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EVAPOTRANSPIARATION

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PREFACE

Evapotranspiration is an important component of the hydrologic cycle. Water works as the medium of absorption and transport of nutrients from the soil, plays important role in plant photosynthetic process, is medium of transport of metabolites, and forms part of structure of the plant tissues. Evapotranspiration is the basic process that governs the state and movement of water in the Soil-Plant-Atmospheric continuum (SPAC). It is itself controlled by availability of water in the root zone soil, plant characteristics including transport resistances at various stages in the SPAC, and atmospheric evaporative demand. As time after irrigation or rainfall proceeds, water from the crop root zone continously depletes, resulting in the stress condition in the root zone. Due to stress, several plant functions like photosynthesis, cell division and enlargement, nutrient uptake, and thus growth and development processes are affected resulting in to reduction in the otherwise realizable yield. Therefore it is essential to keep the root zone well supplied with water by resorting to irrigation. To qualify water status which determines the irrigation needs of a crop, it is desirable that the component of evapotranspiration is adequately quantified so that crops are irrigated at appropriate time before stress conditions may develop affecting the yield.

Many relations, developed either experimentally or theoretically are available. In fact a huge number of empirical relations developed by different scientists for their works are available. However these are location specific and may not be good else where. There are some other methods like eddy-correlation and aerodynamic estimates that require instrumentation not practicable at most of the sites. Some of the simpler relations like those of Blaney and Criddle for example are easy to compute however the estimates are reliable only at intervals like monthly and seasonal. In contrast variations of combination method originally proposed by Penman provide reasonable accuracy at shorter intervals of few hours to few days. Radiation methods proposed by Jensen and Haise and FAO version of Makkink formulae, and Hargreave method are other alternatives that may yield reasonable estimates or scheduling crop irrigation. Pan evaporation method can be used where USWB Class A pan is installed following recommended installation procedures under specific fetch conditions.

The valuable document has been prepared by Dr.Ashwani Kumar, Professor and Head, Dept. of Soil & Water Engineering, Rajendra

Agricultural University, Pusa, Bihar. In this publication an attempt has been made to present available methodologies on computation of evapotranspiration in a shape that this important component of the hydrologic cycle could be quantified with desirable degree of accuracy based on the needs and available meteorological data. Where possible empirical relations and available tables have been reproduces from literature to facilitate computation by using one or the other method. Materials reproduced from various sources have been acknowledged. An extensive list of literature used is appended for the benefit of the readers.

(SATISH CHANDRA)

EVAPOTRANSPIRATION

1.0 INTRODUCTION

Water is an important input for plant life. Water is both a reactent and medium of transport. It is needed in photosynthetic conversion of CO_2 in to carbohydrates, as a medium for transport of supplies of nutrients from soil, and of growth material photosynthesized. When water demand in the Soil-Plant-Atmosphere-System (SPAS) exceeds supply, stress is said to have occurred. Water diffuses in to the atmoshpere by the physical process of evaporation from soil surface and through plant stomata, called transpiration. Transpiration is far in excess of water needed by plants in their actual metabolic activities and as structural component. Daily flow through this pathway is of order of 1 to 10 times the water held in plant tissues,10 to 100 times water used in expansion of plant cells or 100 to 1000 times water used in photosynthesis.

Evaporation is the process by which liquid water passes directly in to the vapour state. The primary source of water for plants is the soil water storage in the root zone. The driving force responsible for transport of water from soil through plant to atmosphere is vapour pressure gradient between the root zone soil moisture and the atmosphere. Transpiration (Tr), the amount of evaporation from plant leaves, is directly proportional to energy gradient and inversely proportional to resistance in the soil-plant-atmospheric (SPAS) pathway. Water moves from soil into and through plants along the gradient of decreasing water potential in the SPAS. The pathway may be divided as -

i) Movement within soil to reach the roots,
ii) Movement from soil to roots xylem,
iii) Movement from root xylem vessels to leaves, and finally exit to atmosphere.

The quantity of water evaporated from soil surface and transpired from leaves (hereafter called transpiration) may vary from 700 mm to 900 mm/year in subhumid to 550 to 750 mm/year in humid areas for vegetative surfaces. It includes evaporation of liquid or soild water from soil and plant surfaces plus transport of liquid water through plant tissues expressed as latent heat transfer per unit area or its equivalent depth of water per unit area. As compared to this, consumptive use is the quantity of water lost in evapotranspiration, stored in plant tissues and that consumed in metabolic activities, the later part being only a small fraction of the former.

1.1 Potential Evapotranspiration (PET) and Actual Crop Evapotranspiration (ETa or ETc)

Potential Evapotranspiration (PET) is the rate at which water is available, would be removed from a cropped field expressed as the Latent heat of evaporation or equivalent depth of water per unit area. It is the rate that will prevail when soil and canopy surface is at or near saturation point. Due to reduction in soil moisture potential, increase in resistance to diffusion through soil and from leaves, partial shading of ground by the canopy during early stages and death and senescence of plant organs, crops always do not transpire at potential rate. The ETa is the actual ET rate of specific crop at specific growth stage and prevailing weather conditions. Thus,

$$ETa = Kc\ Eto \tag{1}$$

or

$$Kc = ETa/ETo \tag{2}$$

where, Kc is a coefficient called crop coefficient, and varies with crop, its growth stage, and soil moisture conditions etc.

1.2 Reference Crop Evapotranspiration (ETr or ETo)

To correlate ETa with estimated evaporative potential, need has been felt to use some crop as standard. Two standares are in use with either Grass or Alfalfa as reference crop.

(i) Grass Based Reference Crop Evapotranspiration (ETo)

A grass based reference was defined by Doorenbos and Pruitt (1977) as the rate of Evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and no short of water. This standard compares with the concept of Potential Evapotranspiration originally given by Penman (1948, 1949).

(ii) Alfalfa based Reference crop Evapotranspiration (ETr)

This standard was defined by Jensen et al. (1970) with alfalfa as reference crop and is in wide use in the western

United States.. This represents the upper limit or maximum rate of evapotranspiration that occurs under given climatic conditions with a field having a well watered agricultural crop like alfalfa with 12 to 15 inches of top growth.

2. Estimation and Measurement of Evapotranspiration

A number of approaches are in use world over for estimation of ET. They vary in ease of computation, accuracy, cost and period over which estimates are reliable. ET estimation methods may be divided in to three categories

(i) Hydrologic water balance
(ii) Micro meteorological methods, and
(iii) Empirical methods.

2.1 Hydrologic Water balance

Hydrologic water balance can be computed for any region, irrigation command or individual holdings by soil water depletion sampling and/or lysimeters.

2.1.1 Soil Water Depletion:

Over any land area, ‘A’ in appropriate units,
Change in storage = Input - output

$$Dw + Ds = [\{Pe+I + Vni/A\} - \{ET+Vno/A\}] \qquad (3a)$$

where D_w (that drains below the root zone and may join the water table) and D_s are net changes in ground water and soil moisture storage, Pe the effective precipitation, I the irrigation water applied, all in units of depth, and V_{ni} and V_{no} are net water volume inputs to and output from the land area due to surface or sub surface lateral flow. In large areas V_{ni} and V_{no} may balance each other and the equation may reduce to

$$D_s + D_w = [P_e + I - ET] \qquad (3b)$$

Quantity Ds is measurable as difference of root zone moisture contents over a time period. If deep drainage Dw is assessed by some means, ET can be computed as balance.

$$ET = [P_e + I]-[D_w + Ds] \quad (4)$$

Error is possible in assessment of drainage component (Dw). All the water that drains below may not join ground water table. thus care had to be taken in computing Dw. Number of techniques are known for measuring soil moisture depletion Ds over any selected time interval.

2.1.2 Lysimeters

Lysimeters are containers that isolate the plant root - zone soil volume hydrologically from the surrounding soil. Plants are grown in these containers. Different components of the water balance equation are controlled or known here. It does not allow lateral flow, and gravitational flow is either controlled or measurable through drain tube at the bottom. Gain in root zone soil moisture is by irrigation or precipitation only, which can be accurately measured. The loss is only due to ET which thus can be estimated as balance of input and change in soil moisture storage in the container. Besides tensiometers, psychrometer, or any other non disturbing moisture meters have been used, and various weighing devices have been employed to determine changes in soil moisture storage in the lysimeters. For areas where shallow ground water table exists artificial water table can be created in lysimeters. Depending on the crop and measurement accuracy desirable various kind of lysimeters have been designed. Starting from 200 liters Oil drums to large diameter, 2 to 3 meter deep metal, concrete or PVC containers with or without artificial suction control devices at the bottom to simulate root zone soil water potential variations have been employed. Mechanical (modified platform balance), hydraulic, pneumatic, electro-mechanical and electronic weighing devices have been used in weighing lysimetric installation. Pruitt and Angus (1960), Slatyer and Mcllroy, (1961), Pelton (1961), van Bavel (1962), Mcllroy and Angus, (1963), Ritchie and Burnett (1968), Rosenberg and Brown (1970) have discussed the details of design installation and operation of different type of weighing and non weighing lysimeters. For daily or short intervals of measurements, weighing lysimeters are required, however weekly or longer periods of measurements can be made in non-weighing lysimeters with reasonable accuracy.

Lysimeters are normally installed in the centre of a large field with long obstruction free upwind distance (fetch). In design and installation of lysimeters care need to be taken to assure representative conditions inside the container as compared to the surrounding field.

Lysimeters, because of their accuracy are used for testing other methods of estimation and for calibration of empirical and micrometeorological methods.

2.1.3 Pans and Atmometers for measurement of Potential ET

Evaporation from pans and atmometers and water bodies, irrigated soil and irrigated vegetation have been found to be well correlated. They yield reasonable values at relatively low cost.

Atmometers

Atmometers are devices made of porous ceramic or porous paper surfaces, coloured black or white and connected to some small water reservoir. Black surface absorbs solar radiation where as white reflects. The difference in evaporation from two devices, therefore, is a measure of radiation incident or the atmohpheric evaporative demand. The commonly used Piche atmometer is made of flat horizontal disk of blotting paper, both sides exposed to air. The black and white spherical porous porcelain atmometer of Livingston(1935) and Bellani black-plate atmometers are some of the popular atmometers in use. These are sensitive to wind and atmospheric humidity and thus should be used for long term evapotranspiration computation with due care after local calibration and under suitable installation conditions only.

Evaporation Pans

Evaporations pans varying in size from small cans to large floating pans have been used for correlating pan evaporation data with potential evaporation. These include U.S. Weather Bureau Class A Pan, Colorado Sunken Pan, British Standard Pan, Australian Pan etc. The Class A Evaporation pan is in use in many parts of the world including India as part of standard equipment in meteorological observatories. It is 121 cm in diameter, 25.5 cm high and made of 22 gauge G.P. Sheet or 0.8 mm Monel metal. It is installed following rigid standards with at least 300 meter fetch (upwind distance of dry/wet boundary). It is mounted on an 15 cm high wooden platform with soil build up to 5 cm. below the pan. Water level is maintained below 5 cm from the top of rim of the pan, and refilled when falls to 7.5 cm. It is painted with aluminum paint annually. It is covered with a fine wire net to prevent animals drinking the water. The pan data is converted to grass based potential evapotranspiration using a pan coefficient Kp, eg.

$$ETo = Kp\ Epan \quad (5a)$$

and

$$ETcrop = Kc.\ ETo. \quad (5b)$$

The pan coefficient for class A pan varies from 0.6 to 0.8.

In pans, unlike crops where transpiration ceases during night time, water loss continues during night. Further, since wind profile, soil and aerial thermal environments, heat storage of water and crops, and internal resistance conditions are different in pans as compared to crops, specific installations need be properly calibrated. Table 1 reproduced from Doorenbos and Pruitt (1977) lists pan coefficients for two prevelent installation conditions of Class A pan.

Both pans and atmometers are passive devices. They are open to almost same atmospheric evaporative demand as the crop plants but they lack the internal plant resistance and differ in internal thermal properties. The relative sensitivity of pans and atmometers to relative humidity, wind and radiation varies as shown in Table 2.

High correlation of Epan with ETo has been reported over weekly to monthly periods. In limiting water situations, however, correlation is low. Penman (1948) noted that ETo/Epan was 0.6 for November to Februrary, 0.7 for March, April, September, and October and 0.8 for May through August.

Stanhill (1961) found monthly ETo (mm/day) for alfalfa to be related to Class A pan by the relation

$$ETo=0.70\ Epan+0.47; \ r^2=0.95 \quad (6a)$$

and for weekly periods,

$$ETo=0.75\ Epan+0.36; \ r^2=0.77 \quad (6b)$$

2.2 Micro-meteorological Methods

Micro-meteorological measurements can be used to quantify the evapotranspiration losses from cropped areas. Important methods include Eddy Correlation, Aerodynamic, Resistance, Energy balance and combination of energy balance and aerodynamic approaches. Due to assumptions invlolved and measurement difficulties the aerodynamic

Table 1. Pan Coefficient Kp for Class A pan (Taken from Doorenbos and Pruitt, 1977)

		Case A+ Surrounded by green crop				Case b++ Surrounded by dry fallow		
RH mean %		low (<40)	medium	high (>70)		low (<40)	medium	high(>70)
Wind km/	Fetch				Fetch			
Light <175	0	0.55	0.65	0.75	0	0.70	0.80	0.85
	10	0.65	0.75	0.85	10	0.60	0.70	0.80
	100	0.70	0.80	0.85	100	0.55	0.65	0.75
	1000	0.75	0.85	0.85	1000	0.50	0.60	0.70
Moderate	0	0.50	0.60	0.65	0	0.65	0.75	0.80
175-425	10	0.60	0.70	0.75	10	0.55	0.65	0.70
	100	0.65	0.75	0.80	100	0.50	0.60	0.65
	1000	0.70	0.80	0.80	1000	0.45	0.55	0.60
Strong	0	0.45	0.50	0.60	0	0.60	0.65	0.70
425-700	10	0.55	0.60	0.65	10	0.50	0.55	0.60
	100	0.60	0.65	0.70	100	0.45	0.45	0.60
	1000	0.65	0.70	0.75	1000	0.40	0.45	0.55
Very Strong	0	0.40	0.45	0.50	0	0.50	0.60	0.65
> 700	10	0.45	0.55	0.60	10	0.45	0.50	0.55
	100	0.50	0.60	0.65	100	0.40	0.45	0.50
	1000	0.55	0.60	0.65	1000	0.35	0.40	0.45

Note +In Case A pan is installed in variable length green surrounding beyond which atleast 50 meter wide dry fallow strip in the upwind direction.

++In Case B the Pan is installed in a dry surrounding of variable lenght beyond which green strip at least 50 meters wide in the upwide direction.

*Fetch is unrestricted uniform upwind distance in meters.

Table 2. Relative sensitivity of pans and atmometers

Device	The relative sensitivity to		
	radiation	humidity	wind
Pan	80:	6:	14
Atomometer	41:	7:	52

Table 3. Selected values of aw, bw in f(u) = aw +bw(U2), and (es-ea) method in Penman relations.

No.	Author(s)	Reference Crop	aw	bw	Method for calcu of (es-ea)
1	Penman 1963	Clipped grass	1.0	0.00621	1
2	Wright and Jensen (1972)	Alfalfa	0.75	0.0115	2
3	Doorenbos and Pruitt. (1977)	Grass	1.0	0.01	1
4	Wright (1981)	Alfalfa	time variant		2

methods have not found popular use. Lemon etal. (1973) have reported a comprehensive model of transport of moisture and carbon dioxide in and above plant canopies which they named Soil- Plant-Atmosphere-Model (SPAM). The aerodynamics of transport processes and evaluation of different varialbes and parameters are discussed by them.

2.2.1 Energy Balance Bowen Ratio Method

Energy balance at the crop surface can be written as:

$$R_N - LE - C - G - J + M = 0 \quad (7a)$$

where

$$R_N = (Q+q)\ (1-\alpha) - (I_U - I_P) \quad (7b)$$

the net gain due to short wave (Q the direct and q, the diffuse component) and long wave (I_u away from and I_p incident at the land surface) components of radiation. α is the reflectivity of the surface, LE the latent heat of evaporation (loss), G the ground heat flux (-ve down ward), C the sensible heat flux (-ve upward), J is the change in heat storage in canopy, and M is net metabolic heat gain in canopy.

The component J and M are quite small as compared to other component and may be neglected. The equation modifies thus to

$$R_N - G = LE + C \quad (8)$$

G the ground heat flux can the estimated at any time t of the day with a suitable equation. Thus if all the other component of equation (8) are known, LE can be computed as difference

$$LE = (R_N - G) - C \quad (9)$$

Bowen (1926) considered ground heat flux to be very small when water is not limiting. He defined as quantity, B, called Bowen ration as ratio of sensible to latent heat. Thus

$$\beta = C/LE \quad (10a)$$

Replacing $C = -pCp\ K_H\ (dT/d_Z)$, and evaporative flux by $LE = -K_w\ (de/d_Z)$, (p being density and Cp the specific heat of air) and concidering measurements of temperature T and water vapour pressure e at two heights within the characteristic boundary layer, eq. (10a) can be rewritten as

$$\beta = (pCp / LE) \quad (T_2 - T_1) / (e_1 - e_2) \tag{10b}$$

Equation (8) then modifies to

$$LE = (R_N - G) / (1 + \beta) \tag{11}$$

Thus if β is measured, for which only temperature, 'T' and vapor pressure 'e' need be measured at any two heights, LE can be computed with the knowledge of R_N. Assumption here is that the coefficients of turbulent diffusivities for heat and water vapour are equal, eg. $K_H = K_W$. The error envolved in estimated LE is quite small due to error in β calculated assuming $K_H = K_W$. Fritschen (1965) in a comparison observed that Bowen ratio method can be successfully used to determine short term evaporative flux which can be summed for longer periods. He found relative error less than 5% as compared to weighing lysimeter.

Pristley and Taylor (1972) show that for water surface and well watered vegetation free from advection, Bowen ratio may be written as

$$\beta = [(1-1.26(s/(s+r))] \; [1.26 \; s/(s+r)]^{-1} \tag{12a}$$

or

$$\beta = (0.8 \; r/s) - 0.2 \tag{12b}$$

where s is slope of saturation vapor pressure - temperature curve and r the psychrometer constant (r = 0.667 at 20°C and sea level).

Because of ease of measurement and relative accuracy, Bowen ratio method can be used as an test standard when access to other more accurate methods like lysimeters are not available.

2.2.2 The Combination Approach

Penman (1948) proposed an empirical equation to compute open water surface evaporation E_o as,

$$E_o = [sH + 0.28 \; Ea] / (s + 0.27) \tag{13}$$

where E_o is open water surface evaporation mm/day, s the slope of saturation vapor pressure-temperature curve (mm Hg/°F) for water at mean air temperature, Ta; H the net radiation (mm/day), 0.27 is psychrometer constant, (r, mm Hg/°F). He defined wind effect in term Ea as :

$$E_a = 0.35 \ (ea-ed) \quad (1+U_2/100) \ \text{mm/day} \qquad (14)$$

where ed and ea are saturation vapor pressure at dew point (Td), and at mean air temperature (Ta), U_2 is wind velocity miles/ day at a height of 2 meters above the surface. Since this equation has both energy and aerodynamic terms, it came to be known as combination equation. This equation has strong physical basis and was derived theoreticaly later on by Monteith (1963) and van Bavel (1966). Penman (1949) modified his method for potential evapotranspiration and conducted extensive tests, that yielded satisfactory results. He defined Eo as the potential evapotranspiration from a extended surface of short green grass which fully shades the groud, exerts little or negligible resistance to flow of water and is always well supplied with water. Eo can not exceed free water surface evaporation under the same weather in this definition.

The equation derived by Monteith (1963, 1973) is reproduced below.

$$LE = [s(R_N-G)+p \ Cp(e_2(Tz)-e(z))/R_2]/(s+r^*) \qquad (15a)$$

$$r^* = r(R_a+R_c) \ /R_a \qquad (15b)$$

where $es(T_z)$ and e (z) are saturation vapor pressure at temperature T(z) and actual vapor pressure of water at height Z of mesurement, and Rc the canopy resistance, (Monteith, 1973). The Monteith equation is versatile and can be used for actual eT under any internal water status during potential or non-potential phases as the resistance terms take care of the same. However computation of these resistances pose a problem in application of Monteith equation.

Many version of the combination formula exist now as modified by various workers to suite specific data set and situations. Three popular versions are described below.

Ritchie(1972) modified the Penman equation for computation of Et from row crops where the original conditions of 'completely shading the ground' may not be valid for quite some time. Penman equation as used by Ritchie(1972) is

$$Eo = [(s/r)\ Rno+0.262\ f(u)\ (eo-ea)]\ /[(s/r)+1] \tag{16}$$

$$Rno = (1-\alpha)\ Rse \tag{17a}$$

$$\alpha=\alpha s+0.25(0.23-\alpha s)\ LAI \tag{17b}$$

where Rno is net radiation at the top of the canopy, Rse is the solar radiation, albedo $\alpha = 0.23$ for full canopy, αs the albedo for bare soil and LAI the leaf area index. The wind function is

$$f(u)=(1+0.00621.U_2) \tag{17c}$$

He divided the ET in to components of Plant Tanspiration (Ep) and Soil surface evaporation (Es).

$$ET = Es+Ep \tag{18}$$

The soil evaporation takes place in two stages. the constant rate stage, Eso, when the water is not limiting, continues till a depth U evaporates, followed by Stage II or the falling rate stage as the soil dries and supply of water to the evaporation site becomes limiting, till the next water application (irrigation or precipitation)..

$$Eso=(s/(s+r))\ Rns \tag{19a}$$

where,

$$Rns=Rno\ \exp(-0.398\ LAI) \tag{19b}$$

Es=ESI, till U the upper limit of cumulative depth of evaporation is reached. During constant rate phase,

$$ESI\ =Eso \tag{19c}$$

Beyond that, soil evaporation is a function of time 't' in days from the day this limit is reached and soil hydraulic characteristic αh. For any day cumulative soil evaporation is

$$\Sigma ESII = \alpha h\ \ t^{1/2} \tag{19d}$$

and on t^th^ day soil evaporation Es(t) is estimated as difference.

$$Es(t) = \alpha h\ t^{1/2} - \alpha h\ (t-1)^{1/2} \quad (19e)$$

The plant Transpiration component Ep is dependent on degree of cover expressed in terms of LAI. For LAI between 0.1 and 2.7

$$Ep = Eo\ (-0.21+0.70\ LAI^{1/2}) \quad (20a)$$

$$Ep = Es \text{ for } LAI<0.1 \quad (20b)$$

For LAI>2.7, soil evaporation ceases to be effective as most of the energy is absorbed by the plant canopy and Ep equals potential ET. Thus,

$$Ep = Eo \text{ for } LAI>2.7 \quad (20c)$$

On the day of irrigation or precipitation, the soil moisture status is updated returning to ESI or ESII phase. The method is suitable for computer computation.

2.2.3 FAO Method

Doorenbos and Pruitt (1977) presented another modification to Penman equation. They presented a form of the equation which can be solved with the help of local data and Tables provided by them. Thier equation is also known as FAO method. The FAO method defines grass based References Crop ETo mm/day as

$$ETo = C[W\ Rn+(1-W)0.27\ f(u).(ea-ed)] \quad (21)$$

$$f(u) = (1+U2/100)\ ;\ u2 \text{ in km/day} \quad (22a)$$

where W is temperature related weighing factor,

$$W = s/(s + r)), \quad (22b)$$

and (ea-ed) the difference between saturation vapor pressure at mean temperature and mean actual vapor pressure of the air, mb. Vapour pressure ea=f(Tmean) and ed=f(Tdew) can be read from Table 4, if dew point temperature Tdew is known. If Rh mean is known then

$$ed=ea(Tmean)\ [(Rhmax+Rhmin)/2] \quad (23a)$$

It may also be computed from Table 5 as

Table 4. Saturation vapour Pressure (ea) mb as a function of Mean Air temperature (T °C) (Reproduced from Dooreboss and Pruitt, 1977)

T	0	1	2	3	4	5	6	7	8	9	10	11	12	14
ea	6.1	6.6	7.1	7.6	8.1	8.7	9.3	10.0	10.7	11.5	12.3	13.1	14.0	15.0
T	14	15	16	17	18	19	20	21	22	23	24	25	26	27
ea	16.1	17.0	18.2	19.4	20.6	22.0	23.4	24.9	26.4	28.1	29.8	31.7	33.6	35.7
T	28	29	30	31	32	33	34	35	36	37	38	39		
ea	37.8	40.1	42.4	44.9	47.6	50.3	53.2	56.2	59.4	62.8	66.3	69.9		

Table 5. Vapour pressure (ed) mb from Dry and wet Bulb Temperature (*C) Reproduced from Dooreboss and Pruitt, 1977)

	Wet Bulb depression °C, Altitude 0-1000 meters											
Dry bulb	0	2	4	6	8	10	12	14	16	18	20	22
40	73.8	64.7	56.2	48.4	41.2	34.4	28.2	22.4	17.0	12.0	7.4	3.0
38	66.3	57.8	50.0	42.8	36.0	29.8	24.0	18.6	13.6	9.0	4.6	0.6
36	59.4	51.6	44.4	37.6	31.4	25.6	20.2	15.2	10.6	6.2	2.2	
34	53.2	45.9	39.2	33.0	27.2	21.8	16.8	12.2	7.8	3.8		
32	47.5	40.8	34.6	28.8	23.4	18.4	13.8	9.4	5.4	1.6		
30	42.4	36.2	30.4	25.0	20.0	15.4	11.0	7.0	3.2			
28	37.8	32.0	26.6	21.6	17.0	12.6	8.6	4.8	1.2			
26	33.6	28.2	23.2	18.6	14.2	10.2	6.4	2.8				
24	29.8	24.8	20.2	15.8	11.8	8.0	4.4	1.1				
22	26.4	21.8	17.4	13.4	9.6	6.0	2.7					
20	23.4	19.0	15.0	11.2	7.6	4.3	1.1					
18	20.6	16.6	12.8	9.2	5.9	2.7						
16	18.2	14.4	10.8	7.5	4.3	1.4						
14	16.0	12.4	9.1	5.9	3.0	0.1						
12	14.0	10.7	7.5	4.6	1.7							
10	12.3	9.1	6.4	3.3	0.7							
8	10.7	7.7	4.9	2.3								
6	9.3	6.5	3.9	1.5								
4	8.1	5.5	2.9	0.9								
2	7.1	4.5	2.3									
0	6.1	3.7	1.5									

$$ed=f[Tdry,\ (Tdry-Twet)]. \qquad (23b)$$

C is an adjustment factor to compensate for the effect of day and night time weather conditions. Values of W, ea, and ed as function of temperature are tabulated in Doorenbos and Pruitt (1977).

2.2.4 Estimation/Measurement of Net Radiation

The solar radiation Rs need to be measured or estimated with a suitable equation for the location. A simple equation of the form

$$Rs=(a+b.n/N)\ Rsx \qquad (24a)$$

has been suggested (Doorenbos and Pruitt, 1977) for approximate locations which should be used with caution and only if locally developed better relations are not available. Rsx is the maximum possible extra-terrestrial radiation.

The net radiation R_N is difference of net short wave receipt and long wave radiaition lost to atmosphere.

$$RN=Rns-Rn1 \qquad (25a)$$

and

$$Rns=(1-\alpha)Rs. \qquad (25b)$$

The net long wave component is given as

$$Rn1=[a(CR)\quad +b]\varepsilon\sigma(T_k)^4 \qquad (25c)$$

with T_k temperature in degree kelvin. Idso and Jackson (1969) gave an expression for estimating emmissivity ε.

$$\varepsilon=-0.02+0.261\ \exp[-7.77/1000\ (273-T_k)^2] \qquad (25d)$$

However, if ed is know, following equation may be used.

$$R_{n1}=[a(CR)+b]\ [a_1+b_1\ (ed)]\sigma T_k^4 \qquad (25e)$$

$$=a(CR)\ +b]\quad [a_1+b_1\ (ed)]11.71x10^{-a}\ (T_k)^4 \qquad (25f)$$

where CR is dimensionless cloudiness ratio, ed in (mb). This has been expressed and tabulated in Doorenbos and Pruitt (1977) in the form of

$$Rn1=f(n/N).f(ed).f(T). \tag{25g}$$

Tables 4 to 11 reproduced from Doorenboss and Pruitt (1977) give various values needed in manual computation of ET by FAO method. Doorenbos & Pruitt (1977) use $CR = n/N$, $a=0.9$, $b=0.1$ $a_1=0.34$, and $b_1=0.044$. n/N is the ratio of actual(n) to maximum possible (N) sunshine hours for the day of the year at the location. Burman etal. (1980), Jensen (1974) and Wright (1982) use $CR = Rs/Rsx$, the ratio of Rs to clear day solar radiation. Values of Rsx the maximum extra-terrestrial radiation and N the maximum possible sunshine hours are fixed for any location for each day of the year and tables are available (see Table 6,7). Jensen (1974), Burman etal. (1980), and Doorenbos and Pruitt (1977) define T_K as daily mean temperature.

Value of α, the short wave albedo varies from 0.23 to 0.24 for alfalfa (Wright, 1982). Average values of 0.23 (Jensen, 1974) and 0.25 (Doorenbos and Pruitt, 1977) have been suggested for most of the crops. Values of α in the above range may not yield significant difference in R_N. Net long wave radiation can be computed using following type of equation (Jensen 1974), Doorenbos and Pruitt, Burman etal 1980).

$$R_N=A+B \quad Rs \tag{26a}$$

Constants A and B need to be evaluated at the location with acutal measurements. Kumar (1984) developed following equation for wheat crop,

$$R_N=0.49940+0.773 \quad Rs \tag{26b}$$

2.2.5 Soil Heat Flux

Soil heat flux G is many a times neglected because at full crop cover on daily basis it is close to zero. Jensen (1974) and Wright (1982) discuss computation of G.

Kumar etal. (1984) applied the method of overspecification of boundary data (Singh and Sinha, 1977,1979) for computation of ground heat flux at different moisture contents in a wheat field and bare soil surface. Alternately ground heat flux may be computed using empirical relations of the form

$$G=f(R_N, \quad LAI) \tag{27a}$$

Table 6 Extra terretrial radiation Ra mm/day for days of the Year in the Northen Hemisphere (Reproduced from Doorenboos and Pruitt, 1977)

Lat	Jan	Feb	March	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
50	3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2
48	4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7
46	4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3
44	5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7
42	5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2
40	6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7
38	6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1
36	7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6
34	7.9	9.4	12.4	14.8	16.8	15.5	13.4	15.5	13.4	10.8	8.5	7.2
32	8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8
30	8.8	10.7	13.1	15.2	16.5	17.0	16.8	15.7	13.9	11.6	9.5	8.3
28	9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8
26	9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3
24	10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7
22	10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2
20	11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7
18	11.6	13.0	14.6	14.4	15.6	16.1	16.1	15.8	14.9	13.6	12.0	11.1
16	12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6
14	12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0
12	12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5

Table 7. Mean Daily duration of maximum possible Sunchine Hours (N) (Reproduced from Doorenboss and Pruitt, 1977)

Latitude	Months of the Year										
North	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
South	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
50	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.4	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	14.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

Table 8. **Value of weighting factor (1-W) as a function of temperature, and Ultitude in meters, Factor W can be drived as (W - 1-(1-W) (Reproduced) from Dooreboss and Prtuitt, 1977)**

Temp Ulti.	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
0	.57	.54	.51	.48	.45	.42	.39	.36	.34	.32	.29	.27	.25	.23	.22	.20	.19	.17	.16	.15
500	.56	.52	.49	.46	.43	.40	.38	.35	.33	.30	.28	.26	.24	.22	.21	.19	.18	.16	.15	.14
1000	.54	.51	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.20	.18	.17	.15	.14	.13
2000	.51	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12
3000	.48	.45	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12	.11
4000	.46	.42	.39	.36	.34	.31	.29	.27	.25	.23	.21	.19	.18	.16	.15	.14	.13	.12	.11	.10

Table 9. Conversion of extra terrestrial Radiation (Ra) to net Solar radiation Rns Rns=(1-r)(0.25+-50 n/N); for reflectivity r=0.25 (Reproduced from Doorenboss and Pruitt, 1977)

Ratio n/N	0.0	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75	.80	.85	.90	9.5	1.0
Rns	.19	.21	.22	.24	.26	.28	.30	.32	.34	.36	.37	.39	.41	.43	.45	.47	.49	.51	52	.54	.56

Table 10. Functions f(T), f(ed) and f(f) in FAO Method for computation of Net Radiation
(Reproduced from Doorenboss and Pruitt, 1977)
$[F(T) = \sigma T_k^4]$

T °C	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
f(T)	11.0	11.4	11.7	12.0	12.4	12.7	13.1	13.5	13.8	14.2	14.6	15.0	15.4	15.9	16.3	16.7	17.2	17.7	18.1

[f(n/N)=0.1+0.9 n/N]

n/N	0	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75	.80	.85	.9	.95	1.0
	.10	.15	.19	.24	.28	.33	.37	.42	.46	.51	.55	.60	.64	.69	.73	.78	.82	.87	.91	.96	1.0

[f(ed)=0.34-0.044. ed]

Vap. pressure ed mb	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
Function f(ed)	.23	.22	.20	.19	.18	.16	.15	.14	.13	.12	.12	.11	.10	.09	.08	.08	.07	.06

Table 11. **adjustment factor C in FAO Penman methods**
(Reproduced from Doorenboss and Pruitt, 1977)
RH max=30% RHmax=60% RHmax=90%

Rs mm/day	3	6	9	12	3	6	9	12	3	6	9	12
Uday m/sec												
Uday/Unight = 4.0												
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.79	.84	.92	.97	.92	1.00	1.11	1.19	.99	1.10	1.27	1.32
6	.68	.77	.87	.93	.85	.96	1.11	1.19	.94	1.10	1.26	1.33
9	.55	.65	.78	.90	.76	.88	1.02	1.14	.88	1.01	1.16	1.27
Uday/Unight = 3.0												
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.76	.81	.88	.94	.87	.96	1.06	1.12	.94	1.04	1.18	1.28
6	.61	.68	.81	.88	.77	.88	1.02	1.10	.86	1.01	1.15	1.22
9	.46	.56	.72	.82	.67	.79	.88	1.05	.78	.92	1.06	1.18
Uday/Unight = 2.0												
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.6	1.10	1.10
3	.69	.76	.85	.92	.83	.91	.99	1.05	.89	.98	1.10	1.14
6	.53	.61	.74	.84	.70	.80	.94	1.02	.79	.92	1.05	1.12
9	.37	.48	.65	.76	.59	.70	.84	.95	.71	.81	.96	1.06
Uday/Unight = 1.0												
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.64	.71	.82	.89	.78	.86	.94	.99	.85	.92	1.10	1.05
6	.43	.53	.68	.79	.62	.70	.84	.93	.72	.82	.95	1.00
9	.27	.41	.59	.70	.50	.60	.75	.87	.62	.72	.87	.96

For wheat following empirical equation, a function of LAI, was found to be reasonably good (Kumar, 1984) in wheat.

$$G/R_N=0.508 \exp(-0.408 \text{ LAI}); \quad r^2=0.944 \tag{27b}$$

Correction factor C

C is reference independent. It takes care of day-night wind condition and other weather condition. Table 11 can be used to read or interpolate vlaues of C as a fucntion of day time wind speed, day/night wind ratio and maximum daily relative himidity. a regression equation for C was proposed by Frevert etal. (1982), which is as under.

$$C=ao+al\ Rh_m + a2\ Rs + a3\ U_d + a5\ U_d\ DN_R +$$

$$+a6\ Rh_m\ Rs\ U_d + a7\ Rh_m\ Rs\ DN_R \tag{28}$$

where,

a_o = 0.687006,
a_1 = 0.0027864,
a_2 = 0.0181768
a_3 = -0.0682501,
a_4 = 0.00126514
a_5 = 0.0097297
a_6 = 0.43025 {E-4}, and
a_7 = 0.92118[E-7]
Rh_m = % Rh maximum of the day
Rs = solar radiation mm/day
U_d = day time wind speed m/sec
DN_R = Day/night wind ratio

2.3 Empirical Methods for Computation of Evapotranspiration

Large number of empirical equations based on temperature, pan evaporation, radiation, wind, sunshine hours or combination of two or more variables have been reported. Some of them which have found wider use are discussed below.

2.3.1 Radiation Methods

Two forms of radiation equations are in wide use. Makkink (1957) method or the FAO Radiation method is good for 10 to 30 days intervals).

$$Eto= a+b\ (s/(s+r))\ Rs \tag{29a}$$

Frevert etal.(1982) gave value of a and b as

$$b = a_o+a_1\ R_n mean+a_2\ Ud+a_3\ Rhmean\ Ud+ a_4\ Rh\ mean^2 + a_5\ Ud^2 \tag{29b}$$

$a = -0.3;$ $a_o= 1.0656$ $a_1 = -0.0012795,$ $a_2 =0.044953,$ $a_3=-0.00020033;$ $a_4 = -0.000031508;$ $a_5=-0.0011026.$

Doorenbos and Pruitt(1977) modified Makkink formula as under,

$$ETo = C[W.Rs]\ mm/day \tag{30}$$

where Rs is solar radiation, mm/day and W and C as defined earlier in FAO method.

Another radiation method is due to Jensen-Haise (1963). It needs elevation and temperature data besides Rs, and is compatiable with alfalafa reference. This is good for estimates for 5 days and above.

$$ET = C_T(Tmean-T_2)\ Rns \tag{31a}$$

$$C_T = 1/(C_1+ 7.3\ CH) \tag{31b}$$

$$C_H = (50\ mb)/(e_2-e_1) \tag{31c}$$

$$C_1 = 38 - El/152.5 \tag{31d}$$

$$T_2 = -2.5-0.14(e_2-e_1)-E]/550. \tag{31e}$$

ET has unit of Rn (mm/day), $Rns=Rs(1-\alpha)$, e_2 and e_1 are saturation vapor pressures at long term mean daily maximum and minimum temperatures of the warmest month in the year, and E the elevation (m).

It was observed that with slight modification ET estimated by Jensen and Haise radiation formula (ETJ& H), is highly compatible with Doorenbos and Pruitt ETo (ETD&P) at Ludhiana (Kumar, 1989).

$$ETJ\ \&H=A(Tmean-Tx)Rns.10/1]+B \tag{32}$$

A=0.74716 (which is computed CT for Ludhiana), B = 0.46354, and the latent heat at mean air temperature L = 595-0.59 Tmean. Then ETD&P is linear function of ETJ&H as shown below.

$$ET_{D\&P}=0.46354+0.74716\ ET_{J\&H};\ r^2=0.98271 \quad (33)$$

Other corrections like C can be applied to it as in the Doorenbos and Pruitt equation.

2.3.2 Blaney and Criddle Method

Blaney and criddle method has been very widely used because of its simplicity and data requirements for acceptable monthly/seasonal ET estimates. It has also been modified number of times (USDA 1970, Doorenbos & Pruitt 1977, Borelli 1982).

$$Eto=a_b \quad +b_b\ f \quad (34a)$$

$$f \doteq p(0.46\ T+8.13) \quad (34b)$$

$$a_b= 0.043\ Rhmin-(n/N)-1.41. \quad (34c)$$

$$b_b= ao + a_1\ Rhmin+a2\ \ n/N+a3\ Ud + a4\ Rhmin +$$

$$+ a5\ Rhmin\ Ud$$

$a0= 0.81917$, $a_1=-0.0040922$, $a2=1.0705$, $a3=0.65649$,
$a4=-0.0059684$, $a5=-0.0005967$.

where ETo is in mm/day, T the mean monthly temperature. The form proposed by Doorenbos & Pruitt (1977) is

$$ETo=C[p(0.46\ T+8)]\ \ mm/day \quad (35)$$

Here C is adjustment factor, a function of minimum relative humidity, sunshine hours and day time wind, p (Table 12), the mean daily percentage of annual day time hours for the month and latitude, and T the mean daily temperature for the month.

2.3.3 Other empirical Methods

Thornthwait (1948) considered consumptive use as an exponential function of mean monthly air temprature, disregarding its dependence on wind and humidity etc.

Table 12. Mean daily percentage p of Annual daytime Hours for different latitudes
(Reproduced from Doorenboss and Pruitt, 1977)

Lat North	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lat South	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
60	.15	.20	.26	.32	.38	.40	.41	.34	.28	.22	.17	.13
58	.16	.21	.26	.32	.37	.40	.39	.34	.28	.23	.18	.15
56	.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
54	.18	.22	.26	.31	.36	.38	.37	.33	.28	.23	.19	.17
52	.19	.22	.27	.31	.35	.37	.36	.33	.28	.24	.20	.17
50	.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
48	.20	.23	.27	.31	.34	.36	.35	.32	.28	.24	.21	.19
46	.20	.23	.27	.30	.34	.35	.34	.32	.28	.24	.21	.20
44	.21	.24	.27	.30	.33	.35	.34	.31	.28	.25	.22	.20
42	.21	.24	.27	.30	.33	.33	.34	.31	.28	.25	.22	.21
40	.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35	.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30	.24	.25	.27	.29	.31	.32	.31	.30	.28	.26	.24	.23
25	.24	.26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20	.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15	.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.26
10	.26	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
5	.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27

Table 13. Daily Basal Crop coefficients for dry soil surface condition (From Wright, 1981)

	Basal Crop Coefficient Kcb									
	% time from planting to effective crop cover									
Crop	10	20	30	40	50	60	70	80	90	100
Small grains	0.15	0.16	0.20	0.28	0.55	0.75	0.90	0.98	1.00	1.02
Beans	0.15	0.17	0.18	0.22	0.38	0.48	0.65	0.78	0.93	0.95
Peas	0.20	0.17	0.16	0.18	0.20	0.28	0.48	0.67	0.86	0.95
Potatoes	0.15	0.15	0.15	0.21	0.35	0.45	0.60	0.72	0.78	0.80
Corn	0.20	0.17	0.15	0.15	0.16	0.20	0.30	0.50	0.80	1.0
Winter wheat	0.65	0.70	0.75	0.80	0.85	0.90	0.95	0.98	1.00	1.02
DT days after effective cover										
	10	20	30	40	50	60	70	80	90	100
Small grains	1.02	1.00	0.80	0.50	0.25	0.10	0.10			
Beans	0.95	0.94	0.65	0.36	0.18	0.15	0.10			
Peas	0.93	0.82	0.50	0.37	0.20	0.10	0.10			
Potatoes	0.80	0.80	0.75	0.74	0.73	0.72	0.70	0.50	0.25	0.20
Corn	0.95	0.95	0.93	0.91	0.89	0.83	0.76	0.30	0.20	0.15
Winter wheat	1.02	1.00	0.96	0.50	0.20	0.10	0.10			

Hargreave (1985) formula is based on solar radition mean temperature, (Tmean) and difference of maximum and minimum temperatures (Tdiff=Tmax-Tmin), Rs is in mm/day.

$$ETo=10\ [0.0024\ Rs\ Tdiff^{0.5}\ (Tmean+17.6)]\ \text{mm/day} \qquad (36)$$

A comparison of four methods (Lysimeter, Blaney and Criddle, FAO Radiation, and Christiansen (1968)) for computation of Crop ET at Ludhiana depicted radiation estimates to be more closure to lysimeter data (Mishra et al. 1983).

2.4 The Crop Coefficient (Kc)

Since the actual crop evapotranspiration is difficult to measure it can be derived from reference evapotranspiration which is easy to determine. Normally it is transformed to actual crop evapotranspiration by using a multiplier Kc, called crop coefficient which is ratio of actual to reference crop evapotranspiration.

$$Kc = \frac{(\text{Actual Crop Evapotranspiration, ETc})}{(\text{Reference Evapotranspiration, ETo})} \qquad (37)$$

The Crop Coefficient incorporates the effect of the crop, its growth stage, it density, and other cultural factors affecting water use to modify the potential or reference crop evapotranspiration. Tables of Kc values for many crops in USA have been published for the two standards (Wright 1981, 1982; Doorenbos and Pruitt, 1977). When Reference crop evapotranspiration is used as standard, Kc value relevant to that (grass or alfalfa) reference crop should be used.

2.4.1 Alfalfa based crop coefficient.:-

Jensen (1974)defined crop coeficient as a ratio of ET from a specific crop at a specific stage of growth to potential ET at that time. The crop coefficients (Jensen, 1974) were alfalfa based, however since they were proposed prior to the reference crop definition, term potential ET was used which was actually alfalfa based. These were based on an average crop condition and not as accurate as those develop by Wright (1982) based on Lysimeter measurement. Table 13 lists selected crop coefficients for alfalfa reference.

2.4.2 Grass related crop coefficients:-

Doorbenbos and Pruitt (1977) defined crop coefficient as ratio between crop ET and reference crop (grass) when crop is grown in large fields under optimum growing condition. Their version of Kc permits its use in radiation, Penman, Blaney & Criddle and Pan evaporation methods for estimation of Eto. They divide the growing season in to 4 stages of intial, crop development, mid season and late season. During initial season when crop is sparse, Kc depends on rainfall or irrigation frequency. Initial season comprises germination to early growth with ground cover < 10%, Development stage from initial up to effective cover (70%-80% ground cover), Mid season from Crop development stage to start of Maturation indicated by leaf dropping and yellowing, and Late Season as the period beyond Maturation to harvesting. For initial stage Kc is read from fig.1 & 2 and for development stage Kc is interpolated between intitial and mid season values.

2.4.3 Correction for wet soil moisture and limited soil moisture conditions

Jensen etal. (1971), Burman(1980) and Wright (1981, 1982), discuss corrections in crop coefficient due to limiting soil moisture condition. Wright (1981) defines Kc the grass or alfalfa based crop coefficient as

$$Kc \quad = Kc_b \ \ ka+Ks \qquad (38a)$$

In the above K_{cb} is basal crop coefficient, Ka an empirical factor to decrease crop ET because of dry soil profile and Ks to increase crop ET for wet soil surface after rainfall or irrigation. Jensen etal (1971) define Ks as

$$Ks \ \ (K_1 \ - \ Kc_i) \quad exp(-A \ \ t); \quad K_1>Kc_i \qquad (38b)$$

where t is number of days after rains or irrigation, A, an coefficient for soil characteristics and evaporative demand etc., Kc_i = Kc_b at the time of irrigation, and K_1 is a threshold crop coefficient which indicates crop canopy development, where soil evaporation is no more important. Jensen (1971) defined Ka for limiting soil water condition as

$$Ka=Ln(Asm+1) \ /Ln(101). \qquad (38c)$$

where Asm is % of available soil moisture. Wright (1981) has suggested another correction for wet condition. He observed that

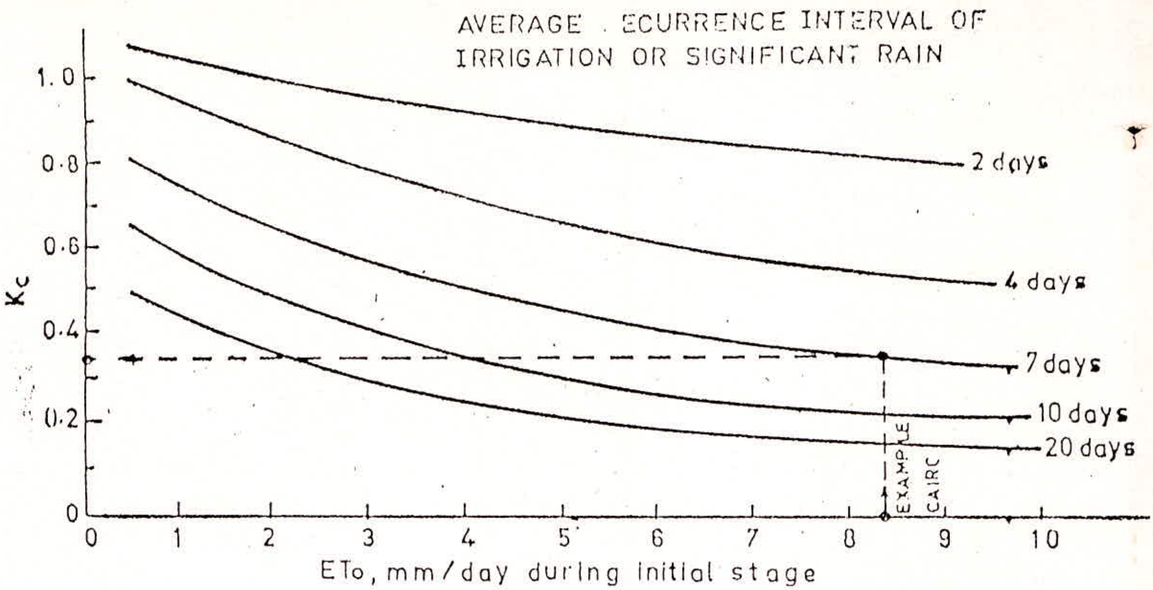

FIG. 1 Average value for initial crop development stage as related to level of ETo and frequency of irrigation and/or significant rain

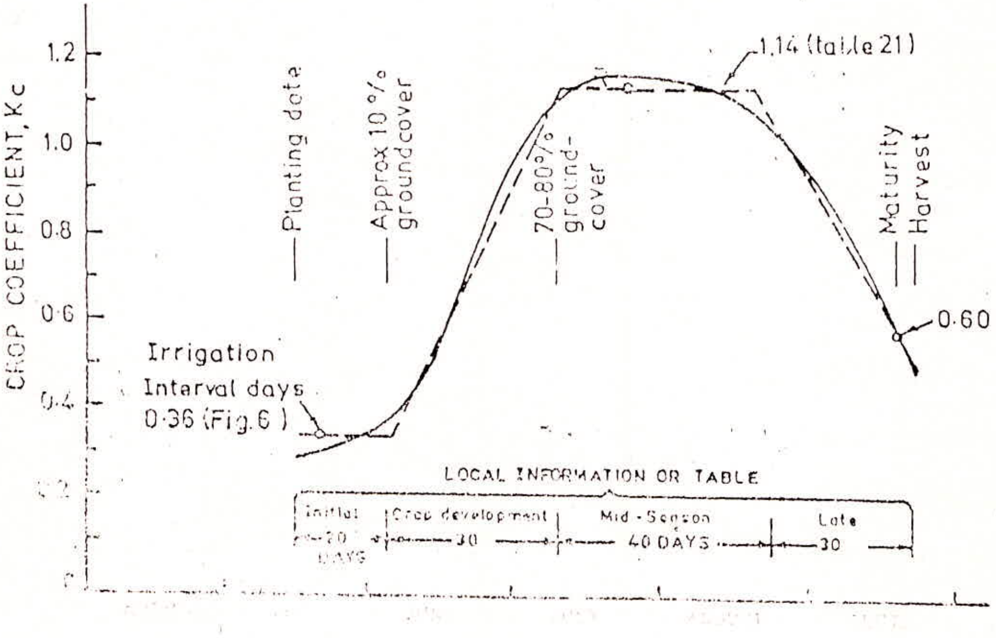

FIG. 2 Example of crop coefficient curved

Penman wind function was not very good for arid climates. He proposed new crop coefficient relation as under.

$$Kc=Kcb+(1-Kcb)[1-t/td)^{1/2}]\ \ f(w) \tag{38d}$$

where t is number of days after major rainfall or irrigation, td the number of days for the soil surface to dry after irrigation or rain, and f(w) is relative proportion of wet soil surface(=1 for heavy and 0.5 for partial wetting). td may vary with climate and soil from 3 to 6 or 7 days.

2.5 Factors affecting Evapotranspiration

Evapotranspiration is an energy driven process. Firstly energy should be availabe external to the plant to meet the latent heat required for evapotranspiration. Secondly, the water evaporated from the canopy mixes in to the immediate environments as net upward flux which is dependent on wind conditions. Besides, there are factors internal to and influenced by plant species which affect water loss by ET and briefly discussed below.

2.5.1 Plant Factors

Plant factors affect ET in a complex way. The evaporating site being leaves, ET rate is governed by the gradient of vapor concentration between leaf mesophyll cell wall and the atmosphere. Resistance is offered by the substomatal and stomatal cavities and the aerodynamic boundary layer on the leaf surface.

All plant species that are short dense and uniformly vegetated, actively growing, infinite in extent, and have access to unlimited water supplies will transpire alike because the ET is then determined by weather only (Penman 1956). In general seasonal ET will be determined by the length of period plant species maintain green cover.

Specific plant characteristics that influence ET include factors like reflectivity of leaf canopy to solar radiation, degree of plant cover, plant population and row spacing which affect light interception and its filtering to the ground surface, plant rooting characteristics that determine the accessible soil volume, and stage of crop growth which determines the degree of cover, biomass, rooting depth and extent. The ET has been observed to decline as soil water availability diminishes. Ritchie etal.(1972) have shown that after a critical level of water loss, evaporation is limited by soil moisture status.

2.5.2 Soil Factors

Soil factors like color, slope, surface roughness and crop residue effect energy absorbing capacity as the surface reflectivity changes. A cloddy surface has lesser reflectance. A land slope facing south receives greater reflectance than bare soil . However when land surface is covered with crop, crop factors prevail. Restriction on energy available for evaporation will reduce evaporation losses at any site.

2.5.3 Cultural Fctors

Cultural factor like irrigation, tillage practices, mulching; and existence of shallow water table etc. have influence on ET. Reduction in ET between two irrigations is larger if larger the interval and is more visible during early season when crop cover is meager. High water content if maintained through out, increases seasonal water use. Percentage wet area also affects ET during the period of incomplete cover which may be as much as up to 20% but seasonal value may never exceed 5%. In wide row crops, fruits and vine yards etc. significant saving can be achieved by partial wetting around the plants only.

Tillage practices affect soil water storage and depth of effective root zone. They also affect the water transmission rate and the heat budget of soil surface therefore affecting the soil surface evaporation.

3.0 CONCLUSION/REMARKS

This chapter of Science Education series is devoted to understanding and estimation of evapotranspiration. The importance of evapotranspiration in crop water management need not be imphasised here. A large volume of literature appeares every year on estimation of this variable. Evapotranspiration estimation methods can be classified as

i. empirical based on micrometeorological measurements,
ii. aerodynomic approach,
iii. Energy balance-Bowen ratio approach,
iv. Combination method and
v. Estimation based on Pan Evaporimeter measurements.

Popular equations in either of these approaches are described and their merits discussed. Two versions of combination equation with grass and alfalfa as reference crops are described to compute reference crop evapotranspiration. Suitable relations to estimate computation parameters commonly costly to measure and not available are given. Where availab,e parameters have also been reproduced in tabular forms for convenience of use. Where tables are not available or these are not suitable specially in computer computations, suitable equations are given. Reference crop coefficient for both grass and alfalfa crop references are tabulated for selected crops together with pan coefficients for two standard fetch conditions of pan evaporimeter installations. Crop coefficients and pan coefficient need be used with care as they are to be used as guides when locally developed coefficients are not available. Where available, locally developed coefficients are available these should be preferred.

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