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GRANDESCUNT AUCTA LABORE

CLIMATOLOGICAL BULLETIN

NO. 25
APRIL 1979

McGILL UNIVERSITY, MONTREAL

ISSN 0541-6256

The CLIMATOLOGICAL BULLETIN is published twice a year in April and October. The subscription price is Five Dollars ($5.00) a year. Please address orders and inquiries to:

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805 Sherbrooke Street West
Montreal, Quebec, Canada
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CLIMATOLOGICAL BULLETIN

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No. 25 April 1979

EMPIRICAL METHODS FOR ESTIMATING INCOMING LONGWAVE RADIATION FOR CLOUDLESS WINTER DAYS AT RESOLUTE, N.W.T.

by

Philip W. Suckling and Mark E. Wolfe*

Introduction

Incoming longwave radiation (L↓) from the atmosphere is an important source of energy for the Earth's surface since, in its absence, the surface would be 30 to 40°C cooler (Brazel and Osborne, 1976). Therefore, it is a very important term in the surface radiation balance. Unfortunately, L↓ is not routinely measured in Canada. Thus, one must resort to estimation techniques or models to evaluate its magnitude.

In order to estimate any radiative term, whether incoming shortwave or longwave radiation, it is often customary to evaluate for cloudless conditions and then correct for cloud (Sellers, 1965; Davies et al, 1975; Suckling and Hay, 1976, 1977). For the evaluation of longwave radiation from cloudless skies, empirical formulae based on statistical relationships between longwave radiation and measured meteorological variables have often been implemented. These meteorological variables usually include screen-level values of temperature and humidity (usually vapour pressure) or temperature alone.

LeDrew (1975) found that problems arose when he attempted to estimate cloudless sky incoming longwave radiation ($L{\downarrow}_o$) from screen-level

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climatological data for high altitude regions in Colorado. Since the empirical models were suspect in an alpine environment, it was decided to test their validity in another environment with extreme conditions, the Arctic. The purpose of this study is to test existing formulae for estimating incoming longwave radiation under cloudless conditions at Resolute, N.W.T. (74°43' N, 94°59' W). New versions of some of these models will be devised using the data from Resolute. From this study it will be possible to assess the type of model most appropriate for an Arctic environment.

Empirical Formulae for Estimating Cloudless Sky Incoming Longwave Radiation

Following LeDrew (1975), four basic formulae will be tested in this study. Angstrom (1918) suggested the equation

$$L\downarrow_o = \sigma T^4 \ (\alpha - \beta\ 10^{-\gamma e}) \tag{1}$$

where σ is the Stefan-Boltzman constant (5.57×10^{-8} W $m^{-2}K^{-4}$), T is the screen-level air temperature (in degrees Kelvin), e is the screen-level vapour pressure (in millibars) and α, β and γ are empirical coefficients. The values for these coefficients differ depending on how they are obtained and the location under study (Sellers, 1965).

Brunt (1932) gives a formula relating $L\downarrow_o$, the total black-body radiation (σT^4) at absolute screen-level temperature and screen-level vapour pressure, in the form

$$L\downarrow_o = \sigma T^4 \ (a + b\sqrt{e}) \tag{2}$$

where a and b are empirical constants. Again, the values of these constants vary among sets of observations for different locations.

Swinbank (1963) derived the equation

$$L\downarrow_o = A\sigma T^4 + B \tag{3}$$

where A and B are again empirical coefficients. Swinbank derived this relationship based on data from Benson in Britain, Aspendale and Kerang in Australia and in the tropical Indian Ocean.

Idso and Jackson (1969) developed a formula based on experimental data from Point Barrow, Alaska and Phoenix, Arizona as well as Swinbank's Australian and Indian Ocean data. In the formula $L\downarrow_o$ is again specified solely in terms of screen-level air temperature as

$$L\downarrow_o = \sigma T^4 \ \{1 - c\ \exp[-d(273 - T)^2]\} \tag{4}$$

where c and d are empirical constants. Idso and Jackson indicate that the effective emittance of the atmosphere is at a minimum at 273 K and increases symmetrically to approach unity exponentially at higher and lower temperatures. The equation keeps $L{\downarrow}_o$ from crossing over the black-body curve at high and low temperatures and, thus, meets the theoretical limitations imposed on incoming longwave radiation. Based on this evidence and their tests of the model, Idso and Jackson felt that their equation accurately described a general relation between $L{\downarrow}_o$ and screen-level temperature that should be valid at any latitude and for any air temperature.

Studies which have compared the performance of these four formulations have favoured different equations. Morgan et al (1971) found better performance for the Angstrom and Brunt equations compared to Swinbank's for a site near Davis, California. In southern Ontario, Robinson et al (1972) obtained the best performance from the Swinbank approach while, in the Netherlands, Wartena et al (1973) found no statistical preference for any model although they favoured the Brunt formula in their conclusion. Idso (1974) preferred the temperature only models and showed that little difference was obtained between the Swinbank and Idso and Jackson models. He also showed that the Angstrom and Brunt equations produced results that were similar to each other. Not one of these studies, however, has been undertaken in an Arctic environment.

Resolute Data

A total of 65 cloudless days occurred at Resolute during the period November 1963 to December 1972 (Table One). All cloudless days occurred during the winter months November to May with screen-level temperatures ranging from a low of 224 K to a high of 259 K, all well below freezing.

In order to test the accuracy of the empirical formulae, a "measured" value of $L{\downarrow}$ must be known. Although this is not measured directly by the Atmospheric Environment Service at Resolute, incoming shortwave radiation ($K{\downarrow}$), outgoing (reflected) shortwave radiation ($K{\uparrow}$) and net all-wave radiation (Q^*) are measured on an hourly basis. The net longwave radiation (L^*) can be found as

$$L^* = Q^* - (K{\downarrow} - K{\uparrow}). \qquad (5)$$

The net longwave radiation is composed of outgoing and incoming components. Outgoing longwave radiation can be calculated using the Stefan-Boltzman law

$$L{\uparrow} = \varepsilon_s \sigma T_s^{\,4} \qquad (6)$$

TABLE ONE

Cloudless Days at Resolute, Northwest Territories
from November 1963 to December 1972

1963:	Dec. 1	1967:	Jan. 18	1969:	Jan. 11
	Dec. 8		Feb. 25		Jan. 12
	Dec. 31		Nov. 16		Jan. 16
			Nov. 27		Jan. 22
1964:	Mar. 8		Dec. 3		Mar. 2
	Mar. 28		Dec. 30		Mar. 30
	Mar. 30				Dec. 13
	Apr. 22	1968:	Jan. 23		
	Nov. 15		Feb. 8	1970:	Jan. 19
	Nov. 16		Mar. 2		Apr. 19
			Mar. 3		May 11
1965:	Feb. 11		Mar. 9		Nov. 5
	Mar. 24		Mar. 13		Nov. 6
	Apr. 4		Mar. 16		Dec. 22
	Apr. 5		Mar. 28		
	Apr. 19		Mar. 29	1971:	Jan. 26
			Mar. 30		Mar. 8
1966:	Feb. 12		Apr. 24		Mar. 22
	Mar. 2		Apr. 25		Apr. 8
	Mar. 6		May 2		Nov. 20
	May 3		May 3		Nov. 28
	May 6		Nov. 19		Dec. 22
	May 7		Dec. 10		
	Nov. 27		Dec. 28	1972:	Apr. 8

Month	Total # Days
November	10
December	10
January	8
February	4
March	18
April	9
May	6
June - October	0
Total	65

where ε_s is the surface emissivity and T_s is the surface temperature in degree Kelvin. Following Sellers (1965), surface emissivity was assumed to be 0.90.

The Stefan-Boltzman law uses surface temperature rather than screen-level temperature in this case. Problems arise when trying to estimate surface temperature. According to Chang (1972), a surface inversion exists about 80% of the time during the winter in the Resolute region of the Arctic. These inversions are primarily the result of radiative loss from the surface. When Q^* is negative, the surface temperature drops, thus reducing $L\uparrow$ and increasing the conduction of heat from below. According to Gaigerov, the vertical temperature gradients are as large as one degree Kelvin per metre in the layer closest to the snow surface (Chang, 1972). For the present study, it was decided that if the measured Q^* was negative, then an inversion of one degree was assumed to exist between the surface and screen-level height. If Q^* was positive but less than 100 W m^{-2}, screen-level temperature was assumed to be equal to the surface temperature (no inversion in existence), whereas if Q^* was greater than 100 W m^{-2}, the surface was assumed to be one degree warmer (a lapse condition). These divisions were arbitrarily chosen to reflect daytime surface heating.

The sensitivity of $L\uparrow$ to errors in the assumptions for surface emissivity and surface temperature is shown in Table Two. An error of 0.05 in emissivity produces a ±6% error in $L\uparrow$. Assuming a maximum error in surface temperature estimation of one degree Kelvin, an error of ±2% in $L\uparrow$ estimation would occur. The total root mean square error for $L\uparrow$ is therefore ±6.3%.

Davies et al (1970) estimated a ±5.6% instrument error when measuring either $K\downarrow$ or $K\uparrow$ and a ±10.2% measurement error for Q^*. The root mean square error for L^* which is calculated from the above three terms is therefore ±12.8%. The root mean square error for the "measure" incoming longwave radiation is therefore $[(6.3)^2 + (12.8)^2]^{\frac{1}{2}} = \pm 14.3\%$. Any model that produces a root mean square error between the "measured" and the calculated values of $L\downarrow_o$ approaching this value can be considered to perform well.

All the models require hourly values of temperature, while two also require vapour pressure values. The Atmospheric Environment Service measures screen-level temperature (T) and relative humidity (RH) at Resolute. The vapour pressure (e) can be calculated using

$$e = e_s\ (RH) \qquad (7)$$

TABLE TWO

Sensitivity of L↓ to Errors in the Assumptions for Surface Emissivity (ε) and Surface Temperature (T_s)

T_s (K)	L↑ ($W\ m^{-2}$)			
	$\varepsilon = 0.90$	$\varepsilon = 0.95$	$\varepsilon = 1.00$	$\varepsilon = 0.85$
224	126.2			
225	128.5	135.6	142.8	121.3
230	140.3			
235	152.9			
240	166.3			
245	180.6	190.7	200.7	170.6
250	195.8			
255	212.0			
259	225.6			
260	229.1	241.8	254.5	216.4

TABLE THREE

Sensitivity of Calculated $L\downarrow_o$ to Errors in the Relative Humidity using the New Brunt Version for Resolute (Section 5)

RH (%)	235.9 K		224.3 K	
	e (mb)	$L\downarrow_o$ ($W\ m^{-2}$)	e (mb)	$L\downarrow_o$ ($W\ m^{-2}$)
100	0.174	111.34	0.045	90.50
90	0.156	111.28	0.041	90.48
80	0.139	111.21	0.036	90.45
70	0.122	111.14	0.032	90.42
60	0.105	111.06	0.027	90.39
50	0.087	110.97	0.023	90.35
40	0.070	110.88	0.018	90.31
30	0.052	110.78	0.014	90.27
20	0.035	110.65	0.009	90.22
10	0.017	110.49	0.005	90.15
0	0.000	110.09	0.000	89.98

where e_s is the saturated vapour pressure at T. The Goff-Gratch formulation in the Smithsonian Meteorological Tables (List, 1966) was used for calculating the saturated vapour pressure. Relative humidities are usually not reported when the temperature is less than 236 K. In these cases, the relative humidity was assumed to be 70%. The sensitivity of the calculated $L\downarrow_o$ to errors in this assumption is shown in Table Three. No matter which relative humidity is chosen, there is a very small absolute change in the already small vapour pressure values. For even a large difference in assumed relative humidity, there is at most a 1% difference in the calculated incoming longwave radiation in this example.

Model Tests and Performances

Two versions of the Angstrom type model were used as follows:

Source	α	β	γ	Study Location
Sellers (1965)	0.820	0.250	0.094	Germany
Robinson et al (1972)	1.017	0.331	0.020	Lake Ontario

Seven versions of the Brunt type model were tested with values of a and b as follows:

Source	a	b	Study Location
Brunt (1932)	0.47	0.072	mean of 5 European studies
Monteith (1961)	0.53	0.065	Kew Observatory, England
Sellers (1965)	0.605	0.048	medians of 22 evaluations
Morgan et al (1971)	0.66	0.039	Davis, California
Robinson et al (1972)	0.62	0.042	Lake Ontario
LeDrew (1975)	0.491	0.067	Front Range of Colorado
LeDrew (1975)	0.554	0.017*	Front Range of Colorado

(* multiplied by e instead of $\sqrt{e}$ in equation 2)

Besides the original Swinbank version, one additional version was tested at Resolute:

Source	A	B	Study Location
Swinbank (1963)	1.195	-170.9	England, Australia, Indian O.
Unsworth & Monteith (1975)	1.06	-119	England, Sudan

Only the original Idso and Jackson version of their model was used with $c = 0.261$ and $d = 7.77 \times 10^{-4}$.

The performances of the various versions of each model on daily

TABLE FOUR

Model Version	$\overline{L\downarrow_0}$ ($W\ m^{-2}$)	Daily Values RMSE* ($W\ m^{-2}$)	Daily Values RMSE (%)	Hourly Values RMSE ($W\ m^{-2}$)	Hourly Values RMSE (%)
Brunt	100.4	28.19	22.5	31.50	25.1
Brunt-Monteith	111.5	19.10	15.2	23.68	18.9
Brunt-Sellers	124.4.	13.20	10.5	19.21	15.3
Brunt-Morgan	134.3	15.99	12.7	21.23	16.9
Brunt-Robinson	126.7	13.21	10.5	19.24	15.3
Brunt-LeDrew	103.9	25.16	20.1	28.70	22.9
Brunt-LeDrew ('e)	110.2	19.99	15.9	24.34	19.4
Angstrom-Sellers	115.8	16.30	13.0	21.48	17.1
Angstrom-Robinson	136.2	17.07	13.6	22.02	17.6
Swinbank	64.5	63.45	50.6	65.01	51.8
Swinbank-Unsworth	89.8	39.02	31.1	41.41	33.0
Idso and Jackson	170.8	47.30	37.7	49.41	39.4

(* RMSE = root mean square error)

and hourly bases are given in Table Four. The Angstrom model and three versions of the Brunt equation performed best with daily root mean square error values of less than ±14% and hourly values of less than ±18%. These results suggest that the Angstrom and Brunt models which incorporate both temperature and vapour pressure perform much better than the Swinbank and Idso-Jackson models which are dependent solely on temperature. The two versions of Swinbank's model underestimated $L\downarrow_o$ by large amounts while the Idso-Jackson formulation overestimated by large amounts.

New Model Versions for Resolute

Using a linear regression technique, new coefficients were calculated for both the Brunt type model (equation 2) and the Swinbank type model (equation 3). The equation for the Brunt type model that best fits the data for Resolute is

$$L\downarrow_o = \sigma T^4\ (0.627 + 0.017\ \sqrt{e}) \tag{8}$$

while the Swinbank equation that best fits the Resolute data is

$$L\downarrow_o = 0.658\ \sigma T^4 - 4.3\ . \tag{9}$$

The values for A and B for the new Resolute Swinbank equation are considerably different from the two versions previously tested. The coefficient b in the Brunt equation is very small and less than that for any of the other versions.

TABLE FIVE

Performances of the New Brunt and Swinbank Type Versions at Resolute, N.W.T.

	Average Measured $L\downarrow_o$ ($W\ m^{-2}$)	Daily Values		Hourly Values	
		RMSE ($W\ m^{-2}$)	RMSE (%)	RMSE ($W\ m^{-2}$)	RMSE (%)
Brunt version	125.4	13.07	10.4	19.15	15.3
Swinbank version	125.4	13.01	10.4	19.16	15.3

Table Five shows the performance of the new Brunt version and the new Swinbank version for Resolute on a daily and an hourly basis. The models have essentially the same predictive power. This is not surprising since the value of b in the new Brunt model is very small (equation 8) and, for the new Swinbank model, B is close to zero (equation 9). Therefore, both equations are quite similar in that $L\downarrow_o \simeq 0.6\ \sigma T^4$. The new versions do not show much improvement over the Sellers or the Robinson et al versions of the Brunt model (Table Four). These two versions also multiply σT^4 by approximately 0.6.

Conclusions

Using existing versions of four types of models for estimating incoming longwave radiation under cloudless conditions, it was found that the Angstrom model and some versions of the Brunt model were the best for estimating $L\downarrow_o$ at Resolute. These models are dependent on both temperature and vapour pressure. Despite the fact that water vapour content in the Arctic winter is very small, the models dependent on temperature only performed poorly. This result was also found by LeDrew (1975) for an alpine environment.

However, calculation of new coefficients unique to Resolute for both the Brunt and Swinbank models resulted in little difference between model performances. This occurred since the coefficient incorporating the vapour pressure term in the Brunt model was very small. For an Arctic environment such as Resolute, therefore, there is no advantage gained by using a $L\downarrow_o$ model that incorporates a humidity factor. Usage of a temperature only model, however, such as that by Swinbank, requires adoption of appropriate coefficients unique to the particular Arctic environment.

Acknowledgement

Dr. John E. Hay of the University of British Columbia assisted with data acquisition.

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POTENTIAL EVAPOTRANSPIRATION AND WATER DEFICIT IN BANGLADESH USING GARNIER'S MODIFICATION OF THE THORNTHWAITE WATER BALANCE

by

Marie Sanderson and Rafique Ahmed*

Introduction

Water balance studies have become important in recent years in many countries of the world because of the increasing demand for fresh water for agricultural production, industrial development and urbanization. Bangladesh is a country whose economy is dependent mainly on agriculture. Thus, for the planning of irrigation schemes, water resource management, and agricultural operations in that country, it is important to study the components of the water balance, potential precipitation, water surplus, and water deficit. In the present study, the parameters potential evapotranspiration and water deficit are examined.

General Climatic Condition of Bangladesh

Bangladesh is located in the tropical monsoon region. A map of the country showing the climate stations is seen in figure 1a. Its climate is characterized by hot summers, a wet rainy season and mild, dry winters. Mean summer temperatures range from 27°C along the northeastern foothills to about 30°C in the west-central region. April is the hottest month. The temperatures are slightly lower during the monsoon season, signifying the effect of increased cloudiness. Mean January temperature ranges from 18°C along the

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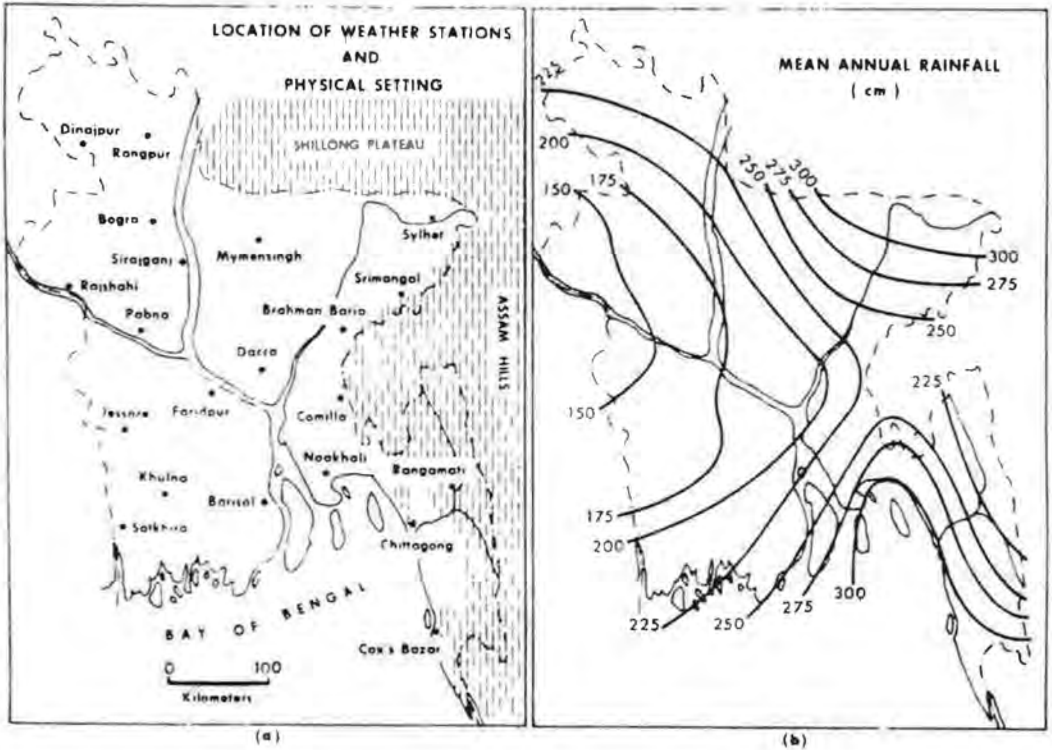


Fig. 1. Weather Stations and Mean Annual Rainfall, Bangladesh.

coastal regions to 10°C along the northern foothills.

The average annual rainfall ranges from 150 cm in the west to 400 cm in the northeast and over 300 cm in the southeast regions (Fig.1b). The monsoon season, June through October, accounts for 80-90% of the annual rainfall, while the pre-monsoon hot season, March through May, accounts for 10-15%. The winter months, November through February, are virtually dry.

Water Balance Models

The general form of the water balance equation can be expressed as:

$$P = ET + R + S$$

where P is precipitation, ET is evapotranspiration, R is runoff and S is storage of water in the soil.

Of the components of this equation P and R can be measured, but the measurement of ET is difficult. However, several techniques have been evolved for the estimation of potential evapotranspiration (PE) and by using a water balance model, ET can be computed. Some of the techniques for estimating PE require sophisticated instrumentation or climatic data which are not usually available in a country such as Bangladesh (Penman, 1948, 1963) (Budyko, 1956). Other techniques involve the use of generally available climatological data, such as temperature, precipitation and humidity (Thornthwaite, 1948, 1955).

The first task of the present study was to develop a model for the computation of PE in Bangladesh using available climatological data. Garnier's modification of the Thornthwaite method of computing PE was used for this purpose (Garnier, 1956).

The Thornthwaite formula for determining PE requires information on temperature and precipitation only, with adjustment for day length. Using lysimetric measurements in West Africa Garnier found that the Thornthwaite model overestimated the PE in the wet season and underestimated it in the dry season. He stated that since PE is not dependent on temperature alone, but is also influenced by the humidity of the air, the saturation deficit of the air must be taken into account.

Saturation deficit (SD) is defined as the difference between the saturation vapour pressure (e_s) and actual vapour pressure (e), i.e., $SD = e_s - e$. The saturation vapour pressure (e_s) for corresponding mean monthly temperatures can be obtained from the Smithsonian Tables (List, 1968). Actual vapour pressure is given as the product of e_s and relative humidity (u), i.e., $e = e_s \times u$. Garnier constructed a table for computing modified values

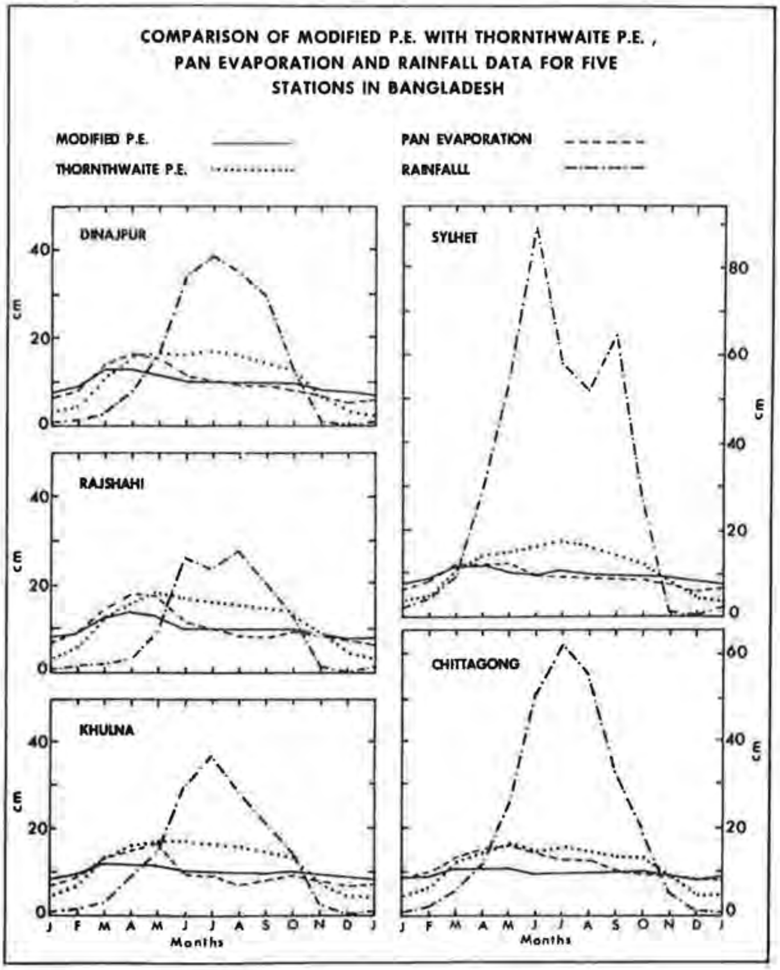


Fig. 2. Evaporation and Rainfall, Bangladesh.

of PE, (PE_M), using the Thornthwaite PE values and the saturation deficit. He found that values of PE_M agreed well with the results obtained from lysimetric observations in Nigeria.

Garnier's modification of the Thornthwaite model was considered appropriate for Bangladesh because the country has seasonal reversal of winds, comparable temperature, humidity and precipitation conditions, with a dry season during the low sun period and a wet season during the high sun period, as has Nigeria.

Comparison between Computed PE and PAN Evaporation Data in Bangladesh

No lysimetric data have been found for Bangladesh but pan evaporation data are available. Some researchers have stated that the evaporation pan is as accurate as any formula or field instrument for estimating PE in a humid climate (Chang, 1965; Ward, 1971). Depending upon the nature of the vegetation cover, the ratio between pan evaporation and PE may vary from 0.9 to 1.1 in a humid climate (Chang, 1968). Thus, a comparison between the PE_M and pan evaporation for Bangladesh was made to test the applicability of Garnier's modification of the Thornthwaite water balance model.

In Bangladesh there are 21 weather stations and 42 pan evaporation stations of standard WMO specifications. These are operated by the Meteorological Department and Water Development Boards respectively. The climatological data are available for a period of more than fifty years, while the pan evaporation data are available for the period since 1961.

Mean monthly values of PE_T (Thornthwaite PE), PE_M (modified PE) and pan evaporation data for five stations in Bangladesh are compared in figure 2. These stations have been selected from different geographic locations and different precipitation regimes. It can be seen from these graphs that the PE_T values are high throughout the summer months, including the monsoon season when the sky remains cloud covered most of the time and the relative humidity is very high. In the coastal location (Chittagong) PE_T is 15-20% higher than the pan evaporation and about 60% higher than the PE_M during this season. But in other locations PE_T is 60-75% higher than pan evaporation and 50-60% higher than PE_M in this season.

On the other hand, during the pre-monsoon season PE_M is lower than PE_T. This is because PE_M takes into account the humidity of the air. It can be seen that pan evaporation is 0-15% higher than PE_M during the pre-monsoon hot season. This is perhaps because during these months, when the daytime temperatures rise to 38°C or more, the metallic container of the

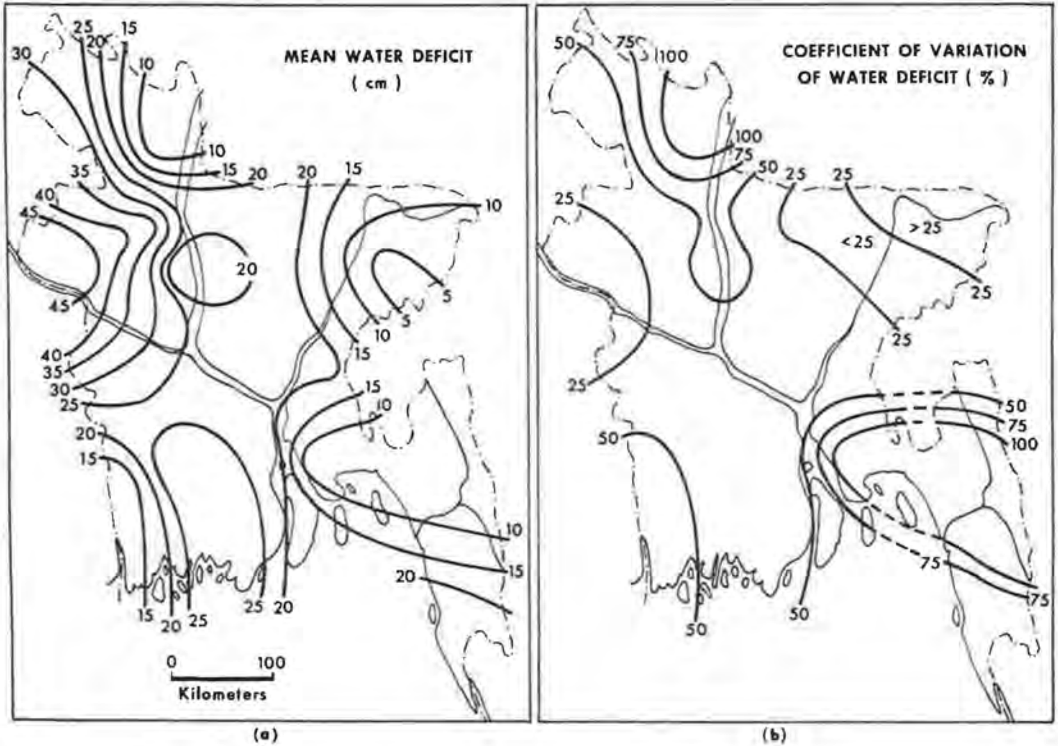


Fig. 3. Water Deficit in Bangladesh

evaporation pan and the water become warmer than the surrounding surfaces, and consequently, the pan evaporation is higher than PE_M during this season.

During the monsoon season, when the sky remains mostly cloudy, and the relative humidity is very high, the pan is cooler than the surrounding surfaces, resulting in 20-25% lower evaporation than PE_M.

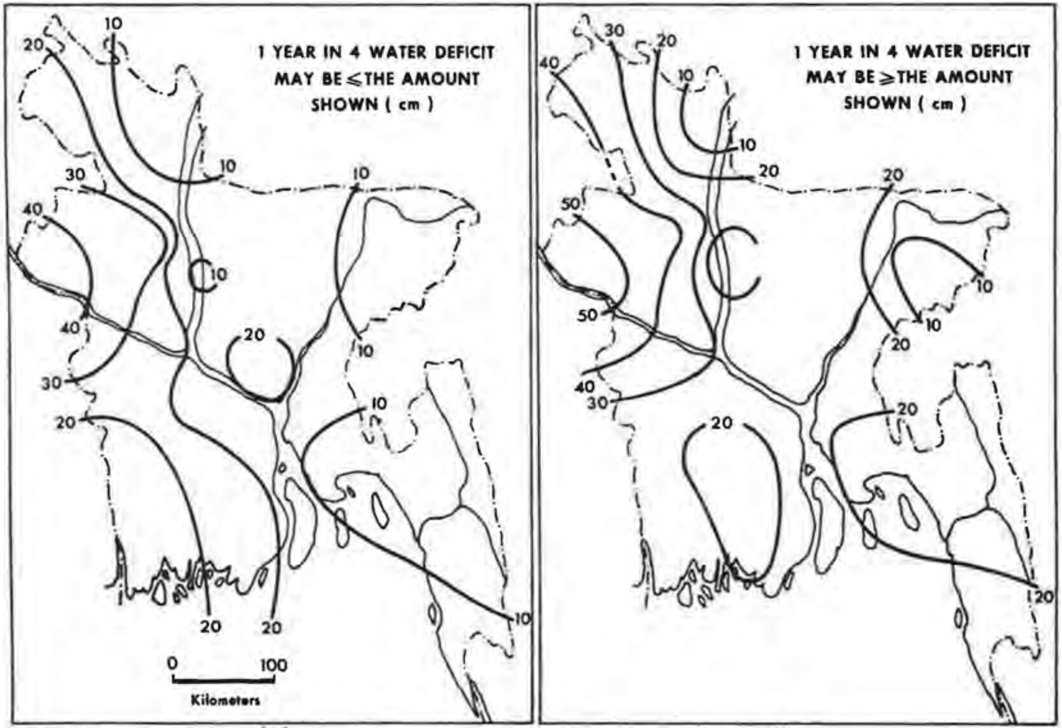
It is observed that the modified potential evapotranspiration (PE_M) follows the trends of the pan evaporation. It is also observed from the preceding discussions that the overestimation of PE during the wet season and underestimation of it during the dry season by Thornthwaite method have been corrected by Garnier's modification. It would appear that Garnier's modification of the Thornthwaite water balance method gives a reasonable estimate of the monthly potential evapotranspiration of Bangladesh. It has consequently been used to estimate the other parameters in water balance (Ahmed, 1978).

The Computation of the Monthly Water Balance in Bangladesh

The water balance computations were done for all the climate stations for the 25 year period, 1948 to 1972 using a computer program of the Thornthwaite water balance with Garnier's modification of PE incorporated. The water holding capacities of the soil-vegetation combinations were determined using data from the Bangladesh Soil Survey Department and Publications in Climatology (1959).

The book keeping procedure of the water balance computations is simple and straightforward. Each month the amount of ET is subtracted from the soil moisture storage, while the precipitation is added. Rainfall in excess of the soil moisture storage capacity is regarded as surplus, including both surface runoff and deep percolation. When the soil moisture storage reaches zero, ET ceases and a water deficit occurs. Thus the water balance model permits a quantitative assessment of monthly and thus annual water deficiency.

The mean annual deficits obtained from the computer program using the 28 years of record of all available stations were plotted in figure 3a and resulting isolines drawn. The highest amount of water deficit in Bangladesh is to be found in the west-central part, i.e., Rajshahi area (more than 40 cm). Water deficit is lowest in northeastern and eastern parts of the country, where the length of the dry season is short and the total rainfall is heavy. It is difficult to explain the existence of an area of low water deficit around Sirajganj in the central region. In other areas



(a) (b)

Fig. 4. Probability of Water Deficit, One Year in Four, Bangladesh.

the water deficit is moderate (20-40 cm).

The coefficients of variability of annual water deficit are mapped in figure 3b. The lowest coefficients (about 25%) are found in the west-central and northeastern parts of Bangladesh. This coincides with the lesser variability of the dry season. High variability of water deficit was observed in the southeastern and northern regions, where the variability of the duration of the dry season is high.

Probabilistic Analysis of Water Deficit

For practical purposes of irrigation planning, it is important to know the probabilities of occurrence of various water deficits. For this reason the twenty-five years of water deficit data for Bangladesh stations were submitted to probability analysis.

For probabilistic studies it is necessary that the data have a normal distribution. The Kolmogorov-Smirnov test was used for this purpose for eight sample stations in Bangladesh. These sample stations were selected from different geographical locations and rainfall regimes. Twenty-five years data for the period 1948-72 were used for this test. It was found that the distribution of water deficit in Bangladesh was either normal or approximately normal.

Based upon the criteria for normal distribution the probability of occurrence of an amount of water deficit in some expected percentages may be obtained from the Z-score, which is given by:

$$Z = \frac{X_i - \bar{X}}{\sigma}$$

where Z = standard error of estimate, which can be found from the Z-score Table for the required percentage of occurrence

X_i = the required figure

$\bar{X}$ = the mean value of the distribution

σ = the standard deviation.

Thus the critical values determining the top 10% and 25% and bottom 10% and 25% of the distribution of water deficit in Bangladesh were determined. For the computation of probabilities the Z-score equation may be written as $X_i = \pm Z \times \sigma + \bar{X}$. 90% of the occurrence will be below $\bar{X} + 1.28\sigma$, and 90% of them will be above $\bar{X} - 1.28\sigma$. These are the cases of extreme events, which will occur in one year in ten. Similarly, 75% of the occurrence will be below $\bar{X} + 0.675\sigma$ and 75% will be above $\bar{X} - 0.675\sigma$. These are lesser extreme or more frequent events that will occur in one year in four.

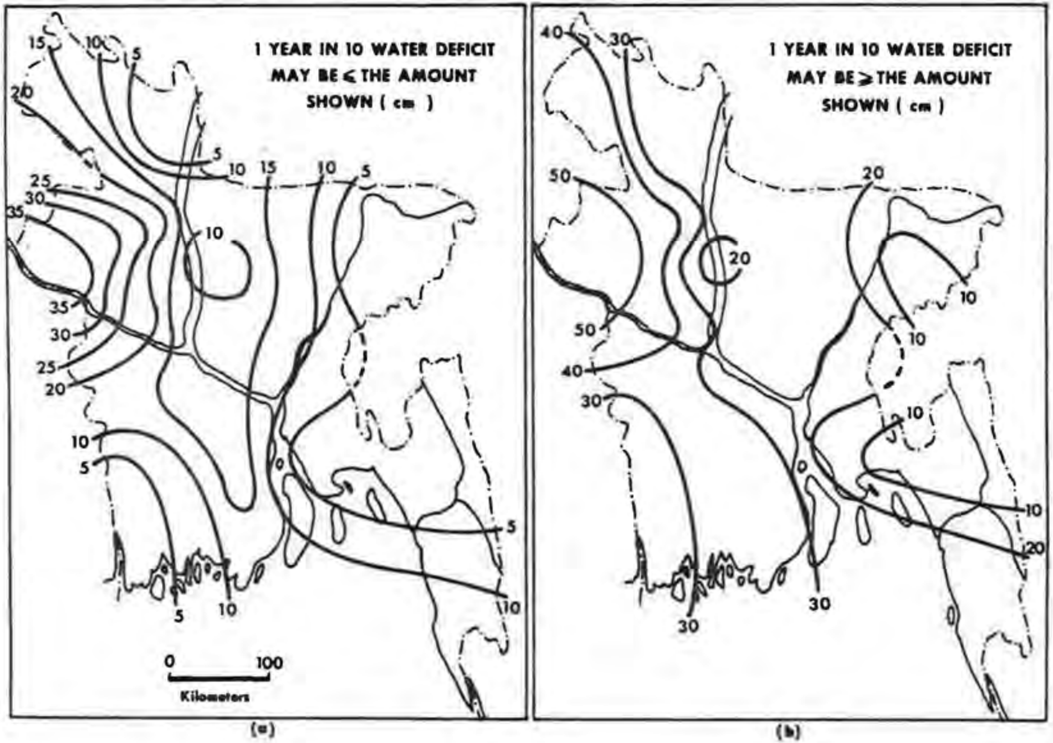


Fig. 5. Probability of Water Deficit, One Year in Ten, Bangladesh.

Maps showing the probable occurrence of water deficits of various amounts in one year in four are seen in figure 4. Figure 4a shows the regions where deficits may be equal or less than the amounts shown, while figure 4b shows regions where deficits may be equal or exceed the amounts shown. The northwest and southeast areas show the greatest variability in the two cases, as would be expected from the coefficient of variation map. Similarly, figure 5 shows the situation which could be expected one year in ten. The advantage of such maps is that the water deficit is given in quantitative terms and its geographic variability is shown.

Conclusions

It is hoped that the present analysis of the water balance of Bangladesh is a worthwhile first attempt in understanding the hydrology of that country.

In the absence of sophisticated climatic data of field observation, the Garnier modification of Thornthwaite's water balance model seems to give a good estimate of monthly potential evapotranspiration in Bangladesh. The use of the modified model has permitted the analysis of the 25 years of records of the 21 climate stations and the mapping of the important parameter of water deficit.

The use of probability analysis has made possible the quantitative mapping of the deficits to be expected in one year in four, and in one year in ten.

It is hoped that the present maps will prove useful in planning irrigation operations and water conservation in Bangladesh.

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ESTIMATING THE WATER RESOURCES OF TROPICAL REGIONS FROM CLIMATIC DATA

by

B.J. Garnier*

Within the tropics the influence of water manifests itself in many ways. In areas where seasonal contrasts are large, striking differences exist between the arid, parched landscapes of the dry season and the rich, green colourings of the humid period. Equally powerful differences may be noted between irrigated and non-irrigated areas. Water, moreover, exerts a profound influence on the daily lives of many tropical peoples. In West Africa, for example, it is common to see water head-loaded in buckets from community taps in cities and towns, while in the country scarcely a stream lacks its bucket-laden clientele.

Water is not by any means a problem of tropical regions alone. Fresh water supplies are one of the major casualties of technological development in the so-called advanced countries. However, the problem in the tropics, which contain a high proportion of the world's under-developed countries, differs from that of more developed regions in that the technological difficulties of developing adequate fresh-water supplies are augmented by ignorance of the amount of water which is, in fact, available. This ignorance, moreover, applies not only to large-scale supplies, but also to the water-availability for small-scale village, town, and city development, together with agricultural intensification or expansion through irrigation. A report of the International

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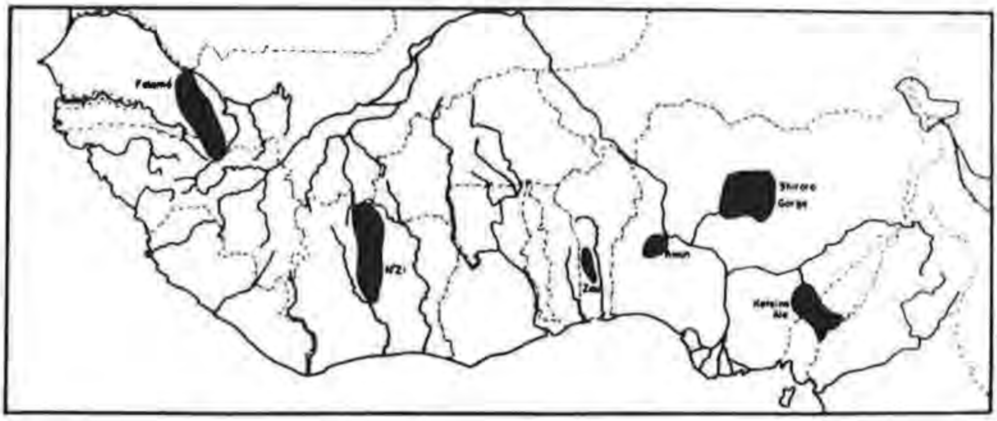
Bank for Reconstruction and Development (1954) speaks for many tropical countries when it says of Nigeria:

> "Nigeria's water resources can undoubtedly be used more intensively
> ..... Yet the basic measurements of the rivers have not been made
> ..... Until a hydrological service has gathered systematic data
> ..... development must be postponed or can be undertaken only with a serious risk of failure". (p.13).

A common way of monitoring water supplies in the face of problems like these is to use stream gauges to measure the run-off from catchment areas. Such methods, while doubtless an accurate means of simple measurement, are nevertheless not wide-spread in the tropics, and those which exist are, or have been, chiefly maintained in connection with large-scale development programmes. Much of the gauging network in Nigeria, for example, is related to investigating navigability on the Niger-Benue waterway system and to the Niger Dam project. Heavy capital investment programmes in Ghana and S.E. Asia are likewise responsible for a knowledge of the water resources of basins like the Volta and the Mekong. Such programmes are expensive and contribute only indirectly to solving the smaller-scale water problems of everyday life connected with agriculture, towns and villages. Unless stream gauge measurements on a local scale are already available, economic development in the latter sense will suffer for many years through an imperfect knowledge of water resources.

A possible way of mitigating this situation is to approach the analysis of water resources from a climatic angle. This involves using existing meteorological data to estimate water resources by means of water balance studies. The latter consists in balancing rainfall against potential evapotranspiration, due allowance being made for the water holding capacities of different soils. The technique is well-known, especially through the work of C.W. Thornthwaite, and needs no description here (Thornthwaite and Mather, 1957). In the present context, however, three aspects of the procedure should be noted: for general purposes the soil moisture holding capacity is deemed to be 300 mm of precipitation; surplus for run-off is not considered as being available unless the soil moisture reservoir is full; and 50% of the surplus available in any one month is regarded as being in transit through the soil so that is appears as the stream discharge of the next month.

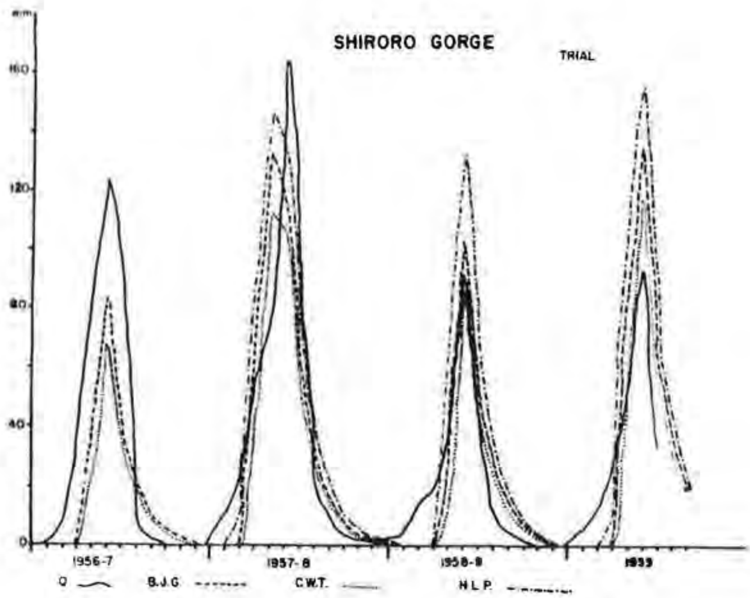
From the various river basins for which measured run-off data are available in West Africa, the Shiroro Gorge catchment was chosen for use as a test case (Fig.1). The catchment has an area of 35,357 km^2 and is located centrally in Nigeria, north of the confluence of the Niger and Benue



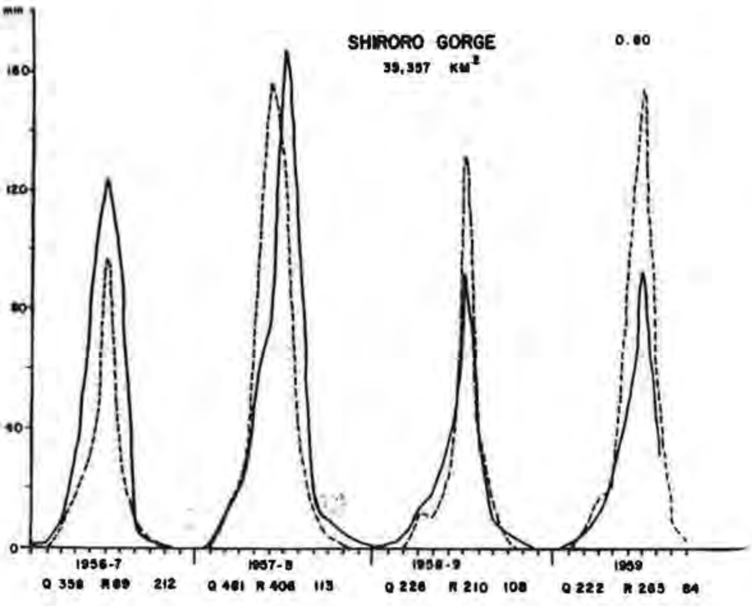
THE WATER RESOURCES OF WEST AFRICA - SAMPLE BASINS

Fig. 1. Basins used in water resource study

rivers. As a result its rainfall varies from the relatively high values of the Jos Plateau and part of the middle belt of Nigeria, to drier conditions further north. Thornthwaite's procedures for estimating run-off were applied to the basin using three different methods of calculating potential evapotranspiration. The results are shown in Fig.2a. In this figure, the solid line (Q) indicates the run-off as measured at the gauging station at the mouth of the catchment. Other lines indicate run-off calculated in different ways: HLP are the results using Penman's method to compute potential-evaporation (Penman, 1948); CWT the results using Thornthwaite's method (Thornthwaite, 1948); and BJG the results using Garnier's modification of Thornthwaite's method (Garnier, 1956). Three aspects of the results are noteworthy: the total run-off for each hydrological year is generally similar whatever method of calculation is used; the peak periods of run-off coincide in every case quite well with the measured peaks; and for each year the calculations delay the start and prolong the end of the run-off periods in comparison with the measured values. When the latter feature is examined more closely it becomes apparent firstly that run-off occurs in the month when precipitation exceeds potential evapotranspiration and before the soil reservoir is full, and secondly that run-off in fact ceases more rapidly than the calculations suggest. The latter observation implies that more than 50% of surplus water



(a) Trial analysis using different methods of evaluating potential evapotranspiration.



(b) Adjusted run-off evaluations.
Solid line: measured run-off.
Dashed line: calculated run-off.

Fig. 2. Comparison of Observed and Calculated Run-off Values for the Shiroro Gorge, Nigeria.

runs off in a given month. Further examination of the data for end of season conditions suggests 70% as a more realistic figure for the percentage of water surplus which runs off each month. The rapid onset of measured, as compared with calculated, run-off at the start of the rains is not unexpected in view of the high rainfall intensity of a typical tropical storm. Studies have shown, for example, that in a tropical storm 75% - 80% of the rain comes in the first 15% - 20% of its duration (Garnier, 1953). Such a concentration means that some surface run-off can be expected at once, and an analysis of the data, for the Shiroro Gorge suggests that from 15% - 20% of the excess precipitation over potential evapotranspiration runs off before the soil reservoir is full.

In the light of these considerations and after some manipulation of the data, it was decided to estimate monthly run-off in the following way:

(1) In a month when precipitation (P) exceeds potential evapotranspiration (PE) and the soil moisture reservoir contains less than 150 mm of moisture, one-tenth of the excess of P over PE is considered as available for run-off.

(2) When P exceeds PE and the soil moisture reservoir contains 150 - 300 mm of moisture, one-fifth of the excess of P over PE is considered available for run-off

(3) When the soil reservoir is full, i.e. contains 300 mm of moisture, all the excess of P over PE is considered available for run-off.

(4) In any month, 70% of the available water runs off in that month and the remainder is held over to augment the available run-off of the next month.

The result of using these procedures for the Shiroro Gorge data are shown in Figure 2b. Potential evapotranspiration was calculated using Garnier's modification of Thornthwaite's system which has been shown elsewhere (Garnier, 1956) as providing a simple and a reliable, generalised estimate of potential evapotranspiration in tropical Africa. The figure at the top right hand of the diagram is the correlation coefficient of Q (measured run-off) against R (calculated run-off). The totals of Q and R, in millimetres, show the run-off for each hydrological year, and they are followed in each case by the ratio Q:R expressed as a percentage.

Since the adjusted procedure for evaluating basin run-off were based on Shiroro Gorge data, it is not altogether surprising that the comparisons of measured and calculated run-off shown in figure 2b are reasonably close. To see if the procedures are valid for other basins in West Africa they were also applied to the different basins shown in figure 1. These basins vary

TABLE ONE

The N'Zi Basin: Measured (Q) and Calculated (R) Run-off

Year	Year	Q mm	R mm	Q:R %
	1954-55	65	75	87
	1955-56	119	382	31
	1956-57	28	52	54
	1957-58	177	252	70

Correlation Coefficient for total period = 0.79

considerably in size and climatic location. The Katsina Ala, for example covers 20,619 km^2 of territory extending from the heavy rainfall area of the Cameroon mountains, through forest and then cultivated woodland savanna lowlands. By contrast the Awun has an area of only 6,960 km^2 and lies within a uniform rainfall zone. The Zou is a small area (8,500 km^2) on the edge of forest and savanna, while the Falémé (28,180 kms^2) starts in savanna and ends in semi-desert.

For each basin Garnier's modification of Thornthwaite's procedure was used to estimate potential evapotranspiration, and the values of this element and also of rainfall were calculated by weighing the values of individual stations according to the proportion of each basin which they represented, due allowance being made for the overall climatic picture and, in some cases, a knowledge of local conditions gained from field experience. The results of the calculations are shown for each basin, except the N'Zi in Figure 3. In each diagram measured run-off (Q) is shown by a solid line and calculated run-off (R) by a dashed line. The totals of Q and R are given below the graphs for each hydrological year; as are the percentage values of the ratio Q:R. The correlation coefficient of Q against R for the whole period in each case is given in the upper right hand part of the diagram. Data for the N'Zi basin are provided in Table One.

It would appear that the method of estimating run-off from climatic data suggested here provides a means of evaluating water supplies in West Africa to within 25% - 30% of the monthly values measured by river gauges. The curves of Q and R are generally similar in each case studies and the time when run-off starts and finishes coincides quite well. Although the method has been developed from West African data, it may well be suitable for other tropical areas, though probably with some modification in the light of broad, regional climatic differences. When applied to a basin in French Guiana Fig. 4, for example, a better correlation was found by returning to a figure

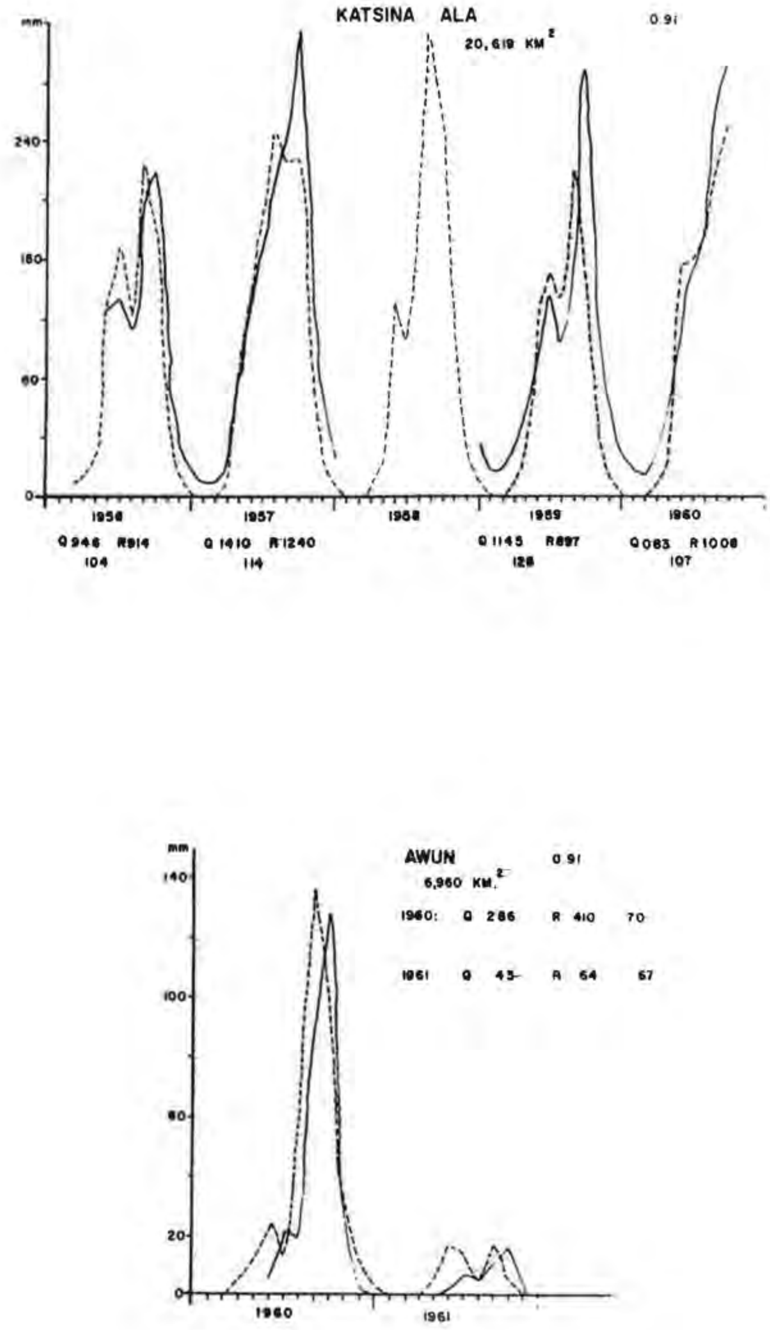
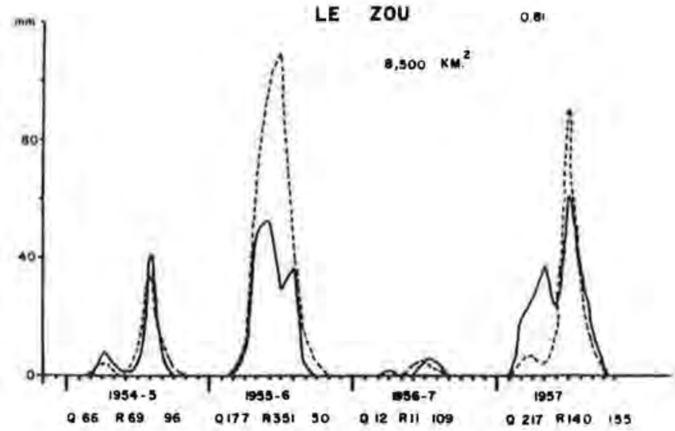


Fig. 3. Measured and Calculated Run-off of Selected West African River Basins.



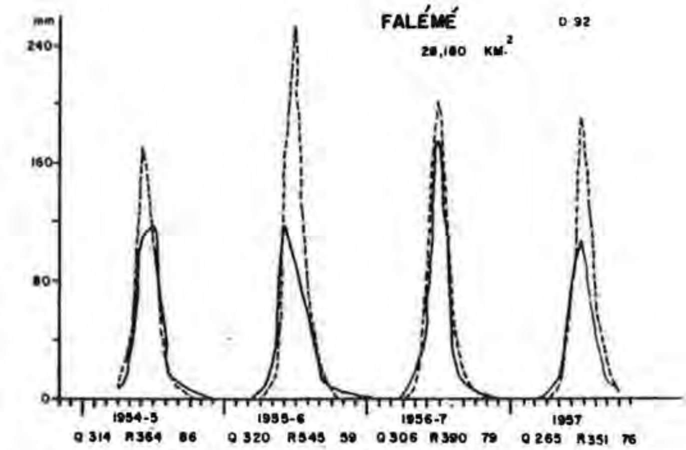


Fig. 3. (continued).

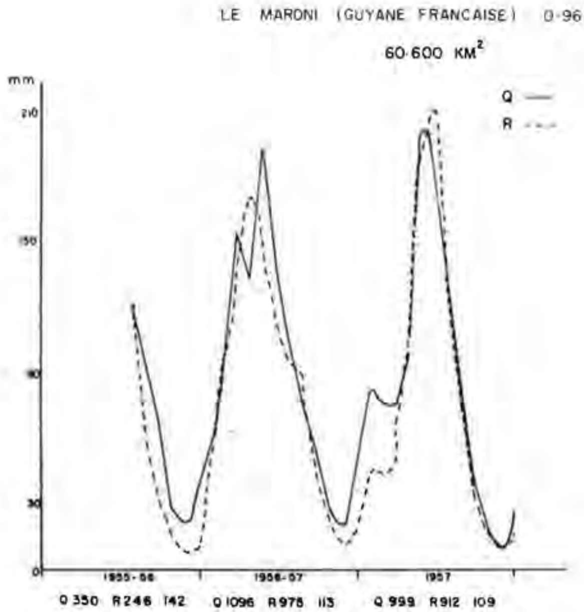


Fig. 4. Calculated and Observed Run-off in French Guiana.

of 50% of available water as run-off for a given month, rather than using the 70% suggested for West Africa. In the case of French Guiana, the percentage of the excess of P over PE available for run-off as used for West Africa was, however, retained.

It is suggested that assessing water resources in this way enables reconnaissance surveys to be rapidly made and provides a guiding framework for more detailed studies. It provides an indication of water potential and in an inexpensive way helps to answer such questions as what areas or catchments might best be surveyed in detail for irrigation or hydro-electric projects; in what areas should schemes of agricultural development be undertaken having regard to water potential; if industrialization or urban expansion is planned, what is involved in providing adequate water supplies; having regard to local or distant, but accessible, water supplies, what level of rural population can be maintained in a given area at an adequate standard of living? Answers to questions like these are fundamental to the successful development of many tropical lands. The methods outlined in this article suggest one way in which climatologists may contribute to this.

Acknowledgements

Financial support for this project was provided by the Indiana University Foundation. Measured run-off data for Nigerian basins came from the Inland Waterways Department, Nigeria, and the Netherlands Engineering and Development Company of Holland. Data for basins in French West Africa and French Guiana were obtained from the publication of ORSTROM, Paris.

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RECENT DOCTORAL THESES OF CLIMATOLOGICAL INTEREST

The list of doctoral theses given below has been extracted from a list of "Recent Geography Dissertations and Theses Completed" compiled by Robert H. Stoddard of the University of Nebraska, which appeared in The Professional Geographer, Vol. 31, No. 1, Feb. 1979, pp. 79-98.

Bailey, William George. "Atmospheric and Surface Control on Evapotranspiration during Soybean Maturation." McMaster University, 1977. Mf., Nat. Library, Ottawa.

Campbell, David J. "Strategies for Coping with Drought in the Sahel: A Study of Recent Population Movements in the Department of Maradi, Niger." Clark University, 1977. Mf., Univ. Microfilms.

Dyke, Arthur Silas. "Quaternary Geomorphology, Glacial Chronology, and Climatic and Sea-Level History of Southwestern Cumberland Peninsula, Baffin Island, Northwest Territories, Canada." University of Colorado, 1977, Mf., Univ. Microfilms.

Fitzgibbon, J.E. "Generation of the Snowmelt Flood in the Subarctic, Schefferville, Quebec." McGill University, 1977. Mf., Nat. Library, Ottawa.

Goward, Samuel N. "The Physical Nature of the Interface as a Factor in Urban Climate." Indiana State University, 1978.

Juvik, James O. "Mountain Fog on Mauna Loa." University of Hawaii, 1977. Mf., Univ. Microflims.

Monteverdi, John Paul. "A Meteorological Analysis of the Variability of Precipitation in the Great Plains, USA." University of California, Berkeley, 1978. Mf., Univ. Microfilms.

Nasuti, James J. "The Diffuse Components of Solar Radiation: Its Distribution and Estimation." University of Hawaii, 1978. Mf., Univ. Microfilms.

Parkinson, Claire L. "A Numerical Simulation of the Annual Cycle of Sea Ice in the Arctic and Antarctic." Ohio State University, 1977. Mf., Univ. Microfilms.

Peake, Jeffrey S. "Seasonal Change in Microclimates of the Colville Delta Alaska." Louisiana State University, 1977. Mf., Univ. Microfilms.

Resosudarmo, Sudjiran. "Climatic Water Balance and Agricultural Production in the Northern Plains of West Java." University of Hawaii, 1977. Mf., Univ. Microfilms.

Roy, John N. "The Simulation of Dry Spell Frequencies." University of Nebraska, 1977. Mf., Univ. Microfilms.

Tolle, Timothy Victor. "Watershed and Climate Influences on Flood Frequency Distributions in the Willamette River Basin." Oregon State University, 1978. Mf., Univ. Microfilms.

Willmott, Cort J. "Radiation Climates in the Conterminous United States." University of California, Los Angeles, 1977. Mf., Univ. Microfilms.

* Mf - available on microfilm

NEWS AND COMMENTS

The Alberta Climatological Association has recently published the record of two Workshops and associated Annual Meetings. The first publication was on the theme of "Applications of Climatology" published in 1977. The second publication, in 1978, covers the proceedings under the title "Climatic Networks". The meeting for 1979 was held on March 2nd, 1979, at the University of Alberta on the theme of "Socioeconomic Impact of Climate". Gordon Mackay of the Atmospheric Environment Service was the keynote speaker, and there were discussions on the following themes: (a) Agriculture and Forestry; (b) Recreation; (c) Urban and Rural Planning; and (d) Industrial Applications.

The Alberta Climatological Association is an informal group made up of persons interested in climatology and its applications in human affairs. Persons interested in the group or interested in receiving its publications are invited to write to Dr. John M. Powell, Canadian Forestry Service, Northern Forest Research Centre, 5320 - 122 Street, Edmonton, Alberta, T6H 3S5.

A recent publication of the Inland Waters Directorate by Stephen Fogarasi and Oleg Mokievsky-Zubok describes the application of principal components technique to the analysis of glacier-climatological data. The paper describes the characteristics and interpretation of the principal components and explains the data transformations and ensuing results. The paper, entitled "Principal Components Analysis on Glacier - Climatological Data for Sentinel Glacier, British Columbia" is No. 95 in the Scientific Series of the Inland Waters Directorate, Ottawa.

Climatology was well represented at the 75th Anniversary Meeting of the Associationsof American Geographers held in Philadelphia from April 21-25, 1979. There was a total of 37 presentations spread over 9 sessions, plus a panel discussion. The great majority of these were in the fields of energy budget studies and climatic change and fluctuations. In addition there was a one-day workshop on "The Applications of Water Budget Climatology to Environmental Impact Assessment and Geographic Research". The enthusiasm for climatology was high at the meeting and led to a large number of persons signing a petition to have climatology recognized by the Association as a special interest group. Robert E. Muller of Louisiana State University, Baton Rouge, organised the petition. A small committee including John Rayner of Ohio State University and Russ Mather of the University of Delaware has been set up with the aim of furthering the petition with the Council of the Association.

A new publication of the Atmospheric Environment Service entitled Climatic Perspectives will be of interest to climatologists inside and outside Canada. Climatic Perspectives is published weekly in English and French in a neat, attractive and easily-handled mimeographed format.

The greater part of the publication deals with the conditions of the given week of publication. These are dealt with in a series of notes, summarizing conditions for the country as a whole and then dealing in more detail with the weather on a regional basis. There is also a tabulation of the week's temperature and precipitation data, including departures from weekly normals, for 166 reporting stations. There are also maps for the whole of Canada showing temperature departures from normal, the distribution of precipitation for the week, the depth of snow on the ground and its water equivalent, and a map and tabulation providing data on heating degree-day accumulation since the preceding first of July. Added to all this is a map providing a 15-day forecast temperature anomaly,forecast from the end of the week covered by the particular number of the publication.

In addition to the foregoing, each number of Climatic Perspectives carries short articles or notes on matter of general or topical interest. There have been discussions on "climatic normals", their validity and how they are obtained, a short study of the urban heat island (Toronto versus the countryside) and a report on an investigation into migraine headaches and the weather. Each number, too, has contained interesting notes and reminders of weather extremes in the past on individual days such as floods, heavy snowstorms, or gales and their effects.

The AES publication has material which can be used in many ways, both in teaching and research. The editor is Terry Allsopp, and inquiries may be addressed to the AES at 4905 Dufferin Street, Downsview, Ontario M3H 5T4, telephone 416-667-4825/4964.

A good deal of media publicity was given some time ago to the idea of towing icebergs from Antarctica to relieve fresh water shortage in desert areas such as Saudi Arabia. The September-October, 1978, number of Focus (American Geographical Society) contains an article on the subject. It is written by Robert H.T. Dodson who is Director of Operations, Saudi Arabia for the Sikorsky Division of United Technologies Corp. The article reviews the fresh water supply in icebergs, discussed towing problems, and considers also their potential for generating electric power. Focus is published bimonthly (except July and August) by the American Geographical Society, Broadway at 156th St., New York, N.Y. 10032, at $2.00 a copy or $8.00 annual subscription.

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No. 2 Weather Conditions in Nigeria, by B.J. Garnier, 163 pp., March 1967, out of print.

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