Agricultural Reviews, 40(1) 2019: 1-11
Print ISSN:0253-1496 / Online ISSN:0976-0539

AGRICULTURAL RESEARCH COMMUNICATION CENTRE
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Evapotranspiration and agriculture-A review

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Received: 05-11-2018 Accepted: 31-12-2018 DOI: 10.18805/ag.R-1848

ABSTRACT

Evapotranspiration (ET), an important component of hydrologic cycle, represents energy interaction between hydrosphere, atmosphere and biosphere. As the term indicates, it combines two processes-evaporation and transpiration. Evaporation is a diffusive process which transfers moisture in the form of vapour from the earth surfaces such as wetted soil mass, plant canopy, open water surface and other moist or wet natural surfaces. The transpiration converts liquid water into vapour form from the tissues of various plant parts such as leaf, stem, flowers, and or roots. The ET process serves as significant contributor of moisture back in to the atmosphere. Sun is the ultimate driving force for this process, exposure of the evaporating surface determines the rate of ET. The major sector of water use in the global as well as local scale, the agriculture sector is highly dependent on the concept of ET for irrigation scheduling. ET based irrigation scheduling is getting wider applications as a means to improve water productivity due to rising concern on water conservation. The environmental demand for water regulates the water requirement of the crops. The process is controlled by other factors like amount of ground coverage by the crops and its geometry, growth stage of the plant, nature and characteristics of the ground surface etc., apart from the meteorological parameters. The concept of reference ET gained importance in agricultural water requirement estimation. The present chapter focuses on the basic concepts and developments of ET and reference ET and their applications in the agriculture sector.

Key words: Agriculture, Evapotranspiration, Hydrologic cycle, Irrigation scheduling, Reference evapotranspiration, Water requirement.

Water is one of the fundamental resources for agriculture. Water availability controls the agricultural operations in both spatial and temporal scale. Precipitation as well as residual soil moisture serves as water source for meeting plant water requirement, and the water requirement of the crops which is not satisfied through these sources has to be supplied by irrigation in order to sustain expected yield. Evapotransporation (ET) process constitutes a major source of loss of applied water to the crop root zone. ET represents the water demand of the prevailing atmosphere for surface sources of water. To schedule irrigation properly, a grower must have a clear account of ET in the respective period of the location of interest. Evaporation can occur from moist soil mass, wetted plant canopy or from open water bodies. Evaporation is the diffusion of water vapour from these wet surface masses to the atmosphere. Water lost from the surface soil layers may be replenished either from precipitation, irrigation or upward movement of water from a shallow water Table thereby the soil will be able to supply water fast enough to satisfy evaporation demand. The evaporation from the soil is determined solely by the meteorological conditions. In the absence of any supply of water to soil surface, evaporation decreases rapidly.

The ET process is found to contribute around 15% of atmospheric water vapour. The transpiration part of ET specifies the role of plants in this earth atmosphere water cycle process. The water molecules present in the soil enters the crop root cells according to potential gradient exist across the plant root soil interface and make its way through the plant body and finally transpires into atmosphere from different plant parts-such as leaves, stem, flowers, and /or roots. Transpiration in combination with the evaporation of moisture that was not directly absorbed by the soil return a significant amount of water vapour to the atmosphere. Apart from the water availability in the top soil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. The geometry of the plant canopy controls the amount of solar radiation available for ET. During the initial crop growth stage, soil evaporation causes predominant loss of moisture, but once the crop is well developed and completely covers the soil, transpiration replaces the role. At sowing time almost 100% of ET is contributed from evaporation, while at full crop cover stage more than 90% of ET comes from transpiration depending upon the type of the crops grown. Through evapotranspiration and hydrologic cycle, forests or other heavily wooded areas typically release significant quantity

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of water at a location. Potential evapotranspiration (PET) is one of the concepts related to ET, which is assumed as the water loss from soil or vegetation surfaces when there is unlimited supply of water to the soil. There is no soil moisture restriction to the process, but the physiology of the plant or the atmospheric demand may be the limiting factors. PET is considered as the maximum rate of ET for a given atmospheric and plant characteristics. Thus in general, any amount of water application to the soil, in excess of this rate will result in water wastage through leaching.

Reference crop evapotranspiration (ET_o) is the evapotranspiration rate from a reference surface. The reference surface closely resembles an extensive area of actively growing green grass of uniform height completely shading the ground and with unlimited availability of soil moisture. The concept of ET_o provides information on the evaporation demand of the atmosphere, independent of the type of the crop, its stage of development and the management practices. As soil moisture is abundantly available at the reference surface, the soil factors do not affect ET_o. Relating ET to a specific surface enables the reference to which ET from other surfaces can be related. ET_o is influenced only by climatic factors. Hence, it can be computed from weather data. ET_o expresses the evaporation power of the atmosphere at a specific location and time of the year.

Reliable estimation of ET is the key aspect of water management, especially in arid and semi-arid regions. The research and developments in this area contribute different approaches for its prediction. This chapter review different methods of ET estimations and related aspects with special emphasis on agricultural water management.

Terminologies Related to ET

Potential evapotranspiration (PET): The concept of PET was suggested by Thornthwaite (1948) who defined it as the evapotranspiration from a large vegetation covered land surface with adequate moisture at all times. Thornthwaite definition connects the PET concept with the available energy for the process. According to Penman (1947) definition a completing shading short green vegetation without any limitation of water availability is the standard for explaining PET. Even though the definition indicates the important characteristics of reference vegetation, the name of the vegetation is not specified. Jensen (1963) assumed PET as the upper limit of ET that would occur with a well watered agricultural crop having an aerodynamically rough surface, such as Lucerne with 30 to 50 cm of top growth.

Apparently the concept of PET can be visualized as the integral effect of all the climatic factors governing the Evapotranspiration process. PET explains the ET process from an active short green vegetation sufficiently provided with water so that remains free from stresses on behalf of soil moisture. PET can be considered as the upper limit of evapotranspiration for a crop under prevailing climatic condition.

Reference evapotranspiration: It is the evapotranspiration rate from a reference surface. The expert panels of FAO on proposed revision of water requirement estimation methodologies (Jensen *et al.* 1990) put forth a definition for the reference surface with a standard crop height of 0.12 m, surface resistance of 70 s m^{-1} and an albedo of 0.23.

The reference crop can be correlated to an actively growing green grass which covers an extensive area under its shade and possesses uniform height with unlimited availability of soil moisture. The concept of reference crop evapotranspiration, ET_o provides information on the evaporation demand of the atmosphere, independent of the type of the crop, its stage of development and the management practices. As soil moisture is abundantly available at the reference surface, the soil factors do not affect ET_o. Relating ET to a specific surface enables the reference to which ET from other surfaces can be related. ET_o is influenced only by climatic factors. Hence, it can be computed from weather data. ET_o expresses the evaporating power of the atmosphere at a specific location and time of the year.

Measurement of evapotranspiration: Several methods have been developed for measurement and estimation of ET. The most common method for the measurement of ET is a lysimeter. The lysimeter is usually embedded within a vegetated soil of known volume. The changes in the soil moisture will be monitored throughout the growth cycle of the crop. The soil moisture measurements will provide for calculations on crop water requirement of that particular crop during different growth stages. There are weighing as well as non-weighing types of lysimeters (Fig 1) (Watson and Burnett, 1995). A lysimeter consists of an inner container with soil and vegetation and an outer container supporting the load cell assembly and drainage arrangements. The amount of irrigation, rainfall, runoff as well as leachate is accounted separately on a weighing scale. Lysimeters are large and expensive equipments, so their availability and applicability is limited. They are often considered as primary

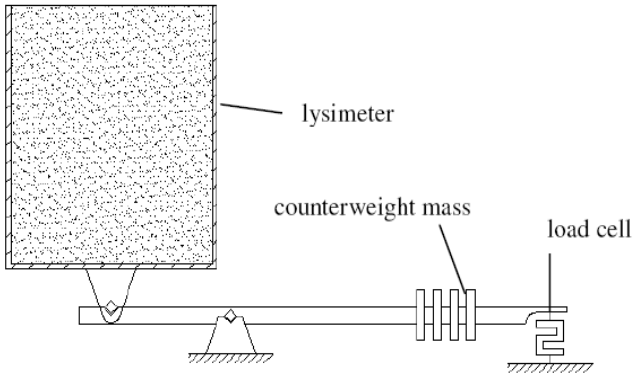


Fig 1: Weighing type lysimeter with counter weight.

measurements to calibrate ET models (Blaney and Criddle, 1950; Hargreaves, 1974; Jensen and Haise, 1963; Lage *et al.* 2003; Penman, 1948; Qiu *et al.* 2002; Tyagi *et al.* 2000).

Energy balance methods are another means for measuring ET based on energy budget methods. Energy balance equation should take into consider all fluxes of energy. The heating and evaporation of water requires energy; therefore, the ET process is limited by the input of energy into the system (*i.e.* incoming solar radiation) (Allen *et al.* 1998; Geiger *et al.* 2003). ET is the one component that links the surface energy balance to the surface water balance, and by knowing the values of the remaining components in either system, ET can be computed. Eq. (1) describes equation for an evaporating surface (Allen *et al.* 1998). The equation only considers energy fluxes in vertical direction and horizontal energy transfer by advection is ignored.

$$R_n - G - \lambda ET - H = 0 \qquad \text{Eq. (1)}$$

where, R_n=net solar radiation, W m^{-2}
G=soil heat flux, W m^{-2}
λET= latent heat flux (equivalent to ET), W m^{-2}
H=sensible heat flux, W m^{-2}

All the terms may be positive or negative. Solar radiation is received by the surface (R_n), while other fluxes are radiating away from the surface, hence will be noted as negative in the given equation. In general, a positive term represents a source of energy to the surface (day time condition), while the negative terms indicates loss of energy from the system (Allen *et al.* 1998; Dingman, 1994; Geiger *et al.* 2003). The magnitude and sign of the energy balance terms depend on several factors, such as day of the year, time of day, and the condition of the atmosphere. R_n, G, and H can all be measured directly, thus permitting the computation of the latent heat flux as a residual (ET). The mass transfer method of computing ET examines the movement of air parcels above a generally homogenous surface. It should be noted that Eq. (5) should be used in areas of generally homogeneous land cover (Allen *et al.* 1998).

The air parcels, also known as eddies, transport water vapor, heat, and momentum to and from an evaporating surface. Assuming that the transport coefficients for heat and momentum are the same as those for water vapour, the evaporation rate can be computed by calculating the positive vertical flux of water vapour from the evaporating surface (Allen *et al.* 1998; Dingman, 1994; Geiger *et al.* 2003). This assessment is typically done using the Bowen Ratio equation (Allen *et al.* 1998). Aside from lysimeters and mass transfer techniques, several other methods exist for measuring ET directly, such as eddy covariance techniques, sap flow method, scintillometric techniques etc. These methods assure accurate estimation of ET over homogeneous area (Liou and Kar, 2014). However, these methods require very high-resolution equipment that is generally cost-prohibitive and labor-intensive. Therefore these methods are typically used for research purposes (Brotzge and Crawford, 2003; Payero *et al.* 2003; Peacock and Hess, 2004; Qiu *et al.* 2002).

At the field level, the most widely adopted technique for reference ET estimation is fixing a metal evaporation pan of standard diameter of 1.20 m on a leveled wooden platform (USWB Class A pan evaporimeter) (Fig 2.). The metal pan will be filled with known quantity of water upto a specified mark few centimeters below the brim level. The loss in water from the pan is measured on daily basis precisely with a vernier caliper in depth units. The pan evaporimeter resembles the conditions of an open water body; the loss in water is attributed to the amount of water lost through evaporation under the influence of prevailing climatic conditions. There is no direct information on transpiration from the measured data set. Hence, a pan coefficient value is recommended to adopt to adjust pan evaporation to reference ET. But, there are chances of night time evaporation due to higher specific heat capacity of water and heat storage within the metal body. It may cause increased estimates of ET. Also, the aero dynamic conditions prevailing over and around the metal may be different from the conditions of plant leaves. The plant leaves possess a control over the ET process through the mechanism of stomata opening, whereas the water in an evaporation pan can easily escape from the air-water interface as long as the climatic conditions maintains a vapour pressure gradient across the interface (Allen *et al.* 1998 ,Barnett *et al.* 1998).

Selection of pan coefficient values for adjusting the measured data to ET is important for proper interpretation. Pan coefficient values can be established for a location provided direct estimates of reference ET is available (eg. lysimeter data) along with the standard metal pan evaporation data, since the ratio of reference ET to pan evaporation gives the pan coefficient values. Apart from that, based on meteorological conditions of a location, pan coefficient values can be chosen from standard Tables or equations. For more details on selection of pan coefficient values the reader

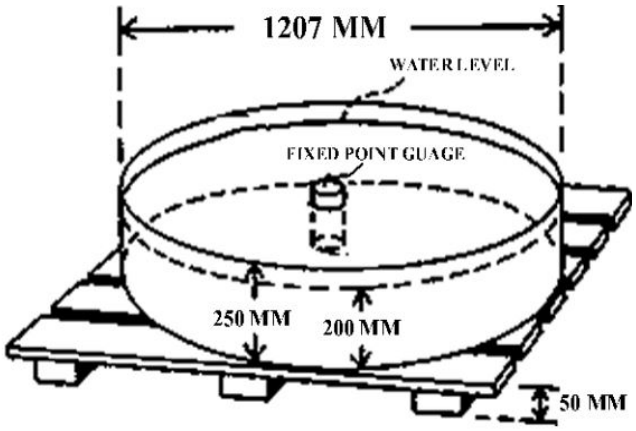


Fig 2: Class A pan evaporimeter with specifications.

may refer corresponding references. A value of 0.7 is usually found to give reasonable results under Indian conditions (Barnett *et al.* 1998; Doorenbos and Pruitt, 1977; Grismer *et al.* 2002; Irmak *et al.* 2002; Jensen and Haise, 1963). Considering the higher cost and inconvenience on obtaining weather data record for ET_0 estimation, pan coefficient based approaches found more practical adaptations at the field scale. If the weather data records are sufficiently available for a location, climate data based models are best recommended over metal pan based measurements. The future facilities may provide cost effective data set over majority of climatic conditions and the same may promote rest of the reference ET estimation models adopting meteorological dataset.

Based on the above discussions the difficulties associated with direct measurement of ET may be understood. Here comes the importance of easier still accurate alternatives for the same. Considering the importance of the concept of ET in different sectors of agriculture, environment, resources planning and management large number of experiments and researches have been conducted all through the world and the same continues. Majority of the results came up with the requirement of meteorological dataset like solar radiation, temperature, humidity, and wind measurements. Many of the models are empirically derived (Blaney and Criddle, 1950; Jensen and Haise, 1963; Thornthwaite, 1948), while certain methods (Hargreaves, 1974; Hargreaves and Samani, 1985; Penman, 1948) have been derived through theoretical approaches that involve a combination of the energy budget and mass transfer methods.

Commonly adopted models for reference evapotranspiration estimation: There are a number of models (empirical, semi-empirical as well as physically based) available for estimation of reference ET developed and adopted in different agro-climatic conditions (Jensen and Haise, 1963). Suitability of such models in a different climatic condition is usually questionable. Hence several studies have been conducted to evaluate the performance of already developed models. In general, these models can be classified into three groups considering the dominant climatic parameter in the model as: combination, radiation-based and temperature-based (Igbadun *et al,* 2006). It is important to understand the input requirements of the models so that these requirements can be considered against the accuracy when determining the optimal model(s). This chapter provides an overview of various reference evapotranspiration models that are commonly used.

Pan coefficient based methods

Pereira model (PC-1)

$$ETO = Epan * K_1 \qquad \text{Eq. (2)}$$

$$K_1 = \frac{0.85*(\Delta+\gamma)}{[\Delta+\gamma\ (1+0.33*u_2)]} \qquad \text{Eq. (3)}$$

where,

ET_o=reference evapotranspiration, mm/day

E_{pan}=Pan evaporation, mm/day

K_1=Pan Coefficient (fraction)

Δ=slope of vapour pressure curve, KPa $^0C^{-1}$

Y=psychometric constant, KPa $^0C^{-1}$

u_2= average daily wind speed at 2 m, m s^{-1}

FAO-24 Pan Coefficient based model (PC-2): Pan coefficient based methods usually measured pan evaporation readings into reference ET with adoption of a suiTable pan coefficient considering prevailing meteorological conditions (Doorenbos and Pruitt, 1977). The FAO 24 Pan Evaporation (PC-2) method takes into account data on relative humidity, wind velocity as well as windward distances. The basic form of the 24PAN model, as described by (Allen *et al.* 1998):

$$ETO = E_{pan} * K_2 \qquad \text{Eq. (4)}$$

The original FAO-24PAN method relies on a series of Tables to determine the appropriate coefficient based upon mean relative humidity, fetch, and wind speed. The regression for green crops, as described by (Allen *et al.* 1998):

$$K_2 = 0.51206 - (0.000321 * u_2) + (0.0422 * \ln(F)) + (0.1434 * \ln(RH)) - (0.00063 * (\ln(F))^2 * \ln(RH)) \qquad \text{Eq. (5)}$$

where,

K_2= pan coefficient

F= fetch distance on one side of the crop, m

RH= mean daily relative humidity, %

The wind speeds must be within the range of 1 to 8 m s^{-1}, mean values of RH must be between 30 and 84 percent, and the fetch distance must be between 1 to 1000 m for adoption of the Eq. (9) [11]. Due to the variable nature of the environment around the evaporation pans used in this study, a fetch distance of 1000 m has been assumed as suggested by (Allen, 2003).

Thornthwaite method (1948): The formula was originally developed for the purpose of a rational classification of the broad climatic patterns of the world. SuiTable coefficients should, therefore, be developed locally for reliable estimation of crop ET values. The proposed formula is as follows:

$$e = 1.6 * \left(\frac{10*t}{I}\right)^{\alpha} \qquad \text{Eq. (6)}$$

where,

e=unadjusted potential evapotranspiration (cm per month) (month of 30 days each and 12 hours day time)

t=mean air temperature, ^oC

I=annual or seasonal heat index, the summation of 12 values of monthly heat indices, i when,

$$i = \left(\frac{t}{5}\right)^{1.514} \qquad \text{Eq. (7)}$$

a=an empirical exponent computed by the equation,

$$\alpha = 0.0000006751 * I^3 - 0.0000771 * I^2 + 0.01792 * I + 0.49239 \qquad \text{Eq. (8)}$$

The value of I can become zero as the temperature is zero or less than zero, but the monthly or annual heat indices are always non-zero values. The Thornthwaite method is widely criticized for its empirical nature, but the same is still adopted widely in those regions where weather data records are not available.

Hargreaves-Samani 1985 (HM): The Hargreaves-Samani model is one of the more representative versions of the older evapotranspiration models(Hargreaves, 1974). The HM model is computationally simple and applicable to a variety of climates using only commonly available meteorological data. The development of such a model intended for simplification of the previous versions by reducing the amount of measured meteorological data to air temperature and by using extra terrestrial radiation (R_a) as a substitute for measured sunshine or radiation data (Allen, 2003). The HM model was later adopted for use by the FAO for areas where air temperature alone is the only available variable (Allen *et al.* 1998; Allen, 2003; Hargreaves and Samani, 1985). The form of the equation presented in FAO 56 (Allen *et al.* 1998) is:

$$ETo = 0.0023 * (T_{mean} + 17.8) * (T_{max} - T_{min})^{0.5} * R_a \quad \text{Eq. (9)}$$

where,

ET_0=potential evapotranspiration, mm day^{-1}
T_{mean}=mean air temperature, ^{0}C
T_{max}=maximum air temperature, ^{0}C
T_{min}=minimum air temperature, ^{0}C
R_a=extraterrestrial radiation, mm day^{-1}

Extraterrestrial radiation can be determined from the Table 2.6 of Annexure 2 of FAO 56 ET manual. Eq. (13) demands data on air temperature and extraterrestrial radiation, but neither considered effect of local humidity conditions, it may impose limitation for adoption of the model to regions where humidity hold more control over ET process. Even then the method can be recommended in different climatic conditions where data availability is the major limitation for estimation f ET.

Turc Method (1968) (TM): The Turc (1961) model (Turc, 1961) was designed for use in Western Europe as a simplification of an older equation (Jensen *et al.* 1990). Turc has been used to some extent in the United States (Amatya *et al.* 1995). The form of the equation defined for operational use is given in Eq. (14) (Allen, 2003):

$$ET_P = a_T * \left[\frac{((23.8856 * R_s) + 50)}{\lambda} * \left(\frac{T_a}{T_a + 15.0}\right) * \frac{0.4}{30.0}\right] \quad \text{Eq. (10)}$$

where,

ET_p=mean daily potential evapotranspiration, mm/day
R_s=daily global solar radiation, MJm^{-2}day^{-1}
T_a=mean daily air temperature, ^{o}C
λ = latent heat of vaporization, MJ kg^{-1}
a_T= a coefficient based on humidity measures

The value of a_T = 1.0 for mean daily relative humidity (RH_{mean}) values above 50 percent. For RH_{mean} lesser than 50 percent, a_T can be calculated suing the empirical equation as follows:

$$a_T = 1 + \frac{50 - RH_{mean}}{70} \quad \text{Eq. (11)}$$

Christiansen method using pan evaporation (1968): This equation was specifically designed for the humid climates of Western Europe (France). The monthly mean values of daily solar radiation and temperature is adopted in this model (estimates on daily basis):

$$ET = 0.755 * E_{pan} * C_T * C_W * C_H * C_S \quad \text{Eq. (12)}$$

Where,

E_{pan}=measured pan evaporation

C terms are dimensionless coefficients for temperature (T), mean wind speed (W), mean relative humidity (H) and percentage of bright sunshine hours (S), where

$$C_T = 0.463 + \left(0.425 * \left(\frac{T_C}{T_0}\right)\right) + \left(0.112 * \left(\frac{T_C}{T_0}\right)^2\right) \quad \text{Eq. (13)}$$

(Default option, T_0=20 ^{0}C)

$$C_W = 0.672 + \left(0.426 * \frac{W}{W_0}\right) - \left(0.0780 * \left(\frac{W}{W_0}\right)^2\right) \quad \text{Eq. (14)}$$

(Default option, W_0=6.7 km hr^{-1})

$$C_H = 1.035 + \left(0.240 * \left(\frac{H}{H_0}\right)^2\right) - \left(0.275 * \left(\frac{H}{H_0}\right)^3\right) \quad \text{Eq. (15)}$$

(Default option, H_0=0.60)

$$C_S = 0.340 + 0.856 * \frac{S}{S_0} - 0.196 * \left(\frac{S}{S_0}\right)^2 \quad \text{Eq. (16)}$$

(Default option, S_0=0.80)

It is an empirical model and can somehow accurately estimate ET on a monthly basis. However, this method cannot be used to calculate ET_c on a daily basis or for shorter time steps. The study on performance of Christiansen method and Penman methods in Malaysia indicated that the Penman method estimates of ET values were better than the Christiansen's method estimates against measured values (Pan) of potential evapotranspiration (Wai *et al.* 2004).

FAO-56 Penman-Monteith based combination formula: The Penman family of models is generally considered as the most accurate ET models virtually in any climate (Barnett *et al.* 1998; Qiu *et al.* 2002). The FAO version of the Penman-Monteith model (referred to as FAO-56PM) is so accurate that it is recommended as the sole method of calculating ET_o, if data are available (Allen *et al.* 1998). The major

limitation to the Penman family of models is that they require many meteorological inputs, thereby limiting their utility in data-sparse areas (Dingman, 1994; Hansen *et al.* 1980).

There are different versions of PM model developed particularly for specific climates and crops. The original Penman equation developed in 1948 is the parent equation for FAO-56 PM model. The new formula ensures a better representation of ET process by accounting two additional resistance terms-the aerodynamic resistance (r_a) and the bulk surface resistance (r_S) (Allen *et al.* 1998). While transporting moisture vapour between the surface of evaporation (surface of plant leaves) and surrounding atmosphere, air may exert resistance to vapour movement, the same is represented by r_a. The surface resistance term models resistance from the soil surface. The combination formula recommended by the Expert Consultation on FAO Methodologies for Crop Water Requirements derived by combining the equation of aerodynamic resistance and surface resistance is stated below:

$$ETo = \left\{ \frac{[0.408 * \Delta * (R_n - G)] + \left[\gamma * \frac{900}{T + 273} * u_2 * (e_s - e_a)\right]}{\Delta + [\gamma * (1 + 0.34 * u_2)]} \right\} \quad \text{Eq. (17)}$$

where,

ET_0 = reference evapotranspiration, mm day^{-1}
R_n = net radiation at the crop surface, $MJm^{-2}day^{-1}$
G = soil heat flux density, MJ m^{-2} day^{-1}
T = mean daily air temperature at 2 m height, ^0C
U_2 = wind speed at 2 m height, m s^{-1}
e_s = saturated vapour pressure, KPa
e_a = actual vapour pressure, KPa
e_s - e_a = saturation vapour pressure deficit, KPa
Δ = slope of vapour pressure curve, KPa $^0C^{-1}$
Y = psychometric constant, KPa $^0C^{-1}$

In Eq. (21) 900 is a conversion factor.

Makkinth Radiation (1957): This model was developed in Netherland as a modification of Penman after comparing the Penman model to lysimetric data (Allen, 2003; Makkinth, 1957). Currently, Makkink is popular in Western Europe (Allen *et al.* 1998) and has been used successfully in the U.S (Amatya *et al.* 1995; Allen *et al.* 1998). The operational form of the Makkinth model is given in Eq. (18) (Allen, 2003).

$$ET = 0.61 * \left(\frac{\Delta}{\Delta + \gamma}\right)\frac{R_s}{58.5} - 0.12 \quad \text{Eq. (18)}$$

where,

R_s is in equivalent energy units, ly day^{-1} and
ET is in mm day^{-1}

FAO-24 Blaney Criddle method: The Blaney-Criddle model is one of the older models being developed for the estimation of ET under arid climate in farm land areas of Western U. S (Hansen *et al.* 1980). The model's relationships were derived from experimental data for a variety of crops over the Western U.S (Blaney and Criddle, 1950). The original model is similar to the classic Thornthwaite model, requiring only temperature and a function of sunlight hours as data input.

Several revisions of the Blaney-Criddle model have been proposed, but the one used in this study was originally described in the FAO-24 manual (Doorenbos and Pruitt, 1977) and modified by Jensen *et al. 1990*. The FAO-24 version introduces the grass reference elements into the equation, allowing the later use of crop coefficients. The model as described by Jensen *et al. 1990* is as follows:

$$ETo = a + bf \quad \text{Eq. (19)}$$

$$f = p(0.46T + 8.13) \quad \text{Eq. (20)}$$

$$a = 0.0043 * RH_{min} - \frac{n}{N} - 1.41 \quad \text{Eq. (25)}$$

$$b = 0.908 - (0.00483 * RH_{min}) + \left(0.7949 * \frac{n}{N}\right) + \left(0.768 * \left(ln(U_d + 1)\right)^2\right) - \left(0.0038 * RH_{min} * \frac{n}{N}\right) - (0.000443 * RH_{min} * U_d) + \left(0.281 * \left[ln\left(\frac{n}{N} + 1\right)\right]\right) - \left[0.00975[ln(U_d + 1)]\right] * [ln(RH_{min} + 1)]^2 \left[ln\left(\frac{n}{N} + 1\right)\right] \quad \text{Eq. (21)}$$

where,

ET_0= reference evapotranspiration, mm day^{-1}

p=mean percentage of annual daytime hours (defined as the percentage of the total annual daylight hours that occur in the time period being examined, such as daily or monthly (Doorenbos and Pruitt, 1977))

T= mean monthly temperature in $^oC^{-1}$ (average of daily maximum and minimum values)

RH_{min} = minimum relative humidity, %
n / N = ratio of maximum sunshine hours to actual sunshine hours
U_d = wind speed during day time at 2 m height, m s^{-1}

Only monthly estimates of meteorological data were taken into account in the original Blaney-Criddle model. The shortest duration of measurement was restricted to monthly estimates, and holds more chances of error for prediction for shorter durations. This limitation was due to the use of temperature as the sole climatic variable (Hansen *et al.* 1980). The 24 - BC version of the model, however, uses humidity and wind speed, thus minimizing this limitation.

Modified Penman Formula (MOD PM): The modified Penman equation involves a revised wind function term. The method uses mean daily climatic data. Since day and night time weather conditions affect the level of evapotranspiration, an adjustment for this is included. The parameters of the equation can be derived from measured climatic data when no direct measurements of required variables are available. In case of unavailability of records on net radiation

of a location of interest, measured data on solar radiation, sunshine duration or cloudiness along with measured humidity and temperature can be used instead.

The Modified Penman equation is stated as follows (Doorenbos and Pruitt, 1977):

$$ETo = c[W * R_n + (1 - W) * f(u) * (e_a - e_d)] \quad \text{Eq. (22)}$$

Where,

ET_0=reference evapotranspiration, mm day^{-1}

e_a=saturation vapour pressure in mbar at the mean air temperature, $^oC^{-1}$

e_d=mean actual vapour pressure of air, mbar

$$e_d = e_a * \frac{RH_{mean}}{100} \quad \text{Eq. (23)}$$

f (u) =a wind related function

(1-W) = a temperature and elevation related weighing factor for the effect of wind and humidity on ET_0 .

W=a temperature and elevation related weighing factor for the effect of radiation on ET_o

R_n=net radiation (same as explained earlier);

R_{nl}= f (t).f(Ed).f (n/N)

C=adjustment factor to compensate for the effect of day and night weather conditions

The wind function f (u) is given by the following relationship (Eq. (29)) (Doorenbos and Pruitt, 1977).

$$f(u) = 0.27\left(1 + \frac{u_2}{100}\right) \quad \text{Eq. (24)}$$

where,

u_2 is the total wind run in km day^{-1} at 2 m height.

FAO-24 Radiation (FAO-24 RD): The FAO 24 Radiation method was first introduced by Doorenbos and Pruitt (1977) as a modification of Makinth model developed in 1957. It was originally suggested that this model be used over a Penman method when measured air temperature and solar radiation were available but wind and humidity data were unavailable or were of questionable quality (Doorenbos and Pruitt, 1977; Jensen *et al.* 1990). However, theFAO-24 RD model performs much better with measured data (Jensen *et al.* 1990). The form of FAO-24 RD is as follows:

$$ETo = a + b\left[\frac{\Delta}{\Delta + \gamma} R_s\right] \quad \text{Eq. (25)}$$

where,

ET_0= grass-reference evapotranspiration, mm day^{-1}

Δ and γ are the same variables defined for Equation 3.16

R_s= solar radiation, mm day^{-1}

a = -0.3 mm day^{-1}

Priestley-Taylor 1972 (PT): The Priestley-Taylor model is essentially a shortened version of the original 1948 Penman combination equation (Jensen *et al.* 1990; Priestly and Taylor, 1972). The model was originally intended to use in large-scale numerical modelling where advection is assumed as small, which allow the aerodynamic component of the original Penman equation to be reduced to a coefficient that modifies the remaining equation (Jensen *et al.* 1990; Katuk and Novick, 2009; Priestly and Taylor, 1972). The PT model was designed to be used in humid areas where surfaces were usually wet (Priestly and Taylor, 1972). The form of the PT used in this study was described by (Jensen *et al.* 1990) as given in Eq. (31).

$$ET = \propto * \frac{\Delta}{\Delta + \gamma} * (R_n - G) \quad \text{Eq. (26)}$$

where,

ET= evapotranspiration, mm day^{-1}

α = 1.26, and all other terms are identical to those defined previously.

According to changes in wind and humidity different values has to be chosen for the coefficient, but it has been found that a value of 1.26 is reasonable across most of the climatic conditions (McAneney and Itier, 1996).

FAO Bulletin No. 24 has recommended Blaney-Criddle, Makkinth Radiation, Modified Penman and Pan Evaporation methods for ET_0. Later on FAO Bulletin No. 56 recommended Penman-Monteith method over others. Christiansen method is used by Indian Meteorological Department (IMD) for estimation of ET_0 in many stations of India. Thornthwaite and Turc methods are relatively simple and require very few parameters. Local studies have been conducted in different parts of India to test the suitability of various empirical estimation models (Khatua and Pasupalak, 2018; Krishna and Lalitha, 2018; Kumar and Kumar, 2012; Yadav *et al.* 2017).

Regional scale estimation of evapotranspiration: Evapotranspiration connects soil-water-plant system to the atmosphere and it is spatially dependent variable. As a regulator of several ecosystem processes, ET controls the large areal distribution of plant communities and vegetation net primary production. In agriculture ET serves as an important parameter to assess irrigation demand. At the local scale field level, observations are necessary for accurate estimation of ET. At the regional level, ground level observations mayn't be available in sufficiently spatially distributed manner and also data management is cumbersome, hence remote sensing data can be used as the one of the best alternative method for spatially distributed ET estimation. Remote sensing extends point measurements or empirical relationships to larger areas, where measured meteorologic data may be sparse. Remote sensing data uses information on parameters like surface temperature, surface albedo and vegetation indices. Multiband sensors (optical, thermal and microwave bands) measures reflected solar radiation and emitted thermal radiation within discrete wavelength intervals from an extended area. The land surface based parameters such as insolation, albedo, land surface temperature (LST) and Normalized Difference Vegetation Index (NDVI) being retrieved from geostationary platform

along with surface energy balance framework will constitute estimates of ET. However, heterogeneity landscape like differences in plant species and plant cover complicate data acquisition.

It is difficult to distinguish between evaporation and transpiration. The rate of water loss from the soil surface as well as from the plant surface depends upon physical and physiological properties of the plant; relative heat flux to the crop and the soil; and the amount of water present in the soil. The 'Leaf Area Index (LAI) of the crop as the ratio of leaf area to the ground area constitutes the effective surface area for water loss from the crop and the amount of shading of the ground surface below. When LAI>3, then transpiration dominates in the ET, since most of the incoming solar radiation being captured by the crop canopy and shaded ground surface. When LAI<3, a greater portion of the incoming solar radiation reaches the ground surface (which may be often wet) and hence soil evaporation predominates.

Basic principles of ET_o based irrigation scheduling: Irrigation scheduling relates the amount of moisture present in soil to the readily available water to the plant (RAW known as Readily Available Water) and the water use by the actively growing crop. RAW is defined as the soil moisture that can be readily extracted by the plants before they suffer from moisture stress and lower growth rate. The basic concept behind RAW is that the soil moisture reduces in the soil as a result of plant extraction reaches a threshold value beyond which water become no more available for extraction by roots. If the irrigation interval is stretched out and cumulative water extraction exceeds estimated RAW value, plant may appear healthy, but growth will be compromised. If the interval prolongs without rain or irrigation, a stage is reached at which the plant water uptake is zero and plants permanently wilt or die. Under low ET_o conditions, more water may be available to the plants. The RAW values have to be chosen according to soil and plant characteristics.

Once the ET_0 has been determined, a crop coefficient must be applied to adjust the value for local conditions and the crop type. ET_o represent the effect of weather conditions, where as the crop characteristics are incorporated into the crop coefficient (K_C). In order to calculate the K_C values varies according to the crop growth stages and its duration. The calculation of crop coefficient is well explained in (Allen *et al.* 1998). Mainly four growth stages are considered-initial stage, crop developmental stage, mid-season stage and late stage. The length of each stage varies depending upon the climate, latitude, elevation and planting date. The maximum ET can be expected during mid-season stage.

Methodology for setting up crop coefficient: The actual crop ET is found out by multiplying ET_o with the crop coefficient value (K_C). The standardized K_C values are globally accepted as their dependence to climatic conditions is limited. The K_C value depends on crop type, crop growth stages, climatic conditions and soil evaporation. In single crop coefficient of FAO, the time averaged crop transpiration and soil evaporation effects are combined into a single coefficient. This method is valid for irrigation systems with several days interval between successive irrigations such as surface irrigation, sprinkler irrigation etc. In case of dual crop coefficient approach, the K_C is replaced as Eq. (27):

$$K_c = K_{cb} + K_e \qquad \text{Eq. (27)}$$

Where, K_{cb} = basal crop coefficient,
K_e=soil water evaporation coefficient.

K_{cb} is defined as the ratio of crop ET to reference ET where surface soil layers are available with sufficient moisture content in crop root zone sufficient to sustain transpiration and it neglect the effect of soil wetting. The K_c component represents the effect of soil wetting by additional sources such as rain or irrigation. The water balance of soil surface layers on daily basis is necessary for computation of K_e. Adoption of this method is limited to research purposes and real time irrigation scheduling involving micro irrigation systems.

Uncertainties of evapotranspiration estimation: The accurate estimation of evapotranspiration still pose challenges, as none of the measurement methods are adequate to fully represent the process of ET, the engine of hydrologic cycle. The behavior of hydrologic cycle to the changing climate is a major concern of the scientific community, which also points to the importance of accurate estimation of ET. Understanding and quantifying the processes governing ET is key to open up the uncertainties.

The movement of water in the hydrological cycle starts with its movement through the complex soil profile. The moisture present in soil moves in the direction of largest potential energy gradient from wetter regions to drier soil pores adjacent to root system. Water enters into the plant system through the heterogeneous root membrane and then passes through the tortuous complex network within the xylem. It experiences phase transition at the leaf-air interface and results transpiration. The vapour pressure gradient as the driving for transpiration is controlled by the turbulent eddies within the canopy of the plant into the free atmosphere. The size and energy associated with these eddies are determined by geometry of the canopy area, local weather forcing and landscape heterogeneity. This space and time dimensionality is actually beyond the scope of computational approaches. Relating water movement to its driving forces across all the interfaces poses scale issues, as the representative elemental volume is not the same in soil-plant-atmospheric system.

One of the major theoretical challenges in soil physics is to associate the existing water movement equations with the spatial heterogeneities of the soil properties,

macroporosity, preferential flows of water and nutrient discontinuities. The current approaches take into account an appropriate representation of water and solute movement in porous media. The prediction of the onset of embolism (cavitation) in the plant xylem requires microscale thermodynamic description of air and water microfluid dynamics not captured by macroscopic flow equations such as Poiseulle's law (Katuk and Novick, 2009). Thorough experimentation with strong theoretical support is essential to account the exact effect of plant hydraulic system into ET estimation. The idealistic nature of Navier-Stock equations to account mass, momentum and energy exchange also contribute uncertainties as describing boundary conditions at the plant-atmosphere interface is complicated by stochasticity in geometry and evolution at multiple scales.

The uncertainties related to ET retrieved from remote sensing are explained by Liou and Kar, (2014) as follows:

- The surface temperature from thermal infrared (TIR) radiation data is affected by surface emissivity and atmospheric corrections (1-3 K), which can be rectified through satellite observations or with high spectral resolution
- Cloud conditions results in bias in the data as it obstruct the view. Usually, higher spatial resolution is associated with lower temporal frequency and vice versa. Larger time in acquiring satellite imagery make the ET estimates impractical in operational applications. Gap filling and coupling models were considered as solution to this problem
- The differentiation between direct and diffuse radiation is not considered in radiation estimation and hence it may cause in significant variation in final result of ET.
- Temporal and spatial measurements of air temperature and its spatial representativeness introduce uncertainties in ET estimates in certain methods, as they use (T_{aero} - T_{air}). Wind speed and aerodynamic surface characteristics pose a major challenge.
- Till now, there is no universal model, which estimate ET throughout the world irrespective of the land surface, climate and terrain characteristics
- Due to differences in climate and terrain conditions and sparse distribution of meteorological stations in the study region, the interpolation technique mayn't be appropriate to give accurate results. Nocturnal transpiration and dew may also affect significantly the ET estimation. The nocturnal transpiration may constitute a significant proportion of day time transpiration (25%) as per studies with sap-flow measurements. Nocturnal transpiration at sites with high LAI, the error may be higher because of its association with nocturnal vapour pressure difference and wind speed. Presence of dew drops on the vegetation surface may results wrong information on the temperature predictions based on radiation data from satellites. While collecting information from the field the plants mayn't be watered sufficiently all the time, which causes erroneous values of ET. There are more chances of such conditions during data acquisition in early morning (such as AVHRR) and late afternoon periods (such as AVHRR). Hence, many recent studies concentrate on the dew impact on data acquisition and final estimates and corresponding corrections.

CONCLUSION

The field measurements of evapotranspiration such as lysimeter experiment are very accurate, but are, however, laborious, costly and time consuming. Therefore ET is often predicted on the basis of climatological data. A large number of methods were developed for estimation of ET_0 by several authors. The approaches relate the magnitude and variation of ET to one or more climatic factors such as temperature, day length, humidity, wind, sunshine, etc. Experts and researchers all over the world recommend the adoption of the Penman-Monteith combination method as standard for ET_0 and advised procedures for calculation of various parameters. However, other developed methods may continue to be used by practitioners either because of traditional usage or because of their simplicity and less input data requirements. But most of the models were calibrated and validated in temperate regions. Therefore local calibration and validation of ET_0 models other than FAO-56 Penman-Monteith is important in arid and semi arid environments.

Lot of research has been carried out till now for establishing accurate methods for the estimation of crop evapotranspiration. The Penman Monteith families of equations were found to be superior over other existing methods as it predicts ET consistently in different climatic conditions (Allen *et al.* 2005). This approach estimate reference evapotranspiration, which is then multiplied with the crop coefficient (K_c) to obtain actual crop evapotranspiration (ET_c). Recent review papers shows inadequacies of this approach as they are based on a fixed canopy surface resistance. There are methods (Shuttleworth, 2006; Todorovic, 1999) which doesn't involve crop coefficient, instead use variable surface resistance values. The future researches still have scope to work for improved estimation of actual evapotranspiration. Local validation and calibration of simpler models are necessary for ungauged watersheds of arid and semi-arid climate, since water management is foremost important in such areas. The changing climate scenario should be taken into account in future research methodologies and the modification of existing methods should also be considered.

Certificate: The work produced in this chapter is in its original form. The author didn't receive any financial support or institutional support on behalf of this work. The author is thankful to all of her beloved teachers and parents for their mental support and encouragement. The author ensures that the article and nor its any data send elsewhere for publication.

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