Catchment geomorphology and its relationship with streamflow — A case study of selected drainage basins in Peninsular Malaysia

C.H. PEH
Department of Geography
University of Malaya
Kuala Lumpur

Abstract: Hydrogeomorphological studies have stressed the significance of catchment geomorphology and its causal link with streamflow parameters. Such studies are invaluable not only from the standpoint of the dynamics of fluvial geomorphology but its practical value for streamflow prediction/ estimation purposes. A classic example of such studies is illustrated by the work of Carlston (1963). Utilizing a single morphometric property, drainage density, the theoretical link between catchment geomorphology and basin runoff response can be summarized in the modified Jacob groundwater flow model equation $T = WD^{-2}/8h_0$, in which T is transmissibility, W is recharge, D is drainage density and h_0 is the height of the water table at the water table divide.

This study of 15 drainage basins in Peninsular Malaysia attempts to test the significance of basin morphometric variables such as drainage density, stream magnitude, relief ratio, ruggedness number and bifurcation ratio in influencing basin runoff response such as baseflow, peakflow and flood runoff. Correlation and multiple regression analyses are used to establish the relationships between basin morphometric variables and basin runoff response. It is concluded that basin morphometric variables are closely related to runoff response and the empirical equations established can be utilized for streamflow estimation on ungauged basins.

INTRODUCTION

The drainage basin constitutes one of the most fundamental spatial unit in which geomorphological and hydrological processes operate. The intrinsic property of the drainage basin of having topographically well-defined boundaries enables the formulation and computation of mass/energy balances. The manner in which the energy inputs are imported through the drainge system governs the efficiency of geomorphic and hydrological processes, which in turn is conditioned by the physical attributes of the drainage basin. Such complex interactions between drainage basin form and process is perhaps best reflected in Strahler's concept of the drainage basin as an open system tending to achieve a 'steady state' of operations, the achievement of steady state being manifested in the development of certain topographic characteristics of an 'invariant nature' (Strahler, 1964). Similarly, Horton's concept of the system of fluvial morphometry in drainage basins is based on the theory that for a given intensity of erosional processes acting upon a mass of given physical properties, the conditions of surface relief, slope and channel configuration reach a time-independent steady state in which morphology is adjusted to transmit through the system just the quantity of debris and excess water characteristically produced under the controlling regimen of climate (Horton, 1945).

Much can be argued for and against the validity of such concepts, but nevertheless, such studies clearly illustrate the importance of the physical form (morphometry) of drainage basins in conditioning the efficiency of denudational and hydrological processes and in

which drainage basin form can be taken to reflect the relative efficiency and magnitude of basin processes. Knowledge of such interrelationships is important because it reflects the way in which varied form and process elements in a drainage basin are adjusted. Sherman (1932) empirically illustrates that basins with different shapes and slopes gave different unit hydrographs. Taylor & Schwartz (1952) has shown the effects of drainage basin characteristics on unit hydrograph lag and peakflow. Strahler (1964) has drawn up hypothetical basins of extreme and moderate values of bifurcation ratio and the postulated effects on the shape of the stream hydrograph and runoff response in general.

It is in this general perspective that this study on catchment geomorphology and its effects on streamflow is conceived. A study of this nature is significant not only for the elucidation of certain theoretical concept in geomorphology and hydrology but also its practical and relevance in the assessment of water yields, runoff response and the flood potential of drainage basins.

Basin Morphometry

A host of morphometric parameters exist in geomorphic and hydrologic literature. However, only certain morphometric parameters are quantified in this study and these are: basin area, Shreve magnitude, frequency of 1st order streams, bifurcation ratio, ruggedness number and drainage density (Tables 1 & 2). Topographic maps with a scale of 1:63360 are used in determining the morphometric parameters of the study basins.

Basin Area

Drainage basin area is perhaps the most frequently employed morphometric variable used in the estimation of streamflow characteristics from drainage basins. The significance of basin area has long been recognized and has always featured itself in most prediction models for instance in the most commonly used flood-estimation formula, basin area is an important variable as illustrated in the general equation:

$$Q_p = CiA \qquad (1)$$

where:

Q_p = peak instantaneous discharge.
C = a dimensionless coefficient normally considered
    to be a function of catchment characteristics.
i = average rainfall intensity.
A = basin area.

The influence of basin area is clear if one considers the two extreme end members of the size-area spectrum, i.e., of a very large basin and a very small basin, the volume of streamflow or water yield is directly correlated with basin area. However, for basins whose areas are clustered around a relatively narrow range, the effects of basin area can be precluded or masked by the effects of other basin factors. This is clearly illustrated in a study by Rodda (1969) of basins ranging in size from 7.8 km² to 195 km² where basin area as a variable by itself was empirically found to have little significance in influencing the mean annual flood. It is also clear from the studies by Rodda (1969), Benson (1962), Carlston (1963), Morisawa

(1962), Kowall (1976), Patton & Baker (1976) and that for a detailed study of factors influencing streamflow characteristics of basins, consideration of basin area alone is inadequate.

A total of 18 drainage basins ranging in size from 60 km² to 3341 km² were selected for the purpose of this study (Figure 1, Table 1).

Drainage Density. The density of the stream network has long been recognised as a morphometric characteristic of fundamental hydrologic significance. This arises from the fact that drainage density is a sensitive parameter which reflects the interaction between basin form and process. Horton (1932) introduced the concept of drainage density into geomorphic and hydrologic literature and can be defined as follows:

$$Dd = \frac{L}{A} \tag{2}$$

where,

$\quad Dd \quad = \quad$ drainage density (length per unit area).
$\quad L \quad = \quad$ total length of streams in a basin.
$\quad A \quad = \quad$ basin area.

The hydrologic significance of this parameter also stems from its theoretical relationship with the constant of channel maintenance and the length of overland flow. The constant of channel maintenance, which is defined as the basin area required to maintain each unit length of stream, is derived by taking the reciprocal of drainage density (1/D). One half the value of the constant of channel maintenance gives the average horizontal distance between divide and channel in a basin (Horton, 1945). This is generally termed the length of overload flow (l_o).

$$l_o = \frac{1}{2D} \tag{3}$$

It theoretically follows that the higher the drainage density, the shorter the distance that surface runoff must travel to a stream channel (length of overland flow) and provided that other factors affecting runoff response remain the same, the shorter will be the time required for surface runoff to reach a stream channel. Also, drainage density is theoretically inversely related to the relative permeability of a landsurface. It has been observed that streams tend to be more numerous where the landsurface is made up of relatively impermeable material. The relatively low infiltration capacity of such material tend to generate more surface runoff and hence the formation of more surface channels. This is in contrast to terrains which consist of permeable materials where most of the runoff tend to be slow subsurface seepage following the infiltration of precipitation. Based on the above theoretical considerations, it follows that basins with relatively high drainage densities should be characterized by relatively higher flood peaks, hydrographs with shorter time bases, faster recessions and a larger value of the direct runoff-baseflow ratio.

Drainage densities for the study basins were derived from measurements based on the blue-line stream network as depicted on topographic maps at a scale of 1:63360 produced by
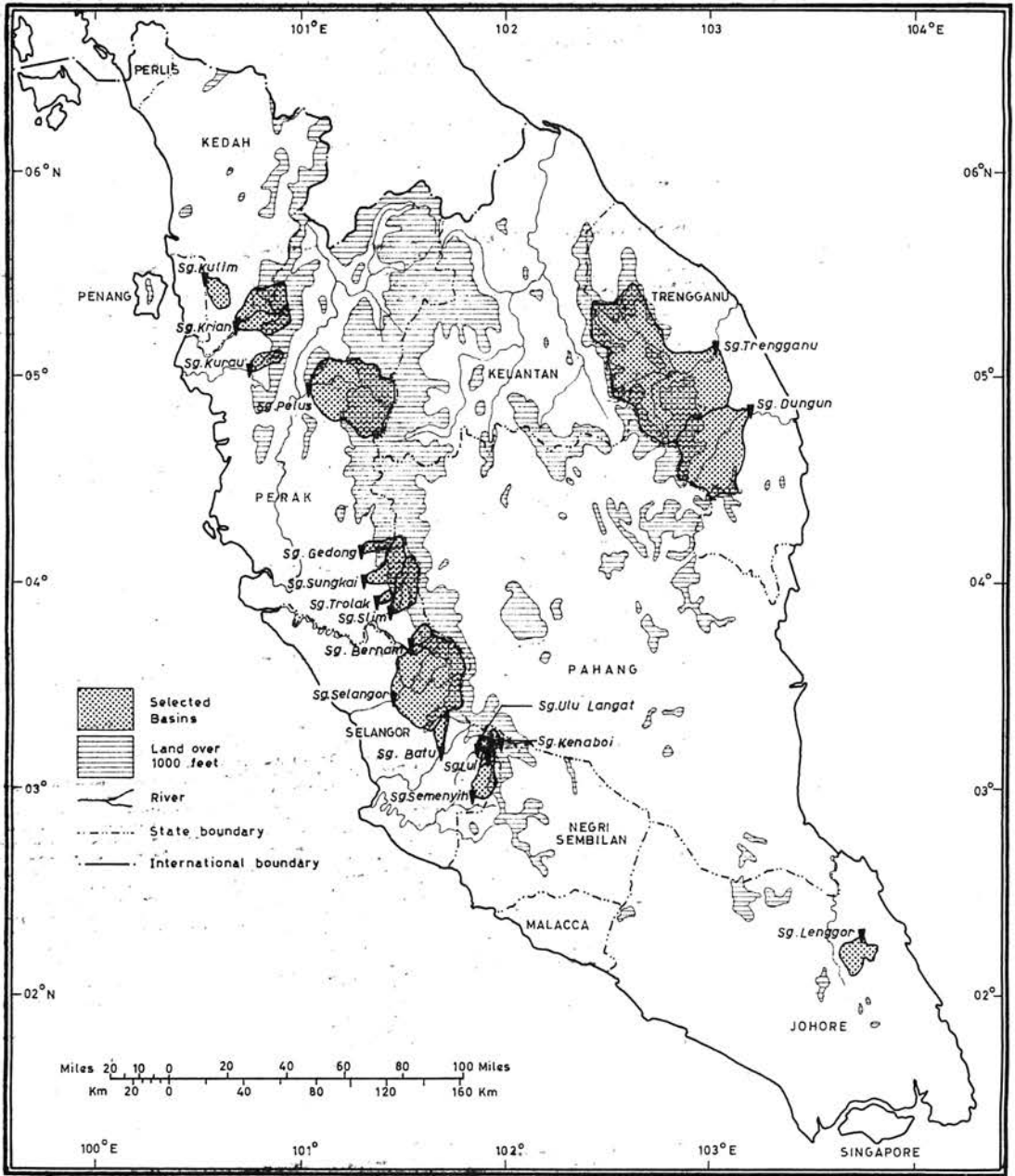
Fig. 1. Location of study basins.

TABLE 1

MORPHOMETRIC PROPERTIES OF SELECTED DRAINAGE BASINS IN PENINSULAR MALAYSIA

Drainage Basin	Location of Streamflow Gauging Station**	Area* (km2)	Shreve Magnitude	F** (No./km2)	Drainage Density (km/km2)	Bifurcation Ratio
1. Sungai* Terengganu	103° 3' E, 5° 8' N	3341	23820	7.13	2.85	4.31
2. Sungai Selangor	101° 27' E, 3° 24' N	1450	6988	4.82	2.62	3.97
3. Sungai Dungun	103° 12' E, 4° 50' N	1414	11663	8.25	3.09	3.32
4. Sungai Pelus	101° 2' E, 4° 54' N	1388	4913	3.54	2.46	3.90
5. Sungai Krian	100° 40' E, 5° 12' N	694	2282	3.29	2.15	4.14
6. Sungai Slim	101° 25' N, 3° 50' N	455	1875	4.12	2.43	4.02
7. Sungai Kurau	100° 44' E, 5° 1' N	337	1066	3.16	2.09	4.09
8. Sungai Sungkai	101° 19' E, 3° 59' N	293	1148	3.92	2.49	4.10
9. Sungai Semenyih	101° 51' E, 2° 57' N	218	1161	5.33	2.56	4.13
10. Sungai Lenggor	103° 44' E, 2° 16' N	207	1262	6.09	3.02	3.77
11. Sungai Bernam	101° 32' E, 3° 41' N	186	722	3.88	2.43	4.37
12. Sungai Kenaboi	102° 4' E, 3° 7' N	174	716	4.11	2.19	3.88
13. Sungai Batu	101° 41' E, 3° 11' N	145	657	4.53	2.47	3.71
14. Sungai Kulim	100° 31' E, 5° 26' N	136	379	2.79	2.14	4.00
15. Sungai Gedong	101° 17' E, 4° 7' N	104	383	3.68	2.36	4.46
16. Sungai Ulu Langat	101° 51' E, 3° 12' N	75	427	5.69	2.56	3.54
17. Sungai Lui	101° 52' E, 3° 11' N	69	356	5.16	2.61	4.37
18. Sungai Trolak	101° 23'E, 3° 54' N	60	197	3.28	2.87	3.80

* Sungai denotes river
** All gauging stations are equipped with automatic water-level recorders and are maintained by the Drainage and Irrigation Department, Ministry of Agriculture, with the exception of Sungai Kenaboi and Ulu Langat which were maintained by Binnie and Partners.
* Area refers to basin area upstream from gauging point.
** Frequency of Strahler 1st order streams.

TABLE 2
MORPHOMETRIC PROPERTIES OF SELECTED DRAINAGE BASINS IN PENINSULAR MALAYSIA

Drainage Basin	Average Relief (m)	Basin Length (km)	Ruggedness Number	Mainstream Length (km)	Gradient of Mainstream Channel (m/km)
1. Sungai Terengganu	701	63	1.86	106	10.70
2. Sungai Selangor	780	47	2.43	69	19.42
3. Sungai Dungun	623	50	1.93	72	19.71
4. Sungai Pelus	1146	43	2.82	40	45.75
5. Sungai Krian	1061	36	2.28	40	45.75
6. Sungai Slim	1102	35	2.30	43	32.91
7. Sungai Kurau	737	22	1.79	27	37.29
8. Sungai Sungkai	1159	33	2.89	37	57.02
9. Sungai Semenyih	441	23	1.13	24	29.41
10. Sungai Lenggor	176	19	0.48	25	20.06
11. Sungai Bernam	869	16	2.11	18	107.91
12. Sungai Kenaboi	1035	24	2.27	27	41.68
13. Sungai Batu	431	21	1.06	26	54.47
14. Sungai Kulim	233	18	0.49	25	20.86
15. Sungai Gedong	792	20	1.87	24	63.84
16. Sungai Ulu Langat	912	10	2.33	11	86.14
17. Sungai Lui	525	11	1.37	12	43.95
18. Sungai Trolak	378	13	0.86	15	50.39

the Malaysian Survey Department. Drainage densities for the study basins were found to range from 2.09 to 3.09 km/km^2 (Table 1).

Shreve Magnitude and Frequency of lst Order Streams (F_1).

These two morphometric parameters are measures of stream channel frequency based on Shreve's ordering system. Although drainage density measurements are indirect expressions of the closeness of spacing of stream channels in a basin, it does not show whether the stream network is made up of a small or large number of streams of a particular order. Strahler (1964) has shown that two drainage basins may have the same drainage density but differ in dissection simply due to differences in the number of stream channels. In this study, two simple measures of stream frequency were quantified namely, Shreve Magnitude which is simply the number of lst Order stream channels and F_1 being the frequency of first-order streams expressed on a per unit basin area basis as follows:

$$F_1 = \frac{\sum_{i=1}^{k} Nu}{A_k} \qquad (4)$$

where,

$$\sum_{i=1}^{k} Nu = \text{total number of stream segments of all}$$
orders within the drainage basin of Order k.
$$A_k = \text{area of drainage basin of Order k.}$$

The frequency of lst Order streams is considered to be of hydrologic and geomorphic significance as 1st Order streams constitute up to 80% of the total number of stream segments and total length of streams in a drainage basin and hence its potential significance as fundamental energy cells of the basins.

Bifurcation Ratio.

The bifurcation ratio represents the ratio of the number of stream segments of a given order to the number of stream segments of the next successively higher order. This is defined as follows:

$$Rb = \frac{Nu}{Nu + 1} \qquad (5)$$

Computation of an average value of the bifurcation ratio (Rb) or a given channel network can be made by determining the slope (b) of the fitted regression of the logarithm of number of stream segments (ordinate) on stream order (abscissa):

$$\log Nu = a - bu \qquad (6)$$

$$\overline{Rb} = \text{antilog b} \qquad (7)$$

Strahler (1964) postulated that the bifurcation ratio interacting with basin shape influences streamflow in the manner that hydrographs tend to be characterized by relatively low and attenuated peak flows in long narrow basins with high bifurcation ratios, whereas rotund basins with low bifurcation ratios can be expected to have sharply peaked hydrographs. Similarly, McCullagh (1978) relates that as the value of the bifurcation ratio is reduced, the runoff response of the drainage basin especially in generating peak discharges is increased and hence increasing the flood potential of the basin. The reasoning being that in basins of low bifurcation ratios, there will be a lesser number of stream channels linking one order to the other and hence, the quicker will runoff reach the mainstream channel thereby producing a more peaked hydrograph.

Ruggedness Number.

This morphometric property is a dimensionless product of mean basin relief and drainage density. The hydrologic significance of basin relief has been noted by numerous investigators (Horton, 1945; Strahler, 1958). Basins with high ruggedness numbers can be perceived as having high relief, fine drainage texture, relatively short lengths of overland flow across steep slopes and high stream gradients. The combination of these factors might result in far higher flood peaks for an equivalent rainfall input than for basins having a low ruggedness number.

STREAMFLOW CHARACTERISTICS

Streamflow characteristics that are quantified include the maximum hydrograph peak discharge (Q_p), parameters reflecting maximum streamflow/flood runoff conditions such as discharge events which have frequencies of occurrence which equalled to 1% of time (Q_1), 5% of time (Q_5) and 10% of time (Q_{10}), mean daily discharge (MDD), median discharge (Q_{50}), parameters which reflect low streamflow/baseflow discharge levels such as the Q_{90} (discharge levels which occur 90% of time) and the Q_{99} (discharge levels with 99% of time) and lastly the flood potential index (FPI) which is actually a ratio between Q_1 and Q_{50}. All the streamflow parameters with the exception of Q_p, mean daily discharge and the FPI were obtained from the flow duration curves plotted for the basins (Figures 2 & 3).

Catchment Geomorphology and Streamflow Relations

Catchment geomorphology and streamflow relations were analysed using stepwise multiple regression and simple correlation analyses. The following relationships are noted:

Firstly, drainage density is significantly correlated with Q_p, Q_1, FPI and Q_{99} (Tables 3 & 4). Drainage density was found to be positively correlated with Q_p, Q_1 and the flood potential index (FPI) and negatively correlated with Q_{99}. It is interesting to note that Q_p, Q_1 and FPI are streamflow indices which reflect flood runoff conditions or more specifically, the overland flow and the relatively rapid interflow (sub-surface) component of basin runoff. Such indices generally depict the ability of the basin in generating fast runoff responses.

In contrast, Q_{99} reflects low, baseflow conditions resulting from slow sub-surface seepage, slow release from bank storage and groundwater discharge. This streamflow index generally depicts the storage capacity of the basins.

Carlston (1963) in his study of 15 basins in the eastern U.S.A. found similar relationships
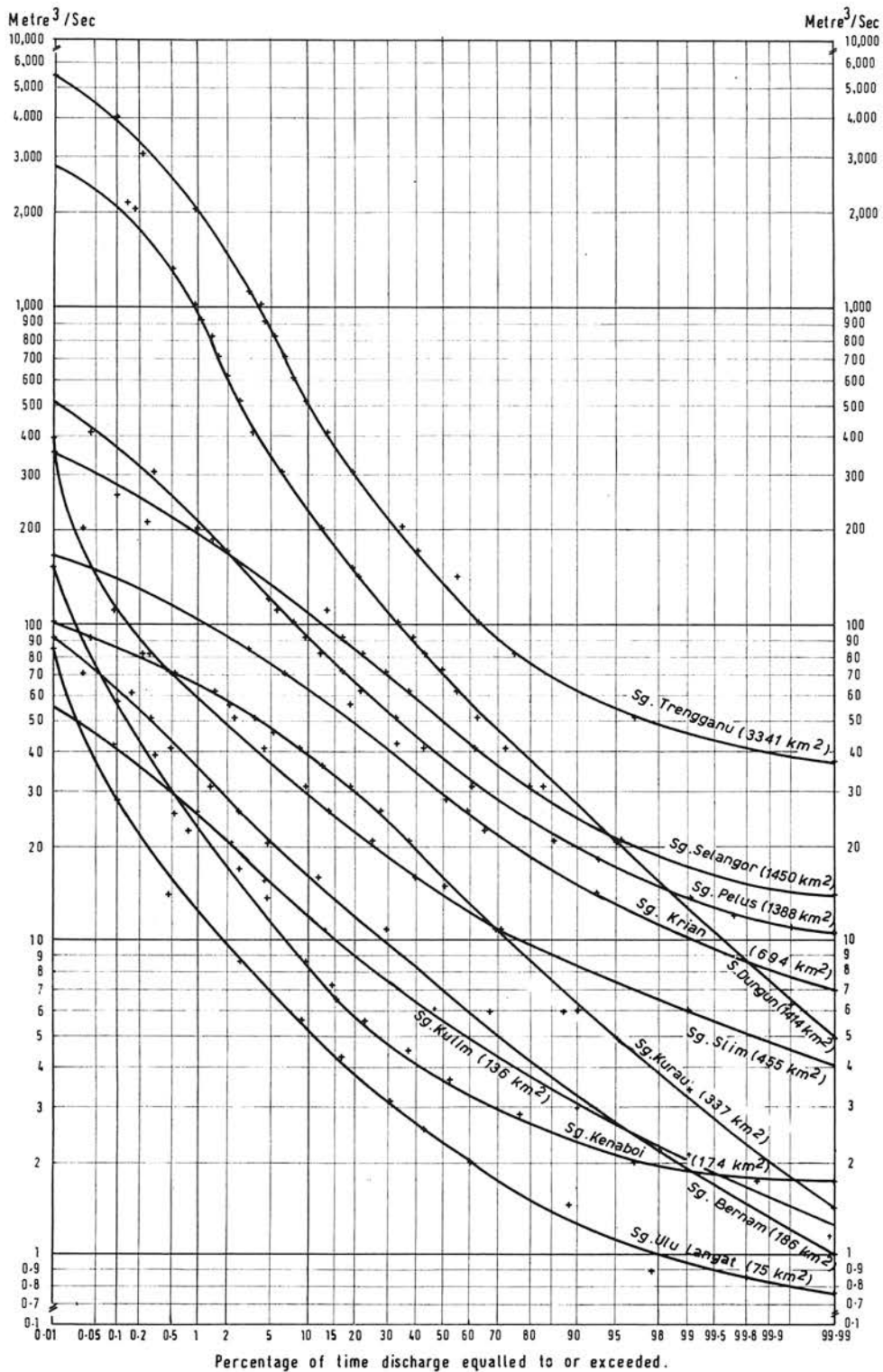
Fig. 2. Flow duration curves of study basins based on mean daily discharge (1965-1980).
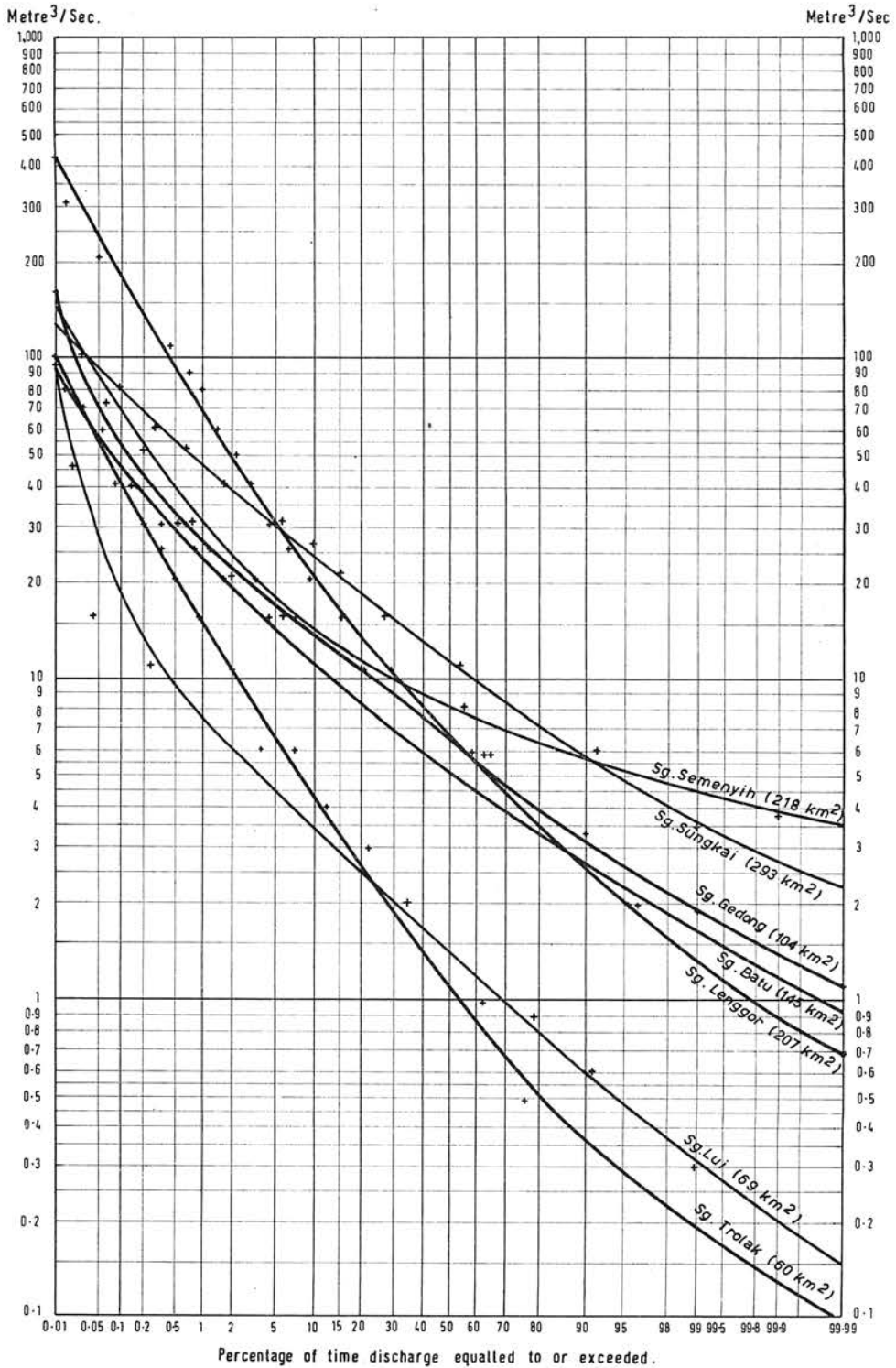
Fig. 3. Flow duration curves of study basins based on mean daily discharge (1965-1980).

between drainage density and streamflow indices depicting conditions of flood runoff and baseflow/low runoff. According to Carlston, drainage density and runoff are theoretically related to the transmissibility of the terrain as shown by the modified Jacob's groundwater model equation:

$$T = \frac{WD^{-2}}{8h_O} \qquad (8)$$

where,

T = transmissibility of the terrain.
D = drainage density.
W = recharge (accretion to the water table).
h_O = height of water table at the water table divide.

As groundwater discharge or baseflow vary directly with terrain transmissibility, base-flow should also vary according to the above equation, i.e. an inverse relationship should exist between baseflow and drainage density. Carlston further deduced that a positive relationship should exist between streamflow indices reflecting flood runoff conditions (particularly the mean annual flood and drainage density, as decreased transmissibility (decreased baseflow) would increase the volume of surface flow component and hence leading to increased drainage densities.

The significant, positive correlations of Q_p, Q_1 and FPI with drainage density of this study would seem to lend support to Carlston's hypothesis that drainage densities are efficient removal of flood runoff and higher drainage densities are evolved to accommodate the greater magnitude of flood runoff of drainage basins.

Although the results of this study indicate a negative correlation between Q_{99} and drainage density (Tables 3 and 4) a large amount of unexplained variance still exists. This can be attributed to unaccounted factors such as bank storage which is independent of terrain transmissibility and the anisotrophic nature of the weathered regolith of the drainage basins.

Significant, positive correlations are also obtained between basin morphometric variables pertaining to stream-channel frequency and streamflow indices reflecting flood runoff conditions. Shreve Magnitude is significantly correlated with flood flows which occur 1%, 5% and 10% of time, while channel frequency of first-order streams is significantly correlated with the maximum instantaneous peak discharge (Q_p), and flood flows which occur 1% of time (Q_1) (Table 3). These significant, positive correlations further support the view that the channel frequency of first-order streams is closely adjusted to flood runoff. This is to be expected as the channel frequency of first-order streams constitute up to 80% of the total number of ordered stream segments. A greater number of first-order stream channels and hence higher drainage densities would have evolved to accommodate a greater volume of flood runoff.

The apparent lack of correlation between basin ruggedness number and streamflow indices can perhaps be attributed to the gross, unweighted values of basin relief computed in this study. Studies by Paton & Baker (1976) have highlighted the theoretical significance of

C.H. PEH

TABLE 3

CORRELATION ANALYSES OF BASIN MORPHOMETRIC AND STREAMFLOW VARIABLES[*]

	Shreve Magnitude	F1	Drainage Density	Bifurcation Ratio	Ruggedness Number
Q_p	−0.09	0.57*	0.66*	−0.23	−0.29
Q_1	0.47*	0.50*	0.57*	−0.22	−0.16
Q_5	0.46.	0.38	0.39	−0.09	−0.15
Q_{10}	0.54*	0.29	0.27	−0.03	0.00
Q_{90}	0.24	0.01	−0.39	0.20	0.17
Q_{99}	0.26	−0.05	−0.46	0.19	0.07

* Streamflow variables expressed on a per unit basin area basis.

TABLE 4

STEPWISE MULTIPLE REGRESSION FORMULAE DESCRIBING RELATIONSHIPS BETWEEN STREAMFLOW VARIABLES AND MORPHOMETRIC VARIABLES*

Equation	Correlation Coefficient (r)	F Ratio	Significance Level	Standard Error of Estimate
$FPI = 1.43 D^{0.30} Rb^{-0.26} F_1^{-0.77}$	0.83	10.29	0.001	0.13
$Q_p = 43 D^{4.56} A^{-0.22}$	0.76	10.04	0.001	0.22
$Q_1 = 17 D^{2.60}$	0.57	7.58	0.01	0.19
$Q_5 = 1.49 D^{0.15} SM^{0.69}$	0.58	3.85	0.05	0.14
$Q_{10} = 29 SM^{0.15}$	0.54	6.76	0.01	0.13
$Q_{50} = 1.45 A^{-0.23} D^{-0.11} SM^{0.31}$	0.41	0.93	NS	–
$Q_{90} = 1.42 D^{-0.15} A^{0.11}$	0.51	2.70	NS	–
$Q_{99} = 1.41 D^{-0.26} SM^{0.17}$	0.63	4.91	0.02	0.17

* Streamflow variables expressed on a per unit basin area basis.   NS = Not Significant

this morphometric property of drainage basins and have obtained significant correlations with streamflow indices particularly those reflecting the flood potential of basins. Also, the bifurcation ratio is uncorrelated with most of the streamflow indices quantified, despite its theoretical importance as deduced by Strahler (1964) and others. The importance of bifurcation ratio is only realised in the stepwise multiple regression analysis where together with drainage density (D) and frequency of first-order streams (F1), it is significantly correlated with the flood potential index of the basins (Table 4). A negative regression coefficient was obtained reflecting the concept by Strahler that assuming other factors to remain the same basins with lower bifurcation ratios will tend to have a greater flood potential as flood runoff is channelized through the stream network relatively faster as compared with those having higher bifurcation ratios.

CONCLUSION

The importance of catchment geomorphology influencing streamflow variation between drainage basins is apparent from this study. It is concluded that the drainage network adjust to and reflect the magnitude and frequency of dominant runoff events. Basin drainage area alone is inadequate to account for streamflow variations between catchments as reflected in the multiple regression analyses where the best correlations obtained involve drainage density as one of the independent variables.

ACKNOWLEDGEMENTS

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