Estimating Solar Radiation and Evapotranspiration Using Minimum Climatological Data (Hargreaves-Samani equation)

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Abstract: Procedure is introduced to estimate the solar radiation and subsequently reference crop evapotranspiration using minimum climatological data. The paper describes a modification to an original equation which uses maximum and minimum temperature to estimate solar radiation and reference crop evapotranspiration. The proposed modification allows for correcting the errors associated with indirect climatological parameters which affect the local temperature range. The proposed modification improves the accuracy of estimates of solar radiation from temperature.

Introduction

Reference Crop Evapotranspiration (ET_0) is a key component in hydrological studies. ET_0 is used for agricultural and urban planning, irrigation scheduling, regional water balance studies and agro-climatological zoning. Various equations are available for

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estimating ET_0. These equations range from the most complex energy balance equations requiring detailed climatological data (Penman-Monteith, Allen, 1989) to simpler equations requiring limited data (Blaney-Criddle, 1950, Hargreaves-Samani, 1982,1985). The Penman-Monteith equation is widely recommended because of its detailed theoretical base and its accommodation of small time periods. However, the detailed climatological data required by the Penman-Monteith, are not often available especially in developing nations. For example, in the continent of Africa, there is one such weather station for every three million hectares (Jagtap, 1991). Even in more developed nations, the climatological data are often limited. In the state of Texas, there is one such weather station for every 40,000 ha of irrigated land (Henggeler et al, 1996). On the other hand, the instruments which are used to measure the weather parameters , specifically, solar radiation and humidity are often subject to stability errors. It is common to see a drift of as much as 10 percent in pyranometers (Sammis, 1998). Henggeler et al (1996) observed that relative humidity sensors are losing about 1 percent in accuracy per installed month. Considering the paucity of such climatological data and the impact of microclimates on weather parameters, it is desirable to be able to estimate ET_0 for locations where the full range of reliable climatological data are not currently available.

Literature Review

The most important parameters in estimating ET_0, are temperature and solar radiation. According to Jensen (1985), at least 80 percent of ET_0 can be explained by temperature and solar radiation. Hargreaves and Samani (1982) recommended a simple equation to estimate solar radiation (R_s):

$$R_s = (KT)(R_a)(TD)^{0.5} \tag{1}$$

where TD = maximum daily temperature minus minimum daily temperature (^{0}C) for weekly or monthly periods; Ra = extraterrestrial radiation (mm/day); and KT = empirical coefficient. Combining equation 1 with the original Hargreaves equation (Hansen et al, 1979) resulted in a simplified equation which requires only temperature and latitude (Hargreaves and Samani, 1982, 1985). The simplified equation is:

$$ET_0 = 0.0135(KT)(R_a)(TD)^{1/2}(TC+17.8) \tag{2}$$

where $TD = T_{max}-T_{min}$ (^{0}C), and TC is the average daily temperature (^{o}C). Equation 2 explicitly accounts for solar radiation and temperature. Although relative humidity is not explicitly contained in the equation, it is implicitly present in the difference in maximum and minimum temperature. The temperature difference (TD) is linearly related to relative humidity (Hargreaves and Samani, 1982). Equation 2 has been successfully used in some locations for estimating ET_0 where sufficient data were not available to use other methods (Orang et al 1995). Even though equation 2 does not account for advection, it has been successfully used even in advective conditions when calibrated against wind data (Salazar, 1987).

Hargreaves (1994) recommended using KT = 0.162 for "interior" regions and KT = 0.19 for coastal regions. However, there is an implicit assumption in both equations 1 and 2 which could result in significant errors in some conditions. Both 1 and 2 assume that the difference in maximum and minimum temperature is directly related to the fraction of extraterrestrial radiation received at the ground level. However, there are factors other than solar radiation, cloudiness, and humidity that can influence the difference in maximum and minimum temperature in a given location. These factors include: latitude, elevation, topography, storm pattern, advection, and proximity to a large body of water. For example, at low latitudes, the temperature difference becomes negligible and consequently equations 1 and 2 become insensitive and could significantly underestimate both solar radiation and ET_0 as demonstrated by Jagtap (1991). The following describes a methodology for correcting KT in order to avoid large errors.

ADJUSTING KT

Allen (1995) recommended a correction factor for KT. Allen (1996) suggested using $KT = 0.17(P/P_o)^{0.5}$ for interior regions and $KT = 0.2(P/Po)^{0.5}$ for coastal regions to account for proximity to a large body of water and elevation effects on the volumetric heat capacity of the atmosphere, where P = mean monthly atmospheric pressure of the site and P_o = mean monthly atmospheric pressure at sea level. However, not all coastal regions are the same. For example, the coastal site of Los Angeles (CA) has a KT value of 0.21 while the coastal site of Portland (ME) has a KT value of 0.13 (Samani and Pessarakli, 1986). Using the above equations proposed by Allen (1996), the KT values for both sites will be equal to 0.2. Besides, increases in elevation do not always result in a lower KT value. For example, in the country of El Salvador, within the same latitude of 13 degree N, the elevation rises rapidly from 0 to 2400 m, and the average monthly TD changes from 14.6 ^{o}C at 0 elevation to 7.16 ^{0}C at the elevation of 2400 m. Using the proposed equations will result in significant underestimation of solar radiation in this case due to the reduced temperature difference at higher altitude.

Average monthly temperature and radiation data for a period of 25 years are reported by Knapp et al. (1980) for the continental United States. Using average monthly data for the entire year, from 65 weather stations located between 7 to 50 degree, N latitude in the United States, the following relationship was developed between TD and KT.

$$KT = 0.00185(TD)^2 - 0.0433\ TD + 0.4023, \qquad R^2 = 0.70,\ S.E. = 0.0126, \qquad (3)$$

The actual data points and the fitted curve are shown in Figure 1.

The relationship shows that KT itself is a function of temperature difference. As temperature difference decreases, the KT changes from a low value of 0.13 to a high value of 0.24, a variation of as much as 85 percent. The relationship also shows that in advective environments where the temperature difference often exceeds 14 ^{o}C, there is a sudden rise in KT value. This explains the underestimation of ET_0 in dry climates using equation 2 (Henggeler et al, 1996).

A comparison was made between calculated values of monthly KT , based on actual TD and solar radiation data, and the KT values estimated from equation 3 and the equations proposed by Allen (1995). The actual KT values were calculated using regression based on monthly average solar radiation data and TD values for 25 years based on equation 1. Five weather stations (two coastal stations, one island and three inland stations) were selected at random, for the comparison. These weather stations were not included in the development of equation 3. The results of the comparison are shown in Table 1. The comparison in Table 1 shows that the maximum error in estimating KT based on previous method (Allen, 1995), was 54 percent while the maximum error associated with equation 3, was 15 percent.

SUMMARY AND CONCLUSIONS

Considering the paucity of detailed climatological data around the world, there is a need for methods which can estimate reference evapotranspiration with limited data. This paper describes a method to estimate solar radiation from latitude and maximum and minimum temperature. A modification is proposed to original equation which was introduced in 1982. The proposed modification minimizes the error associated with estimating solar radiation, thus improving the estimation of reference evapotranspiratrion. The maximum error in estimating the solar radiation with the proposed modification was 15 percent.

Table 1. Comparison between calculated and estimated values of KT

Station	Elevation (m)	TD, ^{o}C	KT, estimated Allen,1995	KT, estimated Equation 3	KT, Calculated Equation 1	% error Allen,1995	% error Equation 3
Portland, Maine	19	11.4	0.2	0.15	0.13	54	15
San Francisco (CA)	5	9.1	0.2	0.16	0.15	33	6.7
Tucson, AZ	779	15.2	0.16	0.17	0.17	5.9	0
El Paso, TX	1194	15.4	0.16	0.18	0.18	11	0
Salt Lake City, UT	1288	14.2	0.16	0.16	0.17	0	5.9
Hilo, Hawaii	11	8.83	0.2	0.16	0.15	33	6.7

APPENXID I. REFRENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

ET_0 = reference crop evapotranspiration;

KT = coefficients which relates global solar radiation to the temperature difference

P = mean monthly atmospheric pressure;

P_0 = mean monthly atmospheric pressure at sea level;

R_s = global solar radiation;

R_a = extraterrestrial radiation;

TD = difference between maximum and minimum temperature ^{0}C;

TC = average temperature ^{0}C;

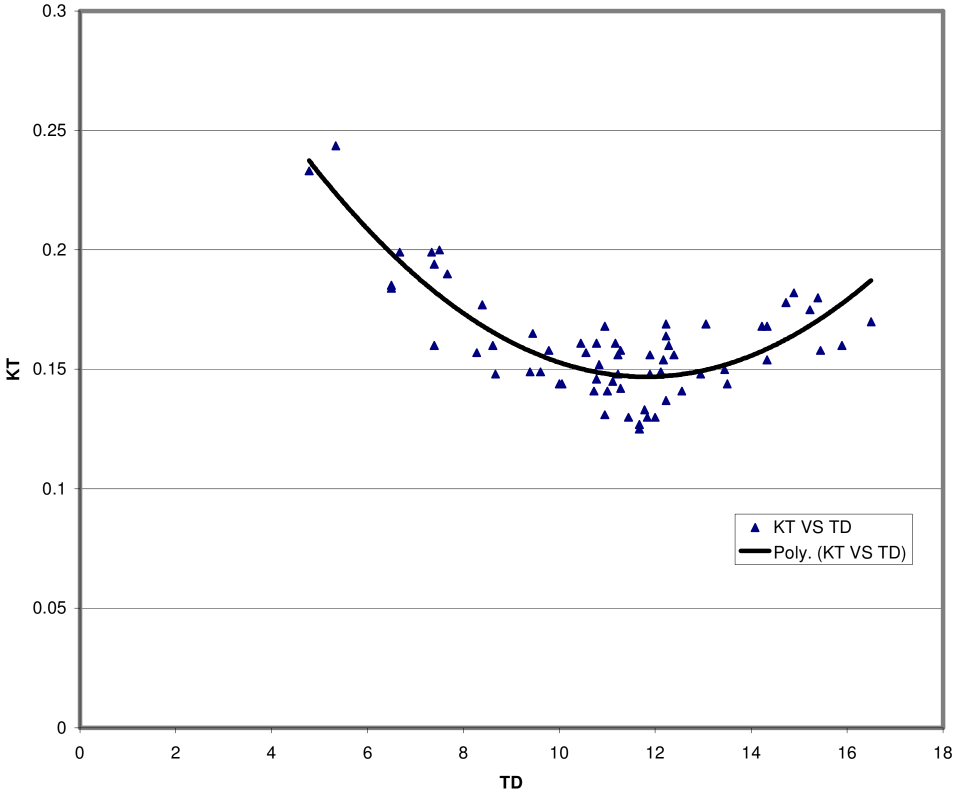

Figure 1. The relationship between KT and TD (^{0}C)

Equation to calculate RA (Mj/m2/d) is as follows (Ref. FAO 56) :

$$Ra = \frac{1,440}{\pi}(\, G_{sc}.d_r)[\psi_s \sin(\varphi)\sin(\delta)+\cos(\varphi)\cos(\delta)\sin(\psi_s)]$$

where;

G_{sc} = solar constant (0.0820 Mj/m2/min)

d_r = inverse relative distance from earth to sun

$d_r = 1+ 0.033\cos[\frac{2\pi(JD)}{365}]$

and,

JD = day of the year

ψ_s = sunset hour angle (rad)

$\psi_s = \arccos[-\tan(\varphi)\tan(\delta)]$

δ = solar declination (rad) = $0.409\sin(2\pi.\frac{JD}{365}-1.39)$

φ = latitude of location (rad)

MJ/m2/d can be converted to mm/d as; mm/d=MJ/m2/d/2.43

Or from the table in the following page (Ra = mm/d)

Northern Hemisphere													Southern Hemisphere												
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Lat	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2	50°	17.5	14.7	10.9	7.0	4.2	3.1	3.5	5.5	8.9	12.9	16.5	18.2
4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7	48	17.6	14.9	11.2	7.5	4.7	3.5	4.0	6.0	9.3	13.2	16.6	18.2
4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3	46	17.7	15.1	11.5	7.9	5.2	4.0	4.4	6.5	9.7	13.4	16.7	18.3
5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7	44	17.8	15.3	11.9	8.4	5.7	4.4	4.9	6.9	10.2	13.7	16.7	18.3
5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2	42	17.8	15.5	12.2	8.8	6.1	4.9	5.4	7.4	10.6	14.0	16.8	18.3
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8*	15.7	13.9	11.6	9.5	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8