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ROLE OF HYPSOMETRY AND PLANFORM IN BASIN HYDROLOGIC RESPONSE

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ABSTRACT

The effects of variations of drainage basin morphometry and relief characteristics on flood peak magnitude and time-to-peak are investigated using simulated stream networks. The networks are produced by three models: headward growth, systematic capture, and minimum power relaxation. Translational and kinematic wave flood routing were used to generate synthetic hydrographs. Peak discharge and time-to-peak are predictable to a high degree by five different sets of morphometric-relief parameters. In order of decreasing order of importance in predictive ability the parameters characterize basin size, relative relief, basin concavity, and basin shape. Both simulated and natural stream networks exhibit strong dependence of planimetric morphometry upon basin concavity. The effect of this dependency is to increase the effect of basin concavity upon flood hydrographs.

KEY WORDS Drainage basin Hydrograph Geomorphology Morphometry Flood routing

INTRODUCTION

For many years hydrologists have recognized that variations between drainage networks in their planimetric and topographic structure has pronounced effect upon their hydrology, particularly their flood response. A number of approaches has been taken to investigate these effects, including statistical characterization of natural basin flow characteristics in relation to morphometric parameters, experiments on model basins, flow routing using specific channel network parameterization, and various theoretical approaches. The present study is theoretical, using stream networks simulated by three models to investigate the effects of the planimetric and profile structure of basins upon flood response.

The empirical approach produced largely inconclusive and often conflicting results regarding the role of basin morphometry and relief upon basin hydrologic response (Woodruff and Hewlett, 1970; Smart, 1978; Patton, 1988). The only basin characteristics that are found to correlate at a significant level with flood response (peak discharges or basin lag time) in almost all studies are basin area and often some measure of basin relief, such as relief ratio or average channel gradient (Sherman, 1932; Taylor and Schwarz, 1952; Potter, 1953; Morisawa, 1962; Benson, 1962, 1964; Thomas and Benson, 1970; Alexander, 1972; Heerdegen and Reich, 1974; Murphey *et al.*, 1977; Boyd, 1978; Betson, 1979). Regional studies that include other morphometric parameters in multiple regressions against peak discharge or time-to-peak (such as shape factors, profile curvature, and Horton–Strahler bifurcation, length, slope, and area ratios (Horton, 1945; Strahler, 1964)) generally result in insignificant relations with these parameters (Morisawa, 1962; Benson, 1962, 1964; Thomas and Benson, 1970; Heerdegen and Reich, 1974). Exceptions include slight correlations of peak flows with length ratios (Maxwell, 1960), with the product $R_b R_s / R_l$ (bifurcation, slope and length ratios, respectively) Anderson, 1949; Anderson and Trobitz, 1949), and with a 'topographic factor' $F_1 R_c R_h$ (first order stream frequency, basin circularity, and relief ratio, respectively) (Morisawa, 1962). Harlin (1984) found that time–to–peak correlates with various statistical parameters of the hypsometric function (skewness and kurtosis of the hypsometric integral or its density), and Murphey *et al.*, (1977) correlate time-to-peak with a basin shape parameter. Additionally, Patton and Baker (1976) find peak discharges in small basins to

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be related to Shreve magnitude, ruggedness, relief ratio, drainage density, and stream frequency. However, with the exception of magnitude, these factors varied in significance and often in direction of effect among their various study sites. Such variability and lack of significance of morphometric parameters in empirical studies is not surprising, since uncontrolled differences in rainfall, slope, and channel characteristics commonly mask the more subtle effects of morphometry on hydrologic response.

Another approach is experimental study of model basins. Black (1972) and Black and Cronn (1975) created models of drainage basins and studied effects of individual parameters on response to artificial precipitation. Basin slope, drainage density, and shape were all shown to have strong effects on peak discharge and time-to-peak. Although model basins permit excellent control over individual parameters, construction costs generally limit the range of morphometric variation that can be investigated. Parker (1977) related peak discharges in experimental basins eroded by artificial rainfall to ruggedness number (relief times drainage density). Use of experimental basins is limited by the length of time necessary to create or erode the basin and limitations on the range of morphometric parameter variation that can be achieved.

Various studies have combined hydrologic or hydraulic flow routing with representations of basin morphology to investigate hydrologic response. The most straightforward of these approaches utilize the structure of actual networks combined with flow routing techniques for flow prediction, and many such models have been created for particular river systems. Of these approaches the simplest is probably that of Surkan (1979), which utilizes a digital generalization of the stream network together with hydrologic flow routing either with or without a storage term. The studies of interest here are those that are concerned with the effects of variations in network morphology upon hydrologic response. Such models generally assume the Shreve (1966, 1967) random topology model with the further assumption that stream lengths and drainage areas of individual links also follow a random distribution independent of link magnitude except for distinct populations for interior and exterior links (Smart, 1968; Shreve, 1969). One class of these models summarizes stream network structure by the bifurcation, length, and area ratios and models the instantaneous unit hydrograph in terms of these ratios (Rodriguez-Iturbe and Valdes, 1979; Gupta *et al.*, 1980; Hebson and Wood, 1982, 1986; Kershen and Bras, 1983; Wood and Hebson, 1986; Garbrecht and Shen, 1988; Agnese *et al.*, 1988). Another approach is to use the magnitude-diameter distribution of the network instead of order-ratios (Kirkby, 1976, 1986; Gupta and Waymire, 1983; Troutman and Karlinger, 1985, 1986, 1989; Karlinger and Troutman, 1985). Most such models assume that flow velocities are independent of link magnitude, citing empirical observations that flow velocity changes very slowly downstream (Leopold and Maddock, 1953; Pilgrim, 1977). However, a few models have allowed for downstream variations in flow velocities (Kershen and Bras, 1983; Agnese *et al.*, 1988; Garbrecht and Shen, 1988).

As part of a theoretical treatment of stream network development (Howard, in press) computer-generated drainage networks were created by three different models and a variety of model parameter values. These simulated networks provide the opportunity to clarify the effects of both planimetric form and relief structure of drainage basins upon hydrologic response without the obscuring effect of the natural variability of slope response. Several features of the simulated networks and the present techniques are novel:

1. A total of 702 networks with magnitudes ranging from 113 to 989 allow detection of subtle morphometric and relief effects upon basin response.
2. The planimetric morphologies of the simulated basins range from headward growth networks (Howard, 1971a), which generally have irregular shapes and stream courses that wander much more excessively than natural networks, to minimum power networks, which are more compact and regular than natural networks. Thus the range of simulated morphologies spans and exceeds that of natural streams. Similarly, the networks are simulated with a wide range of downstream concavities.
3. In this study a large number of morphometric and relief parameters are measured for the simulated basins and tested for their relative efficiency in predicting hydrologic response.
4. Previous studies have not extensively examined relief effects on drainage basin response, which affect hydrologic response both directly through the steepness and concavity of stream segments and indirectly through the influence of channel gradients upon the development of the basin planimetric structure.

This study shows that flood response characteristics (specifically, peak discharge and time-to-peak) of large drainage basins can be represented by four to seven parameters measuring the planimetric and relief characteristics of the basins. Several different combinations of morphometric parameters give about the same predictive power.

DRAINAGE BASINS

Network hydrologic response is studied in this paper by use of simulated stream networks. Simulated rather than natural networks are used because relief characteristics and formative processes can be controlled, and they utilize networks already generated for a companion study (Howard, in press). Three types of networks were used. The first are random networks generated on a 100 × 100 square grid by *headward growth* (Howard, 1971a) inward from the edges of the matrix. Each interior matrix node has a channel emanating from it, and each node may either be a source node (no inflowing channels) or may receive up to two inflowing channels. Thus the drainage density is essentially areally uniform. These networks have topological and scale properties that are similar to natural networks, although their shape tends to be more irregular (Figure 1a).

A second set of networks are produced by headward growth but are subsequently modified by systematic *capture* (Howard, 1971b). The capture process assumes that channel gradients, S, within the network obey the relationship

$$S = K_1 Q_d^{\,z}, \tag{1}$$

where Q_d is a representative discharge. In this and subsequent formulas subscripted K's are constants of proportionality that are assumed to be temporally and areally invariant. The exponent z typically falls in the range of $-0{\cdot}15$ to $-0{\cdot}75$ in natural stream networks (Howard, 1971b, 1980; Flint, 1974; Knighton, 1984,

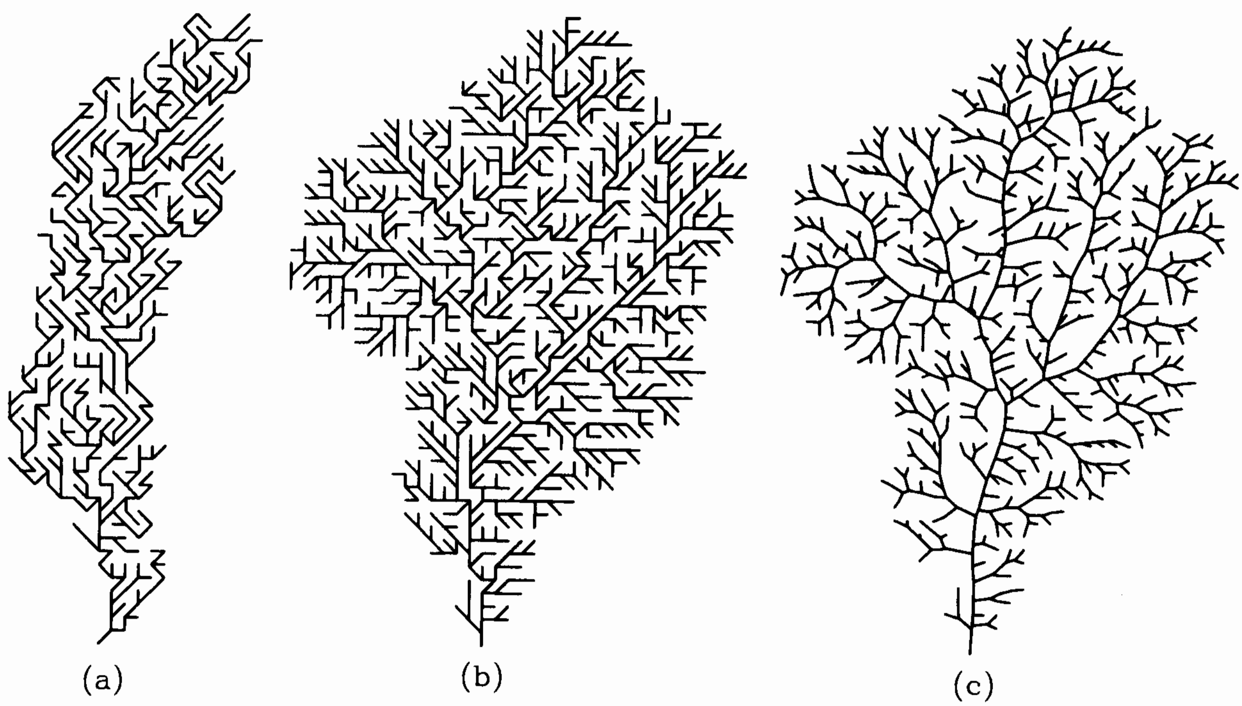

Figure 1. Representative channel networks produced by headward growth, capture, and minimum power simulation models for $z = -0{\cdot}5$. (a) stream network produced by headward growth (part of a drainage pattern developed on a 100 × 100 matrix); (b) headward growth network after modification by systematic capture (note that the drainage area and basin boundaries have changed relative to original network in (a)); (c) network resulting from minimum power optimization of systematic capture basin

1987). In the capture simulations and the hydrologic studies reported below, each unit length of channel on the matrix (the unit of measurement being the lateral spacing between grid points) is assumed to have a unit drainage area contributing directly to the link. Rearrangements (captures) occur within the network where the gradient from a given node point to an adjacent node is greater than the downstream gradient of the existing channel emanating from the node. However, captures are not permitted if they would create junctions with more than two incoming streams. Both the headward growth and capture networks are modified from the Howard (1971a,b) models by allowing streams to flow in any of eight directions rather than just four. The shape of the networks generated by the capture process depend upon the exponent z, being narrow and subparallel for z only slightly less than zero and more pear shaped to irregular with z closer to $-1{\cdot}0$. Howard (1971b) shows that the capture-modified networks have shapes and dimensionless properties closer to those of natural networks than the unmodified headward growth networks (Figure 1b).

The final set of networks are capture networks that are further modified by migration of the node points in order to minimize the total stream power (*minimum power*) within the network, where stream power over a link of length L is given by the product $Q{\cdot}S{\cdot}L$. Details of the model are presented in Howard (in press). This node migration tends to produce stream junction angles obeying the minimum power criterion of Howard (1971c). The simulated networks are remarkably similar to natural networks in shape and other properties (Howard, in press), with the greatest improvement over capture-generated networks being more direct stream courses (Figure 1c).

HYDROLOGIC MODELLING

The hydrologic flow routing assumes that channel gradients follow Equation 1. The Manning equation is used,

$$V = K_2 \frac{R^{2/3}\, S^{1/2}}{n}, \tag{2}$$

where V is average flow velocity through the cross-section, R is the hydraulic radius, and n is Manning's roughness parameter. A typical hydraulic geometry approach (Leopold and Maddock, 1953) is adopted, such that local discharge, Q, is resolved into a representative downstream component, Q_d, that varies systematically through the network (such as the mean annual flood) and a temporal at-a-station deviation, δ:

$$Q = \delta\, Q_d. \tag{3}$$

Channel width, W, is assumed to follow a relationship combining at-a-station and downstream hydraulic geometry:

$$W = K_3 Q_d{}^b \delta^c, \tag{4}$$

and Manning's n also can vary systematically downstream or at-a-station:

$$n = K_4 Q_d{}^f \delta^g. \tag{5}$$

Since

$$Q \cong WRV, \tag{6}$$

the following hydraulic geometry relationship results for flow velocity when δ is eliminated:

$$V = K_5 Q^{[\cdot 4(1-c) - \cdot 6g]} Q_d^{[\cdot 4(c-b) + \cdot 6(g-f) + \cdot 3z]}, \tag{7}$$

where K_5 combines the constants of proportionality:

$$K_5 = K_1^{\cdot 3} K_2^{\cdot 6} / (K_4^{\cdot 6} K_3^{\cdot 4}). \tag{8}$$

Note that for a typical downstream hydraulic geometry with $b = 0{\cdot}5$, $Q = Q_d$, and $f = g = 0$, this implies that velocity is independent of drainage area for z equal to $-2/3$. This is near the average value in natural networks (Howard, 1971b; Flint, 1974). However, many natural networks display concavities (z exponent) significantly different from $-2/3$, so that stream velocities should show systematic downstream increases ($z > -2/3$) or decreases.

Flood routing was conducted for the simulated drainage basins discussed above with the following further assumptions:

1. The drainage basins are assumed to be large enough that hillslope travel times are rapid compared to flow through the drainage network, so that the network structure controls flood response (Kirkby, 1976).
2. Translational or kinematic flow routing is assumed in order to permit ready scaling of hydrographs between basins of different sizes.
3. The input to the stream system is assumed to be an areally uniform instantaneous impulse whose magnitude for each stream link is proportional to the link length.
4. The hydraulic geometry exponents take on the values $b = 0{\cdot}5$ and $c = 0{\cdot}3$, in accord with observations (Leopold and Maddock, 1953; Knighton, 1984, 1987). Very few observations have been made of downstream and at-a-station variation in roughness (see summary in Knighton, 1984; 1987). Common usage assumes no at-a-station variation ($g = 0{\cdot}0$), and in this study it is also assumed that $f = 0{\cdot}0$.

Two types of simulations have been conducted. In the first the impulse input is assumed to be a small perturbation on a steady discharge, so that δ is essentially a temporal and areal constant (K_6), such that $Q \approx K_6\, Q_d$. Thus Equation 7 can be simplified by combining exponents. Also it is assumed

$$Q_d = K_7 A^e, \tag{9}$$

with $e = 1{\cdot}0$. What is of interest is the propagation of the perturbation through the stream system. The assumptions in this case allow a simplified translational treatment of flood routing similar to the method used by Surkan (1969) in which the contribution from each link at the outlet is calculated independently, because the flow velocities vary with location in the network but not with time.

In a second set of simulations, the initial flow discharge is assumed to be small compared to the flood runoff so that local flow velocities vary both spatially and temporally. For this case initial flow discharges are negligible and an areally uniform impulse discharge $q_0 \cdot \triangle t \cdot l$ (q_0 is the applied discharge per unit channel length per unit time, l is the individual segment length, and $\triangle t$ is the simulation time increment) is applied to each stream segment and routed through the network with velocites given by Equation 7 using the kinematic wave approximation (note that Q_d is temporally constant but varies areally).

The minimum power and capture networks were created with an assumed value of basin concavity, z. In the flow routing relief is generated using the appropriate value of z and a range of assigned values of K_1 in Equation 1. Although relief is not involved in creation of the headward growth networks, relief is generated using assigned values of z and K_1.

Two types of investigation into flood response were conducted. In the first the effects of relief are examined by categorizing basins according to the model type (headward growth, capture, or minimum power). In the second the basins form a collective database to examine the relative ability of morphometric parameters to predict flood characteristics.

Effects of relief and basin type on flood response

The translational flood routing results in a hydrograph of the flow perturbations from the mean, in which the peak discharge, Q_p, and time-to-peak, T_p, are of primary interest. The hydraulic geometry equations permit scaling of hydrographs from all basis with $A > 200$ to an equivalent drainage area of 200 to give average Q_p and T_p for all the larger basins in a given simulated network.

Of particular interest are the effects of network type and the assumed gradient exponent, z, on hydrologic response. However, in order to compare basins the effects of relief variations must be accounted for. Several strategies could be used for relief normalization. One is to make K_1 the same for all networks, so that all networks have the same gradient at unity drainage area (at the headwaters for the assumed scaling). However, gradients downstream will be much less for values of $z < < 0$ than for $z \approx 0$. Other approaches include normalizing on average channel bed elevation, average channel gradient, maximum channel gradient, channel gradient at the basin mouth, and relative gradient from basin mouth to the headwaters. The choice of normalization has considerable effect on the relative role of z in hydrologic response. A normalization based upon equal relative basin gradients, or relief ratio, is reported here, because it gives results intermediate among the various choices, and relief ratio is commonly used as a morphometric parameter. Figure 2 shows typical longitudinal stream profiles for basins with different values of z but equivalent relief ratio.

Hydrograph simulations were grouped by the type of simulation model: (1) the initial headward growth networks that were generated by a process that did not depend upon basin relief or channel gradients (labelled 'grow' in the Figure 3); (2) the capture networks ('capture') in which the pattern of channel reorganization depends upon the assumed value of z; and (3) the further modification of the capture networks by the minimum power relaxation ('minpower'), which also functionally depends upon z. Figure 3A shows the dependency of average normalized Q_p upon z for these simulated networks, and Figure 3B shows T_p.

All of the headward growth networks have the same topological, size and shape properties, on the average, because the z parameter was not involved in the simulation process. Therefore the variations of Q_p and T_p with z reflect only the role of the concavity of the basin in flood response. As should be expected based on examination of Figure 2, Q_p becomes smaller and T_p larger as z decreases. However, the capture basins, which

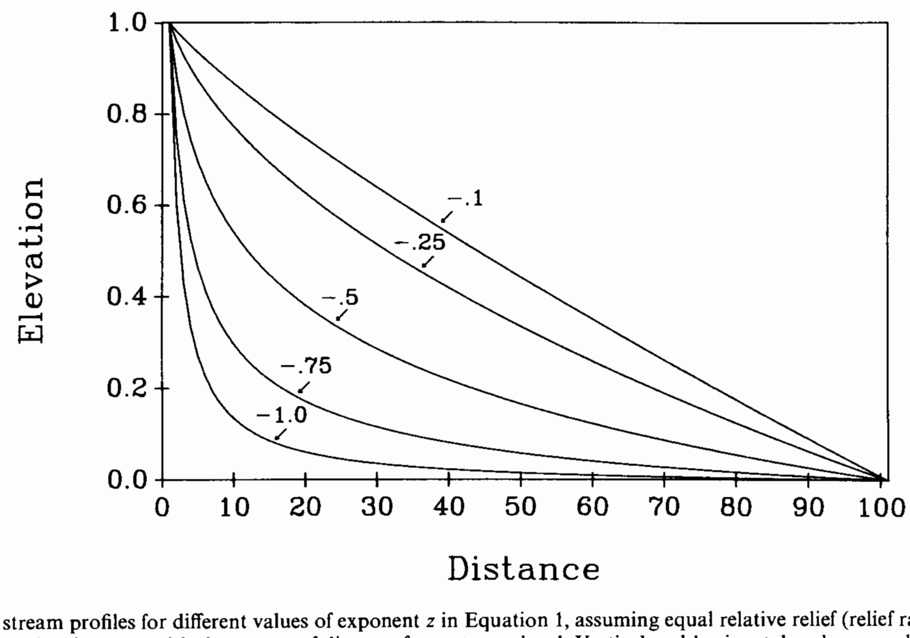

Figure 2. Main stream profiles for different values of exponent z in Equation 1, assuming equal relative relief (relief ratio). Discharge is assumed to increase with the square of distance from stream head. Vertical and horizontal scales are arbitrary

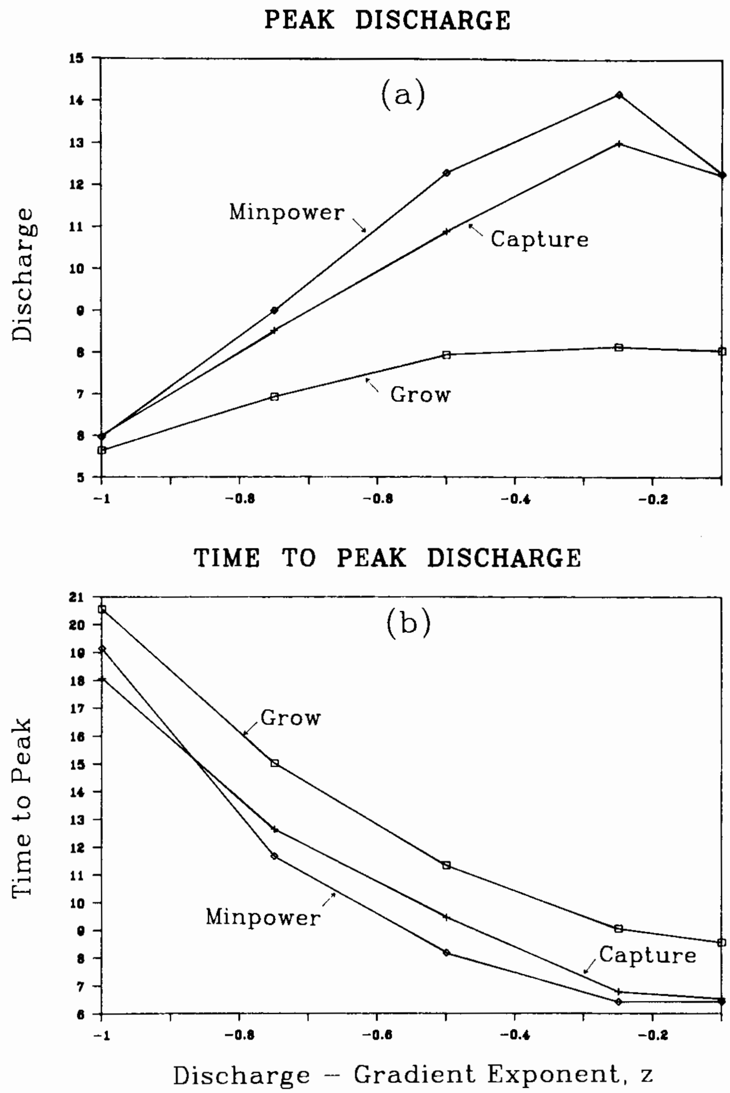

Figure 3. Peak discharge (a) and time to hydrograph peak (b) as functions of stream model type and basin concavity (the exponent z in Equation 1). Each point is the average of several basins scaled to a drainage area of 200. Translation flood routing is assumed governed by Equation 7. Results are stratified by model type: headward growth 'grow'; systematic capture 'capture'; and minimum power optimization 'minpower'. Vertical scales are arbitrary

have partially adjusted their topology and shape to variations in z, exhibit additional effects, in that Q_p tends to be larger and depends more strongly on z, and T_p is smaller than for the unmodified headward growth basins. The basins that are further modified by minimum power adjustment show even stronger effects of z, with peak discharges ranging by more than a factor of two for the range ($-1{\cdot}0 < z < -0{\cdot}1$). The higher Q_p and shorter T_p values for the capture and minimum power networks relative to the headward growth networks results from the shorter stream routes and more compact basin shape for the former.

Thus relief plays at least three roles in determining hydrologic response of drainage basins. The most obvious role is played by average relief or average gradients, in that flow velocities and peak discharges increase with relief or gradient increases. Two other effects are related to the distribution of relief in the drainage basin, which is measured here by the parameter z determining basin concavity. This parameter has both direct and indirect effects. For basins of the same shape and topology, peak discharge increases and time to peak decreases as the basin becomes less concave. However, in natural basins the shape and topology adjust through time to basin concavity, with effects that enhance the role of concavity in determining flood peaks and travel times.

Multivariate estimation of flood response

This section examines the predictive ability of morphometric parameters for flood response, using the simulated basins and the flood routing discussed above. A number of morphometric parameters were defined and measured for the simulated basins, and they were used in multiple regression relationships to predict Q_p and T_p. Four to seven parameters were required to give very good explanatory power for T_p and Q_p ($R^2 \simeq 0{\cdot}9$). Since considerable multicolinearity exists between many of the defined morphometric parameters, several subsets of the parameters give approximately equal explanatory power. Five such subsets are discussed below.

In the calculation of the multiple regression relationships data from all headward growth, capture, and minimum power networks with $L_{tot} \geq 200$ were used, for a total of 702 basins. The minimum, mean, and maximum values of drainage area, A, were 219, 463, and 1408, respectively, and for topological magnitude, M, were 113, 293, and 989. Regressions were conducted stepwise using SPSS. All variables with the exception of the exponent z and measures of kurtosis and skewness were logarithmically transformed. Table I presents the estimated regression exponents and the partial correlation coefficients between the independent variables and the dependent variable.

Form-Based Drainage Basin Parameters. The parameters used in the multiple regression are the exponent, z, the drainage area, A, the relief ratio, R_r, (defined as the ratio of the maximum basin relief to the maximum distance from the basin outlet to its perimeter, L_{max}), a basin shape parameter, S_f, (drainage area divided by $L_{max}{}^2$), a form factor, F, (the total channel length divided by the square of the average flowpath length to the basin outlet), and a flow indirectness parameter, I (average ratio of flowpath length to straight-line distance to the basin outlet for all node points). The drainage area and relief ratio are included to account for scale and relief effects, whereas the remainder are dimensionless parameters describing aspects of planimetric or cross-sectional basin shape. The resulting equations for the translational flow routing are:

$$Q_p = K_q A^{\cdot 71} 10^{0\cdot 28z} F^{\cdot 12} R_r{}^{\cdot 20} S_f{}^{\cdot 34} I^{-\cdot 86}, (R^2 = \cdot 95)$$

and (10)

$$T_p = K_t A^{\cdot 41} 10^{0\cdot 42z} F^{-\cdot 75} R_r{}^{-\cdot 26} S_f{}^{\cdot 32} I^{-\cdot 22}. (R^2 = \cdot 93)$$

The estimated coefficients for the kinematic wave flow routing are generally very close to corresponding translational routing values except for those independent variables with low partial correlation coefficients (Table I), although the constants K_q and K_t and the hydrograph shape are different. In general the estimated exponents for time-to-peak are closer in value for translational and kinematic routing than they are for peak discharge. This pattern pertains also for the other sets of basin parameters discussed below.

The exponents for area in estimating flood peaks resulting from studies of natural and experimental basins generally range from about 0·5 to 0·9, with a modal value of about 0·75, close to the 0·71 value from the present study (e.g. Brush, 1961; Benson, 1962, 1964; Thomas and Benson, 1970; Alexander, 1972; Heerdegen and Reich, 1974; Black and Cronn, 1975; Murphey *et al.*, 1977; Boyd *et al.*, 1979; Troutman *et al.*, 1989). Similarly, observed exponents for the exponent of drainage area in estimating T_p generally range from 0·3 to 0·5, with a most common value close to that resulting from the present study (Nash, 1960; Alexander, 1972; Heerdegen and Reich, 1974; Black and Cronn, 1975; Boyd, 1978; Boyd *et al.*, 1979). Empirical studies generally find peak discharge related to the 0·3 to 0·6 power of channel gradient or relief ratio (Benson, 1962, 1964; Thomas and Benson, 1970; Black, 1972; Patton and Baker, 1976) and time-to-peak related to the −0·3 to −0·4 power of long profile channel gradient (Black, 1972; Inman, 1987). Empirical studies incorporating basin shape factors generally find them to have insignificant explanatory power for peak discharge or time-to-peak (Benson, 1962, 1964), which is consonant with the low partial correlation coefficient of S_f in the

Table I. Estimated parameters for regressions of basin parameters on peak flow and time-to-peak

Dependent variable		Independent variables							R^2
				Form-Based Parameters					
		A^a	10^{bz}	F^c	$R_r{}^d$	$S_f{}^e$	I^f		
Q_{pt}	Val	0·71	0·28	0·12	0·20	0·34	−0·86		0·95
	PCC	0·90	0·74	0·11	0·71	0·29	−0·38		
Q_{pk}	Val	0·62	0·53	0·38		0·13	−0·19		0·97
	PCC	0·91	0·96	0·39		0·14	−0·11		
T_{pt}	Val	0·41	−0·42	−0·75	−0·26	0·32	−0·22		0·93
	PCC	0·67	−0·78	−0·47	−0·69	0·22	−0·08		
T_{pk}	Val	0·41	−0·34	−0·80	−0·23	0·37	−0·41		0·94
	PCC	0·72	−0·75	−0·55	−0·70	0·28	−0·17		
				Flowpath-Length Parameters					
		$Ltot^a$	10^{bz}	$L_{av}{}^c$	$L_{se}{}^d$	$10^{eL_{sk}}$	$10^{fL_{kr}}$		
Q_{pt}	Val	1·08	0·46	−0·95		−0·10	0·14		0·92
	PCC	0·87	0·87	−0·72		−0·27	0·35		
Q_{pk}	Val	1·08	0·52	−0·96	−0·16	−0·03	0·14		0·99
	PCC	0·96	0·98	−0·90	−0·09	−0·14	0·58		
T_{pt}	Val		−0·67	0·97		−0·18			0·88
	PCC		−0·91	0·75		−0·37			
T_{pk}	Val		−0·56	0·96		−0·17			0·88
	PCC		−0·90	0·78		−0·39			
				Area-Slope Ratio Parameters					
		A^a	$\Omega_{av}{}^b$	$\Omega_{se}{}^c$	$10^{d\Omega_{sk}}$	$10^{e\Omega_{kr}}$			
Q_{pt}	Val	0·68	−1·55	−1·30	−0·07	0·07			0·93
	PCC	0·80	−0·88	−0·82	−0·07	0·11			
Q_{pk}	Val	0·63	−1·80	−1·77		0·08			0·94
	PCC	0·81	−0·94	−0·93		0·35			
T_{pt}	Val	0·36	2·30	2·01		0·07			0·90
	PCC	0·48	0·92	0·89		0·22			
T_{pk}	Val	0·41	1·92	1·66		0·05			0·88
	PCC	0·55	0·91	0·87		0·15			
				Horton-Strahler Ratio Parameters					
		$N_1{}^a$	$S_1{}^b$	$A_1{}^c$	$R_b{}^d$	$R_l{}^e$	$R_a{}^f$	$R_s{}^g$	
Q_{pt}	Val	0·59	0·24	0·32	2·35	−0·81	−1·06	−0.75	0·93
	PCC	0·80	0·67	0·32	0·34	−0·52	−0·18	−0.91	
Q_{pk}	Val	0·58		0·45	2·75	−1·02	−1·21	−0·63	0·93
	PCC	0·80		0·43	0·39	−0·62	−0·21	−0·90	
T_{pt}	Val	0·61	−0·29	0·69	−2·93	1·19	1·11	1.02	0·89
	PCC	0·71	−0·61	0·46	−0·31	0·54	0·14	0.90	
T_{pk}	Val	0·60	−0·26	0·72	−2·85	0·99	1·32	0·88	0.87
	PCC	0·72	−0·59	0·49	−0·31	0·49	0·17	0·89	
				Diameter-Width Parameters					
		$D_t{}^a$	10^{bz}	$W_t{}^c$	$R_d{}^d$	$R_r{}^e$			
Q_{pt}	Val	0·19	0·41	1·00		0·20			0·88
	PCC	0·24	0·74	0·84		0·54			
Q_{pk}	Val	0·20	0·63	0·82					0·88
	PCC	0·25	0·92	0·79					
T_{pt}	Val	0·89	−0·52		1·37	−0·26			0·91
	PCC	0·76	−0·81		0·42	−0·65			
T_{pk}	Val	0·90	−0·43		1·44	−0·24			0·91
	PCC	0·81	−0·81		0·50	−0·67			

NOTES: Q_{pt}, peak discharge regression using translational routing; Q_{pk}, regression using kinematic routing, T_{pt}, time-to-peak regression using translational routing; T_{pk}, regression using kinematic routing; R^2, R square for regression; a–g, regression coefficients to be estimated; Val, estimated value of regression coefficients; PCC, Partial correlation coefficient between dependent and independent variable. Blank entries signify relationships not significant at 95 per cent level. See text for definition of independent variables.

regressions. However, Murphey *et al.* (1977) find time-to-peak related to the 0·4 power of S_f. The parameters F, I, and z apparently have not been tested against empirical data.

Flowpath length based parameters. An alternative set of parameters involves the moments of the flowpath length based on measuring the distance from each node point in the network to the basin outlet following the channel. The first four moments of the flowpath distribution are expressed as the average, L_{av}, the standard error, L_{se}, the skewness, L_{sk}, and the kurtosis, L_{kr}. The total stream length, L_{tot}, is also used

$$Q_p = K_q L_{tot}{}^{1\cdot 08} 10^{\cdot 46z} L_{av}{}^{-\cdot 95} 10^{-\cdot 10 L_{sk}} 10^{\cdot 14 L_{kr}}, (R^2 = \cdot 92)$$

and (11)

$$T_p = K_t 10^{-\cdot 67z} L_{av}{}^{\cdot 97} 10^{-\cdot 18 L_{sk}}. (R^2 = \cdot 88)$$

This set of parameters has not been used in empirical studies, although some use has been made of either or both of the maximum and the average flow path length (Snyder, 1938; Thomas and Benson, 1970).

Area-Slope Ratio Parameters. Many studies of hillslope and small catchment hydrology utilize a parameter based upon the logarithm of the ratio of the drainage area contributing to a slope segment to the local gradient, $\Omega = Ln(A/S)$ (Beven and Kirkby, 1979; Beven and Wood, 1983; Beven, 1986). Although this parameter has been developed for hillslope processes, its utility for flood prediction in channel networks is investigated here with the interpretation that A refers to the upstream drainage area and S the channel gradient. The distribution is summarized by the first four statistical moments, as above. The relationships that emerge are

$$Q_p = K_q A^{\cdot 68} \Omega_{av}{}^{-1\cdot 55} \Omega_{se}{}^{-1\cdot 30} 10^{-\cdot 07 \Omega_{sk}} 10^{\cdot 07 \Omega_{kr}}, (R^2 = \cdot 93)$$

and (12)

$$T_p = K_t A^{\cdot 36} \Omega_{av}{}^{2\cdot 30} \Omega_{se}{}^{2\cdot 01} 10^{\cdot 07 \Omega_{kr}}. (R^2 = \cdot 90)$$

Note that the gradient exponent, z, is not needed with these parameters. This approach is similar to Harlin's (1984) use of moments of the hypsometric integral in estimation of flood response but is not directly comparable to that study.

Horton-Strahler ratio parameters. Rodriguez-Iturbe and Valdes (1979) investigated the use of the Horton-Strahler order ratios of number (the bifurcation ratio, R_b) length, R_l, area, R_a, and slope R_s as predictors of hydrologic response. In this study these ratios were estimated by least-squares regression of the logarithms of these quantities versus order, although other estimating methods have also been used (Smart, 1978). The resulting equations are:

$$Q_p = K_q N_1{}^{\cdot 59} S_1{}^{\cdot 24} A_1{}^{\cdot 32} R_b{}^{2\cdot 35} R_l{}^{-\cdot 81} R_a{}^{-1\cdot 06} R_s{}^{-\cdot 75}, (R^2 = \cdot 93)$$

and (13)

$$T_p = K_t N_1{}^{\cdot 61} S_1{}^{-\cdot 29} A_1{}^{\cdot 69} R_b{}^{-2\cdot 93} R_l{}^{1\cdot 19} R_a{}^{1\cdot 11} R_s{}^{1\cdot 02}, (R^2 = \cdot 89)$$

where N_1 is the number of first order streams, and A_1 and S_1 are the average values of first-order stream length and gradient, respectively. The estimated exponents for R_b, R_l, and R_a are considerably different from the theoretical values suggested by Rodriguez-Iturbe and Valdes (1979) [0·0, −1·57, and 0·0 for Q_p; 0·55, 1·62 and −0·55 for T_p]. However, these three ratios collectively account for only 5 per cent of the explained variance in the estimating equations. Furthermore, these ratios are strongly correlated in the simulated networks (pairwise correlations as follows: R_b vs $R_l = 0{\cdot}79$; R_b vs $R_a = 0{\cdot}98$; R_l vs $R_a = 0{\cdot}77$), so that estimated regression coefficients are unstable. This suggests that R_b, R_l, and R_a are not efficient estimators of hydrologic response.

Diameter-width parameters. Kirkby (1976), Karlinger and Troutman (1985), and Troutman and Karlinger (1985) propose the topological diameter D_t and width W_t as indices of basin response. In the following regression D_t has been normalized through multiplication by the average link length in the basin, and a diameter ratio, R_d, is defined as the ratio of the average flow path length to the topological diameter (maximum flow path length), both measured in number of links:

$$Q_p = K_q D_t^{\cdot 19} 10^{\cdot 41z} W_t^{1\cdot 0} R_r^{\cdot 20}, (R^2 = \cdot 88)$$

and (14)

$$T_p = K_t D_t^{\cdot 89} 10^{-\cdot 52z} R_d^{1\cdot 37} R_r^{-\cdot 26}, (R^2 = \cdot 91)$$

Again, this set of parameters has not been utilized in empirical studies.

DISCUSSION

It is clear from the regression study that there is more than one way to skin the hydrologic cat. Although the form of drainage basins is infinitely variable in detail, four to seven carefully chosen parameters are sufficient to characterize the effects of morphometry and relief on hydrologic response. Five sets of parameters have yielded roughly equal predictive power. In general terms in the equations related to basin size (A, L_{tot}, D_t, W_t, and $N_1 A_1$) and average channel gradients (R_r, Ω_{av}, and S_1) provide the greatest portion of the predictive power in the estimating equations, followed closely by terms related to basin concavity (z, R_s, and Ω_{se}). However, terms related to more subtle aspects of basin planimetric and cross-sectional shape (F, S_f, I, R_b, R_a, R_l, R_d, and higher moments of L and Ω) are less important; their effects are detectable only in large samples and might reasonably be omitted in practical applications; this also accounts for the usual lack of significance of such parameters in empirical studies.

Because of the large range of form variation in basin form in the present study, the estimated regression coefficients should be generally applicable. Note that the utility of Equations 10–14 does not depend upon the process assumptions of the headward growth, capture, or minimum work models; it is sufficient that the resulting networks have realistic spatial attributes and that they cover the range of variation of morphometric parameters found in natural networks.

However, the present study is limited in several respects:

1. The flow routing does not include possible effects of variations in drainage density. These are primarily associated with differences in hillslope length and slope hydrologic characteristics, and they should therefore be most important in smaller networks in which hillslope travel times equal or exceed channel travel times. Likewise not included are effects of random or systematic variations in rainfall or in slope hydrologic characteristics.
2. At least two parameters are necessary to characterize relief (Equation 1). However, natural networks can exhibit more complicated patterns of gradient, particularly if bedrock reaches occur. More parameters might be required for such situations. Also, some of the sets of relief measures used in the regressions may be more efficient than others in such cases.
3. Linear translational and kinematic flow routing was used in this study. In application to natural networks, more complete routing techniques using diffusion models and more representative input hydrographs would be appropriate.
4. Velocity is not necessarily related to discharge as suggested by Equation 7. More complicated relationships are suggested by Beven (1979), Beven *et al.* (1979) and Agnese *et al.* (1988).

Although this study indicates that several sets of morphometric parameters are useful in estimating flood response, approximately as much effort must be expended in their measurement as is required to apply basin-specific flow routing using an approach similar to that of Surkan (1969) with the enhancement of accounting for spatially variable flow velocities (e.g. using Equation 7). Beven (1986, p. 115) made a similar point: 'Since the form of the drainage network is one of the easiest pieces of information to obtain about a catchment there appears to be no reason why it should not be used directly in a routing procedure'. Nonetheless, theoretical and empirical studies of the effects of basin topology and morphometry upon flood response remain useful for identifying important effects and determining the expected degree of variability among natural networks.

This study indicates that the longitudinal profile of drainage basins plays a greater role in controlling flood hydrology than has been acknowledged in most previous empirical and theoretical studies. Although overall channel gradient or relief ratio have been included in many studies, with few exceptions (Kershen and Bras, 1983; Agnese *et al.*, 1988; Garbrecht and Shen, 1988) basin concavity and its effects on downstream changes of flow velocity have been neglected. The usual assumption of spatially invariant flow velocity, based upon very limited field study using tracers (Pilgrim, 1977; Boyd *et al.*, 1979) and low exponents of velocity in downstream hydraulic geometry relationships (Leopold and Maddock, 1953; Knighton, 1984, 1987), should be reexamined. A useful approach would be to select basins with a range of concavities (values of z) for a comparative study of flow velocities using tracers or of downstream propagation of flood waves.

A final conclusion is that relief and planimetric aspects of drainage basins are interrelated in the sense that basin shape and the angular pattern of stream courses have adjusted through time to the concavity of the stream channel profiles (the z parameter) (Howard, in press). This adjustment is such that the flood peak magnitude and time-to-peak are stronger functions of basin concavity than would otherwise be the case.

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