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An empirical method for estimation of evaporation from free surface of water

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ABSTRACT. A new empirical method has been developed for computing the pan evaporation (*E*) using solar radiation intensities as obtained from the formulæ of Reddy (1971) for total and net radiation intensities. The results obtained are in good agreement with observed values, which are presented. The formulæ of Reddy (1971) for total (*Rt*) and net (*Rn*) radiation intensities are extended to hill stations and are discussed. Curves suitable for direct reading of *Rt*, *Rn* and *E* values to the required accuracy are also presented.

1. Introduction

In a recent paper, Gangopadhyaya *et al.* (1970) had examined different methods [*viz.*, Penman (1948), Kohler *et al.* (1955), Mcllory *et al.* (1961)] of calculation of pan evaporation using meteorological factors. They found only Kohler's method on the average giving closer estimates than the values obtained by other methods. Therefore, they have undertaken to modify Kohler's formula to obtain a close fit with the observed values but as yet these results are not available. However, though the estimations derived from Kohler's method are the best examined so far, they are not good enough. Evaporation is an important factor that has considerable significance in the fields of hydrology, agriculture and water budgeting in general. The network of evaporimeter stations is relatively sparse in this country. In view of the foregoing remarks, an attempt has been made to evolve a new empirical formula for the estimation of pan evaporation from meteorological parameters which are recorded at a larger network of stations. It may be mentioned that there are appreciable variations in the pan evaporation readings. These variations may be attributed to observational errors or poor exposure conditions. This can be seen from the values given in Table 1 for the same station for two different sites located not far from each other.

The two sites do not, however, show significant variations as far the other meteorological parameters are concerned. It is, therefore, presumed that computing evaporation, using a few significant meteorological factors, could provide reasonably accurate and reliable results.

The deviations of the estimated values using the empirical formula for evaporation from the observed are computed and presented for a few Indian stations which are grouped as inland, coastal and hill stations and are situated at different latitudes. The percentage deviations of the estimated values of R_t (by using the formula of Reddy 1971a for inland and coastal stations and using the method given in the present work for hill stations) from the observed values are calculated and presented for a few Indian stations under the above classifications.

In this paper, curves suitable for use for the reading of R_t, R_n and E are also presented.

2. Method and computation

It is a well known fact, that solar radiation has the direct effect on evaporation. Correlation studies by the authors (results are not presented), reveal that pan evaporation is directly proportional to the solar radiation (*i.e.*, to be exact — the product of total and net radiation intensities). It is also noticed, by the authors, in the case of coastal stations situated on the same latitudes, that there is considerable variation in the values of humidity and the number of rainy days, the effect of which is significantly seen in the evaporation values. But in the case of inland stations this effect is insignificant. The authors also find that this can agree with the views of Papadakis (1961) that 'though the increase in the loss of water by evaporation can be attributed to increase in the wind speed, by preventing the formation of layer of moist air over the evaporating surface, a light breeze is enough for this purpose and increase of wind velocity does not add to this effect'.

Keeping these points in view, the following empirical formula was developed for pan evaporation

$$E = \mu \log \phi + e^{f} \qquad (1)$$

where E = Mean pan evaporation (mm) per day in the month

e = exponential function,

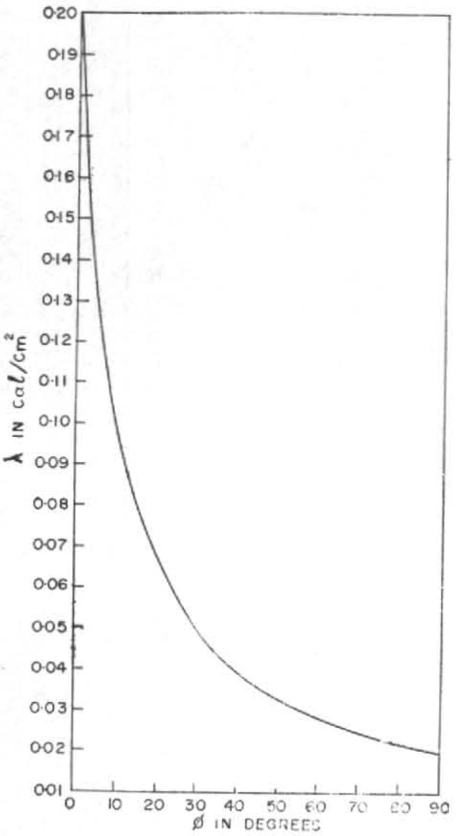

FIG 1–VARIATION OF λ WITH φ

Fig. 1

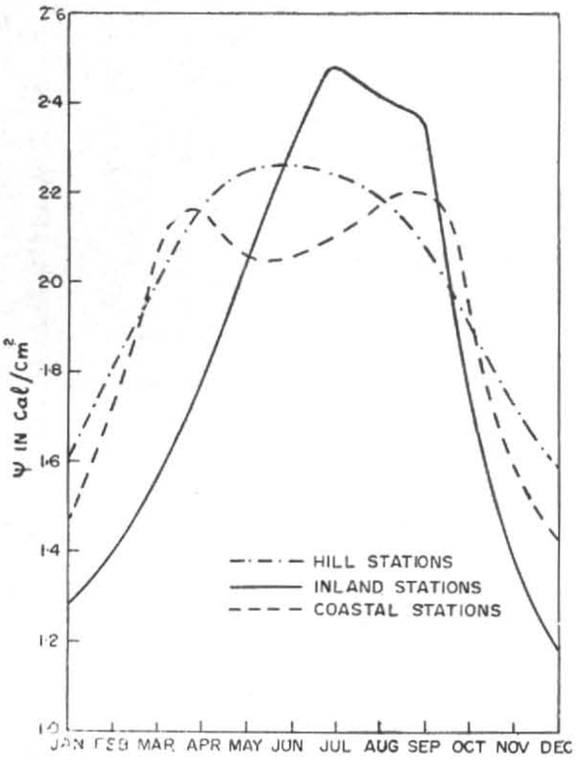

Fig. 2
Variation of ψ with 12 calendar months (hill stations, coastal stations & inland stations)

TABLE 1

Station	No. of years	Average daily evaporation (mm)		Difference (mm)
		Agromet data	I.M.D. data	
New Delhi	7	6·4	7·7	—1·3
Nagpur	7	6·8	6·3	0·5
Sabour	5	5·1	3·9	1·2

ϕ = Latitude of the place, in degrees,

$f = R_t\, R_n \times 10^{-5}$

$$R_t = K(1{\cdot}0 + 0{\cdot}8\, s)\ (1{\cdot}0 - 0{\cdot}2t)/0.1\sqrt{h} \quad (2)$$
cal/cm²/day

[if $h \leq 35\%$ then $h = 35\%$ only]

$$R_n = K\ \ (0{\cdot}6 + 0{\cdot}02\ Ts - 0{\cdot}04\sqrt{h}) - - h\ (4.\,3 - \sqrt{T})\ \text{cal/cm}^2\text{/day} \quad (3)$$

[if T is negative then $\sqrt{-T} = -\sqrt{T}$]

K = Radiation constant at the surface of the observations in cal/cm²/day

$K = (\lambda N + \psi_{i,j} \cos \phi) 10^2$ (in which $i = 1, 2$ for inland and coastal stations respectively) λ and ψ are latitude and seasonal factors respectively (Reddy 1971 a)

and $K = K' + \epsilon$ (for hill stations, in which $K' = (\lambda N + \psi_{3,j} \cos \phi)\, 10^2$, and $\epsilon = 0.5H\, (12 - N) 10^{-2}$, height correction factor H being the height of the place above mean sea level in m)

N = Mean length of the day during the month

s = Mean bright sunshine as fraction of the day length in the month $= n/N$ (hours/hours)

n = mean hours of bright sunshine per day during a month

$t = r/M$ (r = No. of rainy days during the month,

M = No. of days in the month, days/days)

h = Mean relative humidity per day in the month (per cent)

T = Mean daily screen temperature in the month given in degrees centigrade

$\mu = x_i + y_{i,j}$ ($i = 1, 2$ and 3 in which 1 to 3 stand for inland, coastal and hill stations respectively, $j = 1, 2, \ldots\ldots\ldots\ldots 12$ in which 1 to 12 stand for January to December respectively)

$x_1 = 0$,

x_2 = Constant given by Fig. 7,

$x_3 = \phi^{-2} \times 10^2$,

$y_{i,j}$ = Constant given in Table 2.

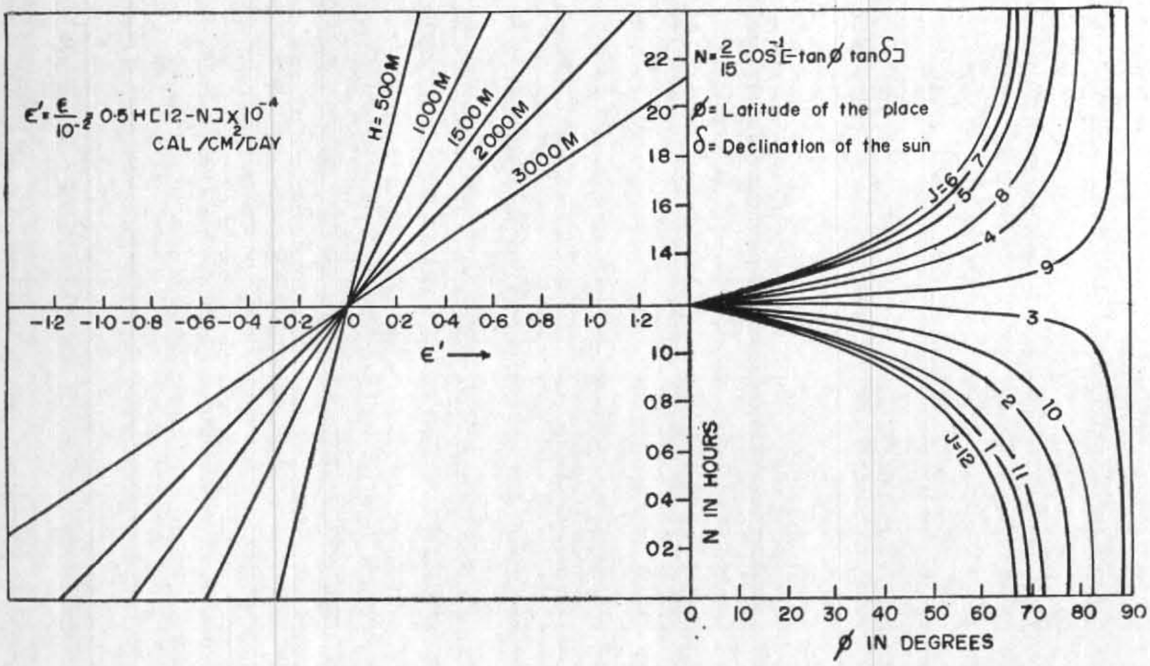

Fig. 3(b)
Variation of ϵ (hill height correction) with ϕ

Fig. 3(a)
Variation of N with ϕ

TABLE 2

i	j = 1	2	3	4	5	6	7	8	9	10	11	12
$y_{1,j}$	2·0	2·5	4·0	4·0	4·0	4·0	2·5	1·5	1·5	2·0	2·0	2·0
$y_{2,j}$	1·0	1·0	1·0	1·0	1·5	1·5	1·5	1·5	1·0	1·0	1·0	1·0
$y_{3,j}$	α	α	α	α	α	α	β	β	β	β	β	β

(α, β are constants which vary with height and latitude), $\alpha = 1300/H \log\phi$, $\beta = 800/H \log\phi$,

Meteorological data taken for computation are shown in Table 3. Fig. 7 is drawn for x_2 against $(\Sigma h_j \, \Sigma r_j) \times 10^{-3}$ where mean r and h are summed up for 12 months (*i.e.*, mean annual total).

Using formulae (1) and (2), the percentage deviations and deviations respectively of the estimated values from observed values are calculated for some Indian stations and tabulated in Appendices 1 and 2.

3. Preparation of curves for R_t, R_n and E

The method of evaluating E, R_t and R_n from the curves using equations (1), (2) and (3) respectively is as follows:

(*i*) *Preparation of curves for the calculation of* R_t

Figs. 1 and 2 are drawn for λ and $\psi_{i,j}$ functions varying with ϕ and j (twelve calendar months) respectively used in the calculation of K. Figs. 3 (a) and 3 (b) are for N and ϵ functions varying with ϕ and height respectively. Figs. 4 (a), 4 (b) and 4 (c) represent the curves drawn with K in case of coastal and inland stations and K' in case of hill stations against ϕ for 12 calendar months. In Figure 5 the curves on the right represent q against s for different values of t and the curves on the left represent q against h for different values of P. Therefore, knowing ϕ, s, t and h the value of R_t is obtained as $R_t = PK$.

$$[P = q/0 \cdot 1\sqrt{h}, \; q = (1 \cdot 0 + 0 \cdot 8s)\,(1 \cdot 0 - 0 \cdot 2t)]$$

TABLE 3

Station	Latitude (°N)	Longitude (°E)	Period of data	No. of years
(a) *Inland stations*				
Hyderabad (Begumpet)	17° 27′	78° 28′	1959-68	10
Poona	18 32	73 51	1962-70	9
Nagpur	21 06	79 03	1959-68	10
Chinsurah*	22 52	88 24	1962-68	7
Ahmadabad	23 04	72 38	1959-67	9
New Delhi	28 35	77 12	1961-67, 70	8
(b) *Coastal stations*				
Trivandrum	08 29	76 57	1959-68	10
Madras	13 00	80 11	1959-68	10
Visakhapatnam	17 43	83 18	1962-68	7
Bombay	18 54	72 49	1959-67	8
Okha	22 29	69 07	1963-67	5
(c) *Hill stations*				
Kodaikanal	10 14	77 28	1959-68	10
Bangalore	12 58	77 35	1959-68	10
Shillong	25 34	91 53	1963-67	5

*Data based on non-rainy days only (observed evaporation)

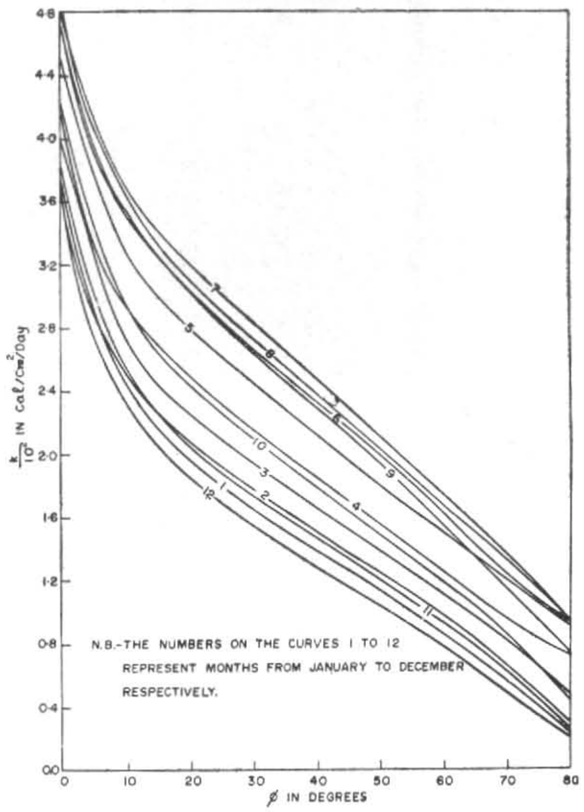

Fig. 4 (a)

Variation of k with ϕ for 12 calendar months (inland stations) for northern hemisphere

(ii) Preparation of curves for the calculation of R_n

Fig. 6 (a) is drawn with h against u for different values of T. In Fig. 6 (b) the curves on the right represent q against s for different values of T and the curves on the left represent q against h for different values of P. Therefore, knowing h, s, T and ϕ the value of R_n is obtained as $R_n = PK—u$.

(iii) Preparation of curves for the calculation of E

Fig. 7 is the curve representing the variation of x_2 with $(\Sigma h_j \, \Sigma r_j) \times 10^{-3}$. Fig. 8 (a) is drawn with ϕ against β for different values of μ', where $\mu' = 1 + x_2$ and $\beta = (1 + x_2) \log \phi$, $\mu'' = \mu \log \phi$. For coastal stations $\mu = y_{2,j} + x_2$. For January to April and September to December, corresponding to ϕ and μ' (*i.e.*, x_2) the value of $\mu'' = \beta$, but for May to August $\mu'' = \beta + \frac{1}{2}$ (β value obtained corresponding to ϕ on $\mu' = 60$ curve). For inland station $\mu = y_{1,j} + x_1$. Here $\mu'' = \beta$ (value corresponding to ϕ on $\mu' = 60$ curve)$\times$ (2 for January, October to December; 1·5 for August and September; 2·5 for February and July; and 4·0 for March to June). For hill stations $\mu = y_{3,j} + x_3$ and $\mu'' = \mu \log \phi$.

Fig. 8 (b) is drawn with R_t against (ef), for different values of R_n. Knowing R_t and R_n from Figs. 5 and 6 respectively, ef can be obtained. Knowing μ'' and ef,, pan evaporation eventually can be obtained from the relation $E = \mu'' + ef$.

4. Discussion of results

Appendices 1(**a**) and 2(**a**) show the mean percentage deviation and deviation respectively of R_t and E as obtained by the use of the Eqns. (1) and (2) from the observed. Appendices 1 (b) and 2 (b) show the mean percentage deviations and deviation of estimated values of R_t and E for individual years, as obtained by the use of the Eqns. (1) and (2) respectively from the observed. On the whole, the results at Appendices 1 and 2 show good agreement with observed values.

Results of R_t — The results of Appendix 1 (a) show that out of ten stations results (*i.e.*, 10 points) only 13 points are having percentage deviations

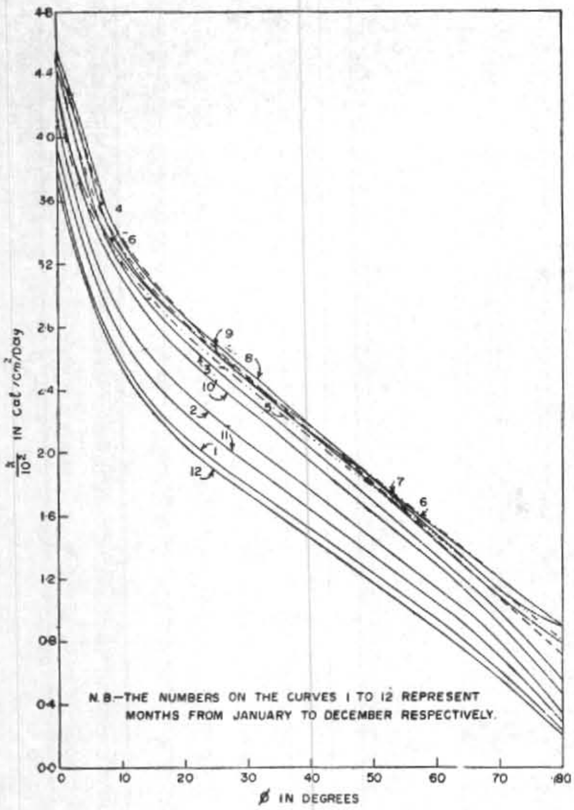

Fig. 4 (b)

Variation of k with ϕ for 12 calendar months (coastal stations) for northern hemisphere

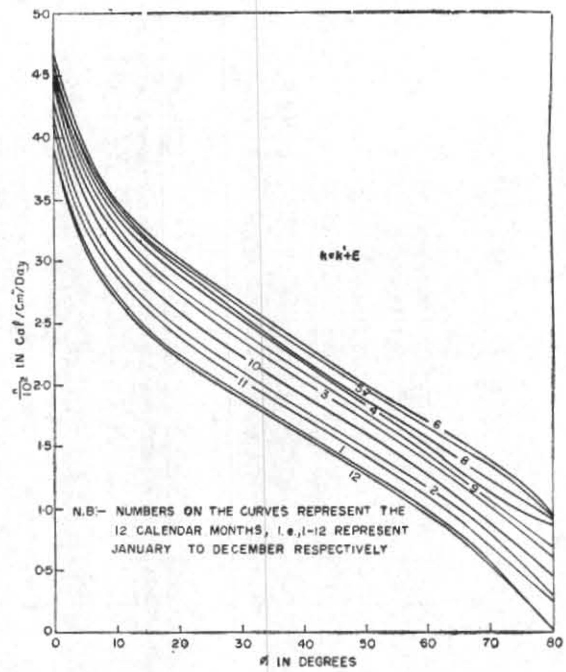

Fig. 4 (c)

Variation of k' with ϕ for 12 calendar months (hill stations) for northern hemisphere

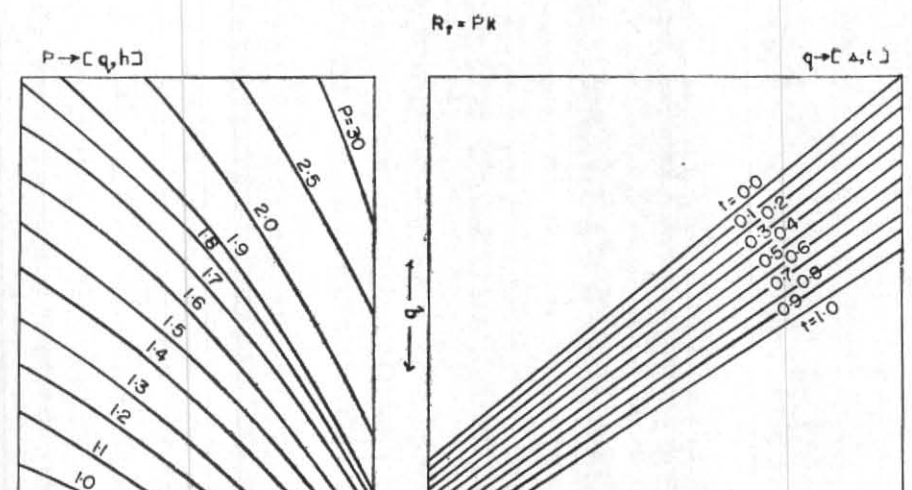

Fig. 5

Variation of P with s, t and h; $s=n$ hr/N hr, $t=r$ days/M days, $h=$R.H. (%); P, $q=$ constants

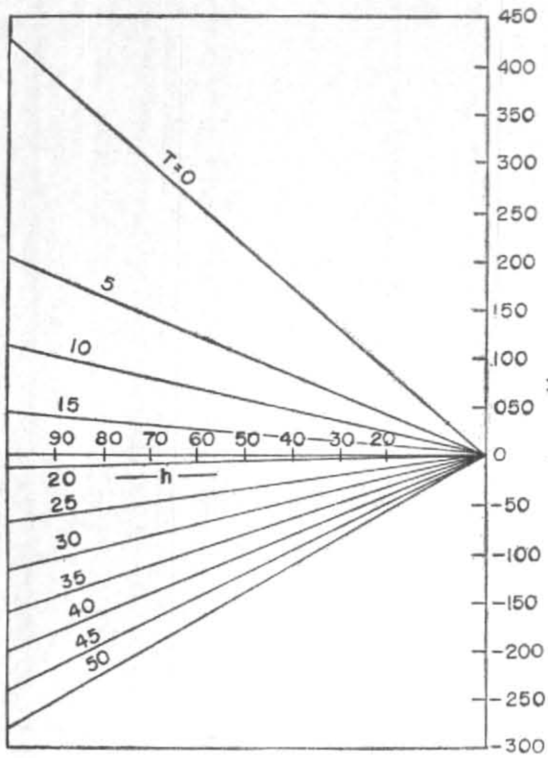

Fig. 6 (a)
Variation of u with h and T

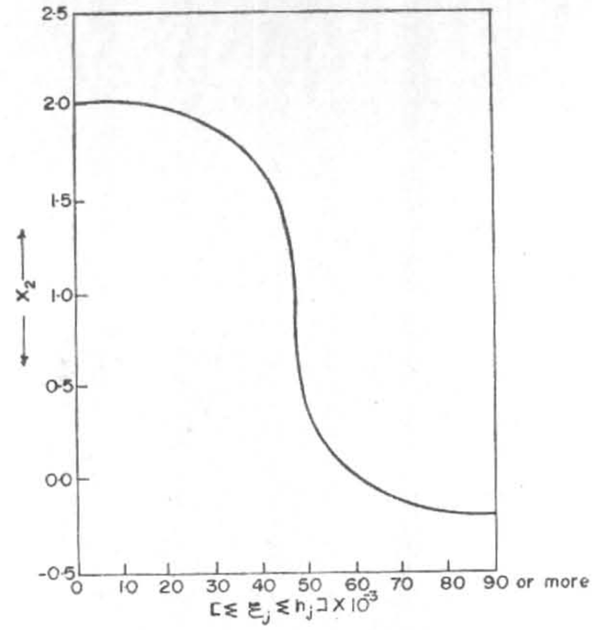

Fig. 7
Variation of x_2 with $[\ \Sigma rj\ \Sigma hj\ ] \times 10^{-3}$

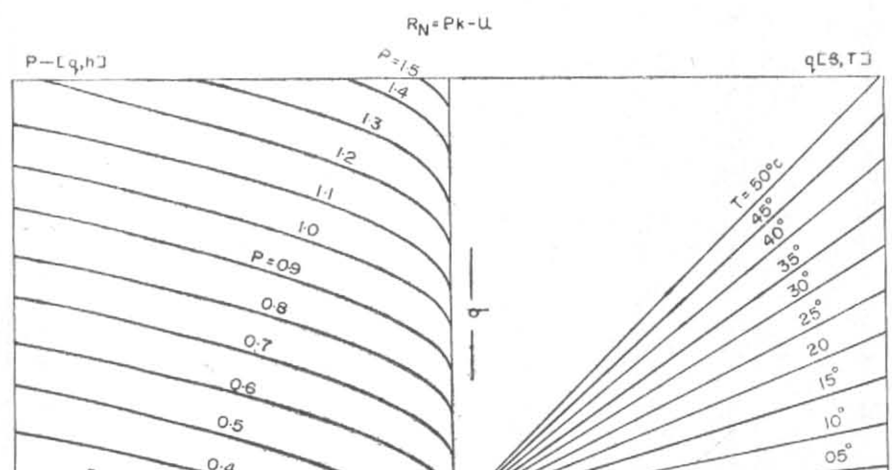

Fig. 6(b)
Variation of ϕ with s, T and h

Figs. 6 (a & b). h—R.H. (%); T—Mean temp. (°C) ; u—cal/cm²/day; P, q—Constants

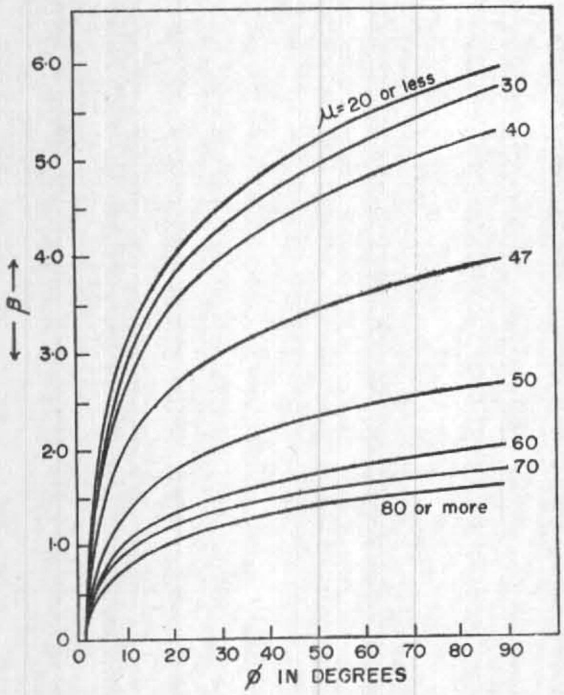

Fig. 8(a)

Variation of β with μ' and ϕ

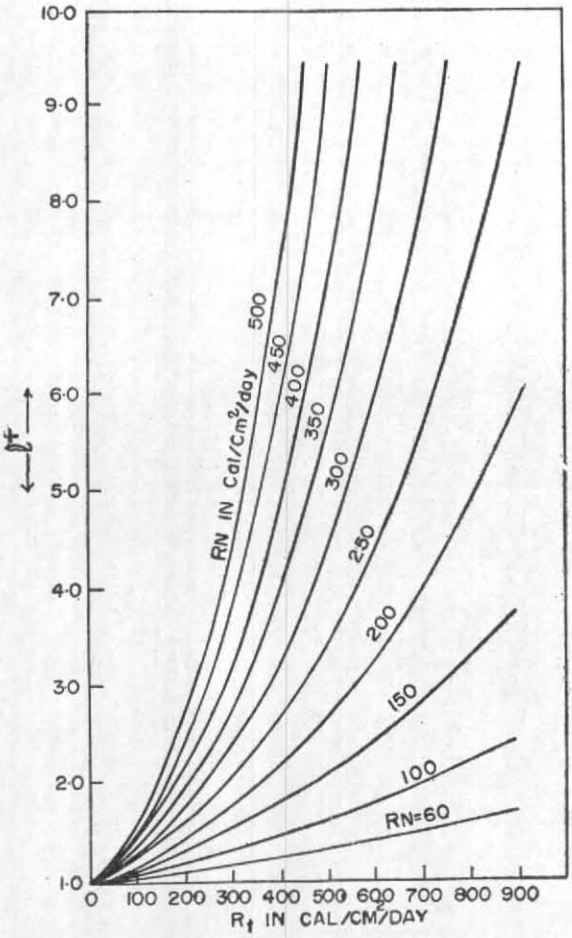

Fig. 8(b)

Variation of e^f with R_t and R_n

more than or equal to 10 per cent from the observed (*i.e.*, 11 per cent of total values). This shows that the results are in good agreement with the observed. Also it is seen that the Eqn. (2) gives most accurate results in the case of coastal stations. Similarly the results at Appendix 1 (b) show that out of three stations considered for individual years (*i.e.*, 5 years — 97 points) 42 points are having percentage deviations more than or equal to 10 per cent from the observed (*i.e.*, 14 per cent of total values). In the case of Ahmadabad four out of twelve points are deviating to the extent of 10 per cent or more and in case of Kodaikanal for 1966 and 1967 the percentage deviations exceeding 10 per cent or more are five out of twelve. Except these two cases, in all other cases the agreement between calculated and observed are good.

Results of E — The results at Appendix 2 (a) show that out of 168 points (*i.e.*, for 14 stations) only 17 points are exceeding the deviation limit of 1 mm or more (*i.e.*, 10 per cent of total values). The results at Appendix 2 (b) show that out of three stations (*i.e.*, 29 years = 348 points) only 27 points are having deviation of 1 mm or more from the observed (*i.e.*, 8 per cent of total values). In the case of Ahmadabad the observed values for October, November, December of 1967, are widely divergent compared to the observed values of the other years for the corresponding months, even though much deviation is not seen in other meteorological elements. A similar situation is observed in the case of Kodaikanal for July, September and November for the year 1959.

On the whole the results at Appendices 1 and 2 show a good agreement for coastal and hill stations, where the local effects on meteorological elements are less. Most of the observed deviations are in case of inland stations. This could be attributed to the greater susceptibility of inland stations to the influence of local factors other than the standard meteorological elements taken into account.

5. Conclusions

(*i*) Appendices 1 and 2 show a good agreement between calculated and observed values, which, in other words means that the empirical methods suggested for E, R_t and R_n are accurate enough to be used in tropical and extratropical regions.

(*ii*) It is observed that even in places on the same latitude, the effect of different meteorological parameters on E, R_t and R_n is not the same but it differs with the location of the station (*i.e.*, depending on whether it is an inland, a hill or coastal station) and the extent to which it is influenced by other local effects.

(*iii*) The results in Appendices 1 and 2 show that the deviations are more in case of inland stations which could be attributed to the greater susceptibility of inland stations to the influence of local factors other than the standard meteorological elements taken into account.

(*iv*) Evaporation studies show that the effect of variation in humidity and number of rainy days is more marked in coastal stations than in inland stations.

(*v*) The negative deviations in evaporation values in Appendix 2 during the months January, February, November and December at most of the stations could be probably attributed to the dew deposition.

(*vi*) Appendix 3 gives the evaporation values obtained using Penman's (1948), Kohler *et al.*'s (1955) formulae and equation (1) for four representative months (*i.e.*, January, April, July and October) for 9 stations. It also contains the deviations from the observed evaporation data for 8 stations (*i.e*, except Jaipur, where observed data are not available). It is seen from this Appendix that the number of values deviating more than 1 mm from observed are : (*a*) 18 in case of Penman's method (60 per cent of the total number of values), (*b*) 13 in case of Kohler's method (40 per cent of the total number of values), and (*c*) 3 in case of the present formula using Eqn. 1 (10 per cent of the total number of values).

(*vii*) Also results of Gangopadhyaya *et al.* (1970) for pan evaporation values for 9 stations, using different formulae (*viz.*, Penman's, Kohler) show that 45 to 60 per cent of calculated values are deviating more than 1 mm from observed values. But in the present study in Appendix 2 (a), it is seen only 10 per cent of calculated values are deviating more than 1 mm from observed values, which show the superiority of this method over those methods. Therefore, the authors now claim that this method can be used to get good estimates of evaporation.

Acknowledgement

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Appendix 1(a)

Mean percentage deviation of estimated values of R_t, as obtained by the use of the formula (2)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	No. of years
						Coastal stations							
Trivandrum	0	0	0	1	3	−7	−1	3	0	0	0	0	9
Madras	1	−1	−1	2	2	8	8	3	3	3	3	2	10
Visakhapatnam	−5	−3	0	−3	−6	0	−2	−4	−5	−2	−2	0	7
						Inland stations							
Poona	4	3	7	1	−2	0	0	4	2	−4	−2	2	9
Nagpur	0	8	9	4	6	2	3	3	0	−4	−2	−4	7
Dum Dum	3	3	0	−7	−10	−10	−3	−7	−2	2	7	9	4
New Delhi	−2	−10	−10	1	0	0	−4	−5	0	0	2	0	7
Ahmadabad	18	14	7	6	7	0	0	−2	−2	7	14	11	9
						Hill stations							
Kodaikanal	−4	2	5	6	3	4	7	2	−5	−5	−8	−12	7
Shillong	7	−4	−7	−2	−12	−3	5	−2	12	0	0	0	2

Appendix 1(b)

Mean percentage deviation of estimated values of R_t for individual years, as obtained by the use of the formula (2)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	P*
						Coastal station (Madras)							
1959	−8	−9	−3	3	3	9	9	7	4	1	10	1	1
1960	−1	−2	2	3	7	8	8	10	3	2	13	−3	2
1961	0	−2	−5	0	7	4	2	−3	−4	−3	0	5	0
1962	3	1	0	−4	8	−1	5	0	4	4	0	−2	0
1963	0	−15	−3	0	1	10	5	4	−4	1	−4	0	2
1964	−6	1	0	3	12	16	9	3	2	3	0	7	2
1965	−5	0	2	0	10	18	9	−3	9	8	0	2	2
1966	−2	−1	4	6	9	6	9	5	8	3	−4	4	0
1967	−1	−3	−3	3	6	8	10	−4	4	4	6	2	1
1968	−1	−3	0	3	4	9	14	15	8	8	2	4	2
P*	0	1	0	0	2	3	2	2	0	0	2	0	12

P*—No. of points exceeding 10 per cent

Appendix 1b (*contd*)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	P*
					Inland station (New Delhi)								
1959	–14	–20	–9	9	–3	–5	7	–7	3	3	4	8	2
1960	–3	4	–14	2	15	–2	0	–4	2	0	8	8	2
1961	–4	–13	–9	–1	–1	–4	0	–4	–1	–3	–5	–2	1
1962	10	–18	–16	4	12	4	–6	–5	–9	2	4	–7	4
1963	–7	–13	–15	4	8	–9	–1	–4	–3	–3	–9	–7	2
1964	–3	–7	–5	–7	3	8	–8	–6	–1	4	4	–3	0
1965	–3	–7	–7	–7	16	25	–9	–5	6	5	2	3	2
1966	3	–9	0	5	4	–4	0	–2	3	6	8	8	0
P*	2	4	3	0	3	1	0	0	0	0	0	0	13
					Hill station (Kodaikanal)								
1962	–	–	2	4	–4	8	5	–4	–8	–1	–12	–19	2
1963	–14	–5	–1	2	1	4	5	–1	–2	–7	7	8	1
1964	4	0	1	6	1	–3	7	8	–7	–7	–14	–8	1
1965	–9	6	9	–3	–1	–5	4	–5	–5	–3	–4	–11	1
1966	–5	2	7	7	13	6	9	5	–10	–10	–17	–16	5
1967	–7	—	6	16	10	7	5	4	10	5	–12	–16	5
1968	4	8	3	3	1	6	12	9	–3	–5	7	–8	1
P*	1	0	0	1	2	0	1	0	2	1	4	4	16

P*—No. of points exceeding 10 per cent

Appendix 2(a)

Mean deviation of estimated values of pan evaporation (E) as obtained by the use of the Eqn. (1)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	@
						Coastal stations							
Trivandrum													
O	4·9	5·5	5·6	5·0	4·6	3·8	3·5	3·9	4·1	3·8	3·5	3·9	
C	4·3	5·3	6·3	5·4	4·6	3·8	3·5	4·3	3·7	3·6	3·3	3·5	
D	–·6	–·2	·7	·4	0	0	0	·4	–·4	–·2	–·2	–·4	0
Bombay													
O	3·6	4·3	5·1	5·7	6·1	4·5	3·0	3·0	3·5	4·0	3·7	3·3	
C	3·5	4·3	5·1	5·9	6·4	4·3	3·3	3·4	3·5	4·3	3·9	3·4	
D	–·1	0	0	·2	·3	–·2	·3	·4	0	·3	.2	·1	0
Madras													
O	4·1	4·9	5·9	6·6	8·3	8·1	6·7	6·3	5·4	4·4	3·8	3·5	
C	3·7	5·0	6·4	7·6	8·4	6·5	5·3	5·6	4·8	4·3	3·4	3·3	
D	–·4	·1	·5	1·0	·1	–1·6	–1·4	–·7	–·6	–·1	–·4	–·2	3

O—Observed C—Computed value D—Deviation @—No. of points exceeding 1·0 mm

Appendix 2a (*contd*)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	@
Visakhapatnam													
O	5·7	7·0	7·4	8·8	9·4	8·1	6·3	6·0	4·9	5·7	6·1	6·0	
C	5·5	6·8	7·6	8·4	9·1	7·1	6·2	6·5	5·8	6·1	5·9	5·7	
D	−·2	−·2	·2	−·4	−·3	−1·0	−·1	·5	·9	·4	−·2	−·3	1
Okha													
O	5·4	5·5	6·5	7·4	10·1	8·8	6·6	6·0	6·4	5·2	6·1	5·6	
C	5·7	6·3	6·7	7·5	8·7	7·8	6·8	6·7	7·0	7·0	6·4	5·8	
D	·3	·8	·2	·1	−1·4	−1·0	·2	·7	·6	1·8	·3	·2	3
						Inland stations							
Hyderabad													
O	5·5	7·3	8·9	9·5	11·5	8·9	6·4	5·9	5·4	5·3	5·3	5·3	
C	4·6	5·8	8·7	10·0	13·5	8·6	5·8	4·7	4·7	5·1	4·6	4·4	
D	−·9	−1·5	−·2	·5	2·0	−·3	−·6	−1·2	−·7	−·2	−·7	−·9	3
Poona													
O	4·7	6·8	8·9	10·7	11·3	7·8	4·5	3·6	4·3	5·1	4·5	4·0	
C	4·5	6·0	8·9	10·8	11·6	8·5	5·2	4·0	4·5	5·3	4·6	4·2	
D	−·2	−·8	·0	−·1	·3	·7	·7	·4	·2	·2	·1	·2	0
Nagpur													
O	4·0	6·0	7·7	9·9	13·2	9·1	4·7	3·8	4·5	4·9	4·3	3·5	
C	4·2	6·0	8·1	10·7	15·0	9·2	5·4	4·0	4·6	5·3	4·6	4·1	
D	·2	0	·4	·8	1·8	·1	·7	·2	·1	·4	·3	·6	1
Chinsurah													
O	3·3	5·0	7·5	9·2	9·2	7·5	5·4	4·4	3·9	3·7	3·2	2·9	
C	3·9	5·2	7·8	8·9	9·3	7·8	5·6	4·5	4·4	4·7	4·3	4·0	
D	·6	·2	·3	−·3	·1	·3	·2	·1	·5	1·0	1·1	1·1	3
Ahmadabad													
O	5·3	6·9	9·0	11·5	13·1	10·2	6·2	4·5	5·3	6·5	5·9	5·3	
C	4·9	6·3	8·9	11·1	13·7	10·5	6·0	4·3	5·2	6·3	5·4	4·8	
D	−·4	−·6	−·1	−·4	·6	·3	−·2	−·2	−·1	−·2	−·5	−·5	0
New Delhi													
O	3·3	4·4	6·4	10·4	12·1	12·3	6·7	5·1	5·1	6·2	4·6	3·3	
C	4·0	5·0	7·6	9·4	11·4	10·0	6·6	4·8	5·2	5·6	4·5	3·9	
D	·7	·6	1·2	−1·0	−·7	−2·3	−·1	−·3	·1	−·6	−·1	·6	3

O—Observed C—Computed value D—Deviation @—No. of points exceeding 1·0 mm

Appendix 2a *(contd)*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	@
						Hill stations							
Kodaikanal													
O	3·1	3·7	4·1	3·5	3·2	2·8	2·4	2·5	2·6	2·1	2·1	2·5	
C	2·9	3·3	3·8	3·5	3·4	2·9	2·5	2·6	2·6	2·4	2·3	2·5	
D	—·2	—·4	—·3	0	·2	·1	·1	·1	0	·3	·2	0	0
Bangalore													
O	4·4	6·3	7·8	7·3	6·4	4·8	3·9	3·8	3·7	3·8	3·6	3·7	
C	4·3	5·8	7·8	8·1	6·8	4·8	3·7	3·7	3·7	3·8	3·6	3·6	
D	—·1	—·5	0	·8	·4	0	—·2	—·1	0	0	0	—·1	0
Shillong													
O	1·7	2·5	3·2	3·6	3·1	2·4	2·1	2·1	2·2	1·9	1·7	1·5	
C	2·0	2·5	2·8	3·1	3·0	2·5	2·2	2·2	2·2	2·0	1·8	1·7	
D	·3	0	—·4	—·5	—·1	·1	·1	·1	0	·1	·1	·2	0

O — Observed average   C — Computed average   D — Deviation   @ — No. of points exceeding 1·0 mm

Appendix 2(b)

Mean deviation of estimated values of E, for individual years, as obtained by the use of the Eqn. (1)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	@
						Coastal station (Trivandrum)							
1959													
O	5·1	5·6	6·1	5·9	4·7	4·4	4·0	4·2	4·3	4·4	3·5	3·8	
C	4·7	5·5	7·0	5·6	3·6	3·2	3·3	4·3	4·1	4·0	3·3	3·6	
D	—·4	—·1	·9	—·3	—1·1	—1·2	—·7	·1	—·2	—·4	—·2	—·2	2
1960													
O	4·6	4·9	5·4	4·4	3·5	3·8	3·4	4·3	3·5	4·0	2·4	3·9	
C	4·3	4·6	6·0	4·5	3·4	3·7	3·3	4·5	3·1	3·7	2·5	3·7	
D	—·3	—·3	·6	·1	—·1	—·1	—·1	·2	—·4	—·3	·1	—·2	0
1961													
O	4·6	4·8	5·9	5·5	4·3	3·7	2·8	3·2	3·9	4·2	3·3	4·1	
C	4·3	4·4	6·4	5·1	4·1	3·4	3·0	3·4	3·8	4·1	3·2	3·5	
D	—·3	—·4	·5	—·4	—·2	—·3	—·2	·2	—·1	—·1	—·1	—·6	0
1962													
O	5·1	5·5	5·5	4·8	3·9	4·4	3·4	4·0	4·0	3·0	4·1	4·1	
C	4·0	5·3	5·8	5·1	4·0	4·2	3·4	4·2	3·6	2·8	3·8	3·6	
D	—1·1	—·2	·3	·3	·1	—·2	0	·2	—·4	—·2	—·3	—·5	1

O—Observed average   C—Computed value   D—Deviation   @—No. of points exceeding 1·0 mm

Appendix 2b *(contd)*

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	@
1963													
O	4·0	5·8	5·2	4·7	4·4	3·9	3·3	3·2	3·9	4·1	3·0	3·8	
C	3·5	5·5	5·5	5·1	5·0	3·9	3·5	3·4	4·5	4·3	3·2	3·6	
D	—·5	—·3	·3	·4	·6	0	·2	·2	·6	·2	·2	—·2	0
1964													
O	4·5	5·5	5·2	5·0	6·0	4·1	3·0	3·8	3·3	3·9	3·7	4·4	
C	4·2	5·2	5·4	6·2	6·1	3·9	3·3	4·0	3·3	3·6	3·5	4·0	
D	—·3	—·3	·2	1·2	·1	—·2	·3	·2	0	—·3	—·2	—·4	1
1965													
O	5·5	5·3	5·9	4·8	4·0	3·6	4·6	4·1	5·0	3·7	3·6	3·5	
C	4·4	4·6	6·6	5·2	4·3	3·9	4·8	4·2	5·0	3·5	3·2	2·7	
D	—1·1	—·7	·7	·4	·3	·3	·2	·1	0	—·2	—·4	—·8	1
1966													
O	5·0	5·9	5·7	5·1	6·1	3·6	3·4	4·6	4·1	3·3	3·7	3·8	
C	4·1	6·2	5·7	5·4	6·5	3·8	3·6	4·7	3·2	3·2	3·4	3·1	
D	—·9	·3	0	·3	·4	·2	·2	·1	—·9	—·1	—·3	—·7	0
1967													
O	5·0	5·9	5·8	5·4	3·9	3·6	4·0	3·5	5·0	3·5	4·2	3·2	
C	4·3	5·7	6·0	6·2	4·3	3·7	3·6	3·7	4·8	3·3	3·7	3·3	
D	—·7	—·2	·2	·8	·4	·1	—·4	·2	—·2	—·2	—·5	·1	0
1968													
O	5·5	6·1	5·7	4·7	5·5	3·3	2·7	4·4	4·4	4·0	3·9	4·4	
C	4·2	6·0	5·0	5·1	6·6	3·3	3·0	5·0	3·5	3·9	3·3	3·6	
D	—1·3	—·1	—·7	·4	1·1	0	·3	·6	—·9	—·1	—·6	—·8	2
					Inland station (Ahmadabad)								
1959													
O	6·0	6·9	10·1	11·1	14·2	10·6	6·6	3·6	3·7	4·6	4·7	4·5	
C	4·6	5·8	9·4	10·9	14·6	11·0	6·2	3·7	4·2	5·0	4·8	4·5	
D	—1·4	—1·1	—·7	—·2	·4	·4	—·4	·1	·5	·4	·1	0	2
1960													
O	4·7	6·1	7·6	11·5	11·8	9·5	6·7	4·2	5·8	7·1	6·1	5·2	
C	4·6	6·2	8·0	11·8	14·0	10·5	6·6	4·0	6·0	6·6	5·8	4·8	
D	—·1	·1	·4	·3	2·2	1·0	—·1	—·2	·2	—·5	—·3	—·4	2
1961													
O	6·9	7·0	10·3	11·6	12·5	10·3	5·1	4·3	4·8	—	5·8	5·0	
C	5·0	6·2	9·8	11·6	12·8	10·3	5·5	4·4	4·4	6·0	5·4	4·8	
D	—1·9	—·8	—·5	0	·3	0	·4	·1	—·4	—	—·4	—·2	1

O—Observed average C—Computed value D—Deviation @—No. of points exceeding 1·0 mm

Appendix 2b *(contd)*

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	@
1962													
O	4·8	6·7	9·4	12·4	14·8	12·0	6·4	5·4	5·9	7·0	5·7	5·4	
C	4·7	6·2	9·2	11·4	14·4	11·8	6·3	5·0	5·4	6·2	5·3	4·6	
D	—·1	—·5	—·2	—1·0	—·4	—·2	—·1	—·4	—·5	—·8	—·4	—·8	1
1963													
O	6·6	8·3	11·2	12·7	15·7	11·0	6·3	4·0	4·6	5·8	4·8	4·6	
C	5·2	6·8	9·5	10·8	15·4	11·8	6·3	4·1	4·8	6·0	4·9	4·6	
D	—1·4	—1·5	—1·7	—1·9	—·3	·8	0	·1	·2	·2	·1	0	4
1964													
O	4·0	7·1	7·9	11·0	11·0	9·1	5·3	4·4	4·8	6·0	5·6	4·9	
C	4·4	6·3	9·0	11·4	13·0	10·4	5·6	4·2	5·4	6·4	5·3	4·7	
D	·4	—·8	1·1	·4	2·0	1·3	·3	—·2	·6	·4	—·3	—·2	3
1965													
O	4·5	6·5	9·0	11·1	11·7	10·5	7·0	5·2	7·4	6·4	5·5	5·0	
C	4·6	6·2	9·3	10·6	12·8	12·0	6·0	5·4	6·8	6·5	5·4	4·8	
D	·1	—·3	·3	—·5	1·1	1·5	—1·0	·2	—·6	·1	—·1	—·2	3
1966													
O	4·5	6·7	8·8	10·7	11·7	8·6	7·4	5·6	6·1	6·2	5·2	5·1	
C	4·6	6·3	8·8	10·4	12·0	9·6	6·3	4·8	6·3	7·1	5·3	4·8	
D	·1	—·4	0	—·3	·3	1·0	—1·1	—·8	·2	·9	·1	—·3	2
1967													
O	5·5	6·4	7·0	11·7	14·3	10·6	4·7	4·1	4·7	8·7	10·2	7·9	
C	5·1	6·3	7·5	10·4	16·3	10·0	5·5	4·0	4·8	6·5	5·6	4·6	
D	—·4	—·1	—·5	—1·3	2·0	—·6	·8	—·1	·1	—2·2	—4·6	—3·3	5
						Hill station (Kodaikanal)							
1959													
O	3·6	4·0	5·6	3·7	3·4	2·9	4·0	3·4	4·3	2·8	3·6	2·9	
C	3·0	3·6	5·6	3·4	3·3	2·9	2·5	2·9	2·7	2·5	2·4	2·5	
D	—·6	—·4	0	—·3	—·1	0	—1·5	—·5	—1·6	—·3	—1·2	—·4	3
1960													
O	2·8	3·6	3·7	3·5	3·5	3·3	2·9	3·3	2·7	2·7	1·8	3·4	
C	2·9	3·1	3·5	3·3	3·0	3·2	2·5	2·8	2·5	2·5	2·3	2·7	
D	·1	—·5	—·2	—·2	—·5	—·1	—·4	—·5	—·2	—·2	·5	—·7	0
1961													
O	2·3	3·4	4·8	3·8	2·8	2·5	1·8	2·3	2·8	2·3	2·1	2·1	
C	2·7	3·0	4·2	3·6	3·1	2·8	2·5	2·6	2·7	2·5	2·5	2·4	
D	·4	—·4	—·6	—·2	·3	·3	·7	·3	—·1	·2	·4	·3	0

O—Observed average C—Computed value D—Deviation @—No. of points exeeding 1·0 mm

Appendix 2b (*contd*)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	@
1962													
O	3·1	2·9	3·9	3·2	2·6	2·9	2·2	2·5	2·5	1·1	2·5	2·4	
C	3·0	2·8	3·5	3·4	3·0	3·2	2·5	2·6	2·6	2·4	2·6	2·5	
D	—·1	—·1	—·4	·2	·4	·3	·3	·1	·1	1·3	·1	·1	1
1963													
O	2·6	3·4	3·8	3·4	3·0	3·1	2·1	2·3	2·4	2·0	1·5	2·6	
C	2·6	3·0	3·3	3·3	3·4	3·0	2·5	2·6	2·7	2·5	2·4	2·6	
D	0	—·4	—·5	—·1	·4	—·1	·4	·3	·3	·5	·9	0	0
1964													
O	4·3	3·9	3·9	4·1	3·2	3·0	1·5	2·2	2·9	2·0	2·2	3·0	
C	3·7	3·4	3·5	4·1	3·5	3·1	2·5	2·6	2·7	2·5	2·5	2·6	
D	—·6	—·5	—·4	0	·3	·1	1·0	·4	—·2	·5	·3	—·4	1
1965													
O	3·1	3·1	4·4	3·1	3·2	3·8	3·3	1·9	2·5	2·4	1·7	2·1	
C	2·8	2·9	3·6	3·3	3·3	3·2	2·8	2·5	2·7	2·6	2·4	2·5	
D	—·3	—·2	—·8	·2	·1	—·6	—·5	·6	·2	·2	·7	·4	0
1966													
O	2·9	3·7	3·9	3·7	4·0	2·2	1·9	2·1	1·8	1·8	1·9	2·3	
C	2·8	3·3	3·6	3·5	4·0	3·0	2·5	2·6	2·5	2·5	2·5	2·5	
D	—·1	—·4	—·3	—·2	0	·8	·6	·5	·7	·7	·6	·2	0
1967													
O	3·0	5·4	3·7	3·9	3·2	2·0	2·5	2·4	2·0	1·3	2·4	1·9	
C	2·8	4·9	3·4	4·2	3·6	2·9	2·7	2·6	2·6	2·4	2·6	2·4	
D	—·2	—·5	—·3	·3	·4	·9	·2	·2	·6	1·1	·2	·5	1
1968													
O	2·9	3·8	3·4	3·1	3·2	2·4	2·0	2·7	2·1	2·2	1·4	2·1	
C	2·8	4·0	3·3	3·4	3·8	3·0	2·5	2·9	2·6	2·6	2·4	2·5	
D	—·1	·2	—·1	·3	·6	·6	·5	·2	·5	·4	1·0	·4	1

O—Observed average C—Computed value D—Deviation @—No. of points exceeding 1·0 mm

Appendix 3

Mean daily evaporation (in mm) as computed from Penman's (1948) (P), Kohler *et al.* (1955) (K) formulae and from Eqn. 1 (E) at four representative months for 9 stations

		Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	@
		Trivandrum				*Madras*				*Hyderabad*				
O		4·9	5·0	3·5	3·8	4·1	6·6	6·7	4·4	5·5	9·5	6·4	5·3	
E	C	4·3	5·4	3·5	3·6	3·7	7·6	5·3	4·3	4·6	10·0	5·8	5·1	2
	D	−0·6	0·4	0	−0·2	−0·4	1·0	−1·3	−0·1	−0·9	0·5	−0·6	−0·2	
P	C	4·0	4·7	3·4	3·7	3·4	5·6	·1	4·2	3·1	5·7	4·2	3·8	6
	D	−0·9	−0·3	−0·1	−0·1	−0·7	−1·0	−1·6	−0·2	−2·4	−3·8	−2·2	−1·5	
K	C	4·6	5·3	3·9	4·2	4·0	6·5	6·1	4·8	4·2	7·4	5·4	4·7	3
	D	−0·3	0·3	0·4	0·4	−0·1	−0·1	−0·5	0·4	−1·3	−2·1	−1·0	−0·6	
		Bombay				*Visakhapatnam*				*Ahmadabad*				
O		3·6	5·7	3·0	4·0	5·7	8·8	6·3	5·7	5·3	11·5	6·2	6·5	
E	C	3·5	5·9	3·3	4·3	5·5	8·4	6·2	6·1	4·9	11·1	6·0	6·3	0
	D	−0·1	0·2	0·3	0·3	−0·2	−0·4	−0·1	0·4	−0·4	−0·4	−0·2	−0·2	
P	C	3·7	5·3	3·3	4·4	3·0	5·4	3·8	4·0	2·9	5·5	4·0	4·3	8
	D	0·1	−0·4	0·3	0·4	−2·7	−3·4	−2·5	−1·7	−2·4	−6·0	−2·2	−2·2	
K	C	3·8	5·4	3·4	4·5	3·0	5·4	3·9	4·4	3·0	5·4	4·1	4·4	6
	D	0·2	0·3	0·4	0·5	−2·7	−3·4	−2·4	−1·3	−2·3	−6·1	−2·1	−2·1	
		Calcutta				*Jaipur*				*New Delhi*				
O		2·4	6·2	4·2	3·3	—	—	—	—	3·3	10·4	6·7	6·2	
E	C	3·0	5·3	4·0	3·7	4·2	10·6	8·2	5·9	4·0	9·4	6·6	5·6	1
	D	0·6	−0·9	−0·2	0·4	—	—	—	—	0·7	−1·0	−0·1	−0·6	
P	C	2·0	5·7	3·7	3·8	2·2	6·0	4·1	4·7	1·5	5·3	4·6	3·9	4
	D	−0·4	−0·5	−0·5	0·5	—	—	—	—	−1·8	−5·1	−2·1	−2·3	
K	C	2·2	5·6	3·8	4·0	2·4	5·7	4·2	4·6	1·9	5·1	4·6	4·0	4
	D	−0·2	−0·6	−0·4	0·7	—	—	—	—	−1·4	−5·3	−2·1	−2·2	

O—Observed average C—Computed value D—Deviation @—No. of points deviating more than 1·0 mm