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Estimation of water balance of Mahanadi catchment upto Hirakud dam site (1962-1966) by Thornthwaite's technique

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ABSTRACT. A presentation of water balance of Mahanadi catchment upto Hirakud dam site by Thornthwaite's method has been made. For this purpose values for the monthly water deficit, water surplus, soil moisture utilisation and soil moisture recharge for the years from 1962 to 1966 have been tabulated and presented graphically.

1. Introduction

The *Mahanadi* is one of the major rivers of the country. It originates near Sihawa at an elevation of 442 m above sea level in the extreme southwest of Raipur district in Madhya Pradesh. Flowing initially in a northeasterly direction and then in a southeasterly direction, it enters Orissa and finally drains into the Bay of Bengal. The upper portion of the river catchment upto Hirakud (Fig. 1) is controlled and its area is 82880 sq. km. The major portion of the catchment which lies in Madhya Pradesh is mostly under forests. The annual normal rainfall is 139·6 cm, of which 87 per cent occurs during the southwest monsoon period. The mean annual evaporation over the controlled catchment area is about 200·0 cm with slightly lower values of evaporation over the eastern parts and higher over the western parts. Further the evaporation is higher in the summer season being of the order of 80·0 cm and lower in the winter season when it is about 30·0 cm. The soil in the basin is mainly of red and yellow type with mixed red and black soil also occuring in many parts of the catchment.

2. Methodology

The concept of book keeping procedure using meteorological parameters for the estimation of climatic water balance was developed by Thornthwaite (1948). The climatic water budget was then modified by Thornthwaite and Mather (1955) to make it more useful over a wide range of soil and vegetation condition. For this the field capacity of the soil was increased from 10 to 30 cm and the rate of soil moisture depletion was found to follow an exponential decay law. Subba Rao and Subrahmanyam (1961) have estimated monthly and yearly run-off from the *Mahanadi*, *Kosi* and *Ashni* rivers assuming the field capacity as 200 mm. Rao *et al.* (1970) have computed climatic water balance for about 350 stations in India on the basis of methodology developed by Thornthwaite and his associates. The above procedure has, therefore, been utilised broadly in the present study.

Numerical values of water surplus and water deficit are computed by the application of simple book keeping technique. For this purpose the precipitation has been considered as income and potential evapotranspiration as outgo. The soil moisture has been treated as reserve that may be drawn as it lasts. The water balance provides the value of evapotranspiration, water deficit and water surplus in the basin. Further, moisture deficit is a measure of droughts and it provides an understanding of economic feasibility of water irrigation. On the other hand, moisture surplus in other periods, provide sufficient water accumulation to permit irrigation during dry period, besides giving an indication of the state of soil for scheduling of time and amount of irrigation.

Information on water surplus is also important for any hydrologic studies which deals with the recharge of the ground watertable or with a runoff in the streams and rivers. It also provides a knowledge of the magnitude of stream flow.

For computation purposes, precipitation (P) is compared with potential evapotranspiration (P_E) on a monthly basis. (P--P_E) may be zero, positive or negative. Positive value of (P--P_E)

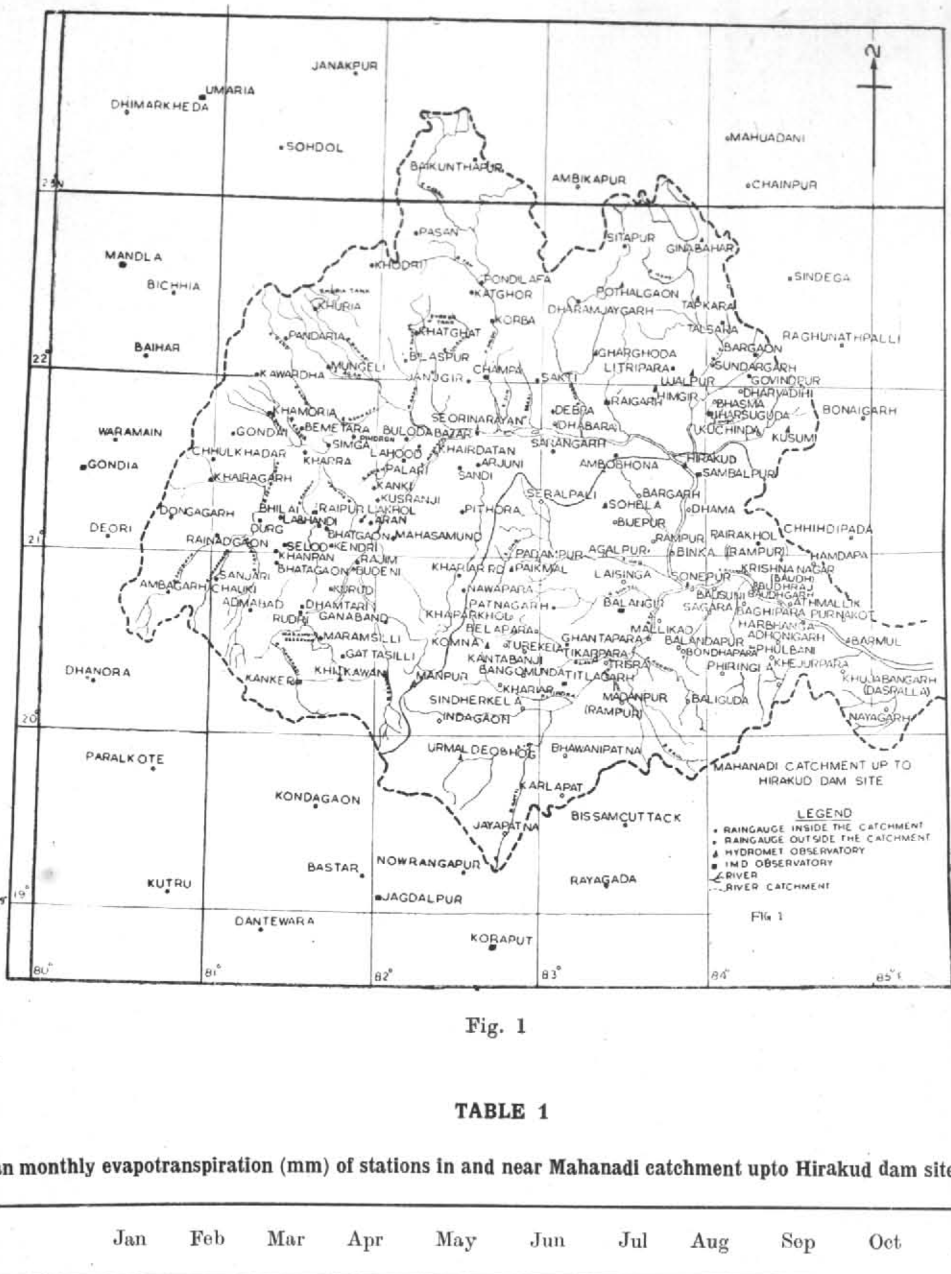

Fig. 1

TABLE 1

Mean monthly evapotranspiration (mm) of stations in and near Mahanadi catchment upto Hirakud dam site (1962)

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Raipur	82 ·5	106 ·1	148 ·8	192 ·3	213 ·9	158 ·1	110 ·7	104 ·5	109 ·2	121 ·5	90 ·3	75 ·3
Jharsuguda	76 ·6	99 ·7	147 ·3	179 ·1	196 ·2	130 ·5	99 ·5	95 ·2	94 ·2	118 ·1	89 ·4	86 ·2
Sambalpur	73 ·5	97 ·2	141 ·7	177 ·6	204 ·9	149 ·1	114 ·7	111 ·9	119 ·7	120 ·3	89 ·7	74 ·7
Ambikapur	69 ·8	90 ·2	140 ·4	182 ·1	209 ·6	165 ·0	124 ·9	109 ·7	112 ·2	104 ·5	78 ·3	60 ·1
Raigarh	72 ·9	94 ·4	136 ·1	165 ·0	191 ·0	124 ·5	100 ·8	91 ·5	92 ·1	114 ·7	81 ·9	70 ·1
Kankar	79 ·7	101 ·4	149 ·4	179 ·4	199 ·0	152 ·7	112 ·2	102 ·6	113 ·1	115 ·9	89 ·1	71 ·9
Umaria	62 ·9	80 ·1	122 ·8	169 ·2	196 ·9	177 ·6	112 ·8	97 ·7	99 ·3	107 ·0	73 ·2	55 ·5
Jagdalpur	79 ·4	97 ·4	138 ·0	157 ·2	159 ·7	119 ·7	89 ·6	93 ·3	96 ·6	101 ·7	86 ·1	72 ·5
Champa	81 ·8	100 ·5	147 ·9	178 ·8	201 ·8	145 ·8	103 ·2	96 ·1	96 ·3	115 ·0	92 ·1	75 ·0
Cuttack	82 ·2	106 ·1	160 ·3	172 ·2	193 ·1	119 ·4	118 ·4	112 ·2	112 ·8	108 ·8	97 ·2	79 ·7

indicates excess of water which is available during certain period in the year for soil moisture recharge and run-off. This happens only when precipitation adds to the soil moisture upto its maximum value of water holding capacity that the resultant water turns into run-off. Further the values of actual evapotranspiration (A_E) is equal to (P_E) when ($P—P_E$) is positive as evapotranspiration can proceed unhindered because of adequacy of available moisture.

When ($P—P_E$) is zero, the potential loss of moisture is exactly supplied by the precipitation and no excess water is available for soil moisture or surface run-off. Negative value of ($P—P_E$) indicates the amount by which the precipitation falls short of the potential water need of vegetation covered area. The value of actual evapotranspiration (A_E) is equal to the precipitation *plus* the amount of water drawn from the soil moisture storage. Accumulated values of ($P—P_E$) in such a case give an estimation of the moisture stored in the soil at the end of the period of negative ($P—P_E$), *i.e.*,

$$\text{Storage} = \text{Field capacity} \times \exp\left[\frac{-\Sigma\,(P-P_E)}{\text{Field capacity}}\right]$$

The amount by which the potential and the actual evapotranspiration differs in any month is the moisture deficit for that month. On the other hand when the soil moisture storage reaches the field capacity, any excess precipitation is treated as moisture surplus resulting in surface run-off. For medium basin of the type of controlled portion of the Mahanadi catchment, it is generally experienced that during rainy months about 70 per cent of the surplus water contributes to the surface run-off and the remaining 30 per cent of the surplus water is retained in the catchment as storage and the same is available for run-off during the subsequent months.

3. Data used

The precipitation data of 72 stations including observatory stations located uniformly in the catchment are collected from rainfall volumes of Madhya Pradesh and Orissa for the period 1961 to 1966. While computing yearly data value of soil moisture retention of December 1961 (Table 2a) has been carried over to January 1962. Potential evapotranspiration for 9 stations in and near the catchment, *viz.*, Raipur, Kanker, Umeria, Jagdalpur, Champa, Raigarh, Sambalpur, Jharsuguda and Ambikapur has been estimated by Penman's method. The details of computation have been given in the Appendix. The mean monthly evapotranspiration of these stations is included in

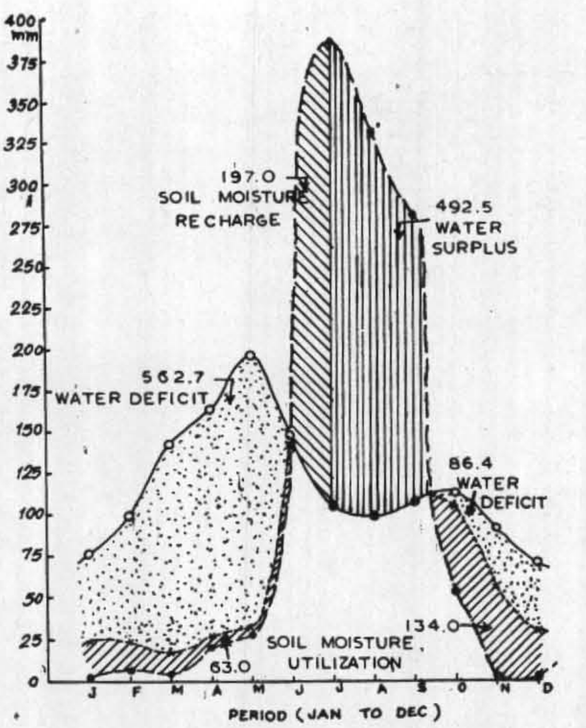

Fig. 2. Water balance of Mahanadi catchment (1963)

Table 1. The water holding capacity of the soil has been adopted to be 200·0 mm after taking into consideration the nature of the soil and the general terrain condition of the study area.

4. Discussion and results

Values have been computed by utilising the above mentioned data. These values give the magnitude of the various parameters of water balance of Mahanadi catchment year by year from 1962 to 1966 (Table 2 a & b) as also their average values for the same period (*see* Figs. 2-6).

For the year 1962, the various water balance parameters are given in Table 2 (b). It may be seen that precipitation (P) varied from a low value of 1·1 mm in January and 0·4 mm in November to higher values of about 100·0 to 300·0 mm in the rainy months of June to September. The annual precipitation recorded was 878·9 mm. The potential evapotranspiration was 75.4 mm in January and its value increased gradually to 197.0 mm in May. Thereafter, it decreased to 147·0 mm in June and 100·3 mm in August. During the rainy months of July, August, September and October, potential evapotranspiration was of the order of 110·0 mm and remained more or less constant. In November and December it

TABLE 2

Water balance of Mahanadi catchment

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
						(a) 1961							
P	1·3	34·7	1·8	6·4	13·9	330·0	483·0	441·3	431·4	69·8	1·5	4·6	
P_E	79·4	89·8	153·7	174·2	194·8	134·3	103·8	97·4	90·8	100·2	82·2	66·1	
$(P—P_E)$	—78·1	—55·1	—151·9	—167·8	—180·9	195·7	379·2	343·9	349·6	—30·4	—80·7	—61·5	
Acc. $(P—P_E)$										—30·4	—111·1	—172·6	
S							200·0	200·0	200·0	172·0	114·0	83·0	
$\triangle S$								0	0	—28·0	—58·0	—31·0	
A_E								97·4	90·8	97·8	59·5	35·6	
W_D								0	0	2·4	22·7	30·5	
W_S								343·9	340·6	0	0	0	
D_t								103·2	133·1	39·9	12·0	3·6	
R_0								240.7	310·7	93·2	27·9	8·4	
						(b) 1962							
P ..	1·1	7·7	10·4	9·1	13·3	112·2	289·2	215·5	173·6	18·7	0·4	27·7	878·9
P_E	75.4	96.3	141.4	175.6	197.0	147.0	107.6	100.3	103.6	109.7	85.6	71.3	1410.8
$(P—P_E)$	—74·3	—88·6	—131·0	—166·5	—183·7	—34·8	181·6	115·2	70·0	—91·0	—85·2	—43·6	
Acc. $(P—P_E)$	246·9	—335·5	—466·5	—633·0	—816·7	—851·5	—	—	—	—91·0	—176·2	—219·8	
S	57·0	36·0	19·0	8·0	4·0	3·0	184·6	200·0	200·0	126·0	82·0	66·0	
$\triangle S$	—26·0	—21·0	—17·0	—11·0	—4·0	—1·0	181·6	15·4	0·0	—74·0	—44·0	—16·0	
A_E	27·1	28·7	27·4	20·1	17·3	113·2	107·6	100·3	103·6	92·7	44·4	43·7	726·1
W_D	48·3	67·6	114·0	155·5	179·7	33·8	0·0	0·0	0·0	17·0	41·2	27·6	684·7
W_S	0·0	0·0	0·0	0·0	0·0	0·0	0·0	99·8	70·0	0·0	0·0	0·0	169·8
D_t	1·1	0·3	0·1	—	—	—	—	29·9	30·0	9·0	2·7	0·8	
R_0	2·5	0·8	0·2	—	—	—	—	69·9	69·9	21·0	6·3	1·9	172·5

All parameters in mm

P =Precipitation A_E =Actual evapotranspiration

P_E =Potential evapotranspiration, W_D =Water deficit

Acc. $(P—P_E)$=Accumulated $(P—P_E)$ -ve values, W_S=Water surplus

S =Storage=F. C. $\times$ exp. $\left[\frac{\Sigma—(P—P_E)}{\text{F. C.}} \right]$ D_t =Detention

$\triangle S$ = Change in storage R_0 = Run-off

F. C. =Field capacity of the soil

again decreased to 85·6 mm and 71·3 mm respectively. The annual potential evapotranspiration in 1962 was 1410·8 mm.

During the period from January to June and October to December the water need of vegetation exceeded precipitation. The storage, therefore, lowered down and the lowest value of storage was 3·0 mm, about 1·5 per cent of the field capacity in June 1962. During rainy months of July, August and September, water needs of plants fell much below the precipitation, thereby making the rain water surplus. In the initial stages starting with the months of July, the surplus rain water replenished soil moisture that was used up during earlier months. In the months of August and September the surplus water after bringing the storage back to field capacity of 200·0 mm yielded surface run-off. The storage, which remained at field capacity during the months of August and September decreased during October, November and December.

As precipitation exceeds the water needs during the rainy months, the surplus water is retained in the lower layers of the soil. The actual evapotranspiration (A_E) equals to potential evapotranspiration (P_E) during this period. But when (P) was less than (P_E) during the periods, from January to June and from October to December, the soil dried up, the actual evapotranspiration was less than the potential evapotranspiration and a moisture deficit equal to the difference between these two quantities existed. The total potential evapotranspiration in the catchment during the year 1962 was 1410·8 mm while the actual evapotranspiration was 726·1 mm thereby resulting in a water deficit of 684·7 mm during the year.

From a perusal of graphs shown in Figs. 2, 3, 4 and 5 respectively, the values of various parameters of water balance pertaining to years 1963, '64, '65 and 1966 it is seen that though almost similar features with regard to water surplus and water deficit epoch are found, yet with regard to their magnitudes large variations exist. Generally, July, August and September are water surplus months but in the year 1962 there was no surplus water available during the month of July and in the year 1965 even in the month of August there was no surplus water. This resulted in a low value of 169·8 mm of surplus water in 1962 and as low as 63·1 mm only in 1965 due to scanty rains. Correspondingly there was large deficit in these years as much as 684·7 mm in 1962 and 1728·1 mm in 1965.

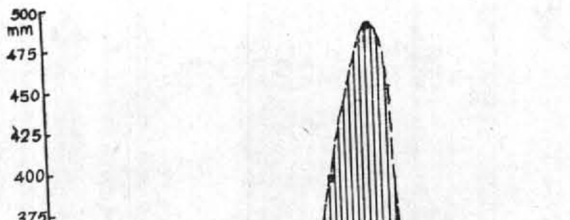

Fig. 3. Water balance of Mahanadi catchment (1964)

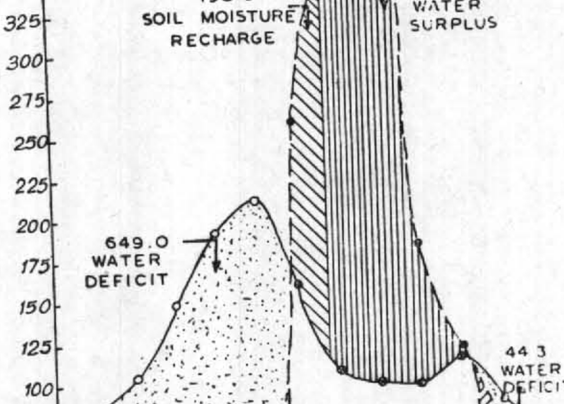

Fig. 4. Water balance of Mahanadi catchment (1965)

5. Average conditions in the basin

The average monthly conditions of precipitation, potential evapotranspirations and other parameters in the water balance are shown in Fig. 6 which depicts the march of these parameters through the year graphically.

Potential evapotranspiration varies continuously through the year from the low value of 70·5 mm in December and 78·1 mm in January to a high value of 200·5 mm in May being the highest value for the year. The total average potential evapotranspiration (P_E) for the year is 1437·4 mm. The precipitation (P) is much more variable than potential evapotranspiration (P_E). It is as low as 4·1 mm in November and 4.4 mm in January and as high as 316·2 mm in July and 281·4 mm in August respectively. The average annual precipitation in the portion of the catchment under study is 1061·2 mm.

The demand for water in terms of potential evapotranspiration is very much in excess of the precipitation during the periods from January to May and October to December. During the periods from January to May, the water deficit increased month by month and the maximum water deficit occurs in May when its average value is 183·9 mm. This water deficit period is again repeated during the period from October to December. The total water deficit, on an average during the year is 674·6 mm.

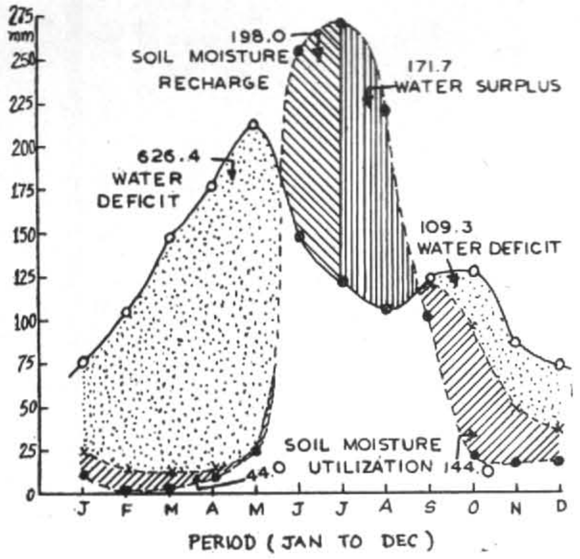

Fig. 5. Water balance of Mahanadi catchment (1966)

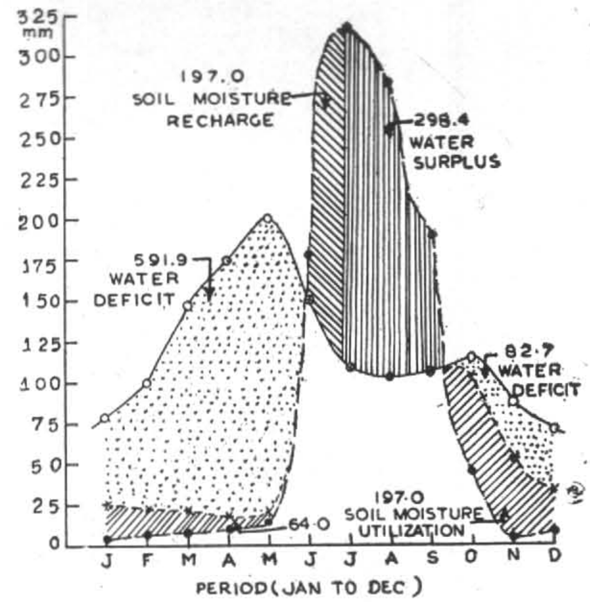

Fig. 6. Water balance of Mahanadi catchment (1962-66) average

It is only during the rainy months of July, August and September that the excess water over and above the potential evaporation needs is stored in the soil resulting in the upper layers attaining the field capacity of 200·0 mm in these months. Any excess precipitation in these months contributes to water surplus as run-off. The average total surplus water round the year is 298·4 mm only.

6. Soil moisture utilization

During the non-rainy months from January to May and from October to December, evaporation needs are not fully supplied by precipitation in the catchment under study. This part of the requirement is, however, met from the moisture stored in the soil. The average accumulated need for this water round the year is 197·0 mm.

7. Soil moisture recharge

After the spells of water deficit and constant use of soil moisture storage to supply some of the needs of plants and crops, it is only in the month of July when appreciable rain occurs that the soil comes back to its field capacity of 200·0 mm after the supply of 197·0 mm of water as water recharge.

8. Conclusion

An analysis of data shows tentatively that the basin falls short of the potential water needs of crops and vegetation during the period from January to May and again from October to December. It is only during the months of July, August and September when sufficient surplus water is available as storage and run-oft. Therefore the finding would seem to show that the basin is actually very much in deficit of its potential water needs through the year.

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REFERENCES

Rao, K. N., Georgo, C. J. and Ramasastry, K. S. 1970 Scientific paper presented at Technical Conference of Hydrological and Meteorological Services, Geneva, WMO No. 304.

Subba Rao, B. and Subrahmanyam, V. P. 1961 Estimation of yields from river basins by a modification of Water Balance procedure of Thornthwaite, *Indian J. Met. Geophys.*, **12**, p. 339.

Thornthwaite, C. W. 1948 An approach towards a Rational Classification of Climate, *Geographical Rev.*, **38**, 1.

Thornthwaite, C. W. and Mather, J. R. 1955 *Water Balance*, Publication in Climatology, **8**, 1.

Appendix

Penman's formula for the computation of potential evapotranspiration is as follows

$$P_E = \frac{\frac{P_0}{P_h} \cdot \frac{\triangle}{\gamma} \left[R_A \left(1-r\right) \left\{ 0.29 \cos\varphi + 0.52\,(1-m) \right\} - \sigma\, T^4 \left(0.56-0.092 \sqrt{e_d}\right) \times \left(0.10 + 0.90\,(1-m)\right) \right] + 0.35 \left(e_a - e_d \right) \left(1 + u/100 \right)}{\left(\frac{\triangle}{r} + 1\right) \frac{P_0}{P_h}}$$

where,

P_E = Potential evapotranspiration (mm/day)

R_A = Incident radiation outside the top of the atmosphere on horizontal surface expressed in mm of evaporable water /day.

r = Albedo = 0·25

m = Average cloudiness at 0830 and 1730 hr expressed as a decimal factor.

T = Mean temp. in degree Absolute.

σT^4 = Black body radiation at mean temp.

e_a = Saturation vapour pressure in mm of Hg.

e_d = Actual mean vapour pressure in mm of Hg.

u = Wind speed at 2 m above the ground (miles/day)

$\triangle$ = Rate of change of saturation vapour pressure with temp. (mb/°C)

γ = Psychrometric const. (mb /°C)=0·66 mb/°C

φ = Latitude of the station

P_0 = Sea leval pressure 1013·2 mb

P_h = Station level pressure (mb)

The formula has been computerised and results on evapotranspiration for the ten stations have been obtained on computer.

One example of estimation of evapotranspiration for Raipur for January 1962 by Penman's formula, worked out is given below:

$P_0 = 1013.2$ mb	$\phi = 21.2°$	Max. temp. = 26.3°C	t (mean) = 18.9°C
$P_h = 981.9$ mb	$m = 0.12$	Min. temp. = 11.6°C	$T = 291.9$°A
$e_a = 16.39$ mm	$r = 0.25$	$\sigma = 2.01 \times 10^{-9}$ mm / day	
$e_d = 10.95$ mb (8.23 mm)		$u_h = 4.5$ km / hour	

$$\triangle = \frac{e_a}{T} \left(\frac{6790.498}{T} - 5.02808 \right) \text{mb}/°\text{C}$$

$$= \frac{16.39 \times 1.333}{291.4} \left(\frac{6790.498}{291.4} - 5.02808 \right) = 1.37 \text{ mb}/°\text{C}$$

$$\sigma T^4 = 2.01 \times 10^{-9}\,(291.4)^4 = 14{\cdot}59 \text{ mm / day}$$

$$u = u_h \left(\frac{2}{h}\right)^{0.17} \times \frac{5}{8} \times 24 = u_h \times 11.4 = 4.5 \times 11.4 = 51.3 \text{ miles / day}$$

$$P_E = \frac{\dfrac{1013.2}{981.9} \times \dfrac{1.37}{0.66}\left[10.58\left(1 - 0{\cdot}25\right)\left\{0.29 \times 0{\cdot}9323 + 0.52\left(1 - 0.12\right)\right\} - 14.59\left(0.56 - 0.092 \times 2.8\right)\left(0{\cdot}10 + 0.90\,(1 - 0.12)\right)\right] + 0.35\left(16.39 - 8.23\right)\left(1 + \dfrac{51.3}{100}\right)}{\left(\dfrac{1.37}{0.66} + 1\right)\dfrac{1013.2}{981.9}}$$

$$= \frac{8.33}{3{\cdot}18} = 2.62 \text{ mm / day} = 2.62 \times 31 = 81.2 \text{ mm / month}$$