Journal of Hydrology, 87 (1986) 201–222
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

[3]

REVIEW OF RELATIONSHIPS BETWEEN GEOPHYSICAL FACTORS AND HYDROLOGICAL CHARACTERISTICS IN THE TROPICS

PIERRE L. DUBREUIL

Laboratoire d'Hydrologie, ORSTOM, 213 Rue Lafayette, 75010 Paris (France)

(Received October 22, 1984; accepted after revision April 17, 1986)

ABSTRACT

Dubreuil, P.L., 1986. Review of relationships between geophysical factors and hydrological characteristics in the tropics. J. Hydrol., 87: 201–222.

The hydrological behaviour of catchments of different sizes and in various environments has generally been explained through geophysical factors that distinguish between them. In this review paper an inventory is made of the research work of French hydrologists in tropical regions over the last 30 years.

Many hydrological studies have been carried out for different sizes of catchment and periods of time. They have dealt with runoff volumes, flood peaks and flood patterns. The most significant geophysical factors have been identified, and their influence upon hydrological characteristics has been determined. General formulae and relationships have been suggested. Key roles are played by: the soil–vegetation complex, which affects rainfall-runoff transformation; and the drainage area and the slope index, which affect nearly all the hydrological parameters.

An analysis of various ranges of catchment sizes has been made in order to better understand the effects of geophysical factors upon hydrological phenomena; the change in size alters the nature or the intensity of these effects.

INTRODUCTION

Dubreuil (1985) has reviewed French research into runoff generation in the tropics over a 30-year period. That review shows that generation of the different types of runoff is comparable to that described by numerous authors for temperate and cold zones, but also that the intensity of the phenomena can vary from one climatic zone to another. In the review data are used from plots of a few m^2 and from small watersheds of a few km^2. The conditions of runoff occurrence are comparable on plots and small watersheds, as are the types of quantitative relationships and their causes. Nevertheless there are some differences in their relative intensities due to the scale variation.

The present paper reviews French research in the tropics into the relationships between geophysical factors and hydrological characteristics. These studies may be divided into two categories. On the one hand studies on small representative basins and experimental plots give flood data. On the other hand, hydrological monographs for larger catchments summarize data for

0022-1694/86/$03.50

monthly and annual di
categories provides an
Three approaches a
on physical reasoning
Strict rules for the
parameters have beer
selection of the approp
accuracy. Such rules l
basins compiled by Du
large catchments.

MAIN EXPERIMENTAL

The following fac
instantaneous discha
and annual scales. T

NOTATION

A	km^2	
Ag	%	
C	%	
Hs, Hs_{10}, Hs_1	mm	
H_t, H_d, H_m, H_a	mm	
I		
Ih		
K, K_{10}	%	
Kc		
Lq	km	
Q, Q_{10}	m^3/	
Qx, Qx_{10}	m^3/	
R, R_d, R_m	mm	
R_a	mm	
R_{10}	mm	
RD	mm	
S		
SI	m/k	
Tb	h	
tp	h	
Vs	m^3	volume of surface runoff; $Vs = H_s.A \cdot 10$
Vt, Va	m^3	volume of runoff within a given period of time $Vt = H_t.A \cdot 10^3$, annual value
$\alpha = Qx_{10}/Q_{10}$		shape coefficient of the 10-year flood hydrograph

39624

B

Flood volumes

Table 1 summarizes the results of work conducted on annual and 10-year floods in small and medium watersheds. It is worthwhile analysing the arguments used in the major studies which deal with flood volumes before considering the corresponding maximum instantaneous discharge. The analysis of rainfall–runoff relations for individual storms leads to a formula of the type $K = f(\mathrm{R}, Ih)$ where Ih is the antecedent precipitation index characterizing soil saturation of the watershed before the storm under consideration (Dubreuil, 1985).

The study by Rodier and Auvray (1965) was based on two assumptions.

(a) The 10-year flood is generated by the 10-year storm falling on soils of medium or high saturation; Ih is therefore known.

(b) In western Africa, the 10-year storm is generally the only storm within 24 h and represents almost all the rain observed within that period — the same is true of most heavy rainfall events. This may not be the case in the rain forest, but reliable information is lacking.

Therefore, in the family of curves $K = f(R)$ with a constant Ih, Rodier and Auvray consider the curve with the selected Ih only, and they go on to determine the 10-year runoff coefficient K_{10} corresponding with the daily 10-year depth of rainfall R_{10}. Statistical analysis of rainfall records shows a close relationship between R_{10} and Ra (mean annual depth of rainfall); many authors use either variable.

Rodier and Auvray (1965) thought that it was too difficult or too restrictive to represent relief and soil–cover complex of the watersheds by numerical parameters alone. Therefore, they established 6 classes of relief, Ri, and 5 classes of permeability, Pj. Each watershed is integrated into a paired class Ri:Pj. The variation of runoff coefficient, K_{10}, with drainage area A, was then determined graphically for the pairs of Ri:Pj for all areas with a wide range of climates, and hence, rainfall characteristics.

Working in Madagascar, Duret (1976) used regression analysis and made the following two assumptions: (1) for a heavy storm with at least a ten year frequency, the runoff coefficient, K, can be expressed as $K = (1 - a/R)^b$; (2) the concentration time of the watershed increases with drainage area and in inverse ratio with catchment slope. Duret therefore argued that the discharge Qx_{10} must be consistent with the equation:

$$Qx_{10} = k \cdot A^c \cdot I^d \cdot R_{10}^e \left(1 - \frac{a}{R_{10}}\right)^b \cdot Kc^f \qquad (1)$$

where Kc is the shape coefficient of the watershed (Gravelius' index) and a, b, c, d, e, f and k are parameters derived from regression analysis. Duret found that values of $a = 36$ and $b = 2$ fitted the data from 39 gauging stations; the runoff coefficient in eqn. (1) is thus:

TABLE 1

Flood volumes and discharges (small and medium watersheds)

Authors	Geographic area	Ranges of validity	Method used	Relations or formulas
Rodier and Auvray (1965)	Western Africa, 60 watersheds	$2 < A < 120\,\mathrm{km}^2$	Graphical approach	$K_{10}\,(A, Ri, Pj, Ra)$ $Qx_{10} = K_{10} \cdot R_{10} \cdot \frac{A \cdot \alpha}{Tb}$
Vuillaume (1969)	Semi-arid Niger, 5 watersheds	$1 < A < 10\,\mathrm{ha}$	Graphical approach	$H_{sl} = -aA + bS + CAg + dC + e$
Duret (1976)	Madagascar, 39 watersheds	$200 < A < 50.000\,\mathrm{km}^2$	Regression analysis	$Qx_{10} = 0.025A^{0.80} \cdot I^{0.32} \cdot R_{10}\left(1 - \frac{36}{R_{10}}\right)^2$
Molinier (1981)	Congolese Savanna, 3 watersheds	$1 < A < 100\,\mathrm{km}^2$	Graphical approach	$Qx_{10} = 46.8 \log (A - 1.7) + 35.6$
Puech and Chabi-Gonni (1983)	Western Africa, 160 watersheds	$2 < A < 120\,\mathrm{km}^2$	Regression analysis	$Qx_{10} = k \cdot A^{a} \cdot SI^{b} \cdot Ra^{-c}$
Guiscafré et al. (1976)	Martinique, 7 watersheds	$4 < A < 80\,\mathrm{km}^2$	Graphical approach	$Qx_{10} = 200\,(1.6 \log A - 1)$

Note: a, b, c, d, e, k . . . etc., adjustment parameters (> 0). Various specific catchment parameters: Ag, % soil clay content; C, percentage of cultivated area; I, slope index as $I = 1.5SI$; Ri, relief class; Pj, permeability class.

$$K_{10} = \left(1 - \frac{36}{R_{10}}\right)^2$$

In western Africa, Puech and Chabi-Gonni (1983) also used this approach in their analysis of data from ORSTOM's representative basins (Dubreuil, 1972). These authors take a to equal 0, thus removing K_{10} from the evaluation of maximum instantaneous discharge, implicitly assuming that the depth of runoff depends only on rain.

Duret's equation seems to be a simplification of the U.S. Soil Conservation Service equation:

$$Kr = \frac{(P - aK)^2}{P + 4\,ak}$$

where parameters a and k depend on the vegetation and the soil of the watersheds, respectively. This simplification is undoubtedly too optimistic since it implies that the soil–cover complex does not influence the runoff coefficient of the heavy rains observed both in Madagascar and in western Africa. The importance of this was shown in Rodier and Auvray's earliest work (1965), carried out using purely physical reasoning and a graphical approach. This method seems the best suited to describing the complex role played by soil and vegetation in the evaluation of K_{10}. It is, however, very difficult for non-hydrologists to apply and the choice of the pair $Ri{:}Pj$ for an ungauged watershed is highly subjective. This typology must be made more precise using knowledge of soil surface crusts and the results of current experiments with rainfall simulators (Dubreuil, 1985).

The graphs plotted by Rodier and Auvray (1965) show that for watersheds smaller than 200 km^2: (a) runoff coefficient K_{10} increases considerably with low soil permeability as well as with relief; (b) K_{10} generally increases with the depth of rainfall except on the crust soils observed in the arid and semi arid zones; for watersheds with crust soils, runoff is higher than for those observed in the tropics with similar $Ri{:}Pj$; (c) for watersheds of between 20 and 50 km^2 in arid and semi-arid regions only, K_{10} decreases with drainage area and can be expressed as:

$$K_{10} = a - b \log A$$

Thus the role played by geophysical factors in determining the runoff coefficient clearly shows that a separate analysis is needed for the arid and semi-arid zones which are affected by impervious soil surface crusts and hydrographic degradation.

The major objective of work in progress is to improve the typology of the permeability classes; this is being achieved. When analysing the results obtained on 24 tropical forested watersheds, Rodier (1976) used 6 classes of decreasing permeability, plus a detailed description of the soils in each case; slope index is used instead of relief class. Casenave et al. (1982) conducted tests with a rainfall simulator on 10 forested watersheds in Ivory Coast. From these he describes the overall runoff coefficient, K_{10}, in terms of each soil type present by:

$$K_{10}(120) = a \log (\Sigma hi \cdot Ai) - b$$

where K_{10} is calculated for a rainfall of 120 mm, whatever the local value of R_{10} may be; *hi* is the depth of surface runoff on a bare soil with a rainfall of 120 mm and a constant antecedent saturation index *Ih*; *Ai* is the area of soil type *i*.

This runoff index *hi* for a given soil subject to given rainfall can thus be used in setting permeability classes.

Vuillaume (1969) proposed a simple additive expression for surface runoff, Hs_1, in which Hs_1 decreases with drainage area but increases with slope, soil clay content and cultivated area.

Similar factors are again observed, with clay content representing the impermeability of the soils. Rainfall was not included because the study was limited to a micro-zone with constant rainfall. Runoff increases with cultivation (here millet), which may be because of incomplete soil cover by the crop. Finally, the additive effect of the factors may arise simply from the limited range of sizes of watershed (1 to 10 ha).

Maximum instantaneous discharges

The peak discharge of the 10-year flood can be expressed by:

$$Qx_{10} = K_{10} \cdot R_{10} \cdot \frac{A \cdot \alpha}{Tb} \qquad (2)$$

where α and *Tb* are, respectively, the dimensionless shape coefficient and the base time of the 10-year flood hydrograph (see next section). Assuming that the base time is of the form $A^a\, SI^{-b}$, then Qx_{10} can be expressed in terms of rainfall *Ra* or R_{10}, relief *Ri* or slope index *SI*, and drainage area *A*.

Comparison of the studies reviewed in this paper reveals an anomaly in Puech and Chabi-Gonni's (1983) work. They found that for the complete sample of over 140 values, the peak discharge is given by:

$$Qx_{10} = 131 A^{0.68} SI^{0.56}\, Ra^{-0.68}$$

Thus, an increase in rainfall gives a decrease in Qx_{10}, which cannot be physically correct. However, for the 38 watersheds with annual rainfall between 400 and 800 mm:

$$Qx_{10} = 2.54 A^{0.67} SI^{0.43}$$

Therefore, it is possible that the apparent negative effect of rainfall arises from including data from arid and semi-arid regions.

It should be noted that the exponents of *A* and *SI* in the regressions from the studies given in Table 1 range from 0.67 to 0.80 and from 0.32 to 0.56, respectively.

Medium and large watersheds are generally studied by statistical analyses

TABLE 2

Flood discharges (medium and large watersheds)

Authors	Geographic area	Ranges of validity	Formulas obtained	
Hiez and Dubreuil (1964)	French Guiana (rain forest)	5000–50.000 km^2	$Qx_{10} = 0.658A^{0.84}$ $= 0.073A^{1.04}$	(1)
Dubreuil et al. (1968)	Jaguaribe watershed (semi-arid northeastern Brazil)	200–6.000 km^2	$Qx_{10} = B \cdot A^{0.516}$ $\mathrm{B} = (7.5Ra - 50\mathrm{S.S} - 925)\mathrm{D.P.}$	(2)
Billon et al. (1974)	Chari watershed (Central African Republic and Chad)	8000–80.000 km^2	$Qx_{10} = 25.2A^{0.425}$	
Dubreuil et al. (1975a)	Sanaga watershed (Cameroon)	1000–70.000 km^2	$Qx_{10} = 0.93A^{0.76}$ $= 0.22A^{0.86}$	(3)

(1) Depending on different physiographic regions. (2) S.S., percentage of sedimentary soils; D.P., shape of the drainage pattern. (3) Depending on different relief characteristics.

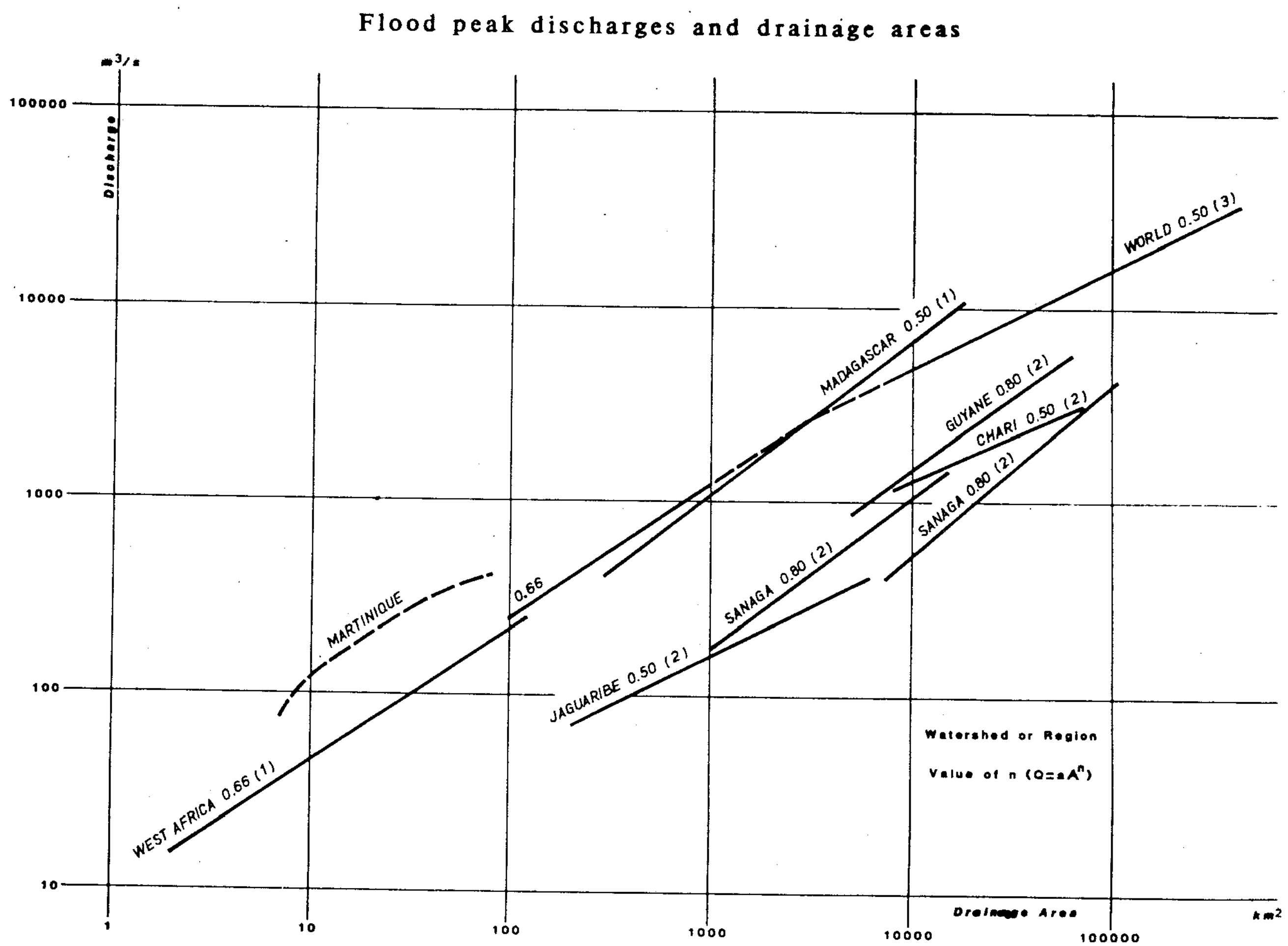

Fig. 1. Flood peak discharges and drainage areas : (1) = from Table 1; (2) = from Table 2; (3) following Pardé (1951).

of the series of flow data. The main results obtained are given in Table 2. The results for large watersheds (over 5000 km^2) are all consistent: the ten year flood is influenced by the drainage area:

$$Qx_{10} = aA^n \tag{3}$$

The equations of this type in Table 2 and similar equations derived from the results of Table 1 are shown in Fig. 1. This shows that: (1) n is close to 0.80 in the tropical and forest zones with high rainfall; and (2) n is close to 0.50 in the semi-arid and tropical zones with lower rainfall.

The study of the Jaguaribe watershed, composed of medium-sized sub-watersheds (200–6000 km^2) in the semi-arid area of northeastern Brazil, is apposite. Dubreuil et al. (1968) show that parameter a of eqn. (3) depends on three environmental factors: (1) annual rainfall, which has a positive influence on Qx_{10}; (2) percentage of sedimentary soils, which reduces flood peaks; and (3) the shape of the drainage pattern: radial shape increases peak discharge rainfall, parallel shape decreases peak discharge.

The percentage of sedimentary soils is analogous to the permeability class and the shape of the drainage pattern corresponds to the watershed shape coefficient Kc. Whatever the size of watershed, the geophysical factors used to explain flood characteristics are broadly similar.

Flood hydrograph

The parameters of the flood hydrograph are the rise time tp, the base time Tb, the maximum instantaneous discharge Qx and the shape coefficient α which is the ratio of the peak discharge Qx_{10} to the mean discharge Q_{10}, for the 10-year flood.

Base time is often difficult to measure. Generally, it is estimated by identifying the change in slope of the recession curve plotted on semi-log paper — if there are many changes of slope, the last change is used. This should indicate the start of a new flow regime composed only of base flow, once surface and subsurface runoffs are exhausted (Dubreuil, 1974). This method is rather subjective and may lead to some inaccuracies in the selected values of Tb. Some researchers advocate the use of a triangular hydrograph, which obviates this difficulty as α becomes constant and equal to 2.

Without going as far as the triangular hydrograph, various workers have tried to simplify the shape of the hydrograph by suggesting a rectilinear rise combined with a recession curve which is either exponential or hyperbolic (Roche, 1967; Moniod, 1969). This so-called standard hydrograph displays particular qualities: for instance, in the case of the equilateral hyperbola, the recession curve may be written as:

$$Q(t) = Qx \cdot \frac{a - t}{a + ht}$$

TABLE 3

Parameters of the ten year flood hydrograph

Authors	Geographic area	Ranges of validity	Formulas obtained
Rodier and Auvray (1965)	Western Africa (semi-arid, tropical) 60 watersheds	$2 < A < 120\,\mathrm{km}^2$	tp and $Tb = f(Ri, \sqrt{A}$ or $\log A)$ $\alpha = f(Ri, A)$
Rodier (1976)	Forest zone, 24 watersheds	$2 < A < 100\,\mathrm{km}^2$	tm and $Tb = f(a\sqrt{A} + b)$ with $a = (m - n \log SI)(R_a KC - q)$D.P. (1) $\alpha = f(A)(Ri)$
Naah (1979)	Central Cameroon (tropical), 5 watersheds	$1 < A < 100\,\mathrm{km}^2$	$tp = \log A + 0.4$ $Tb = 3.75 \log A + 1$
Guiscafré et al. (1976)	Martinique, 7 watersheds	$4 < A < 80\,\mathrm{km}^2$	$Tb - tp = 0.14A^{0.37}$ $h = 13.5 - 5.8 \log A$ h parameter of the hyperbolic recession curve
Molinier (1981)	Congolese savanna, 3 watersheds	$1 < A < 100\,\mathrm{km}^2$	$Tb = 153e^{0.08}Lq$
Bailly et al. (1974)	High-altitude forest Madagascar	$10 < A < 100\,\mathrm{ha}$	$tm = aA + b$ (1)

(1) D.P. shape of the drainage pattern: a, b, m, n, q . . . being adjustment parameters of the regression analysis.

t being the time calculated from the occurrence of Qx; a, the recession time (e.g., $a = Tb - tp$); and h, an adjustment parameter.

Expressions for flood hydrograph parameters are given in Table 3, and are generally consistent with respect to the role of geophysical factors. Rodier and Auvray's graphical adjustment (1965) shows that times tp and Tb increase in proportion to $\sqrt{A}$ for watersheds with low gradients and in proportion to log A for watersheds with steep gradients. On steep watersheds, the hydrograph times increases less rapidly with drainage area.

A more detailed analysis, made by Rodier (1976) in the forest zones, shows a variation of the type: $a\sqrt{A} + b$, where the value of a varies in inverse ratio to log SI. However, two qualifications must be made: (1) tp and Tb increase for very elongated watersheds with a value of $Kc > 1.40$; (2) an increase in tp and Tb is seen if the drainage pattern is parallel, or a decrease if it is centripetal-dendritic (differences of about ± 10%).

Comparison of trends in the values of tp and Tb for a given drainage area in the different geographic areas shows that base and rise times are much greater in the tropical and the forest zones than in the arid and semi-arid zone. Such variations may be accounted for by: (a) the attenuating effect of vegetation, which is increasingly felt and is still considerable even in the forest zone in line with the litter cover of the soil: (b) in semi-arid zones, floods are generally due to surface runoff alone, whereas in tropical zones a considerable proportion of a flood is generated by sub-surface runoff. In forest zones subsurface runoff predominates (Dubreuil, 1985).

Finally, the combined influence of the geophysical factors on tp and Tb can be expressed by the function:

$$tp, Tb = f(A^a \cdot SI^{-b} \cdot Kc^c \cdot dV^d \cdot DP) \qquad (4)$$

where dV is the density of the vegetation and DP is a corrective factor related to the shape of the drainage pattern.

The relation of the shape coefficient α of a hydrograph to any 10-year flood of non-standardized type has not been the subject of detailed study. Table 4 details the mean values suggested by Rodier and Auvray (1965) and Rodier (1976), and seems to show that the coefficient increases with area, slope and elongation of the watershed. So for catchments of less than 100 km², α can be expressed as:

$$\alpha = f(A^a, SI^b, Kc^c) \qquad (5)$$

The values of α are higher in the semi-arid zone or impervious and sloping tropical zone than in the forest; therefore, the flood is all the steeper where high runoff occurs in the watershed.

It is logical that coefficient α should depend on the main physical factors which influence Qx and Tb. But it must be understood that the estimation of α depends on Tb, which itself is relatively inaccurate. A more comprehensive understanding of the shape coefficient will result from a better evaluation of Tb.

TABLE 4

Ranges of variation in the shape coefficient α of the 10-year flood hydrograph (according to Rodier and Auvray, 1965, and Rodier, 1976)

	Area (km^2)					
	2	5	10	25	50	100
	Values of α:					
Arid, semi-arid zone	2.6	2.6	2.6	2.6	3	3.10
Impervious and sloping tropical zone	3	3	3	3	4.5	4
Permeable, relatively level tropical zone	…	…	… 2.5	…	…	…
Sloping forest	2		2.3	…	2.4^{*1}	…
Relatively level forest	1.9		2.2	…	2.3^{*1}	…

^{*1}Values to be increased from 0.1 to 0.2 if $Kc > 1.60$.

Monthly and annual volumes of runoff

Apart from storm-flood events, the studies deal with monthly and annual volumes of runoff, which are generally expressed in terms of catchment runoff, Ht. For storm-flood events the relationships $Hs = f(R, Ih)$ for a given watershed are either linear if there is only surface runoff, or parabolic, as demonstrated in a previous review (Dubreuil, 1985).

The various studies concerning the daily, monthly and yearly rainfall–runoff relationships will be examined first, then the role played by geophysical factors in determining the mean annual volume of runoff will be reviewed. The main results obtained are given in Table 5.

The relationship between the depth of runoff and rainfall can be written as:

$$Ht = f[k(R - Po)] \tag{6}$$

for daily (Girard, 1975), monthly (Ibiza, 1983) or yearly timescales (Dubreuil et al., 1986). For surface runoff on a daily basis, the relationship is linear; for monthly or annual runoff, the shape is hyperbolic or parabolic.

Modelling on a daily basis, Girard (1975) finds the k ranges from 0.04 to 0.80 and can be compared to a runoff coefficient. It seems to depend on the permeability of soils and area, such that $k = f(1/Pj, A)$, which is quite consistent with the results obtained with storm-flood events.

The correction parameter Po (eqn. (6)) should depend on the maximum (or useful) soil retention capacity. This is similar to the index Ih which characterized the antecedent soil moisture.

Ibiza (1983) devised a model for the evaluation of monthly runoff based on the evaporation balance and the effect of persistence from month to month.

TABLE 5

Volumes of runoff

Authors	Geographic area	Ranges of validity	Method used	Formulas obtained
Girard (1980)	Semi-arid western Africa, 33 watersheds	0.1–150 km^2	Modelling (daily basis)	$H_d = Ko(R_d - Po)$ $Ko = f(1/Pj, A)$, $Po = f(\mathrm{AW})$ (1)
Ibiza (1983)	Martinique, Ivory Coast, Tunisia, 10 watersheds	0.2–15 km^2	Modelling (monthly basis)	H_m = hyperbolic function of R, ETP and AW (1)
Dubreuil et al. (1968)	Semi-arid northeastern Brazil, Jaguaribe watershed	200–6000 km^2	Regression analysis	$H_a = f[\Sigma_1^{12}(R_m - Ro)]$ $H_a = CA^{-0.10}$ $C = (aR_a + b\mathrm{TMG} + c\mathrm{DD})$ (2)
Dubreuil et al. (1975a)	Tropical forest Cameroon, Sanaga watershed	1000–100.000 km^2 $1700 < R_a < 1900$ mm	Regression analysis	$H_a = -275 \log Lq + 1240$ $H_a = aS + b$ $H_a = 0.50R_a - 250$
Moniod et al. (1977)	Tropical western Africa, Volta watershed	6000–60.000 km^2 $700 < R_a < 1400$ mm	Regression analysis	$RD = 0.8R_a + 100$
Dubreuil and Vuillaume (1975)	All tropical zones, 128 watersheds	10–100 km^2	Regression analysis	$H_a = KRr + f(\mathrm{FG})$ $Rr = \Sigma_1^{12}(Rm - 1/36\mathrm{PET})$ (3)

(1) AW, available water of soils; ETP, potential evapotranspiration.
(2) TMG, percentage of crystalline rocks; DD, degree of clearing; *Ro*, regression parameter.
(3) FG, geophysical factor; PET, pan evapotranspiration.

Two of the model parameters seem to depend on soil texture and on plant cover. These results, obtained from very small watersheds in tropical, forest and mediterranean (and therefore semi-arid) zones, are promising as they improve our understanding of the effect of the soil cover complex and therefore how the parameters affect the performance of the model.

The larger the timescale, the more important the role of rainfall becomes in the evaluation of runoff. Therefore, few studies emphasize the secondary role played by geophysical factors in the relationship between mean annual runoff and rainfall. This is particularly true where studies were made in homogeneous geographic zones with limited area and high rainfall.

On an annual basis, eqn. (6) can be written as:

$$Ha = kRa + k'$$

where k is a parameter and k' is a function of geophysical factors. Parameter k-values: 0.16 for $600 < Ra < 750$ mm; 0.33 for $750 < Ra < 1000$ mm in sedimentary soils; 0.64 for $750 < Ra < 1000$ mm in crystalline soils.

Likewise, Dubreuil and Vuillaume (1975), identified the following k-values: 0.15 for the semi-arid zone $Ra < 650$ mm; 0.47 for the tropical zone $Ra > 700$ mm; 1.05 for the forest zone.

The negative influence of drainage area has been emphasized by several authors. Whether it is expressed in the form A^{-n} (n ranging from 0.10 to 0.50) or in the form $-\log A$, the effects are remarkably consistent. Given an increase in drainage area from 1 to 10, the mean annual runoff, Ha, decreases by about 50% on small watersheds situated in the semi-arid zone (hydrographic degradation); 33% on small tropical watersheds (Dubreuil and Vuillaume, 1975); and 20% on large watersheds such as the Jaguaribe and the Sanaga (Dubreuil et al., 1968, 1975a).

Many studies show that slope has a positive effect on runoff, larger catchments generally have lower slopes, though statistically this relationship is not very significant (Dubreuil et al., 1975b); hence runoff tends to decrease as area increases.

Detailed studies by Dubreuil et al. (1968) and Dubreuil and Vuillaume (1975) also identified the following geophysical factors: the nature of the geological formation (crystalline or sedimentary); the density of natural vegetation; the degradation of the drainage pattern and the formation of flood plains.

In semi-arid zones, flow is generated mainly by surface runoff, therefore it is more abundant on soils derived from crystalline rocks than on sedimentary formations. Flood plains have high evapotranspiration losses and infiltration losses, which reduce streamflow. Dubreuil and Vuillaume (1975) point out that this considerable decrease is almost equal to the median value of the mean runoff (60 mm/year) observed on small watersheds.

The influence of cultivation following the clearing of natural vegetation has not been thoroughly researched on the experimental watersheds covered by these two studies. However, the following observations may be made.

(1) Where mean annual rainfall is below 650–700 mm, crops reduce mean annual runoff, probably because they consume more water than the herbaceous stratum.

(2) Where rainfall exceeds 650–700 mm, the reverse is true, either because crops consume less water than the tree stratum (now cleared) or because soil exposure promotes runoff.

Comparative analysis of past studies made on erosion plots and experimental watersheds might lead to a refining of these preliminary observations, perhaps to the extent of providing a quantitative evaluation by crop type.

For example, the results presented in Table 6 were obtained from the experiments conducted on small watersheds in Madagascar over ten years. Bailly et al. (1974) show that the watersheds can be compared according to their plant cover and changes in that cover, thus confirming the results quoted above. The behaviour of modified watersheds depends on the initial environment, as follows: in a forest, any cultivation leads to a considerable increase in mean annual runoff; for natural grassland subjected to burning every two years and consequently lacking dense plant cover, any modification leads to a decrease in the mean annual runoff.

Finally, the installation of anti-erosive structures followed by contour cultivation reduces runoff to a greater extent than traditional cultivation or reafforestation.

COMMENTS ON THE RESULTS

The analyses of the following hydrological characteristics have been reviewed: flood volume and runoff coefficient, maximum instantaneous discharge, flood hydrograph parameters (time and shape), monthly and annual volume of runoff. Various rainfall parameters have been used as inputs in the rainfall runoff relations.

To identify the environment's influence on hydrological characteristics, the following physical catchment characteristics have been used: drainage area, slope index, catchment shape, drainage pattern, soil and vegetation indices, etc. To reveal the influence of geophysical factors on a particular characteristic, it is necessary: (a) to study limited climatic and geographic areas, since comprehensive generalisations may lead to false conclusions and even to misinterpretation, if made at random; (b) to classify geophysical factors hierarchically and to give priority to independent factors.

A comparative analysis made of the interactions of geophysical parameters on some 240 small watersheds in the tropical zone (Dubreuil et al., 1975b) has revealed the advantage of using drainage density and Horton's bifurcation and length ratios in addition to area and slope index as all these parameters are relatively independent. Nevertheless, none of these parameters was considered in the works recorded. Moreover, drainage density must be related to runoff capacity and Horton's ratios are representative of the drainage pattern.

TABLE 6

Influence of crops on annual runoff (Madagascar) (according to Bailly et al., 1974)

Watershed area	Annual runoff, H_a (mm)	Runoff coeff., K (%)	Ratio to the benchmark (BM)
(1) Forest zone, altitude 1000 m, R_a = 1890 mm, 1 to 2 ha			
Secondary forest (BM)	56	2.9	1
Rice on burning + fallow	144	7.6	2.6
Crops with anti-erosive structures	89	4.7	1.6
(2) Tropical zone, high-altitude grassland at 1500 m, R_a = 1715 mm, 3 to 5 ha			
Grassland with burning (BM)	221	12.1	1
Grassland without burning	121	6.5	0.55
Crops with anti-erosive structures	48	2.6	0.2
Reafforestation with pine	42	2.4	0.2

DRAINAGE AREA

Table 7 summarizes the effect of drainage area on the characteristics discussed earlier. The maximum instantaneous discharge as well as the rise and base times of a flood increase with area. The most common relation between maximum instantaneous discharge and drainage area is $Qx = a\,A^n$. This relationship is plotted in Fig. 1 for all the papers reviewed here. Relative homogeneity is observed, as well as a tendency for the exponent n to increase from 0.50 in the arid and semi-arid zones to 0.80 in zones with higher rainfall.

However, it should be noted that each individual study deals only with a limited range of catchment area, with the ratio of the smallest to the largest being 1 to 10 or at most, 1 to 100. This is the case despite a total range of area from 2 to 100,000 km^2.

Pardé (1961) made the most complete and comprehensive analysis of the intensity of floods all over the world, and he believes the equation $Qx = a\,A^n$ has worldwide significance. Given a previously determined n, he tries to account for all the variability of the intensity of the discharge through the numerical value assumed by the coefficient a. His results are not completely conclusive and Pardé suggests that n must range from 0.66 in the small and medium watersheds to 0.50 in the very large watersheds, the transition being made at around 5000 km^2 (see Fig. 1).

Two observations may be made. Firstly, it is a mistake to hope that all the variability of the intensity of floods could be accounted for merely by the study of the numerical value of the parameter a. The identification of the environmental, climatic and geophysical factors which account for the value of the parameter a would be more appropriate, as was shown by examples quoted in

TABLE 7

Influence of the drainage area

Geographic area	Mathematical formula	Hydrological characteristic	Type of the influence
Arid zones	$\log A$	Runoff coefficient, K	Inversely proportional
Any zones	A^n	Maximum instantaneous discharge, Qx	Proportional
Arid zones	$n = 0.50$		
Other zones	$n = 0.80$		
Watersheds with high rainfalls, low and moderate gradients	$A^{0.50}$	Rise and base times tp, Tb	Proportional
Watersheds with low rainfalls and steep gradients	$\log A$	idem	idem
Arid, tropical zones	A^{-n} ($n = 0.10$) or $\log A$	Annual runoff H_a	Inversely proportional
Small watersheds, arid zones	A increasing from 1 to 10	Decrease of H_a by 50%	
Small watersheds, tropical zones	idem	Decrease of H_a by 33%	
Large watersheds	idem	Decrease of H_a by 20%	

Tables 2 and 5 (Dubreuil et al., 1968). Secondly, the relationship between Qx and A varies markedly with drainage area. The relationship remains stable only within a given range of areas.

The evolution of these phenomena may be assessed at 4 different scales.

(1) At the scale of hill slopes, which are characterized by a homogeneous or easily describable environment without any stable water sources to concentrate runoff.

(2) At the scale of the small watershed, which is characterized by permanent and stable streams, a heterogeneous and still easily describable environment (like a set of homogeneous elements) and which can be affected by a single storm to give a significant flood.

(3) At the scale of the medium watershed, where the role played by runoff propagation in the drainage pattern becomes significant in comparison to that of runoff generation on smaller areas, and where precipitation is characteristically very patchy (except for cyclonic rains).

(4) At the scale of the large watershed, where runoff is composed of separate events whose origins are different, and where differences in climatic and physical environments may be observed.

It will be noted that all the studies mentioned in Fig. 1 concern either small watersheds or medium watersheds, as ranked above, and that all of them show a linear relation $\log Qx/\log A$ for the range of catchment areas covered (with the exception of Martinique, which shows a convex curve).

It would be foolhardy to follow Klein's (1984) example and give values to the limits of the various catchment sizes under consideration. These values depend on the general climatic and physical conditions prevailing in the great geographic area and, in the tropical zone, these general conditions are so variable that thorough studies of the catchment size in relation to hydrological phenomena are essential prior to devising a classification which sets limiting values.

The hydrographic degradation and increased evapotranspiration losses which are typical of the arid and semi-arid zone appear to be the only clear characteristics of the tropical zone. These factors lead to a decrease in the runoff coefficient and annual runoff as drainage area increases (Table 7).

THE SOIL-COVER COMPLEX

While precipitation is the input of the production function, the soil-cover complex plays the role of discriminating element. Unfortunately the fieldwork carried out in tropical zones did not allow this soil-cover complex to be characterized by numerical parameters and this may not indeed be possible, given the extreme diversity of the soils and of the corresponding plant covers.

The complexity of the problem forced Rodier and Auvray (1965) to attempt a typology of soil–cover complexes using permeability classes. Nowadays some improvements are necessary and a few individual examples have shown the role played by the percentage of clay, stable aggregates and organic matter. Although the role of soil texture and structure is indisputable, it does not seem possible either to describe or explain it by using a few numerical elements from soil physico-chemical composition. The analysis of experiments using the rainfall simulator should improve our interpretation of the role of the soil–cover complex (Casenave et al., 1982), but much remains to be done.

For example, such factors as the formation of impervious surface crusts in the arid and semi-arid soils or the type and density of natural or cultivated cover and cultural practices, seem to play a significant and often prevailing role. Table 8 presents data on the role played by the soil–cover complex and shows the shortage of studies concerning crops and cultural practices on watersheds. Some progress could be made in this field by analysing plot experiments to evaluate erosion.

RELIEF AND SLOPE INDEX

Relief and slope index are of minor importance compared to drainage area or soil–cover complex, but their impact is clear. Higher relief leads to higher runoff propagation on the hill slopes and in the streams. The runoff coefficient is greater at the outlet of a watershed of a given size. There is an increase in the flood peak discharge and a decrease in runoff times, though the first effect prevails as the shape coefficient also increases with relief. Watersheds with strong relief show short and steep flood hydrographs.

Annual runoff should decrease as drainage area increases (Table 7). However, it is well-known that slope also decreases as area increases (Dubreuil et al., 1975b). Therefore, in order to break away from this second physical rela-

TABLE 8

The role of the soil-cover complex

Hydrological characteristic affected	Geographic area	Type of occurrence	Direction of variation
Runoff coefficient K	All	Permeability class, P_j	Opposite (to increasing P_j, decreasing K)
idem	idem	Clay content, Ag	Same direction
idem	idem	Percentage of stable aggregates Percentage of organic matter	Opposite
Maximum instantaneous discharge, Qx	Arid and semi-arid zones[*1]	Crystalline soils (%)	Same direction
		Sedimentary soils (%)	Opposite direction
Mean annual runoff H_a	Arid and semi-arid zones[*1]	Crystalline soils (%)	Same direction
		Sedimentary soils (%)	Opposite direction
	idem	Cultivated soils (%)	Opposite direction
	Tropical and forest zones	Cultivated soils (%)	Same direction
Shape coefficient α of the hydrograph	All	Vegetation density	Same direction

[*1] In arid and semi-arid zones, surface runoff is the main element of flow.

tionship, it was suggested that a specific gradient be used, such as $SI \cdot A^{0.50}$ (Dubreuil and Vuillaume, 1975). The parameter has a positive effect on annual runoff at the outlet of small watersheds. Two explanations may be given: (1) a steep gradient contributes to runoff at the storm scale, raises the production function and reduces losses by evapotranspiration; (2) a steep gradient contributes to lateral transfer via the water table, thus enhancing recovery of the subsurface flow and possibly providing a substantial base flow contribution.

MORPHOLOGICAL PARAMETERS

The shape coefficient *Kc* of a watershed and the equivalent rectangle defined by Roche (1963) are not independent for small watersheds: $Lq = A^{0.5} \cdot Kc^2$. (Dubreuil et al., 1975b). Therefore, the shape coefficient will influence hydrological characteristics depending on runoff length, as follows: (a) if the shape coefficient is very high ($Kc > 1.40$) then hydrograph times *tm* and *Tb* are increased; (b) the shape coefficient α of the hydrograph also varies in the same direction as *Kc*.

Thus, when the watershed is very elongated, it takes a longer time for the hydrograph to flow, but it remains steep.

The influence of the drainage pattern is important in two respects. Firstly, in the arid and semi-arid zones, the degradation of the drainage pattern and the early emergence of flood plains reduce runoff volumes. On the other hand, the flood hydrograph depends on the shape of the drainage pattern: (a) a radial drainage pattern gives an increase in peak discharge and short and steep hydrographs; (b) a parallel drainage pattern will give the opposite effect.

The effect observed is ± 10% of the values of *Qx*, *tm* and *Tb*, all other factors being constant, on medium-sized watersheds in the semi-arid and tropical zones (Dubreuil et al., 1968). The effect also exists on small forested watersheds (Rodier, 1976) where it does not seem to be easily distinguished from that of the shape of the watershed. The sample analysed by this author shows that the radial drainage patterns generally correspond to compact watersheds with low *Kc* values (< 1.30), while the parallel drainage patterns are most often found in elongated watersheds with high *Kc* values (> 1.25). Therefore the influences of these two factors are contradictory.

CONCLUSION

The main influences of drainage area, slope and soil–cover complex, already known and observed by hydrologists, have been reidentified and evaluated for the intertropical zone.

Firstly, the influence of drainage area is noted and it is emphasized that it is necessary to make analyses at various scales of catchment in order to take full account of the processes involved (Pilgrim et al., 1982).

Secondly, the identification of the role played by the soil–cover complex in the rainfall–runoff relationship is discussed. Although it is easy to identify and understand this factor, there are still many unknowns and some difficulty is classifying the complex into parameters. A typological analysis is still needed, but this must use a more precise definition of runoff capacity classes than is now available.

A good example of the difficulty encountered in describing geophysical parameters is given by the regional analysis of mean annual yields in Sahelian Africa (Rodier, 1975), which details the ranges of yields for various classes of watersheds. The typological analysis used to classify the watersheds is based on a detailed description of morphology, soils and slopes of typical catchments.

ACKNOWLEDGEMENT

The author wishes to thank J.A. Rodier for reading this paper. His great experience has been extremely helpful in preparing the final version.

REFERENCES

Bailly, C., Benoit de Coignac, G., Malvos, C., Ningre, J.M. and Sarrailh, J.M., 1974. Etude de l'influence du couvert naturel et de ses modifications à Madagascar — Bois et Forêts des tropiques. Cah. Sci., 4, CTFT, Nogent.

Billon, B., Guiscafré, J., Herbaud, J. and Oberlin, C., 1974. Le bassin du fleuve Chari. Monogr. Hydrol., 2, ORSTOM, Paris, 450 pp.

Casenave, A., Guiguen, N. and Simon, J.M., 1982. Etudes des crues décennales des petits bassins versants forestiers en Afrique tropicale. Cah. ORSTOM, Sér. Hydrol., XIX (4): 229–252.

Dubreuil, P., 1966. Les caractères physiques et morphologiques des bassins versants; leur détermination avec une précision acceptable. Cah. ORSTOM, Sér. Hydrol., III: pp 13–30.

Dubreuil, P., 1972. Recueil des données de base des bassins représentatifs et expérimentaux 1951–1969. ORSTOM, Paris, 916 pp.

Dubreuil, P., 1974. Initiation à l'analyse hydrologique. Masson, ORSTOM, 216 pp.

Dubreuil, P., 1985. Review of field observations of runoff generation in the tropics. J. Hydrol., 80: 237–264.

Dubreuil, P. and Vuillaume, G., 1975. Influence du milieu physico-climatique sur l'écoulement de petits bassins intertropicaux. Int. Assoc. Sci. Hydrol. Publ., 117: 205–215.

Dubreuil, P., Girard, G. and Herbaud, J., 1968. Monographie hydrologique du bassin du Jaguaribe, Cearà, Brésil — Mém. ORSTOM, 28, 385 pp.

Dubreuil, P., Guiscafré, J., Nouvelot, J.F. and Olivry, J.C., 1975a. Le bassin de la rivière Sanaga — Cameroun. Monogr. Hydrol., 3, ORSTOM, Paris, 350 pp.

Dubreuil, P., Morell, M. and Séchet, P., 1975b. Comportement et interactions des paramètres physiques de petits bassins versants semi-arides et intertropicaux. Cah. ORSTOM, Sér. Hydrol., XII (1): 13–36.

Duret, L., 1976. Estimation des débits de crue à Madagascar. Bassins de 10 à 50.000 km^2. Edit. Rép. Malgache, 134 pp.

Girard, G., 1975. Les modèles hydrologiques pour l'évaluation de la lame écoulée en zone sahélienne et leurs contraintes. Cah. ORSTOM, Sér. Hydrol., XII (3): 189–221.

Guiscafré, J., Klein, J.C. and Moniod, F., 1976. Les ressources en eau de surface de la Martinique. Monogr. Hydrol., 4, ORSTOM, 212 pp.

Hiez, G. and Dubreuil, P., 1964. Les régimes hydrologiques en Guyane française. Mém. ORSTOM, 3, 119 pp.

Ibiza, D., 1983. Un modèle simplifié de calcul des écoulements mensuels par bilan hydrique. Cah. ORSTOM, Sér. Hydrol., XX (1): 3–46.

Klein, M., 1984. Effect on catchment size on runoff relationships — A comment. J. Hydrol., 71 (1/2): 191–195.

Molinier, M., 1981. Etude hydrologique des bassins de la COMBA — Rép. popul. du Congo. Cah. ORSTOM, Sér. Hydrol., XVIII (2–3): 75–190.

Moniod, F., 1969. Calcul automatique des paramètres de l'hydrogramme standard. Cah. ORSTOM, Sér. Hydrol., VI (2): 77–98.

Moniod, F., Pouyaud, B. and Séchet, P., 1977. Le bassin du fleuve VOLTA. Monogr. Hydrol., 5, ORSTOM, 513 pp.

Naah, E., 1979. Etude des caractéristiques hydrologiques sur un ensemble de bassins représentatifs des terrains précambiens de la Vina du Nord (Cameroun). Thèse 3è Cycle, Univ. Paris VI, 177 pp.

Pardé, M., 1961. Sur la puissance des crues en diverses parties du monde. Géographica, Ed. Inst. Eleano, Zaragoza, 293 pp.

Pilgrim, D., Cordery, I. and Baron, B., 1982. Effects on catchment size on runoff relationships. J. Hydrol., 58 (3–4): 205–221.

Pilgrim, D., 1983. Some problems in transferring hydrological relationships between small and large drainage basins and between regions. J. Hydrol., 65 (1–3): 49–72.

Puech, C. and Chabi-Gonni, D., 1983. Méthode de calcul des débits de crue décennale pour les petits et moyens bassins en Afrique de l'Ouest et Centrale. Edit. Provis. Com. Interafr. d'Et. Hydrol., Ouagadougou, 79 pp.

Roche, m., 1963. Hydrologie de surface. ORSTOM, Gauthier-Villars, Paris, 430 pp.

Roche, M., 1967. Recherche d'un hydrogramme standard. Cah. ORSTOM. Sér. Hydrol., IV (1): 27–44.

Rodier, J.A., 1975. Evaluation of annual runoff in tropical African Sahel. ORSTOM, Trav. Docum., 145.

Rodier, J.A., 1976. Estimation des débits de crues décennales pour les petits bassins forestiers en Afrique tropicale. Cah. ORSTOM, Série. Hydrol., XIII (4): 243–268.

Rodier, J.A. and Auvray, C., 1965. Estimation of discharges of ten years floods for catchments with a surface area less than 200 sq.km in West Africa. ORSTOM, Paris.

Vuillaume, G., 1969. Analyse quantitative du rôle du milieu physico-climatique sur le ruissellement et l'érosion à l'issue de bassins de quelques hectares en zone sahélienne (Niger). Cah. ORSTOM, Sér. Hydrol., VI (4): 87–132.

monthly and annual discharges as well as for floods. Comparison of these two categories provides an insight into the effect of scale.

Three approaches are used: regression analysis, a graphical approach based on physical reasoning, and the use of deterministic models.

Strict rules for the calculation and determination of all these geophysical parameters have been used (Dubreuil, 1966). These cover, for example, the selection of the appropriate scale for topographical maps to achieve the desired accuracy. Such rules have been applied systematically to all the representative basins compiled by Dubreuil (1972) as well as the hydrological monographs for large catchments.

MAIN EXPERIMENTAL RESULTS

The following factors are reviewed in turn: flood volumes and maximum instantaneous discharges, shape of floods and runoff volumes on daily, monthly and annual scales. The symbols used are listed in the Notation.

NOTATION

A	km^2	watershed area
Ag	%	soil clay content
C	%	percentage of crops in the watershed
Hs, Hs_{10}, Hs_1	mm	depth of surface runoff, value for the ten year storm, value for the annual storm
H_t, H_d, H_m, H_a	mm	depth of runoff, daily value, monthly value, annual value
I		slope index such as $I = 1.5$ SI
Ih		antecedent precipitation index
K, K_{10}	%	runoff coefficient, value for the 10-year storm
Kc		shape coefficient of the watershed, $Kc = 0.28\ P.A.^{0.50}$, P being the perimeter of the watershed
Lq	km	length of the equivalent rectangle of a watershed such as $Lq = A^{0.50}Kc^2$
Q, Q_{10}	m^3/s	mean discharge, value for 10-year flood
Qx, Qx_{10}	m^3/s	maximum instantaneous discharge, value for 10-year flood
R, R_d, R_m	mm	rainfall depth, daily rainfall depth, monthly value
R_a	mm	mean annual depth of rainfall
R_{10}	mm	daily depth of rainfall (10-year frequency)
RD	mm	runoff deficit $RD = R_a - H_a$
S		slope index such as $S = 0.035SI^{0.50}$
SI	m/km	overall slope index of a watershed
Tb	h	base time of the flood hydrograph
tp	h	rise time of the flood hydrograph
Vs	m^3	volume of surface runoff; $Vs = H_s.A \cdot 10^3$
Vt, Va	m^3	volume of runoff within a given period of time $Vt = H_t.A \cdot 10^3$, annual value
$\alpha = Qx_{10}/Q_{10}$		shape coefficient of the 10-year flood hydrograph