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Climatic variations and crop irrigation requirements*

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ABSTRACT

Irrigation requirements are probabilistic in nature due to random nature of rainfall and evapotranspiration. A water balance procedure in which rainfall and evapotranspiration are considered as stochastic variables is considered. Box and Cox transformation and normal distribution were applied to estimate weekly rainfall and evapotranspiration. Total probability theorem and leaky law of probability was applied for handling zero data in rainfall and evaporation data. Siddeek and Azahar procedures were compared to estimate weekly irrigation requirements for *kharif* groundnut crop. It is very interesting to note that Siddeek procedures give conservative estimates of irrigation requirements for arid regions than Azahar approach. This is because, for a particular probability of irrigation requirement, the probability of evaporation demand is less than Azahar estimates as rainfall is very less. The cumulative irrigation requirements were fitted with Pearl Reed model and Gompertz model. Forecasting accuracy of Gompertz model was better than Pearl Reed model.

Key Words : Probability, Box-Cox transformation, normal distribution, irrigation requirements.

Efficient management of rainfall is only possible by designing and operating the system to capture the maximum amount of rainfall without affecting the crop and retaining in the field. This also means adjusting irrigation schedules in such a way as to take into consideration the expected rainfall. The irrigation requirements are not deterministic, and can assume any value. Each value is associated with a probability level and is to be interpreted in a probabilistic sense. The system can be operated at higher and lower probability levels during moisture sensitive and less sensitive periods. Researchers used various combinations of rainfall and evaporation probabilities like 60 percent rainfall, 40 percent evapotranspiration, 70 percent rainfall and 30 percent evapotranspiration, and 80 percent and 20 percent etc to estimate irrigation requirements at different probability levels. The difficulty with this approach is that for a particular probability of irrigation water requirements what should be the respective probabilities of rainfall and evaporation is not known.

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Siddeek *et al.* (1988) developed a procedure for estimating probabilistic irrigation requirements for low land rice cultivation. Later on, Azahar *et al.* (1992) developed another procedure, which yield conservative estimates of irrigation water requirements than Siddeek. In this study Siddeek and Azahar procedures were compared to estimate irrigation water requirement at various reliability levels for *kharif* groundnut. Description of these two approaches is presented below.

MATERIAL AND METHODS

Distribution fuctions for irrigation requirements

a. Sidduk et al. (1988) approach

Irrigation scheduling is essentially governed by the net irrigation requirements, which in turn is obtained through a water balance relationship. The water balance equation is expressed as:

$$W_j = W_{j-1} + RF_j - ETA_j + IR_j \qquad (1)$$

where j = time period index; W_j = moisture level at the end of the period j; W_{j-1} = initial moisture status for the period j; RF_j = rainfall during the period j; ETA_j = actual evapotranspiration during the jth period; IR_j = irrigation in the j th period. The irrigation requirements need the value of rainfall and evapotranspiration as input variable. The actual crop evapotranspiration is expressed as:

$$ETA = ETM \quad \text{for } ASM_j \geq (1\text{-}p)\ MSM \qquad (2a)$$

$$= \{ASM_j * ETM\} / [(1\text{-}p)\ MSM \quad \text{for } ASM_j \leq (1\text{-}p)\ MSM \qquad (2b)$$

$$p = EXP(-0.1184\ ETM - 0.0309) \qquad (2c)$$

$$ETM = K_c\ EV_j \qquad (2d)$$

$$EV_j = K_p\ E_{pan} \qquad (2e)$$

where ETM = crop evapotranspiration; MSM and ASM represent maximum and actual (at period j) available soil moisture; p = fraction of total available soil water when actual evapotranspiration (ETA) equals potential crop evapotranspiration (ETM). The values of p for different crops and rate of potential evapotranspiration are listed by Doorenbos and Kassam (1979). A regression equation was developed to the table values of p for groundnut and is presented in eq. 2c. K_p = Pan coefficient; EV = crop evapotranspiration; K_c = Crop coefficient. The models for pan coefficient (Snyder 1981) and groundnut crop coefficient (Subbaiah 2000b) is given by

$$K_p = 0.482 + 0.024 \ln(F) - 0.000376\ U + 0.0045\ H \qquad (3)$$

$$K_c = \Sigma\ Aj\ D^{j-1} \qquad (4)$$

where, $A_0 = 0.451$; $A_2 = 0.0419$; $A_3 = 0.315 \times 10^{-2}$; $A_4 = 0.765 \times 10^{-4}$; $A_5 = 0.118 \times 10^{-5}$ $A_6 = 3.841 \times 10^{-6}$; $A_7 = 0.226 \times 10^{-10}$; D = Days from the date of sowing. The good ness of fit and standard error for the above equation (4) is found to be 0.962 and 0.13. The maximum requirement of crop irrigation is expressed as:

$$IR_j = K_c\ EV_j - RF_j - W_{j-1} \qquad (5)$$

In (5), IR_j may be negative which

indicate zero requirements. By using the estimates of $(K_c\ EV_i\ -\ RF_i)^*$ for various probability levels net irrigation requirements can be determined. Let A, R and H are the probability distribution functions of evapotranspiration (EV_i), rainfall (RF_i) and irrigation requirement (IR_i), respectively.

$$A(x) = P\,(EV_i \le x) \quad (6)$$

$$R(r) = P\,(Rf_i \le r) \quad (7)$$

$$H(z) = P\,(IR_i \le z) \quad (8)$$

By combining equation (8) with equation (5) H(z) may be expressed as

$$H(z) = P(IR_i \le z) = P\,[(K_c\,EV_i - RF_i) \le z] \quad (9a)$$

$$H(z) = P\,[\,EV_i \le (z + RF_i / K_c)\,] \quad (9b)$$

Considering the Fig (1), the event ($K_c\ EV_i \le a$ and $RF_i \ge b$) is contained by the event ($K_c\ EV_i - RF_i \le a\text{-}b$). Therefore assuming the EV_i and RF_i to be statistically independent, we may write

$$P\,(K_c\,EV_i \le a)\,.\,P\,(RF_i \ge b) \le P\,(K_c\,V_i - RF_i \le a\text{-}b) \quad (10)$$

Using eq. (9a), $H(u) \ge P\,(K_c\,EV_i \le a)\,.\,P\,(RF_i \ge b) = A\,(a/K_c)\,(1\text{-}R(b))$ (11)

where, u = a – b. Since for the normal distribution the probability mass after the mean ± 3 standard deviations becomes negligible. The best results can be obtained using eq. (11) if a sound probability distribution is selected for both the rainfall and evapotranspiration data series. Since the numerical values of $A\,(a/K_c)$ and R (b) can be estimated easily using standard normal tables, a lower bound for H(u) can be computed without any difficulty. For a given value of H(u) there may be many combinations for the values of $A(a/K_c)$ and [1- R(b)] that satisfy equation (11). Siddeek *et al.* (1988) used a combination in which both the values of $A(a/K_c)$ and [1 - R(b)] were taken equal to the square root of a given value of H(u). For instance for H(u) = 81 % this combination yields $A(a/K_c)$ = 90 % and [1 - R(b)] = 90 %. However, this combination gives very conservative estimates of expected rainfall. Since in planning and operation of large irrigation systems the objective is to save irrigation water as much as possible but within economical limits, a combination that contributes towards relatively more water savings is desirable.

b. Azahar et al. (1992) approach

Let D_1, D_2, D_3, D_4, D_5 and D_6 be the probability domains of joint probability region for rainfall and evaporation as shown in the (Fig. 1).

$$D_1 = [\,1 - A(a/K_c)]\,R(b) \quad (12)$$

$$D_2 + D_3 = [\,1 - A(a/K_c)]\,[1\text{-}R(b)] \quad (13)$$

$$D_4 = A\,(a/K_c)\,[\,1 - R(b)] \quad (14)$$

$$D_5 + D_6 = A(a/K_c)\,R(b) \quad (15)$$

$$H(u) = D_4 + D_3 + D_5 \quad (16)$$

For non-exceedence and exceedence probabilities of $K_c E_v$ [i.e. $A(a/K_c)$] and RF [i.e. 1 –R(b)],

$$D_3 + D_5 > D_2 + D_6 \quad (17)$$

Addition of eq.13 and eq. 15 gives

$D_2 + D_3 + D_5 + D_6 = 1 - A(a/K_c) - R(b) + 2 A(a/K_c) R(b)$ (18)

And by using (17), the following equation is obtained.

$D_3 + D_5 > (D_2 + D_3 + D_5 + D_6 / 2) = [1 - R(b) / 2] - [A(a/K_c) / 2] + [A(a/K_c)R(b)]$ (19)

Substituting (14) and (19) in (16)

$H(u) = D_4 + D_3 + D_5 = A(a/K_c)[1-R(b)] + [1 - R(b)/2] - [A(a/K_c)/2] + [A(a/K_c)R(b)]$

$= [A(a/K_c)/2] + [1 - R(b)/2]$

$H(u) \geq [A(a/K_c)/2] + [1 - R(b)/2]$ (21)

Equation (21) gives a combination for the values of $A(a/K_c)$ and $[1-R(b)]$ in which the same values for $A(a/K_c)$ and $[1-R(b)]$ can be chosen as given for H(u). According to this equation, for a value of H(u) = 81 percent, a value of 81 % will be assigned to both the $A(a/K_c)$ and $[1-R(b)]$. This approach gives relatively less conservative estimates for the expected rainfall than the approach proposed by Siddeek *et al.* (1988). The above distribution function needs the data i.e. rainfall and evaporation to follow normal distribution. Most of the hydrological and climatological data are highly skewed and the normal distribution does not provide a good fit to a set of observations. It is often convenient to seek the normalization by transformation in order to utilize the simple properties of the normal distribution function. Out of many transformations most widely accepted is Power (Box-Cox, 1964) transformation (Azahar *et al.* 1992; Subbaiah, 2000). Leaky law of probability along with power transformation is adopted to handle zero values in rainfall series. Discussion on application of these transformations with total probability theorem and leaky law of probability to normal distribution is given by Subbaiah (2000a).

Growth models

Two growth models mainly Pearl Reed model and Gompertz model were fitted to compute the cumulative irrigation requirements

a. Pearl Reed model

The model in simplest form can be expressed as:

$$Y_c = K / (1 + e^{a+bx}) \quad (22)$$

Where, Y_c = Cumulative rainfall deficit, x = Standard week and K, a, b = Model constants. To fit the data in the model 'Selected Point Method' (Frederic et al. 1982) is used which requires choosing three equidistant points on the time scale x_0, x_1 and x_2; near the beginning, middle and end respectively. The corresponding values of Y are designated as Y_0, Y_1 and Y_2. The month or week corresponding to x_0 is taken as origin. The time variable x and the position of origin may be defined by x = x-c. Here, x = Week or month number, c = Number of week or month where x is taken. The values of the constants are obtained by using the following relationships:

$$K = [Y_1^2 (Y_0 - Y_2) - 2Y_0Y_1Y_2] / [Y_0Y_2 - Y_1^2] \quad (23)$$

$$a = \ln (K - Y_0 / Y_0) \quad (24)$$

$$b = 1/N \ln [Y_0(K-Y_1) / Y_1 (K-Y_0)] \quad (25)$$

where, N = number of months or weeks from x_0 to x_1 or from x_1 to x_2

b. Gompertz model

The equation for the Gompertz model is expressed as:

$$Y_c = Ka^{b^x} \quad (26)$$

Which may be put in logarithmic form as: $\log Y_c = \log k + (\log a) b^x$ (27)

The fitting of the Gompertz model is logarithms of the absorbed data and may be accomplished in manner exactly paralleling the fit of the modified exponential. The expression is

$$b^N = (\Sigma_3 \log Y - \Sigma_2 \log Y) / (\Sigma_2 \log Y - \Sigma_1 \log Y) \quad (28)$$

$$\log a = (\Sigma_2 \log Y - \Sigma_1 \log Y) (b-1) / (b^N-1)^2 \quad (29)$$

$$\log k = 1/N [\Sigma_1 \log Y - (b^N-1 / b-1) \log a] \quad (30)$$

If it is desired to obtain the value of k without first computing log a and b, use

$$\log k = \frac{[(\Sigma_1 \log Y)(\Sigma_3 \log Y) - (\Sigma_2 \log Y)^2]}{N[\Sigma_1 \log Y + \Sigma_2 \log Y - 2\Sigma_2 \log Y} \quad (31)$$

where, Y = Predicted cumulative rainfall deficit, N = Number of weeks from x_0 to x_1 or from x_1 to x_2 and a and b = Model constants.

RESULTS AND DISCUSSION

Daily rainfall data for 43 years (1957-1999) and evaporation data for 21 years (1980 -2000) were collected from meteorological observatory situated at Gujarat Agricultural University, Junagadh. The performance of power transformation in modifying the skewness and kurtosis is presented in Table: 1. It is clear that in all weeks skewness has been brought to near the recommended limit as compared to the other transformations. The mean and the standard deviation of C_s were 0.088 and 0.267 and for kurtosis coefficient 2.6347 and 1.0899 respectively. Adopting the James (James 1982) transformation for normal probability paper the transformed variates obtained from Power transformations were plotted on a ordinary graph paper and the slope (m), intercept (C) and regression coefficient (r) for each week were determined. (Table 1). This linear equation can be adopted to determine rainfall availabilities at different return intervals for various weeks. Power transformation was also unable to normalize data series having a very high standard deviation even though there were no zeros present. This leads to the conclusion that power transformation is effective only for data series that do not have many zeros and are moderately dispersed, which is again difficult to meet in case of weekly rainfall. The situation of getting too many zeros in rainfall data can be visualized during 23, 24 and 40 standard weeks. The Leaky law, which also accounts for the zeros present in the original data, provided the best results

Table 1: Estimates of rainfall and evaporation data of *kharif* season for Junagadh

Item	Data	Variable	Standard Weeks																	
			23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Rainfall	Historical	Mean (mm)	21.25	23.84	75.21	70.68	77.50	87.70	103.03	69.55	57.82	60.22	82.73	23.16	51.73	30.47	24.68	25.63	12.01	10.60
	Date	SD (mm)	51.26	41.17	225.99	115.31	91.36	110.81	116.48	101.87	76.20	95.82	235.49	34.51	106.72	40.24	42.93	49.87	17.56	27.02
		C_s	3.874	2.145	5.590	3.104	1.419	1.126	1.265	1.545	2.365	2.477	5.410	2.805	3.906	1.946	3.147	3.100	1.400	3.200
		C_k	20.01	7.104	35.30	15.16	4.981	5.615	4.073	9.610	10.10	8.810	33.09	11.62	19.21	5.724	14.74	12.86	3.820	12.83
	Trans	λ	0.01	0.13	0.20	0.26	0.35	0.32	0.34	0.28	0.31	0.21	0.22	0.31	0.24	0.32	0.25	0.01	0.16	0.01
	formed	C_s	0.442	0.00	-0.05	0.013	0.002	0.00	0.00	0.043	0.035	0.078	0.034	0.005	0.00	0.024	0.036	0.000	0.009	1.08
		C_k	1.365	1.419	3.205	2.131	2.040	2.546	2.187	3.289	2.938	4.301	5.532	2.743	3.286	2.04	2.195	1.168	1.415	2.35
	Linear	C	-12.7	4.81	8.53	10.70	14.77	14.15	15.95	11.26	11.36	8.48	8.83	7.95	8.93	9.13	6.97	1.28	4.07	-0.36
	Regression	M	76.98	10.28	9.79	11.06	12.71	11.46	12.39	9.13	8.97	6.38	7.69	8.00	9.00	9.40	8.47	82.82	8.51	0.61
		r	0.755	0.869	0.943	0.955	0.946	0.968	0.975	0.956	0.955	0.948	0.961	0.957	0.943	0.939	0.799	0.866	0.870	0.67
Evapo-	Historical	Mean (mm)	8.85	8.08	6.29	6.12	6.04	5.22	4.00	4.17	4.07	3.57	3.50	3.68	3.83	4.15	3.95	4.50	4.49	5.04
ration	Data	SD (mm)	2.51	2.73	2.62	2.66	2.53	1.77	2.21	1.97	2.14	1.42	1.25	1.43	1.22	1.39	1.46	1.39	1.30	1.25
Data		C_s	-1.86	-1.49	-0.91	-0.71	-0.21	-0.38	-0.08	-0.49	0.67	0.98	-0.16	-0.10	0.62	-0.27	-0.48	-0.29	0.12	1.05
		C_k	9.01	5.50	3.48	3.46	3.15	5.29	3.04	3.03	5.52	7.04	5.56	3.01	3.63	3.89	3.29	4.13	3.65	4.03
	Trans	λ	1.89	2.43	1.82	1.45	1.01	1.08	0.93	1.26	0.69	0.53	0.99	0.80	-0.17	1.05	1.30	1.08	0.64	-1.85
		C_s	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19	-0.18	-0.19	-0.18	-0.18	-0.18	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19
		C_k	4.538	2.995	2.787	2.717	3.140	4.895	3.054	2.729	4.740	5.781	5.574	3.093	2.874	3.799	3.260	4.106	3.564	2.81
	Linear	C	51.66	58.04	29.77	16.31	8.31	6.99	5.28	7.55	3.96	2.11	3.96	3.64	1.47	5.13	6.57	5.72	3.42	0.52
	Regression	M	29.34	37.48	21.35	11.51	5.43	4.00	4.23	5.67	2.94	0.66	2.52	2.36	0.55	3.09	4.43	3.27	1.60	2.25
		r	0.964	0.995	0.973	0.981	0.999	0.942	0.973	0.986	0.952	0.942	0.955	0.984	0.983	0.979	0.988	0.980	0.954	0.96

Table 2: Irrigation requirements (mm) of groundnut cultivar using Siddeek and Azahar procedures

Week	Procedure	Probability levels (%)								
		10	20	30	40	50	60	70	80	90
23	Azahar Siddeek	22.25 22.78	24.15 21.47	- -	- -	- -	- -	- -	- -	- 9.15
24	Azahar Siddeek	5.16 8.95	8.84 9.80	9.73 19.73	11.36 18.70	- -	- -	- -	- -	- 0.00
25	Azahar Siddeek	0.00 4.71	0.00 9.36	5.94 21.10	11.50 19.42	21.91 17.52	20.07 15.28	17.71 12.20	14.19 6.75	5.82 0.00
26 to 33	Azahar Siddeek	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00
34	Azahar Siddeek	10.06 7.20	8.59 5.71	7.38 4.51	6.28 3.38	5.11 2.22	3.81 0.99	2.36 0.00	0.48 0.00	0.00 0.00
35 & 36	Azahar Siddeek	1.03 0.00	0.25 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00
37	Azahar Siddeek	6.59 5.78	6.24 5.12	5.82 4.55	5.38 3.89	4.86 3.11	4.20 2.20	3.20 0.88	1.74 0.00	0.00 0.00
38	Azahar Siddeek	0.00 0.76	0.00 1.93	2.18 20.33	4.75 18.76	21.09 17.19	19.39 15.45	17.33 13.34	14.64 10.61	10.25 6.04
39	Azahar Siddeek	13.40 12.94	15.30 12.47	13.74 19.83	14.13 18.40	20.60 16.97	18.98 15.45	17.10 13.75	14.82 11.65	11.37 8.50

when tested to fit the weekly rainfall series. The Kolmogorov-Smirnov test showed that this law could fit 98 % of the data. Similar procedure was duplicated for the evaporation data for kharif season. The mean and standard deviation of skewness coefficient were 2.85 and 0.986 and for kurtosis coefficient 5.25 and 1.212. These results (Table 1) indicate the non-adaptability of normal distribution directly to kharif evaporation series. The James transformation was also applied to the evaporation data and the values of slope, intercept and regression coefficient was determined (Table 1).

Irrigation requirements

Nearly 96 % of rainfall occurs from June to September. For attaining maximum water use efficiency, the vegetative and

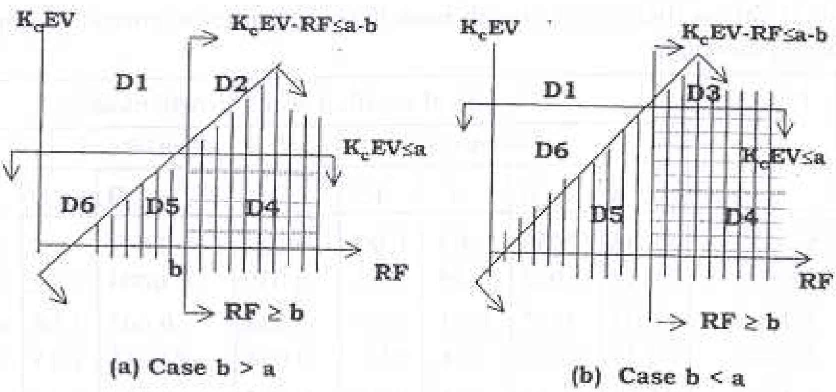

Fig. 1 : Joint probability region for evaporation and rainfall

reproductive growth stages of groundnut should synchronize with July and late September and the ripening periods with the drier months. Although it is desirable to begin land preparation during June, farmers do not necessarily adhere to a fixed schedule. Therefore the proposed method should be flexible enough to estimate irrigation requirements for varying land preparation data. For calculating the irrigation requirements at various probability levels, the onset weeks were varied. This is because of varied availability of crop period with probability of assurance. Subbaiah (2000b) recommended that for probabilities 10 to 40 % the onset weeks should be considered as 23rd and 24th standard weeks respectively. For other probability levels, 25th standard week was recommended as the initial week.

The weekly irrigation requirements for groundnut were estimated at various probability levels using Siddeek as well as Azahar approaches (Table2). The results reflect that irrigation is needed during 23rd and 24th standard weeks at low probability levels (i.e. at 10 % and 20 % probability levels). This is mainly due to the scanty amount of rainfall received during these two weeks. The rainfall values were found to be extremes during these two weeks. At all probability levels, the Irrigation requirements from 26th to 33rd standard weeks as well as 35th and 36th standard weeks were found to be zero. The total requirements of irrigation water for groundnut at 50 % and 80 % were found to be 73.57 mm and 45.87 mm for Siddeek procedure and 57.01 mm and 29.01 mm for Azahar procedure. Based on the actual values of irrigation requirements for groundnut crop the Azahar procedure is suggested for real time prediction of irrigation requirements for groundnut at various probability levels.

Growth models

These estimated irrigation requirements (Table 2) were fitted with

Table 3: Empirical coefficients of growth models for irrigation requirements (mm) of *kharif* groundnut

Probability level (%)	Procedure	Empirical coefficients of growth models							
		Gompertz				Pearl Reed			
		A	B	C	R^2	A	B	C	R^2
10	Siddeek	23.35	1033	1.07	0.99	0.023	0.013	0.8	0.97
	Azahar	26.15	1.002	1.49	0.78	0.039	-0.0004	1.32	0.75
20	Siddeek	60.05	0.52	0.93	0.97	0.038	-0.007	1.08	0.94
	Azahar	30.24	1.014	1.28	0.91	0.034	-0.0015	1.15	0.90
30	Siddeek	25.30	1.33	1.08	0.95	0.012	0.021	0.92	0.95
	Azahar	13.91	1.011	1.39	0.90	0.075	-0.0022	1.26	0.60
40	Siddeek	20.63	1.53	1.06	093	0.014	0.021	0.92	0.93
	Azahar	18.08	1.067	1.20	0.89	0.076	-0.0204	1.07	0.89
50	Siddeek	17.51	1.00	1.85	098	0.059	-0.0007	1.32	0.96
	Azahar	21.80	1.001	1.65	0.95	0.046	-0.0001	1.52	0.85
60 0.96	Siddeek	15.26	1.00	2.00	0.96	0.07	-0.000086		1.55
	Azahar	20.04	1.001	1.72	0.95	0.05	-0.0001	1.52	0.78
70	Siddeek	-	-	-	-	-	-	-	-
	Azahar	17.68	1.0	1.79	0.94	0.0015	0.15	0.87	0.66
80	Siddeek	-	-	-	-	-	-	-	-
	Azahar	14.18	1.00	2.21	0.89	0.07	0.00	2.12	0.62

Gompertz and Pearl Reed models. The constants A, B and C for these two models for cumulative rainfall deficits for Siddeek and Azahar along with the coefficient of determination and per cent average absolute deviation are presented in Table 3. The Gompertz model give more reliable results than Pearl Reed model. Hence in the present effort, Gompertz model is recommended for predicting the cumulative rainfall deficits at various probability levels. The values of A, B and C for Gompertz and Pearl Reed model could not be obtained at 70 %, 80 % and 90 % assurance levels for irrigation requirements estimated through Siddeek approach. This is mainly because the data was not synchronizing with the characteristics recommended for Gompertz and Pearl Reed model. Similarly the constant values could not be obtained for 90 % probability levels for irrigation requirements value obtained through Azahar procedures.

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