[Schumm: badlands]

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EVOLUTION OF DRAINAGE SYSTEMS AND SLOPES IN BADLANDS AT PERTH AMBOY, NEW JERSEY

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ABSTRACT

To analyze the development of erosional topography the writer studied geomorphic processes and landforms in a small badlands area at Perth Amboy, New Jersey. The badlands developed on a clay-sand fill and were morphologically similar to badlands and areas of high relief in semiarid and arid regions. A fifth-order drainage system was selected for detailed study.

Composition of this drainage network conforms to Horton's laws. Within an area of homogeneous lithology and simple structure the drainage network develops in direct relation to a fixed value for the minimum area required for channel maintenance. Observed relationships between channel length, drainage-basin area, and stream-order number are dependent on this *constant of channel maintenance* which is in turn dependent on relative relief, lithology, and climate of any area.

Other characteristics of the drainage network and topography such as texture, maximum slope angles, stream gradients, drainage-basin shape, annual sediment loss per unit area, infiltration rate, drainage pattern, and even the morphologic evolution of the area appear related to relative relief expressed as a *relief ratio*, the height of the drainage basin divided by the length. Within one topographic unit or between areas of dissimilar but homogeneous lithology the relief ratio is a valuable means of comparing geomorphic characteristics.

Hypsometric curves are available for a series of 11 second-order drainage basins ranging in stage of development from initial to mature. Relief ratio and stream gradients attain a constant value when approximately 25 per cent of the mass of the basin has been eroded. Basin shape becomes essentially constant at 40 per cent of mass removed in accord with Strahler's hypothesis of time-independent forms of the steady state.

Comparison of the drainage pattern as mapped in 1948 with that of 1952 reveals a systematic change in angles of junction and a shift of the entire drainage pattern accompanying changes in the ratio between ground and channel slope.

Field observations and experimental studies suggest that badland slopes may retreat in parallel planes and that the rate of erosion on a slope is a function of the slope angle. The retreat of slopes may not conform to accepted concepts of runoff action as a function of depth and distance downslope. Runoff occurs as surge and subdivided flow which may be closely analogous to surficial creep.

Rills follow a definite cycle of destruction and reappearance throughout the year under the action of runoff and frost heaving.

At Perth Amboy, slopes are initiated by channel degradation and maintained by runoff and by creep induced through frost heaving. Runoff or creep may form convex divides, and both parallel and declining slope retreat are important in the evolution of stream-carved topography.

Hypsometric curves reveal that the point of maximum erosion within a drainage basin migrates upchannel and that the mass-distribution curve of any basin has a similar evolution to that of the longitudinal stream profile.

Comparative studies in badland areas of South Dakota and Arizona confirm conclusions drawn at Perth Amboy and show the importance of infiltration of runoff on topographic development and of subsurface flow in slope retreat and miniature pediment formation.

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Introduction

The factor of time has been a major difficulty in investigations of the evolution of landforms. Laboratory scale models which operate rapidly are unsatisfactory because scale ratios cannot be suitably maintained. An alternative exists, however, in studies of badland regions of the western United States, where detailed investigations (Smith, In press) within small areas undergoing rapid erosion have led to inferences concerning processes operating on morphologically similar but larger erosional landforms.

Small badland areas developing in clay pits on the Coastal Plain of New Jersey were also suitable for study and could be observed during an annual cycle of climatic changes. A. N. Strahler and D. R. Coates of Columbia University had selected one area at Perth Amboy, New Jersey for detailed study and mapping in 1948. In 1951 the writer began his investigation of the area using Strahler's map as a basis for morphometric studies.

Several methods were used to evaluate the effectiveness of the erosive processes and to study the evolutionary development of badland topography: (1) Topographic and drainage maps, made with plane table and telescopic alidade, were sufficiently detailed for measurement of all components of the drainage net with planimeter and chartometer. A statistical analysis of the data followed. (2) Stakes placed along stream and slope profiles permitted repeated measurements of erosion within selected basins. (3) Photography from selected stations, combined with remapping, gave information on changes within the system. (4) Experiments made upon samples of fill from the Perth Amboy area showed the effect of slope angle on sediment loss and upon size of entrained particles of the eroded material. (5) Comparative field studies were made in selected badland areas of the western United States.

Landforms are functions of structure, process, and stage; all differences in landforms can be explained through combinations of these factors. Geomorphologists have emphasized striking form differences but have neglected the importance of persistent similarities among forms of geologically and climatically diverse areas. The morphology of the small badland areas is remarkably similar to youthfully dissected areas of high relief such as the recently uplifted mountains of the West, or any region of recent uplift that has not been severely glaciated. Scale of topography may have less influence than other factors in the creation of distinctive features of the landforms.

The project's primary objective was to study the development and modification of badlands, but it may also be considered a type of large-scale model study, with the hope that some of the conclusions reached at Perth Amboy may be extended in a tentative way to larger areas.

Fenneman (1922, p. 126) suggested the value of such studies in developing an understanding of the development of erosional landforms:

"The physiographer's conception of the progressive dissection of peneplains, as of other plains, is based mainly on the growth of gullies. Rapid downcutting, steep sides, V-shaped cross section, and branching enter most abundantly into his mental pictures of an upland of homogeneous material or horizontal rocks that is undergoing dissection, especially when erosion is vigorous."

Acknowledgments

This investigation formed part of a quantitative study of erosional landforms sponsored by the Geography Branch of the Office of Naval Research as Project Number NR 389-042 under Contract N6 ONR 271, Task Order 30, with Columbia University.

The writer wishes to thank Prof. A. N. Strahler, who sponsored the project, for the use of data collected at Perth Amboy before 1951, and for the topographic map of the area (Pl. 1). Professor Strahler and members of the Seminar in Geomorphology at Columbia University during the years 1952 and 1953 gave much valuable criticism and advice. Messrs. J. T. Hack, L. B. Leopold, H. V. Peterson, and M. G. Wolman of the U. S. Geological Survey, Prof. John Miller of Harvard University, and Professor Strahler read and offered valuable suggestions for improvement of the manuscript.

During the field season of 1952 Mr. Iven Bennett of Rutgers University acted as field assistant. M. Rossics and A. H. Schumm also helped in the field. Mr. A. Broscoe kindly furnished the drainage map of the Chileno Canyon drainage basin.

General Description of the Perth Amboy Locality

The Perth Amboy badlands, where most of the investigation was made, were located on the western boundary of Perth Amboy, New Jersey, on the north bank of the Raritan River between the two highway bridges over the river. The area was conspicuous because it was anomalous in the humid climate of New Jersey and resembled larger badlands of the more arid West (Pl. 2, figs. 1, 2, 3). The Perth Amboy badlands are not unique, however; badlands have developed elsewhere in humid climates. Rapid badland erosion is occurring in the Ducktown Copper Basin of Tennessee where 10½ square miles are devoid of vegetation because of destruction by smelter fumes. It is considered the largest bare area in any humid region of the United States (Hursh, 1948, p. 2). Similar erosion occurs where volcanic ash covers the surface sufficiently to destroy vegetation (Segerstrom, 1950).

All the erosion forms in this badlands area were developed after 1929 when waste and overburden from other pits backfilled the abandoned clay pit at this site, producing a bench or terracelike deposit 40 feet high whose steep front and gently sloping upper surface rapidly gullied. The terrace as a whole was still in a youthful stage at the beginning of this study. Alluvial fans had been built along its base (Pl. 1, fig. 1, 2). The easily eroded terrace might be considered the initial stage of landform development of the theoretical Davisian cycle, with the elevated flat-terrace surface representing a rapidly elevated peneplain. Similar small badlands have developed elsewhere in the area where removal of vegetation and Pleistocene deposits have exposed the soft Cretaceous Raritan clays.

Plans for continued field studies to observe the cycle of development were unfortunately concluded when the area was leveled for construction purposes in the summer of 1953.

Reports of the nearest weather station at New Brunswick, New Jersey, 8½ miles northwest, reveal that erosion up to 1948 was accomplished by a total of 844 inches of precipitation and that mean yearly precipitation was [illegible] inches (U. S. Weather Bureau, 1929–194[illegible]). These figures contribute to a statement of general climatic conditions but not to a quantitative evaluation of the effect of rainfall, because there are no data on the local intensities of precipitation during this period. Intensities here are not low, however, compared with storms in the badland regions of the West. The maximum intensities of precipitation of any storm over periods of time ranging from 2 to 100 years may be expected in the eastern portion of the humid regions of the United States (Yarnell, 1935). Undoubtedly the erroneous impression of higher intensities in the arid West is due to the destructive nature of runoff on sparsely vegetated slopes.

Temperatures during this period ranged from 0° to 95°F., indicating that frost heaving is probably important during the 5½ months between the first and last severe frosts. The [illegible]

west orientation of the major drainage channels affects the microclimatic environment, subjecting the north- and south-facing slopes to different frequencies of freeze and thaw.

In spite of high precipitation the sterility of the fill and the rapidity of erosion prevented the growth of vegetation within the basin studied, except for one wild cherry tree and a small patch of poison ivy on the western drainage divide.

The fill forming the terrace at Perth Amboy is essentially homogeneous and the topography shows no persistent control by structure or lithology. Mr. Richard Chorley of Columbia University made a grain-size analysis of the fill, showing that it is 67 per cent sand, 22 per cent silt and clay, and 11 per cent gravel. The almost equal amounts of silt and clay were determined by the low plasticity of the finer fraction of the sediment (Burmister, 1952, p. 102). A cumulative percentage curve was plotted for the sample (Fig. 1) and from this Hazen's "effective size", designated D_{10} by Burmister, was obtained. The quantity D_{10} is the grain size in millimeters for which 10 per cent of the material is finer. For the Perth Amboy fill D_{10} is 0.04 mm. Using this value the fill characteristics important to this study can easily be determined using Burmister's charts: (1) the drainage of the fill is fair with a coefficient of permeability approximately 0.004 cm/sec.; (2) the capillarity is moderate with an approximate rise of 5.0 feet; (3) the frost-heaving characteristics are moderate to objectionable.

It may be suspected that frost heaving probably modifies the topography somewhat because the soil has moderate to objectionable frost-heaving characteristics and the low temperatures at Perth Amboy cause frequent freezing during the winter months.

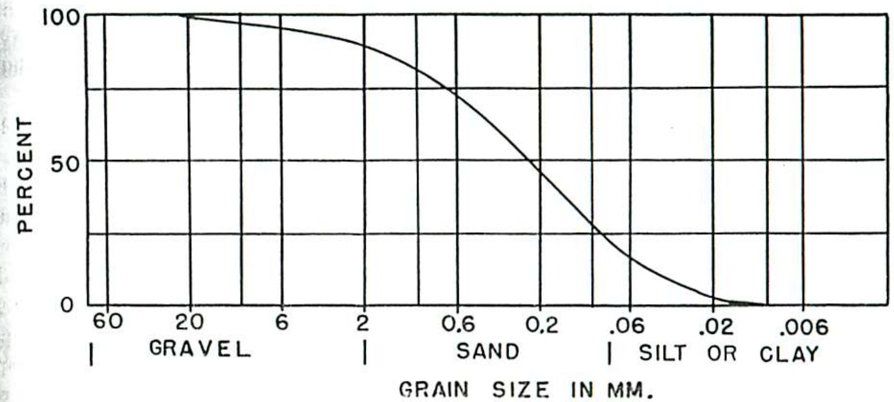


Figure 1.—Grain-size Distribution of Perth Amboy Fill

The importance of the values for capillarity and permeability are apparent from Burmister's (1952, p. 83) statement that, during excavation, slopes seldom need to be cut flatter than 45° "in soils containing more than about 5% silt except where surface erosion of the slopes by the rapid runoff of rainwater is excessive." The 5 per cent silt causes enough capillary cohesion in the soil to maintain steep slope angles, and the permeability is low enough to aid runoff. Thus, steep slopes are maintained, but erosion is rapid.

The effect of capillary cohesion within the Perth Amboy fill makes the mean maximum slope angle for the area 48.8°, and thus the slopes are classified by Strahler (1950, p. 693) as high-cohesion slopes.

The drainage basin selected for intensive study was mapped in 1948 by Strahler and Coates of Columbia University on a scale of 1 inch equals 10 feet (Pl. 1). The contour interval is 1 foot. The drainage pattern was mapped with particular care so that all drainage-basin characteristics could be measured; all channels possessing recognizable drainage areas were considered permanent drainage features and mapped as such.

The drainage basin mapped was that of a fifth-order stream network. Streams are designated on the basis of orders; all unit or fingertip stream channels without tributaries are first-order streams (Horton, 1945, p. 281); the junction of two streams of the same order forms a stream of the next higher order.

In all the drainage basins studied the streams are assigned order numbers following the method outlined by Strahler (1952b, p. 1120) whereby the higher stream-order numbers are not extended headward to include smaller tributaries, but refer to segments of the main channel (Fig. 9). With the Horton classification, the higher stream-order numbers include the smallest headward extension of the main stream. Using Strahler's method, the two major channels joining at point H (Pl. 1) are third-order; using Horton's method, the south tributary would be the extension of the fifth-order channel and would be eliminated from studies involving third-order channels. This method will be referred to again in a discussion of channel lengths.

The fifth-order basin mapped includes 3531 feet of drainage channels within an area of 31,027 square feet. The drainage density (Horton, 1945, p. 283), equal to the sum of the channel lengths in miles divided by the area of the drainage basin in square miles, is 602, indicating that within an area of this type 602 miles of drainage channels occur for every square mile of drainage basin. This value is indicative of the fine texture of the area. Although the density is high compared to a typical value of 5 to 20 for humid regions, it is not high for badland topography.

Within the mapped area the first-, second-, and third-order stream basins show a transition from maturely developed topography near the mouth of the main stream, where the main channel has widened the valley until small segments of flood plain have developed, to progressively more youthful basins toward its head, where the tributaries are eroding into portions of the undissected surface of the fill.

The mean length of the first-order channels is 10.1 feet, and the mean drainage area is 85.0 square feet, indicating the small scale of the topography. The hypsometric integral (Strahler, 1952b) for the entire fifth-order network is 70 per cent, indicating that erosion has removed a minimum of 30 per cent of the total mass of the basin. This figure is reasonably accurate because the upper surface of the terrace into which the system developed is still preserved in the headwater areas. Although the terrace is not a natural deposit and the drainage is developing on a small scale, investigation of principles of drainage-network development is aided by knowledge of several factors not available in the study of the geomorphic evolution of other areas.

The homogeneity of the fill aided development of an insequent drainage pattern on the terrace. The rapid erosion developed youthful V-valleys with steep straight slopes descending from convex or sharp-crested divides. The longitudinal profile of the main channel, typical of streams growing headward into an upland surface, had a concave lower segment and an upper convexity where degradation was most rapid. Tributary profiles varied with stage from convex-up, where the streams were unable to maintain themselves against the rapid degradation of the main channel in the headwater areas, to concave-up where the main channel appeared to be at grade.

Stream-channel erosion with sheet and rill erosion on the slopes were the dominant geomorphic processes observed. Wind erosion was negligible, but frost action became important during the winter months.

Characteristics of the Drainage Network

Components of the Drainage Network

Morphometric studies of drainage-network components at Perth Amboy included measurements of all stream-channel lengths and drainage-basin areas for all stream orders, so that each component could be studied independently. Stream-order analysis permits comparison of the drainage network developed on the Perth Amboy terrace with patterns originating under natural conditions. Horton (1945) proposed certain laws of drainage composition which assume an orderly development of the geometrical qualities of an insequent drainage system. These laws were applied to data obtained from morphometric measurements on the Perth Amboy map (Pl. 1) to determine whether they conformed; if they did, conclusions from the Perth Amboy study might apply to other larger areas. Geometry of two other fifth-order basins was measured for comparison with Perth Amboy basin (Table 2): Chileno Canyon basin (Chileno Canyon, California,

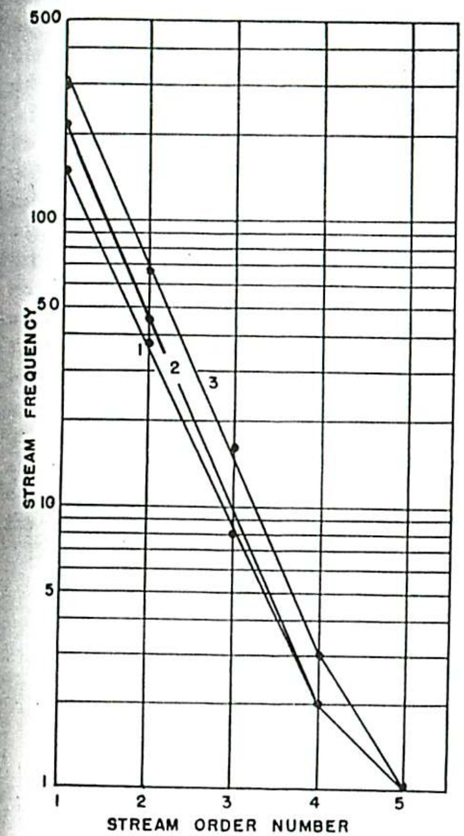


FIGURE 2.—RELATION OF NUMBER OF STREAMS OF EACH ORDER TO ORDER NUMBER
(1) Perth Amboy, (2) Chileno Canyon, (3) Hughesville area

quadrangle) and Mill Dam Run basin (Hughesville, Maryland, quadrangle).

The law of stream numbers, first of Horton's laws of drainage composition, is stated as follows (Horton, 1945, p. 291): "The numbers of streams of different orders in a given drainage basin tend closely to approximate an inverse geometric series in which the first term is unity and the ratio is the bifurcation ratio." If a geometric series exists, a straight-line series of points results where the numbers of streams of each order are plotted on a logarithmic scale on the ordinate against order numbers on an arithmetic scale on the abscissa. This has been done in Figure 2, in the manner of Horton's graphs. All three sets of points show a marked up-concavity at the lower end, suggesting that the geometric progression is not closely observed in the higher orders, but the Perth Amboy data show general similarity with the rest

TABLE 1.—METHOD OF DERIVING WEIGHTED MEAN BIFURCATION RATIO

1 Stream order	2 Number of streams	3 Bifurcation ratio	4 No. of streams involved in ratio	5 Products of columns 3 and 4
1	214			
		4.78	259	1238.0
2	45			
		5.63	53	298.4
3	8			
		4.00	10	40.0
4	2			
		2.00	3	6.0
5	1			

Total number of streams used in Col. 4 = 325.
Sum of products of Col. 5 = 1582.4.

Weighted mean bifurcation ratio $= \frac{1582.4}{325} =$ 4.87.

and there is no reason to believe that any fundamental dissimilarity exists.

The weighted mean of the Perth Amboy bifurcation ratio is 4.87. Bifurcation ratio is the ratio of the total number of streams of one order to that of the next higher order (Horton, 1945, p. 280), *e.g.*, a basin with 20 second-order channels and 60 first-order channels would have a bifurcation ratio between these two orders of 3. Because of chance irregularities, bifurcation ratio between successive pairs of orders differs within the same basin even if a general observance of a geometric series exists. To arrive at a more representative bifurcation number Strahler (1953) used a weighted-mean bifurcation ratio obtained by multiplying the bifurcation ratio for each successive pair of orders by the total number of streams involved in the ratio and taking the mean of the sum of these values (Table 1).

The second law stated by Horton (1945, p. 291) concerns stream lengths: "The average lengths of streams of each of the different orders in a drainage basin tend closely to approximate a direct geometric series in which the first term is the average length of streams of the first order.”

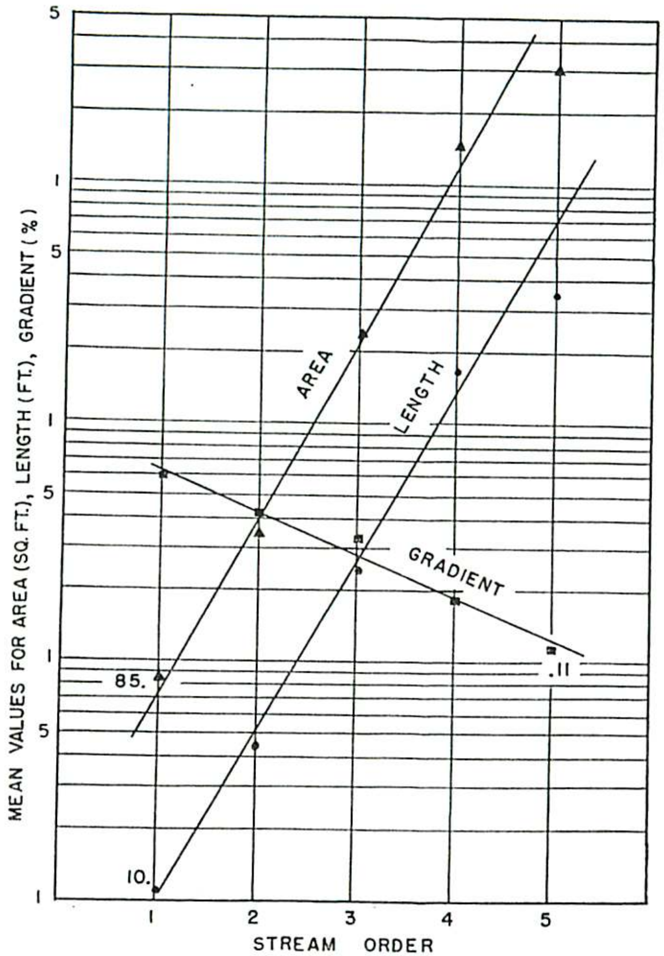


FIGURE 3.—RELATION OF MEAN BASIN AREA, MEAN STREAM LENGTH, AND MEAN STREAM GRADIENT TO STREAM ORDER

The length of streams of each order was obtained by measuring all the drainage channels within a basin of a given order; the length of the fifth-order stream at Perth Amboy is the total length of all the channels within the basin. This method differs from Horton's, but the total channel lengths may be more meaningful when considered within the area of each drainage basin. Using this method, however, the mean stream-length plots (Figs. 3, 5) for the Perth Amboy, Chileno Canyon, and Mill Dam Run systems adhere to Horton's law of stream lengths although the value of the length of the fifth-order stream is low in two cases. Because integer values only are used for order numbers continued channel development might be expected to raise the value of the fifth-order length, bringing it closer to the fitted regression line. The shortness of the fifth-order segment at Perth Amboy may be due to the truncation of the drainage pattern at the front of the terrace. In Figure 4 both the Hughesville and Perth Amboy drainage patterns have short fifth-order segments in comparison to that of the Chileno Canyon area. This may explain the low fifth-order channel lengths and areas for those two basins (Figs. 3, 5).

Horton's third law (1945, p. 295) states:

“There is a fairly definite relationship between slope of the streams and stream order, which can be expressed by an inverse geometric series law.” The Perth Amboy stream slopes appear to conform (Fig. 3). In this case the gradient is obtained by dividing stream length measured from mouth to headwaters by the elevation difference.

Horton's laws may require revision because he obtained his data from old maps of small scale on which he measured as stream channels only the blue drainage symbols, thus omitting a large part of the first- and second-order channel network. His statements are sound, however, in the light of investigations made on modern topographic maps, either mapped for the purpose (Perth Amboy basin) or selected because of their large scale and detailed representation of topography (Hughesville and Chileno Canyons quadrangles). These undoubtedly afford data more precisely representative of the natural development of drainage systems than the old maps.

The writer compared the Hughesville and

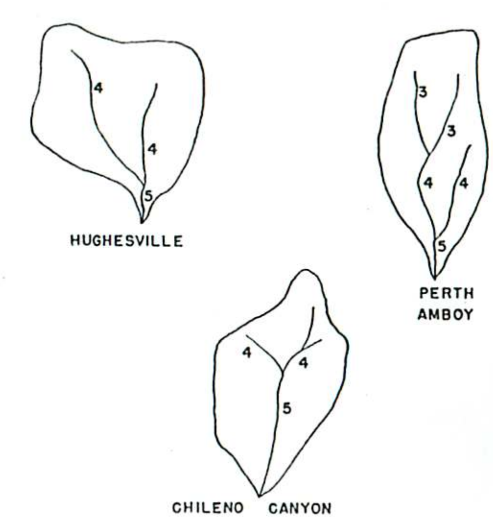


FIGURE 4.—COMPARISON OF SHAPE OF BASIN AND MAIN DRAINAGE ELEMENTS OF THREE AREAS

Numbers indicate order of main drainage channels

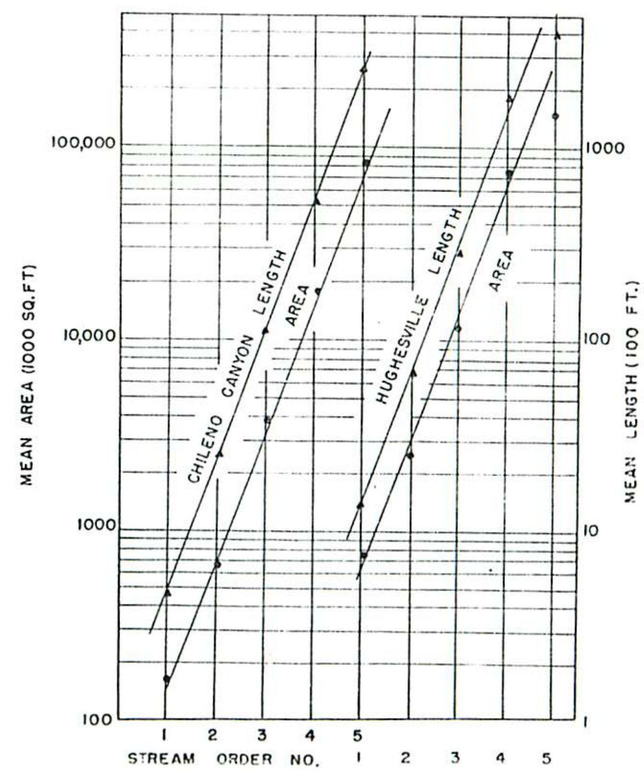


FIGURE 5.—RELATION OF MEAN BASIN AREA AND MEAN STREAM LENGTH TO STREAM ORDER

TABLE 2.—DRAINAGE-NETWORK CHARACTERISTICS

Basin	Order number	Number of streams	Mean length (ft.)	Mean area (sq. ft.)	Mean gradient (%)
Perth Amboy	1	214	10.1	85.0	59.9
	2	45	40.4	343	40.6
	3	8	242	2360	33.7
	4	2	1660	14600	18.2
	5	1	3530	31000	11.1
Chileno Canyon	1	296	482	167000	....
	2	66	2560	872000	....
	3	16	11400	3890000	....
	4	3	51100	18100000	....
	5	1	254000	86100000	....
Hughesville	1	150	1420	781000	....
	2	37	6860	2540000	....
	3	8	28400	12000000	....
	4	2	180000	78800000	....
	5	1	397000	154000000	....

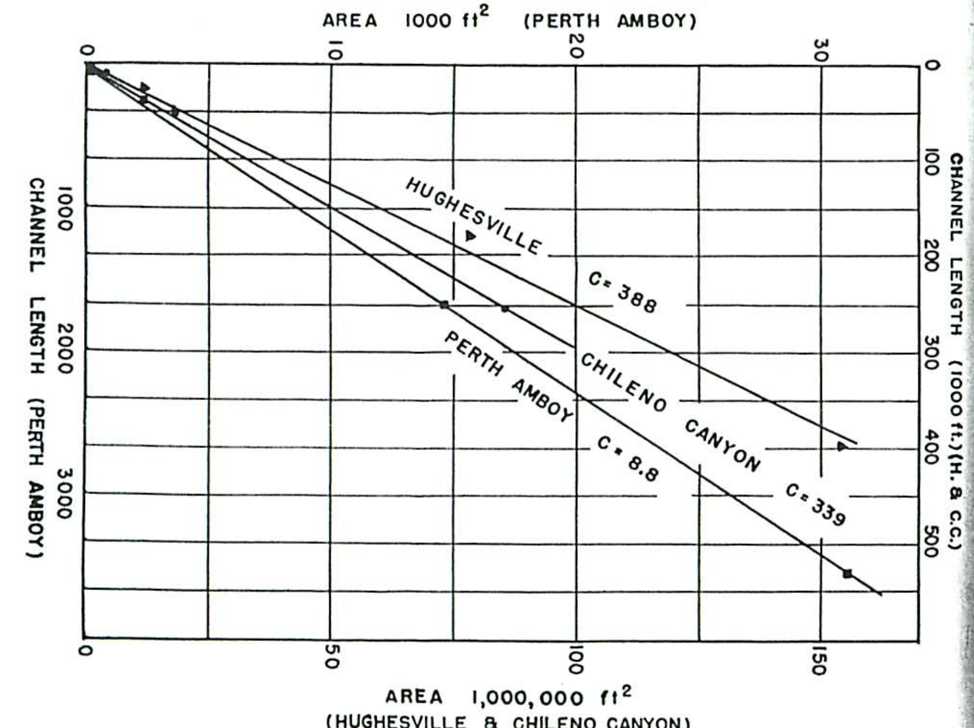


FIGURE 6.—RELATION OF MEAN STREAM LENGTH OF EACH ORDER TO MEAN BASIN AREA OF EACH ORDER

Chileno Canyon maps with aerial photographs so that the blue drainage lines could be extended to what appeared to be the correct length and small tributaries were also added to the drainage pattern. This method brought the length of channels close to the maximum value, perhaps obtainable only by detailed remapping in the field.

Further investigations included map measurement by polar planimeter of all drainage-basin areas. Horton (1945, p. 294) inferred that mean drainage-basin areas of each order should form a geometric series. A plot of the mean areas of stream basins of each order for the three basins compared above (Figs. 3, 5) reveals this relationship. A fourth law of drainage composition may therefore be formulated in the style set by Horton: the mean drainage-basin areas of streams of each order tend to approximate closely a direct geometric series in which the first term is the mean area of the first-order tasins. It could be assumed that such a relationship would exist if there were any connection between the length of a stream and the size of its drainage basin.

In Figures 3 and 5 the parallelism of the plots of mean stream length and mean drainage-basin area is striking and suggests a directly proportional relationship between the two. Figure 6 shows a plot of the mean drainage-basin areas

and mean stream-channel lengths for the three areas. The scatter of the Perth Amboy data is slight around a regression line fitted by the method of least squares and is described by the regression equation $Yc = 56.8 + 8.77X$. The ratio between mean area and length values is thus approximately 9. The calculated ratio for the Chileno Canyon basin is 339 and for the Mill Dam Run basin 388.

The significance of the ratio is that it represents in square feet the area required to maintain 1 foot of drainage channel. It is the quantitative expression of one of the most important numerical values characteristic of a drainage system: the minimum limiting area required for the development of a drainage channel. This value, *the constant of channel maintenance*, is a measure of texture similar to drainage density; it is in fact, equal to the reciprocal of drainage density multiplied by 5280 (because the channel-maintenance ratio is expressed in square feet while drainage density is expressed in miles). Along with drainage density this constant is of value as a means of comparing the surface erodibility or other factors affecting surface erosion and drainage-network development. A related texture measure is Horton's (1945) length of overland flow, the distance over which runoff will flow before concentrating into permanent drainage channels. The length of overland flow equals the reciprocal of twice the drainage density.

The discovery of the above relationship permits statement of a fifth law of drainage composition: the relationship between mean drainage-basin areas of each order and mean channel lengths of each order of any drainage network is a linear function whose slope (regression coefficient) is equivalent to the area in square feet necessary on the average for the maintenance of 1 foot of drainage channel. This law requires an orderly development of any drainage network, for the extension of any drainage system can occur only if an area equal to the constant of channel maintenance is available for each foot of lengthening drainage channel.

Limiting Values of Drainage Components

In addition to a lower limiting area necessary for channel maintenance there may be expected upper limits to basin areas and stream lengths of each order beyond which new tributaries or

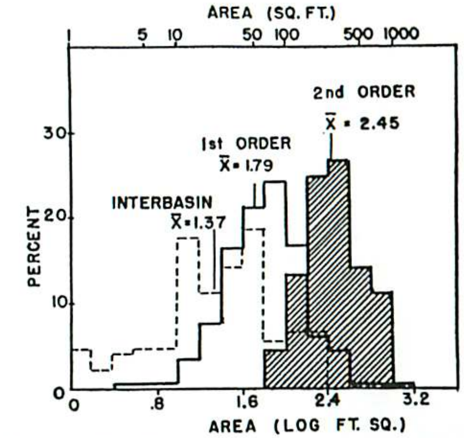


FIGURE 7.—FREQUENCY-DISTRIBUTION HISTOGRAMS OF THE LOGS OF DRAINAGE-BASIN AREA

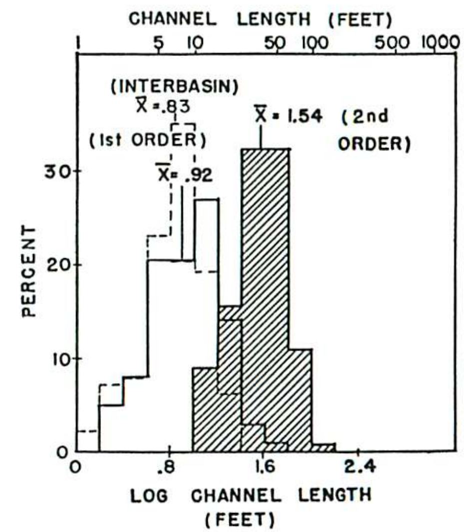


FIGURE 8.—FREQUENCY-DISTRIBUTION HISTOGRAMS OF THE LOGS OF STREAM-CHANNEL LENGTHS

relationships would appear in frequency-distribution histograms of the basin areas and stream lengths of each order and further confirm the principle of a channel-maintenance constant.

Frequency-distribution histograms of the stream lengths and basin areas show a marked right skewness, which appears to be corrected by plotting log values on the abscissa (Figs. 7, 8; Tables 3, 4). All measurements are made on a topographic map and are therefore taken from the horizontal projection of the drainage-basin elements rather than from true lengths and surface areas. Frequency-distribution study is number of streams in the third and higher orders. A study of the first- and second-order basin areas and interbasin areas may be ade-

TABLE 3.—FREQUENCY DISTRIBUTIONS OF LOGS OF CHANNEL LENGTHS*

Sample	Class mid-values in logs of lengths in feet										$\overline{X}$	s	N
	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9	2.1			
First order channels	11	17	45	45	58	30	6	2	...	...	.92	.302	214
Second-order channels	...	...	...	...	4	7	14	14	5	1	1.54	.21	45

* In this and all following tables and figures, $\overline{X}$ is the arithmetic mean, s is the standard deviation, and N is the number of items in each sample.

TABLE 4.—FREQUENCY DISTRIBUTIONS OF LOGS OF DRAINAGE-BASIN AREAS

Sample	Class mid-values in logs of area in square feet															$\overline{X}$	s	N
	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1			
First-order areas	...	2	2	6	17	34	45	50	34	12	8	1	1	1	...	1.79	.19	214
Second-order areas	...	...	...	...	..	..	..	..	2	7	11	12	7	5	1	2.45	.284	45

quate, however, to determine if a transition phase exists between orders.

Between adjacent drainage basins are *interbasin areas*, those roughly triangular areas which have not developed a drainage channel (Fig. 9), but which drain directly into a higher-order channel. The histograms of first- and second-order basin areas and interbasin triangular areas are superimposed in Figure 10 (Table 5); the histograms of first- and second-order stream lengths are compared with maximum interbasin-slope lengths in Figure 11 (Table 6). Figures 7 and 8 compare the histograms of the logarithms of basin area, channel length, interbasin areas, and interbasin maximum lengths. The discussion of limiting values of drainage components may be followed on either set of figures.

An overlap between the areas of each histogram suggests that transformation from first to second order takes place within a wide range of values. In Figure 10 interbasin areas show a sharp decrease in frequency for areas above 50 square feet, which is well below the mean of the first-order areas. Of the 27 interbasin areas over 50 square feet, 12 seemed capable of developing a channel at any time; the remaining 15 were irregular, wider than long, or were on rounded spurs where the divergence of orthogonals downslope prevents the concentration of runoff. From this investigation alone it is difficult to set limiting area above which channel development may be expected on the interbasin areas, especially since the comparison of triangular interbasin areas with elliptical first-order basins is questionable.

Areas of first-order basins rise sharply at the 10-square-foot class limit. Two first-order basins of less than 10 square feet were mapped by Strahler and Coates, but a field check revealed that these did not contain permanent drainage channels. The fact that areas of less than 10 square feet are remarkably free of drainage channels coincides with the concept of a constant of channel maintenance of about 9 (8.77). Thus, no permanent channel will develop without a drainage area of about 10 square feet, while the channel can lengthen only with the average increment of 9 square feet of area for each additional foot of length.

Most of the overlap between the first- and second-order areas falls between 50 and 150 square feet, although some first-order areas range up to 650 square feet. Again an inspection

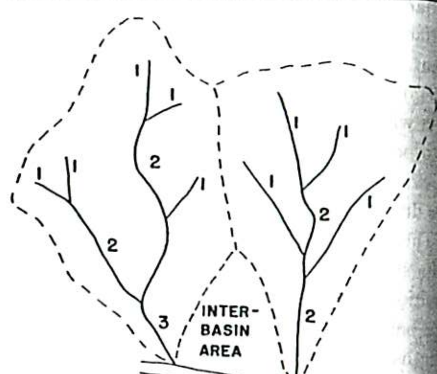


FIGURE 9.—POSITION OF INTERBASIN AREA AND METHOD OF CLASSIFYING STREAMS BY ORDER NUMBER

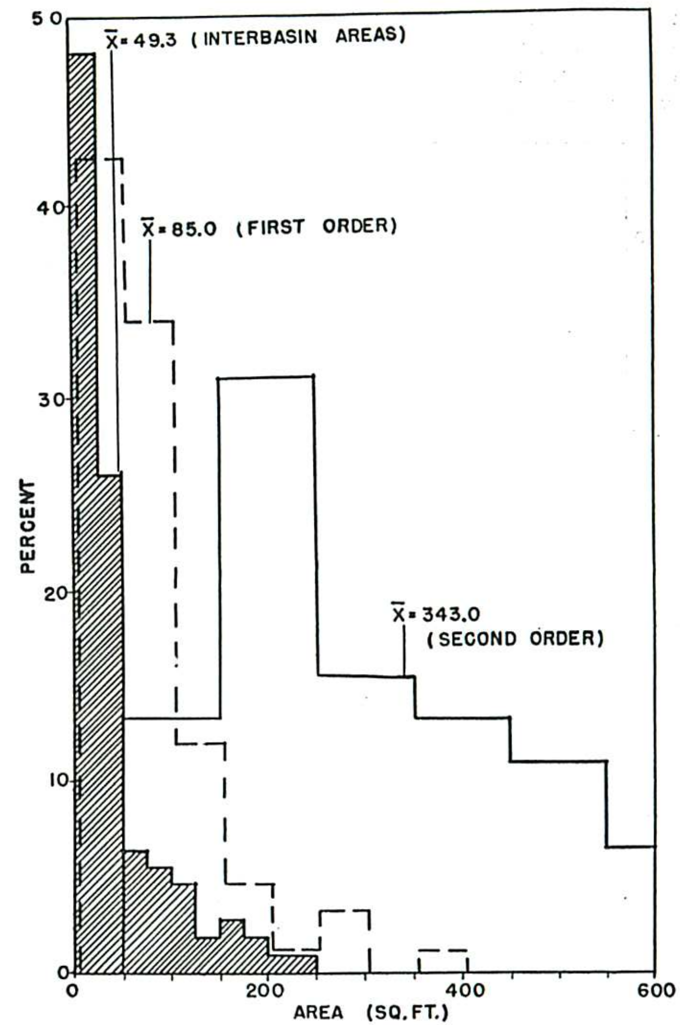


FIGURE 10.—FREQUENCY-DISTRIBUTION HISTOGRAMS OF FIRST- AND SECOND-ORDER BASIN AREAS AND INTERBASIN AREAS

TABLE 5.—FREQUENCY DISTRIBUTIONS OF FIRST- AND SECOND-ORDER DRAINAGE-BASIN AREAS AND INTERBASIN AREAS

Sample	Class mid-values in square feet													$\overline{X}$	s	N
Mid-values	30	80	130	180	230	280	330	380	430	480	530	580	630	$\overline{X}$	s	N
First-order areas	91	73	26	10	3	7	0	2	0	0	0	1	1	85	80	214
Mid-values	100	200	300	400	500	600	700	800	900	1000	1100	...	...	...	...	...
Second-order areas	6	14	7	6	5	3	2	0	1	0	1	...	...	343	218	45
Mid-values	12.5	37.5	62.5	87.5	112.5	137.5	162.5	187.5	212.5	237.5	..	...	...	...	...	...
Interbasin areas	51	28	7	5	5	3	4	3	1	1	..	...	...	49.3	49	108

of individual basin characterstics within the zone of histogram overlap is profitable. Of the 46 first-order areas greater than 110 square feet, 29 are of very youthful basins including broad, gently sloping surfaces with only traces of channels on the flat undissected divide areas. With further development these would evolve to a higher order, for their longitudinal profiles are still essentially convex-up, retarding rapid tributary extension into their headwater areas. Thirteen of the 46 are narrow almost rill-like basins unable to broaden because of adjacent more aggressive basins. The remaining 4 of the 46 first-order basins larger than 110 square feet have no obvious reason for not developing into second-order channels. Although it is difficult to explain peculiarities of individual drainage basins it seems a fair generalization that first-order channels with areas greater than 100 square feet are unstable and ready for subdivision.

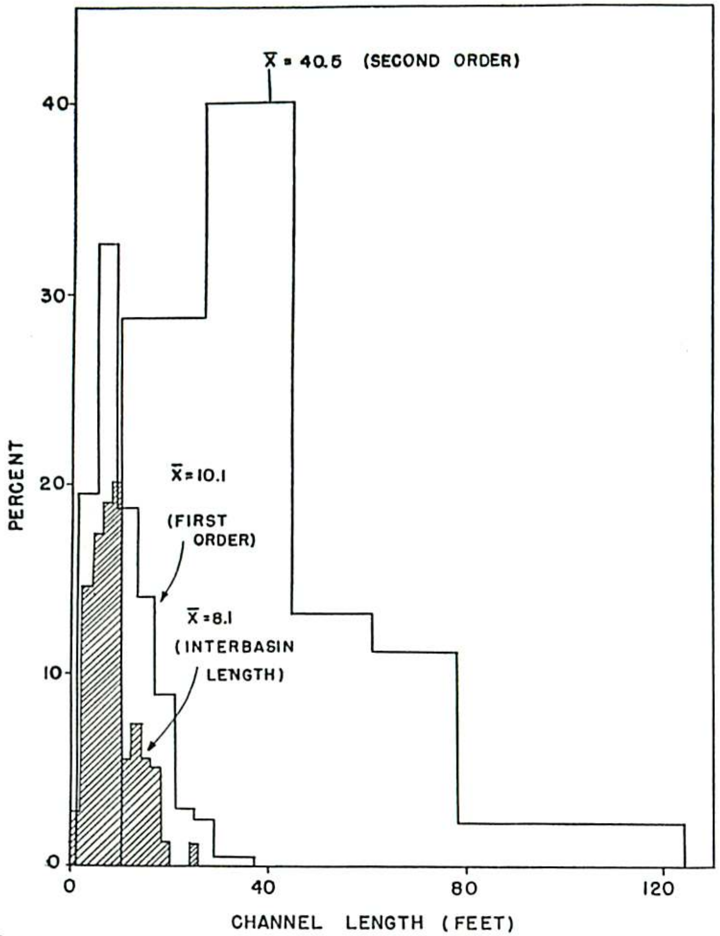


FIGURE 11.—FREQUENCY-DISTRIBUTION HISTOGRAMS OF FIRST- AND SECOND-ORDER CHANNEL LENGTHS AND MAXIMUM INTERBASIN LENGTHS

The smallest second-order channel area is 65 square feet. The class limits of the second-order areas within the overlap are 50 and 150 square feet (Fig. 10). Within this size range are six second-order basins which have developed tributaries recently and are capable of enlarging by headward extension so that the lowest-frequency class of the second-order area histogram would disappear unless replaced by new units created by bifurcation of first-order channels. Youthfulness of the entire system at Perth Amboy prevents the recognition of narrow transition zones between orders. A similar study in a fully extended mature drainage system might show sharper distinctions.

In accordance with the fifth law of drainage composition, stream-length frequency distributions are similar to the area distributions. Maximum interbasin-slope lengths cannot be directly compared to actual stream lengths because a channel developing on the interbasin surface will not extend the entire length of the slope. Nevertheless, a sharp drop in frequency at 10 feet suggests that at lengths above this runoff surfaces are unstable in form and will tend to develop channels (Fig. 11). Twenty-six interbasin areas with lengths greater than 10 feet had no channels. Seven were very narrow with little drainage area. The remaining 19, as previously noted under the discussion of interbasin areas, are irregular or on rounded spurs, while 4 seem capable of developing channels.

TABLE 6.—FREQUENCY DISTRIBUTIONS OF FIRST- AND SECOND-ORDER CHANNEL LENGTHS AND INTERBASIN LENGTHS

Sample	Class mid-values in feet														$\overline{X}$	s	N
Mid-values	3	7	..	11	..	15	..	19	..	23	..	27	31	35			
First-order lengths	42	70	..	40	..	30	..	19	..	6	..	5	1	1	10.1	6.08	214
Mid-values	18.5	35.5	..	52.5	..	68.5	..	86.5	..	103.5	..	120.5	..	..	..	...	...
Second-order lengths	13	18	..	6	..	5	..	1	..	1	..	1	..	..	40.4	23.4	45
Mid-values	1	3	5	7	9	11	13	15	17	19	21	23	25	..	..	...	...
Interbasin lengths	3	16	18	21	23	5	8	5	5	2	0	0	2	..	8.06	4.17	108

The lower values for first-order stream lengths are not significant because all channels must originate from a point and then lengthen. The region of transition between first- and second-order stream lengths lies between 9 and 17 feet, but 17 feet is not the upper limit of first-order lengths. Of 27 streams longer than 17 feet, 20, within basins considered previously under the discussion of areas, were in very youthful or narrow basins; the remaining 7 seemed capable of change. All but 1 of the 12 second-order channels between 10 and 17 feet will continue to develop, eliminating these streams from the frequency class. Youthfulness of the area probably masks a more distinct transition zone.

Within the Perth Amboy drainage network there are recognizable limits to the areas and lengths of streams of each order. First-order streams have an upper limiting length between 9 and 17 feet and an upper limiting area between 65 and 110 square feet. The limited number of stream orders considered and the subjective evaluation of parts of the data make it more appropriate to set a lower limit below which higher orders cannot exist. The first-order streams require more than 10 square feet for development; second-order streams will not normally evolve from first orders until the drainage area is equal to 65 square feet and the first-order channel is longer than 10 feet.

The writer remapped the drainage pattern in 1952 and compared it with the pattern mapped in 1948, aiding the study of channel alterations within the zones of transition. In all cases the addition of channels occurred only in basins above the size limits set from the frequency-distribution analysis. No channels developed on areas less than 10 square feet. Four new channels developed on interbasin areas, all but one (46.5 sq. ft.) greater than 50 square feet. Twelve new tributaries developed on first-order channels, forming several new second-order basins. Each new basin was youthful (developing headward into the as yet undissected fills), and almost all exceeded 110 square feet. Four were within the transition zone between first- and second-order areas. The newer field study, therefore, seems to confirm the existence of the zones of transition and upper limiting values of development related to the constant of channel maintenance. The constant of channel maintanence, therefore, may be applied to the as yet undissected portions of a drainage system to aid in the prediction of areas of future sediment loss.

Form of the Drainage Basins

In addition to indices of drainage-network composition based on stream orders other important geomorphic characteristics are shape of the basins, relief, surface slope, drainage density, and stage of geomorphic development. Geomorphic development can be evaluated by means of the hypsometric integral (Strahler, 1952b). If each characteristic had a numerical value, comparisons could be made between topographic units. It may be appropriate to set up standards of comparison from the available information which can be modified later or rejected if unacceptable.

Relief is analyzed by a *relief ratio*, defined as the ratio between the total relief of a basin (elevation difference of lowest and highest points of a basin) and the longest dimension of the basin parallel to the principal drainage line. This relief ratio is a dimensionless height-length ratio equal to the tangent of the angle formed by two planes intersecting at the mouth of the basin, one representing the horizontal, the other passing through the highest point of the basin. Relief ratio allows comparison of the relative relief of any basins regardless of differences in scale of topography. Recent field studies, however, reveal that residuals or abnormally high points on the divide should be ignored when obtaining the total relief of a basin (Hadley and Schumm, In preparation).

The shape of any drainage basin is expressed by an *elongation ratio*, the ratio between the diameter of a circle with the same area as the basin and the maximum length of the basin as measured for the relief ratio. This ratio is the same as the Wadell sphericity ratio used in petrology (Krumbein and Pettijohn, 1938, p. 284), where the ratio approaches 1 as the sediment grain, or in this case the shape of the drainage basin, approaches a circle. Miller (1953, Ph.D. dissertation, Columbia University) used a similar measure, the *circularity ratio*, which is the ratio of circumference of a circle of same area as the basin to the basin perimeter.

Table 7 compares Strahler's data (1952b, p. 1134) on five mature drainage basins with the writer's data obtained from the more youthful Perth Amboy and Hughesville areas and the Chileno Canyon area.

The writer compared relief ratio and drainage density for fourth- and fifth-order channels (Fig. 12, Table 7) and found a definite positive trend in the mature basins. Points for the youthful Hughesville and Perth Amboy basins displace upward to positions well above the

TABLE 7.—DRAINAGE-BASIN CHARACTERISTICS

Area	Drainage density (miles/sq. mi.)	Relief ratio	Elongation ratio	Gradient (%)	Mean maximum slope angles (%)
1. Gulf Coastal Plain	4.6	.008	.975	0.33	5.9
2. Piedmont	6.9	.025	.935	1.13	17.5
3. Ozark Plateau	13.8	.062	.692	3.52	53.7
4. Verdugo Hills	26.2	.245	.594	22.46	99.0
5. Great Smoky Mts.	14.2	.267	.760	12.33	86.7
6. San Gabriel Mts.	15.6	.220	.675	17.2	73.4
7. Hughesville	13.6	.006	.730	0.22	7.0
8. Perth Amboy	602.0	.117	.602	11.1	110.8

trend line. When the values for the individual third-order basins of each of the two youthful areas are plotted (Fig. 13), the points show a positive trend similar to the plot of the mature basins. Thus, within homogeneous areas of similar development the drainage density is a power function of the relief ratio.

In Figure 14 the relief ratio shows a close correlation with stream gradient. The gradient values are means for the entire stream length and thus would approach the value of the relief ratio if the stream length was measured to the drainage divide. In general, the gradient so measured will be less than the relief ratio, for meandering or the usual lack of straightness of a channel will increase the stream length beyond the drainage-basin length.

Valley-side slope angles are also clearly related to the relief ratio. In Figure 15 three values would lie well to the right of a line fitted to the other points. This may be the result of obtaining the mean slope values from topographic maps in these cases; all the data were not measured in the field, and slopes measured on maps usually are lower than field measurements (Strahler, 1950, p. 692).

In Figure 16 the shape of the drainage basin is plotted against relief. The trend is negative

and may indicate that as the relief ratio increases the drainage basin becomes more elongate. The data are not conclusive, but the steeper the slope on which small basins develop

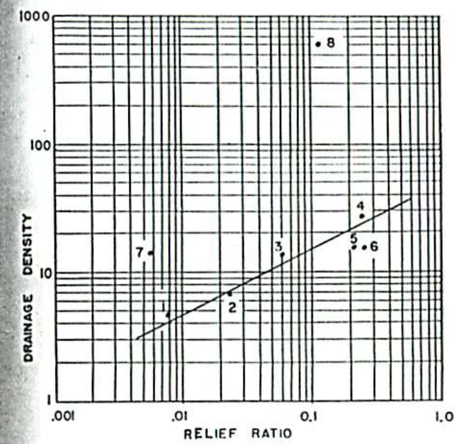


FIGURE 12.—RELATION OF DRAINAGE DENSITY TO RELIEF RATIO

Numbers refer to basins described in Table 7

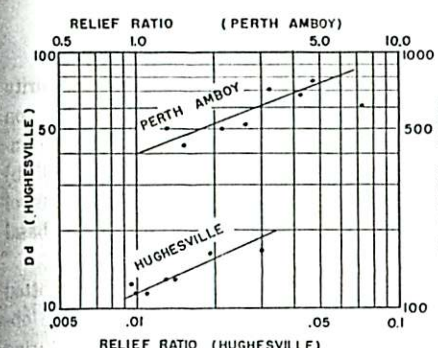


FIGURE 13.—RELATION OF DRAINAGE DENSITY TO RELIEF RATIO OF THIRD-ORDER BASINS

the more closely spaced are the drainage channels, resulting in more elongate basin shapes.

One practical application of the relief ratio is in estimation of sediment loss. Figure 17 shows the direct relation between mean relief ratio for several areas in Utah, New Mexico, and Arizona and mean annual sediment loss as estimated from sedimentation in small stock reservoirs. Once the characteristic regression trend has been established for a region the investigator may select areas of high potential sediment production from topographic maps (Schumm, 1955).

Various interrelationships among drainage-basin characteristics have been previously determined. Langbein (1947, p. 125) states that steep land slopes are generally associated with steep channel slopes and fine texture, and that

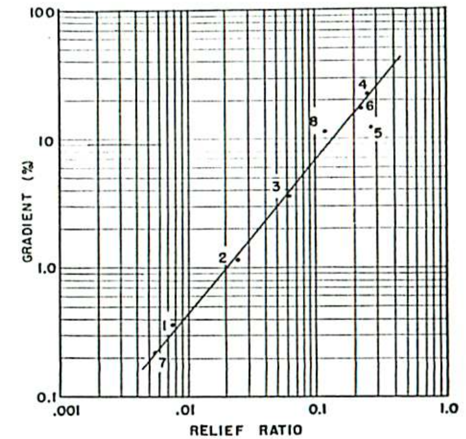


FIGURE 14.—RELATION OF MEAN STREAM GRADIENTS TO RELIEF RATIO

Numbers refer to drainage basins described in Table 7

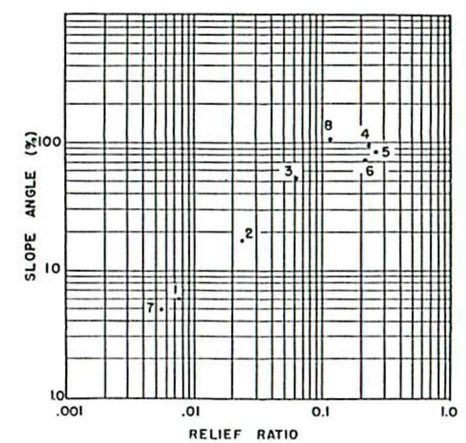


FIGURE 15.—RELATION OF MEAN MAXIMUM-SLOPE ANGLES TO RELIEF RATIO

Numbers refer to drainage basins described in Table 7

altitude of a basin above its outlet increases with steepening land and channel slopes. Paulsen (1940, p. 440) found that infiltration increases with decrease in mean land slope, explaining in part the increase of sediment loss with the relief ratio. Strahler (1952b, p. 1136) observed that the hypsometric integral decreased as basin height, slope steepness, gradient, and drainage density increased.

Although more data are desirable the relationships observed suggest that the geomorphic character and even rates of erosion may be predicted from the relief ratio, although it is only a geometrical element which is probably related to lithology, structure, stage, vegetation, and climate.

The above relationships when considered in the light of recent discussions of the quasi equilibrium between the hydraulic and geomorphic characteristics of stream channels (Leopold and Maddock, 1953; Wolman, 1955; Leopold and Miller, in press) suggest that when more information becomes available this concept of quasi equilibrium in graded and ungraded stream channels may extend to the landforms adjacent to the stream channels, and close interrelationships may be found among the geomorphic, hydrologic, and hydraulic characteristics of a topographic type.

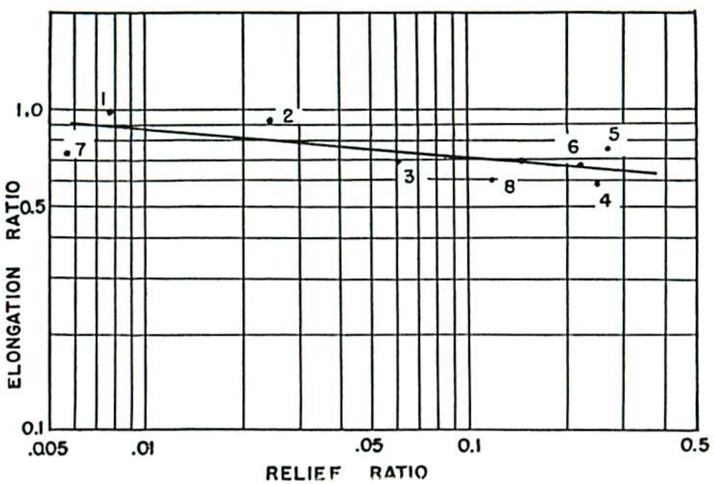


FIGURE 16.—RELATION OF ELONGATION RATIO TO RELIEF RATIO
Numbers refer to drainage basins described in Table 7.

Basin Form Related to Geomorphic Stage of Development

During geomorphic development basin forms change with time. According to the classic Davisian analysis, relief, slope of valley walls, stream gradients, and drainage density increase rapidly during youth to a maximum in early maturity, then decline slowly throughout later maturity and old age. A unique opportunity to study stage changes was afforded by the developmental sequence of drainage basins tributary to the main channel at Perth Amboy. Eleven second-order drainage basins forming a sequence from earliest youth to late maturity were selected for map study and a comparison of hypsometric integrals. The hypsometric integral is a measure of stage (Strahler, 1952b) because it expresses as a percentage the mass of the drainage basin remaining above a basal plane of reference.

Figure 18 shows hypsometric curves plotted for each basin in the sequence. Data are obtained from the topographic map by measuring the total area of each basin with a planimeter, then measuring the area between each contour and the basin perimeter above it. Each area is converted into a percentage of total basin area, so that a cumulative percentage curve can be plotted, each area value corresponding to a percentage of the total height of the basin. Using this hypsometric curve it is possible to read the percentage of total basin area above any percentage of total height. The area-altitude relations of the basin are thus revealed by a curve illustrating in dimensionless co-ordinates the distribution of mass within the drainage basin (Langbein, 1947, p. 140; Strahler, 1952b). Area under the hypsometric curve is the hypsometric integral, expressed as per cent.

An integral of 60 per cent indicates that erosion has removed 40 per cent of the mass of the basin between reference planes passing through summit and base. Strahler (1952b) discussed in more detail the hypsometric curve and its use in geomorphic research.

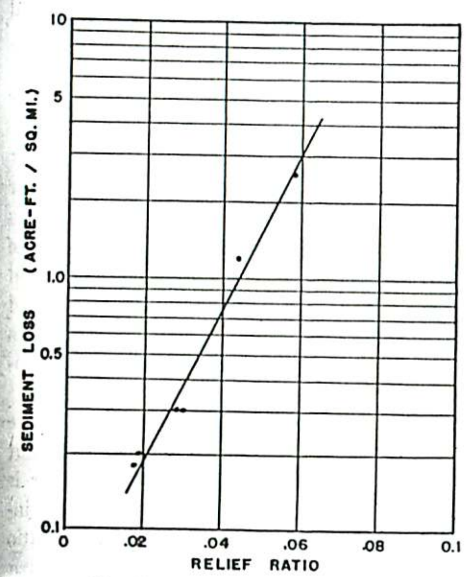


FIGURE 17.—RELATION OF MEAN ESTIMATED ANNUAL SEDIMENT LOSS TO RELIEF RATIO
From the U. S. Geological Survey studies of reservoir sedimentation in New Mexico, Arizona, and Utah

The 11 second-order basins selected for this study were of approximately the same area so that the series of hypsometric curves illustrate basin development with time accompanying lowering of the main channel through 40 feet of total relief. The convex curves with high integrals (Fig. 18) reveal youthful inequilibrium; the curves of more mature basins show the beginning of the typically mature sigmoid curve. The percentage curves cannot show continued down-wasting of the basin, because when maturity is reached curves tend to stabilize between integrals of 40 and 60 per cent. Strahler uses this stable integral as the point of onset of the equilibrium stage of drainage-basin development. Only basins containing monadnocks of resistant rock develop integrals markedly less than 40 per cent.

A better picture of the sequence of natural basin changes in terms of total erosional reduction may be obtained by plotting percentage of area against percentage of total elevation of the terrace at Perth Amboy rather than against

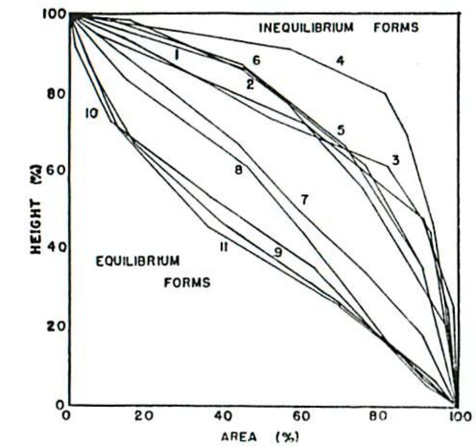


FIGURE 18.—SEQUENCE OF SECOND-ORDER HYPSOMETRIC CURVES
From Perth Amboy.
Numbers increase from youthful to mature basins

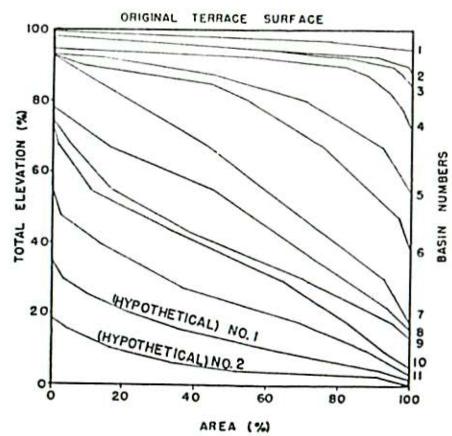


FIGURE 19.—SEQUENCE OF SECOND-ORDER HYPSOMETRIC CURVES
Per cent area is plotted against per cent of total relief at Perth Amboy. Numbers increase from youthful to mature basins and are the same areas as shown in Figure 18.

total relief within each basin. This method (Fig. 19) is more satisfactory because the square in which the curves are plotted may be visualized as a vertical section through the entire terrace at Perth Amboy. Each curve occupies its true relative vertical position within that mass and reveals the degradational history of the basin. The 100 per cent elevation line should be visualized as the upper surface of the terrace, the base as the level of the main stream's mouth. The right edge of the chart is the locus of points of junction of second-order tributaries with some higher-order stream. Each

TABLE 8.—DRAINAGE-BASIN CHARACTERISTICS OF THE SECOND-ORDER SEQUENCE

Basin number	Per cent mass removed	Relief ratio	Elongation ratio	Gradient (%)	Drainage density (mi./sq. mi.)
1	2.4	.049	.993	4.0	553
2	4.9	.121	.648	14.4	504
3	5.6	.158	.595	18.6	270
4	9.5	.156	.645	21.8	241
5	17.2	.330	.783	42.0	672
6	23.5	.575	.725	52.0	560
7	39.8	.590	.507	58.3	610
8	50.8	.660	.473	67.5	895
9	60.8	.710	.474	65.5	1230
10	64.6	.620	.478	51.5	1150
11	77.0	.690	.530	50.7	1320

line represents the distribution of mass within a second-order basin at a different stage of development, the position of its mouth controlled by the degrading stream to which it is tributary.

To determine the nature of basin-form changes with time, or stage of evolution, an important index is the percentage of mass removed at each position in the sequence of basins. This value, obtained by measuring the area above each curve and comparing it to the total area of the diagram, is a measure of the mass removed in relation to the total available for removal.

Percentage of mass removed, relief ratio, stream gradient, basin shape, and drainage density were determined for each of the 11 basins whose curves are drawn in Figure 19. The data for each basin in the sequence (Table 8) are plotted against corresponding per cent of mass removed (Fig. 20). The plot of relief ratio with per cent removed (A) reveals that with initial dissection the relative relief rapidly increases. A sharp break in the continuity of the plot occurs when approximately 25 per cent of the mass of the basin is removed, after which the relief ratio remains almost constant to 80 per cent of mass removed; beyond 80 per cent, data are lacking.

The stream-gradient plot (B) shows a similar form. The rapid increase in gradient is checked at approximately 25 per cent of mass removed; a decrease in gradient sets in at the upper part of the plot after a maximum value reached at 50 per cent removal. This agrees with the typical descriptive concept of stream development, but, in comparison to the rapid early increase in gradient, the portion of the plot above 25 per cent is essentially constant.

Maximum slope angles were not obtained for each basin, but, because these values cluster closely about a mean value for any homogeneous area (Strahler, 1950, p. 685), and because the close relationship between stream gradients and maximum slope angles has been established (Strahler, 1950, p. 689), any plot of slope angles and mass removed would be expected to approximate the gradient curve.

The relationships of basin shape and drainage density to stage (Fig. 20C, D) are less clear, but after early variations in which the basin is close to a circular shape the influence of increased relief is felt and the elongation ratio decreases to a constant of about 0.5 at 40 per cent mass removal, indicating that the basin maximum length is twice the diameter of a circle of the same area. The drainage-density plot is not regular, probably because of a high degree of length variability in the low order of the streams used. Nevertheless, the plot suggests rapid early increase in drainage density, followed by a decreasing increment. Probably continued headward development of the drainage channels continues until late in the erosion cycle, lagging behind the early stability of other basin characteristics. If other series of basins could be studied similarly, the additional data might lead to the establishment of a general system of basin evolution.

In summary, the form of the typical basin at Perth Amboy changes most rapidly in the earliest stage of development. Relief and stream gradient increase rapidly to the point at which about 25 per cent of the mass of the basin has been removed, then remains essentially constant. Because relief ratio elsewhere has shown a close positive correlation with stream gradient, drainage density, and ground-slope angles, stage of development might be expected

to have little effect on any of these values once the relief ratio has become constant.

The Perth Amboy data thus support the concept of a steady state of drainage-basin development as outlined by Strahler (1950, p. 676)

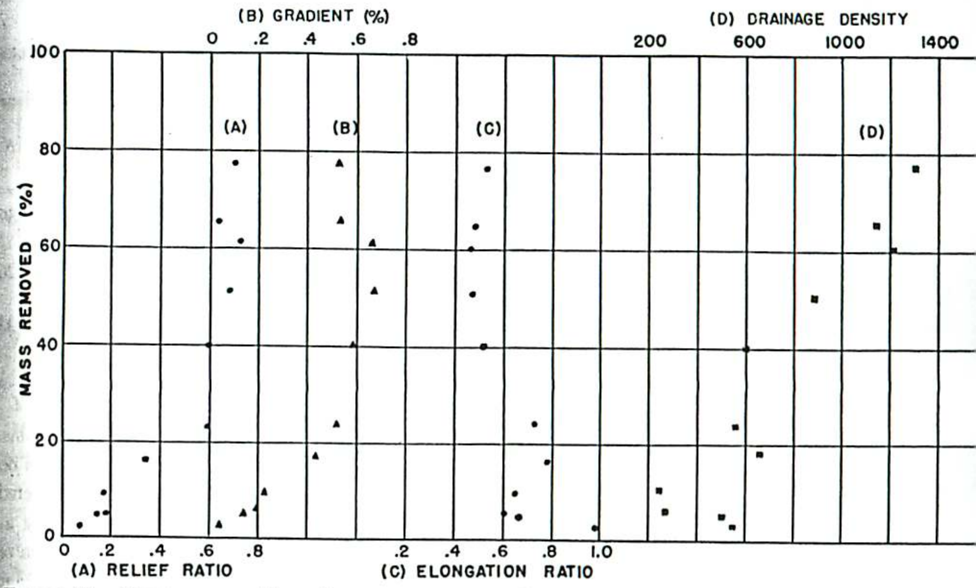


FIGURE 20.—RELATION OF MASS REMOVED WITHIN A BASIN TO RELIEF RATIO, GRADIENT, ELONGATI RATIO, AND DRAINAGE DENSITY

who compares a graded drainage system with an open dynamic system in a steady state:

> "In a graded drainage system the steady state manifests itself in the development of certain topographic form characteristics which achieve a time-independent condition. (The forms may be described as "equilibrium forms"). Erosional and transportational processes meanwhile produce a steady flow (averaged over periods of years or tens of years) of water and waste from and through the landform system. . . . Over the long span of the erosion cycle continual readjustment of the components in the steady state is required as relief lowers and available energy diminishes. The forms will likewise show a slow evolution."

This hypothesis of time-independent forms and basin characteristics is supported by the constancy of the values of the basin parameters in the Perth Amboy sequence of second-order basins, once the amount of mass removed has exceeded 25 per cent.

EVOLUTION OF THE DRAINAGE NETWORK

Effect of Stage on Angles of Junction

In the early stage of basin development

establish major drainage divides; the re ratio then reaches a fixed value, but changes channel network continue until a large port of the basin mass is removed. Thus, the rel ratio becomes fixed before other network char teristics become constant. This is especially tru of drainage density in the Perth Amboy area

Angles of junction of tributaries, resurveye in 1952, showed some marked differences fro corresponding angles in the 1948 map. Th writer reasoned that systematic changes wer occurring in the drainage pattern as a norma part of the erosional development of the basin Horton (1945, p. 349) recognized that the cours followed by a new tributary is governed b both the slope of the ground over which i flows and the gradient of the channel to which it is tributary. Where the ground slope is grea in relation to the gradient of the master stream a tributary joins at almost right angles; where master-stream gradient and valley-side slope are almost the same the tributary almost parallels the main channel, joining it at a small angle. Horton expresses this as follows:

$$\cos Zc = \tan Sc/\tan Sg$$

where the cosine of the entrance angle or angle of junction, measured between the tributary equals the ratio of the tangent of the main channel gradient to the tangent of the gradient of the tributary stream or of the ground slope over which the tributary flows. It follows that

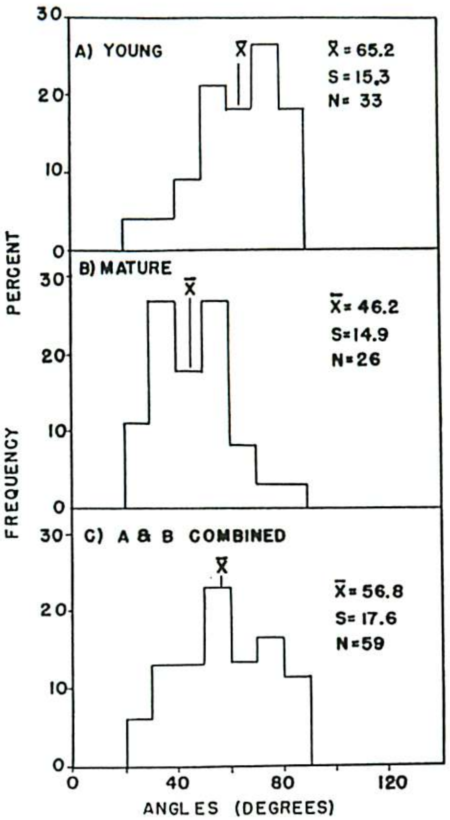


FIGURE 21.—FREQUENCY-DISTRIBUTION HISTOGRAMS OF YOUNG, MATURE, AND COMBINED ANGLES OF JUNCTION

during the early part of basin development, stream-entrance angles change with stream gradients.

Thus, a tributary will develop with an initially large angle of junction; then as the ratio between the two gradients increases the angle of junction decreases. Horton notes that as the ratio increases from 0.3 to 0.9 angles decrease from 72.3° to 25.5°. The decrease is accomplished by lateral migration of the tributary toward the main channel and down-valley shift of the junction.

The writer measured 61 entrance angles on the 1948 Perth Amboy map. The frequency-distribution histogram is broad and flat-topped with angles ranging from 24° to 90° (Fig. 21C; Table 9).

If the assumed changes occur, then by classifying all entrance angles according to stage of development of their tributary drainage basins a significant difference should occur between

TABLE 9.—FREQUENCY DISTRIBUTIONS OF ANGLES OF JUNCTION

Sample	Class mid-values in degrees							$\bar{X}$	s	N
	25	35	45	55	65	75	85			
Combined angles	4	8	8	14	8	10	7	56.8	17.6	59
Mature angles	3	7	5	7	2	1	1	65.2	15.3	26
Young angles	1	1	3	7	6	9	6	46.2	14.9	33

the means of youthful and more mature basins. The basins were separated into two groups on the basis of the existence of flat, undissected areas within the drainage areas, classifying as young basins capable of headward extension or having undissected areas within their drainage areas. The frequency-distribution histograms of each group (Fig. 21) show an expected overlap, but the means of the two groups are significantly different as judged by a t-test. The mean of the youthful class is 65°, that of the older group 46°. The probability that such a difference or greater would occur by chance alone is about 1 in 10,000. A reasonable explanation of the observed difference in angles is the shifting of tributary channels in response to changes in the gradient ratio.

A similar test was applied to angles of bifurcation, defined as the angles between two approximately equal first-order branches. In this case, the stream has bifurcated at its upper end, whereas in the tributary junction referred to above a branch has grown from the trunk of an existing major drainage line. Twenty angles of bifurcation were measured from youthful drainage basins having undissected areas. The mean is 62.1°, compared with the mean of the youthful angles of tributary junction, 65.2°. The frequency distributions of both samples have such great dispersions that this observed difference in means is not significant.

Remapping of the drainage pattern revealed changes in the values of tributary entrance angles and angles of bifurcation. Table 10 shows data for mean entrance angles and angles of bifurcation measured from the 1948 and 1952 drainage maps. There is a decrease of 5.3° in the

TABLE 10.—ANGLES OF BIFURCATION AND ANGLES OF JUNCTION

	Mean angles (degrees)		Standard deviation (s)		Number in sample (N)	
	1948	1952	1948	1952	1948	1952
Angles of bifurcation	62.1	53.3	13.4	17.5	20	12
Angles of junction:						
Total	56.8	53.6	17.6	18.5	59	46
Young	65.2	59.9	15.3	17.1	33	29
Mature	46.2	43.0	14.9	14.9	26	17

mean of the youthful tributary-junction angles, but the standard deviation of each distribution is so large that a statistical test of the significance of difference between the means shows that such a difference would be expected through chance alone 20 per cent of the time and is not significant. This is true also of the difference between the mature angles, 3.2°.

The means of the young angles in both 1948 and 1952 are significantly different from those of the mature angles. It is interesting to note that the means for the total, youthful and mature angles decreased by several degrees during the 4-year period. The difference in each case is not statistically significant but suggests that with more time a significant change might occur.

Only the angles of bifurcation showed a significant reduction, 8.8°, between 1948 and 1952. Only 12 of the 20 original angles could be recognized and measured in 1952. The extreme youthfulness of the newly formed drainage basins, with rapid lowering of channel gradients in progress, is the cause of the great change in bifurcation angle.

A comparison of the drainage patterns showed marked drainage changes. Twelve new tributaries were added to the drainage system between mappings. Coincidentally, 12 others were eliminated, 6 by abstraction or lateral expansion of a more competent neighbor, 2 by angle reduction to the minimum with collapse of the divide and union of the streams, while the remaining 4 were in small, shrinking basins surrounded by headward-growing channels. Two of these channels were originally near the lower limiting area of channel formation, 11.8 and 15.3 square feet. It is interesting to note that both stages of Glock's (1931) drainage-development series are represented here: extension and integration, with abstraction as the major process of integration. Capture occurred in two other instances. Examples of the straightening of the stream channels were numerous.

One other change of pattern noted is the lateral shift of the major tributaries toward the center of the basin. This migration toward a common axis within the system is gradual, but the asymmetry of all high-order transverse-valley profiles testifies to its presence.

A series of drainage patterns traced from the 1948 and 1952 maps (Fig. 22) illustrates some of the changes during that period. The basins illustrated have steep channel gradients, and erosion would be rapid. In addition, the fill is easily eroded and presents few structural obstacles to drainage-channel modifications.

The following generalizations summarize changes in the drainage network at Perth Amboy: A tributary to a channel of higher order develops with an entrance angle dependent on the ratio between channel and ground slope. Because of relatively slower degradation of the main channel, a downstream migration of the point of junction occurs with lessening of the entrance angle. If the ratio between main-channel gradient and tributary gradient remains constant (steady state), no changes in junction will occur except those caused by chance structural irregularities in the fill. As channel gradation spreads throughout the entire system the main-channel gradient will first reach an essentially constant value, but the tributary gradient will continue to lower, with a lessening of the junction angle. When the junction angle becomes very small, lateral planation removes the intervening divide, and the junction migrates upstream. Comparable evolution of stream-entrance angles and drainage patterns in other regions may occur only in youthful areas with a high relief ratio, but similarities between Perth Amboy and other areas in other aspects of drainage-basin morphology suggest that similar changes although perhaps less obvious, are nevertheless slowly occurring in all expanding drainage systems.

Because the observed drainage-pattern changes were occurring mainly as the stream channels were rapidly downcutting, any uplift of a land surface might initiate the same changes. Studies of drainage patterns on the Pleistocene terraces of the Atlantic Coast, for example, might indicate that height above base level and stage are correlatable with angles of junction.

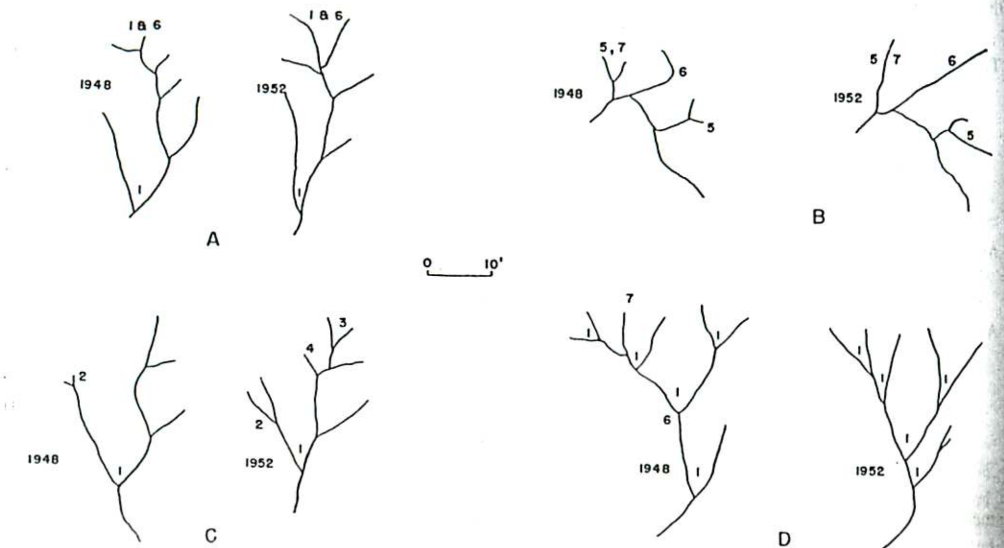


FIGURE 22.—DRAINAGE-PATTERN CHANGES IN SELECTED BASINS BETWEEN 1948 AND 1952 AT PERTH AMBOY

Basins A, C, and D are steep gradient streams. Basin B is a youthful basin on the upper surface of the terrace. Drainage changes are indicated by numbers on the figures:

1 Angle of junction change
2 Migration of junction
3 Bifurcation
4 Addition of tributary
5 Angle of bifurcation change
6 Channel straightening
7 Elimination of tributary

Evolution of the Perth Amboy Drainage Pattern

From the observed systematic drainage changes at Perth Amboy and the known development of a network within the limiting values of basin area, it may be possible to deduce from the existing pattern the initial and future patterns.

In the initial stage the steep front of the terrace was probably strongly rilled. Because the upper surface of the terrace drained toward the front the rills quickly advanced across the lip of the terrace onto the essentially flat upper surface. The channels most favored by chance encounter with weak patches of fill deepened and grew rapidly toward the divides of the individual small watersheds. These deeply cut permanent channels followed the path of initial drainage concentration manifested as faint channel traces on the upper surface. Channel traces of this type were observed at Perth Amboy in areas of headward channel development. The permanent channels follow these faint swales on the original surface because there the discharge of runoff is concentrated from the entire watershed. A headward developing incised channel is hydrophilic, advancing always toward maximum water supply.

The most vigorously developing initial rill channel thus dominated its less effective neighbors and established itself as the axis of a broadening ovate drainage basin. Its permanence was decided initially by a favored position in line with the axis of a shallow watershed on the terrace surface from which it was supplied with more runoff than its competitors. It may also have struck zones of weaker material in its bed. The added runoff allowed deepening of the drainage channel with corresponding oversteepening and collapse of its valley-side slopes. As soon as lateral expansion of the drainage basin produced sufficiently long slopes, tributary development set in on these slopes.

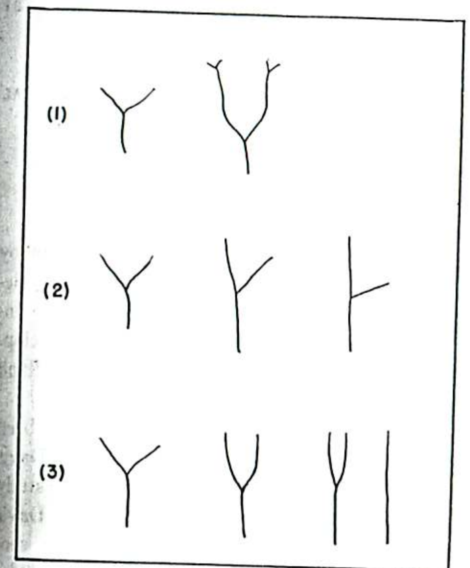


FIGURE 23.—POSSIBLE DEVELOPMENT OF ANGLES OF BIFURCATION

(1) Angle remains unchanged; (2) One channel becomes dominant; (3) On steepest slopes angles decrease and channels unite.

As the channel outstripped its neighbors the expanding drainage area permitted its bifurcation. The comparison of angles of bifurcation on the 1948 and 1952 maps suggests three predictions of possible future development of a bifurcated channel: (1) both segments of the bifurcated channel continue to grow headward unchanged in angle (Fig. 23, 1); (2) one segment becomes dominant and straightens its channel, while the other segment becomes tributary (Fig. 23, 2); (3) on steep slopes the angle of bifurcation reduces in accordance with the Sc/Sg ratio, and the two segments become one (Fig. 23, 3).

It is postulated that (2) occurred in the early stages of the Perth Amboy development, thus forming the first major tributary (Fig. 24, 1, 2). The tributary end grew normal to the main channel until it came under the influence of the forward slope of the terrace when its growth direction altered and its upper segment developed parallel to the main channel (Fig. 24, 3). Perhaps the next permanent bifurcation was as indicated in Figure 24, 3, followed by headward growth (Fig. 24, 4) and other branches and bifurcations to yield the major elements of the present pattern (Fig. 24, 5; Pl. 1).

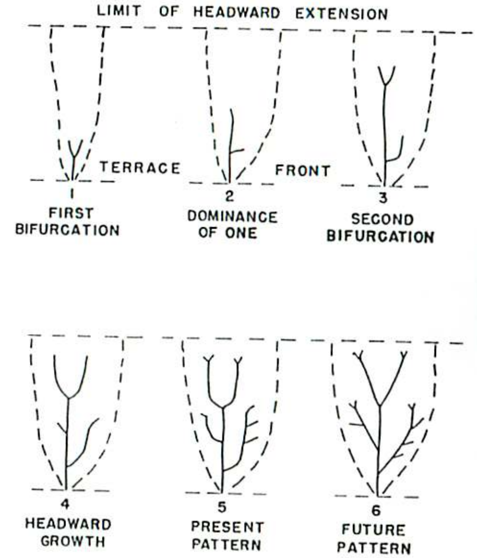


FIGURE 24.—SUGGESTED EVOLUTION OF THE PERTH AMBOY DRAINAGE PATTERN

As these streams incised their channels secondary tributaries formed on the slopes of the valley walls. These tributaries were under the influence of the rapidly degrading main channels; many still are in the youthful headwater areas. Figure 25 is a frequency-distribution histogram of the angles measured between tributaries and the segments of the main channel (Table 11). The modal class lies between limits of 90° and 100°, indicating a right-angle pattern in accordance with a low Sc/Sg ratio. The earliest-formed of these tributaries became the most important and hindered the development of younger neighbors on adjoining slopes. This is borne out by the fact that the mean distance separating first-order streams along the main channel (4.3 feet) is smaller than the mean distance separating first- and second-order stream channels (7.6 feet). Order number thus provides a rough means of classifying channels

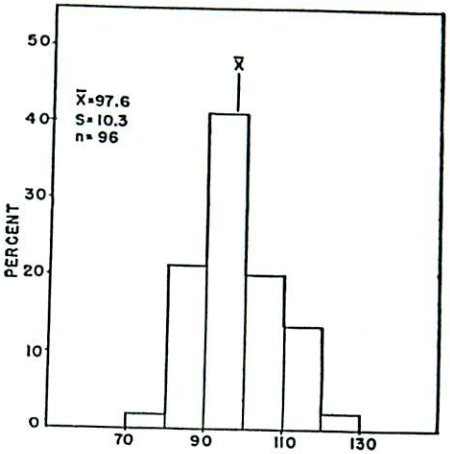


FIGURE 25.—FREQUENCY-DISTRIBUTION HISTOGRAMS OF ANGLES BETWEEN TRIBUTARIES AND SEGMENTS OF THE MAIN CHANNEL

TABLE 11.—FREQUENCY DISTRIBUTION OF ANGLES BETWEEN TRIBUTARIES AND MAIN CHANNEL

Sample	Mid-values in degrees						$\bar{x}$	s	N
	75	85	95	105	115	125			
Angles of junction	2	20	40	19	13	2	97.6	10.3	96

according to age; the oldest tributary channels have the higher order number.

The present faintly trellised pattern of the principal large-order channels (Fig. 24, 5; Pl. 1) is not considered permanent. It is supposed that the angles of junction become smaller with the increased Sc/Sg ratio, and the lateral shifting of the larger tributaries toward the main channel would result in the acute-angled dendritic drainage pattern that is typical of mature areas of simple structure. This change would involve considerable lateral planation and channel straightening, with a modified final pattern perhaps like that in Figure 24, 6.

If, as previously noted, a positive relationship exists between stream gradients, maximum slopes, and relative relief (expressed as the relief ratio), it follows that the Sc/Sg ratio should vary as the relief ratio. Because entrance angles, and therefore the total drainage pattern, are dependent on this Sc/Sg ratio, similar areas differing only in relative relief probably have recognizable differences in drainage pattern, at least in the early stages of development.

FIELD OBSERVATIONS AND EXPERIMENTAL STUDIES ON THE DEVELOPMENT OF BADLAND TOPOGRAPHY

Field-Erosion Measurements

Field and experimental work at Perth Amboy was designed both to verify conclusions derived from map analysis and to obtain new insight into processes operative in the development of erosional landforms of the badland type.

Many recent geomorphic studies have been strongly influenced by the work of W. M. Davis and Walther Penck. Each approached the study of landforms with a separate purpose. Davis considered description of landforms for geographical purposes the aim of the geomorphologist, whereas Penck attempted to use the development of landforms as a key to the Earth's recent structural history and the nature of the diastrophic forces.

A chief point of controversy between Davis and Penck is the manner of retreat of slopes. Penck (1953) maintained that on a stable mass initial stream incision produces steep, straight slopes which retreat at a constant angle, that upwardly convex slopes indicate accelerated uplift, and upwardly concave slopes decreasing rate of uplift. Davis (1909, p. 268) imagined that the angle of valley-side slopes normally declines with time and reduction of relief.

Erosion on slopes at Perth Amboy was measured to clarify the basic geomorphic problem of slope retreat under the limited conditions of badland erosion.

The measurement of erosion on the badland slopes was accomplished by simple and inexpensive means. Wooden dowels ¼ inch thick and 1½ feet long were driven into the slopes at 1-foot intervals on downslope profile lines, orthogonal to the contours from crest to base of each slope (Fig. 26), and normal to the slope until flush with the surface.

Stake profiles were placed on 16 diversely oriented slopes, some with sharp crests and others with convex divides. On Plate 1, short lines labeled "P" locate profile lines. All slopes were composed of similar material; all had a measurable exposure of the stakes. The length of stake exposed, measured to the nearest tenth of an inch, indicated the depth of erosion at that point on the slope. The last measurement was made on September 10, 1952, when

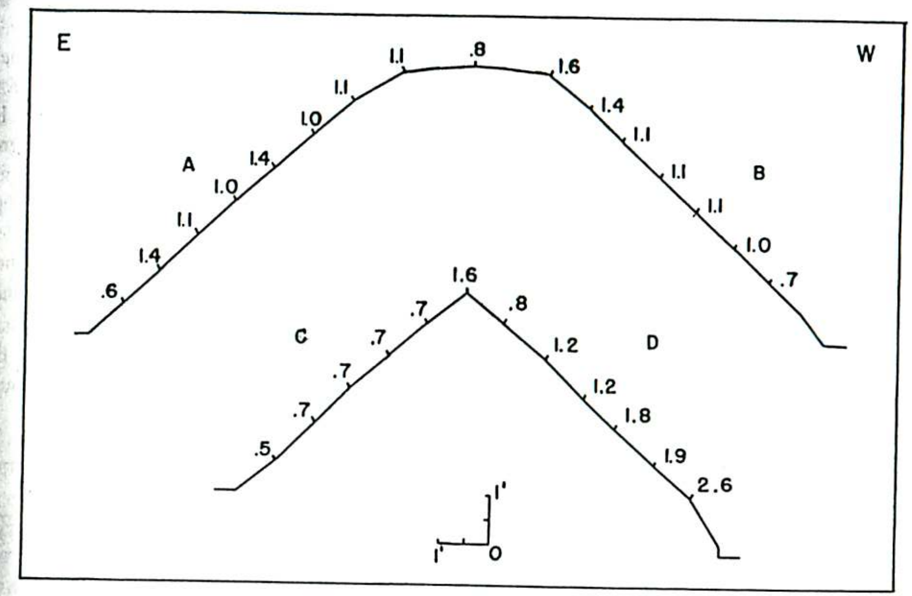


FIGURE 26.—TYPICAL PERTH AMBOY SLOPE PROFILES

Ticks on profiles show position of stakes; numbers indicate depth of erosion in inches. Profiles A, B, and C are typical of the area; profile D shows a basal convexity.

youthful, degrading, intermittent gully channel at the base. Slopes were selected, however, that showed no severe effects of rilling and offered no problem in the determination of a straight, downslope profile line. Slopes ranged from 6 to 14 feet long. The 16 profiles were installed on June 15 and July 1, 1952, but because a negligible amount of erosion occurred between those dates, they are treated as a group.

Slope angle and distance between successive stakes were measured at the time of installation, and the original slope profiles thus plotted. All profiles are remarkably straight except for those segments forming convex divides or where minor irregularities occur (Fig. 26). The straightness of profiles is characteristic of maturely dissected regions of steep slopes of widely differing scales of length, formed under various climatic and geologic conditions (Lawson, 1932, p. 711; Strahler, 1950, p. 681).

Measurement of erosion on the slopes began after the first runoff sufficient to produce a the measurement of slope angle and distance between successive stakes was repeated. During the 10 weeks of observation the depth of erosion differed both from slope to slope and from point to point on each slope. Erosion depth was greatest on sharp-crested divides and least on convex divides, but seemed to be essentially uniform along the straight segments of each slope, where a mean of 0.9 inch of material was removed.

Only two of the slopes investigated showed a measurable change of angle. Both had steepened, but neither had a simple, straight profile at the starting date in June. Slight convexities initially existing at the slope base caused increased erosion at those points so that, by the end of the observation period, the characteristic straight profile had been restored. Slope D (Fig. 26) shows this steeper basal segment caused by rapid channel undercutting. To determine significant increase or decrease of slope angle, only the straight parts of the profiles were used.

Erosion depth obtained from stakes on the convex divides, on sharp-crested divides, and in channel bottoms were eliminated by discarding all values of stakes at the crest or base of the

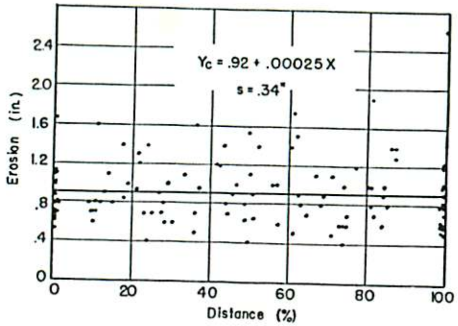


FIGURE 27.—REGRESSION FITTED TO A SCATTER DIAGRAM OF DEPTH OF EROSION ON PER CENT OF DISTANCE FROM TOP OF THE STRAIGHT SLOPE SEGMENT

erosion depths fall between 0.4 and 1.6 inches. On a given profile the depth of erosion was generally highly uniform for all stakes, whereas the mean depth differed considerably from one profile to another. Because absolute values for erosion are plotted on the ordinate the broad scatter zone produced (Fig. 27) fails to reveal the uniformity of erosion depth on a single slope. The marked differences in average from one profile to the next may be explained by variations in microclimatic environment, degree of compaction and permeability of the clay fill, or by slight compositional variations from slope to slope. For example, mean erosion on one slope was 0.6 inch but on another 1.3 inches. Consequently, when all readings are combined on one diagram, the scatter of points is wide.

A regression line fitted to the points of the scatter diagram by the method of least squares

TABLE 12.—EROSION MEASURED ALONG THE SLOPE PROFILES

Stake No.	Erosion at each stake in inches													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Profile														
A1	1.6*	.7	.7	.7	.7	.5	...	...	...	....	..	..	..	..
A2	.8*	1.7	1.4	1.1	1.1	1.1	1.0	.7	...	....	..	..	..	..
A3	.8*	1.1	1.1	1.0	1.4	1.0	1.1	1.4	.6	....	..	..	..	..
B1	.7*	1.1	1.0	1.4	1.2	1.2	...	...	...	....	..	..	..	..
B2	.3*	.5	.9	.8	.8	.6	.5	.6	...	....	..	..	..	..
C	.3*	.5*	.7	.8	.6	1.0	.8	1.0	.6	....	..	..	..	..
D1	1.3*	.8	.6	.7	.7	.8	.9	.7	.8	....	..	..	..	..
D2	1.3*	.9	1.0	.4	.4	1.0	...	...	...	....	..	..	..	..
E1	1.5*	.8	1.2	1.2	1.8	1.9	2.6	...	...	....	..	..	..	..
F	1.0*	.9*	.7	.7	.6	.4	.8	.8	.9	2.3*	..	..	..	..
G	.3*	.6	.8	.4	.5	.7	.5	1.0	1.4	1.2	..	..	..	..
H	.4*	1.1	1.3	1.2	1.4	1.0	1.0	...	...	....	..	..	..	..
I	.8*	.9*	1.0	.8	.9	.7	1.0	.9	1.0	.7	.6	.9	.8	.6
J	.8*	1.0	.9	.9	.6	.6	...	...	...	....	..	..	..	..
K	.7*	.7*	.8	1.6	1.4	1.6	1.6	1.5	.6	1.3	..	..	..	..
L	.7*	.9	.8	.7	.9	.8	.5	...	...	....	..	..	..	..

* Reading eliminated from regression Figure 27.

slope profile which deviated by 10° or more from the straight segment. These values are nevertheless listed (Fig. 27; Table 12) with the 113 readings of erosion depth that remained. These remaining values were combined into one scatter diagram by the use of a dimensionless parameter: per cent of distance from upper to lower end of the straight slope segment. Most

(Croxton and Cowden, 1939, p. 655–657) has the equation

$$Y_c = 0.92 - .00025X.$$

A *t*-test, to determine the validity of the null hypothesis that the deviation from zero slope, shown by the regression equation, can be attributed to chance sample variations alone

when sampling from a population with zero slope, reveals a probability greater than 0.65. Thus at least 65 times in 100 this great a trend or greater would occur. Lack of significant trend suggests that erosion is uniform along the straight segment of the slopes.

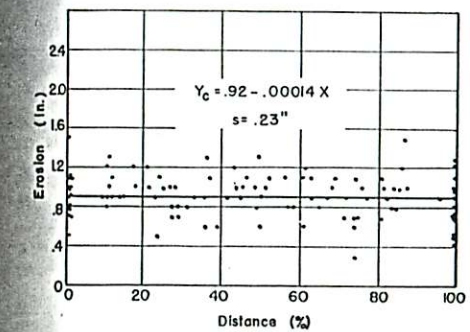


FIGURE 28.—REGRESSION LINE FITTED TO ADJUSTED VALUES OF FIGURE 27

In order to take into account the uniformity of erosion depth on a given slope profile and decrease the scatter about the regression line the mean of erosion for each slope was adjusted by addition or subtraction to equal the mean of all, 0.92 inch. Thus independent, and for this purpose, irrelevant variations in erosion from slope to slope were minimized. For example, to the values of one profile for which the mean depth of erosion is 0.6, a constant, 0.32, was added in order to increase the sample mean to 0.92. An appropriate constant was subtracted from each mean greater than 0.92 and added to each less than 0.92. Figure 28 shows the decreased scatter produced by plotting the adjusted values. In addition to adjusting the means of each slope profile, the data of one profile (Fig. 26, D) were eliminated because the basal segment of this slope had been abnormally steepened by channel undercutting. Because the inclusion of this abnormal profile in the regression analysis of Figure 27 did not produce a significant trend, its elimination here would have little effect on the acceptance of the null hypothesis. The regression line fitted to the data on Figure 28 has the equation

$$Y_c = 0.92 - .00014X.$$

The estimated standard deviation, *s*, of the regression is decreased by 0.2 inch from the value for the unadjusted regression line in Figure 27. The probability of this great a departure from zero slope by chance sample variations alone is found to be greater than 70 per cent, again sustaining the null hypothesis.

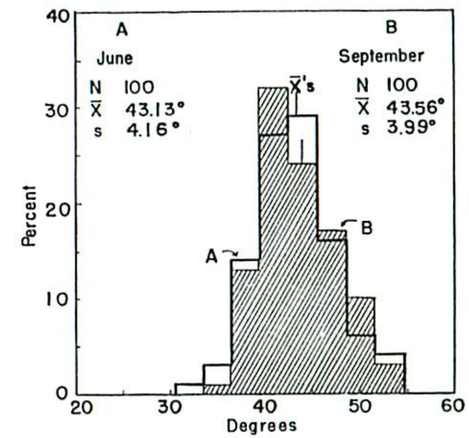
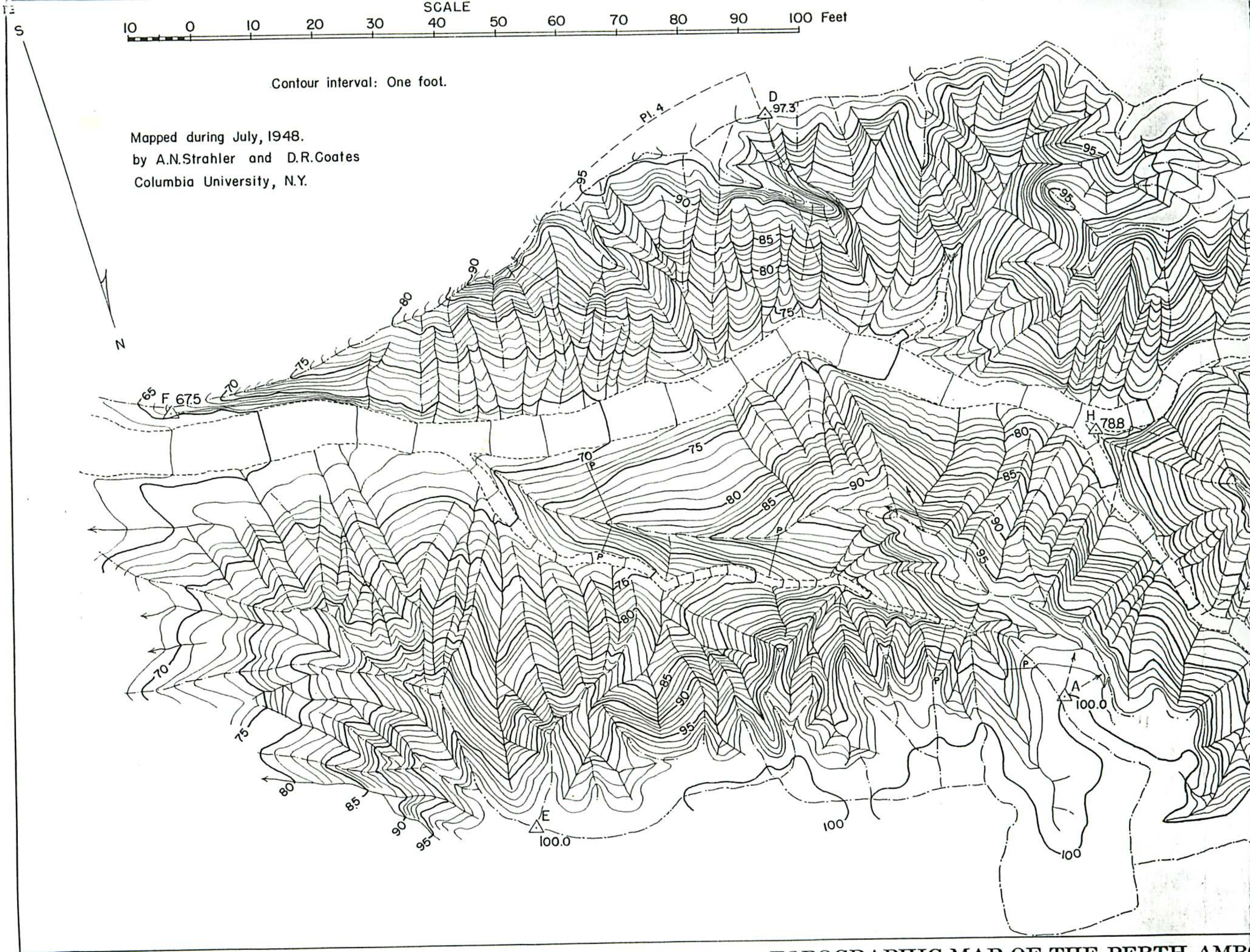
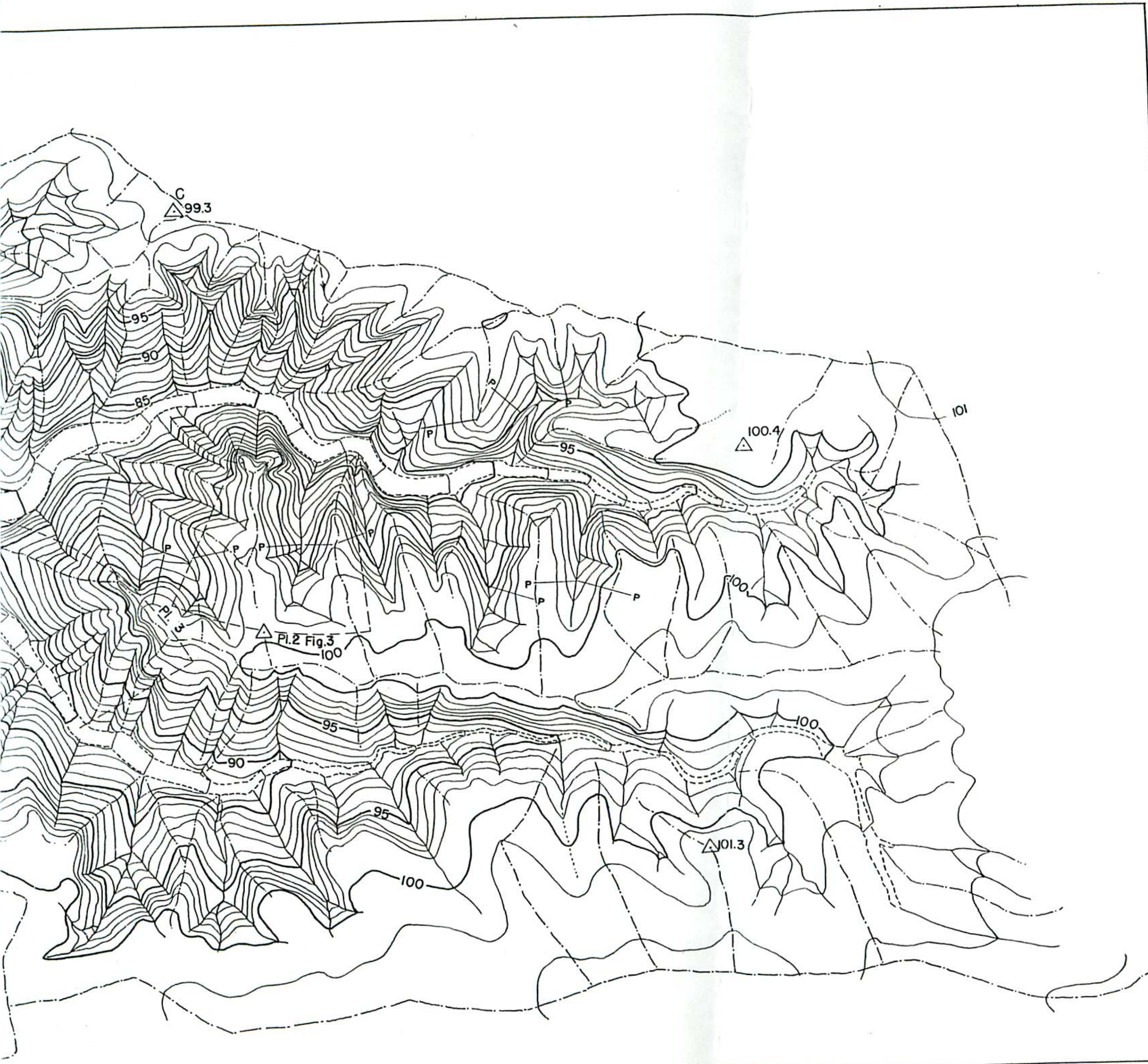


FIGURE 29.—FREQUENCY-DISTRIBUTION HISTOGRAM OF ANGLES BETWEEN STAKES MEASURED IN SEPTEMBER SUPERIMPOSED ON HISTOGRAM OF ANGLES MEASURED IN JUNE

It is possible to check the conclusion suggested by the previous tests because the slope angles between surface points at successive stakes had been measured both at the beginning of the investigation and at the end. Consequently, a lack of significant difference between the means of these two slope-angle samples would support the hypothesis of uniform erosion depth. Again end values deviating 10° or more from the straight profile lines were discarded. One hundred slope angles measured in June and July remained, and the corresponding angles measured in September were similarly selected. Because each angle refers to 1 foot only of the slope profile, any change of slope angle along the straight slope segment would be recorded. Figure 29 (Table 13) shows the frequency-distribution histogram of the angles measured in September superimposed on that of the angles measured in June. The means of the two samples differ by half a degree. Because the September slope-angle measurements were taken at the same profile points as the June–July slope angles, the sample data are paired. Where sample observations are paired in this way the mean of the differences is tested under



TOPOGRAPHIC MAP OF THE PERTH AMBO



ERTH AMBOY BADLANDS

Much work must be done before a workable theory of erosional landform development can be projected from detailed field examination and measurements of topographic characteristics and geomorphic processes, but there is no alternative to an empirical quantitative approach if these relationships are to be clarified in realistic terms.

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