation requirement.

CONCLUSIONS

Because of the demographic explosion water and water use are becoming of rapidly increasing importance. The success or failure of many social and economic programs is very closely associated with the skills and knowledge that can be brought to bear upon the solution of complicated water management problems. More accurate or usable methods of computing evaporation and evapotranspiration can provide a material assistance in planning and operations.

The modified Hargreaves formula, equation 2, provides a simple and reasonably reliable method of calculating evaporation. The Christiansen-Mehta formula, equation 6, provides a more sophisticated means of computing evaporation from a Class A pan.

Computed or measured evaporation provide the most desirable index of irrigation requirements. Crops are grouped together based upon similar irrigation requirements and a comprehensive system of irrigation requirement computations is developed.

Computed evaporation may in many instances be a more reliable index of irrigation requirements than measured evaporation.

Measured evaporation is subject to errors or differences resulting from differences in pan exposure and from errors of operation or measurement. Pan evaporation undoubtedly provides a less desirable index than the formula during hot dry windy weather.