CHAPTER 5 DRAINAGE BASINS
From Ritter et al., 1995

Introduction

Two basic generalizations about rivers were realized long before geomorphology emerged as an organized science: (1) streams form the valleys in which they flow, and (2) every river consists of a major trunk segment fed by a number of mutually adjusted branches that diminish in size away from the main stem. The many tributaries define a network of channels that drain water from a discernible, finite area which is the **drainage basin,** or **watershed,** of the trunk river.

The drainage basin is the fundamental landscape unit concerned with the collection and distribution of water and sediment. Each basin is separated from its neighbor by a **divide,** or **interfluve.** Thus, the basin can be viewed as a geomorphic system or unit. As we will soon see, the basin is inexorably linked with hillslope processes that contribute water and sediment to the channel network in accord with the regional climate, underlying bedrock and tectonic regime, and land use by humans (fig. 5.1). Any feature or portion of the basin can be considered a subsystem having its own unique set of processes, geology, and energy gains and losses. Furthermore, because it is possible to measure the amount of water entering the basin as precipitation and the volume leaving the basin as stream discharge, hydrologic events can be readily analyzed on a basinal scale. Likewise, much of the sediment produced within the basin is ultimately exported from the basin through the trunk river. Thus, considered on a long temporal scale, the rate of lowering of the basin surface can be estimated.

The output from a given basin compartment serves as input to the master channel and influences downstream channel characteristics and hydrologic processes in rivers. The mechanics of fluvial processes usually reflect some balance between the amount of sediment supplied for transport and the water available to accomplish this task. Throughout the discussion of drainage basins and fluvial systems, we will frequently refer to the concepts illustrated in figure 5.1 as we describe the interrelationships between various components of the fluvial system and the regulatory influence of the external variables of water and sediment in the adjustment and evolution of basins and channels.

Most Earth scientists are introduced to watersheds when they learn that drainage patterns or individual stream patterns commonly mirror certain traits of the underlying geology, described in figure 5.2 and table 5.1. Because the gross character of these patterns is evident on topographic maps and aerial photos, the patterns are useful for structural interpretation (Howard 1967) and for approximating lithology in a study of regional geology.

In a hydrologic sense, however, prior to World War II most basins were described in qualitative terms such as well-drained or poorly-drained, or they were connoted descriptively in the Davisian scheme as youthful, mature, or old. The mechanics of how river channels or networks actually form and how water gets into a channel was poorly understood by geologists and

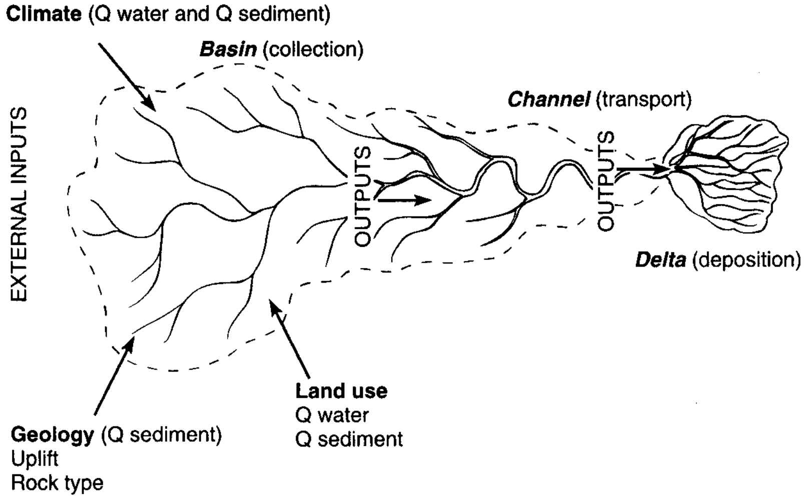
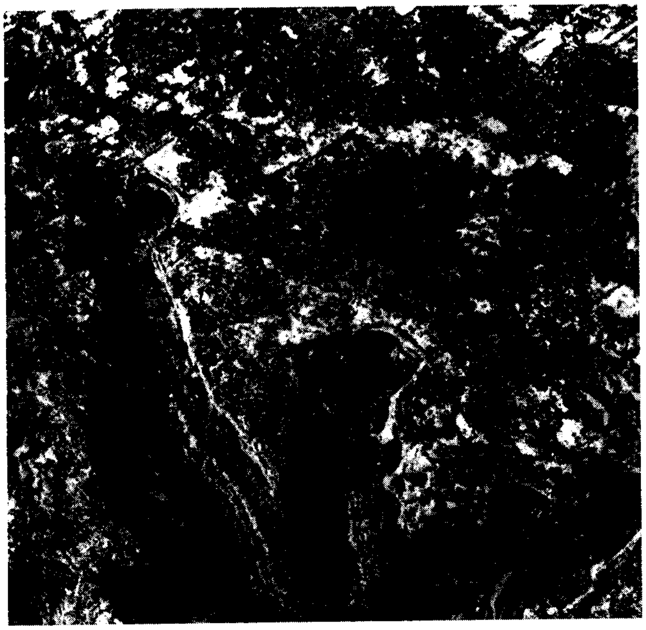


FIGURE 5.1
Schematic surface components of the fluvial system. The tributaries provide links between lithology and climate and are adjusted to both. Channel characteristics vary in response to the external variables of sediment and water discharge (Q), which are influenced naturally from climate, tectonic, and lithologic factors. Human influence also modifies these variables through land use alterations.

(A)

(B)



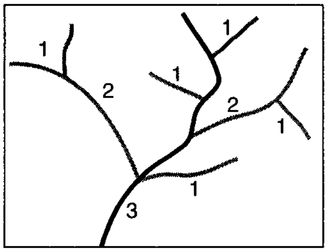
(C)

FIGURE 5.16

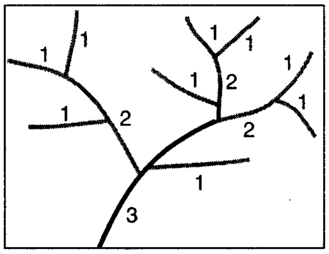
Earth examples where groundwater seepage and sapping processes have played a major formative role in valley development. (A) Northeast Kohala coast of Hawaii. The large, amphitheater-headed valleys have major springs at their head, fed from high-level aquifers (see Kochel and Piper 1986). The small, less-incised valleys in between are fed only by runoff. (B) Tributaries up-dip from the Colorado River have been significantly enlarged by groundwater-sapping processes in the permeable Navajo Sandstone. Note the lack of tributaries down-dip (to the bottom left). Runoff-dominated drainage systems typically show less influence on structural control. (C) Headward end of tributaries in the Navajo Sandstone of the Colorado Plateau in northern Arizona. Note the extension of valley heads along major joints where groundwater flow is enhanced. Compare to the right-angle junctions of valley heads on Mars in figure 5.15B.

Basin Morphometry

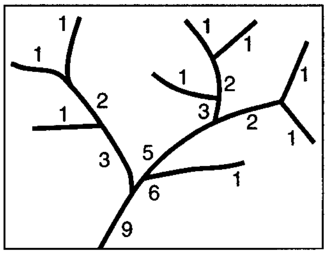
The drainage basin, the fundamental unit of the fluvial landscape, has been the focus of research aimed at understanding the geometric characteristics of the master channel and its tributary network. This geometry is referred to as the **basin morphometry** and is nicely reviewed by Abrahams (1984). Increasingly, studies have used the patterns of basin morphometry to predict or describe geomorphic processes; for example, it has been used to predict flood peaks, to assess sediment yield, and to estimate erosion rates (for example, Baumgardner 1987; Gardiner 1990). Some researchers believe that basin morphometric studies may ultimately be extended to show the influence of basin characteristics on channel cross-sections and channel attributes.



Horton (1945)



Strahler (1952)



Shreve (1967)

FIGURE 5.17
Methods of ordering streams within a drainage basin.

One of Horton's greatest contributions was to demonstrate that stream networks have a distinct fabric, called the *drainage composition,* in which the relationship between streams of different magnitude can be expressed in mathematical terms. Each stream within a basin is assigned to a particular order indicating its relative importance in the network, the lowest order streams being the most minor tributaries and the highest order, the main trunk river.

Figure 5.17 shows several methods of ordering steams. Horton's cumbersome method was refined by Strahler (1952a) so that stream segments rather than entire streams become the ordered units. In Strahler's system, a segment with no tributaries is designated as a first-order stream. Where two first-order segments join they form a second-order segment; two second-order segments join to form a third-order segment, and so forth. Any segment may be joined by a channel of lower order without causing an increase in its order. Only where two segments of equal magnitude join is an increase in order required. The Strahler method created an apparent omission in accounting of low-order tributaries that was later accommodated in another network ordering scheme proposed by Shreve (1966a, 1967). The Shreve Magnitude, as it is called, considers streams as links within the network, with the magnitude of each link representing the sum of the link numbers of all the tributaries that feed it; that is, networks in which the downstream segments are of the same magnitude have equal numbers of links within the basins. Shreve's designations thereby express the number of first-order streams upstream from a given point. Geomorphologists investigating relationships between rainfall and runoff find the Shreve Magnitude system useful. Because the first-order streams serve as the primary collectors of rainfall within a basin, they are better flood flow predictors than the Strahler ordering system (Patton and Baker 1976). Shreve's system appears in many of the sophisticated runoff modeling packages which are beyond the scope of this discussion (for example, see Smart and Wallis 1971; Abrahams 1980; Abrahams and Miller 1982).

Every basin possesses a quantifiable set of geometric properties that define the linear, areal, and relief characteristics of the watershed (table 5.2), known as the basin morphometry. These variables correlate with stream order, and various combinations of the parameters obey statistical relationships that hold for a large number of basins. Two general types of numbers have been used to describe basin morphometry or network characteristics (Strahler 1957, 1964, 1968). *Linear scale* measurements allow size comparisons of topographic units. The parameters may include the length of streams of any order, the relief, the length of basin perimeter, and other measurements. The second type of measurement consists of *dimensionless numbers,* often derived as ratios of length parameters, that permit comparisons of basins or networks. Length ratios, bifurcation ratios, and relief ratios are common examples. Table 5.2 shows the most commonly used linear, areal, and relief equations, but numerous others have been derived from these.

Linear Morphometric Relationships The establishment of stream ordering led Horton to realize that certain linear parameters of the basin are proportionately related to the stream order and that these could be expressed as basic relationships of the drainage

TABLE 5.2 Common morphometric relationships.

Linear Morphometry	
Stream number in each order (N_o)	$No = R_b{}^{s-o}$
Total stream numbers in basin (N)	$N = \dfrac{R_b{}^s - 1}{R_b - 1}$
Average stream length	$\bar{L}_0 = \bar{L}_1 R_L{}^{o-1}$
Total stream length	$L_o = \bar{L}_1 R_b{}^{s-1} \left(\dfrac{u^s - 1}{u - 1}\right)$ where $u = R_L/R_B$
Bifurcation ratio	$R_b = N_o/N_{o+1}$
Length ratio	$R_L = \bar{L}_o/\bar{L}_{o+1}$
Length of overland flow	$\ell_o = \dfrac{1}{2D}$
Areal Morphometry	
Stream areas in each order	$\bar{A}_o = \bar{A}_1 R_a{}^{o-1}$
Length-area	$L = 1.4A^{0.6}$
Basin shape	$R_F = \dfrac{A_o}{L_b{}^2}$
Drainage density	$D = \dfrac{\Sigma L}{A}$
Stream frequency	$F_s = \dfrac{N}{A}$
Constant of channel maintenance	$C = \dfrac{1}{D}$
Relief Morphometry	
Relief ratio	$R_h = H/L_o$
Relative relief	$R_{hp} = H/p$
Relative basin height	$y = h/H$
Relative basin area	$x = a/A$
Ruggedness number (Melton 1957)	$R = DH$

Adapted from Strahler 1958.
s = order of master stream, o = any given stream order, H = basin relief, P = basin perimeter.

composition. Much of linear morphometry is a function of the *bifurcation ratio* (R_b), which is defined as the ratio of the number of streams of a given order to the number in the next higher order (using Strahler ordering). The bifurcation ratio allows rapid estimates of the number of streams of any given order and the total number of streams within the basin. Although the ratio value will not be constant between each set of adjacent orders, its variation from order to order will be small, and a mean value can be used. Also, as Horton pointed out, the number of streams in the second highest order is a good approximation of R_b. When geology is reasonably homogeneous throughout a basin, R_b values usually range from 3.0 to 5.0.

The *length ratio* (R_L), similar in context to the bifurcation ratio, is the ratio of the average length of streams of a given order to those of the next higher order. The length ratio can be used to determine the average length of streams in an unmeasured given order (L_o) and their total length. The combined length of all streams in a given basin is simply the sum of the lengths in each order. For most basin networks, stream lengths of different orders plot as a straight line on semilogarithmic paper (fig. 5.18), as do stream numbers. The re-

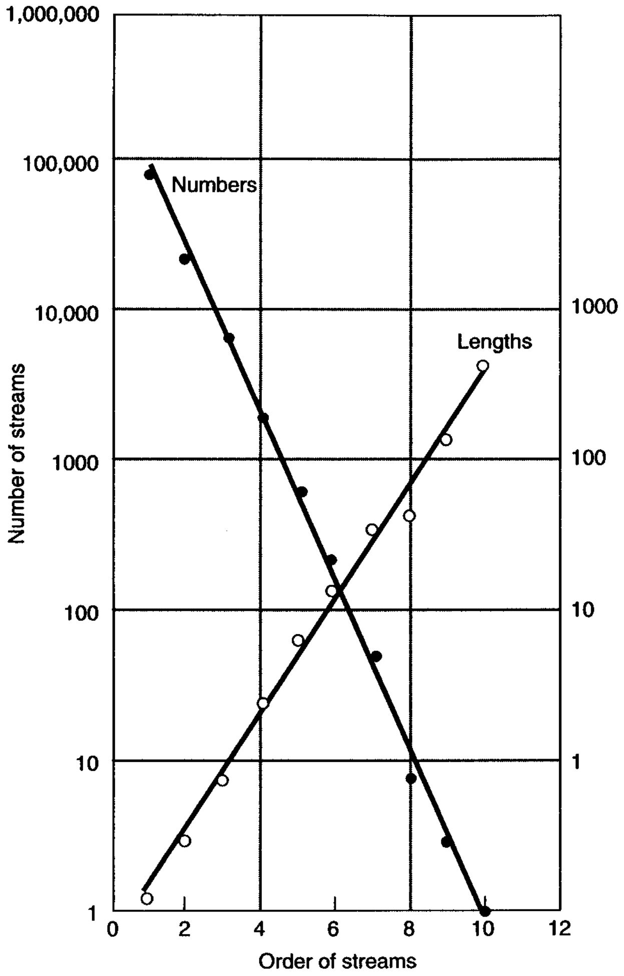


FIGURE 5.18

Relation of stream order to the number and mean lengths of streams in the Susquehanna River basin.

(After Brush 1961)

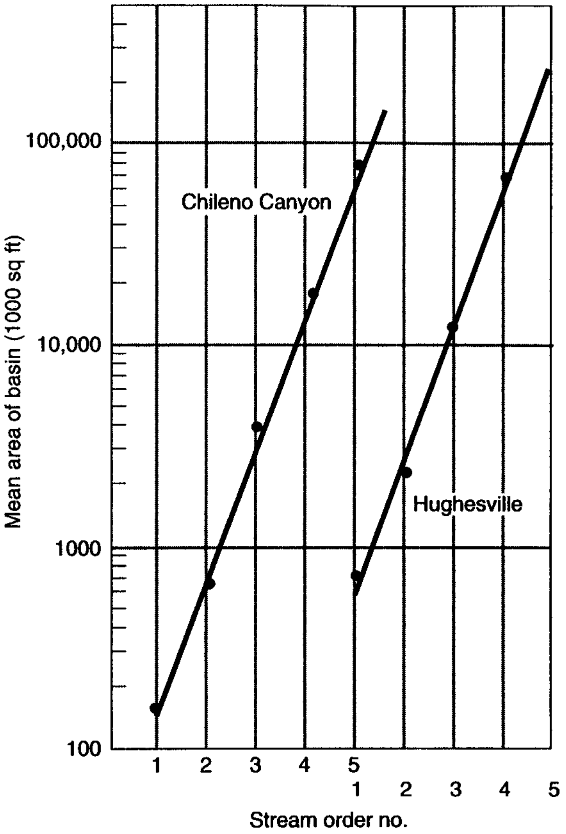


FIGURE 5.19

Relationship between stream order and mean basin area in two drainage basins.

(After Schumm 1956)

lationships between stream order and the number and length of segments in that order have been repeatedly verified and are now firmly established (Schumm 1956; Chorley 1957; Morisawa 1962; and many others).

Areal Morphometric Relationships The equity among linear elements within a drainage system suggests that areal components should also possess a consistent morphometry, because dimensional area is simply the product of linear factors. The fundamental unit of areal elements is the area contained within the basin of any given order (A_o). It encompasses all the area that provides runoff to streams of the given order, including all the areas of tributary basins of a lower order as well as interfluve regions. Schumm (1956) demonstrated (fig. 5.19) that basin areas, like stream numbers and lengths, are related to stream order in a geometric series.

Although area by itself is an important independent variable (Murphy et al. 1977), it has also been employed to manifest a variety of other parameters (see table 5.2), each of which has a particular significance in basin geomorphology, especially in regard to the collection of rainfall and concentration of runoff. Numerous studies have been successful in formulating relationships between basin area and discharge. One of the more important areal factors is *drainage density* (*D*), which is essentially the average length of streams per unit area and as such reflects the spacing of the drainageways. Drainage density reflects the interaction between geology and climate. As these two

TABLE 5.3 Summary of sample morphometric data for drainage basins in various regions.

Parameters[a]	Central Texas	Utah Wasatch	South California	Indiana	West Pennsylvania	Virginia	West Texas
	(19)[b]	(11)	(12)	(10)	(12)	(1)	(25)
A (km^2)	12.4	29.7	2.3	156.8	122	34.1	32.8
L (km)	9.2	9.8	2.0	26.8	26.8	8.3	9.1
W (km)						4.7	3.5
R (km)	.11	1.24	.44	.05	.28	.50	.71
S	4.5	4.5	4.6	5.9	5.4	4.0	5.0
D (km/km^2)	4.05	5.58	13.7	3.83	2.31	2.3	4.9
M						80	253
R	.55	6.25	5.78	.25	0.59	1.1	3.5
F_s (per km^2)	28.7	12.4	133.3	11.0	8.4	13.8	44.2
R_b						4.4	4.5
K						1.6	2.0
Geology	Carbonate	Mixed sedimentary	Mixed metamorphic and igneous	Sandstone and shale	Sandstone and shale	Metamorphic	Carbonate

(Patton and Baker 1976)

[a] S = average Strahler order, K = shape based on lemniscate, M = Shreve magnitude.

[b] Number of basins.

factors vary from region to region, large variations in D can be expected (table 5.3). In general, resistant surface materials and those with high infiltration capacities exhibit widely spaced streams, consequently yielding low D. As resistance or surface permeability decreases, runoff is usually accentuated by the development of a greater number of more closely spaced channels, and thus D tends to be higher. As a rule of thumb, where geology and slope angles are the same, humid regions develop thick vegetal cover that increases resistance and infiltration, thereby perpetuating drainage density lower than would otherwise be expected in more arid basins. Thus, drainage density not only reflects the geologic framework, but it may serve as a useful parameter in climatic geomorphology (Daniel 1981). Methods for rapid estimation of drainage density have been devised (McCoy 1971; Mark 1974; Richards 1979; Bauer 1980).

Drainage density has also been used as an independent variable in the framing of other morphometric parameters. For example, the *constant of channel maintenance* and the length of overland flow (see table 5.2) both utilize a reciprocal relationship with density to demonstrate the link between factors that control surface erosion and those that describe the drainage net (Schumm 1956). The constant of channel maintenance indicates the minimum area required for the development and maintenance of a channel; that is, the ratio represents the amount of basin area needed to maintain one linear unit of channel length. As Schumm points out (1956, p. 607) this relationship requires that drainage networks develop in an orderly way because the meter-by-meter growth of a drainage system is possible only if sufficient area is available to maintain the expanding channels.

Relief Morphometric Relationships A third group of parameters shown in table 5.2 indicates the vertical dimension of a drainage basin; it includes factors of gradient and elevation. Like stream numbers, length, and area, the average slope of stream segments in any order approximates a geometric series in which the first term is the mean slope of the first-order streams. This relationship is reasonably valid as long as the geologic framework is homogeneous. Channel slopes and surface slopes are closely akin to the parameters for length. Horton suggested, for example, that the length of overland flow as a function of only the drainage density is at best an approximation because overland flow also depends on slope parameters.

As relief refers to elevation differences between two points, slopes that connect the points are the integral factors affecting the flow of runoff. The most useful relief parameters are the *maximum basin relief* (highest elevation on the basin divide minus the elevation of the mouth of the trunk river) and the *divide-averaged relief* (the average divide elevation minus the mouth elevation). The *relief ratio* (Schumm 1956), the maximum

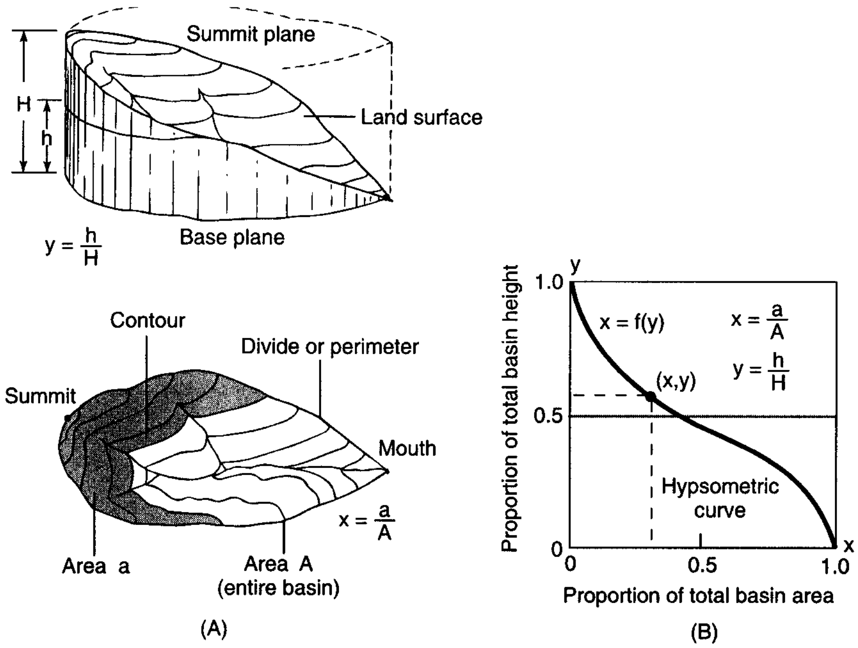


FIGURE 5.20

Ingredients of a hyposometric analysis. (A) Diagram showing how dimensionless parameters used in analysis are derived. (B) Plot of the parameters to produce the hyposometric curve.
(Strahler 1952b)

basin relief divided by the longest horizontal distance of the basin measured parallel to the major stream, indicates the overall steepness of the basin.

A different relief relationship is found by *hypsometric analysis* (Strahler 1952b), which relates elevation and basin area. As figure 5.20A shows, the basin is assumed to have vertical sides rising from a horizontal plane passing through the basin mouth and under the entire basin. Essentially, a hypsometric analysis reveals how much of the basin occurs within cross-sectional segments bounded by specified elevations. The relative height (y) is the ratio of the height (h) of a given contour above the horizontal datum plane to the total relief (H). The relative area (x) equals the ratio a/A, where a is the area of the basin above the given contour and A is the total basin area. The hypsometric curve (fig. 5.20B) represents the plot of the relationship between y and x and simply indicates the distribution of mass above the datum. The form of the curve is produced by the *hypsometric integral (HI)*, which expresses, as a percentage, the volume of the original basin that remains. In natural basins most *HI* values range from 20 to 80 percent, higher values indicating that large areas of the original basin have not been altered into slopes. Although computing the hypsometric integral can be tedious, methods have been introduced which streamline the procedure (Chorley and Morley 1959; Haan and Johnson 1966; Pike and Wilson 1971). Some researchers have found it to be an effective means of describing successive phases of landscape evolution (for example, Miller et al. 1990).

Basin Morphometry and the Flood Hydrograph

The application of geomorphic principles to environmental hazards, such as flood potential, has led to a significant amount of research attempting to identify relationships between basin morphometry and stream flooding (see review in Patton 1988). Clearly, the shape and character of a stream flood hydrograph should be affected greatly by the manner in which a basin collects

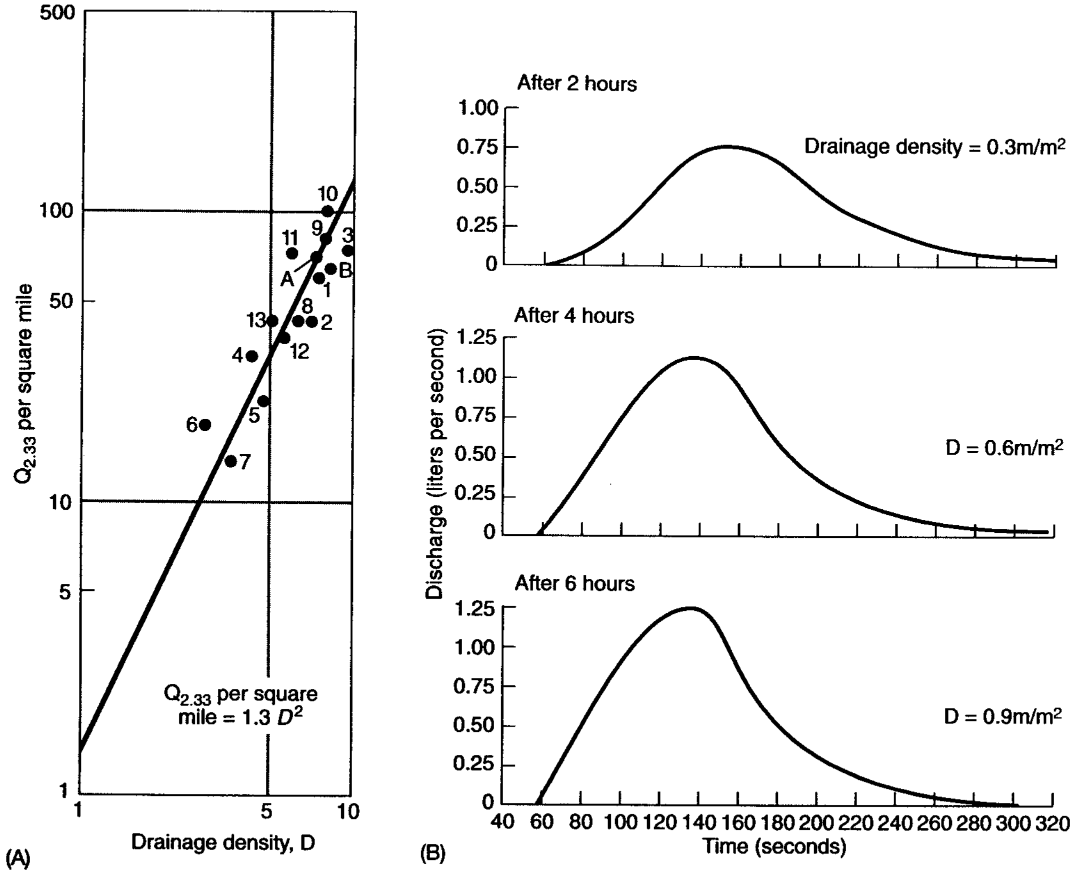


FIGURE 5.21

(A) Discharge (mean annual flood, $Q_{2.33}$) controlled by drainage density in 13 basins. (B) Effect of increasing drainage density on flood hydrograph in an experimental drainage system.

(A): (Carlston 1963), (B): (Zimpfer 1982)

and routes water through its network. Stream hydrology, as defined by the flood hydrograph and by time elements such as flood frequency and lag, is significantly related to many components of basin and network morphometry. The interdependence of morphometry and hydrology is statistically real but does not necessarily indicate a cause and effect relationship; given two apparently related factors, one factor is not necessarily the cause of changes in the other. The high correlation probably exists because both factors vary in a consistent way with the same underlying climatic and geologic controls. In general, area and relief factors are closely related to flow magnitude, and length elements to the timing of hydrologic events. All morphometric types, however, are themselves so complexly woven together that no single factor can be isolated as a completely independent variable (Murphey et al. 1977).

Because basin area and peak discharge are highly correlative, we could expect that many other areal parameters will be similarly related to discharge. Every factor involving area differs in its success as a predictor of discharge, but one parameter, drainage density, seems to have considerable value as a gage of peak flow. In a study of 15 small basins in the southern and central Appalachians and the Interior Lowland Plateau region, Carlston (1963) demonstrated a very close relationship between drainage density and mean annual flood (fig. 5.21A). Notably, the basins in his sample have wide variations in relief, valley-side and channel slopes, and precipitation characteristics; yet none of these factors disrupts the flood magnitude–drainage density relationship. Similar relationships have been observed in experimental studies (fig. 5.21B). Carlston suggests that the general capacity of a terrain to infiltrate precipitated water and transmit it through the underground system is the prime controlling factor of the density–mean annual flood relationship in basins up to 260 km^2 in area. In larger basins, channel transit time plays the dominant role in the flow character. The rate of base flow, found to be inversely related to

TABLE 5.4 Regression formulas for predicting flood magnitudes from drainage basin morphometry in diverse hydrogeomorphic regions.

Region	Equation	R^2	Probability
Central Texas	$Q_{max} = 17{,}369M^{0.43}(R)^{0.54}F^{-0.96}$	0.85	0.001
	$Q_{max} = 36{,}650M^{0.64}(R_h)^{0.54}(D)^{-1.68}$	0.74	0.01
Southern California	$Q_{max} = 155M^{1.04}(R)^{-0.83}F^{-0.73}$	0.85	0.001
	$Q_{max} = 380M^{0.89}(D)^{-1.87}$	0.86	0.0001
North-Central Utah	$Q_{max} = 23M^{0.90}(R)^{1.19}F^{-1.58}$	0.72	0.005
	$Q_{max} = 38{,}618M^{2.20}(R_h)^{2.51}F_1{}^{-3.73}$	0.83	0.005
Indiana	$Q_{max} = 424M^{0.46}(R)^{0.73}F^{0.21}$	0.67	0.01
	$Q_{max} = 424M^{0.82}(R_h)^{0.67}(D)^{0.56}$	0.66	0.05
Appalachian Plateau	$Q_{max} = 100M^{0.79}(R)^{0.19}F^{-0.29}$	0.92	0.0001
	$Q_{max} = 38M^{0.89}(D)^{-0.50}$	0.91	0.0001

Source: Patton and Baker 1976.

M = basin magnitude, R = ruggedness number, F_1 = first-order channel frequency; D = drainage density, R_h = relief ratio, Q_{max} = maximum peak discharge.

drainage density, is also dependent on terrain transmissibility. Thus, as Horton suspected earlier, high transmissibility (as evidenced by infiltration capacity) spawns low drainage density, high base flow, and a resultant low-magnitude peak flood. In contrast, an impermeable surface will generate high drainage density and efficiently carry away the abundant runoff; base flow will be low and peak discharge high.

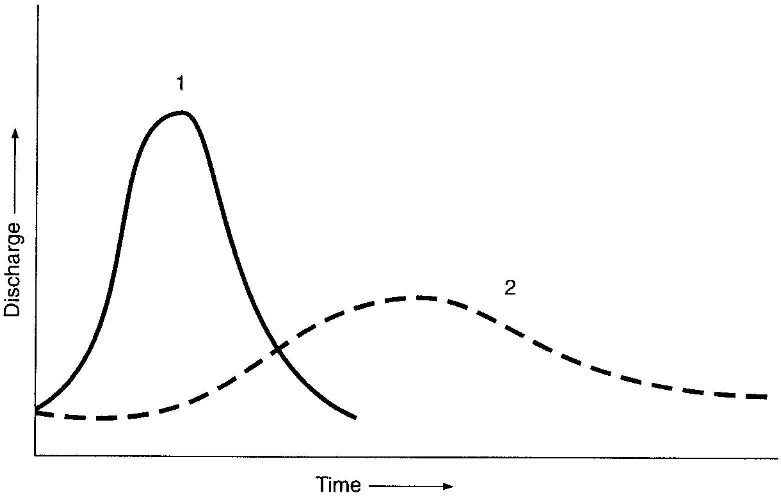
Patton and Baker (1976) demonstrated predictive relationships between several morphometric parameters and peak flood discharges for streams in several physiographic regions of the United States (tables 5.3, 5.4). They found that areal morphometric parameters such as drainage density and stream frequency accounted for much of a model's ability to predict peak discharge, along with the relief measure known as *ruggedness number* (*R*) which is the product of relief and drainage density. These data were used to develop an index of flash flood potential (Beard 1975). Patton and Baker found that basins with high flash flood potential had greater ruggedness numbers than low-potential watersheds. Dingman (1978), however, warned that the relationship between drainage density and flow can be overridden by other effects in the basin such as floodplain or channel storage. In addition, where saturated overland flow is the major source of runoff, drainage density may not be related to the efficiency at which a basin is drained. Costa (1987) investigated the morphometry of basins associated with the largest historic floods in the United States. Although these flash flood basins did not uniformly possess the basin attributes expected from studies like that of Patton and Baker (1976), Costa was able to find some commonalties. Basins with flashy or peaked flood hydrographs generally contained significant area of exposed bedrock, occurred in semiarid to arid climates, were short, and had high relief.

In recent years a large amount of research has focused on the development of more sophisticated models of runoff that are linked closely with geomorphic attributes of the basin and their impact on the production of floods. One of the predominant models is the **geomorphic unit hydrograph** (Rodriquez-Iturbe and Valdez 1979). The success of modeling efforts have been mixed (Patton 1988), partly because of our incomplete understanding of the complex interrelationships between rainfall-runoff events and the contributing basin networks. Further work using small, instrumented watersheds, as well as numerical analytical approaches that explore relationships between the geomorphic unit hydrograph and basin parameters (Chutha and Doodge 1990), will refine our understanding and perhaps lead to more reliable models for predicting floods using basin parameters.

Abrahams (1984) aptly summed up the difficulties in elucidating quantitative relationships in basin networks by noting that the apparent randomness arises largely from independent variation of a large number of factors such as lithology and microclimate. The possible interrelationships between hydrology and morphometry are seemingly infinite, and the parameters are so complexly related that equations will not explain all the variability. Still, the hydrogeomorphic approach has some validity and should not be abandoned in future research. The hydrogeomorphic approach is especially applicable in determining regional flood hazards (Baker 1976). Figure 5.22 is a schematic model showing the expected influence of variations in

FIGURE 5.22

Idealized flood hydrograph and generalized responses to drainage basin characteristics. The effect of an individual characteristic is shown assuming the other characteristics are held constant.



Characteristic	Flashy (hydrograph 1)	Sluggish (hydrograph 2)
Basin area	Small	Large
Drainage density	High	Low
Basin magnitude	High	Low
Relief	High	Low
Ruggedness number	High	Low
Basin shape	Equidimensional	Elongate
Soils	Thin	Thick
Vegetation	Dense	Sparse
Storm track	Down the basin	Up the basin

basin morphometry on the flood hydrograph based on generalizations from a large number of studies. In each case, the influence of a specified morphometric variable is displayed assuming that all other morphometric, geologic, and climatic variables remain constant. Although the relationships summarized here are somewhat qualitative until more conclusive research is completed, they offer a general guide for planners making an initial assessment of expected flood character in ungaged basins.

Basin Evolution

Although morphometric values differ from basin to basin, each network still obeys the statistical relationships discussed above. Many authors have suggested that morphometry reflects an adjustment of geomorphic variables that is established under the constraints of the prevailing climate and geology (for example, Chorley 1962; Leopold and Langbein 1962; Strahler 1964; Doornkamp and King 1971; Woldenberg 1969). Essentially, once a network is established, the basinal characteristics can be defined by the same quantitative terms at any time during the drainage growth. As the basins and networks evolve, an equilibrium is eventually produced by the interplay of climate and geology and maintained as a time-independent phenomenon. Once the components within a basin become balanced, any changes in climate or geology will be compensated for by adjustments of the basin parameters in such a way that the relationships of drainage composition will be preserved. As originally conceived, however, these relationships issued from well-developed stream systems, and the measurements needed to derive the equations were made on topographic maps of these basins. Such an approach provides no insight as to how quickly morphometric balance is attained or what changes in its character occur as the basin ages. It seems appropriate, therefore, to consider the influence of time on the morphometry of a basin.

Some studies have touched on the question of how rapidly morphometry is established and what changes occur in its nature as the basin evolves. These studies found that a quantitatively balanced drainage net forms rapidly in erodible material. This was clearly demonstrated by Schumm (1956) in the Perth Amboy, N.J., badlands, by Morisawa (1964) on the uplifted floor of Hebgen Lake, Mont., and by Kirkby and