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Modelling of Crop Reference Evapotranspiration: A Review

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Abstract:

Efficient irrigation water management requires a good quantification of evapotranspiration. The precise estimation of water requirement of crop is very important factor in the application of irrigation design and scheduling. Water relation model are essential component of all crop model because of critical role of water status has in determining growth, productivity and produce quality. Irrigation futures aim to identify an appropriate model for the calculation of reference crop evapotranspiration. Different climatological methods are using for estimating reference crop evapotranspiration on a daily basis. Some of these methods are based on combination theory and others are empirical methods based primarily on solar radiation, temperature and relative humidity. This paper evaluate and review the use of different evapotranspiration models and data in studies of geographical ecology it is also used in the estimation of daily water requirements for agricultural crops grown in different climatic regions of India and worldwide.

Keywords: Crop evapotranspiration, crop coefficient, reference evapotranspiration, reference ET models.

1.0 Introduction:

Evapotranspiration is important parameters in hydrologic cycle because it has represented a considerable amount of moisture lost from a catchment. As precipitation falls on earth and soaks into the soil, a plant absorbs it and then transpires it through its leaves, stem, flowers, and roots. Accurate estimation of the reference crop evapotranspiration (ET_0) is investigated due to its critical role in affecting determination of crop water use efficiency in agricultural ecosystems. Appropriate models needs to account for processes such as water uptake from soil water transport through plant and water loss. Review published studies of different models used for determination of reference evapotranspiration. The United Nations of Food and Agricultural Organization (FAO) proposed a methodology for computing crop evapotranspiration (ETo) and crop coefficient (Kc) (Doorenbos and Pruitt 1977). Crop coefficients depend on several factors including crop type, canopy, height stage of crop growth and density (Allen *et al*. 1998). To schedule irrigation properly, an accurate and standard method is required to estimate crop water requirement. Prediction methods of crop water requirements, was stated by several authors (Chiew *et al*. 1995; Allen 1996). A large number of models were developed to estimate ET_0 for use in environments that lack direct ETo measurements (Pereira and Pruitt 2004, Gavilain *et al*. 2006).

An international scientific community has accepted the FAO-56 Penman-Monteith model as the most precise one for its good results when compared with other models in various regions of the entire world (Chiew *et al*. 1995, Garcia *et al*. 2004, Gavilain *et al*. 2006). Estimation of reference ET_o by globally accepted FAO-56 P-M (Allen *et al*. 1998) requires the weather parameters like maximum and minimum temperature, solar radiation, sunshine hours, wind speed, relative humidity. The local calibration and validation of other models is more important in semi arid and arid regions than the temperate climate because most of these models were calibrated and validated in temperate environment (Dehghani Sanji *et al*. 2003).The study revealed the errors and areas that are most affected when using the un-calibrated coefficients, and discussed the consequence of such error on agricultural production, and proposed practical solutions to avoid large errors. The purpose of this paper is to review the measurement and calculation methods that could be used to provide daily reference evapotrnanspiration and to assessment the performance of simpler reference evapotranspiration models that require less readily available. This type of study is intended to make the research community aware of such errors so that more appropriate choice of these coefficients is made. In addition the purpose future research needs to address deficiencies in our current knowledge base.

2.0 Crop Evapotranspiration:

Evaporation is an important component of the water cycle, where liquid water on the surface of the earth vaporises into the atmosphere. This occurs from large water bodies such as oceans, lakes and rivers, as well as from plants and the soil. The term evapotranspiration' refers to the combined processes of transpiration and evaporation from vegetation and the surrounding soil. The Plant growth and productivity are directly related to the availability of water (Rosenberg *et al.*, 1983). Only about 1% of the water taken up by plants is actually involved in metabolic activity; most of the water is vaporised into the air, cooling the plant and preventing overheating. Since large quantities of energy are required to change phase from liquid to vapour (2.45MJ/kg for water 0°C), transpiration is a very effective means for the dissipation of heat.

3.0 Reference Crop Evapotranspiration Models:

Many investigators have developed equations of reference evapotranspiration. The following commonly used reference evapotranspiration models were selected for the calculation of crop evapotranspiration (Water requirement of the crop).

3.1 Penman FAO-24 Model:

Penman (1948) originally proposed an equation for estimating evaporation from free-water surface and then applied empirical coefficients to convert estimated evaporation to reference evapotranspiration from vegetated surfaces. Penman assumed that the heat flux into and out of the soil is small enough to be conveniently ignored. By combination method, the reference evapotranspiration rate from a short green crop completely shading the ground and never short of water is expressed in generalized form as follows (Doorenbos and Pruitt, 1977).

$$\lambda ET_0 = \frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma} 6.43(1.0 + 0.53U_2)(e_s - e_d) \quad (1)$$

3.2 Penman-Monteith FAO-56 Model:

Penman (1948) did not include a surface resistance function for water vapour transfer. For practical applications, he proposed an empirical equation for the wind function. The combination equation with aerodynamic and surface resistance term is called the Penman-Monteith equation. This equation does not reconcile thermodynamic resistance to sensible heat and vapour transfer, and surface resistance to vapour transfer. The resulting model represents a basic general description of the evapotranspiration process as follows (Allen *et al.*, 1998)

$$\lambda ET_o = \frac{\Delta}{\Delta+\gamma^*}(R_n - G) + \frac{\gamma}{\Delta+\gamma^*} k_1 \frac{0.622\,\lambda\,\rho}{P}\frac{1}{r_a}(e_z^o - e_z)$$

$$r_a = \frac{\ln\left[\frac{(z_w - d)}{z_{om}}\right]\ln\left[\frac{z_p - d}{z_{ov}}\right]}{(0.41)^2 U_z} \quad (3)$$

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right) \quad (4)$$

To adjust wind speed data obtained at elevations other than the standard height of 2 m, following equation is used (Allen *et al.*, 1998)

$$U_2 = U_z \frac{4.87}{\ln(67.8_z - 5.42)} \quad (5)$$

3.3 Kimberly-Penman Model:

Wright (1982) presented variable wind function coefficients for reference evapotranspiration at Kimberly, Idaho, USA, expressed as fifth-order polynomials with calendar day, D, as the independent variable. The resulting equations were later simplified and known as Kimberly-Penman model. The model is given as follows.

$$\lambda ET_r = \frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma} 6.43\, W_f\,(e_z^o - e_z) \quad (6)$$

$$w_f = a_w + b_w u_2 \quad (7)$$

$$a_w = 0.4 + 1.4 \exp\{-[(D-173)/58]^2 \quad (8)$$

$$b_w = 0.605 + 0.345 \exp\{-[D-243)/80]^2 \quad (9)$$

$$e_z^o - e_z = \frac{e^o(T_{max}) + e^o(T_{min})}{2} - e^o(T_{dew}) \quad (10)$$

3.4 Priestley-Taylor Model:

Priestley and Taylor (1972) proposed a simplified version of the combination equation for use when surface areas are generally wet, which is a condition required for reference evapotranspiration. The aerodynamic component was multiplied by a coefficient α_1, when general surrounding areas were wet or under humid conditions. The model is given as follows.

$$E = \alpha_1(\Delta/(\Delta+\gamma))\,(Rn-G) \quad (11)$$

3.5 Jensen-Haise Alfalfa Reference Model:

Jensen and Haise (1963) evaluated 3,000 observations of evapotranspiration as determined by soil sampling procedures over 35-year period. Jensen *et al.*, (1970) proposed following equation for estimating reference evapotranspiration using solar radiation and mean air temperature:

$$\lambda ET_r = C_T (T - T_x) R_s \quad (12)$$

$$C_H = \frac{5.0\ kPa}{(e_2 - e_1)} \quad (13)$$

C_1=38 - (2 * Elev/305) and C_2 = 7.3 °C (14)

T_x=-2.5 -1.4 (e_2 - e_1) - Elev / 550 (15)

3.6 Hargreaves Grass Related Model:

Hargreaves and Semani (1985) proposed several improvements for the Hargreaves (1968) model for estimating grass-related reference evapotranspiration. The Hargreaves model was derived from eight years of cool season Alta Fescue grass lysimeter data from Davis, California. The developed model is as follows

$$ET_o = 0.0023\ R_A\ TD^{1/2}\ (T + 17.8) \quad (16)$$

3.7 SCS Blaney Criddle Model:

Blaney and Morin (1942) first developed an empirical relationship between evapotranspiration and mean air temperature, average relative humidity, and mean percentage of daytime hours. Blaney and Criddle (1962) later modified this relationship by excluding humidity term. The basic assumption was that evapotranspiration varies directly with the sum of the products of mean monthly air temperature and monthly percentage of annual daytime hours for an actively growing crop with adequate soil moisture. The model is given as follows

$$U = KF = \Sigma kf \quad (17)$$

3.8 FAO-24 Blaney-Criddle Model:

Doorenbos and Pruitt (1977) presented the most fundamental revision of the Blaney-Criddle model since its introduction. The FAO-24 Blaney-Criddle model estimates a grass related reference crop evapotranspiration. The FAO-24 Blaney-Criddle model is based on the general linear relationship found between measured reference evapotranspiration and the Blaney-Criddle factor from many worldwide sites in various classifications based on ranges of daytime wind speed, minimum RH and sunshine expressed as n/N. The model is presented as follows

ET_o = a + bf (18)

f =p (0.46 T + 8.13) (19)

a = 0.0043 RH_{min} - n/N - 1.41 (20)

b = a_o + $a_1.RH_{min}$ + a_2.n/N + $a_3.U_d$ + $a_4.RH_{min}$n/N + $a_5.RH_{min}.U_d$ (21)

3.9 FAO - 24 Pan Evaporation Model:

Doorenbos and Pruitt (1977) provided detailed guidelines for using evaporation data to estimate reference evapotranspiration. The FAO-24 coefficients relating USWB Class-A pan data to evapotranspiration from short (88-15 cm) irrigated grass turf are given. Some adjustments would be needed to relate to K_P for a taller reference crop (that is, alfalfa with full cover conditions) especially in hot, drier climates where height of crop and aerodynamic roughness have a greater effect on evapotranspiration than in humid climates. For taller and aerodynamically rougher crops, the values of K_P would be higher and would vary less with differences in weather conditions as compared to values for shorter and smoother grass surfaces. The relationship is as follows

$$ET_0 = K_p\ E_{pan} \quad (22)$$

3.10 Christiansen Pan Evaporation Model:

Christiansen (1968) developed an equation for estimating reference crop evapotranspiration, from USWB Class A pan evaporation and several weather parameters. The model for reference evapotranspiration and coefficients produced by Christiansen is as follows:

$$ET_0 = 0.755\ E_V\ C_{T2}\ C_{W2}\ C_{H2}\ C_{S2} \quad (23)$$

The coefficients are dimensionless

$$C_{T2} = 0.862 + 0.179 \frac{T_c}{T_{Co}} - 0.041 \left(\frac{T_c}{T_{co}}\right)^2 \quad (24)$$

where T_c is the mean temperature in °C and T_{co} = 20°C

$$C_{W2} = 1.189 - 0.240 \left(\frac{W}{W_o}\right) + 0.051 \left(\frac{W}{W_o}\right)^2 \quad (25)$$

$$C_{H2} = 0.499 + 0.620 \left(\frac{H_m}{H_{mo}}\right) - 0.119 \left(\frac{H_m}{H_{mo}}\right)^2 \quad (26)$$

Where, H_m is the mean relative humidity expressed decimally and H_{mo} = 0.60

$$C_{S2} = 0.904 + 0.0080 \left(\frac{S}{S_o}\right) + 0.088 \left(\frac{S}{S_o}\right)^2 \quad (27)$$

3.11 Hargreaves-Samani (982, 85):

Parameters required (Net radiation, min/max temperature).

$$ET_0 = 0.0135(KT)(R_a)(TD^{1/2})(TC + 17.8) \quad (28)$$

$$KT = 0.00185(TD)^2 - 0.0433TD + 0.4023 \quad (29)$$

3.12 Generalized Form of Standardized Equation:

The ASCE TC standardized procedure for computing reference evapotranspiration is based on the Penman-Monteith Equation and more specifically on simplifying the version of the Penman Monteith Equation recommended by ASCE (Jensen *et al.*, 1990).

The recommended general computation procedure is provided below

$$ETsz = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (30)$$

ET_{SZ}=standardized reference crop evapotranspiration (mm d^{-1} mm h^{-1})

3.13 Notations:

λ	latent heat of vaporization MJ kg^{-1}	γ	psychometric constant, k. Pa. °C^{-1}	R_n	net radiation, MJm-2d-1
Δ	slope of saturation vapour pressure temperature curve, k Pa °C^{-1}	G	heat flux density to the ground, $MJm^{-2}d^{-1}$	U_2	horizontal wind speed at height 2.0 m, m s^{-1}
e_a, e_d	water vapour pressure in air, kPa	U_z	wind speed at height z. ms^{-1}	ρ	density of air, kgm^{-3}
C_p	specific heat at constant pressure, $MJkg^{-1°}C^{-1}$	P	atmospheric pressure, kPa	γ^*	psychometric constant modified by the ratio of canopy, resistance to atmospheric resistance
Δ	slope of saturated vapour pressure curve of air at mean air temperature, mbar	N	actual duration of bright sunshine hour	N	maximum possible hours of sunshine hour
Ra	mean extraterrestrial radiation, mm day^{-1}	Ta	mean air temperature, °K = (273 + °C)	G	daily soil heat flux, mm day^{-1}
R_A	extraterrestrial radiation, mm day^{-1}	T	mean air temperature, °C	ET_o	Ref. evapotranspiration mm day^{-1}
U	estimated evapotranspiration (consumptive use) in mm	K	An empirical consumptive use factors for the season or growing period	t	mean monthly air temperature (°C) and
p	mean monthly percentage of annual daytime hour	RH_{min}	the minimum daily relative humidity, percentage	K_p	coefficient relating evaporation from a USWB Class A pan

3.14 Input Data for Evapotranspiration:

Any evapotranspiration model have limited by the quality, quantity and availability of input data. The data required for estimation of reference evapotranspiration are as: minimum daily temperature (°C), maximum daily temperature (°C), precipitation (mm), pan evaporation (mm), relative humidity, sunshine hours and wind speed.

4.0 Review Methodology of Reference Evapotranspiration:

The most widely used approach is the one recommended by the Food and Agriculture Organization (FAO), where ET is calculated by a reference crop evapotranspiration (ET_0) multiplied by crop specific coefficient (Allen *et al.*, 1998). Therefore, the correct estimation of ET_0 is critical to accurately calculate ET. Methods to calculate ET_0 are well established; however, its accuracy is affected in many ways. First, it depends on the choice of ET_0 method and over the last 60 years, a large number of ET_0 methods have been developed. These methods are generally categorized as temperature, radiation, and combination-based according to the type of input data required. It is well recognized that if ET_0 is calculated by different methods, and for the same location and using the same meteorological dataset large variations will be obtained (Al-Ghobari, 2000, De Bruin and Stricker, 2000, Eitzinger *et al.*, 2004, Kashyap and Panda, 2001, Liu and Lin, 2005 and Suleiman and Hoogenboom, 2007). Although the combination based Penman-Monteith (P-M) equation is considered the best method (Allen *et al.* 1998) across a wide range of climates and is recommended by the FAO as the standard method (referred to as FAO-56 P-M), there is evidence that other methods performed better for certain climates (Al-Ghobari, 2000, De Bruin and Stricker, 2000 and Lascano and van Bavel, 2007). Therefore, to reduce the uncertainty associated with the ET_0 method selected a systematic evaluation is needed to verify its accuracy for the local climate. There are different procedures for the calculation of ET via the Penman-Monteith method. Currently the standardized reference evapotranspiration equation has been recommended for use by the American Society of Civil Engineers (ASCE 2005). This method is a variation of the P-M method and attempts to standardize the use of one method amongst many users. The equation provides a recommended determination of reference ET for a well-watered short (ETo) or tall grass surface. It needs to be recognized that there is a difference between that of 'potential evapotranspiration' and that of 'reference evapotranspiration'. Potential ET is that considered from a wet surface that is non-specific as to crop type. Reference ET refers to the ET from a reference grass surface of specific characteristics and that is well watered (Allen *et al*.1998). Although there are a number of models for calculating daily ET using temperature and relative humidity (RH) along with xtraterrestrial solar radiation (Ra) (Baier and Robertson 1965; Linacre 1977; Hargreaves and Samani 1985), the performance of many of these models has not been compared to ETo across the whole of the Canadian Prairies. Grace and Quick (1988) compared several models for calculating PET in the semi arid climate surrounding Lethbridge, Alberta. Droogers and Allen (2002) found that including a rainfall term with a modified monthly Hargreaves method (Hargreaves and Samani 1985) significantly improved its estimation of the FAO-56 Penman-Monteith method for global arid regions.

The calculated ET_0 also depends on how other input parameters are calculated. Many parameters that explicitly appear in the ET_0 equations are not directly measurable or the measurements are too costly, and therefore have to be estimated from other easily measured variables. For example, in the FAO-56 P-M equation, three main input parameters are net radiation (Rn), actual vapour pressure (ea), and soil heat flux (G), which are frequently not measured and are empirically calculated. Taking e_a as an example, it can be calculated based on relative humidity, dew point temperature and wet bulb depression, (Allen *et al*. 1998), and other alternative methods (Irmak *et al*. 2003, Nandagiri and Kovoor, 2005 and Yoder *et al*. 2005). Accuracy of ET_0 is also affected of using the FAO recommended coefficients instead of locally calibrated ones on the estimation of $ET_{0.}$ Kjaersgaard *et al*. (2007) found that the FAO recommended coefficients for the clear sky long wave radiation obtained satisfactory Rn estimation in a sub-humid climate. Tamm (2002) reported that using the FAO recommended net emissivity coefficients equally accurate Rn estimation with locally calibrated ones, whereas using the FAO recommended cloudiness coefficients remarkably decreased Rn estimation accuracy relative to locally calibrated ones. In present context, we have set out the derivations of the most commonly used calculation methods and in so doing have highlighted the strengths and weaknesses of various approaches. The primary reason for doing this is to develop a systematic and quantitative assessment of the appropriateness of a standardised estimation of reference evapotranspiration (ET_o).

4.1 Model Parameterization:

It is still a quite common practice to use the FAO recommended crop coefficients to calculate ET_0 (Du *et al*. 2001 and Wang *et al*. 2002). However, direct use of the FAO coefficients had significant effect on calculated ET_0 in most cases. The studies have shown that input parameters in the FAO-56 P-M calculated by different methods significantly affect the accuracy of ET_0. By comparing 12 vapour pressure deficits (VPD) and 27 Rn calculation methods in a humid climate, Yoder *et al*. (2005) found that the percent mean error in estimated daily ET_0 ranged from −1% to −8% for VPD methods and from −0.3% to −20% for Rn methods. In a humid tropical climate, Nandagiri and Kovoor (2005) found monthly ET estimated by some non-recommended alternatives for radiation yielded considerable different ET_0 estimated from the FAO recommended ones. When Rn and Rs were both replaced by the non-recommended algorithms, monthly ET_0 deviated by 8%. These variations are comparable with those of Yoder *et al*. (2005) and larger than those of Nandagiri and Kovoor (2005). This further highlights the importance of local calibration of these coefficients.

The FAO-56 P-M equation is highly rated across a wide range of climates (Allen *et al*., 1998), and often used as a reference standard (Irmak *et al*. 2002 and Liu *et al*. 2006) to evaluate ET_0. Yoder *et al*. (2004) Estimated daily reference crop evapotranspiration (ETo) is normally used to determine the water requirement of crops using the crop factor methods. Many ETo estimation methods have been developed for different types of climatic data, and the accuracy of these methods varies with climatic conditions. The study, pair−wise comparisons were made between daily ETo estimated from eight different ETo equations and ETo measured by lysimeter to provide information helpful in selecting an appropriate ETo equation for the Cumber land Plateau located in the humid Southeast United States. Based on the standard error of the estimate the relationship between the estimated and measured ETo was the best using the FAO−56 Penman−Monteith equation. The results support the adoption of the FAO−56 Penman−Monteith equation for the climatological conditions occurring in the humid Southeast. The modern combination equation applied to standardized surfaces is currently referred to as the Penman-Monteith equation (P-M). It represents the state of the art in estimating hourly and daily ET. When applied to standardized surfaces it is now called the Standardized Reference ET Equation (ASCE-EWRI 2005).

Wang Yu-Min (2011) investigates missing data procedure developed by FAO and to verify its suitability under the climatic environment of Malawi. The performance of the procedure was analysed by ET_o estimated from the world wide recommended FAO penman Monteith (F-P-M) model with full data set versus FAO-P-M value computed with limited data. The coefficients of determination, standard errors of estimates and estimates rates were used for evaluating the model performance in five production sites in Malawi. The study reveals the suitability of the FAO procedure to estimate other climatic variables which are required in FAO-P-M model when only temperature data is available under the semi arid environment of Malawi. The missing data estimation procedure may help to solve part of the irrigation planning and management problem due to the meteorological data unavailability in some areas. At same time Mohawesh.,O.E.(2011) investigate daily outputs from eight evapotranspiration models were tested against reference evapotranspiration (ETo) data computed by FAO-56 P-M to assess the accuracy of each model in estimating ETo. Models were compared at eight stations across Jordan. Results show that Hargreaves modified models were the best in light of mean biased error (MBE), root mean square error and mean absolute error).

4.2 Views within Article:

Review studies related to determination of evapotranspiration from different models. In this article various techniques employed for measuring of ET and were conducted in variety of period. The model could be used different parameter, finally reference evapotranspiration temporally estimated, because no reference evapotranspiration was measured at experimental site. The reference evapotranspiration validated by different methods. Fashion to the climatic factors affecting the reference crop evapotranspiration. Above study revealed that evapotranspiration value during initial growth period is very low except during irrigation events. Crop evapotranspiration value increase during crop development stage and reach peak during mid season. The ET_c value decline during last crop growth.The radiation methods show good results in humid climates and performance in arid conditions is erratic and tends to underestimate evapotranspiration. The Penman methods may require local calibration of the wind function to achieve satisfactory results. The most commonly used version of the Penman–Monteith equation is based on the use of measured net radiation. Because Penman–Monteith equation has been successfully applied at all scales from single leaves to whole canopies whether in glasshouses (Stanghellini, 1987; Bailey *et al*., 1993).

5.0 Conclusions and Future Prospectus:

Modelling evapotranspiration is a difficult task, particularly across a country as large and diverse climate. The difficulty is further increased by the availability of input data and accurate measurements. A number of methodologies have been reviewed that could be used to calculate reference evapotranspiration. The above review studies have following conclusions:

1) The use of model FAO -Penman- Monteith approach is accepted worldwide.
2) From this review appears that the dual crop coefficient approach results more accurate for estimation of crop water requirements respect to single crop coefficient, such as shows the comparison with dates measured (Er-Raki *et al*., 2009).
3) The process of crop coefficient Development (calibration) is depends on reference evapotranspiration model used for computation of crop evapotranspiration.
4) Different reference evapotranspiration models result in predicting different crop water requirement, when used in combination with literature based or locally calibrated crop coefficients
5) The radiation methods show good results in humid climates where the aerodynamic term is relatively small, but performance in arid conditions are erratic and tends to underestimate evapotranspiration.
6) The Penman methods may require local calibration of the wind function to achieve satisfactory results.
7) Temperature methods remain empirical and

require local calibration to get satisfactory results
8) In some part of World in semi arid climate Hargreaves and Samani (1985) may be suitable for prediction of ET_0

The main challenges likely to be faced by the different methods are:
a) The assessment of systematic and random uncertainties in the model.
b) The development of appropriate reporting tools to summarize the predictions.
c) The availability and quality of meteorological data.
d) The availability of suitable experimental data.
e) The production of suitable crop coefficients.

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