Irrigation Scheduling for Maize and Indian-mustard based on Daily Crop Water Requirement in a Semi-Arid Region

Vijay Shankar, C.S.P. Ojha, K.S. Hari Prasad

***Abstract*—**Maize and Indian mustard are significant crops in semi-arid climate zones of India. Improved water management requires precise scheduling of irrigation, which in turn requires an accurate computation of daily crop evapotranspiration (ET_c). Daily crop evapotranspiration comes as a product of reference evapotranspiration (ET_0) and the growth stage specific crop coefficients modified for daily variation. The first objective of present study is to develop crop coefficients K_c for Maize and Indian mustard. The estimated values of K_c for maize at the four crop growth stages (initial, development, mid-season, and late season) are 0.55, 1.08, 1.25, and 0.75, respectively, and for Indian mustard the K_c values at the four growth stages are 0.3, 0.6, 1.12, and 0.35, respectively. The second objective of the study is to compute daily crop evapotranspiration from ET_0 and crop coefficients. Average daily ET_c of maize varied from about 2.5 mm/d in the early growing period to > 6.5 mm/d at mid season. The peak ET_c of maize is 8.3 mm/d and it occurred 64 days after sowing at the reproductive growth stage when leaf area index was 4.54. In the case of Indian mustard, average ET_c is 1 mm/d at the initial stage, >1.8 mm/d at mid season and achieves a peak value of 2.12 mm/d on 56 days after sowing. Improved schedules of irrigation have been simulated based on daily crop evapo-transpiration and field measured data. Simulation shows a close match between modeled and field moisture status prevalent during crop season.

***Keywords*—**Crop coefficient, Crop evapotranspiration, Field moisture, Irrigation Scheduling

I. Introduction

MAIZE (Zea-Mays) is the most important crop in the world after wheat and rice. It is an important food crop in India and other Asian countries, which occupies an area of 7 million ha in India (Ministry of Information and Broadcasting, 2000). Maize is a cereal grain, with a high nutritional value for both human and animals. Irrigation and rainfall for this crop, is very important as maize is very sensitive to drought. Maize in India is generally produced as 'kharif' crop, which means that it is usually produced in the summers and thus subjected to higher crop evapotranspiration.

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Indian mustard (Brassica juncea) has been an important crop to India for a long period of time with a cultivated area of about 4.5 million ha. It is a very important oil crop in the semi arid and arid climate zones of India, which requires a temperate climate. Yield and quality of these crops often suffers due to deficient water supply and improper scheduling of irrigation. Accessible irrigation water needs to be utilized in a manner that matches the water needs of these crops. Water requirements of the crops vary substantially during the growing period due to variation in crop canopy and climate conditions [9] and [10]. Knowledge of crop water requirements is an important practical consideration to improve water use efficiency in irrigated agriculture. Many studies have been carried out related to irrigation water requirements of Maize [2], [3], [17] and [28] and Indian mustard [20] and [22] for different agro-climates. [21] estimated irrigation requirements of maize using soil moisture depletion studies in field experimental plots, but their study slightly overestimated the crop evapotranspiration by 1.2 -2.7 times as compared to study by [5]. Most of the studies are concentrated on prediction of water stress on yield of these crops, and water use efficiency under limited moisture conditions [16], [21] and [25]. Water use efficiency of these crops can be increased by more accurate estimation of ET_c. ET_c is computed as the product of grass reference evapotranspiration (ET_0), and crop coefficients from literature or actual field studies.

According to the Food and Agricultural Organization of the United Nations (FAO) [27], the Penman-Monteith (P-Mon) method gives more consistent ET_0 estimates and has shown to perform better than other ET_0 methods when compared with lysimeter data. [14] reviewed methods for estimating ET_0 and recommended the P-Mon equation as the preferred method for daily reference *ET*. [18] compared ET_0 values obtained by using the four methods of FAO together with the Harg method and concluded that the modified Penman method (PMon) could be adopted for tropical conditions. [19] compared ET_0 estimates using seven methods with FAO P-Mon method and revealed that temperature-based FAO-56 Hargreaves method and the FAO-24 Blaney–Criddle method provide ET_0 estimates with the highest rankings for semiarid climate. The climate data required to use the P-Mon equation are very vast and not always available. Relatively less data is sometimes available and at some places only pan evaporation data is available in developing countries. It is needed to evaluate different ET_0 methods, so that in absence of detailed data, the method which gives closest statistical proximity to P-Mon

method could be used. Therefore, the first objective of this paper is to assess the relationship between the standard FAO P-Mon method and other ET_0 methods for the semi-arid climate of the region, where the experimental field is located.

To estimate ET_c for irrigation planning on a regional scale, the crop coefficient K_c, which is the ratio of ET_c to grass reference evapotranspiration ET_c, is needed. The crop coefficient K_c value represents crop-specific water use and is required for accurate estimation of irrigation requirements. [9] suggested that Kc values need to be derived empirically for each crop based on lysimeter data and local climatic conditions. Crop coefficient values for a number of crops grown under different climatic conditions were suggested by [9]. These values are commonly used in places where local data are not available. However, they emphasized the strong need for local calibration of crop coefficients under given climatic conditions. [30] also presented crop coefficients for a few crops. The prediction of crop evapotranspiration, crop coefficients (K_c) throughout the growth period are the standard and recommended procedure for calculating crop water requirement (CWR) and scheduling irrigation at a regional level [1]. Since localized K_c values are not always available in many parts of India and due to lack of locally determined crop water use data,the values of K_c as suggested by FAO [1] and [8] are being widely used to estimate CWR and in all cases, no or very little attempt was made to experimentally verify the estimates locally. In absence of Crop coefficients based on lysimeter studies for important crops under the semi-arid climatic conditions prevalent in the Ganges plans of India and similar regions of other Asian countries, the second objective is to derive the K_c values for these crops using daily climatic and crop ET data from Lysimeter for irrigation planning and management at a regional level. The third objective of this paper is to compute daily, seasonal, and peak ET_c rates of Maize and Indian mustard as product of FAO P-Mon reference evapotranspiration and crop coefficients based on Lysimeter studies, modified for daily weather and plant parameter variations.

The ET_c is the sum of root water uptake plus soil evaporation, and the spatial and temporal pattern of soil water use can best be obtained from the accurate profile description of moisture depletion pattern in the root zone of the crops, soil water flux and rooting depth. Crop growth, which to a large extent is reliant on soil moisture availability within the rooting depth, can be sustained by maintaining optimal moisture level in the deficient top layer of root zone. Proper irrigation scheduling has a prominent role in maintaining an optimum level of soil moisture in the root zone. With the help of available daily crop evapotranspiration, root zone moisture profile, soil and plant parameter data development of a simulation for optimal irrigation scheduling has been kept as the fourth objective of the study.

II. Materials And Methods

Lysimeter and field crop experiments were conducted at the experimental fields behind Hydraulics laboratory, Civil Engineering Department, IIT Roorkee, India, from May, 2006 to December, 2006. Roorkee is located on the south bank of the Solani river at $77^{o}53^{"}52^{'}$ E Longitude, $29^{o}52^{"}00^{'}$ N Latitude and 274.0 m altitude above mean sea level. The climate of Roorkee is typical of north-western India, with very hot summers and very cold winters. In terms of precipitation, Roorkee is semi arid. The south-west monsoon generally breaks in mid June and the north-east during November-December. Winters begin from late September and continue through February. The coldest months are generally December and January, when the minimum temperature approaches zero. A rise in temperature is experienced from the beginning of March, which heralds the onset of summer. Climate is composite, hot during summer, cold during winter and humid during Monsoon season. Average maximum and minimum temperatures in January are 20.2°C and 4.5°C and corresponding temperatures in June are 39.6°C and 23.5°C, which account for the coldest and hottest months respectively. The average monthly relative humidity is the lowest (38%) during April, and the highest value of 79% is measured during September. The average annual sunshine duration is 2800 hrs. The average rainfall is 1032 mm, of which 74 % was received from July through September in last five years.

The soil in this region broadly comes under class ‘soils in old alluvial plains’. Soils are classified as deep well drained fine loamy soils on nearly level to level plain with sandy loam surface (Soil Map-National Bureau of Soil Survey and Land Use Planning, Regional Centre Delhi, 2002).

A. Computation of Reference Evapotranspiration

Evapotranspiration is a complex phenomenon because it depends on several climatological factors, such as temperature, humidity, wind speed, radiation, and type and growth stage of crop. Based on daily values of climatic variables monitored at the All Weather Station (AWS) located at radial distance of 500 m from experimental field at National Institute of Hydrology, Roorkee, grass reference evapotranspiration (ET_0) was computed by seven climate-based ET_0 estimation methods for 35 weeks covering a period from May 1st to December 31st, 2006. The details of the methods, with governing equations and supporting parameters are given in Table I. According to [27], Penman–Monteith gives the most consistent ET_0 estimates and has been shown to perform better than other methods when compared with lysimeter data. In areas where limited climatic data are available, other methods can be useful for estimating ET_0.

B. Lysimeter Details

Lysimeters have been installed in open fields, so that actual field conditions could be simulated. In order to find out the crop evapotranspiration during different stages of the crop growth, water balance studies using the Lysimeters have been performed. Percolation to the groundwater table from the root zone is being represented by the drainage from the Lysimeters. Two drainage Lysimeters, 1.5 m deep and with a surface area of $1m^2$, and a drainage arrangement at the bottom have been used in the study. The effective area for crop evapotranspiration was 2 m^2. The height of the Lysimeter rim

was maintained near ground level. The Lysimeters made up of cast iron are provided with 0.01m thick internal hard PVC sheeting to provide insulation against surrounding soil. The height of Lysimeter rim has been kept 0.10 m above the contiguous ground level to minimize the boundary layer effect in and around the Lysimeter, however the soil in Lysimeter was kept at level with soil in surrounding field. At the bottom of both Lysimeters 2cm diameter side drain holes are provided to drain-out the water percolated down. To collect the percolated water a collecting arrangement has been provided, which also measures the volume of water drained out. The drain holes are connected with small equal diameter pipes which opens up in a chamber ($1m^2$ and 2 m deep) provided between both the Lysimeters for the purpose of collecting the drained water.The upper 1.2 m of the Lysimeter is filled with a sandy-silt-loam textured soil, homogeneous throughout the profile, characterized by an organic matter content of 1.1 to 1.2%. The bottom 0.05 m has been filled with a very coarse gravel of size more than 3 cm diameter and above it 0.15 m is filled with gravel of about 2 cm in diameter, to allow drainage toward the pipe and avoid clogging.

Water has been applied in the quantity and distribution required by the crops under study through an optimized irrigation technique.

Soil moisture content along depth in the Lysimeters is required to obtain the change in the soil moisture storage in the Lysimeter. To obtain the periodic change in the soil moisture storage the soil moisture content at different depths at discrete time intervals is needed. High precision soil moisture measurement sensors (Watermark, Irrometer Company, Inc. Riverside CA) were installed at a depth of 0.2m, 0.4m, 0.6m, 0.8m, 1.0m and 1.2m in Lysimeter and adjoining crop fields. Soil suction profile is thus obtained for the period under consideration. The moisture depletion for different layers (0.2m each) is assumed uniformly varying from upper edge to lower edge throughout the depth. The change in the moisture storage in a soil layer is computed by multiplying the change in the moisture content with volume of the soil representing that layer. The volume of the change in soil moisture storage divided by the area gives the moisture storage change in depth units.

TABLE I
DIFFERENT ET_0 ESTIMATION METHODS AND GOVERNING EQUATIONS

Method of ET_0 Estimation	Equations Used		Supporting Equations	Reference
Penman Monteith	$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$	(1)	$\Delta, R_n, G, \gamma, u_2, e_s, e_a$	[1]
FAO-24 corrected Penman (c = 1)	$ET_0 = c\left[\frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma} 2.7 W_f (e_a - e_d)\right]$	(2)	γ, W_f Δ, R_n, G, e_s, e_a	[1] and [9]
Priestley-Taylor	$ETp = \alpha \frac{\Delta}{\Delta+\gamma}(Rn - G)$	(3)	$\alpha, \Delta, \gamma, R_n, G$	[1] and 26]
FAO-24 Blaney-Criddle	$ET_{bc} = a + b\left[p(0.46\bar{T} + 8.13)\right]$	(4)	a, b	[9]
Hargreaves-Samani	$ET_O = 0.0135(KT)(R_a)(TD^{1/2})(TC + 17.8)$	(5)	R_a	[1], [12], [13] and [24]
	$KT = 0.00185(TD)^2 - 0.0433TD + 0.4023$	(6)	KT	
Christiansen	$PET = 0.473\, R_a\, C$	(7)	R_a, C_T, C_H, C_U, C_S, C_E, C_M	[1] and [7]
	$C = C_T C_H C_U C_S C_E C_M$	(8)		
Pan Evaporation	$ET_0 = K_p\ E_{pan}$	(9)	K_p	[1], [23]

C. Crop Details

Both the crops were sown uniformly in Lysimeter and surrounding field so that the field conditions could be simulated in and around the Lysimeters. The sampling site for different plant parameters has been kept in field at 4-5 m away from the Lysimeter. Maize was sown on May 20th and harvested on September 1st of 2006, whereas Indian mustard was sown on September 12th and harvested on December 10th, 2006, both crops having crop periods of 105 days and 90 days respectively. The duration of growth stages I, II, III and IV for both crops were recorded as 17, 30, 34, 24 and 15, 25, 30, 20 days respectively.

Three major factors; Leaf Area Index (LAI), Plant Height and root depth have been recorded at discrete time intervals throughout the crop period for all the three crops grown in the experimental plot. Figs. (1) and (2) show the plant height, root depth and LAI measurements against the crop growth period for maize and Indian mustard respectively. The root depth measurements have been restricted to maximum value in both the cases.

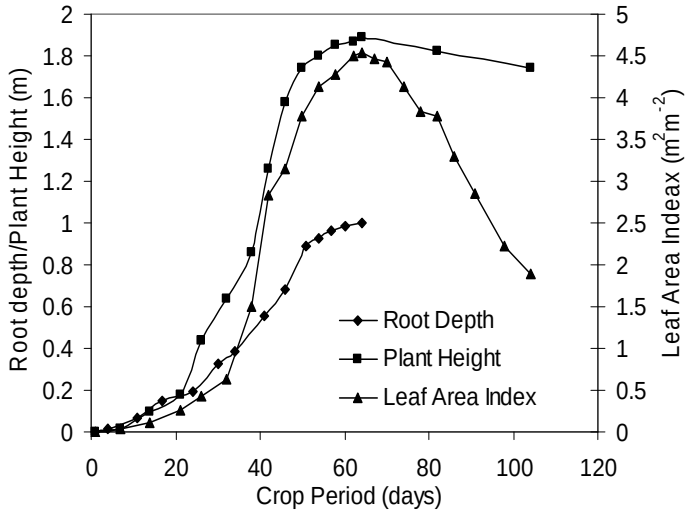

Fig. 1 Field observed plant parameters for the maize crop

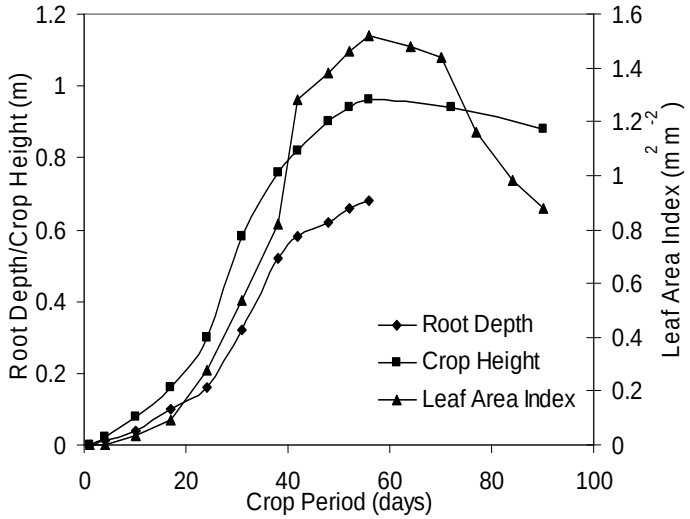

Fig. 2 Field Observed plant parameters for Indian mustard

D. Soil Parameters

Representative soil samples were obtained from the 0-0.3 m, 0.3-0.6 m, 0.6-0.8 m, 0.8-1.0 m and 1.0-1.2 m depth, in the experimental site for testing the soil properties. The cumulative particle size curves obtained through grain size and hydrometer analysis reveal that the soil profile up to 1.2 m is fairly uniform in texture.

For the 0-1.2 m depth mean values of sand, silt and clay of 54.0%, 29.0% and 17.0 % respectively, yielded the U.S.D.A. soil textural class of sandy loam. Based on this whole crop root zone is characterized with uniform sandy loam soil in present study. Bulk density ranges from 1.52 to 1.72 g/cm^3 for different layers with an average of 1.62 g/cm^3. For particle density an average value of 2.61 g/cm^3, which is typical for sandy soils, is obtained. The value of porosity comes out to be 0.38 cm^3/ cm^3. Field saturated hydraulic conductivity an average value of 0.1083 cm/s.

E. Soil Hydraulic and Retention Characteristics

In-situ determination of SMC has been performed, which involves simultaneous in situ measurement of matric potentials and moisture content at the depth of interest because, in hydrologic modeling at field plot or catchment scale, an average SMC which corresponds to the in situ observations is preferred. Pairs of moisture content-matric potential for the four depths (0.3, 0.6, 0.9 and 1.2 m) of measurements have been considered to determine soil moisture characteristics. No clear depth-wise relationship is discernible, indicating the similarity of the retention characteristics of the soil profile, hence, a single SMC represented the entire 0-1.2m soil layer, without loss of much accuracy. [29] relationships have been used to determine the soil hydraulic characteristics in present study. The saturated moisture content θ_s in these relationships was assumed to equal the measured total soil porosity (0.38 cm^3 cm^{-3}). A standard residual moisture content value equal to 0.065 cm^3 cm^{-3} [6] for sandy loam soil (soil type for experimental plot) has been considered. Experimentally obtained value of field capacity (θ_{fc} = 17.6) and SMC deduced value of wilting point (θ_{pwp} = 6.8) has been used in the present study. The available moisture which is the difference of θ_{fc} and θ_{pwp} comes out to be (17.6-6.8) 10.8%. The irrigation is assumed to be supplied at 50% depletion of the available moisture. Hence irrigation has been provided whenever the soil moisture content drops to [17.6-0.5(17.6-6.8)] 12.2 %.

III. Results And Discussion

A. Comparison of Reference Evapotranspiration

Reference evapotranspiration (ET_0) have been computed by earlier stated seven climate-based methods. Penman-Monteith method is supposed to give more consistent ET_0 estimates and has been shown to perform better than other methods in relation to Lysimeter data [27]. The weekly average daily ET_0 (mm/day) is calculated using seven methods; Penman Monteith (P-Mon), FAO corrected Penman (F c P-Mon), Priestley-Taylor (P-T); FAO-24 Blaney- Criddle(F B-C), Hargreaves-Samani (H-S), Christiansen (CHSTN) and FAO pan evaporation (F E-pan). In order to select the best method for estimating ET_0, linear regression is commonly used to describe the association between two variables, X and Y (ET_0 values computed using two different methods). In present study linear regression analysis has been performed between the ET_0 estimates by standard and comparison methods as follows:

$$ET_{\text{Penman-Monteith}} = b \times ET_{\text{method}} \quad (10)$$

Where b = regression coefficient. Regression through the origin has been selected to evaluate the goodness of fit between the ET_0 method estimates and the Penman–Monteith estimates because both values should theoretically approach the zero when the actual ET_0 is zero. The statistical measure of the equation is then called the coefficient of determination (R^2). A value of R^2 close to the unity indicates a high degree of association between the two variables. The ET_0 values obtained by different methods are also compared with Penman Monteith ET_0 estimate by calculating SEE values using equation (11)

$$SEE = \left[\frac{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2}{n-1} \right]^{0.5} \quad (11)$$

Where SEE = standard error of estimate; Y = ET_0 estimated by the standard method (Penman-Monteith method); $\hat{Y}$ = corresponding ET_0 estimated by the comparison method and n = total number of observations. The SEE gives equal weight to the absolute differences between the standard method and the comparison method. It is the measure of goodness of fit between the ET_0 values measured by different methods and the standard method. The SEE has units of *mm/day* and n-1 degrees of freedom. The correlation between Penman-Monteith and other methods for estimating ET_0 has been evaluated.

The ET_0 values estimated by all the chosen methods have been compared with the Penman-Monteith estimates. Performance of different methods indicates that, overall FAO corrected Penman, Blaney-Criddle and pan evaporation methods have been found to be in good agreement with the standard method and provide a reliable alternative to Penman-Monteith method for monsoon type climate in semi-arid region of Roorkee. In the present study reference evapotranspiration has been estimated using Penman-Monteith method.

B. Crop Evapotranspiration

One dimensional crop evapotranspiration (ET_c) and water balance components are computed with data from Lysimeter for different stages of the crops. Moisture change at different depths of soil in Lysimeter gives the change in moisture storage. Crop coefficients are then computed by obtaining the ratio of crop evapotranspiration (ET_c) and reference evapotranspiration (ET_0) for each stage of crop. These crop coefficients (K_c) are then modified for plant height, wind velocity and relative humidity to obtain daily representative crop coefficients [1]. Daily crop coefficients are then multiplied to reference evapotranspiration to get daily crop evapotranspiration.

C. Water Balance

Crop evapotranspiration has been determined from Lysimeter-set up by conducting the water balance studies. Precipitation P, irrigation I, if any and D the quantity of water drained off through the bottom are measured, and crop evapotranspiration is computed using equation (12)

$$P + I = D + ET_c \pm \Delta S \quad (12)$$

Where, ET_c is the crop evapotranspiration and ΔS the change in soil moisture storage, surface and subsurface. The change in the soil moisture for the specific depth (d_z) and for the specific time period is computed as:

$$\text{Moisture storage change, } \Delta S_z = (\theta_{z,final} - \theta_{z,\,initial}) * d_z \quad (13)$$

Where $\theta_{z,final}$ and $\theta_{z,\,initial}$ are final and initial water content in the soil profile in a discrete time interval.

During the crop season most of the ET demand of Maize has been met from monsoon rainfall, which is 467.8 mm. During the entire crop season, only 125.02 mm of water was applied through irrigation to meet the 495.22 mm ET demand of the crop. The water loss beyond the root zone was 97.58 mm. In case of Indian mustard though crop water requirement is quite low (135.6 mm), but due to scanty rainfall during its crop period (64 mm), most of the requirement has been fulfilled with irrigation.

D. Crop Coefficients

Crop coefficient values of the experimental crops have been computed by dividing crop evapotranspiration measured from Lysimeter with reference ET calculated using different ET_0 methods. The entire growing period for all the crops is divided into four growth stages. The stage wise K_c values of Maize and Indian mustard are given in Table II. Growth stages have been considered on the basis of study by [9]. Initial stage corresponds to the germination and early growth when the soil surface is not or is hardly covered by the crop (ground cover < 10 %), crop development stage starts from the end of initial stage to attainment of effective full ground cover (ground cover: 70-80 %), mid season commences from the attainment of effective full ground cover to time of start of maturing as indicated by discoloring of leaves or leaves falling off and late season stage begins from end of mid-season until full maturity or harvest. At sowing and during the early growth period, evaporation from the soil surface is considerable, particularly when the soil surface is wet for most of the time. During full ground cover, evaporation is negligible. The crop coefficient (K_c) for a crop varies throughout the growing season, and its full value will not only depend on the crop development stage but also on the climatic conditions.

1. Maize

During the first stage of crop growth, which covered the period from sowing to the 17days after sowing (DAS), K_c value based on all the methods falls in the range of 0.48 to 0.55. This could be due to low LAI (<0.5) during this stage, which represents that plant factors are insignificant and climate factors are dominant during this stage. During the crop development stage (18^{th} to 47^{th} DAS), K_c values calculated by all methods except H-S method ascended close to 1 with highest value of K_c by P-Mon method as 1.08. The maximum crop coefficients of 1.284 and 1.248 by FAO E-Pan and P-Mon respectively, were recorded during the mid season stage (47^{th}-81^{st} DAS) when LAI was close to 4.5, corresponding the silking stage of maize. After the reproductive crop growth stage (mid-season), the K_c of maize starts decreasing because the LAI starts diminishing. The crop coefficient declined rapidly to 0.747 based on P-Mon method during the last crop growth stage covering the period from 82^{nd} to 105^{th} DAS. The estimated K_c values of maize by the P-Mon method during initial, crop development and reproductive stages (mid-season) were 9.8, 27.1 and 4.7 % higher than the values reported by FAO at these respective growth stages (Table II). [28] estimated K_c values of maize by the P-Mon method during initial, crop development and mid-season stage 37.5, 29.8 and 8.9% higher than the values reported by FAO at these respective growth stages. This divergence could mainly be due to differences in crop duration and climatic conditions.

TABLE II
VALUES OF CROP COEFFICIENTS DERIVED FROM DIFFERENT METHODS

Methods	Crop Stages				Average
	I	II	III	IV	
Maize					
Penman-Monteith	0.549	1.081	1.248	0.747	0.906
FAO corrected Penman	0.529	1.008	1.115	0.779	0.858
Priestley-Taylor	0.489	0.954	0.728	0.509	0.670
FAO Blaney-Criddle	0.534	1.016	1.126	0.872	0.887
Hargreaves-Samani	0.533	1.013	1.103	0.772	0.855
Christiansen	0.522	0.999	0.967	0.639	0.781
FAO E-Pan	0.520	0.997	1.283	0.915	0.929
FAO Values	0.3-0.5	0.7-0.85	1.05-1.2	0.67-0.77	0.75-0.92
Indian Mustard					
Penman-Monteith	0.299	0.599	1.119	0.350	0.592
FAO corrected Penman	0.271	0.544	1.012	0.318	0.536
Priestley-Taylor	0.179	0.366	0.665	0.216	0.357
FAO Blaney-Criddle	0.308	0.470	0.985	0.300	0.516
Hargreaves-Samani	0.250	0.441	0.662	0.174	0.382
Christiansen	0.207	0.374	0.710	0.196	0.372
FAO E-Pan	0.298	0.542	0.942	0.304	0.521
FAO Values[#]	0.35	NA	1.15	0.35	NA

General values for oil crops

At the reproductive growth stage, the Kc value estimated by P-Mon is higher, where as those from FcPn, FB-C, and Hargreaves-Samani methods were highly in the range of the FAO values [1]. During last growth stage also, estimated Kc values by these four methods were well within the range of FAO values [1]. Seasonal average estimated K_c values calculated by the P-Mon, FcPn, H-S and FB-C methods were within the range of K_c values reported by the FAO [1].

2. Indian mustard

The crop coefficient values for the different ET_0 methods at various growth stages are given in Table II. As expected, there is a constantly increasing trend in *Kc* during the crop development growth stage beginning from 16th to 40th DAS. The slow increase in the Kc values from equal to or less than 0.3 to equal to or less than 0.6 by P-Mon and other methods respectively can be attributed to slow increase in LAI from below 0.2 to near 0.8 during this period. The peak *Kc* values of 1.12, 1.01, and 0.99 by P-Mon, FcPen, and FAO B-C methods were observed during mid season stage because of LAI during the this period (41st-70th DAS) acquired the peak value around 1.5 for the crop. In the late season crop growth stage starting from 71 to 90 DAS, the crop coefficient rapidly decreased to 0.35, likely due to fast decline in LAI (0.8).

The K_c values obtained from Penman-Monteith method have been adopted in case of both the crops in the present study. The K_c values obtained are modified for the climatic and plant parameters for calculation of daily crop evapotranspiration.

E. Illustration of the climatic effect on crop coefficients

Values of the crop coefficient for different growth stages, ($K_{c\ ini}$, $K_{c\ dev}$, $K_{c\ mid}$, $K_{c\ end}$) have been calculated for the crops grown, as listed in Table II. The relative impact of climate on K_c is modified by the adjustments to the values from Table II, for variation in climate, mean daily wind speeds and variable crop height. For specific adjustment in climates where RH_{min} differs from 45% or where u_2 is larger or smaller than 2.0 m/s, the K_c values from Table II are adjusted as [1]:

$$K_c = K_{c(Table)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad (14)$$

Where, $K_{c\ (Table)}$ is value for K_c taken from Table II, u_2 is mean value for daily wind speed at 2 m height (m s^{-1}), for 1 m s^{-1} < u_2 < 6 m s^{-1}, RH_{min} is mean value for daily minimum relative humidity (%), for 20% < RH_{min} < 80%, and h is mean plant height (m) for 0.1 m < h < 10 m during the crop season.

F. Daily Crop Evapotranspiration

The maximum value of daily crop evapotranspiration (ET_c) (8.305 mm/day) for Maize occurs on the 64th day from the date
of sowing, and for mustard (2.124 mm/day) on 56th day from date of sowing. Figs. 3 and 4, show crop evapotranspiration, transpiration and evaporation during crop period for Maize and Indian mustard respectively. Continuous fluctuations in the crop evapotranspiration can be attributed to the effect of daily weather parameters, irrigation and rainfall.

In case of maize, since leaf area index is more than 3 for a dominant part of the crop season plant transpiration comes out to be 374.6 mm, which is 75 % of the total crop evapotranspiration, leaving 119.8 mm (25 %) as the soil evaporation, whereas in case of Indian mustard maximum value of leaf area index is near 1.5 only, so plant transpiration is 55.8 mm (42 %) and evaporation (77.7 mm, 58 %) forming a major chunk of the crop evapotranspiration. Since soil evaporation is the potential flux at the soil surface, only transpiration is distributed throughout the root zone and moisture status of the top soil layer being assessed for irrigation, it cannot be ruled out that this ratio will have an impact on the irrigation scheduling for a crop.

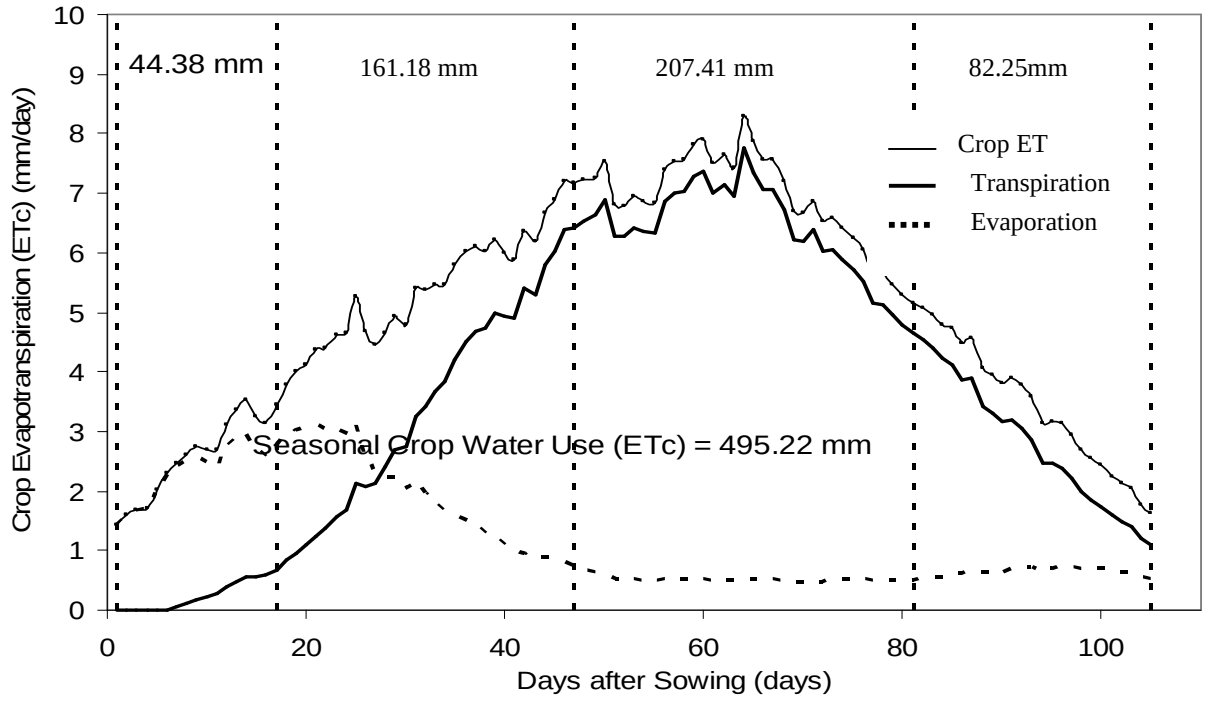

Fig. 3 Crop ET, its components and crop water use for Maize throughout crop period

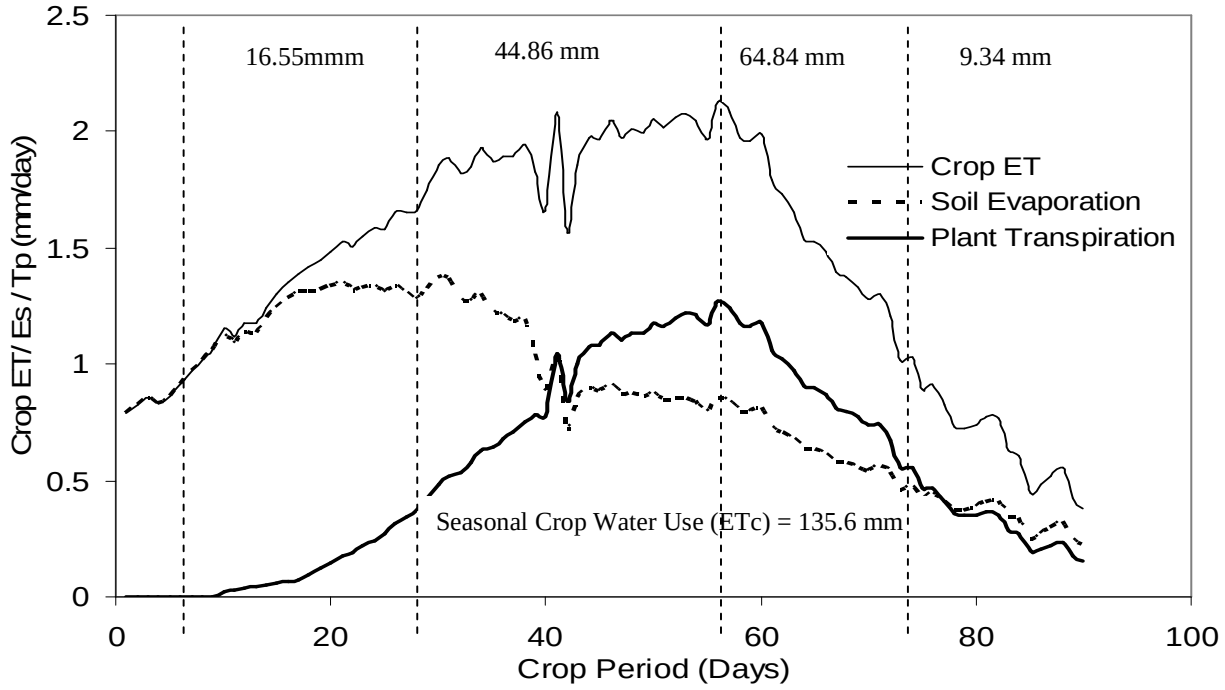

Fig. 4 Crop ET, its components and crop water use for Indian mustard throughout crop period

G.Irrigation Scheduling

Irrigation scheduling has conventionally aimed to achieve an optimum water supply for productivity, with soil water content being maintained close to field capacity. In many ways irrigation scheduling can be regarded as a mature research field which has moved from innovative science into the realms of use, or at most the refinement, of existing practical applications. A numerical simulation has been developed to predict the vadoze zone soil moisture content profiles under transient field conditions by clubbing the soil moisture flow equation with an exponential root water uptake term given by [15]. The simulation uses [29] constitutive relationships. It takes into account a variable transpiration rate and a field measured initial moisture content.

Rainfall, irrigation and evaporation have been treated as sources of non-uniform potential surface flux. Gravity drainage has been assumed at a depth of 2.9 meters below the soil surface. Groundwater was observed to fluctuate between depth of 4.5 m to 5.5 m, at an observation well at Department of Hydrology, IIT Roorkee, which is at a radial distance of about 500 meters from the experimental field.

Solutions to the simulation have been obtained numerically by a fully implicit finite difference scheme, involving a non linear system of equations, which has been linearized using Picard's iterations. The scheme results in a tridiagonal set of simultaneous equations which can be solved rapidly using Thomas algorithm. Determining the water requirements of crops is important for improved scheduling of irrigation, which in turn requires accurate measurement of crop evapotranspiration (ET_c). Soil evaporation, plant transpiration and plant parameters required for input to the simulation are given in the previous sections. An average of the moisture content in the top 0.3 m root zone has been considered in this regards in both simulation and field determination of the moisture status. Optimum moisture conditions has been maintained till middle of late season stage of the each crop, after which no irrigation is basically required by the crop and the moisture depletion in the root zone takes place under limited soil moisture conditions. A reduction factor [11] is introduced into the root uptake term being used to account for the stress due to limited soil moisture. Figs. (5) and (6) show the simulated scheduling of irrigation for both crops under optimal moisture conditions along with field measured moisture status throughout the crop period.

It is evident from Figs. (5) and (6), that application of the simulation to field conditions and comparison of the results with field measured data shows very good agreement. Moisture content measurements have been recorded frequently to assess the soil moisture status needed to plan irrigation events, whereas after irrigation or rainfall event moisture status at different depths of root zone has been recorded 24 hours after cessation of the event. The day and time of the average moisture predicted for onset of irrigation using simulation is very close to the actual measure data. The number of irrigations predicted using simulation are same as actually provided. It can be said that with available soil characteristics data and crop water use/ consumptive use/ crop evaporation data an improved irrigation schedule can be planned, resulting in overall enhanced water use efficiency.

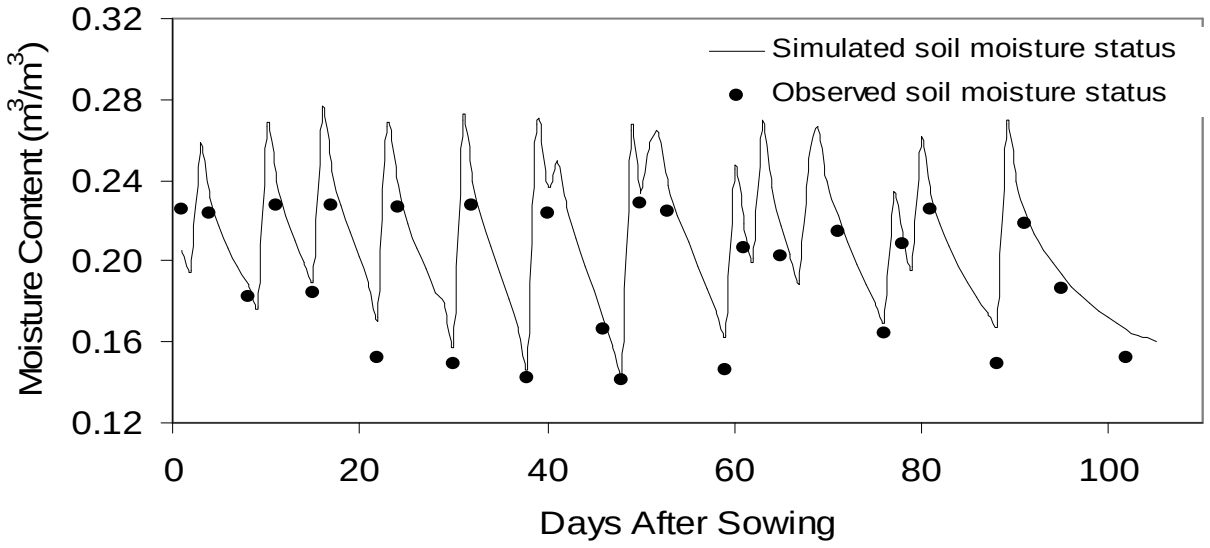

Fig. 5 Simulated schedule of irrigation and field measured soil moisture status for Maize

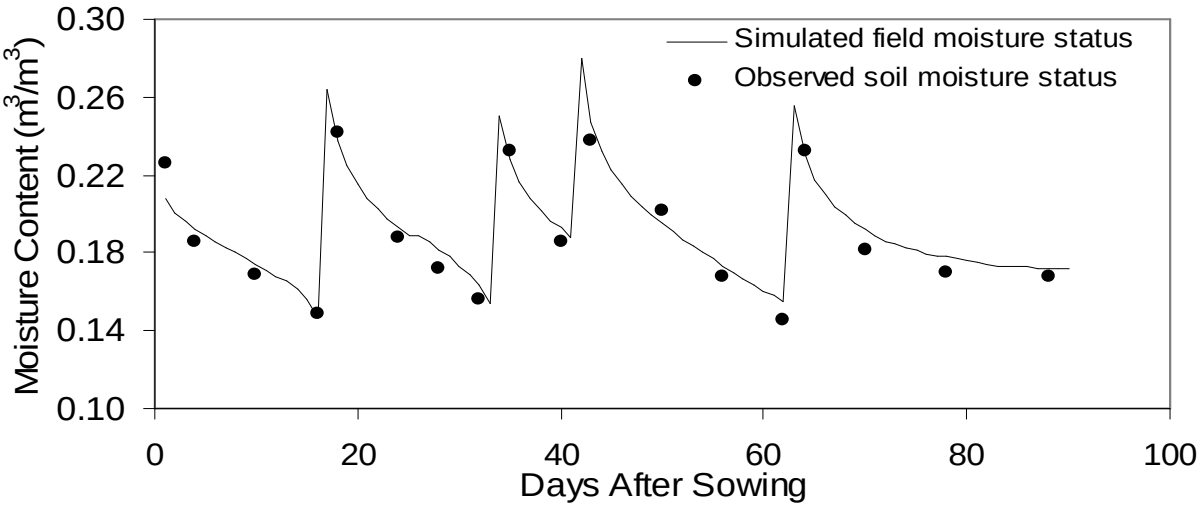

Fig. 6 Simulated schedule of irrigation and field measured soil moisture status for Indian mustard

The estimated values of crop coefficients differ considerably from those suggested by FAO for these crops. There were marked differences between the estimated *Kc* values in this study and values reported by FAO in all the stages except the last growth stage of both the crops. Local calibration of crop coefficients therefore is essential. The crop coefficients developed in this paper can be used for accurate estimation of crop water requirements and, in turn, can be used for irrigation scheduling for similar types of climatic conditions. Average daily ET_c of maize in this environment is 4.9 mm/day, with a maximum value of 8.3 mm/day which occurred on 64 DAS, whereas for Indian mustard average value did not even exceed 1.1 mm/day, with a maximum of 2.12 mm/day on 56 DAS. The crop water requirements and availability of the rain for both the crops is totally different in a way that maize has a high daily and maximum crop water requirement in a rain intensive period, whereas Indian mustard has low daily and maximum crop water requirement. During Maize most of the crop water requirements are met by precipitation, but due to higher daily crop evapotranspiration, during non-rainfall period irrigation is required almost weekly. In case of Indian mustard, most of the crop water requirement is to be met with the irrigation, due to scanty rainfall during its crop period. Accurate determination of crop evapotranspiration leads to improved irrigation scheduling and hence efficient irrigation water use.

IV. Conclusions

A comprehensive analysis of different reference evapotranspiration methodologies indicates that FAO: corrected Penman; Blaney-Criddle and pan evaporation methods can be used as a surrogate for standard P-Mon method to estimate daily ET_0 for areas where limited climatic data are available. The Lysimeter studies on ET_c for maize and Indian mustard during subsequent development stages were conducted under a semi-arid climate at Roorkee in northern Gangetic planes of India.

Stage-wise crop coefficient values for maize and Indian mustard were developed based on ET_c and ET_0, which have been modified for daily values. Daily crop coefficient values represent a purposeful correlation between crop water use of maize and Indian mustard and the biological properties of these crops and climatic conditions under which Lysimeter studies have been carried out. The comparison with K_c values recommended for maize and general oil crops in case of mustard by the FAO (which are generally used in this area), led to a conclusion that the experimentally determined K_c values developed at Roorkee, in present study are higher at all except one (late season) growth stages of these crops. Therefore, these ET_c and K_c values may prove to be better for projecting an accurate estimation of the crop water requirements of these crops particularly in this region. As practically visualized in the present study, this information could be useful for irrigation scheduling of maize and Indian mustard under semi-arid conditions in northern India.

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