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THE ESTIMATION OF POTENTIAL AND CROP EVAPOTRANSPIRATION

By

GEORGE H. HARGREAVES

UTAH STATE UNIVERSITY

Logan, Utah

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George H. Hargreaves[1]

INTRODUCTION

The estimation of potential and/or actual evapotranspiration provide a basic criteria in the calculation of irrigation requirements, water balance studies and determination of moisture availability yield relationships. Although many emperical evapotranspiration equations have been developed and used few have wide application to areas climatically different from those where the emperical equations were derived. This is due principally to the limited number of climatic factors involved and the complex climatic interactions encountered in various locations.

It is believed that it is nearly impossible to derive a single equation for potential evapotranspiration that will be applicable to all climates. However, it is the objective of this paper to present methodology that provides good results for the known climatic variations in the irrigated areas of the world.

Crop coefficients are presented to be used with estimated potential evapotranspiration.

ESTIMATING POTENTIAL EVAPOTRANSPIRATION

The California State Department of Water Resources(1)[2] measured Class A pan evaporation from irrigated grass surrounds and grass and pasture evapotranspiration in various locations representing four distinct climatic zones.

Grass and pasture evapotranspiration averaged about 0.80 times pan evaporation. This relationship was particularly well demonstrated

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[1]Research Engineer, Agricultural and Irrigation Engineering, Utah State University, Logan, Utah.

[2]Numerals in parentheses refer to corresponding items in the Appendix-References.

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by the data from the coastal fogbelt area. Based upon this study it is believed that for fairly large irrigated areas potential evapotranspiration, ETP, can be approximated from the equation

$$ETP = 0.80 \times EVPM \qquad (1)$$

in which EVPM is the measured Class A pan evaporation. This relationship is also probably satisfactory for locations having fairly low sensible heat transfer as is the case for high humidities with low wind velocities.

For highly advective conditions (hot dry windy weather), particularly with bare soil surrounds, the ratio of grass evapotranspiration from lysimeters to pan evaporation may be as low as 0.55 and possibly lower.

Blaney-Criddle, Thornthwaite and Hargreaves(4) have related potential evapotranspiration to day length and climatic factors. A methodology proposed by Christiansen(2) and since used and modified by various graduate students and technicians uses extraterrestrial radiation expressed as units of evaporation and coefficients for the various weather elements.

A modification proposed by Hargreaves(3) can be written

$$ETP = 0.35 \times RT \times C \qquad (2)$$

in which

ETP is potential evapotranspiration

RT is the extraterrestrial radiation expressed as equivalent evaporation by dividing the radiation ($cal/cm^2/day$) by the heat of vaporization at the mean temperature, TM, and converting to appropriate units, usually inches or mm per day or per month (Tables 1 and 2)

$$C = CT \times CH \times CW \times CE \qquad (2a)$$

$$CT = 0.40 + 0.024 \times TM \qquad (2b)$$

(TM is mean temperature in ^{o}C)

$$CT = 0.013 \times TMF \qquad (2c)$$

(TMF is mean temperature in ^{o}F)

$$CH = 0.05 + 1.58 \times (1.00 - HM)^{1/2} \qquad (2d)$$

with a maximum value of 1.00 for values of HM less than .64 (HM is mean relative humidity expressed decimally using integrated values over a 24-hour period)

TABLE 1 EXTRATERRESTRIAL RADIATION IN MM PER MONTH AT 25. DEGREES CENTIGRADE

NORTH						MONTH						
LAT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
60.	44.	94.	214.	342.	471.	514.	506.	406.	261.	143.	58.	30.
58.	58.	109.	229.	352.	477.	515.	509.	415.	275.	158.	72.	43.
56.	72.	123.	244.	363.	482.	517.	512.	423.	288.	174.	86.	56.
54.	87.	137.	259.	373.	487.	519.	516.	431.	301.	190.	101.	70.
52.	102.	151.	273.	383.	492.	520.	519.	439.	313.	205.	116.	85.
50.	117.	166.	287.	392.	496.	522.	521.	447.	325.	221.	131.	100.
48.	133.	180.	301.	401.	500.	523.	524.	454.	337.	236.	147.	115.
46.	149.	194.	314.	409.	504.	524.	526.	460.	348.	251.	162.	131.
44.	165.	208.	327.	417.	507.	524.	527.	466.	359.	266.	177.	147.
42.	181.	222.	340.	425.	510.	524.	529.	472.	370.	280.	193.	163.
40.	197.	235.	352.	432.	512.	524.	530.	477.	380.	294.	208.	179.
38.	213.	248.	364.	438.	514.	523.	530.	482.	389.	308.	223.	195.
36.	229.	262.	375.	444.	516.	522.	530.	486.	398.	322.	238.	211.
34.	244.	274.	385.	450.	517.	521.	530.	490.	407.	335.	253.	227.
32.	260.	287.	396.	455.	517.	519.	529.	493.	415.	349.	268.	243.
30.	275.	299.	405.	459.	517.	516.	527.	495.	422.	360.	282.	259.
28.	291.	311.	415.	463.	516.	513.	525.	497.	429.	372.	296.	275.
26.	306.	323.	424.	467.	515.	510.	522.	494.	435.	383.	310.	290.
24.	320.	334.	432.	470.	513.	506.	519.	499.	442.	394.	324.	306.
22.	335.	345.	440.	472.	511.	502.	516.	500.	447.	405.	338.	320.
20.	349.	355.	448.	474.	508.	497.	512.	499.	452.	415.	351.	335.
18.	363.	366.	454.	475.	505.	491.	507.	499.	457.	425.	363.	350.
16.	376.	375.	460.	475.	501.	485.	502.	497.	460.	434.	376.	364.
14.	389.	385.	466.	475.	497.	479.	496.	495.	464.	442.	388.	378.
12.	402.	393.	471.	475.	492.	472.	490.	493.	466.	451.	399.	391.
10.	414.	402.	476.	474.	486.	465.	483.	490.	468.	459.	410.	404.
8.	426.	410.	480.	472.	480.	457.	476.	486.	470.	465.	421.	417.
6.	438.	417.	483.	470.	474.	449.	468.	482.	471.	472.	431.	430.
4.	449.	424.	486.	467.	466.	440.	460.	477.	471.	478.	441.	441.
2.	459.	431.	488.	464.	459.	431.	451.	472.	471.	483.	450.	453.
0.	469.	437.	489.	460.	451.	421.	442.	466.	470.	488.	459.	464.

TABLE 2 EXTRATERRESTRIAL RADIATION IN MM PER MONTH AT 25. DEGREES CENTIGRADE

SOUTH						MONTH						
LAT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
-2.	479.	442.	490.	456.	447.	411.	432.	459.	469.	492.	467.	475.
-4.	488.	447.	491.	451.	433.	401.	422.	452.	467.	496.	475.	485.
-6.	497.	452.	490.	445.	424.	390.	412.	445.	465.	499.	483.	494.
-8.	505.	456.	490.	439.	414.	379.	401.	437.	462.	501.	489.	503.
-10.	512.	459.	489.	433.	403.	367.	389.	428.	458.	503.	496.	512.
-12.	519.	462.	486.	426.	393.	355.	378.	420.	454.	504.	502.	520.
-14.	526.	465.	484.	418.	381.	343.	366.	410.	449.	505.	507.	528.
-16.	532.	466.	480.	410.	370.	330.	353.	400.	444.	505.	511.	535.
-18.	537.	468.	477.	402.	358.	318.	340.	390.	438.	504.	515.	541.
-20.	542.	469.	472.	393.	345.	304.	327.	379.	432.	503.	519.	547.
-22.	546.	469.	467.	383.	333.	291.	314.	368.	425.	502.	522.	553.
-24.	550.	469.	462.	374.	320.	277.	300.	356.	418.	499.	524.	558.
-26.	553.	468.	456.	363.	306.	263.	286.	344.	410.	496.	526.	562.
-28.	556.	466.	449.	352.	293.	249.	272.	332.	402.	493.	528.	566.
-30.	558.	465.	442.	341.	279.	235.	258.	319.	393.	489.	529.	569.
-32.	559.	462.	434.	330.	264.	221.	243.	306.	383.	484.	529.	572.
-34.	560.	459.	426.	318.	250.	206.	228.	293.	374.	479.	529.	574.
-36.	561.	456.	417.	306.	236.	192.	214.	279.	363.	473.	528.	576.
-38.	560.	452.	408.	293.	221.	177.	199.	265.	353.	467.	526.	577.
-40.	560.	448.	398.	280.	206.	163.	184.	251.	342.	460.	525.	578.
-42.	559.	443.	389.	267.	191.	148.	169.	237.	330.	453.	522.	578.
-44.	557.	438.	377.	253.	176.	134.	153.	222.	318.	445.	519.	578.
-46.	555.	432.	366.	239.	161.	119.	138.	207.	306.	437.	516.	577.
-48.	553.	426.	355.	225.	146.	105.	124.	192.	293.	428.	513.	576.
-50.	550.	419.	343.	211.	131.	91.	109.	177.	280.	419.	509.	575.
-52.	547.	412.	330.	197.	116.	77.	94.	162.	267.	409.	504.	573.
-54.	544.	405.	317.	182.	101.	64.	80.	147.	253.	399.	500.	572.
-56.	540.	397.	304.	167.	87.	51.	66.	131.	239.	388.	495.	570.
-58.	537.	389.	291.	152.	72.	39.	53.	116.	225.	377.	490.	568.
-60.	533.	381.	277.	137.	58.	27.	40.	101.	210.	366.	484.	567.

CH = $0.05 + 1.42 \times (1.00 - HM7)^{1/2}$ with a maximum value of 1.00 for values of HM7 less than .55 (HM7 is the mean of three readings taken at 0700, 1300 and 1900 hours) (2e)

CH = $1.35 \times (1.00 - HM8)^{1/2}$ with a maximum value of 1.00 for values of HM8 less than .45 (HM8 is the mean of three readings taken at 0800, 1200 and 1800 hours) (2f)

CW is a coefficient for wind speed or move-movement

CE = $1.00 + 0.04 \times EL$ (EL is elevation in meters) (2g)

Based upon data from lysimeters planted to grass in Griffith, Australia; Tal-Amara, Abde and Tyr in Lebanon; Davis, California; and Coshocton, Ohio, an equation was developed that combines the concepts of day length and extraterrestrial radiation. The equation can be written

$$ETP = ETF \times CT \times CH \quad (3)$$

in which

ETF = $0.35 \times RT \times DL/12.0$ (DL is mean day length in Hrs for the period)

CT and CH are as defined in Equ. 2. Values of ETF, potential evapotranspiration factor, are given in Tables 3 and 4.

Extraterrestrial radiation is frequently expressed in Langleys per day. The equivalent depth of evaporation per day is obtained by dividing by the latent heat of vaporization, L, which varies somewhat with temperature. The equation may be written

$$L = 595.9 - 0.55 \times T \quad (4)$$

in which T is temperature in ^{o}C.

Tables 1, 2, 3 and 4 are based upon the latent heat of vaporization at 25^{o}C. Lowering the temperature by 10.8 ^{o}C increases L by 1.0%. It is proposed that this small difference not be corrected because of the lack of precision in measuring the weather elements and in the variability in times and manner of measurement.

For most arid areas (mean 24 hour relative humidity of 64 percent or less) Tables 3 and 4 give potential evapotranspiration at 25^{o}C.

TABLE 3 POTENTIAL ET OR ETP FACTOR IN MM PER MONTH AT 25. DEGREES CENTIGRADE

NORTH LAT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
60.	8.	24.	71.	141.	230.	275.	260.	181.	96.	40.	12.	5.
58.	12.	28.	76.	144.	227.	266.	254.	182.	100.	46.	16.	8.
56.	16.	33.	82.	147.	225.	259.	249.	182.	105.	51.	20.	11.
54.	20.	38.	87.	149.	223.	254.	245.	183.	109.	57.	24.	15.
52.	24.	42.	92.	152.	221.	249.	241.	184.	113.	62.	29.	19.
50.	29.	47.	97.	154.	219.	244.	238.	185.	117.	67.	34.	23.
48.	34.	52.	102.	157.	218.	240.	235.	186.	121.	73.	39.	28.
46.	39.	57.	107.	159.	216.	236.	232.	187.	125.	78.	44.	33.
44.	44.	62.	111.	161.	215.	233.	230.	188.	129.	83.	49.	38.
42.	49.	67.	116.	163.	214.	229.	227.	188.	132.	89.	54.	43.
40.	55.	72.	120.	164.	212.	226.	225.	189.	136.	94.	59.	48.
38.	60.	76.	124.	166.	211.	223.	222.	189.	139.	99.	65.	54.
36.	66.	81.	128.	167.	209.	219.	219.	189.	142.	104.	70.	59.
34.	71.	86.	132.	168.	207.	216.	217.	189.	145.	109.	75.	65.
32.	77.	91.	136.	170.	205.	213.	214.	189.	147.	113.	81.	71.
30.	83.	95.	140.	170.	203.	209.	211.	189.	150.	118.	86.	76.
28.	88.	100.	143.	171.	201.	206.	208.	188.	152.	123.	92.	82.
26.	94.	105.	146.	172.	199.	202.	205.	188.	154.	127.	97.	88.
24.	100.	109.	149.	172.	197.	199.	202.	187.	156.	131.	102.	94.
22.	106.	113.	152.	172.	194.	195.	159.	186.	158.	136.	108.	100.
20.	111.	117.	155.	172.	192.	191.	195.	185.	160.	140.	113.	106.
18.	117.	122.	157.	172.	189.	187.	192.	183.	161.	143.	118.	112.
16.	122.	126.	160.	171.	186.	183.	188.	182.	162.	147.	123.	117.
14.	128.	129.	162.	171.	183.	179.	184.	180.	163.	151.	128.	123.
12.	133.	133.	164.	170.	180.	175.	180.	178.	164.	154.	133.	129.
10.	139.	137.	166.	169.	177.	170.	176.	176.	165.	157.	138.	135.
8.	144.	140.	167.	168.	173.	166.	172.	174.	165.	160.	143.	140.
6.	149.	144.	168.	166.	169.	161.	168.	171.	165.	163.	147.	146.
4.	154.	147.	170.	165.	166.	157.	164.	169.	165.	166.	152.	152.
2.	159.	150.	171.	163.	152.	152.	159.	166.	165.	168.	156.	157.
0.	164.	153.	171.	161.	158.	147.	155.	163.	165.	171.	161.	162.

TABLE 4 POTENTIAL ET OR ETP FACTOR IN MM PER MONTH AT 25. DEGREES CENTIGRADE

SOUTH LAT	MONTH JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
-2.	169.	156.	172.	159.	154.	143.	150.	160.	164.	173.	165.	168.
-4.	174.	158.	172.	157.	149.	138.	145.	157.	163.	175.	169.	173.
-6.	178.	161.	172.	154.	145.	133.	140.	153.	162.	176.	173.	178.
-8.	183.	163.	172.	152.	140.	128.	135.	150.	161.	178.	177.	183.
-10.	187.	165.	172.	149.	136.	122.	130.	146.	160.	179.	180.	188.
-12.	191.	167.	171.	146.	131.	117.	125.	142.	158.	181.	184.	193.
-14.	195.	169.	170.	143.	126.	112.	120.	138.	156.	181.	187.	197.
-16.	199.	170.	170.	139.	121.	107.	115.	134.	154.	182.	190.	202.
-18.	203.	172.	168.	136.	116.	101.	110.	130.	152.	183.	193.	206.
-20.	207.	173.	167.	132.	111.	96.	104.	125.	150.	183.	196.	211.
-22.	210.	174.	166.	129.	106.	91.	99.	121.	147.	183.	199.	215.
-24.	213.	175.	164.	125.	101.	85.	93.	116.	145.	183.	201.	219.
-26.	217.	176.	162.	121.	96.	80.	88.	111.	142.	183.	204.	223.
-28.	220.	177.	160.	117.	91.	75.	83.	107.	139.	182.	206.	227.
-30.	223.	177.	157.	112.	85.	69.	77.	102.	135.	182.	208.	231.
-32.	226.	177.	155.	108.	80.	64.	72.	97.	132.	181.	210.	234.
-34.	229.	178.	152.	103.	75.	59.	66.	92.	129.	180.	212.	238.
-36.	231.	177.	149.	99.	69.	54.	61.	87.	125.	179.	214.	242.
-38.	234.	177.	146.	94.	64.	49.	56.	82.	121.	177.	216.	245.
-40.	237.	177.	143.	89.	59.	44.	51.	76.	117.	176.	218.	249.
-42.	239.	177.	139.	85.	54.	39.	46.	71.	113.	174.	219.	253.
-44.	242.	176.	136.	80.	49.	34.	41.	66.	109.	172.	221.	257.
-46.	245.	175.	132.	75.	44.	30.	36.	61.	104.	170.	222.	261.
-48.	248.	175.	128.	70.	39.	25.	31.	56.	100.	169.	224.	265.
-50.	251.	174.	124.	65.	34.	21.	26.	50.	95.	165.	226.	269.
-52.	254.	173.	120.	60.	29.	17.	22.	45.	90.	163.	227.	274.
-54.	258.	172.	116.	54.	25.	13.	18.	40.	85.	160.	229.	280.
-56.	262.	171.	111.	49.	20.	10.	14.	35.	81.	158.	232.	286.
-58.	267.	171.	107.	44.	16.	7.	11.	30.	75.	155.	234.	294.
-60.	273.	170.	102.	39.	12.	5.	7.	26.	70.	152.	238.	303.

The data from Australia, Lebanon, California and Ohio do not define the effect of elevation and excessive overcast or cloud cover on potential evapotranspiration. At Portoviejo, Pichilingue, La Clementina, Milagro, Pasaje, Izobamba and Puyo in Ecuador the Servicio Nacional de Meteoralogia e Hidrologia measures Class A pan evaporation and 24 hour means for temperature and humidity. The percentage of possible sunshine is reported. Elevations vary from 13 to 3058 meters. Mean monthly relative humidities are in the general range of 70 to 90 percent. Ecept for Izobamba the general range for the percentage of possible sunshine is 10 to 40 percent. Wind velocities are generally low.

It is assumed that under these conditions Eq. 1 will be applicable and can be used to evaluate the effects of elevation and percentage of possible sunshine on potential evapotranspiration. Based upon the Ecuadorian data Eq. 3 was evaluated. The results indicate the desirability of adding coefficients for percentage of possible sunshine and elevation. The resultant equation becomes

$$ETP = ETF \times CT \times CH \times CS \times CE \qquad (5)$$

in which

$$CS = 0.45 + 1.45 \times S \qquad (5a)$$

with a maximum value of 1.00 for S greater than 0.38 (S is percentage of possible sunshine expressed decimally)

$$CE = 1.00 + 0.04 \times EL/1000 \qquad (5b)$$

(EL is elevation in meters)

All other factors are as defined in Eqs. 2 and 3.

It is noted that for sunshine percentages above 38 and fairly low elevations Eq. 3 does not require further modification.

CROP EVAPOTRANSPIRATION

A good summary of crop coefficients to be used with Class A pan evaporation from well standardized conditions is given by Middleton, Pruitt, Crandall and Jensen(5). The coefficients apply to full crop cover conditions and have been converted so as to apply to potential evapotranspiration, ETP, Eqs. 3 and 5. Crop evapotranspiration or actual evapotranspiration, ETA, is obtained from the equation

$$ETA = K \times ETP \qquad (6)$$

in which K in a crop coefficient. Crop coefficients based upon those given by Middleton, et al (5) are given in Table 5.

Table 5. Crop Coefficients to be Used with Eqs. 3, 5 and 6

Crop	K	Crop	K
Apples, Delicious	1.31	Potatoes, White Rose (early)	1.21
Alfalfa, Ranger (arid)	1.19	Potatoes, Neted Gem (late)	1.16
Beans, Red Mexican	1.11	Sorgham, NK 140	1.09
Soybeans	1.13	Sorghum d.d. yellow Sooner	0.96
Sugar Beets	1.11	Wheat, Marfed (spring)	1.15
Clover, Ladino	1.15	Wheat, Omar (winter)	1.13
Corn (field)	0.96	Grapes, Concord (no cover)	0.86
Pear, Dark Perfection	1.25	Alfalfa, DuPuits (humid)	1.16
Peaches, Elberta (no cover)	1.00	Rasberries, Payallup	1.24
Peaches, Elberta (alfalfa cover)	1.25	Strawberries, Northwest	0.48

All available sources of crop evapotranspiration data were used to provide a general summary of crop coefficients for both full crop cover conditions and for the growing season average. These coefficients are the best average data available principally from agricultural experiment station data and publications and are given in Table 6.

Although timing of water availability has an important influence on crop growth and yields there is a general relationship between moisture adequacy and production. Scott(6) demonstrates essentially no change in production per unit of water applied between 45 and 75 percent of ETA. The moisture adequacy yield curve became a straight line relationship within that range and yields per unit of water applied fell off with increasing adequacy up to 100 percent of the value ETP x K. The relationship beyond fall adequacy is not given.

Various other crops demonstrate similar production functions with a maximum value of water in the production function occuring at about 75 to 85 percent of fully adequate application.

Table 6. Crop Coefficients, K (for use with potential evapotranspiration ETP)

Crop	Average K for Full Crop Cover	Average Seasonal K
Field and oil crops including beans, castor beans, corn, cotton, flax, peanuts, potatoes, safflower, soybeans, sorghum, sugar beets, tomatoes, and wheat	1.15	.90
Fruits, nuts and grapes		
Citrus fruits (oranges, lemons and grapefruit)	.75	.75
Deciduous fruits (peaches, plums and walnuts)	.90	.70
Deciduous fruits with cover crop	1.25	1.00
Grapes	.75	.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	.95
Sugar cane	1.25	1.00
Summer vegetables	1.15	.85

CONCLUSION

Methodology is presented for estimating potential evapotranspiration based upon data from a wide range of climatic conditions. Use is made of data usually published in most countries. For most climates the only weather data required are mean temperature and mean relative humidity. For arid climates with mean relative humidities generally less than 64 percent (24 hour means) the only weather measurement required is temperature.

Crop coefficients for use with potential evapotranspiration are based upon available sources from various parts of the world. They appear satisfactory for use in connection with prevailing cultural practices.

APPENDIX - REFERENCES

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