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Hargreaves and Other Reduced-Set Methods for Calculating Evapotranspiration

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1. Introduction

Globally, irrigation is the main user of fresh water, and with the growing scarcity of this essential natural resource, it is becoming increasingly important to maximize efficiency of water usage. This implies proper management of irrigation and control of application depths in order to apply water effectively according to crop needs. Daily calculation of the Reference Potential Evapotranspiration (ETo) is an important tool in determining the water needs of different crops. The United Nations Food and Agriculture Organization (FAO) has adopted the Penman-Monteith method as a global standard for estimating ETo from four meteorological data (temperature, wind speed, radiation and relative humidity), with details presented in the Irrigation and Drainage Paper no. 56 (Allen et al., 1998), referred to hereafter as PM:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad (1)$$

where:
R_n – net radiation at crop surface [MJ m^{-2} day^{-1}],
G – soil heat flux density [MJ m^{-2} day^{-1}],
T – air temperature at 2 m height [°C],
u_2 – wind speed at 2 m height [m s^{-1}],
e_s – saturation vapor pressure [kPa],
e_a – actual vapor pressure [kPa],
e_s-e_a – saturation vapor pressure deficit [kPa],
Δ – slope vapor pressure curve [kPa °C^{-1}],
γ – psychrometric constant [kPa °C^{-1}],
The PM model uses a hypothetical green grass reference surface that is actively growing and is adequately watered with an assumed height of 0.12m, with a surface resistance of 70s m^{-1} and an albedo of 0.23 (Allen et al., 1998) which closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, completely shading the ground

and with no water shortage. This methodology is generally considered as the most reliable, in a wide range of climates and locations, because it is based on physical principles and considers the main climatic factors, which affect evapotranspiration.

Need for reduced-set methods

The main limitation to generalized application of this methodology in irrigation practice is the time and cost involved in daily acquisition and processing of the necessary meteorological data. Additionally, the number of meteorological stations where all these parameters are observed is limited, in many areas of the globe. The number of stations where *reliable* data for these parameters exist is an even smaller subset.

There are also concerns about the accuracy of the observed meteorological parameters (Droogers and Allen, 2002), since the actual instruments, specifically pyranometers (solar radiation) and hygrometers (relative humidity), are often subject to stability errors. It is common to see a drift, of as much as 10 percent, in pyranometers (Samani, 2000, 1998). Henggeler et al. (1996) have observed that hygrometers loose about 1 percent in accuracy per installed month. There are also issues related to the proper irrigation and maintenance of the reference grass, at the weather stations. Jensen et al. (1997) observed that many weather stations are often not irrigated or inadequately irrigated, during the summer months, and thus the use of relative humidity and air temperature from these stations could introduce a bias in the computed values for *ETo*. Additionally, they observed that the measured values of solar radiation, *Rs,* are not always reliable or available and that wind data are quite site specific, unavailable, or of questionable reliability. Thus, they recommend the use of *ETo* equations that require fewer variables. These authors compared various methods, including FAO Penman Monteith, PM, and Hargreaves and Samani, HS, with lysimeter data and noted r^2 values of 0.94-0.97, with monthly SEE values of 0.30-0.34mm. Based on these data they concluded that the differences in *ETo* values, calculated by the different methods, are minor when compared with the uncertainties in estimating actual crop evapotranspiration from ETo. Additionally, these equations can be more easily used in adaptive or smart irrigation controllers that adjust the application depth according to the daily *ETo* demand (Shahidian et al., 2009).

This has created interest and has encouraged development of practical methods, based on a single or a reduced number of weather parameters for computing *ETo*. These models are usually classified according to the weather parameters that play the dominant role in the model. Generally these classifications include the *temperature-based models* such as Thornthwaite (1948); Blaney-Criddle (1950) and Hargreaves and Samani (1982); The *radiation models* which are based on solar radiation, such as Priestly-Taylor (1972) and Makkink (1957); and the *combination models* which are based on the energy balance and mass transfer principles and include the Penman (1948), modified Penman (Doorenbos and Pruitt, 1977) and FAO PM (Allen et al., 1998).

Objectives and methods

The objective of this chapter is to review the underlying principles and the genesis of these methodologies and provide some insight into their applicability in various climates and regions. To obtain a global view of the applicability of the reduced-set equations, each equation is presented together with a review of the published studies on its regional calibration as well as its application under different climates.

The main approach for evaluation and calibration of the reduced-set equations has been to use the PM methodology or lysimeter measurements as the benchmark for assessing their performance. Usually a linear regression equation, established with PM *ETo* values or lysimeter readings plotted as the dependent variable and values from the reduced-set equation plotted as the independent variable. The intercept, *a*, and calibration slope, *b*, of the best fit regression line, are then used as regional calibration coefficients:

$$ET_o PM = a + b(ET_o Equation) \tag{2}$$

The quality of the fit between the two methodologies is usually presented in terms of the coefficient of determination, r^2, which is the ratio of the explained variance to the total variance or through the Root Mean Square Error, *RMSE*:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(ETo_{yi} - ETo_{PM}\right)}^{2} \tag{3}$$

and the mean Bias error:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(ETo_{yi} - ETo_{PM}\right) \tag{4}$$

where n is the number of estimates and ETo_{yi} is the estimated values from the reduced-set equation.

2. Temperature based equations

Temperature is probably the easiest, most widely available and most reliable climate parameter. The assumption that temperature is an indicator of the evaporative power of the atmosphere is the basis for temperature-based methods, such as the Hargreaves-Samani. These methods are useful when there are no data on the other meteorological parameters. However, some authors (McKenny and Rosenberg, 1993, Jabloun and Sahli, 2007) consider that the obtained estimates are generally less reliable than those which also take into account other climatic factors.

Mohan and Araumugam (1995) and Nandagiri and Kovoor (2006) carried out a multivariate analysis of the importance of various meteorological parameters in evapotranspiration. They concluded that temperature related variables are the most crucial required inputs for obtaining ETo estimates, comparable to those from the PM method across all types of climates. However, while wind speed is considered to be an important variable in arid climate, the number of sunshine hours is considered to be the more dominant variable in sub-humid and humid climates.

2.1 The Hargreaves- Samani methodology

Hargreaves, using grass evapotranspiration data from a precision lysimeter and weather data from Davis, California, over a period of eight years, observed, through regressions, that for five-day time steps, 94% of the variance in measured *ET* can be explained through average temperature and global solar radiation, *Rs*. As a result, in 1975, he published an equation for predicting *ETo* based only on these two parameters:

$$ET_o = 0.0135\ R_s(T + 17.8) \tag{5}$$

where Rs is in units of water evaporation, in mm day^{-1}, and T in °C. Subsequent attempts to use wind velocity, U_2, and relative humidity, RH, to improve the results were not encouraging so these parameters have been left out (Hargreaves and Allen, 2003).

The clearness index, or the fraction of the extraterrestrial radiation that actually passes through the clouds and reaches the earth's surface, is the main energy source for evapotranspiration, and later studies by Hargreaves and Samani (1982) show that it can be estimated by the difference between the maximum, T_{max}, and the minimum, T_{min} daily temperatures. Under clear skies the atmosphere is transparent to incoming solar radiation so the T_{max} is high, while night temperatures are low due to the outgoing longwave radiation (Allen et al., 1998). On the other hand, under cloudy conditions, T_{max} is lower, since part of the incoming solar radiation never reaches the earth, while night temperatures are relatively higher, as the clouds limit heat loss by outgoing longwave radiation. Based on this principle, Hargreaves and Samani (1982) recommended a simple equation to estimate solar radiation using the temperature difference, ΔT:

$$R_s/R_a = K_T\ (T_{\max} - T_{\min})^{0.5} \tag{6}$$

where Ra is the extraterrestial radiation in mm day^{-1}, and can be obtained from tables (Samani, 2000) or calculated (Allen et al., 1998). The empirical coefficient, K_T was initially fixed at 0.17 for Salt Lake City and other semi-arid regions, and later Hargreaves (1994) recommended the use of 0.162 for interior regions where land mass dominates, and 0.190 for coastal regions, where air masses are influenced by a nearby water body. It can be assumed that this equation accounts for the effect of cloudiness and humidity on the solar radiation at a location (Samani, 2000). The clearness index (Rs/Ra) ranges from 0.75 on a clear day to 0.25 on a day with dense clouds.

Based on equations (5) and (6), Hargreaves and Samani (1985) developed a simplified equation requiring only temperature, day of year and latitude for calculating ETo:

$$ET_o = 0.0135\ K_T\ (T + 17.78)(T_{mzx} - T_{\min})^{0.5} R_a \tag{7}$$

Since K_T usually assumes the value of 0.17, sometimes the 0.0135 K_T coefficient is replaced by 0.0023. The equation can also be used with Ra in MJ m^{-2} day^{-1}, by multiplying the right hand side by 0.408.

This method (designated as HS in this chapter) has produced good results, because at least 80 percent of ETo can be explained by temperature and solar radiation (Jensen, 1985) and ΔT is related to humidity and cloudiness (Samani and Pessarakli, 1986). Thus, although this equation only needs a daily measurement of maximum and minimum temperatures, and is presented here as a temperature-based method, it effectively incorporates measurement of radiation, albeit indirectly. As will be seen later, the ability of the methodology to account for both temperature and radiation provides it with great resilience in diverse climates around the world.

Sepashkhah and Razzaghi (2009) used lysimeters to compare the Thornthwaithe and the HS in semi-arid regions of Iran and concluded that a calibrated HS method was the most accurate method. Jensen et al.(1997) compared this and other ETo calculation methods and concluded that the differences in ETo values computed by the different methods are not larger than those introduced as a result of measuring and recording weather variables or the uncertainties associated with estimating crop evapotranspiration from *ETo*. López-Urrea et al. (2006) compared seven *ETo* equations in arid southern Spain with Lysimeter data, and observed daily RMSE values between 0.67 for FAO PM and 2.39 for FAO Blaney-Criddle. They also observed that the Hargreaves equation was the second best after PM, with an RMSE of only 0.88.

Since the HS method was originally calibrated for the semi-arid conditions of California, and does not explicitly account for relative humidity, it has been observed that it can overestimate *ETo* in humid regions such as Southeastern US (Lu et al. 2005), North Carolina (Amatya et al. 1995), or Serbia (Trajkovic, 2007).

In Brasil, Reis et al. (2007) studied three regions of the Espírito Santo State: The north with a moderately humid climate, the south with a sub-humid climate, and the mountains with a humid climate (Table 1). The HS equation overestimated *ETo* in all three regions by as much as 32%, but the performance of the HS equation improved progressively as the climate became drier. Only further south, at a latitude of 24° S, and in a warm temperate climate did HS provide good agreement with PM, though still with a small overestimation. Borges and Mendiondo (2007) obtained an r^2 of 0.997 for HS when compared to PM, when using a calibrated α of 0.0022 (Sept-April) and 0.0020 for the rest of the year.

On the other hand, in dry regions such as Mahshad, Iran and Jodhpur, India, the HS equation tends to underestimate *ETo* by as much as 24% (Rahimkoob, 2008; Nandagiri and Kovoor, 2006). Rahimkoob (2008) studied the *ETo* estimates obtained from the HS equation in the very dry south of Iran. His data indicate that the HS equation fails to calculate *ETo* values above 9 mm day^{-1}, even when the PM reaches values of more than 13 mm day^{-1} (Fig. 1).

Wind removes saturated air from the boundary layer and thus increases evapotranspiration (Brutsaert, 1991). Since most of the reduced-set equations do not explicitly account for wind speed, it is natural for the calibration slope to be influenced by this parameter. Itensifu et al. (2003) carried out a major study using weather data from 49 diverse sites in the United States. They obtained ratios ranging from 0.805 to 1.242 between HS and PM and concluded that the HS equation has difficulty in accounting for the effects of high winds and high vapor pressure deficits, typical of the Great Plains region. They also observed that the HS equation tends to overestimate *ETo* when mean daily *ETo* is relatively low, as in most sites in the eastern region of the US, and to underestimate when *ETo* is relatively high, as in the lower Midwest of the US. As will be seen later, this seems to be a common issue with most of the reduced set evapotranspiration equations (see section 4.3, Fig. 7).

For the Mkoji sub-catchment of the Great Ruaha River in Tanzania, Igbadun et al. (2006) calculated the monthly *ETo* values of three very distinct areas of the catchment: the humid Upper Mkoji with an altitude of 1700m, the middle Mkoji with an average altitude of 1100 m, and the semi-arid lower Mkoji with an altitude of 900m. Their data indicate a strong relation between the monthly average wind speed and the performance of the HS equation as measured by the slope of the calibration equation (PM/HS ratio). Although the three areas have distinct climates, the HS equation clearly underestimated ETo for wind speed values below 2-2.3 ms^{-1}, and overestimated it for higher wind speed values (Fig. 2).

Trajkovic, et al. (2005) studied the HS equation in seven locations in continental Europe with different altitudes (42-433m) with RH ranging from 55 to 71%, representative of the distinct climates of Serbia. Their data show that despite the different altitudes and climatic conditions, wind speed was the major determinant for the calibration of the HS equation (Fig. 3). The results from these works indicate that wind is the main factor affecting the calibration of the HS equation and that the equation should be calibrated in areas with very high or low wind speeds.

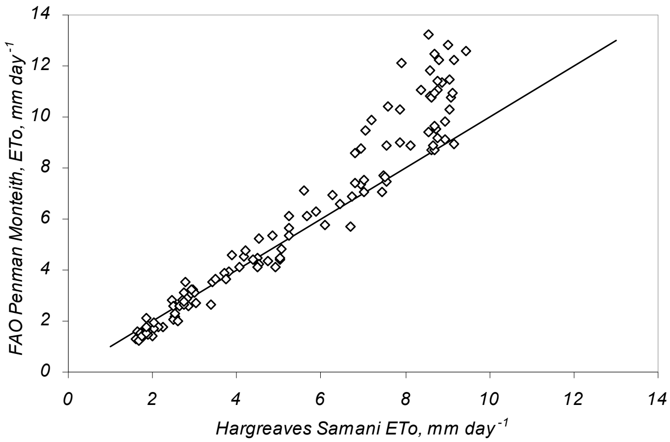

Fig. 1. Relation between *ETo* calculated with the HS equation and the PM for the dry conditions of Abadan, Iran. The Hargreaves Samani equation fails to calculate *ETo* values above 9 mm day^{-1} (data kindly provided by Rahimkoob)

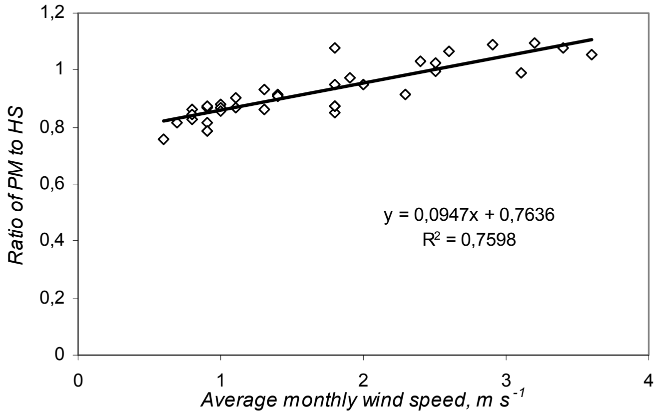

Fig. 2. Correlation between average wind speed and the calibration slope in distinct climates of the Great Ruana River in Tanzania (based on the original data from Igbadun et al. 2006).

Jabloun and Sahli (2008) studied eight stations in the semi-arid Tunisia and concluded that in inland stations, HS tends to overestimate *ETo* due to high *ΔT* values. In the coastal station of Tunis, HS underestimated *ETo* values, which they attributed to an underestimation of *Rs*.
Various attempts have been made to improve the accuracy of the HS equation through incorporation of additional measured parameters, such as rainfall (Droogers and Allen, 2002) and altitude (Allen, 1995). These methodologies have had limited global application, probably because *ETo* is influenced by a combination of different parameters, and although in a certain region there appears to be a good correlation between the calibration slope and a certain parameter, this might not be so in a different climate.
The alternative is to use regional calibration, in which, based on the climatic characteristics of the region, the *ETo* calculated by the HS equation is adjusted to account for the combined

effect of the dominant climate parameters, and thus accuracy of the equations is improved (Teixeira et al., 2008). Table 1 presents a compilation of most of the published studies on the regional calibration of the HS equation. This compilation contains 33 published works covering 21 countries with all types of climatic conditions according to the Koppen classification. Whenever various stations from a similar climate were studied, only parameters from one representative station are presented. In some studies, HS and PM were calibrated against a third methodology (such as Pan A) and thus no direct calibration parameters for the PM/HS regression were provided. In these cases, a linear regression was obtained by plotting the PM calibration equation as the dependent variable and the HS calibration equation as the independent variable. The parameters of the resulting regression equation are then presented as the PM-HS calibration parameters.

In order to contextualize the information and allow for extension of the results to other regions with a similar climate, the locations are grouped according to Koppen climate classification. These calibration coefficients can be used in the area where they were obtained or can be extrapolated for areas with similar conditions where no actual calibration has been carried out yet.

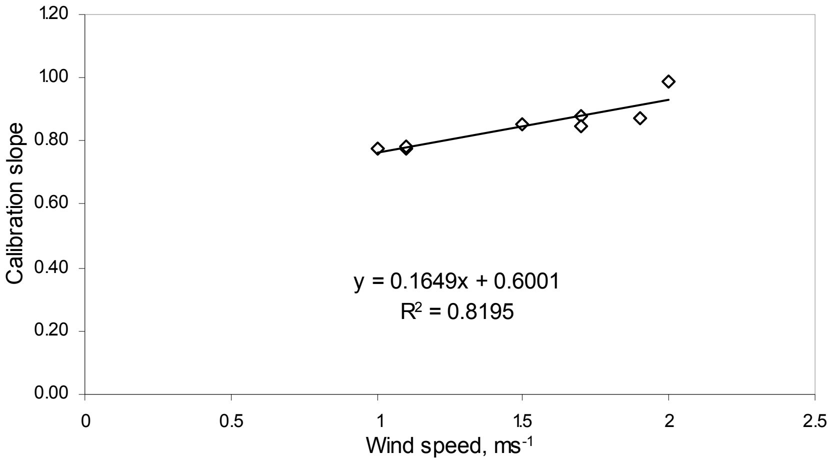

Fig. 3. Correlation between wind speed and the calibration slope for seven different locations in Serbia, representing the diverse local climates (original data from Trajkovic, 2005).

2.2 The Thornthwaite method

Thornthwaite (1948) devised a methodology to estimate *ETo* for short vegetation with an adequate water supply in certain parts of the USA. The procedure uses the mean air temperature and number of hours of daylight, and is thus classified as a temperature based method. Monthly *ETo* can be estimated according to Thornthwaite (1948) by the following equation:

$$Et_0 = ET_0sc\left(N/_{12}\right)\left(dm/_{30}\right) \quad (8)$$

Country	Station	latitude m	Altitude m	Koppen classification	Rainfall mm	RH %	U2 ms^{-1}	Regression adjustment intercept a	Regression adjustment slope b	R2	RMSE	Source
Arid												
Desert												
China, NW	Shandan Heihe R.	38°90' N	1483	BWk	250	40	1.98	0.5431	1.148			Zhao et al. 2005
China, NW	Minle	38°80' N	2271	BWk	100			-0.32	1.065			Zhao et al. 2005
US	Aquila	33°56' N	655	BWh	195	35.3	3.2	0.0378	1.3155			Alexandris, 2006
Steppe												
India	Jodhpur	26°18' N	224	BSh	402	38.9	2.1	-0.3827	1.1924			Nandagiri and Kovoor, 2006
India	Heydarabad	17°32' N	545	BSh	820	65.6	2.8	-1.97	1.48			Nandagiri and Kovoor, 2006
Syria	Tel Hadya	36°01' N	293	BSh	231	57.4	2.82		1.04	0.91		Stockle, 2004
Iran	Shiraz	30°07'N	1650	BSh	306	36.4	2.49	0.41	0.82			Razzaghi and Sepahskah, 2009
Iran	Shiraz	30°07' N	1650	BSh	305.6	36.4	2.49		1.13			Sepashkah and Razzaghi, 2009
México	Progreso (Yucatán)	21°17' N	2	BSh	511			-0.26	1.012	0.78		Bautista et al 2009
Dry summer												
Spain	Daroca (NE Spain)	41°07' N	779	Bsk	364	66.5	1.08	-0.203	0.93			Mártinez-Cob andTejero-Juste, 2004
Spain	Zaragoza (NE Spain)	41°43' N	225	Bsk	353	73.7	2.43	-0.012	0.99			Mártinez-Cob andTejero-Juste, 2004
Spain	Cordoba, inland	37°52' N	117	Bsk	696	63.3	1.6		1.06			Gavilán et al, 2008
Bolivia	Patacamaya and Oruro	17°15'S	3749	Bsk	375	57.4	1.2	0.8622	0.6422			Garcia et al 2004
Spain	Albacete	39°14' N	695	Bsk	283	68.7	1.08	0.34*	1.14*			Lopéz-Urra et al 2005
Spain	Cordoba, inland	37°51' N	110	Bsk	696	63.3	1.6	-1.49	1.3			Berengena and Gavilan, 2005
Tanzania	Lower Mkoji	7°80'	900	Bsh	520			-0.0027	0.9092			Igbadun et al
Mesothermal												
Mediterranean												
Spain	Malaga (Andalucia) Coast	36°40' N	7	Csa	531	68.1	1.9		0.962			Vanderlinden et al., 2004
Spain	Sevilla (Andalucia) interior	37°125' N	31	Csa	473	67.8	0.93		1.165			Vanderlinden et al., 2004
Spain	La Mojonera, coast	37°45' N	142	Csa	272	62.3	1.9		1.27			Gavilán et al, 2008
Portugal, S	Evora	38°55' N	246	Csa	627	63.3	4.3		0.866			Santos and Maia, 2007
US	Davis	38°32' N	18.3	Csa	458	63.3	2.62	-0.844	1.245			Alexandris, 2006
Portugal	Elvas	38°60' N	202	Csa	508	58.2	1.97	-0.08	1.04			Teixeira et al. 2008
Spain	Niebla (Andalucia)	37°21' N	52	Csa	702	65.3	1.3		1.035	0.93		Gavilán et al., 2008
Spain	Vejer Frontera (Andalucia)	36° 17' N	24	Csa	571	69.4	2.9		1.404			Gavilán et al., 2008
Greece	Athens	38°23' N	100	Csa	371	61.8	1.87	0.264	0.781			Alexandris, 2006
USA	Prosser, WA	46°15' N	380	Csb	994	69.7	1.62		1.02	0.98		Stockle, 2004
Spain	Lleida	41°42' N	221	Csb	601	68.8	0.97		1.1	0.95		Stockle, 2004
Dry winter												
Tanzania	Middle Mkoji	8°30'	1070	Cwa	800			-0.4	0.955			Igbadun et al, 2006
Brasil	Douradas, Mato G. Sul	22°16'S	452	Cwa	1603	73.8	1.74	1.73	0.67	0.7		Fietz, 2004
Brasil	S. Mantiqueira, MG		1500	Cwb	2150			0.153	1.16			Pereira et al. 2009
fully humid												
Netherlands	Haarweg	51°58' N	9	Cfb	778	87.3	2.41		1.02	0.91		Stockle, 2004
US	Louisiana, inland	31° N	low land	Cfa	1500	92	0.82	-0.28	1.05			Fontenot, 2004
US	Lousisana, coastal	29° N	low land	Cfa	1500	88.7	0.6	-0.17	0.87			Fontenot, 2004
US	North Carolina, Plymouth	35°52'	6	Cfa	1299	80.2	4.9	0.03	0.83		1.23	Amatya et al. 1995
Brasil	Palotina, Paraná	24°18'S	310	Cfa	1700	73.8	1.74	-108	1			Syperreck, 2006
Brasil	Jacupiranga river, SP	24°29'S	52	Cfa	1879	91.5	0.97	-0.365	1.042			Borges and Mendiondo, 2007

Values in grey are annual averages obtained from Climwat data base.
When calibration parameters of the HS vsFAO PM were not directly provided, linear regression equations were established with FAO-56 PM daily ET0 estimates as the dependent variable and daily ET0 values estimated by HS as an independent variable. The parameters of the regression equation were then presented as the calibration parameters.

Country	Station	latitude m	Altitude m	Classification Koppen	Rainfall mm	RH %	U2 ms^{-1}	Regression adjustment intercept a	Regression adjustment slope b	R2	RMSE	Source
Microthermal												
Fully humid												
Serbia	Kragujevac	44º00' N	190	Dfa		75%	1		0.78		0.451	Trajkovic, 2005
Serbia	Belgrade	44º45' N	132	Dfa	684	69%	1.7		0.99			Trajkovic, 2005
Cro., Ser. Bos.	Zagreb, Sarajevo, etc.	42.6- 46.1	42-630	Dfb		68-76	1.0-1.9		0.424 (3)			Trajkovic, 2007
Canada	Southern Ontario, Drumbo	43º16' N	310	Dfb		79%	1.5		0.74	0.7	0.704	Sentelhas et al. 2010
Canada	Southern Ontario, Harrow	42º12' N	190	Dfb		73%	2.2		0.94	0.64	0.704	Sentelhas et al. 2010
Dry winter												
China	Tibete plateau- Yushu	33º06' N	3681	Dwb	200	45.4	0.83	0.347	0.883	0.91	0.622	Ye et al. 2009
Polar												
Bulgaria	Trace plain, Plovdiv	42º 25' N	160	ET	492				1.11			Popova et al, 2006
Switzerland	Changins	46º24'N	416	ET	904	73	2.5	-0.31	1.12	0.99		Xu and Singh, 2002
Tropical												
Winter dry												
México	Mérida (Yucatán)	20º56' N	15	Aw	11.74			0.1754	1.021	0.78		Bautista et al 2009
Tanzania	Upper Mkoji	9º00'	1700	Aw	1070	77.5	1.23	0.006	0.987			Igbadun et al
India	Kharagpur			Aw				-2.64	1.561			Kashyap and Panda, 2001
India	Bangalore	13º00' N	921	Aw	940	66	1.9	-0.1063	1.0244			Nandagiri and Kovoor, 2006
Nigeria	Abeokuta	7º10' S	62	Aw	1506	92	2.12	-1.41	0.938			Adeboye, 2009
Nigeria	Abeokuta	7º10' S	63	Aw	1506	92	2.12	0.0025 (1)	16.8 (2)			Adeboye, 2009
Brasil	Goiânia, GO	16º28' S	823	Aw	1785	87.9	0.82	0.6923	0.3811	0.47		Oliveira et al. 2005
Brasil	Sooretama (South Espirito Santo	19º22'S	75	Am		75.9	3.34	-2.62	1.572			Reis et al, 2007
Summer dry												
Brasil	Campina Grande	7º14'S	550	As'	700	80	1.38	-0.488	0.893			Henrique, 2006
Fully humid												
Brasil	North Rio de Janeiro	21º19'S	13	Af	1172.9	73.1	0.3	-0.76	1			Mendonça et al 2003
Philipines	Los Banos	14º13' N	41	Af	1987	83.3	1.35		0.96	0.65		Stockle, 2004

* compared with lysimeter values
Values in grey are annual averages obtained from Climwat data base.
(1) (2) (3) Respectively, the K'T, d and e of regionally calibrated HS equation, according to Equation 7 in the text.
When calibration parameters of the HS vsFAO PM were not directly provided, linear regression equations were established with FAO-56 PM daily ET0 estimates as the dependent variable and daily ET0 values estimated by HS as an independent variable. The parameters of the regression equation were then presented as the calibration parameters.

Table 1. Regional calibration for the Hargreaves Samani equation compiled from published works

Where N is the maximum number of sunny hours as a function of the month and latitude and dm is the number of days per month. ETo_{sc} is the gross evapotranspiration (without corrections) and can be calculated as:

$$Et_0sc = 16\left(\frac{10T_a}{I}\right)a \tag{9}$$

where T_a is the mean daily temperature (°C), a is an exponent as a function of the annual index: a = 0.49239 + 1792 × 10^{-5} I - 771 × 10^{-7} I^2 + 675 × 10^{-9} I^3; and I is the annual heat index obtained form the monthly heat indecies:

$$I = \sum_{m=1}^{12}\left(\frac{T_m}{5}\right)1.514 \tag{10}$$

Bautista et al. (2009) found that the precision of the Thorntwaite methodology improved during the winter months in Mexico. Garcia et al. (2004) observed that under the dry and arid conditions of the Bolivian highlands the Thornthwaite equation strongly underestimates ETo because the equation does not consider the saturation deficit of the air (Stanhill, 1961; Pruitt, 1964; Pruitt and Doorenbos, 1977). Additionally, at high altitudes, the Thornthwaite equation also underestimates the effect of radiation, because the equation is calibrated for temperate low altitude climates. Studies in Brazil have shown that the underestimation of ETo produced by temperature-based equations under arid conditions, may be reduced by using the daily thermal amplitude instead of the mean temperature (Paes de Camargo, 2000) as in the case of the Hargreaves–Samani equation.
Gonzalez et al. (2009) studied the Thorthwaite method in the Bolivian Amazon. They observed that the Thornthwaite method underestimates evapotranspiration at all the three stations studied. This is expected, considering that normally this method leads to underestimations in humid areas (Jensen et al., 1990).

2.3 Blaney-Criddle method

The FAO Temperature Methodology recommended by Doorenbos and Pruitt (1977) is based on the Blaney-Criddle method (Blaney and Criddle, 1950), introducing a correction factor based on estimates of humidity, sunshine and wind.

$$ET_o = \alpha + \beta\left[p\left(0.46T + 8.13\right)\right] \tag{11}$$

where α and β are calibration parameters and p is the mean annual percentage of daytime hours. Values for α can be calculated using the daily RH_{min} and n/N as follows:

$$\alpha = 0.043RH_{\min} - \left(\frac{n}{N}\right) - 1.41 \tag{12}$$

$$\frac{n}{N} = 2\left(Rs / Ra\right) - 0.5 \tag{13}$$

For windy South Nebraska, Irmak et al. (2008) compared 12 different ET methodologies and found that the Blaney–Criddle method was the best temperature method and it had an RMSE value (0.64 mm d^{-1}) which was similar to some of the combination methods. The obtained estimates were good and were within 3% of the ASCE-PM *ETo* with a high r^2 of 0.94. The estimates were consistent with no large under or over estimations for the majority of the dataset. They attributed this to the fact that, unlike most of the other temperature methods, this method takes into account humidity and wind speed in addition to air temperature.

Lee et al. (2004) compared various *ETo* calculation methods in the West Coast of Malaysia and concluded that the Blaney-Criddle method was the best, among the reduced-set equations, for estimating ET in the region. They also observed that HS gave the highest estimates followed by the Priestly-Taylor equation. Similarly, in the humid Goiânia region of Brazil, Oliveira et al. (2005) observed that the Blaney-Criddle method produced the best results, next to the full PM equation.

Various studies indicate that the Blaney-Criddle equation might show some bias under arid conditions. For semi-arid conditions of Iran, Dehghani Sanij et al. (2004) found the Blaney-Criddle and the Makkink method to overestimate ETo during the growing season. Lopéz-Urrea et al. (2006) compared seven different methods for calculating ETo in the semiarid regions of Spain and observed that the Blaney-Criddle method significantly over-estimated average daily ETo.

For arid conditions of Iran, Fard et al. (2009) compared nine different methodologies with lysimeter data and observed that the Turc and the Blaney-Criddle methods showed very close agreement with the lysimeter data, while PM showed moderate agreement with the lysimeter data. The other methods showed bias, systematically over estimating the lysimeter data (Fig. 4).

Although recognizing the historical value of the Blaney-Criddle method and its validity, the FAO Expert Commission on Revision of FAO Methodologies for Crop Water Requirements (Smith et al. 1992) did not recommend the method further, in view of difficulties in estimating humidity, sunshine and wind parameters in remote areas. Nevertheless, they emphasized the value of the method for areas having only the mean daily temperature, and where appropriate correction factors can be found.

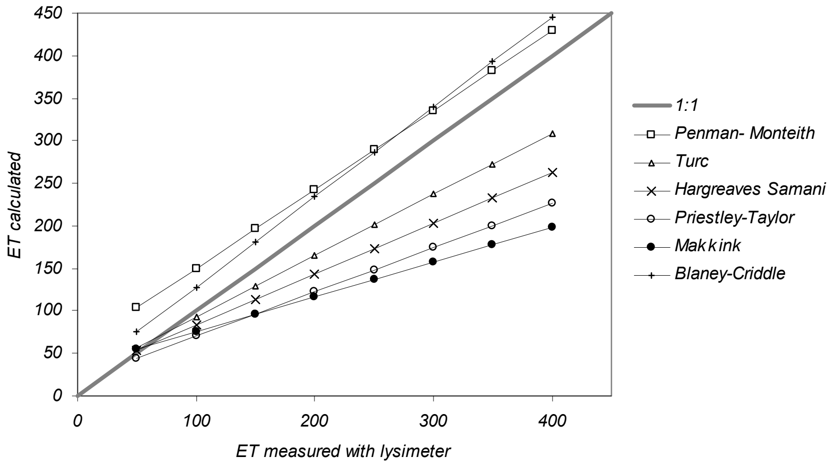

Fig. 4. Comparision of six ET methods with lysimeter data for Isfahan (adapted from Fard et al., 2009).

2.4 Reduced-set PM

The PM methodology has provisions for application in data-short situations (Allen et al. 1998), including the use of temperature data alone. The reduced-set PM equation requiring only the measured maximum and minimum temperatures uses estimates of solar radiation, relative humidity, and wind speed. Solar radiation, *Rs*, MJ m^{-2} d^{-1} can be estimated using equation 3 (Hargreaves and Samani, 1985) or using averages from nearby stations. For island locations *Rs* can be estimated as (Allen et al. 1998):

$$R_s = 0.7R_a - b \quad (14)$$

where b is an empirical constant with a value of 4 MJ m^{-2} d^{-1} . Relative humidity can be estimated by assuming that the dewpoint temperature is approximately equal to T_{min} (Allen 1996; Allen et al. 1998) which is usually experienced at sunrise. In this case, e_a can be calculated as:

$$e_a = e^o\left(T_{\min}\right) = 0.611\exp\left[\frac{17.27T_{\min}}{T_{\min} + 237.3}\right] \quad (15)$$

where $e^o(T_{min})$ is the vapour pressure at the minimum temperature, expressed in mbar. For wind speed, Allen et al. (1998) recommend using average wind speed data from nearby locations or using a wind speed of 2 m s^{-1}, since, they consider, the impact of wind speed on the *ETo* results is relatively small, except in arid and windy areas. The soil heat flux density, *G*, for monthly periods can be estimated as:

$$G_i = 0.07(T_{i+1} - T_{i-1}) \quad (16)$$

where G_i is the soil heat flux density in month *I* in MJ m^{-2} d^{-1}; and T_{i+1} and T_{i-1} are the mean air temperatures in the previous and following months, respectively.

Allen (1995) evaluated the reduced-set PM (using only *Tmax* and *Tmin*) and HS using the mean annual monthly data from the 3,000 stations in the FAO CLIMWAT data base, with the full PM serving as the comparative basis. He found little difference in the mean monthly *ETo* between the two methods. Wright et al. (2000) found similar results in Kimberly, and 75 years of data from California (Hargreaves and Allen, 2003). Other data generally indicate that the reduced-set PM performs better in humid areas (Popova, 2005, Pereira et al., 2003), while HS performs better in dry climates (Temesgen et al. 2005, Jabloun et al. 2008).

Trajkovic (2005) compared the reduced-set PM, Hargreaves, and Thornthwaite temperature-based methods with the full PM in Serbia and found that the reduced-set PM estimates were better than those produced from the Hargreaves and Thornthwaite equations. Popova et al. (2006) found the reduced-set PM to provide more accurate results compared to the Hargreaves equation, which tended to overestimate reference evapotranspiration in the Trace plain in south Bulgaria. Jabloun and Sahli (2008) also found the Hargreaves equation to overestimate reference evapotranspiration in Tunisia and found the reduced-set PM equation to provide better estimates. Nevertheless, the reduced-set PM can produce poor results in areas where wind speed is significantly different from 2 ms^{-1} (Trajkovic, 2005).

3. Radiation based methods

It is known that water loss from a crop is related to the incident solar energy, and thus it is possible to develop a simple model that relates solar radiation to evapotranspiration.

Various models have been developed, over the years, for relating the measured net global radiation to the estimated reference evapotranspiration; such as the Priestley-Taylor method (1972), the Makkink method (1957), the Turc radiation method (1961), and the Jensen and Haise method (1965).

Irmak et al. (2008) compared 11 ET models and studied the relevance of their complexity for direct prediction of hourly, daily and seasonal scales. They concluded that radiation is the dominant driver of evaporative losses, over seasonal time scales, and that other meteorological variables, such as temperature and wind speed, gained importance in daily and hourly calculations.

3.1 The Priestley-Taylor method

The Priestley-Taylor method (Priestley and Taylor, 1972; De Bruin, 1983) is a simplified form of the Penman equation, that only needs net radiation and temperature to calculate *ETo*. This simplification is based on the fact that *ETo* is more dependant on radiation than on relative humidity and wind. The Priestly-Taylor method is basically the radiation driven part of the Penman Equation, multiplied by a coefficient, and can be expressed as:

$$ET_o = \alpha \frac{\Delta\left(R_n - G\right)}{\Delta + \gamma} + \beta \tag{17}$$

where α and β are calibration factors, assuming values of 1.26 and 0, respectively. This model was calibrated for Switzerland (Xu and Singh, 1998) and values of 0.98 and 0.94 were obtained for α and β, respectively. In the Priestley-Taylor equation, evapotranspiration is proportional to net radiation, while in the Makkink equation (section 3.2), it is proportional to short-wave radiation.

Van Kraalingen and Stol (1997) found that application of the Priestly-Taylor equation during the Dutch winter months was not possible because it is based on net radiation. Since net radiation is often negative in the winter, it predicts dew formation, whereas the actual ET is positive. The situation would be different for a humid climate such as the Philippines, or in a semi-arid climate such as Israel, where the equation should compare well with PM.

Irmak et al. (2003) calibrated the Priestly-Taylor method against the FAO PM method using 15 years of climate data (1980–1994) in humid Florida, United States. The monthly values of the calibration coefficient (Fig. 5) show a considerable seasonal variation, aside from the natural difference in annual values. In general, the calibration coefficients are lower in winter months indicating that the Priestley and Taylor method underestimates *ETo*, and they are higher than 1.0 during the summer months, indicating that the method overestimates during the summer months. The long-term average lowest calibration values were obtained in January and December (0.70) and the highest values in July (1.10). These results indicate the importance of developing monthly calibration coefficients for regional use based on historic records. For the semi-arid conditions of southern Portugal, the authors also observed that the Priestley-Taylor method over-estimates daily ETo during the summer months (Shahidian et al., 2007).

Shuttleworth and Calder (1979) showed that Priestley-Taylor significantly underestimates wet forest evaporation, but also overestimates dry forest transpiration by as much as 20%. Berengena and Gavilán (2005) found that the Priestley–Taylor equation shows a considerable tendency to underestimate ETo, on average 23%, under convective conditions.

They concluded that the Priestly-Taylor equation is very sensitive to advection, and local calibration does not ensure an acceptable level of accuracy.

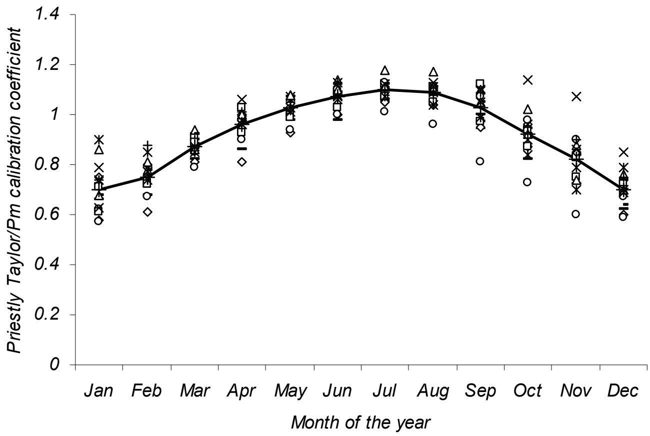

Fig. 5. Average monthly calibration coefficient for the Priestly-Taylor equation against PM for humid southern United States (based on data from Irmak et al. 2003).

3.2 The Makkink method

The Makkink method can be seen as a simplified form of the Priestley-Taylor method and was developed for grass lands in Holland. The difference is that the Makkink method uses incoming short-wave radiation *Rs* and temperature, instead of using net radiation, *Rn*, and temperature. This is possible, because on average, there is a constant ratio of 50% between net radiation and short wave radiation. The equation can be expressed as:

$$Et_o = \alpha \frac{\Delta}{\Delta + \gamma} \frac{R_s}{2{,}45} + \beta \tag{18}$$

where α is usually 0.61, and β is -0.012. Doorenbos and Pruitt (1975) proposed the FAO Radiation method based on the Makkink equation (1957), introducing a correction factor based on estimates for wind and humidity conditions to compensate for advective conditions. This radiation method has been proven valid, in particular under humid conditions, but can differ systematically from the PM reference method under special conditions, such as during dry months (Bruin and Lablands, 1998).

It has also been observed that it is difficult to use this radiation based method during winter months: Van Kraalingen and Stol (1997) found that application of the Makkink equation in Dutch winter months was not possible, though the Makkink equation did not produce negative values for ET, as was the case with the Priestley-Taylor method. Bruin and Lablans (1998) also concluded that there is no relationship between Makkink and PM in the winter months, December and January, since Makkink's method has no physical meaning, in this period.

It is reasonable to expect the Makkink and the Priestley-Taylor equations to compare well with the Penman's method, since in all these approaches the radiation terms are dominant and radiation is the main driving force for evaporation in short vegetation.

ET models tend to perform best in climates in which they were designed. A study by Amayta et al. (1995) showed that while the Makkink model generally performed well in North Carolina, the model underestimated *ETo* in the peak months of summer. Yet, the Makkink model shows excellent results in Western Europe where it was designed, both in comparison to PM as well as to the measured ETo data (Bruin and Lablans 1998, Xu and Singh 2000, Bruin and Stricker 2000, Barnett et al., 1998).

3.3 The Turc method

Also known as the Turc-Radiation equation, this method was presented by Turc in 1961, using data from the humid climate of Western Europe (France). This method only uses two parameters, average daily radiation and temperature and for RH>50% can be expressed as:

$$ET_p = \alpha\left(\left(23{,}9001R_s\right)+50\right)\left(\frac{T}{T+15}\right) \tag{19}$$

And for RH < 50% as:

$$ET_p = \alpha\left(\left(23{,}9001R_s\right)+50\right)\left(\frac{T}{T+15}\right)\left(1+\left(\frac{50-RH}{70}\right)\right) \tag{20}$$

Where α is 0.01333 and Rs is expressed in MJ m^{-2} day^{-1}.
Yoder et al. (2005) compared six different ET equations in humid southeast United States, and found the Turc equation to be second best only to the full PM. Jensen et al. (1990) analyzed the properties of twenty different methods against carefully selected lysimeter data from eleven stations, located worldwide in different climates. They observed that the Turc method compared very favorably with combination methods at the humid lysimeter locations. The Turc method was ranked second when only humid locations were considered, with only the Penman-Monteith method performing better. Trajkovic and Stojnic (2007) compared the Turc method with full PM in 52 European sites and found a SEE (Standard Error of Estimate) of between 0.10 and 0.37 mm d^{-1}. They also found that the reliability of the Turc method depends on the wind speed (Fig. 6). The Turc method overestimated PM ETo in windless locations and generally underestimated ETo in windy locations.
Amatya et al. (1995) compared 5 different ETo methodologies in North Carolina and concluded that the Turc and the Priestley-Taylor methods were generally the best in estimating ETo. They observed that all other radiation methods and the temperature based Thorntwaite method underestimated the annual ET by as much as 16%.
Kashyap and Panda (2001) compared 10 different methods with lysimeter data in the sub humid Kharagupur region of India and observed that the Turc method had a deviation of only 2.72% from lysimeter values, followed by Blaney-Criddle with a 3.16% and Priestly Taylor with a 6.28% deviation (Fig. 7). The Kashyap and Panda data are also important because they show that under sub humid conditions, most of the equations, including the PM, tend to overestimate when evapotranspiration is low, and underestimate when it is high.

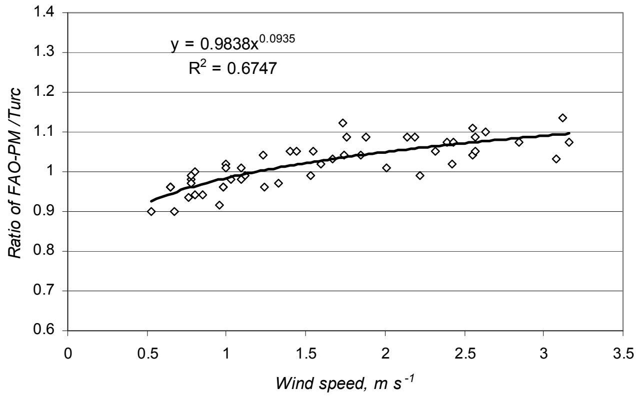

Fig. 6. Effect of wind on the ratio of evapotranspiration calculated with the FAO PM and the Turc methods (based on data from Trajkovic and Stojnic (2007), using average annual values).

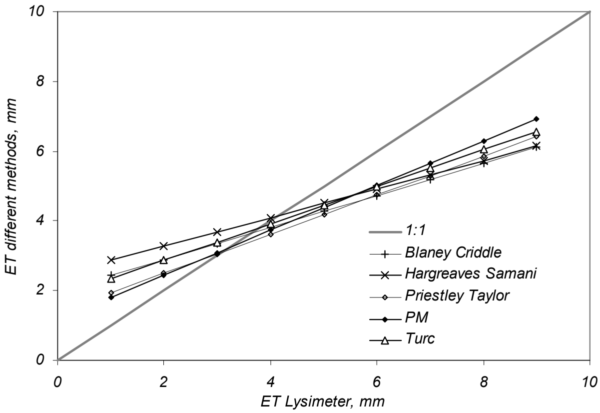

Fig. 7. Comparison of various ETo methods with Lysimeter readings in the sub-humid region of Kharagpur, India (adapted from Kashyap and Panda, 2001).

For Florida, Martinez and Thepadia (2010) compared the reduced-set PM equation with various temperature and radiation based equations and concluded that in the absence of regionally calibrated methods, the Turc equation has the least error and bias when using measured maximum and minimum temperatures. They also observed that the reduced-set PM and Hargreaves equations overestimate ET.

Fontenote (2004) studied the accuracy of seven evapotranspiraiton models for estimating grass reference ET in Louisiana. He observed that, statewide and in the coastal region, the Turc model was the most accurate daily model with a MAE of 0.26mm day^{-1}. Inland, the Blaney-Criddle performed best with a MAE of 0.31mm day^{-1} (Fig. 8).

Hence, it can be safely concluded that the Turc model can be expected to perform well in warm, humid climates such as those found in North Carolina (Amatya et al., 1995), India (George et al., 2002), and Florida (Irmak et al., 2003; Martinez and Thepadia, 2010).

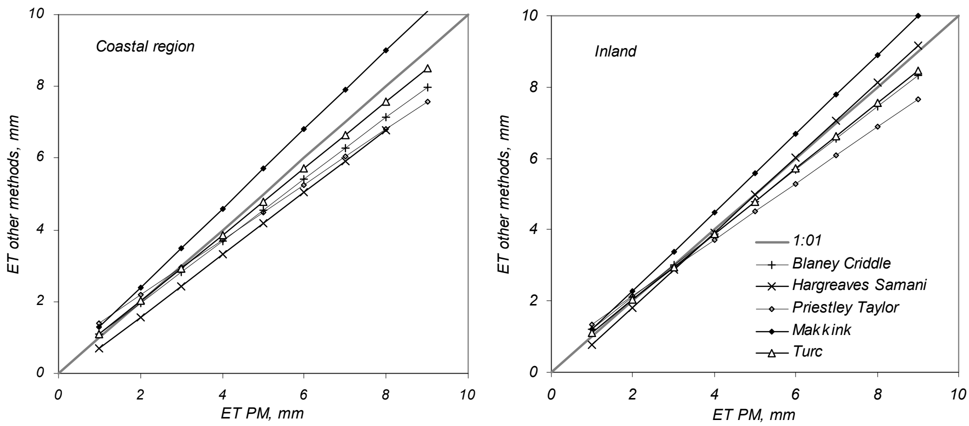

Fig. 8. Comparison of five ET methods with PM in two different regions of Louisiana (Adapted from Fontenote, 1999).

3.4 The Jensen and Haise method

This method was derived for the drier parts of the United States and is based on 3,000 observations of ET. Jensen and Haise used 35 years of measured evapotranspiration and solar radiation to derive the equation, based on the assumption that net radiation is more closely related to ET than other variables such as air temperature and humidity (Jensen and Haise, 1965). The equation can be expressed as:

$$ET = C_t\left(T - T_x\right)R_s \tag{21}$$

The original study of Jensen and Haise provides a calculation procedure to obtain *Rs* from the cloudiness, *Cl*, and the solar and sky radiation flux on cloudless days. The temperature Constant, C_t, and the intercept of the temperature exis, T_x, can be calculated as follows:

$$C_t = \frac{1}{\left[\left(45 - \frac{h}{137}\right) + \left(\frac{365}{e^0\left(T_{\max}\right) - e^0\left(T_{\min i}\right)}\right)\right]} \tag{22}$$

and

$$T_x = -2.5 - 0.14\left(e^0\left(T_{\max}\right) - e^0\left(T_{\min}\right)\right) - h/500 \tag{23}$$

where h is the altitude of the location in m, *Rs* is solar radiation (MJ m^{-2} d^{-1}); e^oT_{max} and e^oT_{min} are vapour pressures of the month with the mean maximum temperature and the month with the mean minimum temperature, respectively, expressed in mbar.

For the humid and rainy Rio Grande watershed in Brazil, Pereira et al. (2009) compared 10 different equations and concluded that the methods based on solar radiation are more accurate than those based only on air temperature, with the Jensen and Haise method presenting the smallest MBE, and thus being the method most recommended for this region.

4. Conclusions

Both temperature and radiation can be used successfully to calculate daily *ETo* values with relative accuracy. All the equations can be used for areas that have a climate that is similar to the one for which the equations were originally developed; while most of the equations can be used with some confidence for areas with moderate conditions of humidity and wind speed.

Regional calibration, especially if including monthly calibration coefficients, is important in decreasing the bias of the ETo estimates. Wind speed can greatly influence the results obtained with reduced-set equations, since wind removes the boundary layer from the leaf surface and can significantly increase evapotranspiration. Relative Humidity is another important factor that can affect the results.

Globally, it is observed that the Turc equation is highly recommended for humid or semi-humid areas, where it can produce very good results even without calibration, while the Thornthwaite equation tends to underestimate *ETo*.

The Priestley-Taylor and the Makkinik equations should not be used in the winter months in locations with high latitude, such as northern Europe.

Both the Hargreaves and the reduced-set Panman-Monteith can be effectively used with only temperature measurements, although the results can be improved if wind speed is taken into consideration.

The use of the reduced-set equations can be very important in actual irrigation management, since the error involved in using these equations can be much smaller than that resulting from using data from a weather station located many miles away.

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