EVAPOTRANSPIRATION IN THE TROPICS

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ABSTRACT

Evapotranspiration in the Tropics

A study was made of monthly rainfall and runoff over a 105,000 square kilometer watershed in northern Thailand. The function of the watershed in producing the runoff hydrograph was simulated using a type of Stanford Watershed Model adapted for operation with an IBM 1130 digital computer. The evapotranspirational losses from the watershed were computed by using the Thornthwaite, Penman, Blaney-Criddle and Blaney-Morin methods of computing the evapotranspiration. By comparing the computed runoff with the observed runoff from the watershed, it is shown that the model most nearly predicted the observed runoff when the Penman or Blaney-Morin methods were used to estimate the evapotranspirational losses. It was concluded that for a tropical environment, evapotranspirational estimates must include a term measuring the relative humidity of the atmosphere. The evaporation of water is often limited by the ability of the atmosphere to carry away the water vapor produced. Those methods of estimating evapotranspiration based only on temperature and radiation or sunshine data consistently over-estimate the evapotranspiration from a tropical watershed.

EVAPOTRANSPIRATION IN THE TROPICS

by

E. F. Schulz and Aolad Hossain

A study was made of the Water Balance of the Upper Chao Phya River Basin in northern Thailand. Rainfall, runoff and monthly average values of climatic data were available for the period 1957 to 1967. The rainfall and climatic data were used to compute the runoff which was compared to the measured runoff. It was necessary to correct the measured runoff for stream diversions used for irrigation purposes.

A water balance can be defined as an analysis or accounting which balances the continuity equation for a watershed either on an average or annual basis or over a shorter interval of time on a dynamic basis. If a long time interval is used, changes in the natural storage elements in the watershed tend to balance out and one can usually achieve an acceptable water balance considering only the precipitation, evapotranspiration and the runoff. Thus for a long time interval, the mean evapotranspiration is approximately equal to the difference between the precipitation and the runoff.

In analyzing a short period, changes in storage and other dynamic features of routing and translation assume a magnitude equal to or greater than the evapotranspiration. Then all of these parameters must be evaluated in order to achieve a water balance.

The purpose of this investigation was to use the water balance to attempt to assess the relative merits of different evapotranspiration equations in a tropical environment. The Thornthwaite and to a lesser extent the Blaney-Criddle methods have commonly been recommended for use here, ECAFE (1968). Brutsaert (1965) in reporting lysimeter experiments in equatorial Africa found that the evapotranspiration measured in the lysimeter was correlated better with the evapotranspiration computed by the Penman or Blaney-Morin equations. All of these equations have been developed from observations in temperature climates. In view of the extensive planning studies being initiated in southeast Asia in connection with the Mekong Project, it was felt that it would be worthwhile if these various equations could be evaluated in a tropical environment. Lacking lysimeter experiments, it was decided to use a water balance model on a relatively simple hydrologic watershed in northern Thailand as a means for testing these equations.

SIMULATION MODEL

In order to minimize the dynamic problems associated with the translation and routing of the floods through the watershed, it was decided to use the water balance on a monthly basis. Using a shorter time interval would have created additional complexity associated with possible energy storage changes and also would have created a necessity for a complete routing of the floods as they occurred. The 105,000 square-kilometer upper Chao Phya River watershed was represented by a mathematical model similar to the Stanford Watershed Model. All of the computations were carried out on the IBM 1130 computer located at the Asian Institute of Technology at Bangkok, Thailand. The Stanford Watershed Model is shown in diagrammatic form in Figure 1.

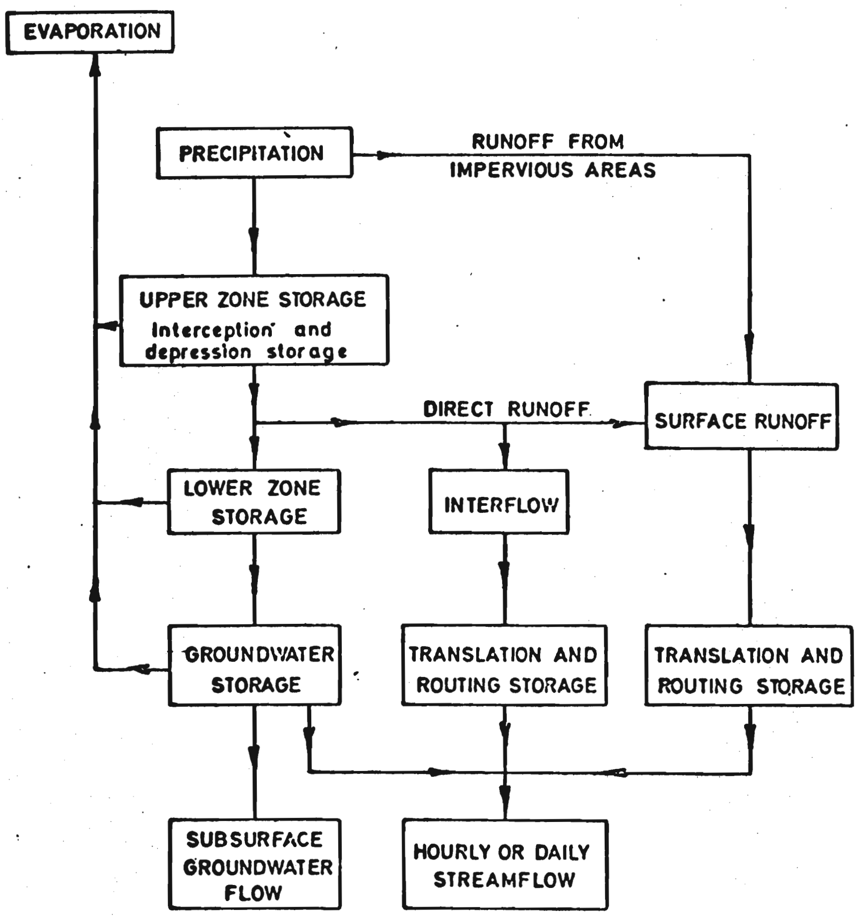

Figure 1... The Stanford Watershed Model

The mathematical model was simplified somewhat because of the 1) limited memory capacity of the computer, 2) the emphasis of the investigation on the evapotranspiration and 3) the simplification of the routing made possible by using the one month time intervals. The AIT model used is shown diagrammatically in Figure 2.

The rainfall input to the watershed was assumed to be disposed of as follows:

1. Surface runoff,
   a) Interflow,
2. Evapotranspiration,
   a) Interception,
3. Accretion to Soil Moisture Storage,
4. Accretion to Surface Water Storage,
5. Accretion to Ground Water Storage.

These elements are represented in the water balance equation:

$$P = ET + \Delta SW + \Delta SM + \Delta GW + R + G \qquad (1)$$

where

P - Equivalent uniform depth of rainfall over the watershed,

R - Surface runoff component of the outflowing streamflow including interflow,

G - Subsurface runoff component of the outflowing streamflow,

ET - Evapotranspiration from the watershed including interception,

ΔSM - Accretion to the soil moisture storage during the month,

ΔSW - Accretion to the surface water storage during the month,

ΔGW - Accretion to the ground water storage during the month.

This equation is true provided there are no surface or groundwater imports or exports of water to or from the watershed.

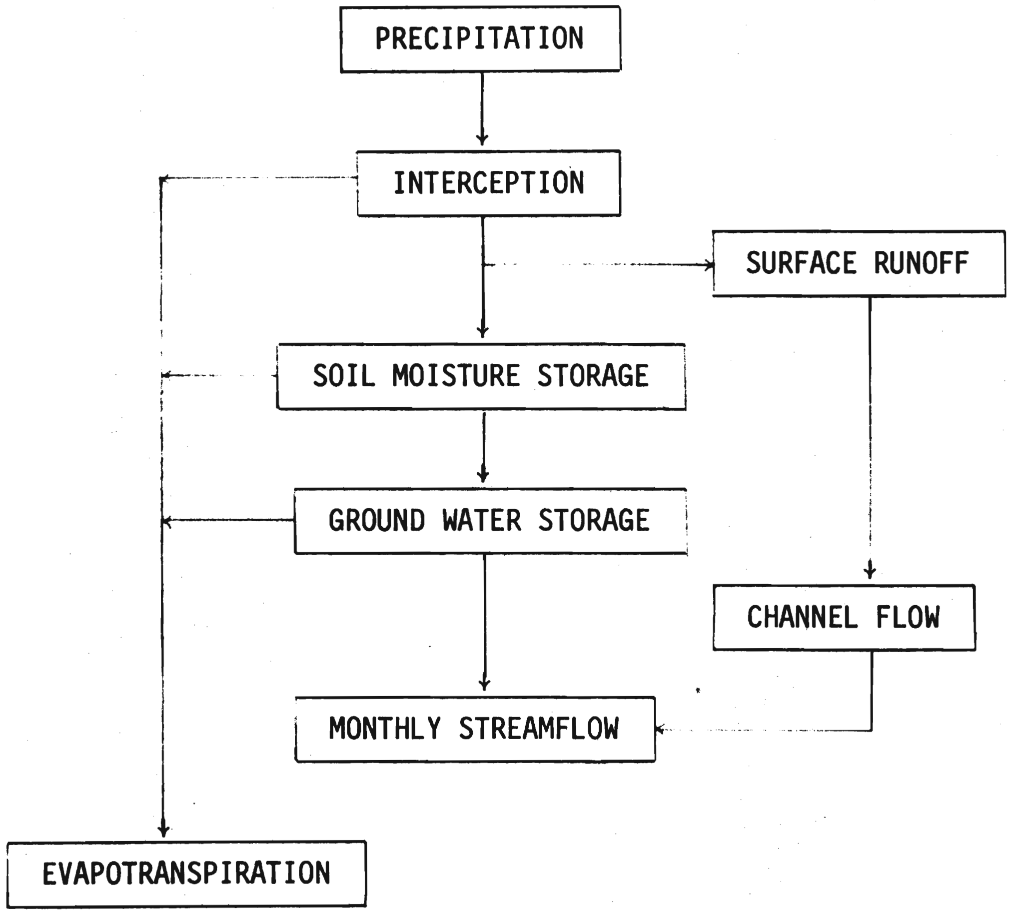

Figure 2... AIT Chao Phya Water Balance

In the water balance for a short period there are two unknowns — evapotranspiration and storage. With two unknowns a second equation is required. This is the one relating evapotranspiration to meteorological factors.

Precipitation: - Precipitation is the most commonly observed element in the water balance of the basin. In maintaining a monthly accounting of the water balance for the catchment, equivalent uniform depth of monthly rainfall over the basin is to be used. The equivalent uniform depth of rainfall over the watershed was determined by the Thiessen Method using the data from 18 rainfall stations.

Interception: - Intercepted rainfall is not available for soil moisture but decreases the actual evapotranspiration draft from the soil moisture. Thus while Interception decreases the Net Precipitation, Burgy and Pomeroy (1958) and McMillan and Burgy (1960) have shown that the evaporation of the intercepted water on the leaf surface causes a corresponding reduction in the evapotranspiration. Interception can be ignored without unbalancing eq. (1).

Evapotranspiration: - A part of the rainfall that falls on the basin is returned to the atmosphere as vapor through evapotranspiration which includes both direct evaporation from water and soil surfaces and plant transpiration. The amount of water returned thru evapotranspiration depends upon the amount of water available, radiation supplied, temperature, humidity and wind velocity. Heat, in excess of that needed for optimum photosynthesis, is dissipated by the plant and by evaporation of transpired water.

Potential evapotranspiration is the water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation. The potential evaporation could be calculated by any one of a number of empirical equations, the Penman, Thornthwaite, Blaney-Criddle, Blaney-Morin or Lowry-Johnson methods.

The 'f' value for the Penman equation for the basin was assumed to be 0.7 except for the flooded rice fields where it is 1.0. The K value in the Blaney-Criddle method was assumed to be 1.0 and the K value in the Blaney-Morin equation was 0.0164.

When rainfall is greater than the potential evapotranspiration, the actual evapotranspiration is equal to the potential evapotranspiration. It has been assumed that when rainfall is less than potential evapotranspiration, a part of potential evapotranspiration would be satisfied by available moisture remaining in the soil until soil moisture storage was depleted.

<u>Surface Water Storage</u>: - Soil moisture is that part of the rainfall which is absorbed in the upper layer of soil where it remains until removed by evapotranspiration. The amount of water available to the plant for transpiration depends on the moisture holding capacity of the soil at field capacity less the moisture holding capacity at wilting point and the depth of the root zone. For a basin where there is a variation of types of soils, depths of soils and depths of root systems for various types of plants at different stages of growth, the equivalent uniform depth of the soil moisture capacity of the watershed can be

estimated by observing the beginning of the soil moisture recharge at the beginning of the rainy season. The volume of rainfall absorbed before there is an appreciable rise in the hydrograph is a measure of the recharge of soil moisture plus the evapotranspiration losses during the beginning of the rainy season.

There is a practical maximum that the soil moisture defiency cannot exceed (the wilting point). There exists at any time a fixed capacity for the basin as a whole. It has been assumed that this soil moisture capacity is unchanging. In this event it is possible to work with the quantities of water in storage or with the deficiencies which is capacity minus storage. The runoff contribution of the storm and the rate of actual evapotranspiration are both dependent upon antecedent soil moisture conditions. It has been found that there is sometimes surface runoff even before the soil moisture capacity is satisfied because locally the rainfall intensity exceeds the infiltration capactiy. The areal inequalities of rainfall cause a certain amount of uncertainty about the actual value of the soil moisture capacity of the basin as a whole.

<u>Ground Water Storage</u>: - The ground water accretion is that part of the rainfall which percolates through the soil to the ground water level. The resultant rise in the ground water level causes an increase in ground water discharge from the ground water storage to the stream channel, until approximately an amount equal to the accretion has drained into the stream channel.

During the rainy season when rainfall is in excess of potential evapotranspiration, a part of infiltrated rain moves down and satisfies any soil moisture deficiency and a part of the infiltrated water percolates down to add to ground water storage. The volume of percolation to ground water is a function of the volume of infiltration less the volume of soil moisture accretion.

Runoff: - That part of the rainfall which travels across the ground surface to the nearest stream and then to the main river system is the runoff. The subsurface flow that travels through the upper layers of soil and ground water flow are included in the runoff when periods as long as a month are considered.

Rainfall in excess of the infiltration capacity of the soil runs over the surface as overland flow. During rainfall the amount of overland flow increases with time due to the declining infiltration capacity. When the soil is at field capacity, the amount of water running over the surface is equal to rainfall less the infiltration capacity of soil, fc, and the evapotranspiration for the period.

It has been assumed that the amount of ground water runoff is a function of the ground water storage.

located approximately in the center of the watershed. The climatic data were punched into IBM cards and computer programs were written which computed the potential evapotranspiration for each month of the period 1957-67 for each of the 10 stations. The evapotranspiration equations used were:

1. Thornthwaite
2. Blaney Criddle
3. Blaney Morin
4. Lowry Johnson
5. Penman.

Other equations considered but not used in this investigation were:

1. Hargreaves
2. Halkias - Veihmeyer - Henrickson
3. Christiansen
4. Munson

The evapotranspiration over the catchment was estimated employing Thiessen weights for the 10 stations. The computed evapotranspiration for the watershed was used as input data in several succeeding steps of the investigation. The various evapotranspiration predictors were tested in a preliminary way against the month's evaporation data measured at Chieng mai. The data were in three groups:

1. Entire year
2. Wet season (May to October)
3. Dry season (November to April)

Table 1 shows the correlation coefficients when the computed evapotranspiration was compared with the Class A Pan evaporation data measured at Chiengmai for the period 1965 to 1967.

Table 1

Correlation Coefficients of Monthly Evapotranspiration with Chiengmai Class A Pan Evaporation

Predictor	Entire Year		Dry Period		Wet Period	
	R	N	R	N	R	N
$E_{Thornthwaite}$	0.55	36	.90	18	.65	18
$E_{Blaney\ Criddle}$	0.51	36	.90	18	.63	18
$E_{Blaney\ Morin}$	0.94	36	.97	18	.84	18
$E_{Lowry\ Johnson}$	0.92	36	.94	18	.90	18
E_{Penman}	0.63	36	.91	18	.85	18

On the basis of the information, the Thornthwaite, Blaney Morin and Penman equations were selected for use in the Chao Phya watershed model. The Blaney Criddle equation was eliminated because of poorer performance than the Blaney Morein (which is somewhat similar in form). The Lowry Johnson equation was dropped in spite of its relatively high correlation coefficient because of a very steep regression line. This equation is based on only temperature data. The correlation coefficient was high because there was so little variation in temperature throughout the year.

The potential evapotranspiration computed by the respective formulae were multiplied by a crop use coefficient to partially account for different crops grown, stages of maturity and farming practices. These adjusted values were punched into IBM cards for eventual use in the Chao Phya watershed model.

Soil Moisture: - The apparent soil moisture capacity of the watershed as a whole was initially estimated by a trial water balance at the beginning of the water year up to the point where the surface runoff began. The average value of soil moisture stored was found to be 23 cm. Later in the simulation studies the assumed soil moisture capacity was varied and the sensitivity of this assumption on the computed runoff was observed.

In the simulation when precipitation was less than potential evapotranspiration, the actual evapotranspiration was equal to precipitation plus the draft from the soil moisture. The draft on soil moisture was modified by the ratio of actual to maximum soil moisture.

$$E_{EXT} = (PET-PRECI) \times \frac{S_{ACT}}{S_{MAX}} \tag{2}$$

where E_{EXT} = evapotranspiration from soil moisture

PET = potential evapotranspiration

PRECI = precipitation

S_{ACT} = actual soil moisture

S_{MAX} = maximum soil moisture at field capacity.

= 23 cm except when the sensitivity of the water balance to this value was being investigated.

It was assumed that soil moisture in any month was equal to last month's soil moisture plus precipitation less actual evapotranspiration, less any percolation to ground water, less surface runoff (if there was any).

Ground Water: - There was considerable ground water storage in the alluvial deposits of the basin. The stored ground water was enough to maintain the dry season flow of the streams.

The approximate rate of percolation to ground water storage was estimated by computing the total volume of ground water runoff in a water year and dividing this volume by the number of months when precipitation was in excess of potential evapotranspiration (available for ground water recharge).

It was expected that any percolation to ground water would be dependent on the soil moisture. With the increasing soil moisture, the amount of water percolating down would increase until the soil field capacity was attained, then the percolation to ground water would be approximately constant (Linsley and Crawford, 1960).

A linear model was assumed to represent the above mechanism. Precipitation above potential evapotranspiration accumulated from the beginning of water year was proportional to the amount of moisture in the soil. It was assumed that percolation to ground water would occur only when the rainfall was in excess of potential evapotranspiration and because most of the ground water recharge occurred during high rainfall months.

$$GRC = (XMN)\,(SMOIS) \tag{3}$$

where

GRC = percolation to ground water

XMN = coefficient depending on the assumed soil moisture capacity

XMN = 0.1455 when SMAX = 23 cm.

SMOIS = actual soil moisture

$$= \sum_{t=0}^{t=n} (\text{precipitation - potential evapotranspiration})$$

from the beginning of water year. Only positive values were accumulated.

It was found that the maximum percolation to the ground water would be around 3.4 cm per month when soil moisture was at the field capacity (all deficient soil moisture storage was satisfied).

a. *Ground water runoff* - It was assumed that ground water flow into the stream was a function of the ground water storage within the basin. A linear model was used:

$$\text{GRUN} = (\text{XR})\ (\text{STORE}) \tag{4}$$

where

GRUN = ground water runoff in any month

XR = coefficient depending on the ground water storage at the beginning of the ground water recession period

XR = 0.4038

STORE = ground water storage carried from the last month.

b. *Ground water storage* - It was reasonable that part of the ground water storage was dissipated by evapotranspiration or deeper percolation which did not contribute to the streamflow at the gaging station. Also there was a minor amount of withdrawal of ground water thru wells in the basin.

The ground water storage was defined:

$$STORE = \sum_{t=o}^{t=n} GRC - \sum_{t=o}^{t=n-1} GRUN - \sum_{t=o}^{t=n-1} XLOST. \quad (5)$$

where

STORE = ground water storage in any month

GRUN = ground water runoff in any month

XLOST = ground water loss in any month, which was assumed to be 0.20 of ground water accretion.

Runoff: -

a. *Irrigation diversion* - Water was diverted for irrigation from all the tributaries of Chao Phya River particularly from the Ping River. Some of the Irrigation Projects had been constructed and operated by Government Agencies. Small projects were constructed and operated by individual farmers or groups of farmers. In all cases the pattern of irrigation use was similar. Water was diverted during the early part of the wet season to supplement the rainfall to irrigate the rice. During the dry season, water was diverted to irrigate smaller areas of dry season crops such as vegetables, peanuts, soybeans, bananas, etc (Montrakun, 1961).

Water diverted for irrigation altered the terms in the water balance equation. In this investigation, it was decided to restore the measured runoff to virgin conditions by adding the irrigation diversions to the runoff records.

b. *Estimation of virgin runoff* - Since the measured runoff at the gaging station was not the actual total runoff of the rivers owing to the irrigation diversions, the virgin runoff was computed by adding the diversions to the measured runoff. On the Mae Wang Irrigation Project, it was found, that during the dry season, the diversions were as high as 50 percent of the runoff in the Wang River. From the irrigation diversion data of the Mae Faek Project it was also found that diversions amounted to as high as 50 percent of the Ping River low flow above Chiengmai. Records of diversion of the Mae Wang Project were better than the Mae Faek Project which had many missing periods, (Engineering Consultants Inc, 1967).

The irrigated areas from each of the four tributaries is shown in Table 2.

Table 2 - Area Irrigated in the Upper Chao Phya River Basin

Basin		Area, hectares
Ping River Basin		128,780
Wang River Basin		14,050
Yom River Basin		3,200
Nan River Basin		67,440
Pump Irrigation		23,380
	Total	236,850

Note: The data were obtained from Royal Irrigation Department. Areas irrigated after 1965 were not included in the above estimate. The data included all forms of diversions for irrigation plus the water pumped directly from the river.

The most complete data on the actual diversions existed for the Mae Wang Irrigation Project. The seasonal distribution of the diversions by this project were assumed to apply to all of the irrigated area in the watershed above the gaging station on the Chao Phya River at Nakhonsawan, Thailand. The total volume of the irrigation diversions then were computed by multiplying the Mae Wang diversions per hectare by the total irrigated area. These diversions in each month were added to the measured runoff to obtain the monthly reconstructed virgin runoff of the Chao Phya River at Nakhonsawan. It should be pointed here that the river emerges from a narrow canyon upstream from the gaging station and that the irrigated areas are situated largely upstream from the canyon section. Thus there is opportunity for return flows and ground water flows which result from the irrigation to return to the river and thus be included in the measured runoff.

The measured runoff, the estimated diversions and the reconstructed virgin runoff are given in Table 3.

Table 3a - Monthly Reconstructed Discharge of Chao Phya River

at Nakhonsawan, cm

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	Meas.	0.362	0.205	0.130	0.126	0.147	0.551	0.881	1.377	4.176	4.904	1.695	0.490
	Divert.	0.243	0.165	0.210	0.255	0.267	0.209	0.219	0.456	0.372	0.351	0.059	0.077
	Total	0.605	0.370	0.340	0.381	0.414	0.760	1.100	1.833	4.548	5.255	1.754	0.567
1958	Meas.	0.263	0.187	0.111	0.079	0.145	0.411	0.996	1.761	3.462	2.765	0.794	0.391
	Divert.	0.088	0.099	0.195	0.091	0.099	0.219	0.414	0.428	0.431	0.499	0.374	0.246
	Total	0.351	0.286	0.306	0.170	0.244	0.630	1.410	2.189	3.893	3.264	1.168	0.637
1959	Meas.	0.195	0.111	0.113	0.079	0.208	0.623	0.861	3.073	5.242	7.942	1.879	0.546
	Divert.	0.194	0.099	0.077	0.057	0.060	0.207	0.450	0.357	0.431	0.475	0.335	0.179
	Total	0.389	0.210	0.190	0.136	0.268	0.830	1.311	3.430	5.673	8.417	2.214	0.725
1960	Meas.	0.275	0.197	0.115	0.077	0.198	0.483	0.760	2.236	4.748	5.748	2.192	0.931
	Divert.	0.169	0.130	0.114	0.086	0.086	0.309	0.371	0.360	0.396	0.413	0.422	0.198
	Total	0.444	0.327	0.229	0.163	0.284	0.792	1.131	2.596	5.144	6.161	2.614	1.129

Note:

Meas. = *Measured discharge at Nakhonsawan.*
Divert. = *Irrigation diversion from Chao Phya River and its tributaries.*
Total = *Measured runoff plus irrigation diversion.*

Table 3b continued

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Meas.	0.347	0.196	0.162	0.145	0.288	1.284	1.476	2.805	6.347	10.460	5.054	1.059
1961	Divert.	0.306	0.255	0.252	0.178	0.317	0.433	0.513	0.428	0.206	0.365	0.315	0.268
	Total	0.653	0.451	0.414	0.323	0.705	1.717	1.991	3.233	6.555	10.825	5.369	1.327
	Meas.	0.581	0.270	0.181	0.126	0.263	0.455	0.897	2.104	4.484	8.453	3.324	0.586
1962	Divert.	0.357	0.215	0.218	0.184	0.236	0.227	0.324	0.442	0.240	0.377	0.419	0.321
	Total	0.938	0.485	0.399	0.310	0.499	0.682	1.221	2.546	4.724	8.830	3.743	0.907
	Meas.	0.212	0.128	0.130	0.105	0.102	0.339	0.799	3.646	4.393	5.746	4.166	1.589
1963	Divert.	0.226	0.222	0.141	0.093	0.048	0.141	0.306	0.470	0.394	0.426	0.380	0.221
	Total	0.438	0.350	0.271	0.198	0.150	0.480	1.105	4.116	4.787	6.172	4.546	1.810
	Meas.	0.355	0.355	0.331	0.350	0.521	0.887	1.421	1.662	3.880	8.132	3.896	1.040
1964	Divert.	0.371	0.249	0.188	0.108	0.298	0.241	0.396	0.365	0.318	0.297	0.255	0.181
	Total	0.726	0.604	0.519	0.458	0.819	1.128	1.817	2.027	4.198	8.429	4.151	1.221
	Meas.	0.482	0.418	0.547	0.546	0.646	0.910	1.172	1.826	3.128	2.731	1.793	0.729
1965	Divert.	0.204	0.148	0.116	0.079	0.125	0.343	0.148	0.376	0.462	0.506	0.354	0.368
	Total	0.686	0.566	0.663	0.625	0.771	1.253	1.320	2.202	3.590	3.237	2.147	1.097
	Meas.	0.422	0.412	0.521	0.458	0.644	1.665	1.269	2.874	5.808	3.879	1.905	0.901
1966	Divert.	0.221	0.142	0.074	0.126	0.171	0.259	0.349	0.409	0.361	0.412	0.324	0.229
	Total	0.643	0.554	0.595	0.584	0.815	1.924	1.618	3.283	6.169	4.291	2.229	1.130
	Meas.	0.555	0.542	0.529	0.505	0.543	0.764	0.930	1.375	2.720	5.310	1.700	0.961
1967	Divert.	0.239	0.176	0.168	0.126	0.171	0.259	0.349	0.409	0.361	0.412	0.324	0.229
	Total	0.794	0.718	0.697	0.631	0.714	1.023	1.279	1.784	3.081	5.722	2.224	1.190

Note:

Yanhee reservoir started storing water from November 1962 the measured runoff also reflects the charge in reservoir storage and evaporation loss from the reservoir.

Bhumiphol Dam was closed in November 1962 to form the Yanhee Reservoir. The capacity of the reservoir is 13,462 million cubic meters which 50 % of the mean annual runoff at the gaging station. After November 1962 when the dam was closed, the runoff records at Nakhonsawan should be corrected for the change in reservoir storage during the month plus the reservoir evaporation less the natural evapotranspiration which would have taken place in the reservoir basin. Some of the data were missing especially during the years 1962 and 1963. The water balance computations for the period after November 1962 do not reflect the same conditions as those before this date. This is apparent from Fig. 3.

c. *Surface Runoff* - From a study of rainfall and runoff records for the basin, it was found that there was runoff before the soil moisture depletions were completely restored. During the smaller storms, it was assumed that the surface runoff would be a function of precipitation when the precipitation was less than the potential evapotranspiration and the soil moisture storage was less than field capacity. This equation was used to compute the surface runoff from the minor storms:

$$RUN = A \times (PRECI)^B \tag{6}$$

where

RUN = the surface runoff

PRECI = precipitation over the basin

A = a coefficient

= 0.0867

B = a coefficient

= 0.6093

These coefficients were evaluated by a regression analysis of the records during those periods when the soil moisture was far below the maximum capacity and rainfall was less than the potential evapotranspiration.

During months when precipitation was greater than potential evapotranspiration and soil moisture storage was high, an exponential model of the following type was assumed:

$$RUN = A \times (TET)^{B} \times (SM)^{C} \tag{7}$$

where

TET = precipitation minus potential evapotranspiration for the month

SM = was proportional to soil moisture storage and was found from the accumulated rainfall less the potential evapotranspiration and percolation to ground water.

A = a coefficient

= 0.0181

B = a coefficient

= 0.09898

C = a coefficeint

= 1.74

These coefficients were also evaluated by a regression analysis of the rainfall and runoff data during periods of heavy rainfall and when the soils were saturated.

During some months when there was exceptionally heavy rainfall, it was found that an additional increment of surface runoff was required to account for the recorded runoff. It was not certain whether this was due to surface runoff itself or to presumed irrigation diversions which did not materialize because of excessive rainfall. This was called XRUN.

d. *Total Runoff* - By comparing the time distribution of the rainfall and runoff, it is realized that there was considerable time delay between rainfall and the resultant runoff. The delay is due to the considerable storage of the rainfall on the surface and in the shallow layers in the soil. It was found that in considering records for a month that 40% of the surface runoff appeared in the stream during the month in which the rainfall occurred. The remaining 60% of the surface runoff appeared in the stream during the following month. (The interflow in this model was included in the surface runoff.)

The ground water component was assumed to have a one month delay time. This means that the ground water storage in any month makes its presence felt as a component of stream flow during the next month. The total runoff was computed by the next equation:

$$TRUN = GRUN + 0.6\ RUN_L + 0.4\ RUN_P + XRUN_L \qquad (8)$$

where

$TRUN$ = total runoff from the basin during the current month

$GRUN$ = ground water component appearing the stream based on the ground water storage during the last month

RUN_L = surface runoff computed for last month

RUN_P = surface runoff computed for the current month

$XRUN_L$ = the excess surface runoff computed for the last month

The terms RUN_L and $XRUN_L$ represent the runoff retained in channel storage, interflow and other surface storage within the basin.

The different elements of the Chao Phya watershed model were combined with the precipitation and the computed evapotranspiration in the computer programs. The output from the computer program was printed out as the computed monthly runoff. The computed monthly runoff was externally compared with the reconstructed virgin runoff hydrograph at Nakhonsawan.

SIMULATION OF THE WATERSHED

The parameters in the simulation model had been evaluated using the rainfall and runoff data during the period 1957 to 1961.

The simulation was always started in May during that time of the year when both the soil moisture storage and ground water storage were depleted to minimum values for the year. The increasing rainfall then served to replenish the various storage features in the catchment. By this way the simulation is rendered most nearly independent of any conditions resulting from the previous year's events.

The results of the simulation are compared in Fig. 3a. This graph shows the results assuming the soil moisture storage capacity was 23 cm. The Thornthwaite equation consistently overestimates the evapotranspiration especially during the wet season. This results in underestimating the runoff.

The underestimation of the runoff by the watershed model using the Thornthwaite equation might be partly overcome by reducing the assumed soil moisture storage capacity. This would hasten the time that excess precipitation would become available for surface runoff. The watershed simulation was repeated for all three evapotranspiration predictors and using different values of the assumed soil moisture storage capacity ranging from 10 cm to 23 cm. The resulting computed runoff hydrograph was compared with the reconstructed virgin runoff hydrograph. A null hypothesis was made to test the difference between the computed runoff hydrograph and the recontructed virgin runoff hydrograph was significantly different from zero.

$$H_o : \hat{R} = R_{virgin}$$

$$H_1 : \hat{R} \neq R_{virgin}$$

where

$\hat{R}$ = mean of computed (simulated) runoff

R_{virgin} = mean of the reconstructed virgin runoff

The t statistic was computed for each simulation. The computed t was compared to the theoretical values of t at the 0.01 and 0.05 level of significance. A comparison of the different values of assumed soil moisture storage is shown in Table 4.

TABLE 4

Comparison of Computed and Virgin Runoff Chao Phya

River at Nakhonsawan

Period - May 1957 to November 1961

N = 67 months

Soil Moisture Capacity	Evapotranspiration Predictors		
	Penman	Blaney Morin	Thornthwaite
10 cm	1.425 NS	1.632 NS	2.660 S
15	1.017 NS	1.219 NS	3.329 S
18	0.736 NS	0.938 NS	3.318 S
20	0.507 NS	0.758 NS	3.355 S
23	0.313 NS	0.570 NS	3.435 S

Note: *NS* *Not significantly different at 0.01 or 0.05 level of significance*

S *Significantly different at both 0.01 and 0.05 level of significance*

The results here show that the computed runoff hydrograph using the Thornthwaite equation was different than the virgin runoff hydrograph regardless of the value of the assumed soil moisture storage capacity. The test of the sensitivity of the simulation model to the range of assumed soil moisture capacity from 10 cm to 23 cm did not disclose any evidence to show that the assumed value of 23 cm should not be used.

Test of the Watershed Model: - The final test of the three evapotranspiration predictors in watershed simulation model occurred when the simulation of the period March 1962 to December 1967 occurred. The comparison of these simulations are shown on Fig. 3(b).

Again the Thornthwaite equation consistently over predicted the evapotranspiration especially during the rainy season. This over prediction resulted in underestimating the runoff hydrograph.

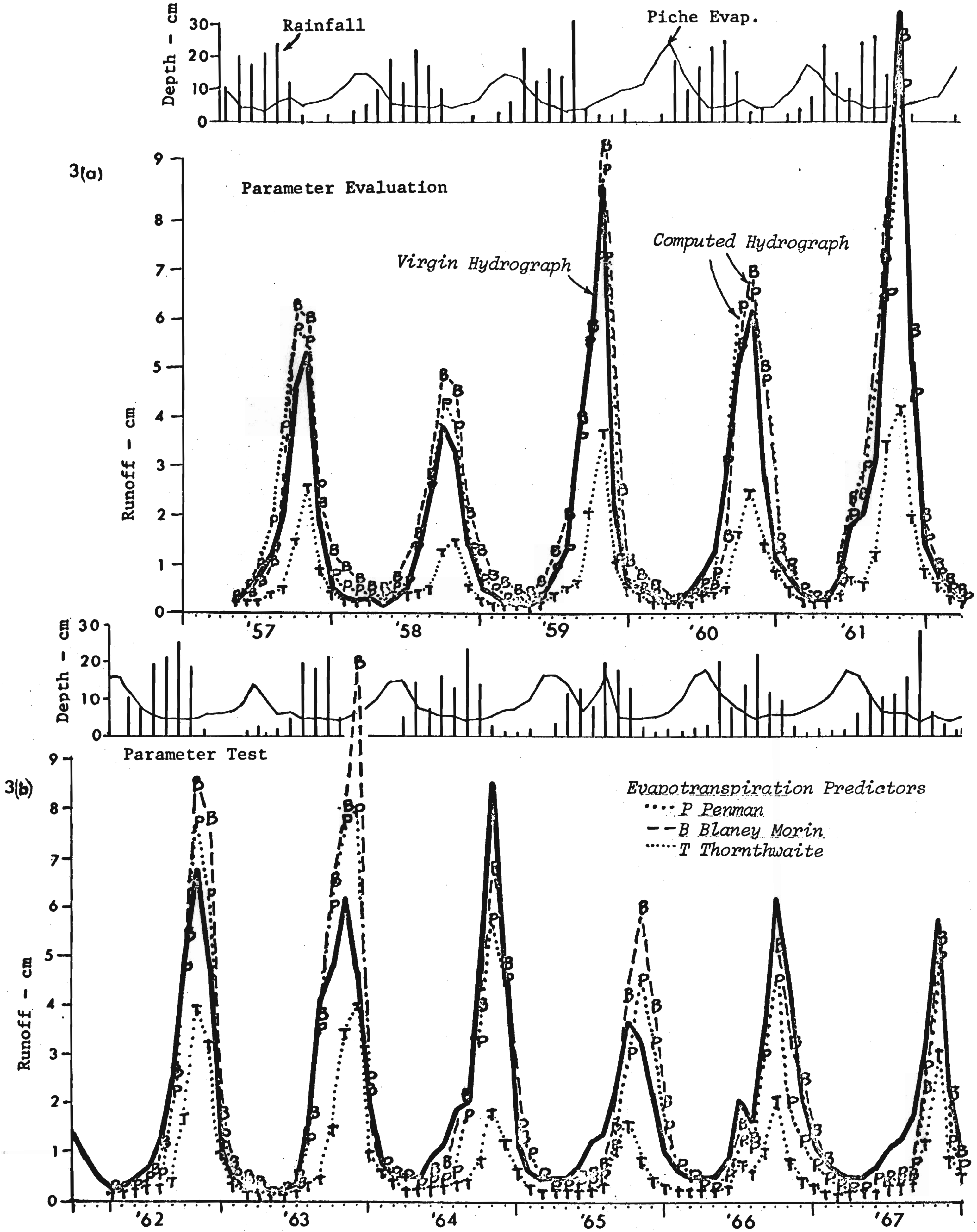

Figure 3... Simulation of Chao Phya Watershed

DISCUSSION OF RESULTS

The general agreement between the virgin runoff hydrograph and the hydrographs computed using the various evapotranspiration predictors was poorer during the test period (1963 to 1967) than during the parameter evaluation period (1957 to 1962).

Performance During Drought: - The bias of the computed runoff compared to virgin runoff changed during the drought years 1957, 1958 and 1965. During these years both the Penman and Blaney-Morin equations underpredicted the evapotranspiration losses. There is no logical reason for this underprediction because these equations have been developed in less humid regions. An explanation may lie in the fact that during the drought years, the volume of water diverted for irrigation may exceed that of the more normal years. It is known that more pumps are used to irrigate lands adjacent to the river during such years. The actual records of water diverted may be much less than is actually used. If this is the case the reconstructed virgin hydrograph should be larger. This would tend to reduce both the error and the bias which is apparent in Fig. 3.

Effect of Yanhee Reservoir: - It is unfortunate that insufficient climatic data were available to complete the simulations before the effects of the Yanhee Reservoir complicated the hydrologic equations representing the watershed. The first effect is apparent by comparing the reconstructed virgin hydrograph and the computed hydrographs during the flood season in 1963 when the reservoir was filling. The 1963 flood was larger than average. During other years of above average runoff, the computed hydrographs using the Penman and Blaney-Morin predictors agreed well with the virgin hydrograph. The data on the reservoir stages during this first year are believed to be unreliable; furthermore the water going into bank storage in the reservoir basin were also removed from the natural runoff hydrograph during this year. These reasons could explain a relatively smaller virgin hydrograph in relation to the computed hydrographs.

The reservoir also captures flood runoff which is released later in the year during the dry season for various beneficial purposes. Examination of the low flow virgin hydrographs during the years 1964, 1965 and 1966 shows this to be the case. The virgin hydrograph is always greater than the computed hydrographs. The rather simple Chao Phya watershed model does not correctly simulate the watershed when reservoir storage is added to the system. At the present time another large storage dam is under construction in the watershed and two more are in the planning stage.

<u>Comparison of the Evapotranspiration Predictors</u>: - The Chao Phya watershed model simulated the reconstructed virgin flow hydrograph best when the Penman equation was used. The Penman equation has a component based on both the energy balance and the vapor flux theory of evaporation. The Penman equation has the most elaborate vapor transfer component of all the methods tested. If sufficient basic data are available, it is believed that the Penman equation should be used for estimating water use in a tropical environment. This is in general agreement with the findings of Brutsaert, 1965. A complete discussion of the Penman and other equations is given by Veihmeyer, 1964.

The Blaney-Morin equation is similar to the Blaney-Criddle equation except that it includes a relative humidity term. This relative humidity term serves as an index to the vapor transport component of the evaporation process. This relative humidity term prevents the equation from overestimating the evaporation based entirely on some combination of the te mperature measurements. The watershed model nearly always overestimated the peak of the hydrograph compared to the hydrograph computed from the Penman equation. The Blaney-Morin equation has simpler requirements as far as basic climatological data are concerned.

The Thornthwaite equation in the watershed consistently produced a hydrograph whose peak was 50% of the virgin hydrograph. During the dry season the computed hydrograph using the Thornthwaite equation was in much better agreement with the virgin hydrograph. Because of its insensitivity to the vapor transport component of the evaporation process, it is recommended that the Thornthwaite equation not be used to estimate evapotranspiration in the humid climate. During the wet period in a tropical climate, the evaporation and evapotranspiration are controlled by the ability of the atmosphere to carry away the water vapor.

CONCLUSIONS

The conclusions of this investigation are summarized as follows:

1. The runoff hydrograph of the Chao Phya River at Nakhonsawan was simulated by a simple watershed model using either the Penman or the Blaney-Morin equation to estimate the evapotranspiration losses.

2. The computed hydrograph most nearly reproduced the virgin hydrograph when the Penman equation was used for estimating the evapotranspiration losses.

3. The depletions of the natural runoff for irrigation purposes must be added to recorded hydrograph to reconstruct the virgin flow hydrograph.

4. Any equation used to estimate the evapotranspiration in a tropical or humid environment must include a relative humidity term which serves as an index measurement of vapor transport component of evaporation process.

5. Any future watershed model of the upper Chao Phya River should include a term which simulates the function of the water storage reservoirs.

6. Data from a Class A evaporation pan may be used to estimate evapotranspiration losses in a tropical environment.

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APPENDIX

The equations used in estimating the potential evapotranspiration are given in this section.

<u>Penman Equation:</u> - The Penman equation can be expressed in an empirical way where the various parameters are derived from climalotogical data. Schulz (1962) has developed a coaxial multiple graph for solving the equation given the climatological measurements in the units usually found in the U.S.

$$ET_p = f\,E = f\left(\frac{\Delta H_o + \gamma E_a}{\Delta + \gamma}\right)$$

where

ET_p	=	potential evapotranspiration, mm/day,
E	=	free water surface evaporation, mm/day,
f	=	a crop use coefficient,
Δ	=	slope of saturation vapor pressure curve at mean air temperature,
γ	=	psychrometric constant,
H_o	=	net solar radiation, mm H_2o/day
	=	$R_c(1-r) - \sigma\, T_a^{\,4}\ (0.56-.092\ \sqrt{e_d})\ (0.1+0.9\ ^n/N)$
E_a	=	vapor flux component (drying power of the air), mm/day,
	=	$(0.175+0.035\ U_2)\ (e_a - e_d)$,
U_2	=	wind velocity at 2 meters elevation, miles/day,

e_a = saturation vapor pressure at the mean air temperature mm Hg,

e_d = actual vapor pressure of the air, mm Hg,

r = albedo of the surface,

$n/_H$ = ratio of actual sunshine to possible duration of sunshine

σT_a^4 = black body radiation at mean air temperature, T_a (expressed in absolute temperature), mm of water,

R_c = mean solar radiation, mm of water evaporation,

Blaney-Morin Equation: - The Blaney-Morin computes consumptive use which is considered to be equal the potential evapotranspiration.

$$ET_{BM} = 0.254\ K\ (1.8T + 32)\ P\ (114 - H)$$

where

ET_{BM} = monthly evapotranspiration, mm,

T = mean monthly air temperature, ^{o}C.

P = monthly percent of annual day time hours,

H = mean monthly relative humidity in percent,

K = monthly crop use coefficient,

= 0.0164 in this investigation.

Thornthwaite Equation: - The monthly evapotranspiration computed by this equation is for a standard month of 360 hours of sunshine. The computed values are then adjusted for the day and month and latitude of the place. When the air temperature exceeds 26.5^{o}C, other values of potential evapotranspiration are given which do not follow the equation.

$$E_T = 1.6 \left[\frac{10T}{I}\right]^a$$

where

E_T = monthly evapotranspiration,

T = mean monthly air temperature, ^oC,

I = an annual heat index which is the summation of monthly heat indices $i = \left[\frac{T}{5}\right]^{1.514}$

$$a = \frac{675\ I^3}{10^9} - \frac{771\ I^2}{10^7} + \frac{1792\ I}{10^5} + 0.49239$$

Blaney-Criddle Equation:- This equation is a simpler form of the Blaney-Morin equation not including the relative humidity term.

$$E_{BC} = 0.254\ KP\ (1.8T + 32)$$

where

E_{BC} = monthly consumptive use, mm

K = monthly crop use coefficeint

= 1.0 in this investigation

T = mean monthly air temperature, ^oC,

P = monthly percent of annual day time hours.

Lowry- Johnson Equation: - The original equation was developed to compute the evapotranspiration for the entire growing season. For this investigation the equation was adapted for monthly use by multiplying the yearly value by the ratio of monthly effective heat / yearly value of effective heat.

of effective heat.

$$E_L = 0.000156\ F + 0.8$$

where

E_L = evapotranspiration for year, inches,

F = effective heat in degree days,

= $(T-32) \times$ number of days,

T = mean monthly air temperature, ^{o}F.