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On the global solar radiation climate and evapotranspiration estimates in India

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ABSTRACT. Constants a and b are worked out utilizing the available data for 17 radiation stations in India for estimating the average monthly global radiation (Q_s) received at any low elevation station in India from the average monthly solar radiation received outside the atmosphere (Q_A) and the actual hours of bright sunshine (n) at the station, using the relation $Q_s = Q_A\,[a + b(n/N)]$ where N = possible hours of bright sunshine. It is suggested that partitioning the Radiation Network by Thiessen's mean method, use can be made of these constants to form estimates of global radiation for any place in India, which compare well with the average global radiation estimates formed from the clear day radiation values and hours of bright sunshine. The importance of global radiation in estimating the pan evaporation from meteorological factors is discussed and computations of the monthly values of pan evaporation for 9 stations located in different Agroclimatic Zones of India for one year are presented to demonstrate the practical applicability of the method suggested for estimating the Q_s values for our country.

1. Introduction

Development of improved methods for estimating evapotranspiration from meteorological parameters is of prime importance to many agrometeorological investigations and particularly to the agroclimatic studies of droughts. Penman (1948) was the first to derive, through a combination of the aerodynamic and energy balance approaches, an equation free from water surface temperature and relating the evaporation rates to the standard meteorological data, *viz.*, mean air temperature, mean dew point temperature, mean wind velocity and mean daily duration of sunshine. The last parameter is required to form the energy balance estimate. Penman (1948) also showed that "evaporation rates from wet bare soil and from turf with an adequate supply of water are obtained as fractions of that from open water, the fraction from turf showing a seasonal change attributed to the annual cycle of length of day light". Very extensive work which it is impossible to adequately mention here has since been done in respect of correlating the measured evapotranspiration rates from lysimeters to the evapotranspiration calculated by various methods in respect of different crops. Eagleman (1967) in a recent study concluded that "average yield of corn, soyabeans and wheat were obtained when total precipitation during the growing season averaged 72 per cent of the maximum evapotranspiration".

Among the methods which have come to be recognized as useful for estimating evapotranspiration we have Penman's method, Graphical Coaxial Technique (developed by Kohler, Nordenson and Fox 1955) and McIlroy method.

(1) *Peman's Method*—The generally accepted current definitive form of the equation (Cocheme and Franquin 1967, Penman 1956) is —

$$E = [\triangle / \gamma \{ (1-r)\, Q_A \; (0 \cdot 18 + 0 \cdot 55\, n/N) - \sigma T^4 (0 \cdot 56 - 0 \cdot 092 \sqrt{e_d})(0 \cdot 10 + 0 \cdot 90\, n/N)\} + 0 \cdot 35\,(e_a - e_d)(0 \cdot 5 + u/100)\,] \div (\triangle/\gamma + 1)$$

where,

- $\triangle$ = slope of the temperature *versus* saturation vapour pressure characteristic for water at mean surface temperature T,
- γ = psychrometric constant,
- e_a = saturation vapour pressure,
- e_d = actual vapour pressure,
- r = surface reflectivity,
- n = actual hours of sunshine,
- N = total possible hours of sunshine,
- Q_A = radiation received outside the atmosphere and
- u = mean daily wind travel.

The first part of the numerator, the energy budget (within middle brackets) estimates net radiation by subtracting the amount of energy reflected back into space from the incoming global radiation. It may be mentioned here that the magnitude of the global radiation is generally

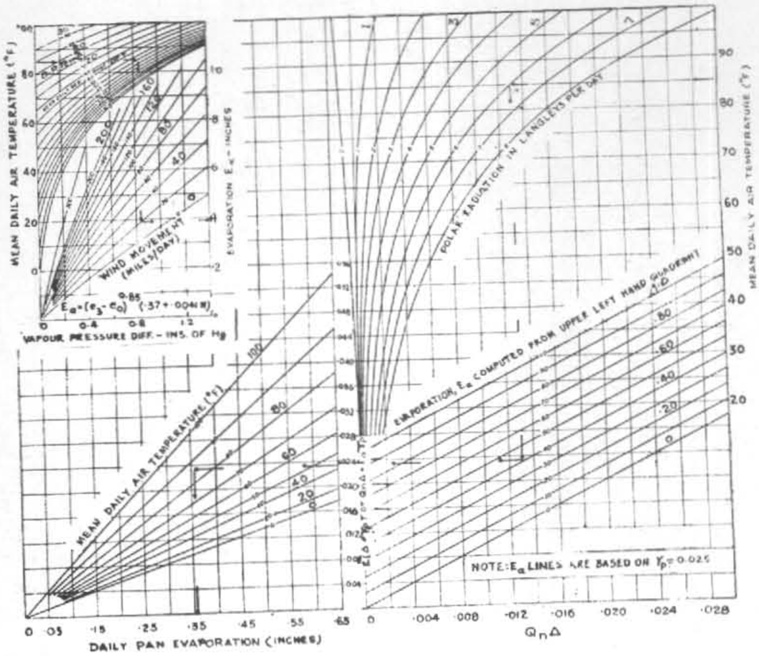

Fig. 1. Revised Class A pan relation of Kohler, Nordenson and Fox:
$E(\triangle + r_p)$ or $Q_n \triangle + E_o \tau_p$

of the order twice or thrice that of the reflected radiation component.

(2) *Graphical Coaxial Technique* (developed by Kohler, Nordenson and Fox 1955)—In this method the mean daily evaporation value for the month is determined graphically from a nomogram using the monthly averages of the daily values of air temperature, dew-point temperature, wind speed and global radiation. Fig. 1 is reproduced from Kohler *et. al* (1955).

(3) *McIlory's Method*—The equation suggested by McIlory (1961) has the form —

$$E = [S / (S + \gamma)] (R_n - G) + h (D - D_o)$$

where,

S = slope of the saturation vapour pressure *versus* temperature curve at mean wet bulb temperature,

γ = psychrometric constant,

R_n = net radiation,

G = heat flux into the ground or water,

h = transfer function empirically determined for each crop or surface and for each location,

D = wet bulb depression at screen height, and

D_o = wet bulb depression at the crop surface.

All these methods described above require a knowledge of global or net radiation. Direct measurements on these parameters are generally available only for a few stations, and it becomes necessary in many cases to estimate these quantities. In the energy budget estimate Penman (1948) used the relation $Q_s = Q_A \times (0{\cdot}18 + 0{\cdot}55\ n/N)$, for the short wave radiation input estimate where Q_s and Q_A denote the radiation from sun and sky and the Angot value of Q_s for a completely transparent atmosphere respectively. The constants 0·18 and 0·55 were based on Rothamstead data over the period 1931—40. Penman (1948) mentions that in the relations $Q_s = Q_A\ [a + b\ (n/N)], a = 0{\cdot}22$, $b = 0{\cdot}54$ for Virginia, U.S.A. (Kimball 1914); and $a = 0{\cdot}25$, $b = 0{\cdot}54$ for Canberra, Australia (Prescott 1940). Fritz and MacDonald (1949) have prepared maps depicting the total radiation received at the surface for the United States, and Mateer (1955) and Drummond and Vowinckle (1957) for Canada and South Africa respectively.

In India, Ramdas and Yegnanarayanan (1954) studied the distribution of total solar radiation Q_o received on horizontal surface on clear days and also the distribution of total solar radiation Q_s received on a horizontal surface for a network of 22 selected stations in the country. Mani *et. al* (1962) have discussed this work in a study on distribution of sunshine and solar radiation over the Indian Peninsula. Venkataraman and Krishnamurthy (1967) in their study of the radiation climate over India remarked that 'the clear-day values of Ramdas and Yegnanarayanan are about 15 per cent greater than the observed values, except at Dum Dum where the over-estimate is 30 per cent and is perhaps due to presence of larger quantities of suspended industrial impurities'. Further, taking into account the fact that even on clear days the value of actual sunshine hours is only 90 per cent of the corresponding possible sunshine hours, Venkataraman and Krishnamurthy have prepared monthly global radiation maps based on estimation of this parameter, for a network of 52 stations, using the relation

$$Q_s = Q_o\ (0\cdot70\ S + 0\cdot4)$$

where Q_o is the expected clear sky radiation for the whole day. It is interesting to note that the monthly patterns of global radiation obtained by them have many dissimilar features of details to the corresponding patterns presented by Mani *et. al* (1962) based on computations of Ramdas and Yegnanarayanan. Authors, therefore, considered it important to study the available global radiation data for the present network of radiation stations in India *vis-a-vis* the hours of sunshine. Some interesting results of this study are presented in this paper.

2. Data

Table 1 shows the stations in India whose daily observations of global radiation and sunshine hours were used in this study. For these 17 stations, the available mean daily values of the global radiation Q_s and the actual hours of sunshine n were tabulated monthwise for the periods ranging from 1 to 9 years. The corresponding observed mean daily values Q_A of the solar radiation received outside the atmosphere as well as the mean possible daily hours of sunshine N were also tabulated monthwise for these stations using the *Smithsonian Tables*. The ratios Q_s/Q_A and n/N were formed. Fig. 2 presents the scatter diagrams of Q_s/Q_A *versus* n/N (mean monthly values) together with the least square fit of the form $Q_s/Q_A = a+b\ (n/N)$ determined for each station.

3. Discussions

Table 1 shows that the values of the constants a and b in the above relation determined for the Indian stations vary in their magnitude over a considerable range. It can easily be verified that for the extreme values of n ($n = 0$ and $n=N$) the average ratios of the radiation received at the surface to that outside the atmosphere turn out to be 43 to 110 per cent due to variation in a and 87 to 110 per cent due to variation in b as compared to the average radiation ratios that would result by using the constants 0·18 and 0·55 determined for Rothamstead. Thus the use of these later values to estimate the global from the solar radiation received outside the atmosphere would result in a considerable under-estimate of evaporation determined by Penman's or Kohler's method in parts of our country.

The value based on all the latest available data of the constants a and b for a large number of stations also provide a useful comparison between the evaporation estimates based on the global radiation values obtained in two ways. In one, the global radiation values were derived from the solar radiation received outside the atmosphere and the hours of bright sunshine and in the other from the extrapolated values taken from the mean monthly maps of global radiation prepared from the clear-day surface radiation values and hours of bright sunshine (Venkataraman and Krishnamurthy 1967).

It is also seen that the corresponding values of the constants a and b differ considerably even for stations at nearly the same latitude. Thus we have for Ahmedabad, Nagpur and Dum Dum the corresponding values of a and b as ·42, ·16, ·29 and ·30, ·68, ·49 respectively. Again for the stations Mangalore, Bangalore and Madras the values of a and b are ·24, ·18, ·30 and ·47, ·62, ·44 respectively. This is to be expected in view of the different average atmosphere over the stations, where apart from the geographical and climatic differences (coastal, continental, arid etc) other factors such as the desert-dust and pollution of the atmosphere through developing industries may also come into play. For the same reasons, the values for the coastal, inland and island stations also do not exhibit any marked similarity.

The question then arises as to how best to estimate the global radiation values from the sunshine hours in the absence of actual data. In

TABLE 1

Station	Lat. (°N)		Long. (°E)		Height a.m.s.l. (m)	Period of data	Computed relations $Q_s = Q_A\ [a+b(n/N)]$ Values of a	b
Minicoy	08°	18′	73°	00′	14	Jul 64–Dec 66	0·3418	0·3048
Trivandrum	08	29	76	57	60	Dec 59–Aug 66	0·3700	0·3827
Kodaikanal	10	14	77	28	2339	Mar 62–Aug 66	0·3435	0·4907
Port Blair	11	40	92	43	79	Jan 64–Dec 64	0·2259	0·4798
Mangalore	12	52	74	51	20	Jan 64–Dec 65	0·2378	0·4653
Bangalore	12	58	77	35	920	Jan 66–Dec 66	0·1804	0·6157
Madras	13	07	80	11	10	Oct 57–Aug 66	0·2985	0·4403
Goa	15	29	73	49	55	Jan 64–Dec 65	0·3644	0·3951
Hyderabad	17	27	78	28	530	Jan 66–Dec 66	0·1422	0·5522
Visakhapatnam	17	48	83	14	41	Jan 61–Aug 66	0·2943	0·4552
Poona	18	32	73	51	555	Jul 57–Jun 66	0·3516	0·3955
Nagpur	21	06	79	03	308	Apr 60–Aug 66	0·1640	0·6762
Dum Dum	22	39	88	27	4	Sep 57–Jun 66	0·2865	0·4885
Ahmedabad	23	04	72	38	55	Feb 62–Feb 67	0·4216	0·2995
Shillong	25	34	91	53	1500	Sep 66–Aug 67	0·1847	0·6589
Jodhpur	26	18	73	01	217	Mar 60–Aug 65	0·3070	0·4898
New Delhi	28	35	77	12	212	Jul 57–Jun 66	0·3145	0·4567

the authors' opinion, a good compromise will be to partition the network of radiation stations by Thiessen and Alter (1911) method. The method was originally developed to find area-means of rainfall over a basin when widely differing records are available at a relatively few irregularly spaced stations. In the application of this method, the adjacent stations from the network are joined by straight lines thus dividing the entire area into a series of triangles. Perpendicular bisectors are erected on each of these lines thereby forming a series of polygons, each containing one and only one station. The entire area within any polygon is nearer to the radiation station contained therein than to any other and it is therefore, compromised that the constants determined in respect of that station should apply to that area. It is to be noted that elevation of the station also plays an important role in the radiation receipt. In the present study however, as will be seen from Table 1, except Kodaikanal and Shillong all the other stations are of fairly low elevations. Similarly, the coastal stations will be contained in the polygons covering the land as well as sea areas which may have different climatological characteristics. In the absence of adequate data over the Arabian Sea adjoining the west coast of India and over the Bay of Bengal, the afore-mentioned compromise is therefore to be accepted. Fig. 3 shows one such scheme of partition utilizing the stations for which the global radiation data have been studied in this paper. With more data from a larger number of stations becoming available in future this scheme of partition is subject to suitable revisions and may be given up altogether only when the radiation network is expanded to cover all the situations.

It is suggested, however, that for the present it would seem logical and practicable to estimate the global radiation values from the values of

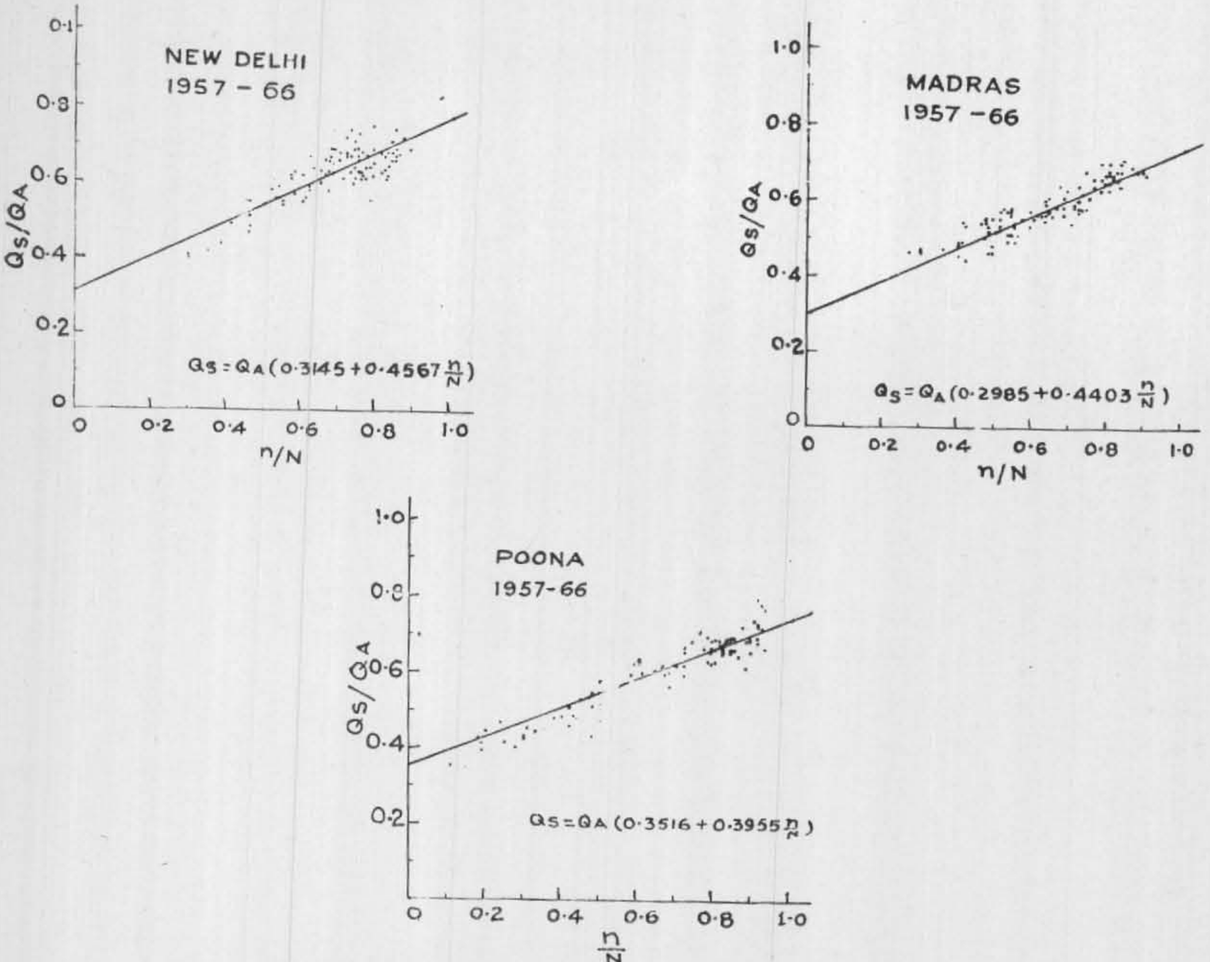

Fig. 2. Regression of mean monthly values of Q_S / Q_A upon n / N

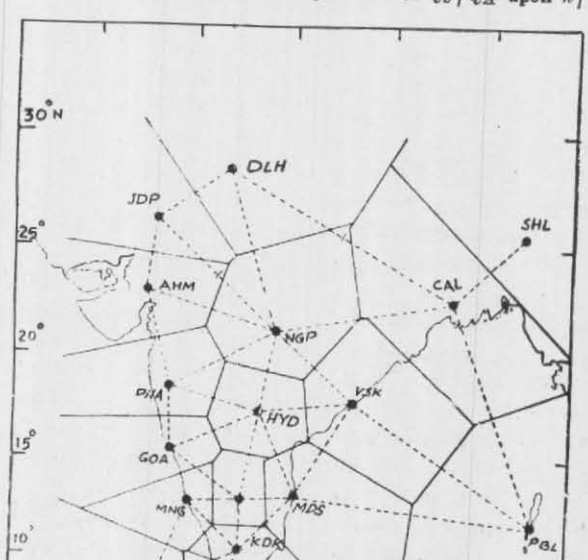

Fig. 3

Partition of the Indian Sub-continent for estimation of the sun and sky radiation with the present network of radiation measuring stations

TABLE 2

Actual and estimates of pan evaporation using Penman's equation and Kohler's graphical technique

Station (Agroclimatic zone)	Estimates*	Mean daily values (mm)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KRIMGANJ (Very wet climate)	1	2·4	3·5	4·7	5·0	4·5	4·2	4·2	3·9	4·7	3·7	3·2	2·4
	2	3·2	3·8	5·4	6·3	5·8	5·4	5·7	5·6	5·1	4·7	3·3	3·0
	3	3·8	3·3	5·6	6·1	4·8	4·3	4·6	5·1	4·6	4·1	2·8	3·6
	4	3·0	4·3	5·5	5·8	5·2	4·7	4·7	4·4	5·4	4·2	3·9	3·0
	5	3·6	4·8	5·6	5·8	4·8	4·8	3·8	3·6	3·1	3·6	3·1	3·6
	6	2·2	3·5	5·2	5·7	5·0	5·0	4·6	..	4·3	3·3	2·3	2·0
CHINSURAH (Wet climate)	1	2·7	4·1	5·5	7·0	6·8	5·5	4·5	4·7	4·4	3·3	3·4	2·6
	2	3·1	4·8	7·1	8·4	7·8	6·6	5·7	5·6	5·8	4·4	3·8	3·2
	3	3·8	5·8	7·9	8·9	8·4	5·8	4·6	4·6	4·8	4·6	4·3	3·8
	4	2·5	4·0	5·5	6·3	6·9	5·2	5·2	5·2	4·9	3·5	3·3	2·5
	5	3·3	5·1	6·3	7·4	6·4	5·3	4·3	4·3	4·8	4·6	3·8	3·1
	6	4·0	5·9	9·0	9·7	8·6	8·6	6·2	6·0	4·9	3·9	3·1	3·2
NEW DELHI (Moderately wet climate and extremes of temperature)	1	1·8	3·0	4·4	5·8	7·3	7·0	6·7	4·4	4·2	4·1	3·2	1·9
	2	1·6	3·9	5·6	7·4	7·8	9·0	8·5	5·8	5·7	5·3	3·9	2·4
	3	2·5	4·3	6·3	7·6	9·7	10·2	8·1	5·6	5·1	6·1	4·8	2·8
	4	2·0	3·4	5·0	6·5	8·0	8·2	7·9	5·4	5·1	4·7	3·6	2·2
	5	3·1	4·6	5·6	7·9	10·2	9·4	8·6	4·6	4·6	6·6	4·1	2·8
	6	2·8	4·0	7·0	9·9	12·9	13·6	11·4	4·6	5·3	5·3	4·8	2·4
NAGPUR (Continental monsoon climate)	1	Meteorological data not available for computation							4·9	5·4	4·9	3·9	2·8
	2								6·5	5·9	5·8	4·8	4·1
	3								4·1	4·8	6·9	4·6	4·3
	4								5·0	5·9	3·0	4·5	3·5
	5								3·6	4·6	3·6	3·8	4·1
	6								1·2	3·3	4·4	4·2	3·6
RAJAMUNDRY (Peninsular SW monsoon and active NE monsoon climate)	1		4·8	5·8	6·4	7·1	6·1	4·2	4·3	5·0	4·7	4·6	3·3
	2		5·6	7·5	8·1	8·0	7·1	5·8	6·1	6·1	5·8	5·1	4·6
	3		6·9	7·6	8·1	8·1	7·6	4·8	4·8	5·8	5·3	8·1	5·1
	4		5·0	6·3	7·0	7·6	7·0	5·2	5·1	5·1	5·3	5·0	3·7
	5		5·6	6·6	7·4	8·4	7·1	4·6	4·6	5·1	4·8	5·6	4·3
	6		7·2	8·6	9·3	11·9	12·4	6·9	5·3	6·8	5·8	5·4	4·9
BELLARY (Peninsular semi-arid climate)	1	4·7	6·0	6·9	7·1	7·8	8·0	8·8	6·0	6·6	4·7	5·3	4·3
	2	4·8	5·7	8·0	7·6	9·0	8·2	7·5	6·4	6·6	5·0	5·6	5·5
	3	6·3	8·4	9·9	9·7	9·9	10·7	7·4	6·3	7·4	6·1	6·6	6·1
	4	5·1	6·6	7·5	7·4	8·3	8·4	7·4	6·2	7·1	5·1	5·8	4·7
	5	5·8	8·6	9·4	9·1	8·6	9·7	8·6	6·9	8·4	6·1	6·9	5·6
	6	7·1	9·8	11·6	12·1	12·7	13·1	11·8	8·8	10·8	7·6	5·7	6·8
PATTAMBI (Active SW monsoon climate)	1	Meteorological data not available for computation								4·7	4·5	4·8	4·5
	2									5·3	4·5	5·2	6·1
	3									4·3	4·6	5·1	6·3
	4									6·1	5·8	6·0	5·6
	5									5·1	4·8	5·1	5·6
	6									5·0	4·7	5·6	5·6
SAMALKOTA (Peninsular SW monsoon and active NE monsoon climate)	1	Meteorological data not available for computation								4·8	4·6	4·6	3·6
	2									5·6	5·0	4·8	5·1
	3									5·3	4·6	4·8	5·1
	4									5·7	5·1	4·9	4·0
	5									4·8	4·6	4·6	4·1
	6									5·4	5·0	4·7	4·1
ADUTHURAI (Northeast monsoon climate)	1	3·3	4·4	5·7	6·1	6·3	7·0	6·1	5·2	6·2	5·9	3·6	3·6
	2	4·6	5·1	7·1	7·2	6·9	7·7	7·2	7·2	6·8	5·6	4·7	4·6
	3	4·6	5·8	6·3	6·9	6·6	8·4	7·1	8·1	6·2	5·3	4·1	3·8
	4	3·7	4·7	6·1	6·6	6·7	7·7	7·3	7·6	6·6	5·4	4·3	4·1
	5	4·3	5·8	5·8	6·6	6·9	8·1	6·6	5·8	6·6	4·8	3·3	5·6
	6	4·4	5·0	5·3	5·8	8·2	10·4	9·0	5·8	5·7	4·6	3·9	4·0

*Evaporation values estimated by

1—Penman's method using constants, $a = 0 \cdot 18$ and $b = 0 \cdot 55$

2 & 3—Penman's and Kohler's method respectively using radiation values extrapolated from the charts prepared by Venkataraman and Krishnamurthy

4 & 5—Penman's and Kohler's method respectively using radiation values estimated by the method indicated in the paper

6—Actual values of evaporation measured by class A pan

TABLE 3

χ^2 values resutling from the observed and estimated pan evaporation values of Table 2

Stations	d.f.	Method 1	2	3	4	5
Karimganj	10	1·05	2·64	2·92	2·20	3·40
Chinsurah	11	6·07	1·82	2·57	5·88	4·77
New Delhi	11	11·99	6·23	3·67	8·48	4·23
Nagpur	4	13·01	26·06	9·29	14·55	6·52
Rajahmundry	10	10·32	4·60	5·59	6·98	6·04
Bellary	11	15·33	13·16	5·80	13·24	6·32
Samalkota	3	0·13	0·30	0·33	0·03	0·10
Patambi	3	0·36	0·10	0·49	0·53	0·05
Aduthurai	11	3·40	4·06	2·96	2·54	2·56
Probability levels corresponding to χ^2 values above						
Karimganj	10	100	99	98	100	96
Chinsurah	11	87	100	100	85	96
New Delhi	11	38	85	98	67	94
Nagpur	4	1	0	6	9	16
Rajahmundry	10	42	91	85	72	81
Bellary	11	17	29	89	28	85
Samalkota	3	99	96	95	100	99
Patambi	3	95	99	92	91	100
Aduthurai	11	98	97	99	100	100
Mean Probability Level Score (per cent)		64·10	77·33	84·66	72·44	85·22

solar radiation outside the atmosphere with the constants determined for the various polygons and the data for sunshine hours (available for a fairly large number of stations in India) for carrying out the agroclimatic and agrometeorological sutdies of evapotranspiration. It is also seen that the use of the clear-day radiation values to estimate the global radiation does not give any particular advantage.

As an example of application of the above suggestions, the computed mean daily values for different months of pan evaporation for each of the 9 stations located in different Agroclimatic Zones of India, for the year 1963, are given in Table 2. The estimates given are —(1) By Penman method using the constants $a = 0 \cdot 18$, $b = 0 \cdot 55$ for the energy budget term ; (2) and (3) by Penman's and Kohler's methods respectively using the radiation values extrapolated from the maps prepared by Venkataraman and Krishnamurthy (1967) ; and (4) and (5) the evaporation values estimated by Penman and Kohler's methods respectively but with the values of global radiation estimated for each of the 9 stations by the Thiessen partition method described earlier in the paper. The values actually observed are also given. All the methods discussed generally give under estimates of evaporation, departures being greater in summer than in winter. Table 3 gives the resulting values of χ^2 and the corresponding probability lavels for all these different estimates of evaporation and clearly brings out the usefulness of the method suggested. It could also be concluded that in the above study, the Kohler's method by and large gave closer evaporation estimates. Work has already been undertaken to modify Kohler's formula to obtain a closer fit with the observed values.

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