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9. ABSTRACT

To estimate the consumptive use of various crops using climatic data, a summary of the procedure for determining evapotranspiration after calibrating the Jensen-Haise equation is as follows: 1) Determine mean daily temperature (T) from daily maximum and minimum temperatures for the season and region under consideration. 2) Convert the corresponding radiation values to equivalent depth of evapotranspiration in inches/day (R_s) using the relation Langleys/day x 0.000673 = inches/day. 3) Substitute the values of T and R_s in the equation, calibrated for that region and compute potential evapotranspiration, E_{tp}. 4) Actual evapotranspiration E_t can be obtained by combining E_{tp} with K_c in equation. Since plants have very poor cover just after planting, E_t is much less than E_{tp}. However the two values tend to approach each other as the crop grows. When plants are assumed to have attained full effective cover and K_c approaches 1, E_t and E_{tp} are nearly the same until maturation begins. During maturation the two curves diverge since E_t goes down because of reduced photosynthetic activity and/or a limited supply of water.

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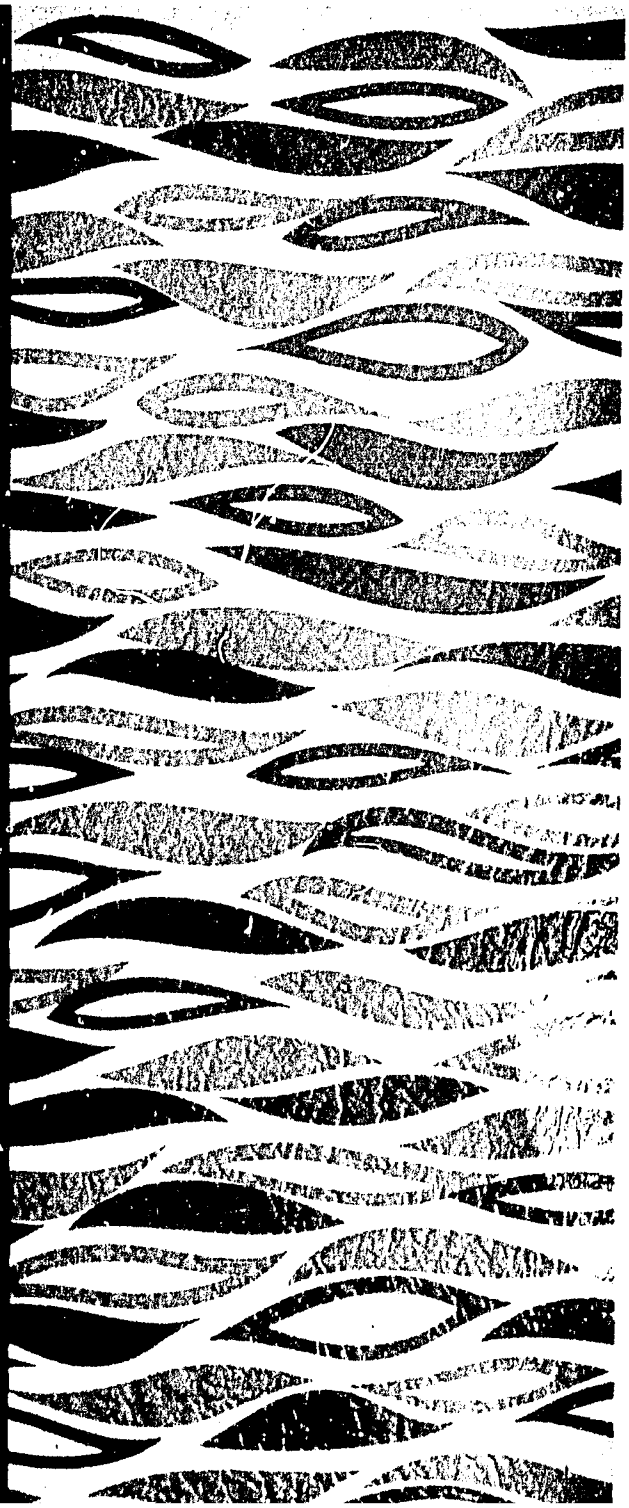
CALIBRATION AND APPLICATION OF THE JENSEN-HAISE EVAPOTRANSPIRATION EQUATION

by Wayne Clyma and
M. Rafiq Chaudhary

Colorado State University
Fort Collins, Colorado
March 1975



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CALIBRATION AND APPLICATION OF THE JENSEN-HAISE EVAPOTRANSPIRATION EQUATION

Wayne Clyma[1] and M. Rafiq Chaudhary[2]

This paper presents the procedure for calibration and application of the Jensen-Haise (1963) evapotranspiration equation to estimate the consumptive use of various crops using climatic data i.e. maximum and minimum temperatures, solar radiation and rainfall; and crop coefficients as given by Jensen (1972).

Jensen and Haise (1963) developed an empirical radiation equation for estimating daily potential evapotranspiration from a well-watered reference crop such as alfalfa in the form:

$$LE = \phi_1 R_s \tag{1}$$

where

LE = the latent heat of vaporization and represents daily evaporative flux in Cal/cm^2/day.

ϕ_1 = the radiation coefficient

R_s = the solar radiation in Langleys/day.

Estimates of evaporative flux in Cal/cm^2/day can be converted to equivalent depth of evaporation, E_{tp}, in inches/day and solar radiation in Langleys/day to inches/day using 585 Cal/cm^3 of water as the heat of vaporization. Jensen and Haise (1963) and Jensen (1966) showed that

$$\phi_1 = C_T (T - T_x) \tag{1a}$$

and therefore equation (1) has been presented in the form:

$$E_{tp} = C_T (T - T_x) R_s \tag{2}$$

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where

E_{tp} = the potential evapotranspiration for reference crop in inches/day.

C_T = the air temperature coefficient which is constant for a given area and is derived from long-term mean maximum and mean minimum temperatures for the month of highest mean air temperature.

T = mean daily air temperature

T_x = a constant for a given area and is merely the linear equation intercept on the temperature axis in the solar radiation - air temperature relationship.

R_s = the daily solar radiation expressed as the equivalent depth of evaporation (in./day)

Jensen (1966) has shown that when properly calibrated, equation (2) can give estimates of evapotranspiration that are of the same amplitude and in phase with measured values.

Calibration of the Equation. One of the limitations of any empirical equation for estimating evapotranspiration is that its constants may not be applicable in other climatic regimes without calibration. Equation (2) contains solar radiation as the major climatological factor and the magnitude of deviation of daily solar radiation from long-term mean has been found to be different for different locations (Jensen 1966). Therefore it was concluded that calibration of the equation may be necessary to assure its accuracy when used under climatic conditions that are significantly different from those under which the equation was derived.

Since Pakistan has two distinct seasons, arid or dry and monsoon or wet, the equation should be calibrated separately for the two climates. As recommended by Jensen and Haise (1963) and Jensen (1966), the month with maximum temperature is used to calibrate the equation for the arid months (September through June) while August is the month of maximum effect of the monsoon for July and August. Monthly mean maximum and mean minimum temperatures for Sargodha obtained from 10 years of record (1963 to 1972) and average solar radiation in terms of equivalent depth of water (in.day) for 5 years of record are shown in Table 1.

Equation (2) primarily needs the determination of two constants C_T and T_x for estimating potential evapotranspiration for a given region and climate. When accurate climatological data are available, these can be derived by

Table 1. Average monthly maximum and minimum temperatures and solar radiation for sargodha.

Month	Max. Temp. °F	Min. Temp. °F	Mean Temp. °F	Solar Radiation in./day
January	68	38	53.0	0.17
February	72	45	53.5	0.21
March	82	54	68.0	0.27
April	92	63	77.5	0.32
May	100	71	85.5	0.44
June	107	80	93.5	0.33
July	102	81	91.5	0.30
August	98	79	88.5	0.29
September	96	74	85.0	0.28
October	92	63	77.5	0.24
November	81	51	66.0	0.19
December	72	41	56.0	0.16

Source: Original data obtained from WAPDA, Water and Soils Investigation Division, Surface Hydrology Project; Annual reports of River and Climatological Data of West Pakistan.

calibration. C_T can be estimated from temperature data during the month of maximum mean air temperature using:

$$C_T = \frac{1}{C_1 + C_2 C_H} \tag{3}$$

where C_1 = 68 - 3.6E/1000 for T in degrees Farhenheit (4a)

or C_1 = 38 - 3.6E/1000 for T in degrees Centigrade (4b)

in which E = the elevation of the area in feet above mean sea level

C_2 = 13°F or 7.3°C depending on the temperature scale used

C_H = the humidity index and can be calculated by means of the following expressiong:

$$C_H = \frac{37.5 \text{ mm } H_g}{e_{s2} - e_{s1}} \tag{5a}$$

or

$$C_H = \frac{50 \text{ mb}}{e_{s2} - e_{s1}} \tag{5b}$$

where

e_{s2} = the saturation vapour pressure in millibars at the mean maximum air temperature during the warmest month.

e_{s1} = the saturation vapour pressure at mean minimum air temperature during the same month.

T_x can be computed from the expression:

$$T_x = 27.5°F - 0.25\,(e_{s2} - e_{s1})\ °F/mb - \frac{E}{1000} - °F \tag{6}$$

~~in which~~ E has the same definition as given already.

To illustrate the procedure, sample calculations for determining the constants of the evapotranspiration equation applicable for the arid season at Sargodha are as follows:

Mean maximum temperature for the month of June = 107 °F = 41.7°C

Mean minimum temperature for the month of June = 80°F = 26.7°C

From a table of saturated vapor pressure versus temperature for water:

$$e_{s2} = 80.730 \text{ mb}$$

$$e_{s1} = 35.025 \text{ mb}$$

From equation (5b):

$$C_H = \frac{50}{80.730 - 35.025} = 1.093$$

$$C_1 = 68 - 3.6 \times \frac{E}{1000}$$

where $E = 600$ ft. for Sargodha

Therefore $C_1 = 68 - 3.6 \times \frac{600}{1000}$

$$= 65.84$$

and $C_2 = 13$

Substituting the values of C_1, C_2 and C_H in equation (3), we get:

$$C_T = \frac{1}{65.84 + 13\ (1.093)}$$

or $C_T = 0.012$

Entering the values of e_{s1}, e_{s2} and E as given above, equation (6) gives:

$$T_x = 27.5 - 0.25\ (80.731 - 35.025 - \frac{600}{1000}$$

or $T_x = 15.4\ °F$

Thus computed values of constants C_T and T_x when combined in equation (2) result in

$$E_{tp} = 0.012\ (T - 15.4)\ R_s \qquad (7)$$

which is the calibrated equation for the arid season for Sargodha. Similarly the equation calibrated for monsoon climate is

$$E_{tp} = 0.011\ (T - 19.9)\ R_s \qquad (8)$$

The estimated monthly evapotranspiration for Sargodha using equations (7) and (8) are presented in Table 2.

Table 2. Mean monthly potential evapotranspiration for Sargodha using mean monthly temperature and solar radiation from Table 1.

Month	Mean Daily in./day	Monthly in.	Accumulated in.
January	0.08	2.5	
February	0.11	3.5	5.6
March	0.18	5.6	11.2
April	0.24	7.2	18.4
May	0.30	9.3	27.7
June	0.32	9.6	37.3
July	0.24	7.4	44.7
August	0.23	7.1	51.8
September	0.24	7.2	59.0
October	0.19	5.9	64.9
November	0.12	3.6	68.5
December	0.08	2.5	71.0

Evapotranspiration

Potential evapotranspiration estimated through equation (2) is, in practice, limited by the factors of stage of crop growth and soil moisture conditions. Therefore, an estimate of actual evapotranspiration (consumptive use) can be obtained from:

$$E_t = K_c \cdot E_{tp} \qquad (9)$$

where K_c is a dimensionless coefficient and represents the combined effects of the resistance of water movement from the soil to various evaporating surfaces in the atmosphere and the relative amount of radiant energy intercepted as compared to a reference crop. These factors are affected by surface soil moisture conditions and the stage of growth of the crop. Lower rates of evapotranspiration occur during early stages of growth when the root system is not fully developed and the plants have reduced leaf area or do not effectively cover the ground. Evapotranspiration increases to the potential value of 100 percent effective cover and K_c approaches 1.0 or sometimes even greater than 1.0 in case of aerodynamically very rough surfaces, thus causing actual E_t to be greater than the potential value obtained from equation (2). During the maturation stage, a reduction in the evapotranspiration rate takes place. The photosynthetic processes slow and then cease as maturation progresses reducing E_t and therefore the value of K_c decreases with the number of days after initiation of the maturation stage (Figure 1). Maturation may be initiated by the crop growth habits, temperature (frost), or moisture stress.

Table 3 presents a summary of crop coefficients (K_c) for a number of crops experimentally determined by Jensen (1972). Part (a) shows the values of the crop coefficient from planting to effective cover. Equation (9) for estimating consumptive use, requires the crop coefficients K_c for each individual day or interval of days of the growing season instead of percent of effective cover. Therefore, conversion of K_c values from percent effective cover to corresponding number of days is required. In part (b) the coefficients are given directly for the number of days after the beginning of the maturation stage and the values for individual days can be obtained by a simple linear interpolation. Wheat was selected as the example crop to illustrate the computation of evapotranspiration estimates and K_c from Table 3 is also plotted in Figure 1.

Evaluation of K_c

In our example wheat is considered to acquire 100 percent effective cover in 95 days, but the actual time depends upon

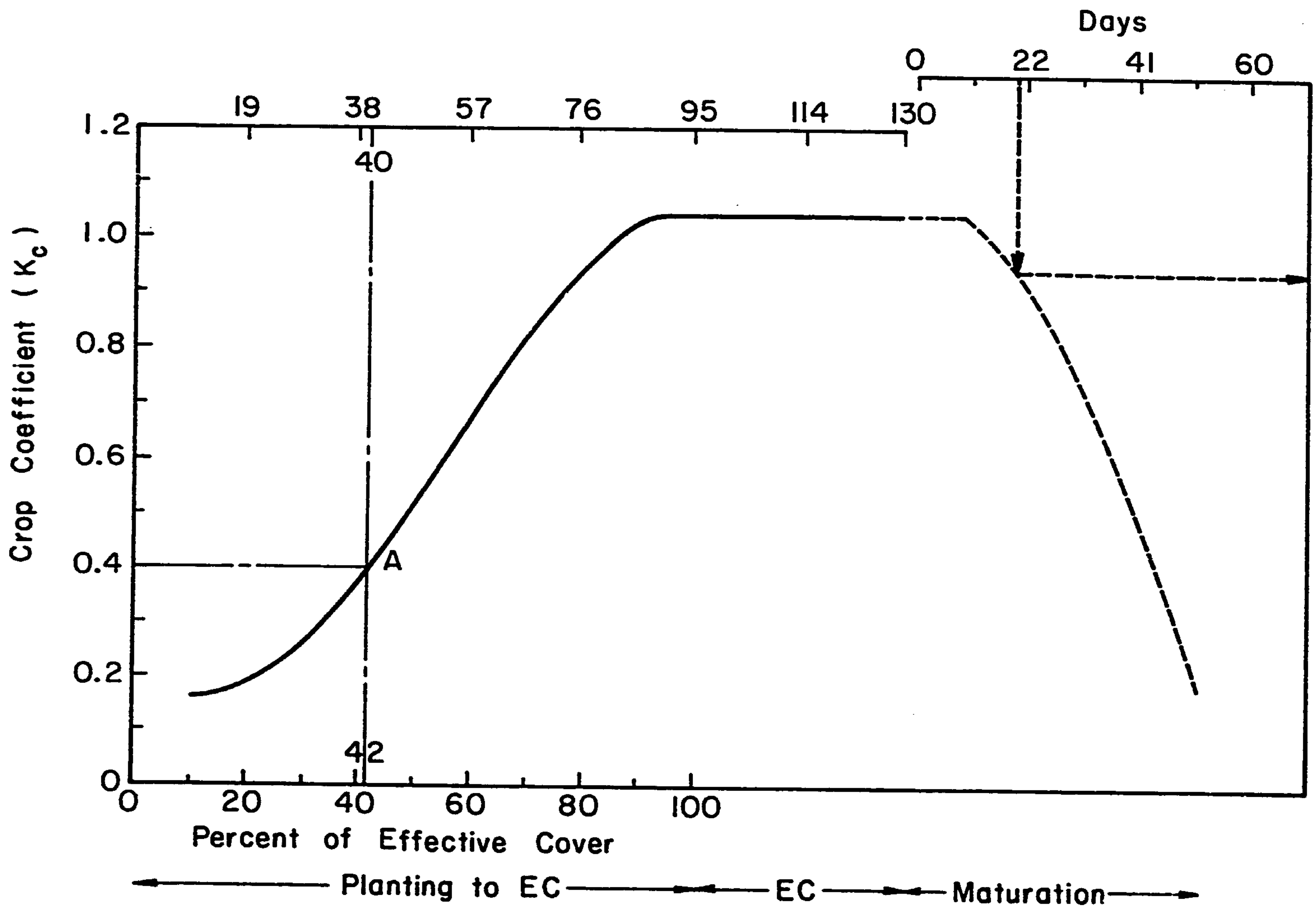

Figure 1. Plot of K_c versus percent of effective cover (EC) and number of days after effective cover for wheat showing the method of evaluation of K_c for individual day of growing season.

the planting date, variety and weather. The values of the coefficient, K_c, for wheat in Table 3 (a) are given for percent of time to effective cover and need to be adjusted for 95 days so that K_c for an individual day may be determined. This is accomplished by converting the day number for which K_c is desired to percent of time to effective cover (PEC) by:

$$PED = (n_x \frac{100)}{95} \qquad (10)$$

As an example, K_c for 40th day after planting can be determined by first finding the corresponding percent of time to effective cover:

$$PED\ 940) = 40 \times \frac{100}{95}$$

$$= 42\ PCT$$

The value of K_c for 42 percent for wheat obtained by linear interpolation from Table 3 is 0.4. Therefore, K_c for 40th day would be 0.4. The K_c value for 95 day after sowing would be that given for 100 percent effective cover and the effective cover period would continue until maturation begins. This period for wheat in this example is from February 3 to March 11 when the maturation stage begins.

The method has been simplified graphically by giving the time scale of 0 to 95 days at the top for the X-axis in Figure 1 and the 0 to 100 percent effective cover at the bottom for the plot of K_c versus percent effective cover. This provides the conversion of number of days to percent effective cover and values for K_c are read directly. K_c for the 40th day is found by drawing a vertical line from the 40th day to meet the plotted curve at A and then extending parallel to the X-axis, reading $K_c = 0.4$ on the Y-axis. Thus, K_c for each day from planting to 100 percent effective cover can be obtained from Figure 1, as explained above.

It can be observed from Table 3 that K_c values for a maturation period of 35 days (from March to April 15) are given directly for the number of days after effective cover instead of percent. Therefore, it requires only linear interpolation between given K_c values for assigning them to each individual day. However in Figure 1 this is shown by a dotted curve with a displaced top right X-axis and K_c can be read directly as indicated by the arrow.

K_c values for two segments of the growing season of wheat, December 10 to December 21, 1970, from planting to effective cover and March 20 to April 1, 1971 for maturation period obtained from Figure 1, are given in Table 4.

Table 3. Values of crop coefficients (K_c) for different crops as determined by Jensen (1972)

(a) For Period from Planting Effective Cover

Crop	Percent of time to Effective Cover									
	10	20	30	40	50	60	70	80	90	100
Cotton	0.15	0.16	0.22	0.31	0.45	0.63	0.81	0.96	1.01	1.01
Small grains	0.16	0.18	0.25	0.37	0.51	0.67	0.82	0.94	1.02	1.04
Beans	0.20	0.23	0.30	0.39	0.51	0.63	0.76	0.88	0.98	1.07
Peas	0.20	0.24	0.31	0.40	0.51	0.63	0.75	0.87	0.97	1.05
Potatoes	0.10	0.13	0.20	0.30	0.41	0.53	0.65	0.75	0.85	0.91
Sugar Beets	0.10	0.13	0.20	0.30	0.41	0.53	0.65	0.75	0.85	0.91
Corn	0.20	0.23	0.29	0.38	0.49	0.61	0.72	0.82	0.91	0.96
Alfalfa	0.36	0.47	0.58	0.68	0.79	0.90	1.00	1.00	1.00	1.00
Pasture	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87

(b) For maturation period

Crop	Days after Effective Cover									
	10	20	30	40	50	60	70	80	90	100
Cotton	0.98	0.93	0.86	0.77	0.66	0.54	0.40	-	-	-
Small grains	1.04	0.94	0.74	0.49	0.19	0.10	0.10	0.10	0.10	0.10
Beans	1.02	0.96	0.85	0.73	0.59	0.45	0.31	0.19	0.10	0.10
Peas	0.98	1.02	0.99	0.76	0.20	0.10	0.10	0.10	0.10	0.10
Potatoes	0.90	0.85	0.75	0.60	0.38	0.10	0.10	0.10	0.10	0.10
Sugar Beets	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Corn	0.99	0.99	0.93	0.82	0.68	0.54	0.40	0.28	0.20	0.17
Alfalfa	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Pasture	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87

Table 4.

(a) Planting to Effective Cover

Date	Day after Planting	Corresponding PEC	K_c
Dec. 10, 73	40	42	0.40
11	41	43	0.41
12	42	44	0.43
13	43	45	0.44
14	44	46	0.45
15	45	47	0.47
16	46	48	0.48
17	47	50	0.51
18	48	51	0.53
19	49	52	0.55
20	50	53	0.56
21	51	54	0.58

(b) Maturation Period

Date	No. of days after effective cover	K_c
March 20, 1973	8	1.04
21	9	1.04
22	10	1.04
23	11	1.03
24	12	1.02
25	13	1.01
26	14	1.00
27	15	0.99
28	16	0.98
29	17	0.97
30	18	0.96
31	19	0.95
April 1	20	0.94

It seems important to mention at this point that the length of the two periods for wheat in our example (effective cover and maturation) have been selected for the Sargodha area may not be applicable to other areas of Pakistan. For evaluating K_c for each day of a given crop and region it is necessary to observe carefully the locally prevailing lengths of these periods. Moreover the K_c values for various crops given in Table 3 are as observed in the U.S.A. and the applicability of these values need to be determined for Pakistan.

Crops like cotton, peas and potatoes, etc. behave almost the same as wheat with regard to K_c as affected by effective cover. Some crops, e.g. fodder crops, sugar beets and sugarcane which continue receiving irrigation and therefore maintain 100 percent effective cover until they are harvested, have no maturation period. Therefore, K_c remains essentially constant after effective cover has been achieved as can be observed from Table 3. However, maize and oats behave either like wheat or like fodder depending on whether it is harvested for grain or fodder. K_c values for each day of the growing season, obtained through the method outlined above, can be combined with equation (9) to determine actual daily evapotranspiration for a given crop.

<u>Summary</u>

A summary of the procedure for determining evapotranspiration after calibrating the Jensen-Haise equation is as follows:

1. Determine mean daily temperature (T) from daily maximum and minimum temperatures for the season and region under consideration.

2. Convert the corresponding radiation values to equivalent depth of evapotranspiration in inches/day (R_s) using the relation Langleys/day x 0.000673 = inches/day.

3. Substitute the values of T and R_s in the equation, calibrated for that region and compute potential evapotranspiration, E_{tp}.

4. Actual evapotranspiration E_t can be obtained by combining E_{tp} with K_c in equation (9). Table 5 showing computed E_{tp} and E_t for the month of December in 1967 for Sargodha has been added as an aid to the explanation of the procedure given above.

Monthly potential and actual evapotranspiration for the wheat season (1967) at Sargodha are presented in Figure 2. Just after planting since plants have very poor cover, E_t is much less than E_{tp}. However, the two values tend to approach each other as the crop grows and after about the 3rd of

February, when plants are assumed to have attained full effective cover and K_c approaches 1, E_t and E_{tp} are near the same until maturation begins. During maturation the two curves diverge since E_t reduces because of reduced photosynthetic activity and/or a limited supply of water.

Table 5. Potential and actual evapotranspiration for the month of December, 1967 (Rabi) at Sargodha

Date	Max Temp °F	Min Temp °F	Mean Daily Temp °F	Solar Radiation Lang/day	Solar Radiation in/day	E_{tp} in/day	K_c	E_t in/day
1	75	45	60	367	0.247	0.130	0.29	0.038
2	76	46	61	85	0.057	0.131	0.30	0.009
3	62	48	55	141	0.095	0.044	0.31	0.014
4	64	46	55	282	0.190	0.089	0.32	0.028
5	65	45	55	268	0.180	0.084	0.33	0.028
6	68	42	44	296	0.198	0.093	0.35	0.033
7	70	42	56	311	0.210	0.100	0.36	0.036
8	70	40	55	311	0.210	0.098	0.37	0.036
9	69	42	56	226	0.150	0.072	0.38	0.027
10	68	47	58	113	0.76	0.038	0.40	0.015
11	69	47	58	198	0.130	0.065	0.41	0.027
12	70	46	58	198	0.130	0.065	0.43	0.028
13	72	47	60	141	0.095	0.050	0.44	0.022
14	71	42	57	282	0.190	0.093	0.45	0.042
15	73	40	57	282	0.190	0.093	0.47	0.044
16	75	39	57	282	0.190	0.093	0.48	0.045
17	73	39	56	268	0.180	0.086	0.51	0.044
18	72	40	56	311	0.210	0.101	0.53	0.054
19	70	41	56	198	0.130	0.062	0.55	0.034
20	68	44	56	184	0.124	0.059	0.56	0.033
21	64	43	54	325	0.220	0.100	0.58	0.058
22	73	44	59	99	0.067	0.035	0.60	0.021
23	68	49	59	85	0.057	0.039	0.62	0.018
24	60	52	56	71	0.048	0.023	0.63	0.015
25	59	51	55	198	0.130	0.067	0.65	0.044
26	64	51	58	42	0.028	0.014	0.66	0.092
27	61	50	56	212	0.140	0.067	0.67	0.045
28	64	46	55	339	0.230	0.107	0.68	0.073
29	63	43	53	85	0.070	0.031	0.70	0.022
30	60	40	40	254	0.070	0.069	0.72	0.050
31	66	39	53	254	0.170	0.075	0.73	0.055
TOTAL								1.130

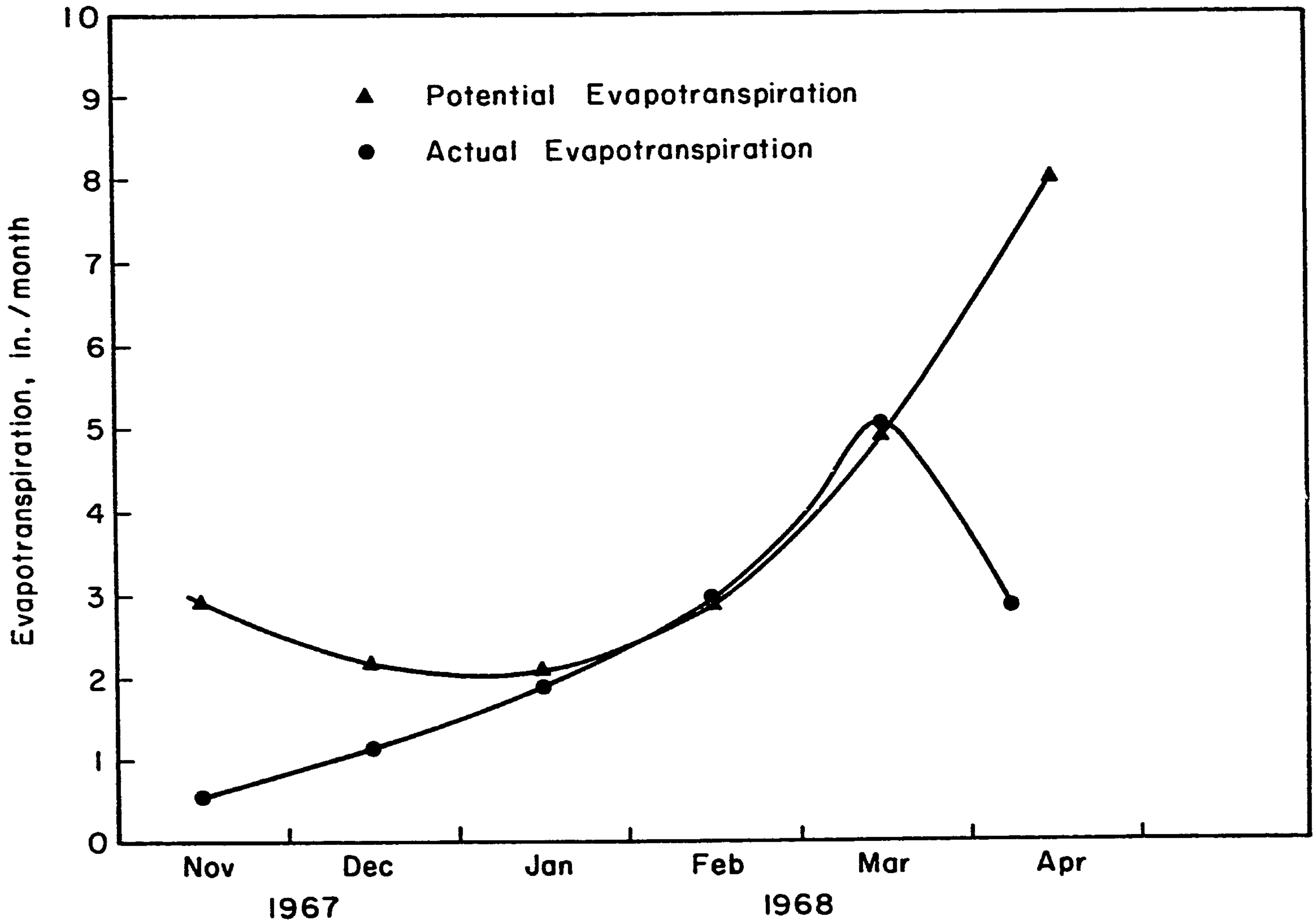

Figure 2. Monthly potential and actual evapotranspiration for wheat 1967-68, Sargodha.

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