Estimation of Potential and Crop Evapotranspiration

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THE engineer or agriculturalist wishing to estimate irrigation requirements may be required to select a method from approximately a dozen frequently used equations. Most of the methods require mean air temperature and some form of radiation or day length. Other factors include saturation vapor density, saturation vapor pressure, vapor pressure deficit, dew point temperature, relative humidity, wind speed, percentage of possible sunshine and elevation. Each method assigns a different degree of importance to the various factors. Nearly all commonly used methods can with minor adjustments be made to produce a good degree of correlation with lysimeter evapotranspiration measured at given locations.

This paper analyzes the relative importance of weather elements on potential evapotranspiration and presents a methodology requiring a minimum of data, providing for simplicity of computation and presenting a good fit of lysimeter evapotranspiration measurements for a wide range of climatic conditions.

IMPORTANT WEATHER ELEMENTS

McGuiness and Bordne (1972) summarized mean lysimeter grass evapotranspiration, ETG, from a 5-term harmonic curve fitted to the average of 15-year lysimeter measurements at Coshocton, Ohio. This procedure eliminates much of the variance from the data. The effects of alternating arctic and tropical air masses is to an important degree compensated. Periods of high advection are largely balanced by data collected during and following rainy periods. The 15-year average data correlate to a significantly higher degree with results from various equations and with the various weather elements than is the case for the data from individual years and provide a good general index of relationships in the Ohio area.

Based upon the average monthly values of ETG given by McGuiness and Bordne (1972) and the climatic data measurements, regression analyses were made. Several elements or factors predict a high percentage of the variance or explained variability in ETG (have high values of R^2). These include the following:

Element or factor	R^2
Dew point temperature	0.88
RS (solar radiation)	0.94
RN (net radiation)	0.94
Extraterrestrial radiation	0.92
Day length	0.90
Mean temperature (degrees Fahrenheit)	0.88
Hargreaves "MF" factor (ref 3)	0.93
MF times mean temperature, deg F	0.99
Christiansen's sunshine coefficient (ref 3)	0.94

The above illustrates the complexity of the problem of developing satisfactory potential evapotranspiration equations. It would seem that there are at least a half dozen different satisfactory ways to start. Since relationships are not all necessarily linear, the above analysis does not prove that one element is superior to another. It is, however, clearly indicated that the unique variance predicted by each element is not great and that there is a high degree of interaction or interdependence in the effects of various weather elements on grass evapotranspiration.

Although the relationship is not linear and the Ohio data (McGuiness and Bordne 1972) do not illustrate its importance, relative humidity becomes an important factor in areas of high relative humidity. If extraterrestrial radiation and/or day length are used, then a factor for sun angle is required for latitudes of about 35 deg or more from the equator.

THE USE OF PAN EVAPORATION AS AN INDEX

Evaporation measurements from the Class A evaporation pan have been widely used as an index of evaporative demand and of potential evapotranspiration. The California State Department of Water Resources (1967) found that Class A pans located on large, well managed, irrigated pastures were better indicators of evaporative demand than those located in non-standardized surroundings. Data presented by Pruitt and Lourence (1968) for three years at Davis, California, indicated that Class A pan evaporation from a pan located on bare ground averaged 1.23 times evaporation from a pan located in an irrigated grass field.

Pruitt, Lourence and Von Oettingen (1972) have used evapotranspiration from alta fescue grass as a standard measurement for developing crop evapotranspiration curves for specific crops. Evapotranspiration, ETG, from alta fescue grass grown on the weighing lysimeters at Davis, California, is used in this study as an index of potential evapotranspiration. Class A pan evaporation, EVP, from a pan located in an irrigated grass area was also reported by Pruitt and Lourence (1968) for the period June, 1964, through May, 1967. Monthly ratios of ETG/EVP varied from 0.72 to 1.04, with an overall average of about 0.80. Although there is considerable scatter in the relationship, ratios of ETG/EVP increase with increasing relative humidity. This is also indicated by data from Aspendale,

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Australia, given by McIlroy and Angus (1964). At Aspendale monthly ETG/EVP ratios for the approximate frost-free months of a three-year period varied from 0.68 to 1.03.

Mustonen and McGuiness (1968) presented monthly values of grass lysimeter evapotranspiration, ETG, for a 15-year period for Coschocton, Ohio. Class A pan evaporation data are available from the summaries of climatic data given by the U.S. Weather Bureau (1958-65). Lysimeter data are not available for 1964. For the May through September growing season for the 7-year period monthly ETG/EVP ratios varied from 0.42 to 1.25. A regression analysis of ETG as a function of EVP indicates that 21 percent of the variance in ETG can be predicted from measured values of EVP. Ratios are not significantly influenced by monthly differences in relative humidity.

A review of data available from the three locations, Davis, Coshocton, and Aspendale, indicates that ETG/EVP ratios are high following rainy periods. During and following rainy weather radiant energy is largely utilized for evaporation and advection is at a minimum. Pan evaporation is reduced relative to plant evapotranspiration resulting in high ETG/EVP ratios. There is a wide fluctuation in ratios with changes in advection when the pan is located in a large irrigated area and a still greater fluctuation under dry land exposures. When precipitation in the general area exceeds potential evapotranspiration over a period of time, average values of ETG/EVP are frequently about 1.00 or more. When the surrounding area becomes quite dry, monthly ratios in the range of 0.65 to 0.80 are more usual.

A generalized relationship or equation for the above ratios is difficult to derive as many factors influence vapor transfer from the pan and advection or sensible heat transfer. Important factors include air mass stability, temperature gradients above the pan and vapor pressure deficit gradients. The normal range of weather elements reported in the climatic data summaries is not sufficient for a definition of these conditions.

Peck (1967) has shown that air circulation or air drainage conditions have significant effects on pan evaporation. These conditions will also influence ETG/EVP ratios. Ratios from pans located in depressions, on small hills, in narrow valleys, or near the foot of mountains may not be typical or representative.

Changes in relative humidity with height above the pan or vapor pressure deficit gradients and turbulent mixing have large influences on ETP/EVP ratios. In the coastal areas of Ecuador, and particularly in the Guayas Basin, cool moist air from the Humboldt current moves inland. Due to a warmer layer above the overcast, turbulent mixing is minimized. Moisture above the cool but modifying sea air increases near the mountains, with little vapor pressure deficit gradient. Under these conditions prevalent at Pichilingue, La Clementina and Pasaje, it is estimated that ETG/EVP ratios average significantly above 1.00 and possibly as high as 1.15 to 1.20.

Pan evaporation data are widely available. Considering the scarcity of lysimeter evapotranspiration data, significant value can be had from evaporation measurements providing an adequate evaluation is made of exposure conditions and climatic environment. However, as shown above, ETG/EVP ratios vary widely with changes in advection and in exposure. Use of the evaporation pan as an index of potential water demand is improved in areas having fairly uniform advective conditions in the various parts of the area and throughout the growing season.

USE OF AN EVAPOTRANSPIRATION EQUATION

In the development of methodology to be used for the estimation of potential evapotranspiration consideration needs to be given to availability of data, simplicity and ease of computation, and consistency and reliability of results over a wide range of climatic conditions. Hargreaves and Christiansen (1973) present equations that provide a good fit of lysimeter data from Davis, California; Coshocton, Ohio; Copenhagen, Denmark; Aspendale, Australia and three locations in Lebanon. Christiansen's Formula represents an attempt to provide the best fit possible of the data using available climatic measurements. Hargreave's Formula emphasizes simplicity and uses a minimum of weather data. It can be written

$$PET = MF \times T \times CH \quad \ldots\ldots\ldots\ldots [1]$$

in which PET is potential evapotranspiration (ETP in the paper by Hargreaves and Christiansen), MF is a monthly factor depending upon latitude as presented in Table 1, T is mean temperature in degrees Fahrenheit and CH is a correction for relative humidity to be used only for mean 24-hr relative humidities greater than 64 percent. As shown by Hargreaves and Christiansen (1973) the coefficient, CH, is not generally required for climatic conditions similar to those prevailing in most of the western portions of the United States. The equation for CH can be written

$$CH = 0.166\,(100 - H)^{1/2} \quad \ldots [1a]$$

in which H is mean 24-hr relative humidity. Adjustments in equation 1a are required whenever relative humidity used differs significantly from a 24-hr mean. For relative humidities of 64 percent or less CH becomes 1.00 and is therefore not required in the equation. Values of MF can also be calculated from a computer program.*

McGuiness and Bordne (1972) compare the 15-year mean values of lysimeter evapotranspiration calculated by formulas proposed by Thornthwaite, Blaney-Criddle, Hamon, Papadakis, Grassi, Stephens-Stewart, Turc, Jensen-Haise, Makkink, Christiansen, Penman, Van Bavel, U.S. Weather Bureau (Lake Evap.), and U.S. Weather Bureau (Pan Evap.). A regression analysis was made between the measured evapotranspiration, ETG, as a function of the values calculated by the above mentioned equations. These results were compared with those from the recent equations given by Hargreaves and Christiansen (1973). A perfect fit of the data would have an intercept of zero, a slope of 1.00 and an R^2 of 1.00. The simplest equation of the 16 evaluated, Hargreaves' Formula, comes closest to meeting these criteria. The regression equation with $R^2 = 0.985$ for ETG and PET in mm per month is

$$ETG = 0.864 + 0.998 \times PET \quad \ldots\ldots\ldots\ldots [2]$$

Equation [1] was evaluated by regression analysis using evapotranspiration data from the following locations and conditions:

*Copies of the computer program may be obtained from the author.

Station	Period	Latitude	Elevation	Type of grass
Davis, California	1960	38° 32′N	18 M	ryegrass
Davis, California	1965	38° 32′N	18 M	alta fescue
Davis, California	1966	38° 32′N	18 M	alta fescue
Coshocton, Ohio	15 yr. ave.	40° 22′N	360 M	deep rooted mix
Copenhagen, Denmark	1971	55° 41′N		grass and clover
Aspendale, Australia	1961	38° S		pasture mix
Tyr, Lebanon	3 yr. ave.	33° 16′N	5 M	ryegrass or ryegrass and Bermudagrass

Values of PET for the 84 months of data were calculated from equation [1] using a computer program. The regression for ETG in mm per month from these values is

$$ETG = 3.72 + 0.966 \times PET \quad \ldots\ldots [3]$$

with a value of R^2 of 0.97. This equation is close to a one-to-one relationship and predicts 97 percent of the variance in measured grass evapotranspiration.

It seems desirable to evaluate equation [1] for climatic conditions prevailing near the equator. Here reliable evapotranspiration data are scarce. Brutsaert (1965) gives lysimeter data for 1957 for Bahiagrass grown in the Ruzizi Valley, Congo Republic, 2 deg to 3 deg S latitude, elevation about 960 m. When the data from the Congo are added to the other data then the regression equation for the 96 monthly values becomes

$$ETG = 3.96 + 0.963 \times PET \ldots [4]$$

with an R^2 of 0.96.

From this analysis it seems evident that equation [1] provides satisfactory results with a minimum of data and a maximum of simplicity and ease of computation.

The correction for relative humidity is a good average value. Significant scatter is to be anticipated, however, as the humidity effect depends upon the thickness of the humid layer, upon temperature gradients and upon turbulent mixing.

For high elevation locations some correction in equation [1] for elevation is desirable. This is because the humid layer is thinner and temperature gradients above the land are much greater. Temperatures fall off rapidly above these high elevation locations resulting in increased turbulent mixing and transport of vapor away from the thin humid layer. Reliable evapotranspiration data are not available from high elevations. Some Class A pan evaporation data can be used to evaluate this effect, providing sound judgment can be made with respect to ETG/EVP ratios. Evaporation data from Ecuador and Central America would appear more consistent with equation [1] if it is assumed that a correction of about 8 percent per 1000 m of increase in elevation above sea level should be applied. This correlation for elevation, CE, will also vary somewhat with topographic surroundings and position, making the effect more pronounced over mountain peaks than over large land masses.

Equation [1] was developed to be used with 24-hr mean temperatures and relative humidities. The climatic data used for the computer program and the regression analysis were not all measured at the same hours. Data from Tyr, Lebanon, are for a different period of years than the evapotrans-

TABLE 1. POTENTIAL EVAPOTRANSPIRATION FACTOR, MF, FOR PET IN MM PER MONTH

NORTH LAT	JAN	FEB	MAR	APR	MONTH MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
60	.061	.177	.525	1.039	1.700	2.026	1.920	1.334	.705	.299	.081	.037
59	.077	.203	.571	1.101	1.770	2.093	1.989	1.407	.757	.334	.100	.049
58	.095	.230	.618	1.161	1.837	2.152	2.054	1.467	.809	.370	.128	.063
57	.114	.258	.666	1.219	1.901	2.210	2.117	1.531	.861	.408	.151	.079
56	.135	.288	.714	1.277	1.962	2.265	2.176	1.592	.913	.447	.174	.097
55	.159	.319	.762	1.334	2.021	2.317	2.233	1.652	.965	.487	.200	.115
54	.183	.352	.811	1.390	2.078	2.367	2.289	1.711	1.017	.528	.227	.138
53	.210	.385	.861	1.445	2.133	2.415	2.340	1.768	1.069	.570	.256	.161
52	.238	.420	.911	1.499	2.186	2.461	2.390	1.824	1.121	.614	.286	.186
51	.268	.456	.961	1.552	2.238	2.506	2.439	1.879	1.172	.658	.318	.213
50	.300	.493	1.012	1.605	2.288	2.548	2.485	1.932	1.224	.703	.351	.242
49	.333	.531	1.063	1.657	2.336	2.589	2.531	1.985	1.276	.749	.386	.272
48	.367	.570	1.115	1.709	2.383	2.628	2.574	2.036	1.327	.796	.422	.304
47	.404	.610	1.167	1.760	2.429	2.665	2.616	2.086	1.379	.844	.460	.337
46	.441	.651	1.219	1.810	2.473	2.702	2.656	2.136	1.430	.892	.499	.372
45	.481	.693	1.271	1.859	2.515	2.736	2.695	2.184	1.481	.942	.539	.409
44	.521	.736	1.324	1.908	2.557	2.769	2.733	2.231	1.532	.992	.580	.447
43	.563	.780	1.376	1.956	2.597	2.801	2.769	2.277	1.583	1.042	.623	.487
42	.607	.824	1.429	2.003	2.636	2.831	2.804	2.323	1.631	1.093	.667	.528
41	.651	.869	1.482	2.050	2.674	2.860	2.837	2.367	1.681	1.145	.712	.571
40	.697	.915	1.535	2.096	2.710	2.887	2.869	2.410	1.730	1.198	.758	.615
39	.744	.962	1.588	2.141	2.745	2.913	2.899	2.452	1.783	1.251	.805	.660
38	.791	1.009	1.641	2.186	2.779	2.938	2.928	2.493	1.833	1.304	.854	.707
37	.841	1.057	1.694	2.229	2.811	2.961	2.956	2.533	1.882	1.358	.903	.755
36	.893	1.106	1.746	2.272	2.842	2.983	2.983	2.572	1.930	1.412	.953	.805
35	.940	1.148	1.789	2.301	2.856	2.987	2.991	2.596	1.967	1.458	.995	.851
34	.979	1.181	1.816	2.309	2.844	2.964	2.972	2.595	1.987	1.491	1.036	.889
33	1.018	1.214	1.842	2.317	2.832	2.941	2.953	2.595	2.006	1.524	1.073	.929
32	1.057	1.246	1.867	2.324	2.819	2.918	2.934	2.594	2.024	1.557	1.110	.968
31	1.096	1.278	1.892	2.330	2.806	2.895	2.915	2.592	2.041	1.589	1.147	1.008
30	1.135	1.310	1.916	2.336	2.793	2.871	2.895	2.589	2.058	1.621	1.184	1.048
29	1.174	1.341	1.940	2.341	2.779	2.847	2.875	2.586	2.074	1.653	1.222	1.088
28	1.214	1.372	1.963	2.346	2.764	2.823	2.855	2.583	2.090	1.684	1.259	1.128
27	1.253	1.403	1.986	2.350	2.750	2.799	2.834	2.579	2.105	1.714	1.296	1.168
26	1.292	1.434	2.008	2.353	2.734	2.775	2.813	2.574	2.119	1.745	1.332	1.208
25	1.332	1.465	2.029	2.356	2.719	2.750	2.792	2.569	2.133	1.774	1.369	1.249
24	1.371	1.495	2.050	2.358	2.702	2.725	2.770	2.563	2.146	1.804	1.406	1.289
23	1.410	1.525	2.070	2.359	2.686	2.699	2.747	2.556	2.159	1.832	1.442	1.330
22	1.449	1.554	2.089	2.360	2.669	2.674	2.725	2.549	2.171	1.861	1.478	1.370
21	1.488	1.583	2.108	2.360	2.651	2.648	2.702	2.541	2.182	1.888	1.514	1.411
20	1.527	1.612	2.126	2.359	2.633	2.621	2.678	2.532	2.192	1.916	1.550	1.451
19	1.565	1.640	2.144	2.358	2.614	2.594	2.655	2.524	2.202	1.942	1.586	1.491
18	1.604	1.668	2.161	2.356	2.595	2.567	2.630	2.514	2.211	1.969	1.621	1.532
17	1.642	1.696	2.177	2.353	2.575	2.540	2.606	2.504	2.220	1.994	1.657	1.572
16	1.680	1.723	2.193	2.350	2.555	2.512	2.581	2.493	2.227	2.020	1.691	1.612
15	1.718	1.750	2.208	2.346	2.534	2.484	2.555	2.482	2.235	2.044	1.726	1.652
14	1.756	1.776	2.222	2.342	2.513	2.456	2.529	2.470	2.241	2.068	1.760	1.692
13	1.794	1.802	2.236	2.337	2.491	2.427	2.503	2.457	2.247	2.092	1.795	1.732
12	1.831	1.828	2.249	2.331	2.469	2.398	2.476	2.444	2.252	2.115	1.828	1.771
11	1.868	1.853	2.261	2.324	2.447	2.369	2.449	2.430	2.256	2.137	1.862	1.811
10	1.905	1.878	2.273	2.317	2.423	2.339	2.421	2.415	2.260	2.159	1.895	1.850
9	1.941	1.902	2.284	2.310	2.400	2.309	2.393	2.400	2.263	2.180	1.926	1.889
8	1.977	1.926	2.294	2.301	2.376	2.278	2.365	2.384	2.265	2.201	1.960	1.928
7	2.013	1.949	2.303	2.292	2.351	2.247	2.336	2.368	2.267	2.221	1.993	1.966
6	2.049	1.972	2.312	2.282	2.326	2.216	2.306	2.351	2.268	2.240	2.024	2.004
5	2.084	1.994	2.320	2.272	2.300	2.185	2.277	2.333	2.268	2.259	2.055	2.043
4	2.119	2.016	2.328	2.261	2.274	2.153	2.247	2.315	2.268	2.277	2.086	2.080
3	2.154	2.037	2.334	2.250	2.248	2.121	2.216	2.297	2.267	2.294	2.116	2.118
2	2.188	2.058	2.340	2.237	2.221	2.089	2.185	2.277	2.265	2.311	2.147	2.155
1	2.222	2.078	2.346	2.224	2.193	2.056	2.154	2.257	2.263	2.327	2.176	2.192
0	2.255	2.098	2.350	2.211	2.165	2.023	2.123	2.237	2.260	2.343	2.205	2.229

SOUTH LAT	JAN	FEB	MAR	APR	MONTH MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
-1	2.288	2.117	2.354	2.197	2.137	1.990	2.091	2.216	2.256	2.358	2.234	2.265
-2	2.321	2.136	2.357	2.182	2.108	1.956	2.059	2.194	2.251	2.372	2.263	2.301
-3	2.353	2.154	2.360	2.167	2.079	1.922	2.026	2.172	2.246	2.386	2.290	2.337
-4	2.385	2.172	2.362	2.151	2.050	1.888	1.993	2.150	2.240	2.398	2.318	2.372
-5	2.416	2.189	2.363	2.134	2.020	1.854	1.960	2.126	2.234	2.411	2.345	2.407
-6	2.447	2.205	2.363	2.117	1.990	1.820	1.926	2.103	2.226	2.422	2.371	2.442
-7	2.478	2.221	2.363	2.099	1.959	1.785	1.891	2.078	2.218	2.433	2.397	2.476
-8	2.508	2.237	2.362	2.081	1.927	1.750	1.858	2.054	2.210	2.443	2.423	2.510
-9	2.538	2.251	2.360	2.062	1.896	1.715	1.824	2.028	2.201	2.453	2.448	2.544
-10	2.567	2.266	2.357	2.043	1.864	1.679	1.789	2.003	2.191	2.462	2.473	2.577
-11	2.596	2.279	2.354	2.023	1.832	1.644	1.754	1.976	2.180	2.470	2.497	2.610
-12	2.625	2.292	2.350	2.002	1.799	1.608	1.719	1.950	2.169	2.477	2.520	2.643
-13	2.652	2.305	2.345	1.981	1.767	1.572	1.684	1.922	2.157	2.484	2.543	2.675
-14	2.680	2.317	2.340	1.959	1.733	1.536	1.648	1.896	2.144	2.490	2.566	2.706
-15	2.707	2.328	2.334	1.937	1.700	1.500	1.612	1.867	2.131	2.496	2.588	2.738
-16	2.734	2.339	2.327	1.914	1.666	1.464	1.576	1.838	2.117	2.500	2.610	2.769
-17	2.760	2.349	2.319	1.891	1.632	1.427	1.540	1.809	2.101	2.504	2.631	2.799
-18	2.785	2.359	2.311	1.867	1.598	1.391	1.504	1.780	2.086	2.508	2.651	2.830
-19	2.811	2.368	2.302	1.843	1.564	1.354	1.467	1.750	2.072	2.510	2.671	2.859
-20	2.835	2.377	2.293	1.818	1.529	1.318	1.431	1.719	2.056	2.512	2.691	2.889
-21	2.860	2.385	2.282	1.792	1.494	1.281	1.394	1.689	2.039	2.514	2.710	2.918
-22	2.883	2.392	2.272	1.767	1.459	1.244	1.357	1.658	2.021	2.514	2.728	2.947
-23	2.907	2.399	2.260	1.740	1.423	1.208	1.320	1.626	2.003	2.514	2.747	2.975
-24	2.930	2.405	2.248	1.713	1.388	1.171	1.283	1.595	1.984	2.513	2.764	3.003
-25	2.952	2.411	2.234	1.686	1.352	1.134	1.246	1.563	1.965	2.512	2.781	3.031
-26	2.975	2.416	2.221	1.659	1.316	1.097	1.209	1.530	1.945	2.510	2.798	3.058
-27	2.996	2.420	2.206	1.630	1.280	1.061	1.172	1.497	1.924	2.507	2.814	3.085
-28	3.018	2.424	2.191	1.602	1.244	1.024	1.134	1.464	1.903	2.503	2.830	3.112
-29	3.039	2.427	2.176	1.573	1.208	.988	1.097	1.431	1.881	2.499	2.845	3.139
-30	3.059	2.430	2.159	1.544	1.172	.952	1.060	1.397	1.859	2.494	2.859	3.165
-31	3.079	2.432	2.142	1.514	1.135	.916	1.023	1.364	1.836	2.489	2.874	3.191
-32	3.099	2.434	2.125	1.484	1.099	.880	.986	1.329	1.812	2.483	2.888	3.217
-33	3.119	2.435	2.106	1.453	1.063	.844	.949	1.295	1.788	2.476	2.901	3.242
-34	3.138	2.436	2.087	1.422	1.026	.808	.912	1.261	1.764	2.469	2.914	3.268
-35	3.157	2.436	2.068	1.391	.990	.773	.876	1.226	1.739	2.460	2.927	3.293
-36	3.140	2.415	2.030	1.348	.945	.731	.832	1.180	1.698	2.430	2.934	3.289
-37	3.120	2.378	1.980	1.297	.896	.686	.784	1.129	1.647	2.385	2.882	3.265
-38	3.090	2.340	1.929	1.246	.847	.643	.738	1.077	1.597	2.339	2.850	3.239
-39	3.058	2.302	1.878	1.196	.800	.600	.692	1.027	1.546	2.293	2.816	3.212
-40	3.025	2.262	1.826	1.146	.753	.559	.648	.977	1.495	2.245	2.780	3.183
-41	2.991	2.222	1.774	1.096	.708	.519	.605	.928	1.444	2.197	2.744	3.153
-42	2.955	2.180	1.722	1.047	.664	.480	.563	.880	1.393	2.147	2.706	3.122
-43	2.918	2.138	1.669	.999	.620	.443	.522	.832	1.343	2.097	2.666	3.088
-44	2.879	2.095	1.617	.951	.578	.407	.483	.786	1.292	2.047	2.626	3.053
-45	2.839	2.050	1.564	.904	.537	.372	.445	.740	1.241	1.995	2.584	3.017
-46	2.797	2.005	1.510	.857	.498	.339	.408	.696	1.191	1.943	2.540	2.979
-47	2.754	1.959	1.457	.811	.459	.307	.373	.652	1.141	1.890	2.496	2.939
-48	2.709	1.912	1.403	.766	.422	.276	.339	.609	1.091	1.836	2.450	2.898
-49	2.663	1.864	1.350	.721	.387	.247	.307	.567	1.041	1.781	2.402	2.855
-50	2.615	1.816	1.296	.677	.352	.220	.276	.527	.992	1.726	2.353	2.810
-51	2.566	1.764	1.242	.634	.319	.194	.246	.487	.943	1.670	2.302	2.763
-52	2.513	1.713	1.188	.592	.288	.170	.218	.449	.894	1.612	2.250	2.715
-53	2.459	1.661	1.133	.551	.258	.147	.192	.412	.845	1.556	2.196	2.664
-54	2.403	1.607	1.079	.511	.229	.126	.168	.376	.797	1.497	2.140	2.611
-55	2.345	1.552	1.025	.473	.202	.106	.144	.341	.750	1.438	2.082	2.556
-56	2.285	1.496	.970	.433	.176	.088	.123	.308	.703	1.377	2.022	2.498
-57	2.221	1.439	.916	.396	.153	.072	.103	.276	.656	1.316	1.959	2.437
-58	2.155	1.379	.861	.360	.130	.057	.085	.246	.610	1.253	1.894	2.374
-59	2.085	1.317	.806	.325	.110	.045	.069	.217	.564	1.189	1.826	2.307
-60	2.012	1.253	.751	.292	.091	.033	.055	[illegible]	.519	1.124	1.755	2.236

TABLE 2. CROP COEFFICIENTS, KC (FOR USE WITH POTENTIAL EVAPOTRANSPIRATION PET).

Crop	*Average KC for Full Crop Cover	†Average Seasonal KC
Field and oil crops including beans, castor beans, corn, cotton, flax, peanuts, potatoes, safflower, soybeans, sorghum, sugar beets, tomatoes, and wheat	1.15	0.90
Fruits, nuts and grapes		
Citrus fruits (oranges, lemons and grapefruit)	0.75	0.75
Deciduous fruits (peaches, plums and walnuts)	0.90	0.70
Deciduous fruits with cover crop	1.25	1.00
Grapes	0.75	0.60
Hay, forage and cover crops		
Alfalfa	1.35	1.00
Short grass	1.00	1.00
Clover pasture	1.15	
Green manure	1.10	0.95
Sugar cane	1.25	1.00
Summer vegetables	1.15	0.85

* To be used in designing system capacity

† To be used in economic calculations. Recommended for scheduling irrigation where soils have good capacites to store available moisture.

piration measurements. These considerations probably result in some errors in computation. However, equation [1] closely approximates the average measured grass evapotranspiration from the locations given above and is therefore considered to be adequate for purposes of scheduling irrigation or for calculating irrigation requirements for purposes of planning and design.

CROP COEFFICIENTS

Crop coefficients used together with PET provide for the estimation of irrigation requirements and for irrigation scheduling. An equation for actual crop evapotranspiration, ETA, similar to that presented by Jensen, Robb and Franzoy (1970) can be written:

$$ETA = KC \times PET \quad \ldots\ldots\ldots\ldots [5]$$

in which KC is the ratio of crop evapotranspiration to that for grass as used by Pruitt, Lourance and Von Oettingen (1972) and PET is potential evapotranspiration from equation [1]. Full crop cover and approximate average seasonal crop coefficients, KC, are reproduced from those given by Hargreaves and Christiansen (1973) and presented as Table 2.

Various methods of scheduling irrigation produce satisfactory results. These include a modified Penman Equation (Jensen, Wright and Pratt 1971), a modified Jensen-Haise method (Jensen, Robb and Franzoy 1970), the Class A evaporation pan (Jensen and Middleton 1965) and others. However, equation [1] predicts 96 percent of the variance in measured grass evapotranspiration from a wide range of climatic conditions and in addition is simple and easy to use. This methodology should therefore be considered for use in those locations where data are available for temperature and relative humidity and where ease of computation is an important consideration. For a major portion of the irrigated areas temperature data alone produce satisfactory results.

CONCLUSION

Grass evapotranspiration or potential evapotranspiration can be approximated from a variety of equations. The most frequently used elements for computation include mean air temperature and some form of radiation and/or day length. Other elements are of relatively minor importance in low elevation arid locations. For these locations the simple equation (PET = MF x T), requiring only temperature measurements produces satisfactory results. In humid areas a correction for mean relative humidity is added.

NOTATION

Notations used in the text are defined as follows:

CE = dimensionless coefficient for elevation

CH = dimensionless coefficient for mean 24-hr relative humidity

ETG = grass evapotranspiration in mm from lysimeter measurements

PET = potential evapotranspiration in mm (monthly)

EVP = measured Class A pan evaporation

H = mean 24-hr relative humidity for the period

KC = crop coefficient for estimating crop evapotranspiration

MF = monthly evapotranspiration factor in mm

T = mean temperature in degrees Fahrenheit

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