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Comparative evaluation of different methods to compute evapotranspiration at different phenological stages in wheat

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ABSTRACT

Evapotranspiration of wheat crop was estimated using different methods viz. lysimeter, USDA Open pan evaporimeter, empirical methods, combination approach and soil water evaporation model. The field experiment was conducted during *rabi* 2006-07 and 2007-08 with two weighing type lysimeters located at the research farm, Punjab Agricultural University, Ludhiana. Among different methods of ET estimation, Papadakis method computed highest rate of PET followed by Hamon and modified Penman method whereas modified soil evaporation model, Thornthwaite, Blaney-Criddle and Stephans & Stewart methods produced lower values of PET as compared to lysimeter ET and open pan evaporation. Modified Jensen & Haise method estimated PET values (346 and 361 mm) closest to lysimeter ET (340 and 341 mm) and open pan evaporation (360 and 432 mm) respectively, for two seasons. PET computed by Blaney-Criddle method showed very good correlation with Lysimeter ET (0.90).

Key words: Evapotranspiration, wheat, vapour pressure deficit, lysimeter, empirical methods, crop coefficient

Reliable estimates on evapotranspiration from cropped surfaces are required for efficient irrigation management. With increasing pressure on water resources from competing users, large emphasis has been placed on water use efficiency in irrigated fields (DehghaniSanij *et al*, 2004). In addition to precipitation and irrigation, evapotranspiration also determines soil moisture in upland fields and vegetation productivity is closely related to evapotranspiration rate. To develop more efficient and sustainable water management techniques for arable regions and to better predict actual and potential crop production, it is necessary to evaluate evapotranspiration (Watanabe *et al*, 2004).

Several direct and indirect methods exist to estimate evapotranspiration which include the use of lysimeters, soil water balance and use of empirical formulae. High cost restricts the utility of lysimeters while soil moisture balance method is laborious and time consuming and also needs sophisticated instruments. The evaluation of ET by empirical methods has great appeal because ET is estimated from standard climatological data as input without disturbing the plant and soil and is also a simple and easy technique.

The empirical models hold good at the locations where they are developed. There is no universal consensus on the suitability of any given model for a given climate. These models require rigorous local calibration before they can be used for the estimation of evapotranspiration for irrigation scheduling. The local calibration and validation are more important in semi-arid environment because almost all the ET models were developed, calibrated and validated for temperate environment using reliable and long-term weather data. In most of the assessments in temperate environment, either Penman model or its modified version outperforms the other models when long-term reliable weather data are used for ET estimation. Limited information, however, exists on models performance in semi-arid environment. Further, long-term weather data is scarce in semi-arid environment, for rigorous model calibration and validation. But once such methods are calibrated carefully for a particular location, these can serve as tools to estimate the rate of evapotranspiration. Hence, a critical assessment of this component is desirable to judiciously use water without affecting the potential yields.

MATERIALS AND METHODS

The field experiment was conducted during *rabi* 2006-07 and 2007-08 with two weighing type lysimeters located at the research farm, Punjab Agricultural University, Ludhiana (30^{o} 54’ N latitude, 75^{o} 45’ E longitude and 247 m altitude).

Data on lysimetric evapotranspiration for wheat and different weather parameters viz. mesh covered pan evaporation (mm), maximum and minimum temperatures (^{o}C), relative humidity (%), sunshine hours, wind speed (km/hr) etc. for the period of investigation were recorded from the agrometeorological observatory located near the experimental field. The lysimeter consists of a large steel container (130cm x 120cm x 90cm) welded at all the corners. The steel tank has a perforated metallic plate bottom at 75 cm depth to facilitate free drainage of excess water. The weighing scale has 2000kg capacity with 200 g divisions. The whole apparatus is enclosed in an outer container (140cm x 140cm x 150cm).

Evapotranspiration of wheat crop was computed by using following methods:

I. Lysimetric Method
II. USDA Open Pan Evaporimeter
III. Modified Penman Method
IV. Papadakis Method
V. Thornthwaite Method
VI. Modified Jensen & Haise Method
VII. Blaney - Criddle Method
VIII. Hamon Method
IX. Turc Method
X. Stephens and Stewart Method
XI. Modified soil water evaporation model

I. Lysimetric method

A weighing type lysimeter was used for recording the daily rate of actual evapotranspiration of wheat crop. The water loss was computed as:

1 kg of weight loss = 0.6 mm of water loss

The crop was sown manually on flat surface in lysimeters on the same day when it was sown in rest of the field i.e. on 1st November, 2006 and 5th November, 2007 during first and second crop season, respectively. One lysimter was kept at optimum irrigation level (recommended 4 irrigations after sowing) whereas the other lysimeter was kept at sub-optimal irrigation level (3 irrigations after sowing).

II. USDA open pan evaporimeter

The observation was taken daily in the morning at 8.30 a.m. from the open pan evaporimeter with the help of fixed-point gauge. Water was added to the pan such that top of fixed point gauge just touched the water level. The amount of water added to the pan with the help of graduated cylinder gave the measure of water evaporated. On a rainy day the level of water in the pan rises. Therefore, while calculating the evaporation, rainfall was added to get the accurate amount of evaporation. There were twenty rings marked on the cylinder. Each ring indicated 0.1 mm of evaporation.

III. Modified Penman method

Based on intensive studies of the climate and measured grass evapotranspiration data from various research stations in the world and available literature on PET, Doorenbos and Pruitt (1977) proposed a modified Penman formula. According to the modified Penman formula:

ET_o = $W \times R_n + (1-W) \times f(u) \times (e_a - e_d)$

Where,

ET_o = Unadjusted PET in mm day^{-1}

e_a = Saturation vapour pressure in mb at mean air temperature (^0C)

e_d = Mean actual vapour pressure of the air in mb

$$= \frac{e_a \times RH_{mean}}{100}$$

f(u) = A wind related function

(1-W) = A temperature and elevation related weighting factor for the effect of radiation on PET

R_n = Net radiation (Same as $Q_n = R_{ns} - R_{nl}$)

R_{ns} = Net incoming short wave radiation

= $Q_A \times (1-r) \times (0.25 + 0.50 \times n/N)$

R_{nl} = Net long wave radiation

= $f(t) \times f(e_d) \times f(n/N)$

the values of which are available form the table

To find PET (adjusted), the unadjusted PET is adjusted for day and night time weather conditions with the help of a figure.

IV. Papadakis method

Papadakis model (1965) for computation of daily PET can be written as:

$$PET = \frac{0.5625\,(e_{max} - e_{min-2}) \times 10}{\text{No. of days in month}} \text{ mm day}^{-1}$$

Where,

e_{max} = SVP (mb) at daily maximum temperature

e_{min-2} = SVP (mb) at dew point temperature

0.5625 = Papadakis constant

Saturation vapour pressure can be calculated from temperature from the following formula:

e_s = $0.61078 \exp(17.269\,T / (T + 237.3))$

where,

T = Temperature (^oC)

V. Thornthwaite method

Thornthwaite (1948) put forth the concept of potential evapotranspiration. According to him, the amount of water lost by evaporation and transpiration from soil surface covered with vegetation is governed by climatic factors and is independent of species when moisture supply is not limiting. It is obtained by the relationship:

$$PET = \frac{k \times e \times 10}{\text{No. of days in month}} \text{ mm day}^{-1}$$

$e = 1.6\,(10T / I)^{a}$

Where,

e = unadjusted PET in cm per month

T = Mean monthly air temperature (^{o}C)

I = Annual or seasonal heat index. It is the summation of twelve values of monthly heat indices 'i'

$i = (T/5)^{1.514}$

a = empirical exponent

k = adjustment factor

$a = 0.000000675\, I^{3} - 0.0000771\, I^{2} + 0.01792\, I + 0.49239$

VI. Modified Jensen and Haise method

Clyma and Chaudhary (1975) gave the following modified version of Jenson and Haise (1963) method for computation of PET:

$PET = 0.012\,(T - 15.4)\, R_{s}$

Where,

T = Mean Temperature in ^{0}F

R_{s} = Solar Radiation in water equivalent (mm day^{-1})

VII. Blaney-Criddle method

Blaney criddle (1950) proposed the following method for the estimation of daily PET:

$PET = (0.0173\, T_{A} - 0.314)\, K_{c}.T_{A}\, (DL / 4465.6) \times 25.4$ mm day^{-1}

Where,

T_{A} = Mean air temperature in ^{o}F

K_{c} = Crop coefficient

DL = Day Length

VIII. Hamon method

For estimation of daily PET, Hamon (1963) method is given as:

$PET = 0.0055\,(DL/12)^{2}\,(AH \times 2.88) \times 25.4$

Where,

PET = Daily potential evapotranspiration in mm

DL = Day Length

AH = Absolute humidity in mm^{-3}

$= 217 \times \frac{e_{d}}{T}$

Where,

e_{d} = Actual vapour pressure (mb)

T = Mean air temperature in degree absolute

IX. Turc method

Turc proposed the following method (McGuinness and Bordne, 1972) for the calculation of daily potential evapotranspiration:

$$PET = \frac{0.40 \times T_{c}\,(TI + 50)}{(T_{c} + 15)\text{ no. of days in month}} \text{ mm day}^{-1}$$

where,

T_{c} = Air temperature in ^{o}C (Mean)

RI = Solar radiation in ly

X. Stephens and Stewart method

Stephens and Stewart (1963) gave the following formula for the computation of PET:

$PET = (0.0082\, T_{A} - 0.19)\,(RI/1500) \times 25.4$ mm day^{-1}

Where,

T_{A} = Mean air temperature in ^{o}F

RI = Solar radiation in ly day^{-1}

XI. Modified soil water evaporation model (Jalota and Arora, 2002)

Jalota and Arora (2002) modified a model of Jalota *et al* (2000) by including transpiration component for assessing daily water balance under cropped soils. In the model,evaporation from the USWB Class A pan was taken as potential evapotranspiration (PET). It provided an upper bound of ET rate in non-advective environments. The PET was then partitioned between potential transpiration (T_m) and potential soil water evaporation (E_m) through green canopy factor (K_t) as follows:

$$T_m = PET \times K_t$$

$$E_m = (1-K_t) \times PET$$

Green canopy factor (K_t) is obtained from the information on progressive leaf area index (LAI) as:

$$K_t = 0.9 \quad (LAI/3.0)^{0.5}$$

The model was employed for assessing water balance components in cropped soils as well as bare soil during intervening periods within a given cropping system.

RESULTS AND DISCUSSION

Lysimeter studies

This technique yields a measurement of total water loss and is useful as an indicator of field water loss, provided suitable precautions are taken. Rates of evapotranspiration measured with lysimeters in wheat crop during *rabi* 2006-07 and 2007-08 are presented in table 1. The evapotranspiration rates in the lysimeters increased gradually with the growth of the crop and reached a maximum value of above 3 mm day^{-1} during the grand growth period and decreased as the crop approached maturity and senescence. As the treatments included different irrigation levels, so one lysimeter received optimal (I4) and the other received sub-optimal (I3) irrigation level. The crop seasonal ET was found to be 339.7 mm and 290.7 mm for the lysimeters with optimal (I_4) and sub-optimal (I_3) irrigation level, respectively during 2006-07 with daily ET rate of 2.2 and 1.9 mm day^{-1} with the same lysimeters. Whereas during 2007-08, the crop season ET was 341.2 and 337.9 mm in the lysimeter with optimal and sub-optimal irrigation levels, respectively. A daily ET rate of 2.1 mm was observed during second crop season for both the lysimeters. Vaughan *et al* (2007) also used weighing lysimeters to make direct measurements of water loss from a growing crop and the soil surface around a crop (evapotranspiration), and thus, provided basic data to validate other ET prediction methods. Daily ET_o predictions were in good agreement with daily lysimeter ET_o measurements for ET_o < 6 mm d^{-1} but tended to be smaller when ET_o > 6 mm d^{-1}.

USDA open pan evaporimeter

The rate of evaporation recorded with USDA open pan evaporimeter has been presented in table 1. The total evaporation for the crop season was found to be 360.3 mm and 432.3 mm with a daily rate of 2.3 and 2.7 mm day^{-1} during 2006-07 and 2007-08, respectively. Frequent rains during first year might have decreased the rate of evaporation due to weak vapour pressure gradient under moist conditions. Among different phenological stages of the crop, the rate of evaporation was found to be highest during soft dough to physiological maturity of the crop during both the years as the temperature increased during the month of March onwards.

Combination approach

The cumulative PET for the growing period of wheat crop and daily rate of PET computed from modified Penman method (combination approach) has been presented in table 1. This method computed cumulative PET of 478 and 517 mm during first and second year, respectively. The daily rate of PET was found to be 3.0 mm for first year and 3.2 mm for the second year. Daily PET rate was highest from soft dough to maturity of the crop during both the years.

Empirical methods

The rates of cumulative PET (mm) and daily rates of PET (mm day^{-1}) computed from different empirical methods have been presented in table 2. Papadakis method computed a cumulative PET of 532 mm and 598 mm during first and second crop season, respectively. Similarly, Thornthwaite method computed 200 and 228 mm, Blaney-Criddle method 196 and 184 mm, Hamon method 518 and 531 mm, modified Jensen and Haise method 346 and 361mm, Stephans and Stewart method 179 and 188 mm and Turc method 288 and 295 mm during first and second crop season, respectively. Almost all the empirical methods produced comparatively higher PET rates during *rabi* 2007-08 than *rabi* 2006-07 except for Blaney-Criddle method, which computed higher PET rate during first crop season.

Lower PET rates during rabi 2006-07 by most of the empirical methods might be due to higher amount of moisture in air as a result of higher amount of rainfall (152 mm) during this period. Papadakis method computed a mean daily PET rate of 3.4 and 3.7 mm day^{-1} for whole crop season during 2006-07 and 2007-08, respectively. Similarly, Thornthwaite method computed 1.3 and 1.4 mm day^{-1}, Blaney-Criddle method 1.2 and 1.1 mm day^{-1}, Stephans and Stewart method 1.1 and 1.2 mm day^{-1} and Turc method 1.6 and 1.8 mm day^{-1} during 2006-07 and 2007-08, respectively. Modified Jensen and Haise method computed PET rate of 2.2 mm day^{-1} and Hamon method computed 3.3 mm day^{-1} each during both years of study. Kingra *et al* (2002) reported that PET computation by various methods was biased and this bias was positive when pan evaporation was low and negative

Table 1: Computation of cumulative and daily rate of actual evapotranspiration, pan evaporation and potential evapotranspiration in wheat during 2006-07 and 2007-08

Growth stage	Lysimeter I (I_4*)		Lysimeter II (I_3*)		USDA Open pan evaporimeter		Combination approach	
	Cumulative PET (mm)	Daily PET rate (mm day^{-1})	Cumulative PET (mm)	Daily PET rate (mm day^{-1})	Cumulative PET (mm)	Daily PET rate (mm day^{-1})	Cumulative PET (mm)	Daily PET rate (mm day^{-1})
				2006-07				
Sowing – Crown Root Initiation	32.6	1.3	25.3	1.0	52.3	2.0	72.0	2.8
Crown Root Initiation – Tillering	18.3	1.5	16.2	1.4	21.1	1.8	25.8	2.2
Tillering – Jointing	51.5	1.7	35.4	1.2	40.5	1.4	58.4	1.9
Jointing – Flag leaf emergence	76.4	2.8	46.7	1.7	48.9	1.8	60.0	2.2
Flag leaf emergence – Flowering	60.3	3.0	68.2	3.4	31.3	1.6	51.3	2.6
Flowering – Soft dough	64.9	3.2	66.5	3.3	54.7	2.7	74.1	3.7
Soft dough – Maturity	42.7	1.7	35.7	1.4	119.5	4.8	136.1	5.4
Sowing – Maturity	339.7	2.2	290.7	1.9	360.3	2.3	477.8	3.0
			2007-08					
Sowing – Crown Root Initiation	31.1	1.2	32.2	1.3	51.9	2.1	67.0	2.7
Crown Root Initiation – Tillering	20.0	1.7	19.8	1.7	17.1	1.4	23.3	1.9
Tillering – Jointing	75.4	2.4	69.9	2.2	50.5	1.6	59.4	1.9
Jointing – Flag leaf emergence	48.6	2.0	47.6	2.0	39.3	1.6	49.9	2.8
Flag leaf emergence – Flowering	32.0	1.5	35.3	1.6	56.7	2.6	64.9	2.9
Flowering – Soft dough	73.4	3.7	68.7	3.4	71.1	3.6	88.4	4.4
Soft dough – Maturity	60.7	2.2	64.4	2.3	145.7	5.2	158.6	5.9
Sowing – Maturity	341.2	2.1	337.9	2.1	432.3	2.7	516.7	3.2

* I_4 refers to four post-sowing irrigations and I_3 refers to three post-sowing irrigations

Table. 2: Computation of cumulative and daily rate of potential evapotranspiration from empirical methods in wheat during 2006-07 and 2007-08

Growth stage	Papadakis method		Thornthwaite method		Blaney-Cri method
	Cumulative PET (mm)	Daily PET rate (mm day^{-1})	Cumulative PET (mm)	Daily PET rate (mm day^{-1})	Cumulative PET (mm)
Sowing – Crown Root Initiation	108.2	4.1	51.3	2.0	23.5
Crown Root Initiation – Tillering	32.7	2.7	8.5	0.7	11.9
Tillering – Jointing	78.3	2.6	14.4	0.5	29.9
Jointing – Flag leaf emergence	85.5	3.2	15.4	0.6	41.1
Flag leaf emergence – Flowering	50.3	2.5	16.7	0.8	34.9
Flowering – Soft dough	58.9	2.9	23.2	1.2	34.9
Soft dough – Maturity	136.2	3.4	79.9	3.2	20.1
Sowing – Maturity	531.7	3.4	199.6	1.3	196.2
Sowing – Crown Root Initiation	112.9	4.5	39.9	1.6	20.2
Crown Root Initiation – Tillering	33.4	2.8	8.8	0.7	14.8
Tillering – Jointing	82.6	2.6	14.3	0.4	45.1
Jointing – Flag leaf emergence	49.4	2.1	6.1	0.3	24.0
Flag leaf emergence – Flowering	68.1	3.1	15.2	0.7	15.3
Flowering – Soft dough	100.5	5.0	48.2	2.4	36.6
Soft dough – Maturity	151.3	5.4	95.6	3.4	27.8
Sowing – Maturity	598.3	3.7	228.1	1.4	183.8

Table. 3: Correlation coefficient between evaporation measured by open pan evaporimeter, evapotranspiration estimated by lysimeter and potential evapotranspiration for wheat crop during *rabi* 2006-07 and 2007-08

Method		Correlation coefficient	
		2006-07	2007-08
Lysimeter ET vs.	Open pan evaporation	0.20	0.10
	Thornthwaite PET	0.29	0.10
	Papadakis PET	0.33	0.0
	Hamon PET	0.06	0.30
	Modified Penman PET	0.19	0.10
	Blaney Criddle PET	0.88	0.90
	Modified Jensen & Haise PET	0.15	0.20
	Stephans & Stewart PET	0.17	0.17
	Turc PET	0.16	0.17
Open pan evaporation vs.	Lysimeter ET	0.20	0.10
	Thornthwaite PET	0.70	0.90
	Papadakis PET	0.80	0.80
	Hamon PET	0.60	0.70
	Modified Penman PET	0.90	0.90
	Blaney Criddle PET	0.30	0.10
	Modified Jensen & Haise PET	0.90	0.90
	Stephans & Stewart PET	0.90	0.90
	Turc PET	0.90	0.90

when pan evaporation was on the higher side as most of the methods over-estimated PET for winter months and under-estimated for summer months. But they found these methods important tools to estimate the rate of PET from pan evaporation and hence for irrigation scheduling of various crops.

Modified soil water evaporation model

Evapotranspiration from wheat crop during both the seasons was also computed by using modified soil water evaporation model (Jalota and Arora, 2002). This model computed potential evapotranspiration of 217 mm during *rabi* 2006-07 and 244 mm during *rabi* 2007-08.

Comparison of ET estimated by various methods

Lysimeter recorded cumulative ET of 339.7 mm and 341.2 mm during 2006-07 and 2007-08, respectively. Similarly, USDA open pan evaporimeter recorded 360.3 mm and 432.3 mm, combination approach 477.8 mm and 516.7 mm and modified soil evaporation model recorded 217.0 mm and 244.0 mm during first and second year, respectively. PET computed by empirical methods showed a great variation as the input weather parameters vary in different methods. Papadakis method computed PET of 531.7 mm and 598.3 mm during 2006-07 and 2007-08, respectively. Similarly, Thornthwaite method computed 199.6 and 228.1 mm; Blaney-Criddle method 196.2 and 183.3 mm; Hamon method 518.4 and 531.4 mm; modified Jensen and Haise method 345.6 and 361.1 mm; Stephans and Stewart method 179.3 and 187.8 mm and Turc method recorded a PET of 288.2 and 295.4 mm during *rabi* 2006-07 and 2007-08, respectively. All the methods computed higher rates of ET during second year than first year except for Blaney-Criddle method, which computed slightly higher PET during *rabi* 2006-07 than that during *rabi* 2007-08.

Correlation studies

Correlation was also studied between open pan evaporation, lysimeter ET and PET computed by different methods (Table 3). PET computed by Blaney-Criddle method showed a very good correlation with lysimeter ET (0.90), whereas other methods did not show good correlation during both the years. In case of correlation with open pan evaporation, lysimeter ET and Blaney-Criddle PET showed least correlation with open pan evaporation, whereas all other methods showed a very good correlation in both the years. Singh (1987) also observed a very good correlation between open pan evaporation and PET computed by different methods for wheat crop, but lower value of correlation coefficient was observed between lysimeter ET and PET as well as open pan evaporation. Rahman *et al* (2008) also reported non-significant correlation between open pan evaporation and lysimeter ET of wheat crop.

ET requirement of wheat at different phenological stages

A study of ET requirement of wheat at different phenological stages indicates that crop water requirement is less during initial growth stages of the crop i.e. up to tillering, but as leaf area index of the crop increases rapidly, the water requirement of the crop increases from jointing to flowering and soft dough stage and again decreases afterwards as the crop approaches senescence and maturity. A comparison of lysimeter ET, open pan evaporation and modified Penman PET also indicates that during initial crop growth stages lysimteter ET is less as compared to open pan evaporation and modified Penman PET, but during rapid increase in leaf area index of the crop, lysimter ET increases as compared to other methods and as the crop approaches senescence and maturity, again lysimeter ET is lower than open pan evaporation and modified Penman PET (Table 1 & 2). The results indicate that when the canopy is not fully developed the rate of water loss is controlled by atmospheric demand and not by the crop.

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