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CONTENTS

HYDROLOGICAL REGIONS IN THE BUNDELKHAND: THE CATCHMENTS OF BETWA AND KEN RIVERS

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Introduction

Rainfall is certainly a basic input parameter in hydrological process but for utilisation purpose it cannot be taken as true measure of the total availability of water. The amount of water left after -satisfying all natural needs like evaporation and transpiration determines the overall availability of water as runoff. Therefore, scientific estimation of water needs becomes necessary. One of the most important methods to determine water needs and subsequent runoff is that of water balance based on climatological approach.

Review of Literature

To determine water need, the concept of potential evapotranspiration introduced by Thornthwaite (1948), still remains the most useful parameter. He related the plant growth and transpiration to temperature and day length. At the same time, another significant attempt towards the estimation of PET was made by Penman (1948). He suggested a combination of two theoretical approaches to evaporation from saturation surfaces -the first being on an aerodynamic basis in which evaporation is regarded as due to turbulent transport of vapour of a process of eddy diffusion and the second being on energy basis in which evaporation is regarded as one of the ways of degrading incoming radiation. To test these theories, he had conducted experiments at Rothamsted and caliberated the results. This computation for PET was further modified by Penman himself in 1955 while carrying out studies in American watersheds. Basic principles and general approaches to describe evaporation were later on outlined by Tanner (1968). In order to overcome the empiricism involved in PET computation, a generalised computer programme has been written by Chidley and Pike (1970) to cater for a number of options in data input. Monteith (1981) discussed various regional applications of PET in different environmental conditions are also being considered (Bruin, 1988). Recently, the multiplicity of approaches to estimate water balance has been demonstrated practically in West-Central Florida. Further, other components of water balance (precipitation, rate of soil moisture rate) have also been evaluated independently from the general equation (Bidlake and Boetcher, 1992). Another conceptual model of water balance has been developed by Ponce and Shetty (1995). Given a set of model parameters, the method can be used to separate annual precipitation into its three major components: surface runoff, base flow and vapourization. Of late, the search for theories and models has, thus enhanced the need for

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precision and improvements in observation and analysis with the availability of remotely sensed data and GIS facility. Regional estimates of evaporation and PET have been made using surface-temperatures, soil moisture, albedo, vegetative cover and incoming solar radiation (Singh and Fiorento, 1996).

After the publication of famous Thornthwaite's article, the concept of classification of climates based on potential e ~ apotranspiration leading to water balance studies became popular in Indian geographical studies too. The most significant and leading contribution in this field was made by Subrahmanyam of Andhra University in 1956. He following the interpolation methods of Carter, prepared maps covering whole of Indian sub-continent to show the spatial pattern of average annual water surplus and deficit. Penman's method was, however, followed lately in Indian studies (Rao et al., 1971). In order to compute PET at all the climatological stations in India, they even introduced some of the modifications in the formula. Till now most of the water balance studies in India make use of this PET as a secondary data source Krishnamurthy and others (1971) have developed a combination approach using Penman's and Kohler's method to estimate PET. A detailed review of all the existing Indian and foreign attempts to estimate PET has been presented by Fannon (1973). In an another comparison of annual water surplus and deficit obtained by averaging the results of 18 years, it was found that the values thus obtained are larger in comparison to those based on mean temperature and precipitation data for 30-year period (1931-60). Further variability in water surplus was greater than the water variability in water deficit at each station (Pandeya and Prasad, 1983). This study is also important in the sense that like the representation of moisture and dryness of climate introduced after the schemes of Kira, De-Martonne, Lang, Koeppen and Thornthwaite, they have also delineated hydrological regions in association with water balance omponents for the stations in Bihar. Some basin-wise water budget studies have also been made to stress the need for conservation of water resources different courses of streams like the highlands of Upper Vaigai can serve to thirsty lands of the basin (Vishwanath and Ganesh (1985). Thus, in the 80's application of water balance studies became popular in India, particularly in the field of agricultural planning based on old classification system of Thornthwaite and Subrahmanyam. Using the latter's moisture adequacy index, a similarity in the cropping pattern and agricultural practices was suggested within each of the identified agro-climatic zones in Maharashtra (Subramaniam and Smannarayana, 1991). The most important agro-climatic information resulting from water balance equation, i.e. the duration of growing season has been used to suggest the length of periods required for various crops in Gujarat (Pandey and Gupta, 1991). A very good picture of the water balance for the normal as well as extreme years has been described to classify the climates in Uttar Pradesh, wheein a comparison id also made for the results based on Thornthawaite and Penman formulae (Devi, 1992). Seasonal water balance and cropping pattern relations in the case of Andhra Pradesh (Madhuramma and Rao, 1993) and departures of moisture indices in Bihar (Dwivedi, 1993) have demonstrated the practical applicability of water balance technique to suggest crop practices and to identify drought prone areas respectively. However, for other extreme, i.e.

flood it was not found to be that useful as exemplified by one study done in West Bengal (Sircar, 1994). Subsequently, a refinement of the some of the broad climate type has also been attempted on all India basis to define climatic map of India based on FAO's model (Mandal and Srinivas, 1996)

In geography thus, there is an overwhelming reliance upon runoff estimates based on climatological water balance approach as compared to yield estimates derived by hydrological correlation. Numerous water balance studies employing empirical approach of Thornthwaite and Penman method pose problems to researcher for determining/adopting value of constants in different regions. The accuracy of results, therefore, can be determined either by direct, i.e. measurements or through cross checking of figures by different methods.

Objectives

The purpose of the present study is, thus, to estimate the quantity of surface water resource in the region and to assess the regional variations in moisture regime

Study Area

A geologically and historically distinct region -Bundelkhand has been selected for study. The boundaries of the region as defined by Singh (1971) have been extended for the entire basins of Betwa and Ken, which are the important southern tributaries of the river Yamuna. It extends from 23°0' N. to 26°30' N and 78°10'E to 81°30'E and covers five districts (including parts) of Uttar Pradesh (Jalaun, Jhansi, Lalitpur, Hamirpur and Banda) and fifteen districts of Madhya Pradesh (Chhattarpur, Tikamgarh, Panna Sagar, Vidisha, Damoh Satna, Datia, Raisen, Jabalpur, Narsinghpur, Guna, Shivpuri, Bhopal and Sehore).

It falls in the transitional zone of rainfall (75 to 125 cm) and geology, in addition to its own central Bundelkhand massif forms the intermediate zone between northern alluvial plains of the Yamuna and the southern Vindhyas plateau. The soil of the region ranging from alluvial deposits to red and black in the south possess different moisture holding capacities. Therefore, large variations are found in irrigation network and agricultural productivity Dissected relief, badlands, ephemeral and non-perennial streams have further accentuated the National problems of the region.

Methods

The present research work is based on secondary data obtained from Indian Meteorological Department (IMD), Central Water Commission (CWC) and Water Development Agency (NWDA)

To estimate the quantity of available runoff, a simple equation put forward by Thornthwaite is used as initial framework. This climatological sed water balance equation (1), requires estimation of every component on its right hand side as shown below:

$$P = PET + R_o \pm \Delta SM \quad \ldots Eq. (1)$$

$$\Rightarrow \text{(surplus - deficit)}\ R_o = PET - P \pm \Delta SM$$

$$\Rightarrow \text{where, surplus} = (P - PET) - |\Delta SM| \quad \text{when } P > PET$$

$$\text{deficit} = PET - AET \quad \text{when } PET > AET$$

PET, the most important factor, is calculated by both the formulae (Penman & Thornthwaite) as listed below :

a) Penman PET (modified form)

Energy -budget term — Aerodynamic term

$$E_t = \frac{P_0/P_h.\Delta/\Upsilon[\{R_A(1-\alpha)\{0.29\cos\phi + 0.52(1-m/10)\} - \sigma T_a^4(0.56 - 0.092\sqrt{e_a})(1-0.09m)\} + \{(1+alt/20{,}000)(0.13 + 0.0016u_2)(e_s - e_a)\}]}{1 + (P_0/P_h.\Delta/\Upsilon)}$$

where, ...Eq. (2)

P_0 = mean sea level pressure (=1013.2 mb)

P_h = mean station level pressure (mb)

Δ = slope of the vapour pressure vs. temperature ($=\partial e_s / \partial T_k$)

Υ = psychometric constant (0.66 mb/^{0}C)

R_A = extra-terrestrial radiation

α = albedo (reflection coefficient=0.25)

ϕ = latitude

m = cloud cover (in tenths of sky)

σ = Stefan Boltzman's constant [$=1.17X10^{-7}$ Ca / K^4/ cm^2/ day]

T_a = average air temperature (Kelvin) ($K=T^0$ (C) + 273.16)

e_a = actual vapour pressure (mb)

e_s = saturated vapour pressure (mb)

u_2 = wind speed (km/day) at 2 metre height [$u\,(2/z)^{0.17}$

z = height of wind speed measurement (33' or10mt)]

alt = height of the station (metres)

Here, e_s is calculated by Goff-Kirchoff formula as

$$e_s = \exp\{54.878919 - \frac{67.04958}{T_K} - 5.20808 \ln T_K\}$$ ...Eq. (3)

(b) Thornthwaite's PET

$$E_t = 16\left[\frac{T_a}{I}\right]^a$$ ...Eq. (4)

where, T_{ai} = mean air temperature (^{0}C)

I = annual heat index [$=\Sigma(T_a/2)^{1.5}$] for i = 1 to 12

a = constant ($0.000000675I^3 - 0.0000771I^2 + 0.0179I + 0.49239$)

Adjusted PE_t = Unadjusted $PE_t \times$ C.F. where, C.F. = correction factor for hours and day in a month

Both the PETs are then compared statistically and graphically with the observed data at nearby observatory, Allahabad as no evaporimeter is installed at any of the five observatories (Bhopal, Sagar, Nowgong, Jhansi, Banda) located within the study area. Even the readings at Allahabad do not correspond with the average time period involved in PET computations. But, still a rough idea can be obtained about an approximation to reality. Thereafter, other components of water balance based on both the methods have been calculated according to the bookkeeping procedure as outlined in the manual published by Thornthwaite and Mather in 1955. Results of the computations are compared graphically and a more clear representation of their areal extent is presented with the help of moisture indices (M.I.) is then used to delimit moisture regions and is given by the expression (Thornthwaite, 1948):

$$M.I. = \left(\frac{100S - 60D}{PET}\right) \text{ or } I_h - 0.6I_a \quad ..Eq. (5)$$

where, I_h (humidity index) = S/PET x 100,

I_a (aridity index) = D/PET x 100

S = annual surplus

D = annual deficit

Thus, positive moisture index indicates wet climate and negative value indicates dry climate. The seasonal concentration of moisture index i.e., I_h and I_a can also be determined within these extremes as shown in Table 1.

Table 1: Moisture Index and its Seasonal Variation in the Classification of climates

Moisture Regions	Climatic Types	Moisture Index(%)	Seasonal Variation of Effective moisture: Moist Climate	The Humidity Index(%)
A	Prehumid	> 100	Little or no water deficiency(r)	0-10
B_4		80-100	Moderate summer deficiency(s)	10-20
B_3		60-80	Moderate winter deficiency (w)	10-20
B_2	Humid	40-60	Large summer deficiency(s_2)	20+
B_1		20-40	Large winter deficiency (w_2)	20+
C_2	Moist Subhumid	0-20		
	-33.0.0		Aridity	
		-66.7 to 33.3	Dry Climate	Index (%)
		< - 66.7		
C_1	Dry Subhumid		Little or no water surplus (d)	0-16.7
D	Semi-Arid		Moderate winter water surplus (s)	16.7-33.3
E	Arid		Moderate summer water surplus (w)	16.7-33.3
			Large winter water surplus (s_2)	33.3+
			Large summer water surplus (w_2)	33.3+

Source: Thornthwaite, C.W. (1948). "An Approach toward Rational classification of climates". *Geographical Review,* 38: 105-67.

The spatial variation in moisture index based on both the methods of PETcomputation is shown by drawing isopleth maps Further, to show absolute contributions of surplus and deficit amount, various combinations of their range are used in the reverse order so that the region having more surplus is superimposed over the region having lower deficit value Thus, the average hydrological regions as suggested by Pandeya and Prasad for the Bihar State are attempted here for the limited stations only because both the methods -Penman and Thornthwaite are used for comparison wherein the former requiring more parameters represents larger territories.

Lastly, the utility of climatological water balance approach in determining the availability of surface runoff at selected points (which may be considered as representative of the yield in the surrounding areas) is compared with the hydrologically determined average surface water yield estimates of the catchments. This yield, although obtained from secondary sources, is also based on indirect estimates of runoff Vi extended from a logarithmic regression equation

$Y_i = aX_i = \log a + b \log X_i$ ...Eq.(6)
where, X_i = annual weighted rainfall
a = intercept and b = slope of equation

Results and Discussions

The most important factor in water Balance computation is PET upon which all other calculations are dependent in a sequence. Therefore, individual components of PET have been discussed first. In Penman's method, evaluation of energy-budget and aerodynamic components helps in understanding of PET variation as described below:

A) Through energv-budget approach $[Q_n = Q_{is} - Q_{rs} - Q_{lw}]$ net energy balance among incoming solar radiation, reflected solar radiation and net long-wave radiation is obtained:

i) Incoming Solar Radiation $[Q_{is} = R_A \{0.29 \cos f + 0.52 (1\text{-}m/10)\}]$

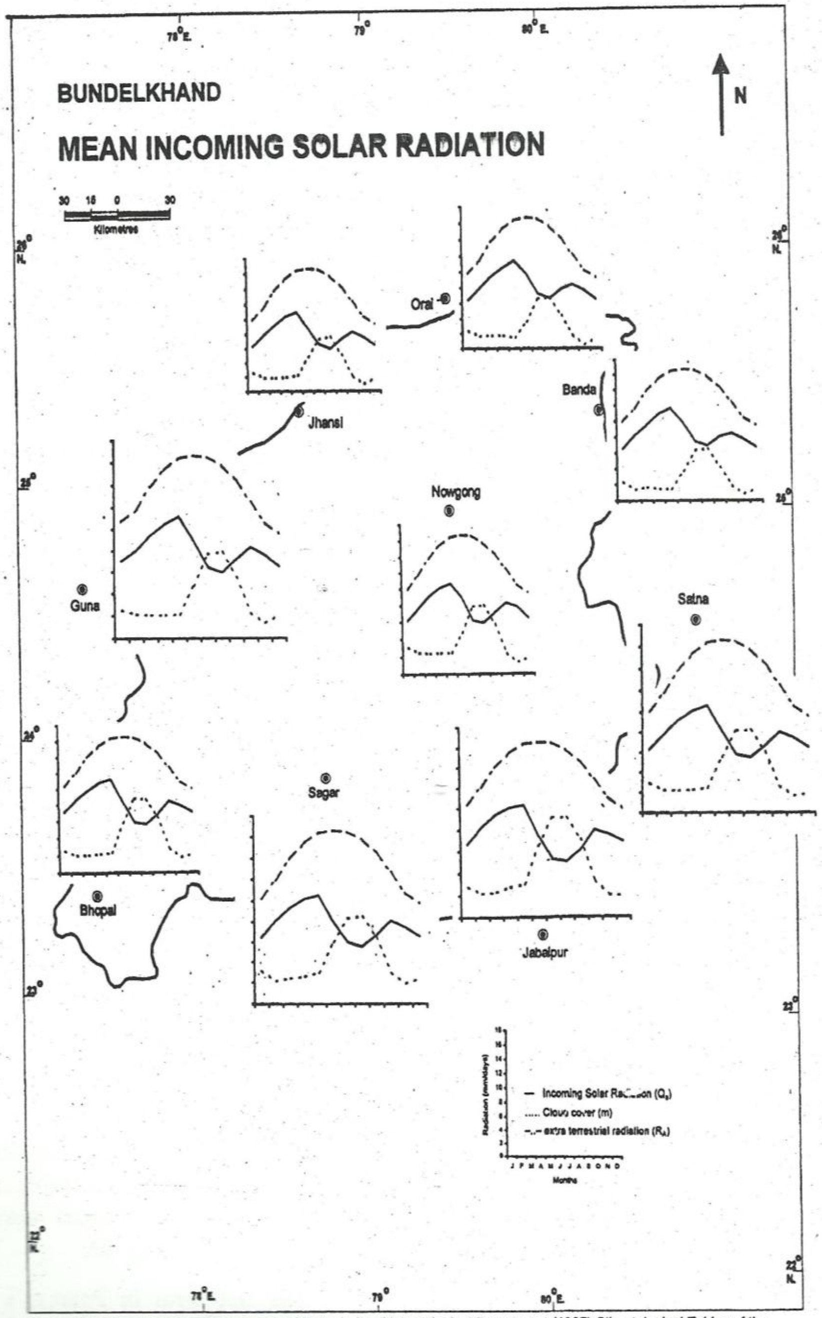
As the latitudinal extent of the region remains between *23°* and 26°N therefore, the value of 0.29 cosf varies slightly from 0.26 to 0.27 only. Thus, first factor in equation (2) can be considered as almost constant. The variation of incoming solar radiation can be explained by extra-terrestrial radiation (RA) and cloud over component (m). The former coefficient (R_A) follows a smooth curve reaching its peak in the month of June when extra-terrestrial radiation, in concomitancy with earth's solar radiation cycle, attains maximam point at the time of summer solstice. On the other hand, cloud cover becomes maximum during monsoon season. Therefore, the fraction of clear sky represented by (1-m/10) gets considerably reduced in the rainy season. It increases thereafter in the post-monsoon season and after registering a slight decrease during winter it again becomes maximum in the pre-monsoon season. The net effect of the two factors thus becomes maximum in the hot summer season whereby May becomes the hottest month of the year.

The spatial variation of incoming solar radiation reflects that there exists common maxim in the month of May at all the observatories. Its magnitude increases towards plateau region mainly because of larger amount of incoming solar radiation received in these lower latitudes (Fig. 1)

ii) Reflected Solar Radiation $[Q_{rs} = aQ_s]$

It is generally taken as percentage of the total incoming radiation Albedo(a) value of 0.05, the reflectivity of water surface was adopted by Penman (1948) to calculate evaporation from free water surface which was then multiplied by various coefficients to get potential evpotranspiration (PET) from-bare soil, grass or other crops. A direct estimate of PET can be made if a suitable reflection coefficient is used in radiation equation itself.

i.e., $Q_s = Q_{is} (1 - a)$
For a = 0.25, $Q_s = 0.75 Q_{is}$
(for vegetation cover as suggested by Monteith.)



Source : Based on data from Government of India, Indian Meteorological Department (1967) Climatological Tables of the Observatories, 1931-60.

Figure 1: Mean Incoming Solar Radiation

Thus, total incoming radiation is taken as 3/4th of Q_{is} which has already been evaluated.

(iii) Net Long Wave Radiation *[$Q_{lw} = sT_a^4$ (0.56 - 0.092 Öe$_a$)(1- 0.09m)]*

Of the three factors involved in the computation of long-wave radiation, sT_a^4 follows the same pattern as that of net incoming solar radiation. It becomes maximum in the month of May. But, its spatial distribution shows a southward decline because of low mean temperature observed in the higher altitudinal zones of plateau region.

As the atmospheric vapour pressure depends directly upon relative humidity, therefore its highest value is reached during monsoon season Conversely, the dryness of air represented by the second term, i.e. (0.56 - 0.092 Öe$_a$) bears a direct relationship with the amount of clear skies represented by the term (1-0.09 m). Due to inverted shape of curves, both these terms attain their maximum value during winter and pre-monsoon season. The combined effect of the two, thus, results in early maxims of net long-wave radiation in the month of March or April than that of net incoming solar radiation. However, the spatial variation reflects the same pattern of increase towards plateau region. (Fig. 2)

B) Evaluation of Aerodynamic term

i) *Wind Speed Function* [f(u) = (0.13 + 0.0016 u_2)]

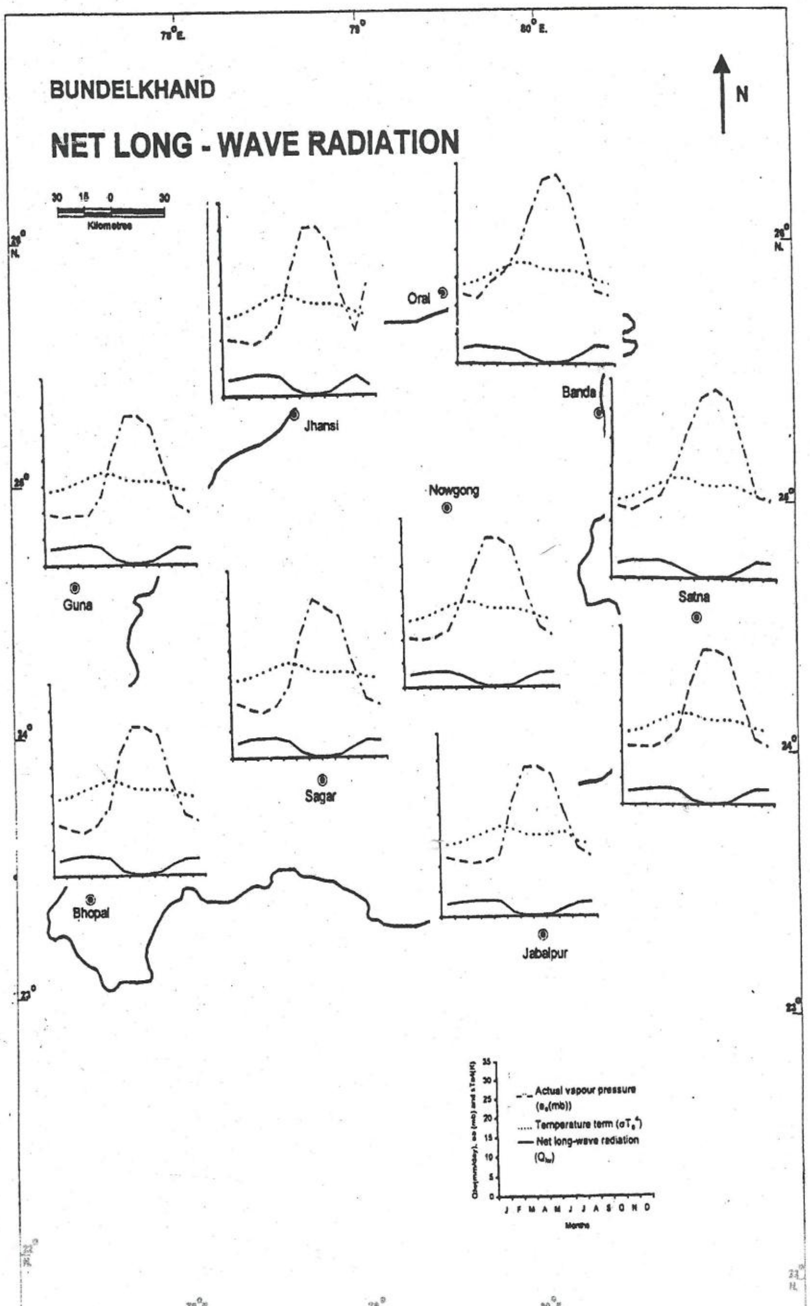
The computations for the wind speed function f(u) bear, obviously, a direct relationship with the mean wind speed. Maximum wind speed is recorded in the month of June when strong winds flow towards north-western low of thermal origin. The magnitude of wind function increases towards plateau region where steeper convergence gradient results in wind speed of more than 13 km/hour during summer.

ii) *Saturation Vapour Pressure Deficit* [(De = e_s-e_a)]

The second term in the aerodynamic equation is known as saturation vapour pressure deficit. Actual vapour pressure increases during monsoon months but due to lower mean temperature, atmospheric vapour pressure becomes closer to saturation limits Therefore, maximum saturation vapour pressure deficit occurs in the month of May because it is in this month heated air gets maximum capacity to absorb moisture. The maximum amount of deficit is found near north-western (Jhansi) and southeastern margins of the region due to lower actual vapour pressure in pre-summer months. To the contrary, the deficit becomes narrower in the intervening valley and plain areas (Fig. 3).

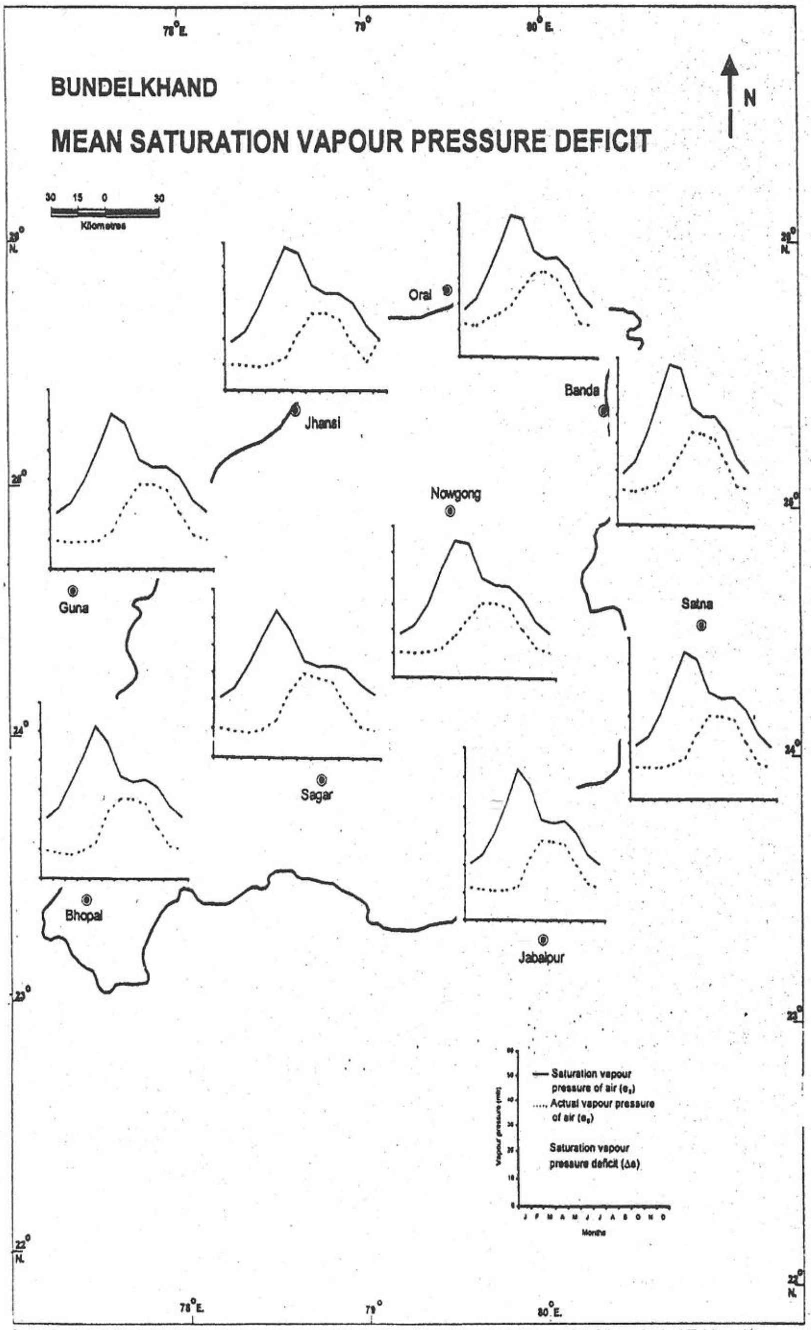
The aerodynamic equation has further been modified by McCulloh to measure the effect of altitude by multiplying it with the factor (1+ alt/20,000). Since the observatories in the study region have comparatively little variation in their absolute heights ranging from 153 to 653 m at Banda Sagar respectively, therefore the correction factor wind function in equation (2) will not account for much differences in aerodynamic term (E_a) obtained previously by multiplying f(u) with De.

The last term in Penman's PET equation is concerned with the determination of a ratio (D/g). The slope (D) is computed by taking derivative of equation (3) w.r.t. temperature.



Source : Based on data from Government of India, Indian Meteorological Department (1967) Climatological Tables of the Observatories, 1931-60.

Figure 2: Net Long-Wave Radiation



Source : Based on data from Government of India, Indian Meteorological Department (1967) Climatological Tables of the Observatories, 1931-60

Figure 3: Mean Saturation Vapour Pressure Deficit

In the final PET computations, the net effect of two approaches gets reflected. The relative importance of various components also varies seasonally. Net radiation (Q_n) shows its maxim in the month of June and thereby reflects the strong contribution of net incoming short-wave radiation as compared to net outgoing long-wave radiation. The contribution of aerodynamic term, on the other hand, becomes maximum during pre-monsoon hot summer season. The contribution of strong winds and high saturation vapour pressure towards the estimation of PET can also be seen in this season. In this context, the importance of dimensionless coefficient (k) cannot be neglected since it is the only term occurring in both the denominator and numerator of Penman's equation. Despite the increase in k value during summer and thereby accounting for larger fraction of denominator, PET value does not decline to the extent that it can delay the maxim produced by aerodynamic term in the numerator. Thus, PET maxima occurs in the months of May. A light increase in PET values also occurs towards the end of monsoon season in September when skies becomes clear.

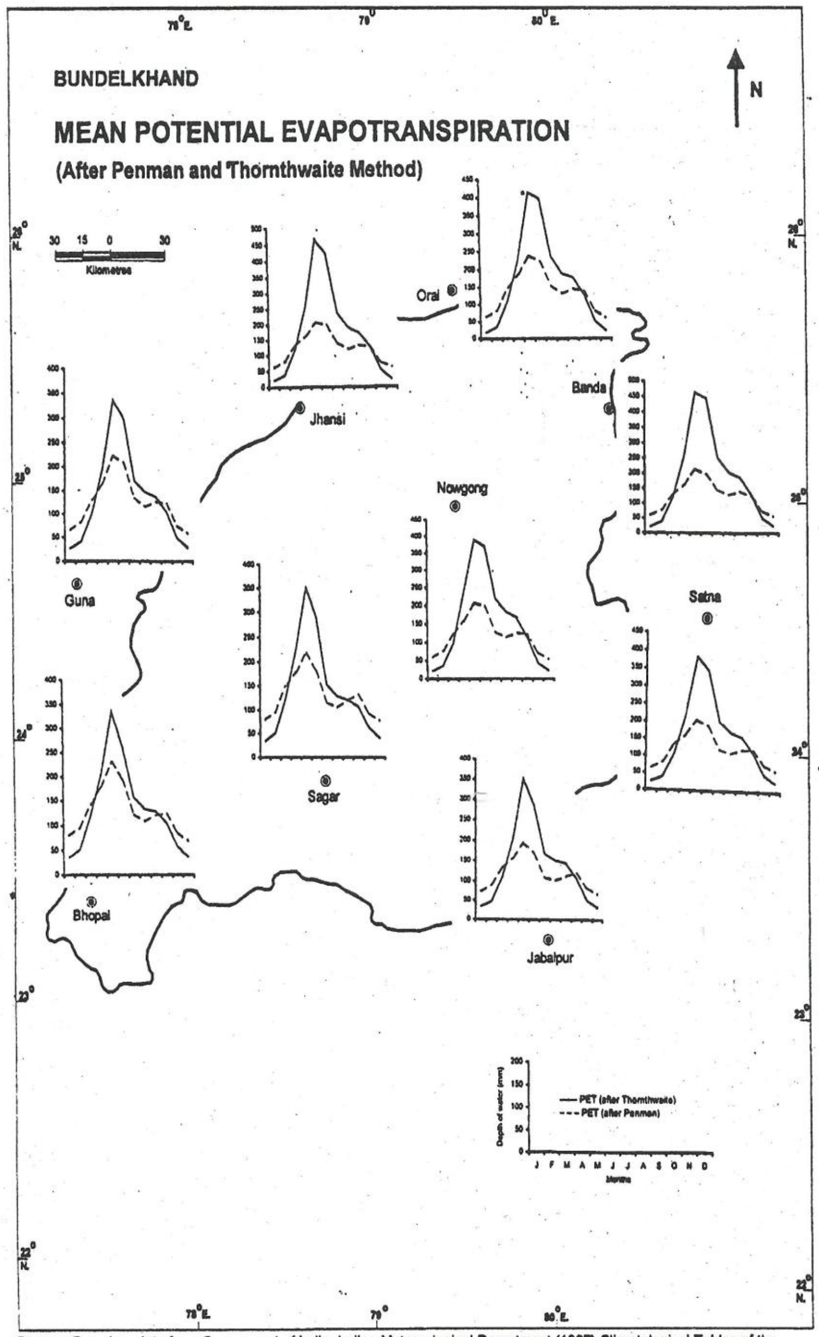
The spatial distribution of annual PET estimate reveals interesting pattern. There occurs a general decline in the PET values from west to east. The highest value of 1658 mm is obtained at Orai towards the north-western margin of the region. It decreases thereafter southwards and eastwards. But east-west decline is more than the north-south. PET estimates range from 1550 mm at Bhopal in the south-western plateau region to a little more than 1400 mm towards the south-eastern plateau.

Potential Evapo-transpiration by Thornthwaite's Method

Thornthwaite's method uses mean daily air temperature, the latitude of the place and the month of the year to compute PET. Its computation also reflects that PET reaches its peak during pre-monsoon hot summer season and thereby coincides with temperature maxim in May. The spatial variation also exhibits an increasing tendency of PET values towards interior plains. It varies from 336.53 mm at Bhopal in the southwest to 467.07 mm at Jhansi in the northwest. Conversely, PET values decrease towards plain areas during winter because of low temperature.

Comparison of Penman and Thornthwaite Method

PET computations following the two methods reveal marked differences in their monthly values (Fig. 4). Thornthwaite's method results in higher estimates of PET during summer months because of maximum heat observed in this season. Penman's method, on the other hand, results in higher estimates of PET during winter because tht cumulative effects of wind speed, cloudiness and other climatic factors outweigh the effect of low temperature observed in this season. However, during spring and autumn season i.e., February-March and October-November, the estimated values of both the PETs tend to converge. It may be due to relatively clearer sky, moderate winds, and low relative humidity in atmosphere, whereby dependence of PET curve on temperature gets increased. Besides the seasonal variations in PET values, the spatial variation also clearly reflects the relative importance of various climatic factors/ parameters.



Source : Based on data from Government of India, Indian Meteorological Department (1967) Climatological Tables of the Observatories, 1931-60.

Figure 4: Mean Potential Evapotranspiration

To compare pan evaporation data at Allahabad with the PET computed through modified Penman's equation, the solar radiation component has been adjusted for the reflection coefficient (a) of 0.05 for open water surface instead of 0.25 used for vegetation cover.

To know the statistical significance of the difference, firstly, in the annual PET values, student's t distribution test is used because sample size is very small (i.e., N = 12 months).

Since both the computed values of t_1 (= -.67) and t_2 (=-1.21) are less than the critical value ($t_{0.05}$ = 2.20), therefore, no significant difference lies between the observed and expected annual means of PET computation following any of the two methods. However, the difference in means following Penman method is lesser than that of following Thornthwaite method of PET.

In order to know the best approximation to reality, individual values of observed data have also been compared with expected values on monthly basis. For this purpose, a goodness of fit test performed with respect to monthly values leads to inference that expected monthly values of PET differ significantly from the observed mean. But, a closer look at individual values shows that except for two values in the month of May and September, i.e. towards the beginning and end of monsoon season, Penman-based PET values show close correspondence with the observed ones. In these transitional months, a slight change in any one of the parameters particularly, cloud cover and wind velocity may account for substantial increases in PET values. It is important to note here that, otherwise, quite apart Thornthwaite-based PET values become closer to observed ones during this period. However, in spite of the gap for some of the months, it becomes clear from the Fig. 5 that on the whole, PET estimates following Penman method are much closer to real situation. In fact, this statistical comparison with the so-called 'real situation' can be relaxed for their absolute figures because comparison between PET estimates using normal climatological data and observed evaporation values for one year is not justifiable to produce reliable and solid interferences. Therefore, only relative differences are taken into account while comparing.

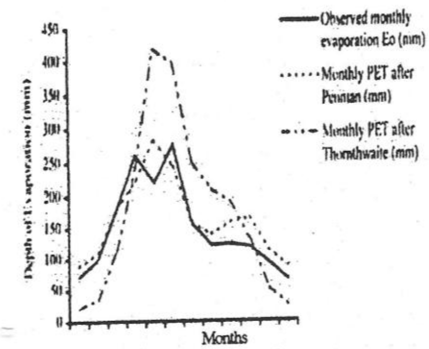


Figure 5: Mean Monthly Evapotranspiration at Allahabad

Water Balance

In other to determine other components of water balance, the procedure adopted by Mather and Thornthwaite is used for both the PET values.

Positive (P-PET) occur during southwest monsoon season. At some of the stations, a slight excess of precipitation over PET is found in the month of January also by Thornthwaite method. During monsoon season, however, they differ in terms of magnitude only.

The severity of dry season increases during the sequence of months with excessive PET and this is expressed as the accumulated potential water loss which is the culmination of negative values of (P-PET) for the dry season only. The total acc. (P-PET) increases almost 10 times at most of the stations just before the beginning of rainy season.

Soil Moisture Storage [SM = AWC. exp{Acc(P-PET}/AWC}]

The difference between P and PET is at least partly made up by withdrawal of soil water. In the study region, the estimates of available water capacity (AWC) vary from 100 mm to 300 mm depending upon soil types and predominant district-wise landuse in the vicinity of meteorological stations. In the forested region of Panna, Raisen and Damoh districts, available water capacity is taken as 250 mm for the alluvial sandy soils found in the valleys. For the observatories located in black soil region around Bhopal and Guna, available water capacity is assumed to be of the order of 100 mm and 200 mm respectively. A lower value of available water capacity is taken at former station (Bhopal) characterized by shallow rooted crops and non-agricultural land-use which leaves very little moisture holding capacity in the soil, whereas due to forest cover a higher value of available water capacity is taken at Guna Elsewhere, moderately rooted crops mainly wheat and rice predominate, and therefore, available water capacity is selected as 150 mm for the alluvial sandy soils in nor thern valley region and 200 mm for the mixed red and black soil region around Jhansi, Tikamgarh, Nowgong and Khajuraho belt despite these preliminary investigations, one can draw only an approximate inference about the regional water balance because available water capacity is based on average rooting depth of vegetation cover and soil conditions in an area which is supposed to be representative of entire influence zone of an observatory.

A total of soil moisture utilisation and recharge, i.e $SWU = [S\ |-DSM_i|] = SWR = [S\ |DSM_i|]$ shows considerable spatial variation in the study region. Monthly value of soil moisture utilisation reflects a steady decline during dry season because stored moisture in the soil diminishes during this season. The recovery is gradual during wet months at stations located in the Bundelkhand plains. Some of stations even do not get their soil recharged till the middle of rainy season. The situation becomes peculiar at Jhansi, particularly in the case of water balance computation initiated after Thornthwaite's PET. On the other hand, an immediate recharge of soil moisture storage is accounted at stations located in upper reaches due to large amount of excess precipitation over water demand.

Actual Evapotranspiration (AET)

Spatial variation in soil moisture utilisation and recharge reveals the fact that real deficit of water should be computed by actual rate of evapotranspiration rather than by potential rate. Even after utilising a part of soil moisture storage the AET falls short of the potential almost everywhere in the study region during dry season and soil moisture storage also goes on diminishing steadily which results in water deficit.

Comparison of water surplus and deficit by two methods

PET differences based on two methods result in variations in the computed values of water surplus, water deficit during southwest monsoon season for the stations located in the plains. Thornthwaite method results in either very little water surplus (Banda, Orai) or zero water surplus (Jhansi) because the positive (P-PET) balance is utilised mostly in soil moisture recharge. The application of Penman method, on the other hand, shows a little water surplus in the plain areas and larger surplus value in the plateau region. Spatial variation in the amount of water surplus towards upper reaches of rivers becomes narrower. The similar trend can be observed in water deficits, which increase in the reverse direction of water surplus. The conspicuous feature of water balance based on Penman method is that the deficits during southwest monsoon season are lower but during the winter season they are higher in comparison to Thornthwaite's results, an inference similar to that of another study done in Uttar Pradesh (Devi, 1993). Despite the higher winter deficits (P-PET values) by Penman's method, annual water deficit remains below that of by Thornthwaite's method. They are reflected in monthly variation as shown graphically in Fig. 6

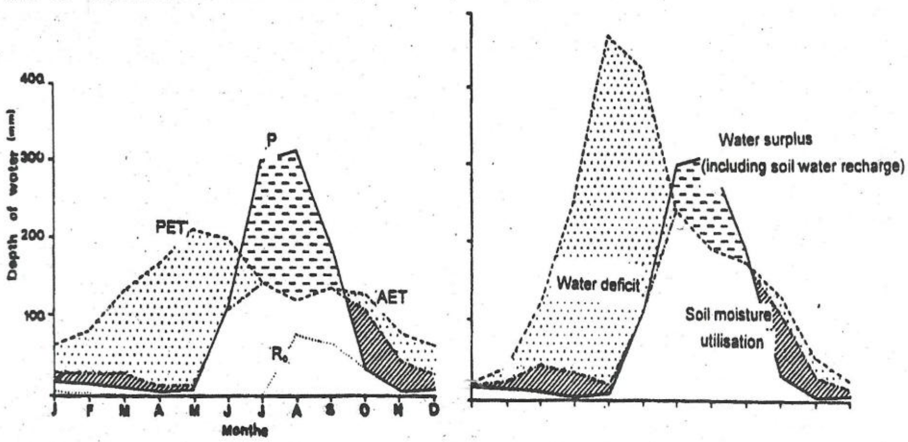


Figure 6a: Average Water Balance at Jhansi

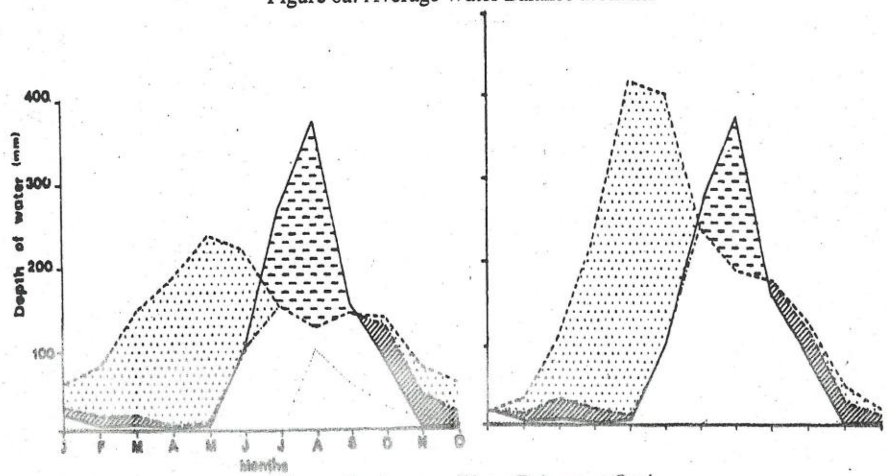


Figure 6b: Average Water Balance at Orai

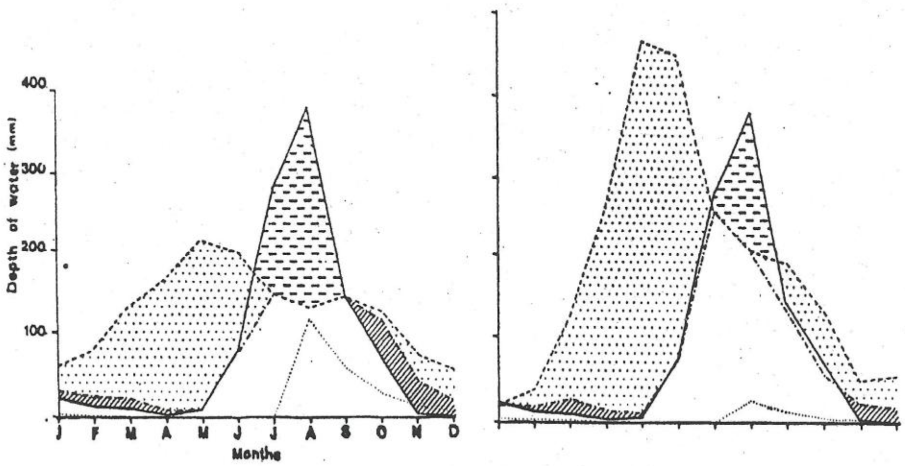


Figure 6c: Average Water Balance at Banda

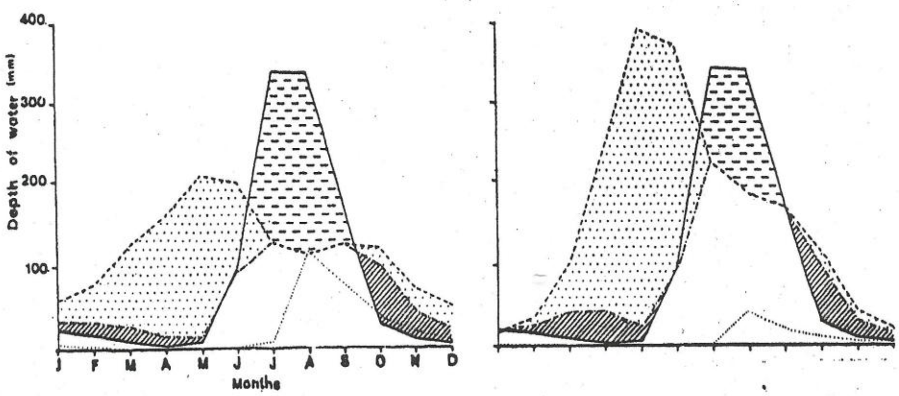


Figure 6d: Average Water Balance at Nowgong

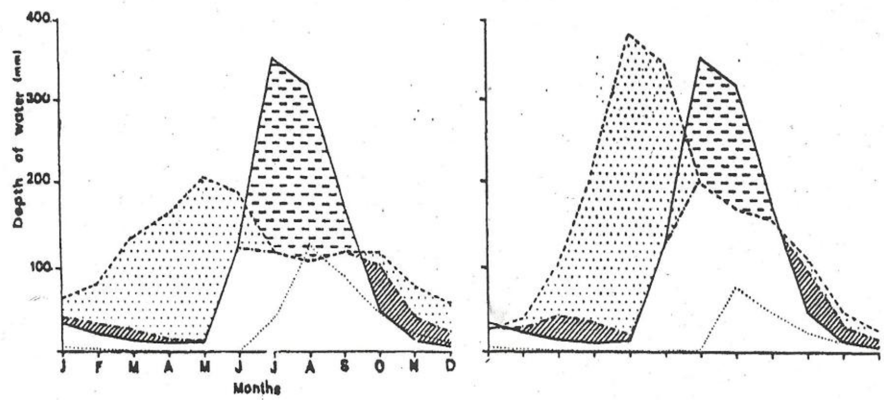


Figure 6e: Average Water Balance at Satna

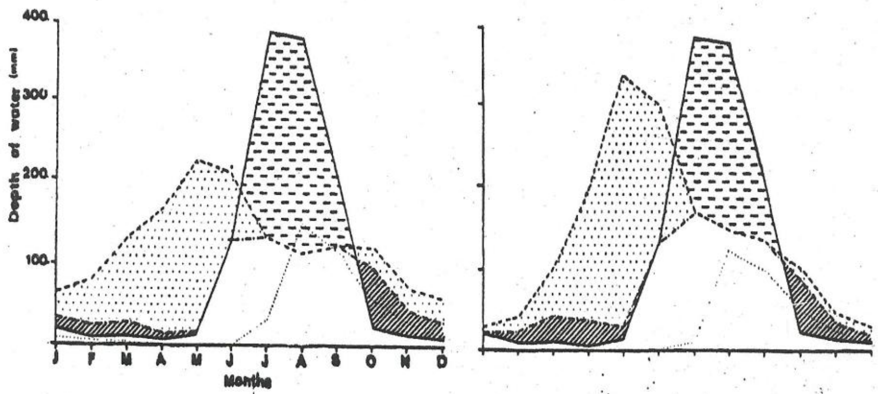


Figure 6i: Average Water Balance at Guna

The above comparison of magnitudes for water surplus and deficit based on two methods becomes clear by comparing their moisture indices since the proportion of surplus and deficit water to water need may not be the same.

Moisture Indices

The computations of annual surplus water, deficit water and the moisture indices based on PET estimation following both Thornthwaite and Penman methods show that in the study area, moisture index comes out to be negative everywhere except at Jabalpur and Sagar. Thus, the area can be divided into two moisture regions:

(i) Moist subhumid (C_2)

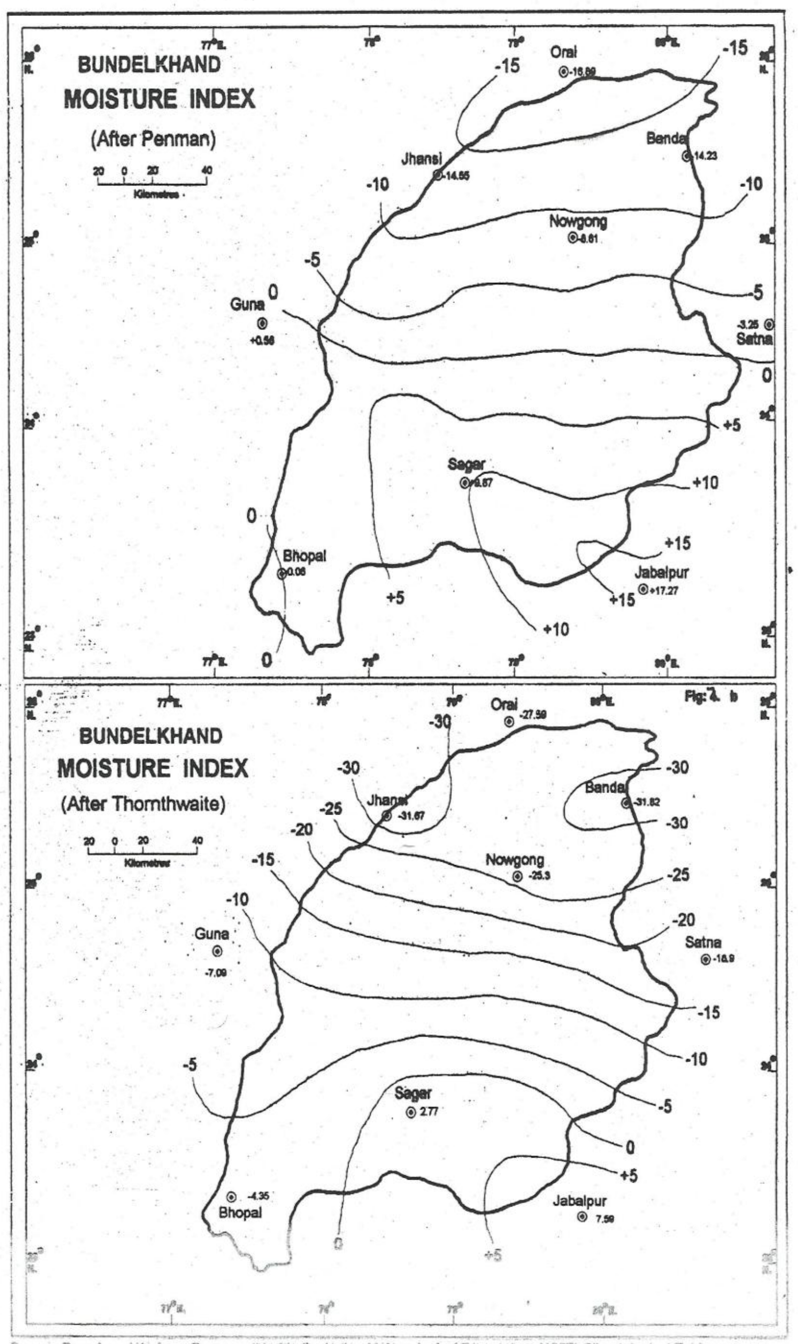
(ii) Dry subhumid (C_1)

Moist subhumid type (C_2) is found only towards southeastern margin of the study region. The slight increase of surplus over deficit, here, results in positive moisture index computed by both Penman and Thornthwaite methods. In rest of the region, moisture indices decline northwestwards, reflecting a closer correspondence with the rainfall pattern. Dry sub humid type (C_1) is found in the northern Bundelkhand plains. Thus, leaving aside the differences in magnitude of moisture indices following both the methods of PET computation, the spatial pattern of moisture condition reveals that there exists an overall annual deficiency of moisture in the study region, particularly towards the northern Bundelkhand plains. The main difference is with regard to the limit of dry subhumid type of climate in the sense that it lies more towards lower reaches if Thornthwaite method is followed (Fig. 7a and 7b).

Hydrological Regions

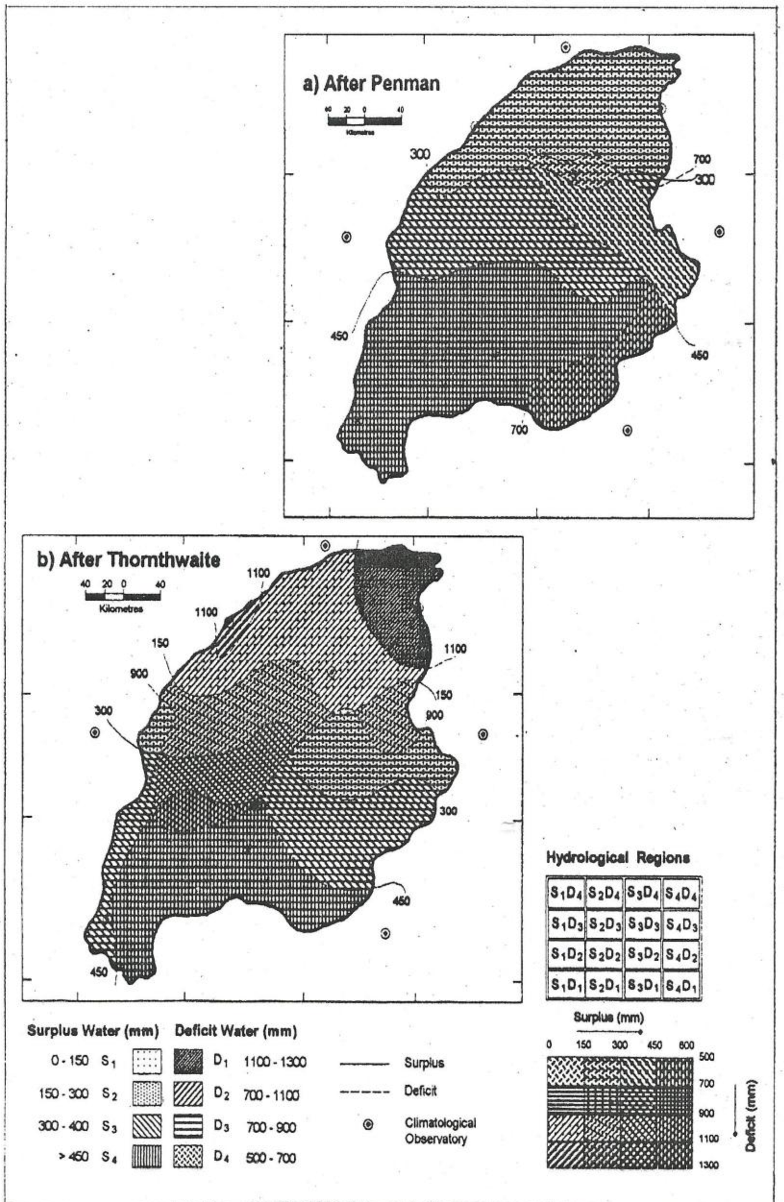
Depending upon range of water surplus and deficit amounts estimated after Thornthwaite and Penman's method of PET, hydrological regions have been formed. It is done by combining four categories of annual surplus and deficits water in the reverse order as given in Fig. 8.

The various combinations of these categories result in the formation of eight hydrological regions. Out of these, six are formed on the basis of Thornthwaite whereas,



Source: Based on data from Government of India, Indian Meteorological Department (1967) Climatological Tables of the Observatories, 1931-60

Figure 7: Moisture Index : (a) after Penman (b) after Thornthwaite



Source: Based on data from Government of India, Indian Meteorological Department (1967) Climatological Tables of the Observatories, 1931-60.

Figure 8: Bundelkhand : Hydrological Regions (a) after Penman (b) after Thornthwaite

Table 2: Hydrological Regions after Thornthwaite and Penman method of PET

Category of Hydrological Region		Thornthwaite	Penman
i	S D	Jhansi, Banda	-
ii	S^1D^1	Orai, Nowgong	-
iii	S^1D^2	Satna	Jhansi, Orai, Banda
iv	S^2D^3	-	Nowgong
v	S^2D^4	Guna, Bhopal	-
vi	S^3D^3	-	Satna
vii	S^3D^4	Sagar	Sagar, Bhopal
viii	S^4D^3	Jabalpur	Jabalpur
	4 4		

Source: Computed from Water Balance Tables

five regions are formed on the basis of Penman's method of PET computation (Table 2).

The implicit assumption in the order of surplus and deficit combination becomes obvious from the above Table 2 that the regions having less surplus value show a combination with larger deficit values. But methodologically, only three combinations, i.e. S_2D_3, S_4D_3 and S_4D_4 are common in both the regions carved out on the basis of Thornthwaite and Penman method The spatial representation/pattern of these categories, however, results in the formation of two more intermediate hydrological regions-one (S_2D_2) by Thornthwaite method and other (S_3D_3) by Penman method. The effect of PET in all estimations is still reflected in Fig. 8a and Fig. 8b where northern Bundelkhand plains occupy intermediate position in the hydrological regions based on Penman method. It is because of higher estimates of surplus water and lesser variation in the estimates of deficit water, low to moderate combinations of moisture regime are shown in the northern and central Bundelkhand region.

However, due to arbitrariness involved in the regionalisation and paucity of meteorological data, the exercise becomes rather redundant with no serious applications. Nevertheless, hydrological regions thus formed highlight the combined role played by surplus and deficit water amounts in their absolute spatial variation.

Hydrological Approach

The runoff determined by climatological approach, when compared with observed discharge figures per unit area, provides interesting results. Plotting of the standard (z) scores obtained from the yield estimates results in a straight line for most of the yield estimates at least in their central portions. Extremes in the Betwa river basin show greater deviation from the normal curve than in the Ken river basin. But, this comparison of extremes cannot be taken as actual measure of variability because the time period used in the estimation of yield series is not the same for the two adjacent river basins. It shows that even 82 year rainfall data as used in the case of Betwa basin is not sufficient to extend the various short-term runoff records. Therefore, for the present situation, the average of 50% and 75% dependable flows obtained from these yield estimates has to be considered within reasonable limits of error.

Comparison of Runoff Estimates by Climatological and Hydrological Approach

The 50% dependable flows of both the Betwa and Ken rivers as determined in the preceding section work out to be 24,720 Mm^3 whereas, runoff estimates derived by climatological approach in the previous chapter provide yield estimates as given in Table 3.

Hydrologically estimated total runoff estimates (24,720 Mm^3) are, thus, far below the climatological estimates (30,916 Mm^3) determined by Penman method whereas they are closer to runoff estimates (21,200 Mm^3) determined by Thornthwaite method. It, however, does not mean that Penman-based estimates of runoff are overestimated but rather due to the fact that observed runoff estimates are considered at their 50% dependability.

Table 3: Surface Water Yield by Climatological Water Balance Approach

Observatories	Runoff estimates (mm)		Percentage of Influence area of observatories	Yield {Mm3)	
	Thornthwaite	Penman		Thornthwaite	Penman
1.Jhansi	0.0	207.8	10.46	0	1,607.96
2. Orai	70.2	222.6	5.11	265.08	840.54
3.Guna	332.7	411.2	6.40	1,574.64	1,946.21
4.Bhopal	448.2	515.4	10.02	3,322.35	3,819.63
5.Sagar	557.2	617.9	28.78	11,862.79	13,155.09
6.Nowgong	83.8	285.1	19.58	1,213.42	4,128.25
7.Banda	50.7	233.7	7.67	27.47	1,325.08
8.Jabalpur	409.4	55M6.9	6.43	1,948.33	2,650.29
9.Satna	176.8	35.0	5.55	726.12	1443.20

Conclusion

It can be concluded here that the utility of these theoretically estimated potential water amounts is limited. On the one hand, climatological estimates of runoff are based on the assumption that the entire landscape is covered with vegetation. Had the evaporation estimates from different surfaces like surface water, bare soil, buildings and even different crops, forests, *etc.* been taken into consideration separately, there would have been more realistic estimates of runoff. Moreover, the large influence area of a polygon around an observatory assumes same type of soil-moisture characteristics, which may not be the case in reality. On the other hand, hydrological estimates also depend upon few runoff measurements Thus both the approaches have their relative merits and demerits in the estimation of reliable runoff amounts. Nevertheless, the inference remains that in the absence of extensive and long-term runoff record, estimates of runoff based on climatological water balance approach can be considered as reliable one to obtain a regional picture of moisture regimes.

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