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COMPARISON OF DIMENSIONLESS UNIT HYDROGRAPHS IN THAILAND AND TAIWAN

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The characteristics of dimensionless unit hydrographs were derived from floods from watersheds smaller than 1000 square kilometers located in Thailand. The dimensionless unit hydrographs were expressed as ratios of q/q_q as a function of t/t_p. These dimensionless unit hydrographs were compared with similar unit hydrographs derived from floods on Taiwan and with the unit hydrographs derived from a mathematical model developed from the two parameter gamma function developed from the theory of the instantaneous unit hydrograph. It was found that the unit hydrographs derived from the Thai watersheds had much longer base length and much longer time to peak than similar unit hydrographs derived from floods on Taiwan. This increase in length of response time is attributed to a larger component of subsurface runoff believed to be present in the floods from tropical watersheds.

The problem of estimating flood peaks from small watersheds is involved in the design of storm sewers, highway drainage, diversion works, bridges, and culverts. The majority of such hydraulic structures are constructed on small watersheds. Since small streams have not been gauged as extensively in the past as have large streams, more of the designs have to be prepared without the benefit of stream flow records. In the design of many hydraulic structures the engineer is concerned not only with the maximum discharge but also with the total volume of runoff and its distribution with respect to time, i. e., the entire runoff hydrograph.

Estimating peak rates of runoff and the design hydrograph is an important problem for engineers, since there are many small structures and their combined total cost may be considerable. Many hydraulic structures are either over-designed or fail due to underestimation of floods, because little information is readily available about the flow of small streams.

In view of the lack of data, various techniques have been developed for the determination of design discharges of small watersheds. Many types of empirical formulas have been used for the determination of the peak discharge. Synthetic hydrographs for ungauged watersheds have been developed where the entire hydrograph is required. Many of the existing methods of peak discharge determination fail to take into account all of the factors upon which the runoff depends. Many of the synthetic hydrographs have been developed for a specific location, and it is thought that they should not be used outside the region where they were developed.

Edson (1951) and Nash (1958) derived a conceptual theory of the unit hydrograph from which mathematical expressions for the unit hydrograph were obtained:

$$Q_t \equiv \left\{V(yt)^z e^{-yt}\right\}/\Gamma(z+1) \qquad \text{(Edson)}$$

$$Q_t \equiv \left\{V k^{-n} e^{-t/k}{}_t{}^{n-1}\right\}/\Gamma(n) \qquad \text{(Nash)}$$

where

Q_t = instantaneous discharge rate at time t
V = volume of surface runoff
y = recession constant
z = exponent depending on shape of time area concentration curve of the watershed
$\Gamma(.)$ = Gamma function
n = shape parameter
e = base of the natural logarithms
and k = a storage constant

A complete unit hydrograph can be computed from these equations provided the parameters can be evaluated. Dimensionless unit hydrographs presented as ratios of q/q_p and t/t_p tend to eliminate influence of the basin characteristics.

Beginning with the above equations, Gray (1961) developed a method whereby the unit graphs were synthesized from measurable topographic characteristics. The parameters of the equation were obtained by regression analysis.

Reich (1962) has developed a method of hydrograph synthesis for ungauged catchments based on the assumption that flood hydrographs could be adequately represented by the three parameter Pearson Type III function. Parameters of this function were correlated directly with storm and catchment features, the significant factors being determined in a stepwise multiple correlation study. The significant factors include the rain storms causing the flood, topographic characteristics, soil type and vegetation on the watershed. Three simple empirical equations from regression analysis were obtained for determination of the three hydrograph parameters, peak rate of runoff, total runoff, time to mass center of area of the hydrograph from peak, which describe the complete hydrograph.

The mathematical expression for the hydrograph curve using the Pearson Type III function is

$$q_t \equiv q_p e^{-t/G} (1 + t/m)^{m/G}$$

where

$m \equiv$ time to peak
$q_t =$ discharge
$q_p \equiv$ peak discharge
$G \equiv$ *time from* q_p to c
$t \equiv$ time
$c \equiv$ time between peak and center of gravity of the hydrograph.

The improvement in the fitting of the theoretical unit hydrograph to the actual hydrograph did not actually off-set the additional complexity arising from having to evaluate another parameter.

I. P. Wu et al. (1964) developed a method for computing design hydrographs in the State of Indiana using the same basic model of the instantaneous unit hydrograph. The shape of the hydrographs were determined by two hydrograph parameters (t_p, time to peak, and K, recession coefficient). The hydrograph parameters were correlated with three measurable watershed characteristics: watershed area A, length of the main stream L, and slope of the main stream S. The average infiltration rates were estimated from a soil map of the State. By knowing the size and shape of the dimensionless hydrograph, a flood hydrograph can be determined assuming a design rainfall over an ungauged watershed.

This basic procedure was used by C. M. Wu (1965) in a study of unit hydrographs on Taiwan.

THEORETICAL CONSIDERATIONS

Nash (1957) proposed a conceptual model of a unit hydrograph by considering that the drainage basin functions as n linear reservoirs in series. By routing a unit inflow through the reservoirs, a mathematical expression for the instantaneous unit graph can be derived. The instantaneous unit hydrograph is a hydrograph resulting from 1 inch (or 1 mm) of rainfall excess generated during an instant of time.

$$Q_t \equiv \frac{VK^{-n}}{\Gamma(n)} e^{-t/K} t^{n-1}$$

or

$$Q_t = \frac{0.278\ AR}{K\Gamma(n)} \left(\frac{t}{K}\right)^{n-1} e^{-t/K} \tag{1}$$

or

$$q_t \equiv \frac{1}{K\Gamma\ (n)} \left(\frac{t}{n}\right)^{n-1} e^{-t/K}$$

in which

Q_t = discharge in cubic meters per second

q_t = discharge per unit of catchment

$q_t = \dfrac{Q_t}{AR}$

t = time in hours after the beginning of direct surface runoff

V = volume of surface runoff in cubic meters

A = area of watershed in square kilometers

R = total runoff in millmeters, which is equal to unity for unit hydrograph

K = storage parameter of the equation having the dimension of time (hrs)

n = a dimensionless parameter of the equation

$\Gamma(.)$ = Gamma function

$\Gamma(n)$ = $(n–1)! = (n–1)\ (n–2)\ (n–3) \ldots$ (for the condition that n is an integer)

$$q \equiv \frac{Q}{0.278A} \equiv \text{cms/km}^2$$

Considering Eq. (1), at $t \equiv t_p$, $Q \equiv Q_p$ at the peak of the hydrograph and differentiating Q with respect to t and equating to zero, the time to peak in Eq. (1) can be expressed as

$$t_p \equiv (n–1)K \tag{2}$$

Solving Eq. (2) for K and substituting into Eq. (1), then

$$Q_t \equiv \frac{0.278\ AR}{t_p} \frac{(n–1)^n}{\Gamma(n)} \left[(t/t_p)\ e^{-t/t_p}\right]^{(n-1)} \tag{3}$$

But Q_p is defined as the peak rate when $t = t_p$, then Eq. (3) becomes

$$Q_p \equiv \frac{0.278\ AR}{t_p}\left[\frac{(n-1)^n}{e^{n-1}\Gamma(n)}\right] \tag{4}$$

in which R is total runoff which is equal to unity for a unit hydrograph,

$$Q_p \equiv 0.278\ \frac{A}{t_p} f(n) \tag{5}$$

From a study of unit hydrographs from floods in Taiwan, C. M. Wu (1956) suggested a practical simplification using an empirical equation obtained by correlating the observed maximum discharge to the ratio of area to the time to peak.

Since the dimensionless unit hydrograph is defined as a graph of q/q_p vs. t/t_p this equation can be obtained from Eqs. (3) and (4)

$$q/q_p \equiv (t/t_p)^{n-1}\ [e^{-(n-1)}]\ (t/t_p - 1) \tag{6}$$

Thus Eq. (6) is an equation for the dimensionless instantaneous unit hydrograph in terms of the parameter n. Fig. 1 is a graph of this equation.

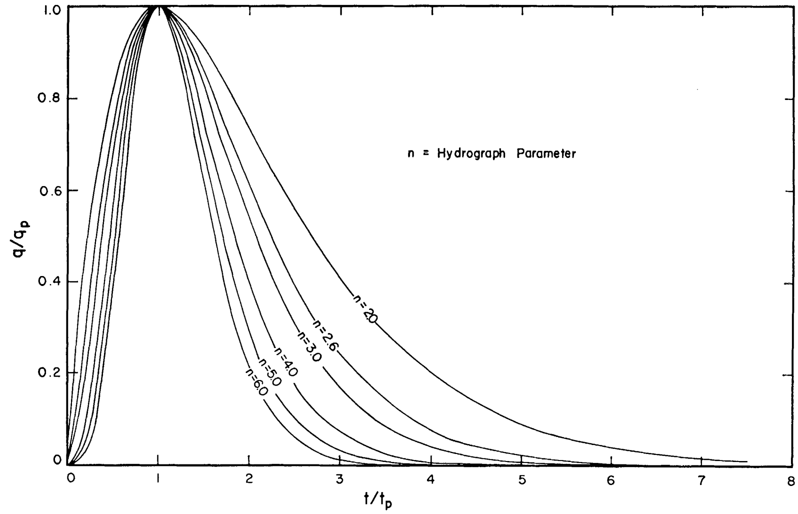

Fig. 1.
Dimensionless instantaneous unit hydrograph.

INVESTIGATION IN THAILAND

Five drainage areas in Thailand were selected for a study of the unit hydrographs derived from observed floods. The catchments ranged in size from 24 to 1,060 square kilometers.

The physical characteristics of a watershed

The watershed is defined as the area within the topographic divide from which surface water could reach the gauging station. The following four pertinent characteristics of the watershed are considered in this analysis.

(1) Watershed area, A, km^2,
(2) Length of the longest watercourse, L, km,
(3) Length of the stream channel up to the center of the watershed, L_c, km,
(4) Overall slope of the longest watercourse, S, m/m.

Watershed area (A) is defined as the area, within the water divide, draining to the gauging station or the structure under design. It is measured from topographic maps and expressed in square kilometers.

Length of the longest watercourse (L) is defined as the length in kilometers measured on a topographic map along the main stream of the watershed, from the gauging station upstream to a point on the watershed boundary determined by extending the longest watercourse to the divide. It is therefore the longest path traveled by a unit volume of surface runoff in reaching the gauging station.

Logarithmic plotting of the length of the longest watercourse against catchment area shows a linear relationship as shown on Fig. 2. The regression equation for both the Thai and the Taiwan data are presented in Fig. 2.

Length of the main stream channel up to the center of the watershed in kilometers (L_c) is defined as the length of the main channel through which a unit volume of surface runoff would have to travel from the center of area to reach the gauging station. The center of area – shown in Fig. 3 – was determined by suspending a cardboard image of the plan view of the watershed by several corners. The center of area will always fall along a vertical line beneath the point of suspension.

Over-all slope (S) of the longest watercourse is defined as the ratio of the fall in elevation of the longest watercourse between the divide and the gauging station to the length of the longest watercourse.

These watershed characteristics are schematically shown on Fig. 3 and tabulated in Table 1.

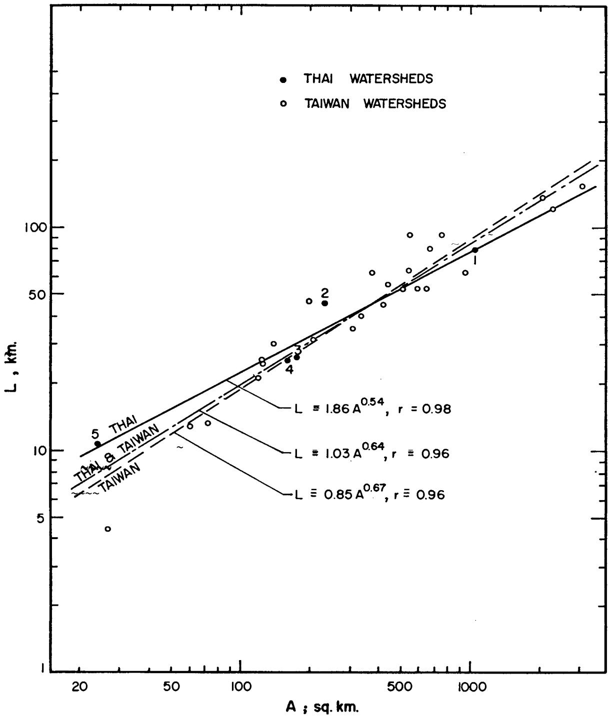

Fig. 2.
Length of longest watercourse vs. catchment area.

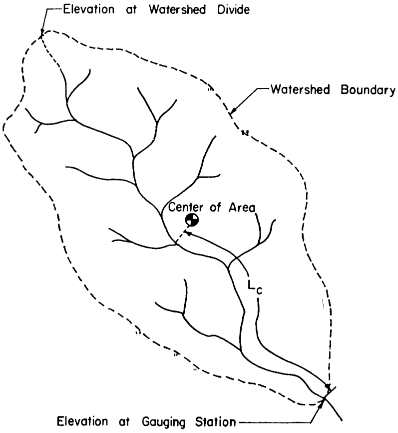

Fig. 3.
Watershed characteristics.

Table 1.
Watershed characteristics

Watershed no.	River	Location		Area (km^2)	L (km)	L_c (km)	S m/m
		at or near	Lat.-Long				
1	Nam Maekhan	Sanpathong	18°42′ N 98°48′48″E	1060	78.7	33.2	0.0112
2	Lam Takling	Kao Yai	14°31′40″N 101°24′09″E	235	44.85	8.75	0.0159
3	Lam Muak Lek	Highway-Bridge	14°38′04″N 101°12′37″E	177	26.45	9.65	0.031
4	Klong Saothong	Khun Tha Le	8°28′18″N 99°50′03″E	163	25.45	11.32	0.0479
5	Huai Mae Nai	Ban Pa Muang	18°54′23″N 98°54′59″E	24	10.65	6.75	0.1014

Derivation of the dimensionless hydrograph

The concept of the distribution graph developed by Bernard (1935) was used in the present analysis.* The time base of the surface runoff was divided into convenient intervals. The selected interval is a convenient multiple of one hour and the interval is about 20 to 25 per cent of the lag time (time from beginning of surface runoff to the point where 50 per cent of runoff occurs). Since the lag time is not known initially, the time interval may be selected as 20 to 30 per cent of the time between beginning of surface runoff and the peak of the recorded hydrograph (the first peak if the hydrograph has multiple peaks). The effective rainfall (which is equal to the depth of surface runoff from the catchment) is distributed tentatively and is then multiplied successively by each of the assumed distribution percentages. The periods and amount (depth) of effective rainfall in multiple period storms and the distribution percentages were adjusted by trial and error until the computed surface runoff converged to the observed surface runoff hydrograph with an error of about ± 5 per cent, and the following listed conditions were verified:

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* The distribution graph is a unit graph presented in histogram form, with the ordinate for each period representing the percentage of total surface runoff that occurs during that period.

(1) The distribution percentages totaled 100 per cent.

(2) The sum of the effective rainfall equaled the volume of the observed surface runoff.

(3) The sum of the computed runoff hydrograph equaled the volume of the effective rainfall.

If inequalities existed in any of these, the error in computations was found and corrected. Small errors are the result of rounding off computations. The rounding errors are eliminated by distributing the rounding approximations among the larger values where the percentage of error due to the rounding off will be minimum.

The dimensionless hydrographs for the five tropical watersheds are shown on Fig. 4. An average line was drawn through the five sets of data. The correlation coefficient of the average line was found to be 0.828.

Evaluation of instantaneous unit hydrograph parameter K and n

The instantaneous unit hydrograph can also be expressed by the equation

$$q = \frac{0.278\,AR}{K\Gamma(n)}\,(t/K)^{n-1}e^{-t/K} \tag{7}$$

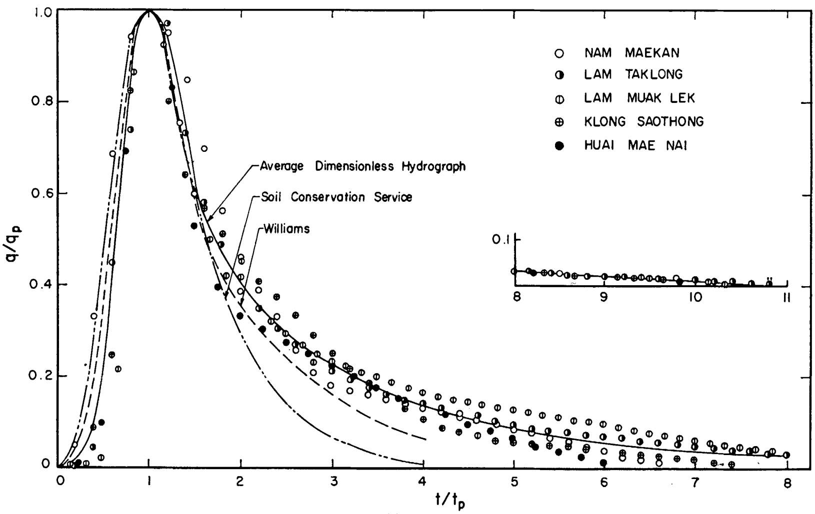

Fig. 4.

Dimensionless unit hydrograph.

In this form the instantaneous hydrograph is defined with two parameters, K and n, which determine the shape of the hydrograph.

Examination of recession curves of the derived unit hydrographs from the floods in Thailand revealed three components. Therefore a variation in storage coefficient must exist, i. e., K_1, K_2, and K_3. Laurenson (1961) studied the recession curves of streams in New South Wales and found that when the recession curve was plotted on semi-logarithmic paper, two or three straight line segments could be identified. Ho (1967) found that most recession curves in western United States could be approximated by three linear segments when plotted on semi-logarithmic paper. Each segment may be specified by a constant K_1, K_2, and K_3. The first storage, representing surface and subsurface flow, is specified by K_1 and K_2. The second storage, representing main channel translation effects, is specified by K_3. Ho had analyzed recession coefficient for several hundred hydrographs in order to establish the three recession components. Insufficient data were available for the stations in Thailand to be able to reach any conclusions regarding the values of the recession coefficients. However, the studies of both Ho and Laurenson have established the fact that several elements exist.

In the recession curve analysis of unit hydrographs derived in Taiwan, C. M. Wu (1965) likewise found that one or more straight lines can be fitted for the recession curve. The first part of the recession curve, which is mainly derived from the main stream channel and valley storage, has been used in his analysis to determine the storage coefficient, K_1. For comparison of results in the present study, the storage coefficient K_1 has been determined in a similar manner.

Considering the expression for the recession curve

$$q_1 = q_0 e^{-\Delta t/K} \tag{8}$$

in which q_0 and q_1 are any two values of the discharge at time t_0 and t_1, time $\triangle t$ is the increment of time from t_0 to t_1 and K is the storage coefficient.

From the above equation, the storage coefficient can be expressed as

$$K = \frac{\triangle t}{2.3 \log q_0/q_1} \tag{9}$$

According to Eq. (9), the dimensionless recession constant (K_1/t_p) of the dimensionless hydrograph obtained from Eq. (6) can be expressed as

$$K_1/t_p \equiv \frac{\triangle t/t_p}{2.3\ \log \left[\dfrac{q_0/q_p}{q_1/q_p}\right]} \tag{10}$$

I. P. Wu et al. (1964) plotted the value of the dimensionless recession con-

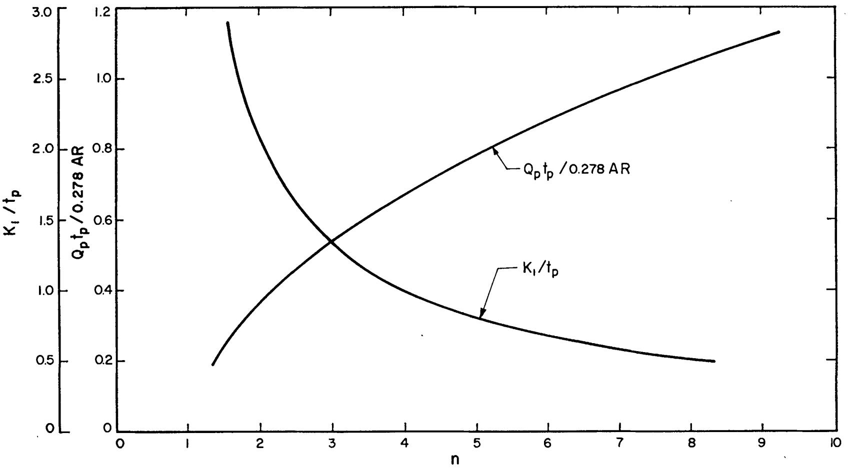

Fig. 5.
Dimensionless peak discharge vs. *n* and dimensionless recession constant vs. *n*.

stant, K_1/t_p, as a function of the parameter n as shown on Fig. 5. Such a diagram can be used for estimating the value of the parameter n when the quantity K_1/t_p is known.

An alternative method for estimating the value of n could be the comparison of the observed dimensionless hydrograph with the theoretical dimensionless hydrograph as shown in Fig. 1 by considering the areas under the hydrographs to be equivalent.

Table 2.
Hydrograph parameters

River	Location	t_p (hr)	t_{lag} (hr)	K_1 (hr)	n	q_p cms/1 mm
Nam Maekhan	Sanpathong	10	13.0	9.66	3.0	17.33
Lam Taklong	Kao Yai	5	7.7	5.6	3.0	7.06
Lam Muak Lek	Highway Bridge	6	11.0	5.24	3,0	4.43
Klong Saothong	Khun Ta Le	10	15.0	9.67	3.5	1.97
Huai Mae Nai	Ban Pa Muang	4	5.25	3.1	3.7	1.0

Table 2 shows the hydrograph parameters: time to peak (t_p), lag time (t_{lag}), and storage coefficient K_1 and the corresponding gamma function argument, n, of the unit hydrographs derived from the observed flood hydrographs.

Prediction of the time to peak and of the storage coefficient from physical watershed characteristics

Snyder (1938), using data from the Appalachian Mountain area, found that the basin lag time (which he defined as the time from center of mass of rainfall excess to peak of the unit hydrograph) was related to watershed length parameters, L and L_c. The U.S. Bureau of Reclamation (1960) used a relationship including channel slope in addition to the length parameter in estimating the time to peak.

The form of the watershed parameter, $LL_c/\sqrt{S}$ had been suggested earlier by Snyder. A linear relationship was obtained from a logarithmic plotting of time to peak, t_p, against the watershed characteristics, $LL_c/\sqrt{S}$. This provides a means for estimating the time to peak for a watershed where streamflow records are not available.

C. M. Wu (1965) investigated the application of the current unit hydrograph

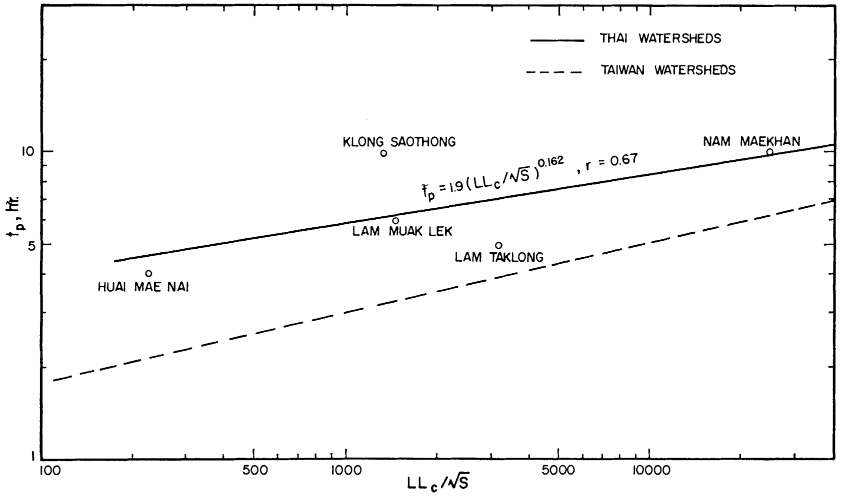

Fig. 6.

Time to peak vs. $LL_c/\sqrt{S}$.

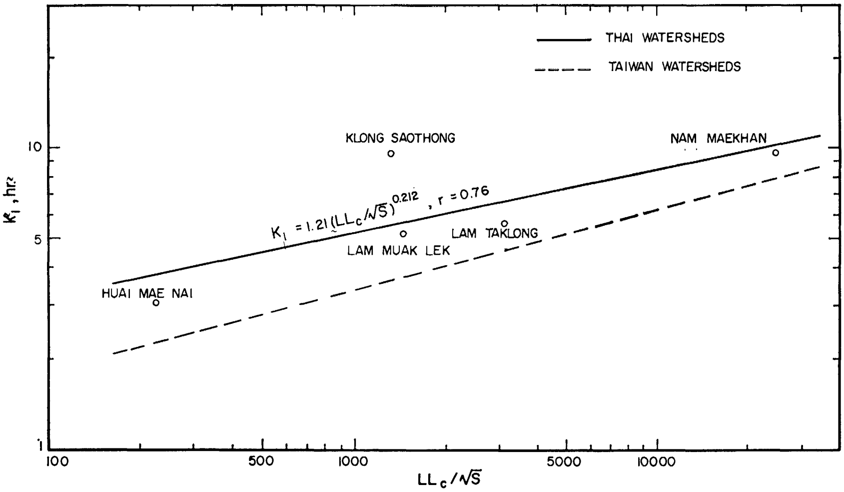

Fig. 7.

K_1 vs. $LL_c/\sqrt{S}$.

concept to the behavior of floods from watersheds on Taiwan. He correlated the hydrograph parameters – time-to-peak (t_p), lag time (t_{lag}), and storage coefficient (K_1) with the watershed characteristics – L, L_c, and S. Wu used data from watersheds ranging from 26.5 to 3,000 square kilometers in size.

The Thai and Taiwan data are compared on Figs. 6 and 7. These graphs are a logarithmic plotting of t_p and K_1 against the watershed parameter, $LL_c/\sqrt{S}$. A regression line was fittted through these points. The regression equation is

$$t_p \equiv 1.9(LL_c/\sqrt{S})^{0.162} \tag{11}$$

with a coefficent of correlation of 0.67 and

$$K_1 \equiv 1.21(LL_c/\sqrt{S})^{0.212} \tag{12}$$

with a coefficient of correlation of 0.76.

In addition the lag time (t_{lag}) has been found in a similar manner. The regression equation is

$$t_{lag} \equiv 3.06(LL_c/\sqrt{S})^{0.152} \tag{13}$$

with a coefficient of correlation of 0.61. The relationship is shown in Fig. 8. It should be noted here that the lag time in this study is defined as the length of

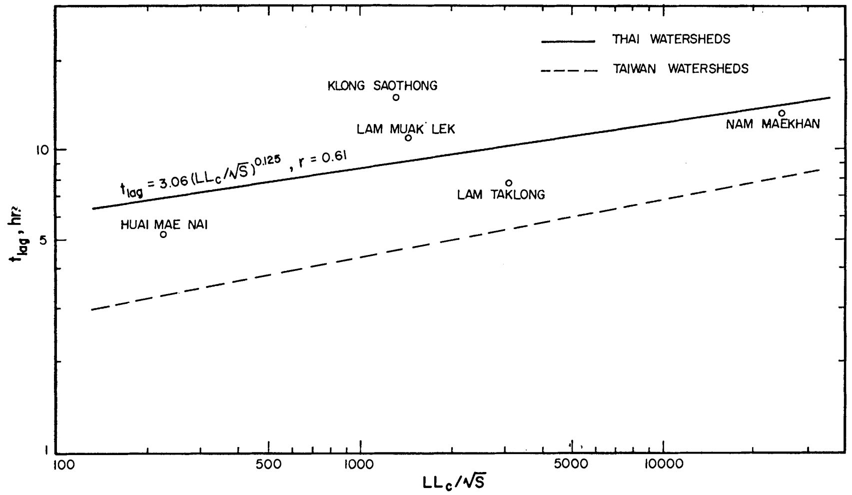

Fig. 8.
Time lag vs. $LL_c/\sqrt{S}$.

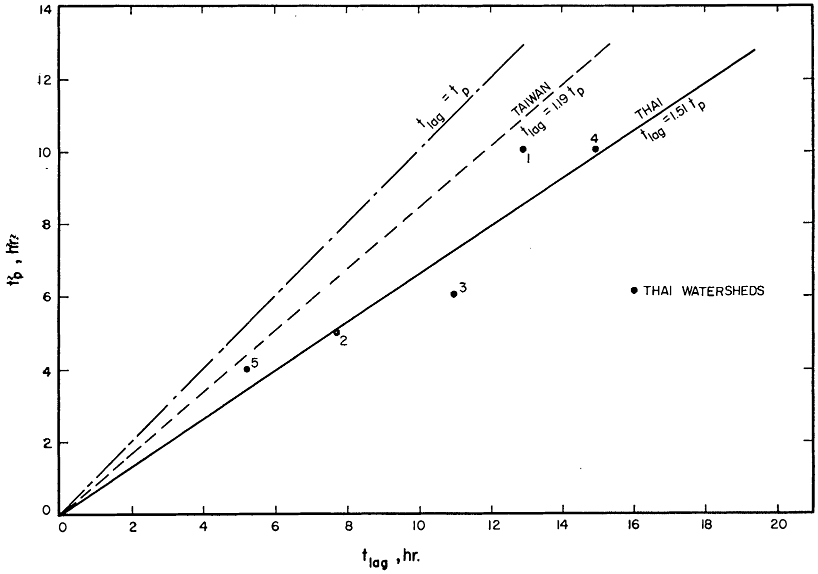

Fig. 9.
Time to peak vs. lag time.

time between the beginning of rainfall excess and the time that 50 per cent of the runoff has occurred. This is not the same as the definition of Snyder.

A comparison of the similar relationship for the flood hydrographs studied in Taiwan are shown in Figs. 6, 7, and 8 as a dashed line.

Plotting of the time to peak against lag time on Fig. 9 shows a linear relationship. This type of graph may be used to convert time to peak to lag time and vice versa.

Prediction of the peak discharge

The peak discharge of a unit hydrograph can be determined from Eq. (5) and Fig. 5 for a known value of the parameter, *n*.

Logarithmic plotting of the peak discharge, q_p against the ratio of catchment area, A, to the time to peak, t_p, was found to be a linear relationship. C. M. Wu

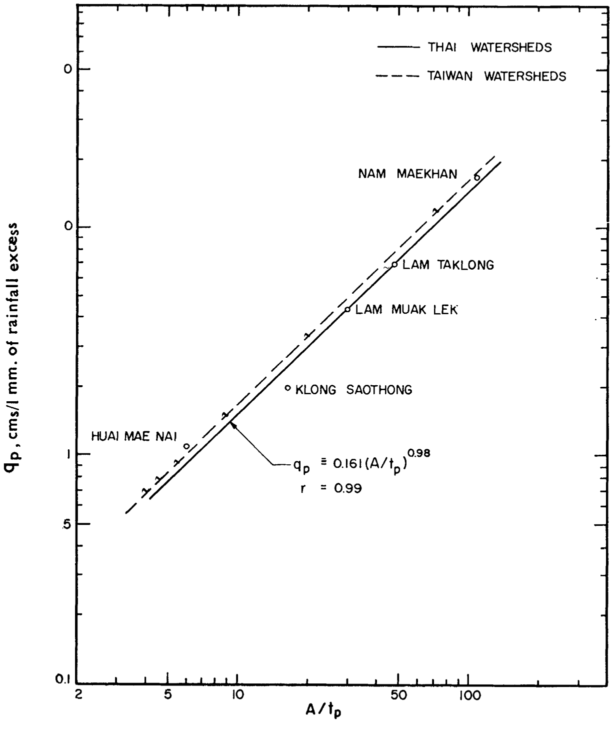

Fig. 10.
Peak discharge vs. A/t_p.

(1965) has shown a similar relationship for the Taiwan data. The agreement between the Thai data and the Taiwan data is good. The empirical equation for the relationship is:

$$q_p = 0.161(A/t_p)^{0.98} \qquad (14)$$

with a coefficient of correlation of 0.99. The relationship is shown in Fig. 10.

A similar logarithmic relationship between peak discharge, q_p, and catchment area is shown on Fig. 11. The agreement between the Thai data and the Taiwan data is not so good when shown in this form.

DISCUSSION OF RESULTS

Comparison of the dimensionless hydrograph with the Soil Conservation Service and Williams' dimensionless hydrographs

The derived dimensionless hydrograph of the selected watershed as shown on Fig. 4 reveals a prolonged and extended recession limb. This is probably the result of one of two causes: (*A*) either the catchment area has relatively large surface storage characteristics or (*B*) an appreciable contribution of flow has occurred as interflow.

The combination of the derived dimensionless hydrographs into an average hydrograph as shown on Fig. 4 is compared with those developed by the Soil Conservation Service and by Williams. Good agreement is observed at the crest because by the method of computation they were made to fit at the peak. The rising limb shows a reasonably good agreement. For the recession limb the average dimensionless hydrograph shows a small deviation from the one developed by Williams and a larger deviation from the Soil Conservation Service curve. The unit hydrographs from tropical watershed delay longer in coming to the peak discharge and the runoff is prolonged more after the peak.

Comparison of derived dimensionless hydrograph with two parameter gamma distribution

Figs 12–16 show the unit hydrographs derived from the floods with the two parameter gamma distribution expressed in dimensionless form for comparison. In all instances the unit hydrograph derived from the observed flood cannot be represented by the theoretical hydrograph based on the two parameter gamma distribution. A hydrograph derived from the two parameter gamma distribu-

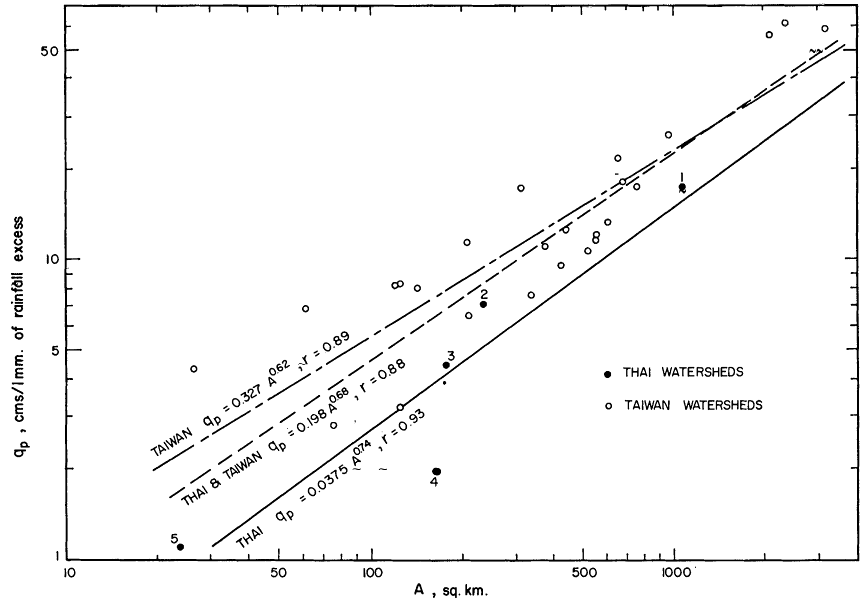

Fig. 11.
Peak discharge vs. catchment area.

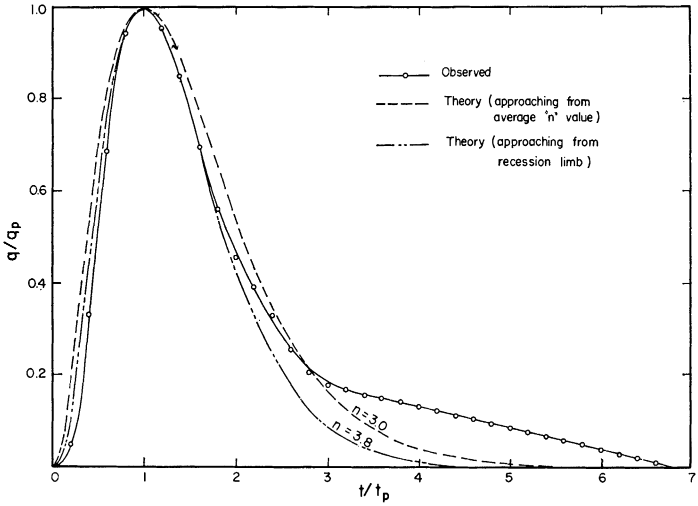

Fig. 12.
Dimensionless hydrograph for Nam Maekhan watershed.

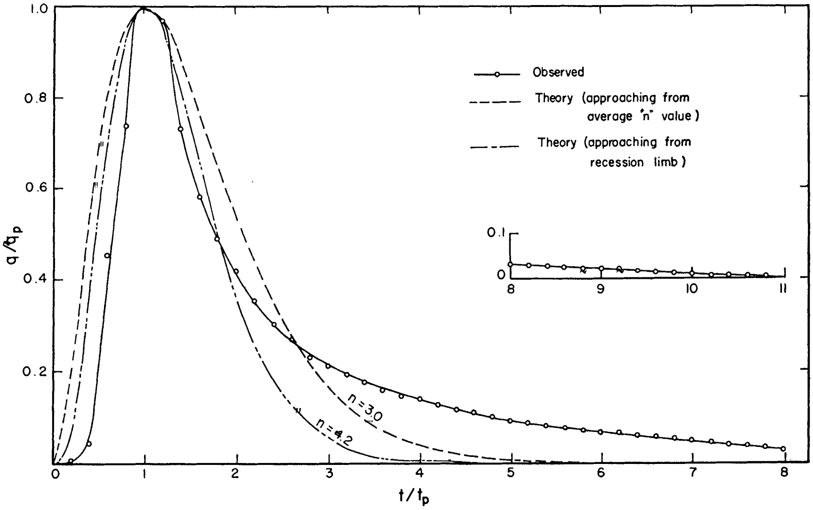

Fig. 13.
Dimensionless hydrograph for Lam Taklong watershed.

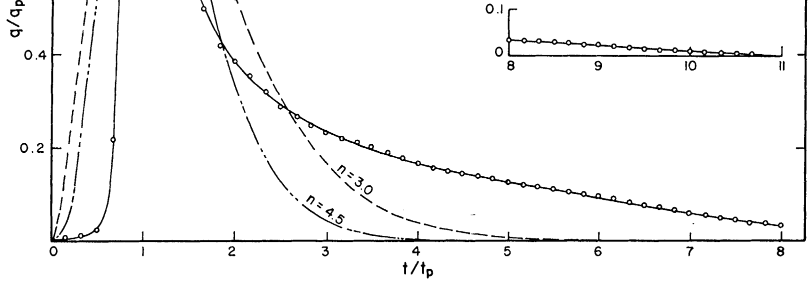

Fig. 14.
Dimensionless hydrograph for Lam Muak Lek watershed.

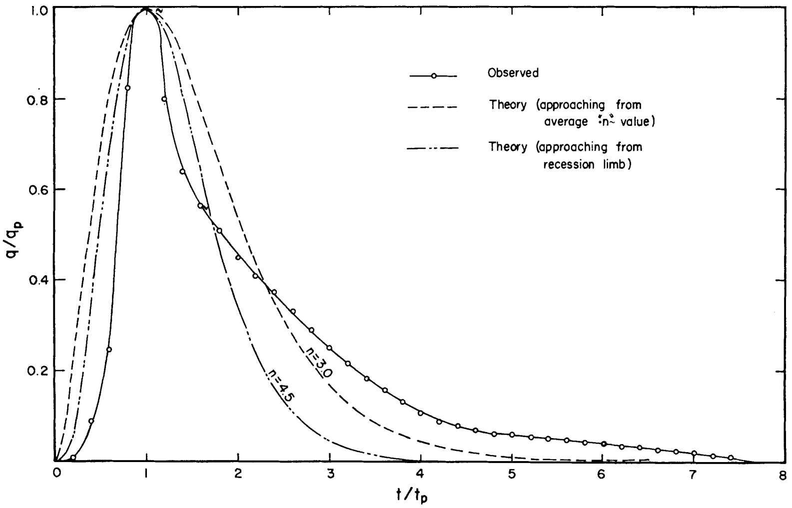

Fig. 15.
Dimensionless hydrograph for Klong Saothong watershed.

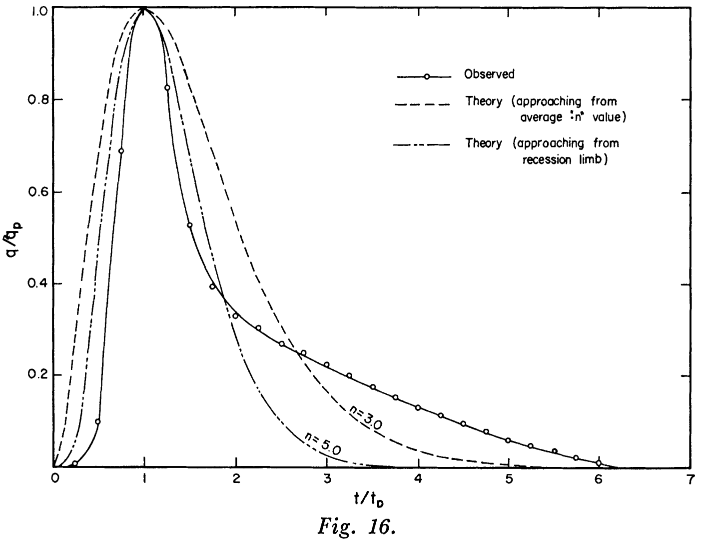

Fig. 16.
Dimensionless hydrograph for Huai Mae Nai watershed.

tion will have too much of the runoff concentrated in the vicinity of the peak and the recession will be too abbreviated.

The conclusion is that, for practical purposes, the average of the dimensionless unit hydrographs shown on Fig. 4 better represents the flood characteristics in a tropical region such as Thailand.

Prediction of time to peak, t_p

From the dimensionless unit hydrograph it is evident that whatever the peak discharge might be, in converting to a runoff hydrograph, the shape of the hydrograph is not altered. The hydrograph shape is affected by the time to peak. Therefore, the time to peak is a significant time parameter in relating watershed influences to the hydrograph shape. Three measurable watershed characteristics, L, L_c, and S, used in this study can be correlated with the time to peak. The empirical relationship is shown as Eq. (11). It can be seen from Fig. 6 that the regression line shows a reasonable agreement with most of the watersheds except watershed 4 located in southern part of Thailand. Since this watershed is located on the eastern coast, it usually experiences the heavy and prolonged rainfall during both monsoon seasons (there is no dry season). A characteristic of a tropical watershed seems to be a poorly developed drainage pattern and a relatively large base flow storage capacity in the mountains. Research in forested watersheds in the United States invariably leads to the conclusion that a forest-covered watershed increases the amount of water infiltrating into the soils. See the discussion by Storey, Hobba, and Rosa in Chow (1964). There is no reason to believe that the jungle-covered tropical watersheds would not behave in the same way.

In the flatter valley lands, rice culture is often practiced. Here the natural drainage which develops is invariably erased by the construction of rice paddies, resulting in a large amount of surface storage and a destruction of the minor channel system which had served to collect the overland flow and accelerate it toward the major streams to become surface runoff. Thus it is logical that where rice culture is practiced, the hydrograph should be delayed in comparison to a virgin watershed.

This watershed (Klong Saothong) had a time to peak of 10 hours where the regression equation derived from the other watershed would have indicated a time to peak of about 6.1 hours. The more tropical the watershed is, the more delayed the surface runoff becomes. This tends to support the previous contention that the floods from a tropical watershed will have a more delayed time to peak and a prolonged recession limb. The surface runoff for a watershed represents the integrated effect of all the basin characteristics and their modifying influence on the translation and storage of the surface detention. Therefore, several factors may be involved in the deviation of time to peak from the regression line.

It is evident from Fig. 9 that Thai watersheds have greater lag time in relation to time to peak than the Taiwan watersheds. This is probably due to Thai watersheds having more delayed surface runoff or the interflow in the recession limb being a more important part in a tropical watershed. All of the Thai unit hydrographs have long recession limbs.

Prediction of storage coefficient, K_1

The storage coefficient is used in determination of parameter, *n,* which is a type of shape factor of the hydrograph. It was decided to use the first part of the recession limb to determine the storage coefficient, K_1. In this part of the hydrograph, the flow is mainly derived from channel storage. The data are shown on Fig. 7 together with a regression line through the points. Comparing watersheds 3 and 4, having more or less the same watershed parameter, $LL_c/\sqrt{S}$, it is seen that watershed 4 possesses higher storage characteristics than watershed 3. Since the storage coefficient also depends on the integrated effect of all the basin characteristics, more information is required on the hydraulic characteristics of the main channel and on the nature of the forest cover and rainfall characteristics before this aspect can be pursued further.

Prediction of peak discharge, q_p

The equation for prediction of the peak discharge has been derived by correlation analysis. The regression equation is shown in Eq. (14). It is evident from Fig. 10 that the values define the regression line quite well. This indicates a reasonable agreement between observed and predicted value. Furthermore, the data on this graph agree well with the data observed on Taiwan.

It is evident from Fig. 11 that Thai watersheds have a lower peak discharge in relation to area than Taiwan because of greater attenuation of the surface runoff.

Regarding the relationship between length of longest watercourse and catchment area as shown in Fig. 2, it was found that Thai watersheds have a longer main channel than Taiwan watersheds for a given area up to about 400 square kilometers.

It is seen from Fig. 2 that a simple power function fits the observed data quite well. The tropical watersheds with extensive vegetative cover resist the natural channel-forming forces, but after the watershed attains a certain size, the flatter valley lands behave more as an impounding feature in the landscape.

CONCLUSIONS

A representative dimensionless distribution graph was derived for an observed flood. These are shown on Figs. 12–16. The following conclusions can be made from a comparison of these figures.

(1) The two parameter gamma distribution does not reproduce the observed distribution graph and is therefore not recommended as a mathematical model for a unit hydrograph for a tropical watershed (see Figs. 12–16).

(2) The combined dimensionless hydrograph can be used to define a unit hydrograph for these tropical watersheds (see Fig. 4 in comparison with Figs. 12–16).

(3) The peak discharge from the parameters gamma distribution tends to overestimate the observed peak discharge, provided the recession limb is made to fit the observed values. If the peak is made to fit the model, then the recession limb is much too short.

(4) The correlation between the unit graph parameters t_p, q_p, and the watershed characteristics resulted in these equations:

$$t_p \equiv 1.9(LL_c/\sqrt{S})^{0.162} \qquad \text{(see Fig. 6)}$$

and

$$q_p \equiv 0.161(A/t_p)^{0.98} \qquad \text{(see Fig. 10)}$$

(5) Since the watersheds used in this hydrograph study range in area from 24 to 1060 square kilometers, the use of the developed procedure is generally recommended for watersheds between 24 to 1000 square kilometer in size.

(6) The Thai watersheds have more delayed surface runoff than the watershed on Taiwan (see Figs. 6, 7, and 8).

(7) The time to the peak can be expressed as a linear function of the lag time for both the Thai and the Taiwan watersheds. The more retarded surface runoff of the Thai watershed is apparent from the comparison between t_p and t_{lag} (see Fig. 9).

(8) The Thai (more tropical) watersheds have longer channels than the Taiwan watersheds when the watersheds have catchments less than 400 sq. km. (see Fig. 2). For larger catchments, this relationship is reversed.

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