Ecohydrologic modeling of crop evapotranspiration in wheat (*Triticum-aestivum*) at sub-temperate and sub-humid region of India

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Abstract: Efficient water management of crop requires accurate irrigation scheduling which, in turn, requires the accurate measurement of crop water requirement. Reference evapotranspiration plays an important role for the determination of water requirements for crops and irrigation scheduling. Various models/approaches varying from empirical to physically base distributed are available for the estimation of reference evapotranspiration. This study identified most suitable reference evapotranspiration model for sub-temperate, sub humid agro-climatic condition using climatic and lysimeter data. The Food and Agriculture Organization (FAO) recommended crop coefficient values are modified for the local agro-climatic conditions. The field experiment was conducted in sub-temperate and sub-humid agro-climate of Solan, Himachal Pradesh, India. Actual crop evapotranspiration for different crop growth stages of wheat (*Triticum-aestivum*) has been obtained from water balance studies using lysimeter set-up. Field observed and computed individual-stage wise crop evapotranspiration values are compared, to identify the most suitable reference evapotranspiration model for computing crop evapotranspiration. Penman Monteith model shows close agreement with observed value with coefficient of determination, standard error estimate and average relative discrepancy values of 0.96, 13.69 and -5.8, respectively. Further, an effort has been made to compare the accuracy of various widely used methods under different climatic conditions.

Keywords: crop coefficient, crop evapotranspiration, reference evapotranspiration, lysimeter

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1 Introduction

Water has been labeled "blue gold" and it is destined to be the critical issue of the 21st century. Globally, irrigation is responsible for 75%-80% of the world-wide spending of water[1-2]. Development of sustainable irrigation practices requires better understanding of biophysical processes of root-water uptake in soil and transpiration from plant canopies[2]. Precise estimation of crop water requirement is very important for irrigation scheduling. Crop evapotranspiration (ET_c) plays an important role in hydrologic cycle because it represents a considerable amount of moisture lost from a plant canopy. Estimation of reference ET_c has immense importance for determination of water demand for crops and irrigation scheduling[3]. The lysimeter method is often expensive, complex and requires skilled manpower. Therefore, mathematical models are commonly used for estimation of ET_c. Many empirical and semi-empirical methods for estimation of reference evapotranspiration (ET_0) exist and are being used by researchers in India and other part of the world. The different methods of ET_0 estimation can be grouped into empirical formulations based on radiation (Priestley-Taylor), temperature (SCS Blaney-Criddle, Hargreaves Samani), combination theory types (Penman Monteith, FAO-24 Penman (c=1), FAO-24 corrected Penman) and pan evaporation (FAO-24 pan). However,

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lysimeter data are believed to be the best reference to assess the performance of any method.

Information on water balance component on cropped soils is crucial for irrigation planning and scheduling at field level[2,4]. The reference[5] provided detailed guidelines for using climatic data to estimate ET_0. Although several methods/equations have been reported in literature for estimation of ET_0[6,7], however, there is no consensus on the suitability of an equation for a given climatic condition and each equation requires rigorous local calibration[8]. The suitability of Penman-Monteith (P-M) Equation was assessed by different authors for different climatic conditions[9-13]. The P-M equation needs meteorological data such as minimum and maximum air temperature, minimum and maximum relative humidity, solar radiation and wind speed[14]. The reference[15] is temperature-based equation proposed for estimating ET_0 which was further modified by reference[5].

A brief history of development by reference[16] and its comparison to ET predicted by the FAO Penman-Monteith method are described to provide background and information helpful in selecting an appropriate reference ET equation under various data situations[17]. The ET_0 method requires only measured temperature data[16], is simple, and appears to be less impacted than Penman-type methods when data are collected from arid or semiarid, non irrigated sites.

India is inherited by a variety of climates ranging from arid to humid. The local scientists generally apply the well-known methods believed to be giving good results in other parts of the world despite the fact that their accuracy is highly sensitive to climate. Therefore, to reduce the uncertainty associated with the ET_0 estimation methods, further systematic studies are required to compare their performance under different climatic condition. This study includes the methodology adopted in achieving the sets of objectives in the light to test suitability of ET_0 model for the sub-temperate, sub-humid agro-climate area of Himachal Pradesh, India.

2 Materials and methods

2.1 Study area

A field experiment on wheat (*Triticum-aestivum*) crop was conducted at Dr. Y. S Parmar University of Horticulture and Forestry, Solan, Himachal Pradesh, India. Solan is located at 30°50' N latitude and 77°11'30" E longitude and 1 260 m above mean sea level. Area falls in a sub-temperate, sub-humid agro-climate and mid-hill zone of Himachal Pradesh. The average rainfall of the area ranges from 1 100-1 300 mm with the most rainfall between June and September. Pan evaporation rate ranges from 1-12 mm/day. The soil is loam type with shallow depth. All the meteorological data required for the estimation of ET_0 have been obtained from All Weather Station at the university. The rainfall pattern of the study area during field experiments for one year is shown in Figure 1.

Representative soil samples have been obtained from the 0-0.3 m, 0.3-0.6 m, 0.6-0.9 m and 0.9-1.2 m depths at experimental site for testing the soil properties. The cumulative particle size curves were obtained through grain size and hydrometer analysis. The textural classification reveals that the soil profile up to 1.2 m is the same (loam type soil), but has different hydraulic properties. The detailed soil properties are shown in Table 1.

Normal agricultural practices have been followed in conducting the field crop experiments. The entire growth period for the crops is divided into four stages: I initial, II Development, III Mid season and IV Late season. Growth stages have been considered on the basis of study conducted by reference[5]. Initial stage corresponds to the germination and early growth when the soil surface covered less than 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. The sampling for different plant parameters such as leaf area index (LAI), plant height and root depth has been recorded at discrete time intervals throughout the crop period. The LAI of crop is used in partitioning ET_c in evaporation and transpiration.

The soil properties *i.e.*, soil texture analysis using sieve and hydrometer, bulk density using core sampler, particle density using pycnometer, and saturated hydraulic conductivity using Guelph type Permeameter. Plant parameters *i.e.*, LAI, crop height and root depth were measured using digital planimeter, measuring tape and trench profile method, respectively.

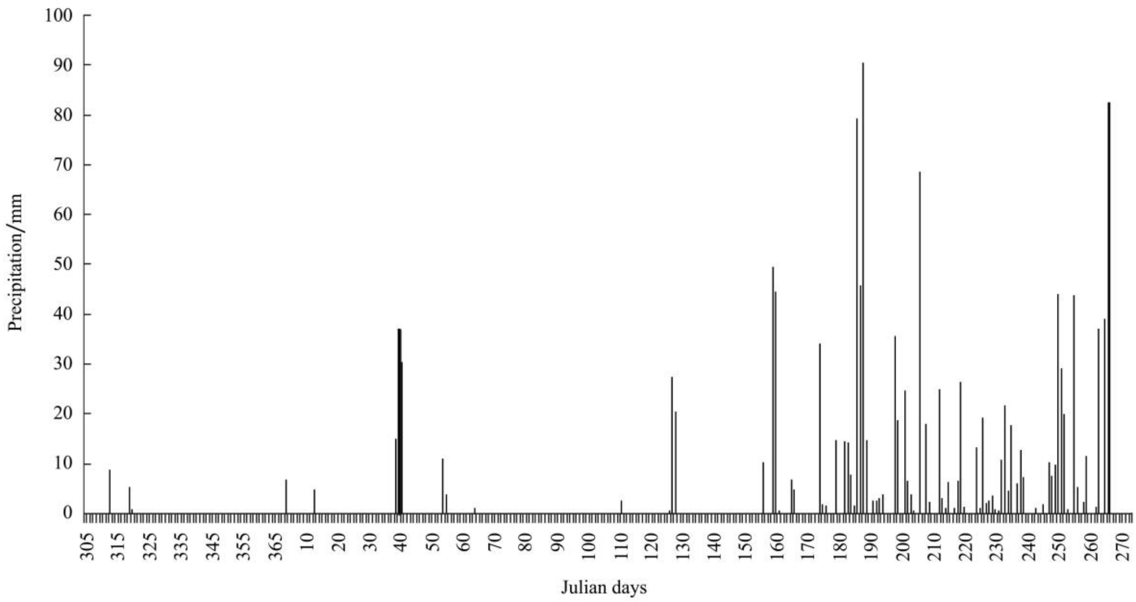

Figure 1 Daily precipitation from November 1, 2009 to September 30, 2010 at Solan

Table 1 Soil textural properties at different depths

Soil depth /cm	Gravel /%	Sand /%	Silt /%	Clay /%	Particle density /g•c.c^{-1}	Saturated hydraulic conductivity Ks/cm•h^{-1}	Field capacity (Fc) /cm^3• cm^{-3}	Permanent wilting point /cm^3• cm^{-3}	Available water /cm^3• cm^{-3}	Bulk density /g•c.c^{-1}
0-30	35.0	47.4	31.2	21.4	2.45	1.05	0.24	0.13	0.12	1.23
30-60	40.4	39.2	35.2	25.6	2.54	0.90	0.23	0.12	0.11	1.3
60-90	36.0	41.0	32.6	26.4	2.51	0.86	0.24	0.13	0.11	1.31
90-120	20.0	39.6	36.4	24.0	2.48	0.80	0.24	0.12	0.12	1.35

2.2 Reference evapotranspiration models

The ET rate from a reference surface, not short of water, is called the reference ET_c or ET_0 and is denoted as ET_0. Many equations/models have been reported in the literature for estimation of ET_0. The ET is a complex phenomenon and depends on several climatological factors. In the present study, six most commonly used models have been used to estimate ET_0 (mm/day) and illustrate in Table 2. The different methods of ET_0 estimation have been grouped into empirical formulations based on radiation; Priestley-Taylor (P-T), temperature; FAO Blaney-Criddle (F B-C), Hargreaves Samani (H-S) and combination theory types; Penman Monteith (P-M), FAO-24 corrected Penman (Fc Pen) and Pan evaporation (F-E Pan). Applicability of any ET model is limited depending upon availability of input data. Variation of ET_0 using different models for one year has been shown in Figure 2.

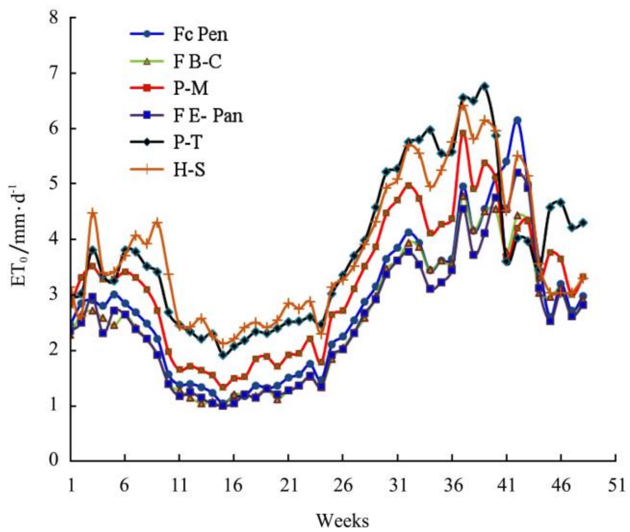

Figure 2 Weekly-average daily ET_0 estimates during crop period

Table 2 Reference evapotranspiration estimation methods

Sr. No.	Method of ET_0 estimation	Equations used	Basic reference	Required meteorological data
1.	FAO-24 corrected Penman (c = 1), (F c P-Mon)	$ET_0 = c\left[\frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma} 2.7W_f\,(e_a - e_d)\right]$	[5]	Net radiation, vapour pressure deficit and wind velocity
2.	Priestley-Taylor (P-T)	$ET_0 = \alpha \frac{\Delta}{\Delta+\gamma}\ \ Rn - G$	[22]	Net radiation, soil heat flux and vapour pressure deficit
3.	FAO-24 Blaney-Criddle (F B-C)	$ET_0 = a + b\left[p\ \ 0.46\overline{T} + 8.13\ \right]$	[5]	Annual day time hours, temperature and wind velocity
4.	Hargreaves-Samani (H-S)	$ET_0 = 0.0135(KT)(R_a)(TD^{1/2})(TC + 17.8)$ $KT = 0.00185(TD)^2 - 0.0433TD + 0.4023$	[16,23]	Net radiation, min/max temperature
5.	FAO Pan Evaporation (F E-Pan)	$ET_0 = K_p\, E_{pan}$	[21]	Pan evaporation
6	Penman Monteith (P-Mon)	$ET_0 = \frac{0.408\Delta\ \ R_n - G\ \ + \gamma \frac{900}{T+273} u_2\ \ e_s - e_a}{\Delta + \gamma\ \ 1 + 0.34u_2}$	[21]	Vapour pressure deficit, radiation flux, wind velocity, temperature and soil heat flux.

2.3 Crop coefficient

The concept of K_c was introduced by reference[18] and further developed by the other researchers[5,19-21]. Changes in vegetation and ground cover mean that the crop coefficient K_c varies during the growing period. The trends in K_c during the growing period are represented in the crop coefficient curve. Only three values for K_c are required to describe and construct the crop coefficient curve: the initial stage ($K_{c\ \mathrm{ini}}$), the mid-season stage ($K_{c\ \mathrm{mid}}$) and at the end of the late season stage ($K_{c\ \mathrm{end}}$). Although, crop coefficients vary from day to day, depending on many factors, they are mainly a function of crop growth and development. FAO guidelines are used for calibration of crop coefficients for crop grown in particular agro-climatic region. FAO proposed $K_{c\ \mathrm{ini}}$, $K_{c\ \mathrm{mid}}$ and $K_{c\ \mathrm{end}}$ values are 0.3, 1.15 and 0.4 for Wheat. From reference[21] method used to compute modified $K_{c\ \mathrm{ini}}$, $K_{c\ \mathrm{mid}}$ and $K_{c\ \mathrm{end}}$ values. The results of modified crop coefficient values, magnitude of parameters involved for modification and the modified crop coefficient values for different growth stages summarized in Table 3. Further, daily ET_c is determined as the product of daily K_c value and potential/ ET_0 obtained from different ET_0 model.

Table 3 Modified values of FAO recommended crop coefficients for local conditions

Crop	Crop coefficients								
	$K_{c\ \mathrm{ini}}$			$K_{c\ \mathrm{mid}}$			$K_{c\ \mathrm{end}}$		
	FAO value	Modifying parameters	Modified value	FAO value	Modifying parameters	Modified value	FAO value	Modifying parameters	Modified value
Wheat	0.3	Wetting frequency = 15 days Avg. ET_0 = 1.9 mm/day	0.38	1.15	u_2 = 2.53 m s^{-1} RH_{min} = 51.3 H = 0.64 m	1.18	0.4	u_2 = 2.16 m s^{-1} RH_{min} = 51.1 H = 0.63 m	0.42

2.4 Water balance

Actual ET_c can also be determined by measuring the various components of the soil water balance in lysimeter. The method consists of assessing the incoming and outgoing water flux into the crop root zone over crop period. The water applied to the crop at the soil surface is taken by plant roots, which absorb water and transmit it to the leaves, from where it is lost to the atmosphere as transpiration. Fluxes such as subsurface flow and deep percolation are difficult to assess for short time periods, hence, soil water balance method usually only gives ET_c estimates over long time periods of the order of week-long or ten-day periods[21].

Precipitation (P), irrigation (I_r), and the quantity of water drained off from the bottom of the Lysimeter (D_r), are carefully measured. Runoff component RO is assumed to be insignificant. Changes in soil moisture storage are measured by soil moisture sampling at different depths of the root zone within Lysimeter. The ET_c is computed using the following water balance equation

$$P + I_r = D_r + ET_c + RO + \Delta S \quad (1)$$

where, ΔS is the soil moisture storage change. The change in the soil moisture for the specific depth (d_z) and for the specific time period is computed as:

$$\text{Moisture storage change } (\Delta S_z) = (\theta_{z,\text{final}} - \theta_{z,\text{initial}}) \times d_z \quad (2)$$

where, $\theta_{z,\text{initial}}$ and $\theta_{z,\text{final}}$ are initial and final water content in the soil profile in a discrete time interval. Table 4 presents the pooled data of two-year cumulative and stage wise precipitation, irrigation, deep percolation along with the ET_c computed using water balance for wheat. It is evident from Table 4 that in wheat crop about 50% of ET_c demand (242.7 mm) has been met with irrigation (195 mm).

Table 4 Water balance components for the crops under lysimeter study

Component /mm	Crop stage				Total /mm
	Initial	Development	Mid-season	Late-season	
	wheat				
Precipitation	0	6.8	104.6	1.0	112.4
Irrigation	20	70	35	70	195
Percolation	8.9	17.5	39.5	4.0	69.9
Moisture storage change (ΔS)	-7.6	21.2	-10.5	-8.3	-5.2
Crop ET (ET_c)	18.7	38.1	110.6	75.3	242.7

Drainage type lysimeter (1.5 m deep with a surface area of 1 m^2) was installed in 2009 in an open field to avoid boundary effects and to simulate actual field conditions. The upper 1.3 m of the lysimeter was filled with a loam textured soil, maintaining hydraulic characteristics of soil in layers similar to original field conditions throughout the soil profile. The detail of the lysimeter set-up has been shown in Figure 3.

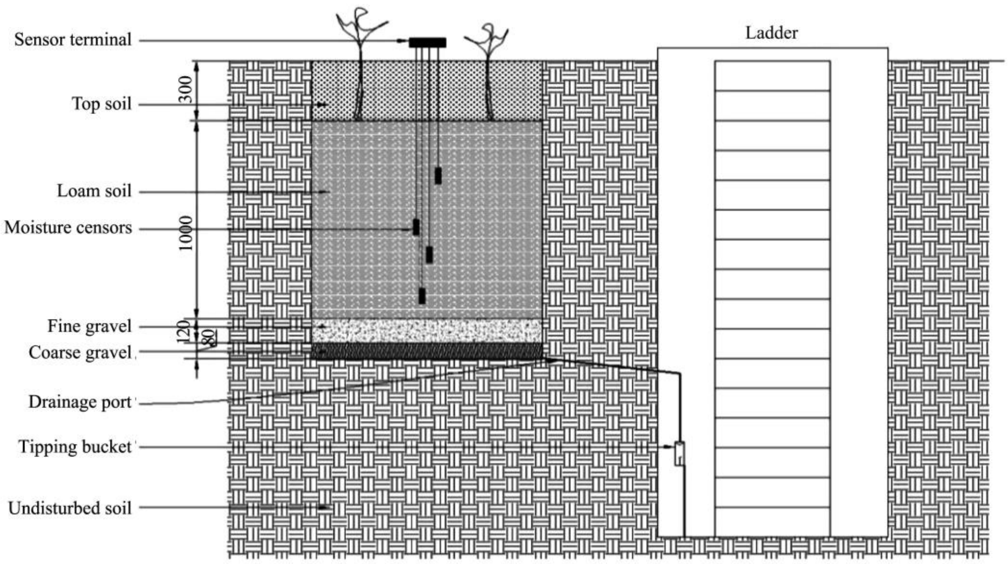

Figure 3 Lysimeter set-up for crop experiment

3 Results and discussion

Depletion of moisture by plant from the root zone is governed by the daily ET_c values. Moisture uptake from root zone is equal to the ET_c. The ET_c estimated by a particular model (product of K_c and ET_0) give the computed ET_c. The ET_c prediction is the basis for assessing the efficiency of different ET_0 models. Actual ET_c for different growth stages of the crop period is obtained by conducting water balance study with lysimeter set-up. The computed and field observed values of ET_c for different stages corresponding to different ET_0 estimation models are compared qualitatively as well as quantitatively.

The qualitative procedure was followed for comparing model predicted and field observed ET_c for different growth stages. To accurately evaluate the methods, the study also follows a quantitative assessment procedure, which involves the use of error statistics which is calculated as[24]:

$$COD = 1 - \frac{\sum_{i}^{n} y_i - \hat{y}_i \;^2}{\sum_{i}^{n} y_i - \bar{y} \;^2} \tag{3}$$

$$SEE = \left[\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n-1} \right]^{0.5} \tag{4}$$

$$ARE = \frac{\sum_{i=1}^{n} \hat{y}_i - y_i}{n|\bar{y}_i|} \tag{5}$$

where, *COD* (coefficient of determination) is coefficient of determination; *SEE* is standard error estimate and *ARE* (average relative discrepancy) is the average relative discrepancy, subscript *i* denotes i^{th} point in the root zone, where moisture content is measured. y_i = Field measured soil moisture content, $\hat{y}_i$ = simulated soil moisture content based on individual method ET_c estimates, $\bar{\hat{y}}$ = average of $\hat{y}_i$, $\bar{y}$ is the average of y_i and n = total number of observation points. A value of COD close to the unity indicates a high degree of association between the observed and simulated values, SEE provides a measure of deviation between computed and observed moisture contents, whereas ARE statistics quantify the extent to which, the computed values overestimate (positive ARE) or underestimate (negative ARE) the measured values[25].

Stage-wise comparison of observed and computed (individual and cumulative) ET_c has been plotted in Figures 4-5. The statistical analyses between observed and computed different ET_0 estimation models based stage-wise ET_c results were summarized in Table 5. It is illustrated in Figures 4-5, that P-T and H-S based values highly overestimate in comparison to field observed values but Fc Pen slightly overestimate. ET_0 estimates obtained, based on P-Mon, F B-C and F E-Pan, underestimate stage wise ET_c for different crop growth stages though, follow the trend of field observed values closely. Cumulative stage-wise ET_c for whole period too, is underestimated by these three methods *i.e.*, P-Mon, F B-C and F E-Pan. For comprehensive evaluation of the agreement between field observed and computed individual stage-wise ET_c, based on different ET_0 values, error statistics of COD, COV and ARE is also computed.

The detailed summary of the statistics error corresponding to different crops is listed in Table 5. The P- M model shows close agreement with COD, SEE and ARE (%) values are 0.96, 13.69 and -5.8, respectively. Although Fc Pen, Fc Pen and F B-C based estimates closely agree with the field observed ET_c values for different crop stages, P-M clearly shows the best agreement among all models.

It can be concluded from results summarized in Table 5 and Figures 4-5 that (i) Different ET_0 models result in predicting different crop water requirement, when used in combination with literature based or locally calibrated crop coefficients. Penman Montieth (P-M) model estimated ET_c gives the most optimal estimate of the crop water requirement of Wheat in sub-temperate and sub-humid agro-climate region of Solan, Himachal Pradesh.

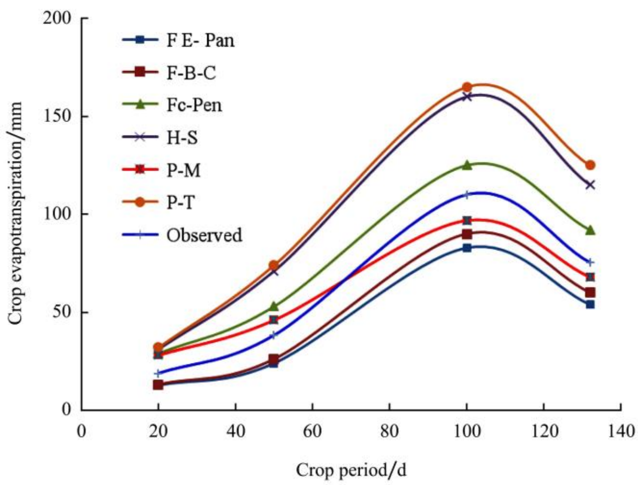

Figure 4 Computed and observed stage-wise crop evapotranspiration for wheat

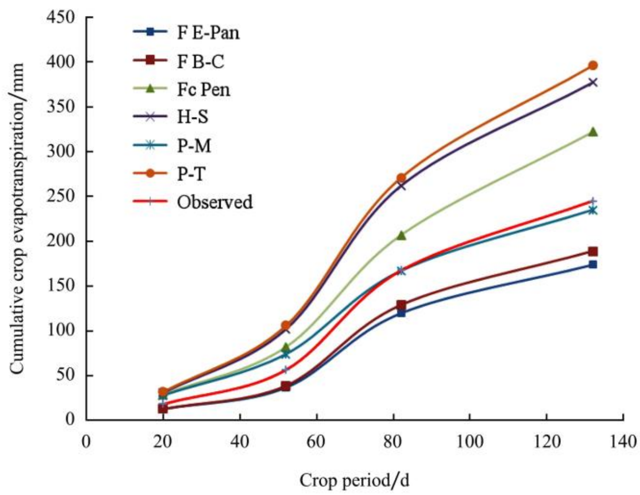

Figure 5 Cumulative and observed stage-wise crop evapotranspiration for wheat

Table 5 Statistical analysis between observed and different ET_0 estimation models based stage-wise crop evapotranspiration

Statistical terms	Reference evapotranspiration method					
	P-M	Fc Pen	P-T	F B-C	H-S	F E-Pan
Wheat						
COD	0.96	0.94	0.63	0.93	0.72	0.92
SEE/mm	13.69	15.38	47.38	17.30	41.25	22.60
ARE/%	-5.80	21.50	62.40	-22.30	54.37	-28.80

Note: *COD*: Coefficient of determination; *SEE*: Standard error estimate; *ARE*: average relative discrepancy.

4 Conclusions

Modeling ET is a difficult task, particularly across a country like India having such a diverse agro-climatic conditions. Results of comparative study of different models have been presented to aid in understanding of the assumptions and limitations. Different most commonly used ET_0 models were tested on the basis climatic data with modified empirical crop coefficient and actual measurements of ET_c. The FAO recommended crop coefficient values are modified for the local agro-climatic conditions. Actual ET_c for different crop growth stages has been obtained from water balance studies using lysimeter set-up. The observed and computed individual-stage wise and cumulative stage-wise ET_c values are compared graphically and statistically to identify the most suitable ET_0 model for computing ET_c. The P-M model estimated ET_c gives the most optimal estimate of the crop water requirement of wheat in sub-temperate and sub-humid agro-climate region of Solan, Himachal Pradesh. Determination of accurate ET_0 motivates researchers to resolve the problem of optimum irrigation scheduling.

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