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# Some Relations Between Streamflow Characteristics and the Environment in the Delaware River Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 417-B

# Some Relations Between Streamflow Characteristics and the Environment in the Delaware River Region

*By* A. G. HELY *and* F. H. OLMSTED

CONTRIBUTIONS TO STREAM-BASIN HYDROLOGY

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# SOME RELATIONS BETWEEN STREAMFLOW CHARACTERISTICS AND THE ENVIRONMENT IN THE DELAWARE RIVER REGION

By A. G. Hely and F. H. Olmsted


## ABSTRACT

Streamflow characteristics are determined by a large number of factors of the meteorological and terrestrial environments. Because of lack of quantitative data to describe some of the factors and complex interrelations among them, complete analysis of the relations between streamflow and the various environmental factors is impossible. However, certain simplifying assumptions and generalizations made possible a partial analysis for the Delaware River region.

For relations involving average runoff or low-flow parameters, average annual precipitation was assumed to be the principal meteorological factor, and geology (a complex of many factors) was assumed to be the principal terrestrial influence, except for that of basin size which was largely eliminated by expression of discharge in terms of unit area.

As a first approximation, physiographic units were used as a basis for classifying the geology. Relations between flow parameters and precipitation are fairly well defined for some physiographic units, but not for those in which the geology varies markedly or the areal variation in average precipitation is very small. These relations provide a basis for adjusting the flow parameters to reduce or eliminate the effects of areal variations in precipitation and increase their significance in studies of the effects of terrestrial characteristics.

An investigation of the residual effect of basin size (the effect remaining when discharge is expressed in terms of unit area) on relations between flow parameters and average precipitation indicates that such effect is negligible, except for very large differences in area.

Parameters that are derived from base-flow recession curves and are related to a common discharge per unit area have inherent advantages as indicators of effects of terrestrial characteristics of basins, because they are independent of areal variations in average annual precipitation. Winter base-flow parameters are also practically independent of the effects of evapotranspiration from ground water. However, in many parts of the region these advantages are reduced or nullified by the difficulties of defining base-flow recession curves, particularly winter curves, with sufficient accuracy.

In the absence of suitable base-flow recession data and a suitable basis for adjusting parameters, the ratio of the discharge equaled or exceeded 90 percent of the time to the average discharge ($Q_{90}/Q_a$), or a similar duration parameter, probably is the best indicator of the influence of terrestrial characteristics, although the ratio may vary somewhat with average precipitation.

In a part of the region where geologic differences are large and areal variations in average precipitation are small, values of $Q_{90}/Q_a$ for each major geologic unit were determined from streamflow records. From these values and the percentage of area represented by each unit, a ratio for each gaging station was computed. Comparison of these computed results with the observed results indicates that nearly all of the variation in the ratio is associated with variation in geology.

The investigation indicates that the original assumptions are correct; average precipitation is the principal meteorological influence and geology is the principal terrestrial influence. Together these two factors account for a very large proportion of the variation in average runoff and low-flow characteristics.


## INTRODUCTION

The quantity and distribution of water in the hydrologic cycle of any region are determined by the meteorological and terrestrial environments. Many characteristics of these environments influence streamflow, and although some of the characteristics can be measured, others can only be described. Interrelations among the characteristics, and changes resulting from man's activities, add to the difficulty of analysis. As a result, for large areas, knowledge of the relations between streamflow characteristics and environment tends to be qualitative rather than quantitative. Quantitative results have been obtained for some relations but these are limited to small, experimental watersheds.

This report presents results of a study of relations between streamflow characteristics, particularly low flows, and the most significant characteristics of the environment. Relations for the entire study area are examined first. These must necessarily be based on a highly generalized classification of terrestrial characteristics (physiographic provinces and subprovinces). Therefore, a more detailed classification of geology in a part of the area that is characterized by large differences in geology but small differences in average annual precipitation was made so that a better comparison of geologic characteristics and streamflow could be made.

Although geology is a complex of many separate factors, it was necessary to resort to the simplification of treating geology as a single factor in parts of the study.

Because of the many factors that affect streamflow, the relations developed are not independent of influences not considered in the analysis; they are comparable to first approximations in a multiple correlation. Lack of sufficiently detailed information to complete the correlation generally precludes much refinement of the first approximations. Nevertheless, the authors believe that the relations developed contribute to better understanding of the influences on streamflow of geology and average annual precipitation, and such understanding is essential to evaluation of effects of less significant factors, such as changes in land use.

Most of the data used in this study were compiled for a report on the water resources of the Delaware River basin and some adjoining areas to the east (Parker and others, 1963). Data for some gaging stations in the northern part of the Susquehanna River basin were added because their inclusion made possible the extension of some relations developed for the Delaware River basin, and also because streamflow parameters were needed for use in a related study involving these drainage areas. The study area is shown on plate 1.

## METEOROLOGICAL AND TERRESTRIAL ENVIRONMENTS

The principal meteorological factors affecting water resources are precipitation and temperature. The former is the source of the water, the latter affects natural water loss by evapotranspiration and also the time distribution of streamflow and ground-water recharge when subfreezing temperatures cause temporary storage of moisture as snow, ice, or backwater in stream channels.

Although short-term rates of precipitation are important in studies of flood characteristics, long-term averages and seasonal variations are more significant in studies of low-flow characteristics. In the study area the long-term averages have a wide range but the seasonal distribution of precipitation is similar in all parts of the area. Consequently, the long-term average is a suitable parameter for use in comparisons of streamflow characteristics and the meteorological environment. Averages for the period 1921–50 are shown in table 1, which summarizes streamflow parameters also.

Average annual precipitation on areas in the Susquehanna River basin was estimated by D. R. Coates (written communication, 1959) from an unpublished isohyetal map prepared by T. E. A. van Hylckama of the Geological Survey. Precipitation on other areas was computed from an isohyetal map of the Delaware River basin and New Jersey (Hely, Nordenson, and others, 1961).

The temporary-storage effect of temperature is relatively unimportant in this study because the season of subfreezing temperatures is a season of relatively high runoff. The effect on annual evapotranspiration, which ranges from 18 inches in the northern part of the area to about 27 inches [1] in the southern part, is more significant. As streamflow is the residual of precipitation minus evapotranspiration (or water loss if underground outflow is significant), the relations between some streamflow parameters and precipitation include effects of temperature.

The terrestrial environment may be classified and measured or described in many different ways. Among the principal factors that influence streamflow parameters are: (a) basin size; (b) basin shape; (c) topography; (d) geology; (e) vegetation; and (f) pavements and structures on land surfaces or in stream channels. Many of these factors are interrelated and it is difficult, or impossible, to separate some of the effects.

The size of the basin is one of the most obvious and important characteristics. Fortunately, its effects on the parameters studied are readily eliminated or reduced to a small residual by expressing streamflow in terms of unit area, or as depth of water on the area, and this procedure is followed throughout the report.

Some characteristics, such as basin shape, influence the magnitude of flood peaks, but have relatively little effect on low flows. The nature of the vegetation, soils, underlying rocks, and the proportion of impervious cover, and the amount of surface storage available largely determine the capacity of a basin to absorb and store precipitation. The latter factors, therefore, have important effects on both low flows and floods.

In parts of the Delaware River basin the effects on low flows of differences in rocks and soils are much greater than the effects of differences in average annual precipitation. Although geology generally cannot be described adequately by parameters, sometimes it is possible to classify areas in some manner to account for major differences in geology. A logical basis for such a classification would be rock types, such as crystalline rocks, carbonate rocks, sandstone, shale, and sand and gravel. However, the geology of most basins in the region of this study is so complex that a more general classification was necessary.

The physiographic units indicated on plate 1 provide a basis for such classification. The hydrologic properties of rocks in some of these units are relatively uniform, but in others there is great variation. Thus, the classification satisfies the requirements only in part but serves as a basis for a first step in defining relations between average annual precipitation, geology, and streamflow.

[1] Natural water loss ranges from 18 to 29 inches but part of the higher losses probably consists of underground outflow.

The region considered lies within two major physiographic divisions, as classified by Fenneman and others (1930): the Atlantic Plain southeast of the Fall Line, and the Appalachian Highlands northwest of the Fall Line. In the Atlantic Plain only the Coastal Plain province is above sea level. This is an area of gentle topography underlain by a seaward-thickening wedge of unconsolidated deposits. The Appalachian Highlands, by contrast, are characterized by more rugged topography and are underlain by consolidated rocks of generally complex geologic structure. The northern part of the highlands was occupied several times by large continental glaciers which modified the topography and left behind extensive deposits of glacial drift.

The region studied includes parts of four provinces within the Appalachian Highlands division: (a) The Piedmont; (b) the New England; (c) the Valley and Ridge; and (d) the Appalachian Plateaus (Fenneman and others, 1930). The provinces are further subdivided into sections or subprovinces, each of which has distinctive topographic characteristics related to the lithology and structure of the rocks and to the geologic history. The boundaries shown on plate 1 are modied and refined somewhat from those of Fenneman and others. The physiographic units used in this report are described in the following paragraphs.

*Coastal Plain.*—The Coastal Plain is a nearly flat to moderately hilly area traversed by streams of gentle gradient which are tidal in their lower reaches. Altitudes reach a maximum of nearly 400 feet above sea level in east-central New Jersey, but more than half the plain is below an altitude of 100 feet. Average land slopes range from about 50 feet per mile in the sandy outer parts to about 250 feet per mile in the hilly northeastern part (data from Langbein and others, 1947).

*Piedmont Upland.*—The Piedmont Upland is the southern section of the Piedmont province. It is a moderately to strongly dissected plateau ranging in altitude from nearly sea level to more than 600 feet. Land slopes average about 450 feet per mile—markedly steeper than in the adjacent Coastal Plain and Triassic Lowland. Most of the area is underlain by crystalline rocks, chiefly schist, gneiss, quartzite, and granitic to ultramafic rocks. These rocks are commonly weathered to depths of several tens of feet. Chester Valley, a straight, narrow lowland trending slightly south of west across the area, is underlain by carbonate rocks (limestone and dolomite) which are somewhat soluble and less resistant to erosion than the adjacent crystalline rocks. The northernmost part of the Piedmont Upland—an area about 2 to 10 miles wide just south of the Schuylkill River between Reading and Phoenixville, Pa.—is underlain by conglomerate and sandstone of Triassic age. This area is included in the Piedmont Upland rather than in the Triassic Lowland because its topography is more like that of the rest of the Piedmont Upland.

*Triassic Lowland.*—The Triassic Lowland, or Piedmont Lowlands as designated by Fenneman and others (1930), is the northern section of the Piedmont province and is generally lower and less rugged than the Piedmont Upland. The underlying rocks, of Triassic age, consist of relatively soft red shale and fine sandstone and of harder diabase, basalt, and argillite, which form ridges, hills, and plateau surfaces. The depth of intense weathering is not as great in most of these rocks as in the crystalline rocks. Average land slopes in the area are about 250 feet per mile—distinctly less than in the bordering Piedmont and New England Uplands, but more than in most of the Coastal Plain.

*New England Upland.*—The New England Upland is the only section of the New England province in the study area. This area commonly is called the Reading Prong in Pennsylvania and the highlands in New Jersey. The topography is characterized by somewhat irregular, subparallel ridges formed of crystalline rocks similar to those in the Piedmont Upland, and intervening valleys formed of weaker rocks, principally carbonate rocks and some shale. The ridges rise from 300 to 800 feet above the valleys and have slopes that range from about 600 to more than 800 feet per mile—decidedly greater on the average than the slopes on the similar rocks in the Piedmont Upland. Most of the New England Upland has been glaciated, although only the northeastern part, in New Jersey, was occupied by the ice of the latest (Wisconsin) stage (pl. 1). In the area of Wisconsin glaciation deposits of till extensively mantle the ridges, and the valleys contain thicker deposits, largely outwash, which nearly everywhere conceal the underlying bedrock. Ponds and marshes characterize the lower parts of the valleys at many places.

*The Great Valley.*—The Valley and Ridge province may be conveniently divided into two subprovinces: The Great Valley which lies between the New England Upland and the ridge known as Blue Mountain in Pennsylvania, Kittatinny Mountains in New Jersey, and Shawangunk Mountains in New York; and a sequence of valleys and ridges to the north, which will, for convenience, be called Valleys and Ridges. The Great Valley, which is a relatively broad lowland ranging in width from 8 to 20 miles, consists of 2 belts of strongly contrasting geology and topography. The southern, narrower, belt is a gently sloping lowland underlain by relatively weak carbonate rocks of complex structure. The northern belt, which rises several hundred feet above the southern lowland along a prominent escarpment, is a dissected surface underlain by more resistant shale, slate, and sandstone beds which also are complexly folded and faulted. The land slope averages about 500 to 550 feet per mile in the northern belt as compared with 200 to 300 feet per mile in the southern belt. The northeastern part of the Great Valley was glaciated, and, like the New England Upland, is largely covered by glacial deposits.

*Valleys and Ridges.*—From Blue Mountain northward to the Appalachian Plateaus the topography is characterized by alternating long, narrow ridges and valleys which extend generally northeast but at many places curve, bend abruptly, or zig-zag according to the trends of the folded structure. The conspicuous ridges are formed of relatively resistant rocks, such as thick-bedded quartzose sandstone and conglomerate, and rise to rather uniform altitudes of 1,500 to 2,000 feet. Lower ridges are underlain by more thinly bedded and softer sandstone and shale, and the valleys are formed of the least resistant shale and carbonate rocks. In the glaciated area most of the larger valleys are occupied by thick deposits of outwash.

*Southern New York section*—The Appalachian Plateaus are underlain by sandstone, shale, and conglomerate similar to the rocks in the adjacent Valley and Ridge province, but the strata are horizontal to gently folded rather than strongly folded and faulted as in the Valley and Ridge province. The southern and western parts of the Appalachian Plateaus are designated the southern New York section (Fenneman and others, 1930). This area is a slightly to moderately dissected plateau lying mostly between altitudes of 1,000 and 1,500 feet. Almost all the plateau has been glaciated; till is extensive but thin, and the larger valleys contain deposits of outwash locally more than 200 feet thick. The drainage has been considerably modified by the effects of the ice, and lakes and marshes dot the flatter parts of the plateau, especially in northeastern Pennsylvania. The principal streams have cut deep, narrow valleys across the region.

*Catskill Mountains.*—The Catskill Mountains form the higher, more rugged section of the Appalachian Plateaus; they differ from the southern New York section chiefly in altitude and relief and in the generally greater proportion of coarse sandstone and conglomerate. Several summits in the Catskill Mountains exceed 4,000 feet in altitude. The boundary of the section is vague and somewhat arbitrary.

## STREAMFLOW PARAMETERS

Large masses of streamflow data are difficult to study or utilize for many purposes unless they can be described by a few distinctive parameters.[2] Many parameters have been used and each provides a numerical measure of some aspect of streamflow. One parameter may be particularly well suited for one purpose and another for a different purpose. If a study is concerned only with rates or amounts of streamflow corresponding to specified conditions, there is generally little or no difficulty in selecting a proper parameter. However, if the study involves the effects of various factors, such as precipitation or some physical characteristic of the basins, the choice is not as simple because each parameter is affected to a different extent by these factors. Information on the nature of these effects aids the hydrologist in selecting parameters and interpreting results of investigations.

Most of the parameters that are commonly used to characterize streamflow are included in four principal classes: (a) Average flows, (b) flow duration, (c) flow frequency, and (d) base flow. Parameters from each of these classes are discussed in following sections:

The locations of the gaging stations used are indicated on plate 1. The station names, the principal physiographic units represented in each basin, and the parameters used are listed in table 1.

## AVERAGE ANNUAL RUNOFF

The average runoff [3] is generally readily available or easily computed and is generally the most useful single streamflow statistic because it can be used to compute total quantities. Although the geologic environment may have marked effects on the average runoff, the average is much less sensitive to geologic differences than are many other parameters because the effects of seasonal changes in storage are minimized. Relations between average annual runoff and precipitation for five of the eight physiographic units are shown in figure 1.

Of the areas studied, the Catskill Mountains have the greatest range in precipitation and the best defined relation. The scatter of the points about the relation line may be attributed chiefly to local differences in geology. However, the point that has the greatest departure from the line represents a small area where the isohyetal lines are closely spaced and an error of 2 inches or more in the average precipitation is possible. Furthermore, some local concentrations of ground water due to the arrangement of fractures in the bedrock are known to exist in the eastern part of the Catskill Mountains and

[2] "Parameter," as used in this report, refers to a characteristic that can be measured as compared with a characteristic that can only be described.

[3] Runoff is streamflow that is not affected by regulation or diversion, and is computed from streamflow records by adjusting for diversion or changes in storage.

TABLE 1.—*Summary of hydrologic parameters for selected gaging stations in Delaware River region*

[Physiographic units: Catskill Mountains (CM), Southern New York section (SNY), Valleys and Ridges (VR), Great Valley (GV), New England Upland (NE), Triassic Lowland (TL); Piedmont Upland (PU), Coastal Plain (CP). $Q_{90}$ estimated from monthly data except as noted.]

| Index No. (See pl 1) | Gaging station | Physiographic units [1] | Drainage area (sq mi) | Averages, 1921–50 | | | $Q_{90}/Q_a$ | $Q_{90}$ (cfsm) | 7-day flow [2] (cfsm) | $R_s$[3] (in) | $R_{1.0}$[4] (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Precipitation (in) | Runoff (in) | Discharge (cfsm) | | | | | |
| | **Hudson River basin** | | | | | | | | | | |
| 1 | Schoharie Creek at Prattsville, N.Y. | CM | 236 | 44.1 | 24.9 | 1.84 | 0.060 | 0.11 | | | 0.37 |
| 2 | Esopus Creek at Coldbrook, N.Y. | CM | 192 | 49.4 | 30.5 | 2.25 | .085 | .19 | | | |
| 3 | Rondout Creek at Lowes Corner, N.Y. | CM | 38.5 | 53.2 | 33.2 | 2.45 | .14 | .34 | | | .56 |
| 4 | Chestnut Creek at Grahamsville, N.Y. | CM | 20.9 | 47.0 | 24.9 | 1.83 | .14 | .26 | | | .56 |
| | **Eastern New Jersey** | | | | | | | | | | |
| 5 | Passaic River near Millington, N.J. | TL | 55.4 | 47.6 | 21.8 | 1.61 | [5] 0.100 | [5] 0.16 | | | |
| 6 | Ramapo River near Mahwah, N.J. | NE | 118 | 44.4 | 23.8 | 1.75 | [5] .14 | [5] .24 | | | |
| 7 | South Branch Raritan River near High Bridge, N.J. | NE | 65.3 | 47.5 | 23.7 | 1.75 | .29 | .51 | | | |
| 8 | South Branch Raritan River at Stanton, N.J. | NE | 147 | 46.1 | 21.8 | 1.61 | [5] .24 | [5] .39 | | | |
| 9 | Neshanic River at Reaville, N.J. | TL | 25.7 | 44.3 | 18.0 | 1.33 | [5] .047 | [5] .062 | | | |
| 10 | South River at Old Bridge, N.J. | CP | 94.6 | 45.8 | 23.6 | 1.74 | | | | | |
| 11 | Deep Run near Browntown, N.J. | CP | 8.07 | 44.5 | 21.3 | 1.57 | | | | | |
| 12 | Matawan Creek at Matawan, N.J. | CP | 6.11 | 44.5 | 21.8 | 1.61 | | | | | |
| 13 | Swimming River near Red Bank, N.J. | CP | 48.5 | 45.1 | 21.0 | 1.55 | | | | | |
| 14 | Manasquan River at Squankum, N.J. | CP | 43.4 | 45.7 | 22.1 | 1.63 | .35 | .57 | | | |
| 15 | Toms River near Toms River, N.J. | CP | 124 | 45.9 | 21.9 | 1.61 | [5] .49 | [5] .79 | | | |
| 16 | Cedar Creek at Lanoka Harbor, N.J. | CP | 56.0 | 47.0 | 24.7 | 1.82 | | | | | |
| 17 | Batsto River at Batsto, N.J. | CP | 70.5 | 46.2 | 23.8 | 1.75 | .47 | .82 | 0.784 | 1.41 | 0.83 |
| 18 | East Branch Wading River at Harrisville, N.J. | CP | 64.0 | 44.0 | 17.6 | 1.30 | .44 | .57 | .485 | 1.02 | .80 |
| 19 | Absecon Creek at Absecon, N.J. | CP | 16.6 | 44.0 | 21.6 | 1.59 | | | | | |
| 20 | Great Egg Harbor River at Folsom, N.J. | CP | 56.3 | 46.1 | 19.7 | 1.45 | .42 | .61 | .564 | 1.11 | .80 |
| 21 | Maurice River at Norma, N.J. | CP | 113 | 45.5 | 19.2 | 1.41 | [5] .461 | [5] .65 | .550 | | |
| 22 | Manantico Creek near Millville, N.J. | CP | 22.3 | 45.5 | 21.9 | 1.61 | .48 | .77 | .592 | | |
| | **Delaware River basin (including areas tributary to Delaware Bay)** | | | | | | | | | | |
| 23 | East Branch Delaware River at Margaretville, N.Y. | CM | 163 | 44.0 | 25.1 | 1.85 | .10 | .18 | .141 | .69 | .40 |
| 24 | Platte Kill at Dunraven, N.Y. | CM | 34.7 | 43.0 | 24.7 | 1.82 | .090 | .16 | .112 | .58 | .33 |
| 25 | Mill Brook at Arena, N.Y. | CM | 25.0 | 48.8 | 30.8 | 2.27 | .12 | .27 | .184 | .85 | .44 |
| 26 | Tremper Kill near Shavertown, N.Y. | CM | 33.0 | 43.7 | 25.5 | 1.88 | .10 | .19 | .120 | .66 | .38 |
| 27 | Terry Clove Kill near Pepacton, N.Y. | CM | 14.1 | 44.0 | 25.5 | 1.88 | .10 | .19 | .082 | .55 | .32 |
| 28 | Fall Clove Kill near Pepacton, N.Y. | CM | 10.9 | 44.0 | | | | | .088 | | |
| 29 | Coles Clove Kill near Pepacton, N.Y. | CM | 28.0 | 44.0 | | | | | .077 | | |
| 30 | East Branch Delaware River at Downsville, N.Y. | CM | 373 | 44.5 | 25.9 | 1.91 | .11 | .21 | .143 | | |
| 31 | East Branch Delaware River at Harvard, N.Y. | CM | 443 | 44.7 | 26.2 | 1.93 | .11 | .21 | .154 | | |
| 32 | Beaver Kill near Turnwood, N.Y. | CM | 40.8 | 54.8 | | | | | .316 | 1.19 | .58 |
| 33 | Beaver Kill at Craigie Clair, N.Y. | CM | 82 | 51.8 | 33.7 | 2.48 | .14 | .35 | .259 | 1.30 | .56 |
| 34 | Willowemoc Creek at Debruce, N.Y. | CM | 40.9 | 53.5 | | | | | .296 | | |
| 35 | Willowemoc Creek near Livingston Manor, N.Y. | CM | 63 | 52.0 | 32.9 | 2.42 | .16 | .39 | .305 | .80 | .44 |
| 36 | Little Beaver Kill near Livingston Manor, N.Y. | CM | 19.8 | 49.3 | 31.1 | 2.29 | [5] .127 | [5] .29 | .183 | .92 | .47 |
| 37 | Beaver Kill at Cooks Falls, N.Y. | CM | 241 | 50.1 | 31.6 | 2.32 | .16 | .37 | .260 | 1.01 | .53 |
| 38 | East Branch Delaware River at Fishs Eddy, N.Y. | CM | 783 | 46.6 | 28.6 | 2.11 | [5] .141 | [5] .30 | .192 | .75 | .42 |
| 39 | West Branch Delaware River at Delhi, N.Y. | CM | 142 | 41.5 | 22.7 | 1.67 | .085 | .14 | .118 | .59 | .39 |
| 40 | Little Delaware River near Delhi, N.Y. | CM | 49.8 | 42.7 | 24.6 | 1.81 | .078 | .14 | .115 | .59 | .35 |
| 41 | Trout creek at Cannonsville, N.Y | CM | 49.5 | 43.4 | 24.8 | 1.83 | .11 | .20 | .133 | .57 | .37 |
| 42 | Oquaga Creek at Deposit, N.Y. | CM, SNY | 66 | 43.0 | 24.2 | 1.78 | .085 | .15 | .072 | .49 | .29 |
| 43 | West Branch Delaware River at Hale Eddy, N.Y. | CM | 593 | 42.6 | 24.2 | 1.78 | [5] .120 | [5] .21 | .138 | .65 | .42 |
| 44 | Callicoon Creek at Callicoon, N.Y. | CM, SNY | 111 | 42.8 | 22.6 | 1.67 | .10 | .17 | .133 | .52 | .36 |
| 45 | Tenmile River at Tusten, N.Y. | SNY | 45.0 | 40.9 | | | | | .094 | .52 | .38 |
| 46 | West Branch Lackawaxen River at Prompton, Pa. | SNY | 59.7 | 45.1 | | | .16 | .30 | .201 | | |
| 47 | Dyberry Creek at Dyberry, Pa. | SNY | 63.2 | 43.1 | | | .092 | .16 | .114 | | |
| 48 | Lackawaxen River near Honesdale, Pa. | SNY | 164 | 43.8 | | | .12 | .22 | .183 | | |
| 49 | Middle Creek near Hawley, Pa. | SNY | 78.4 | 42.8 | | | .080 | .13 | .094 | | |
| 50 | Lackawaxen River at Hawley, Pa. | SNY | 290 | 43.2 | 22.8 | 1.68 | [5] .131 | [5] .22 | .150 | .77 | .50 |
| 51 | Wallenpaupack Creek at Wilsonville, Pa. | SNY | 228 | 42.4 | 20.5 | 1.48 | [5] .200 | [5] .30 | .208 | | |
| 52 | Shohola Creek near Shohola, Pa. | SNY | 82.0 | 44.0 | | | .13 | .25 | .059 | | |
| 53 | Delaware River at Port Jervis, N.Y. | CM, SNY | 3,076 | 43.8 | 24.6 | 1.81 | [5] .154 | [5] .28 | .180 | | |
| 54 | Neversink River at Halls Mills, near Curry, N.Y. | CM | 68 | 56.4 | 38.9 | 2.87 | .20 | .57 | .420 | 1.23 | .53 |
| 55 | Neversink River at Neversink, N.Y. | CM | 92.5 | 54.6 | 36.6 | 2.70 | .21 | .57 | .385 | 1.25 | .60 |
| 56 | Neversink River at Woodbourne, N.Y. | CM | 113 | 52.5 | 34.1 | 2.51 | .18 | .45 | | 1.19 | .59 |
| 57 | Neversink River at Oakland Valley, N.Y. | CM, SNY | 222 | 48.1 | 29.2 | 2.15 | [5] .191 | [5] .41 | .297 | 1.16 | .61 |
| 58 | Neversink River at Godeffroy, N.Y. | SNY | 302 | 47.1 | 27.3 | 2.01 | .16 | .32 | | | |
| 59 | Bush Kill at Shoemakers, Pa. | SNY | 117 | 46.2 | 26.7 | 1.97 | [5] .137 | [5] .27 | .177 | 1.02 | .58 |
| 60 | Flat Brook near Flatbrookville, N.J. | VR | 65.1 | 43.8 | 22.1 | 1.63 | .17 | .28 | .235 | .93 | .61 |
| 61 | Paradise Creek at Henryville, Pa. | SNY | 30.2 | 46.2 | | | | | .850 | | |
| 62 | McMichaels Creek at Stroudsburg, Pa. | VR | 65.3 | 46.1 | 25.7 | 1.89 | [5] .226 | [5] .43 | .340 | 1.17 | .71 |
| 63 | Pocono Creek near Stroudsburg, Pa. | SNY, VR | 38.0 | 46.2 | | | | | .486 | | |
| 64 | Brodhead Creek at Minisink Hills, Pa. | SNY, VR | 259 | 46.1 | | | | | .363 | | |
| 65 | Paulins Kill at Blairstown, N.J. | GV | 126 | 44.0 | 20.2 | 1.49 | [5] .203 | [5] .30 | .237 | .86 | .62 |
| 66 | Pequest River at Huntsville, N.J. | GV | 31.4 | 43.8 | 18.7 | 1.38 | .15 | .21 | .159 | .81 | .59 |
| 67 | Pequest River at Pequest, N.J. | GV | 108 | 42.9 | 18.6 | 1.37 | .23 | .32 | .310 | | |
| 68 | Beaver Brook near Belvidere, N.J. | GV | 36.2 | 44.6 | 19.4 | 1.43 | .12 | .17 | .141 | .84 | .61 |
| 69 | Lehigh River at Stoddartsville, Pa. | SNY | 91.7 | 44.8 | 26.3 | 1.94 | | | .295 | .93 | .60 |
| 70 | Lehigh River at Tannery, Pa. | SNY | 322 | 45.8 | 27.5 | 2.02 | [5] .210 | [5] .42 | .345 | .92 | .56 |
| 71 | Dilldown Creek near Long Pond, Pa. | SNY | 2.39 | 48.0 | | | | | .342 | | |
| 72 | Wild Creek at Hatchery, Pa. | SNY | 16.8 | 48.0 | 28.8 | 2.12 | .23 | .49 | .513 | | |
| 73 | Pohopoco Creek near Parryville, Pa. | VR | 109 | 47.1 | 27.1 | 2.00 | .25 | .50 | .342 | | |
| 74 | Aquashicola Creek at Palmerton, Pa. | VR | 76.7 | 46.2 | 27.2 | 2.00 | .25 | .50 | .420 | .94 | .53 |
| 75 | Little Lehigh Creek near Allentown, Pa. | GV | 80.8 | 43.0 | 15.9 | 1.17 | .43 | .50 | .558 | 1.09 | .98 |
| 76 | Jordan Creek at Allentown, Pa. | GV | 75.8 | 43.0 | 19.5 | 1.44 | .11 | .16 | .103 | .62 | .44 |
| 77 | Monocacy Creek at Bethlehem, Pa. | GV | 44.5 | 42.5 | | | .45 | .50 | .569 | | |
| 78 | Saucon Creek at Lanark, Pa. | NE | 12.0 | 43.0 | | | .22 | .20 | .202 | | |

See footnotes at end of table.

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TABLE 1.—*Summary of hydrologic parameters for selected gaging stations in Delaware River region*—Continued

[Physiographic units: Catskill Mountains (CM), Southern New York section (SNY), Valleys and Ridges (VR), Great Valley (GV), New England Upland (NE), Triassic Lowland (TL), Piedmont Upland (PU), Coastal Plain (CP). $Q_{90}$ estimated from monthly data except as noted.]

| Index No. (See pl 1) | Gaging station | Physiographic units[1] | Drainage area (sq mi) | Averages, 1921–50 | | | $Q_{90}/Q_a$ | $Q_{90}$ (cfsm) | 7-day flow[2] (cfsm) | $R_a$[3] (in) | $R_{1.0}$[4] (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Precipitation (in) | Runoff (in) | Discharge (cfsm) | | | | | |
| | **Delaware River basin (including areas tributary to Delaware Bay)—Continued** | | | | | | | | | | |
| 79 | South Branch Saucon Creek at Friedensville, Pa | NE | 10.6 | 43.2 | ---- | ---- | 0.26 | 0.34 | 0.368 | ---- | ---- |
| 80 | Saucon Creek at Friedensville, Pa | NE | 26.6 | 42.9 | 16.0 | 1.18 | .35 | .41 | ---- | 0.82 | 0.71 |
| 81 | Musconetcong River near Hackettstown, N.J | NE | 70.0 | 45.1 | 22.8 | 1.68 | .14 | .24 | ---- | ---- | ---- |
| 82 | Musconetcong River near Bloomsbury, N.J | NE | 143 | 44.0 | 21.3 | 1.57 | $^{5}$.373 | $^{5}$.58 | ---- | ---- | ---- |
| 83 | Tohickon Creek near Pipersville, Pa | TL | 97.4 | 44.2 | 18.7 | 1.38 | $^{5}$.030 | $^{5}$.041 | .025 | .46 | .34 |
| 84 | Delaware River at Trenton, N.J | Several | 6,780 | 44.5 | 23.7 | 1.74 | $^{5}$.257 | $^{5}$.45 | .343 | ---- | ---- |
| 85 | Assunpink Creek at Trenton, N.J | CP, TL | 89.4 | 44.2 | 17.3 | 1.27 | ---- | ---- | .213 | ---- | ---- |
| 86 | Crosswicks Creek at Extonville, N.J | CP | 83.6 | 45.0 | 19.9 | 1.47 | .35 | .51 | .410 | .96 | .72 |
| 87 | Neshaminy Creek near Langhorne, Pa | TL | 210 | 42.3 | 16.7 | 1.23 | $^{5}$.091 | $^{5}$.11 | .083 | .54 | .46 |
| 88 | North Branch Rancocas Creek at Pemberton, N.J | CP | 111 | 45.2 | 19.7 | 1.45 | $^{5}$.404 | $^{5}$.58 | .460 | ---- | ---- |
| 89 | Schuylkill River at Pottsville, Pa | VR | 53.4 | 48.1 | ---- | ---- | .28 | .55 | .488 | ---- | ---- |
| 90 | Little Schuylkill River at Tamaqua, Pa | VR | 42.9 | 48.0 | 29.1 | 2.14 | .16 | .34 | ---- | ---- | ---- |
| 91 | Tulpehocken Creek near Reading, Pa | GV | 211 | 44.7 | ---- | ---- | ---- | ---- | .446 | ---- | ---- |
| 92 | Perkiomen Creek at Graterford, Pa | TL | 279 | 43.4 | 17.6 | 1.30 | $^{5}$.119 | $^{5}$.15 | .110 | .45 | .37 |
| 93 | Mantua Creek at Pitman, N.J | CP | 6.75 | 45.0 | 22.5 | 1.66 | ---- | ---- | 1.00 | ---- | ---- |
| 94 | Ridley Creek at Moylan, Pa | PU | 31.9 | 43.0 | 17.1 | 1.26 | .30 | .38 | .310 | .91 | .73 |
| 95 | Chester Creek near Chester, Pa | PU | 61.1 | 43.4 | 16.8 | 1.24 | $^{5}$.31 | $^{5}$.38 | .337 | 1.03 | .83 |
| 96 | Oldmans Creek near Woodstown, N.J | CP | 19.3 | 44.5 | 17.4 | 1.34 | .41 | .55 | .405 | ---- | ---- |
| 97 | Christina River at Coochs Bridge, Del | PU | 20.5 | 43.7 | ---- | ---- | .24 | .27 | .228 | ---- | ---- |
| 98 | White Clay Creek above Newark, Del | PU | 66.7 | 43.4 | ---- | ---- | ---- | ---- | .394 | ---- | ---- |
| 99 | White Clay Creek near Newark, Del | PU | 87.8 | 43.3 | 16.6 | 1.22 | .39 | .48 | .397 | .88 | .66 |
| 100 | Mill Creek at Stanton, Del | PU | 12.3 | 43.1 | ---- | ---- | ---- | ---- | .205 | ---- | ---- |
| 101 | Red Clay Creek at Wooddale, Del | PU | 47.0 | 43.5 | 17.0 | 1.23 | .42 | .52 | .392 | .86 | .70 |
| 102 | West Branch Brandywine Creek at Coatesville, Pa | PU | 45.8 | 43.6 | ---- | ---- | .34 | .47 | ---- | ---- | ---- |
| 103 | Brandywine Creek at Chadds Ford, Pa | PU | 287 | 44.1 | 17.5 | 1.29 | $^{5}$.330 | $^{5}$.43 | .400 | .99 | .77 |
| 104 | Shellpot Creek at Wilmington, Del | PU | 7.46 | 42.5 | ---- | ---- | ---- | ---- | .087 | ---- | ---- |
| 105 | Salem River at Woodstown, N.J | CP | 14.6 | 44.5 | 17.6 | 1.30 | .30 | .39 | .209 | ---- | ---- |
| 106 | Leipsic River near Cheswold, Del | CP | 9.2 | 42.4 | 14.7 | 1.08 | .41 | .44 | .378 | .78 | .73 |
| 107 | Murderkill River near Felton, Del | CP | 14.4 | 46.2 | ---- | ---- | ---- | ---- | .192 | ---- | ---- |
| | **Areas in Delaware and Maryland adjacent to Delaware River basin** | | | | | | | | | | |
| 108 | Stockley Branch at Stockley, Del | CP | 5.5 | 47 | 16.9 | 1.24 | ---- | ---- | ---- | 0.88 | 0.71 |
| 109 | Gravelly Fork near Bridgeville, Del | CP | 75.4 | 44 | 14.1 | 1.04 | ---- | ---- | ---- | .80 | .77 |
| 110 | Choptank River near Greensboro, Md | CP | 113 | 45.5 | 17.5 | 1.29 | ---- | ---- | ---- | .77 | .62 |
| | **Susquehanna River basin** | | | | | | | | | | |
| 111 | Charlotte Creek at Davenport Center, N.Y | CM, SNY | 163 | 40.2 | 21.6 | ---- | ---- | ---- | ---- | ---- | ---- |
| 112 | Otego Creek near Oneonta, N.Y | SNY | 108 | 40.0 | 22.6 | 1.67 | 0.10 | 0.17 | ---- | ---- | ---- |
| 113 | Ouleout Creek at East Sidney, N.Y | CM, SNY | 102 | 42.0 | 23.2 | 1.71 | .11 | .19 | ---- | ---- | ---- |
| 114 | Unadilla River near New Berlin, N.Y | SNY | 196 | 40.5 | 23.5 | 1.73 | .11 | .19 | ---- | ---- | 0.38 |
| 115 | Butternut Creek at Morris, N.Y | SNY | 59.6 | 40.8 | 23.2 | 1.71 | .080 | .14 | ---- | ---- | ---- |
| 116 | Chenango River at Sherburne, N.Y | SNY | 264 | 39.3 | 23.2 | 1.71 | .11 | .19 | ---- | ---- | .28 |
| 117 | Canasawacta Creek near South Plymouth, N.Y | SNY | 58.3 | 39.5 | 24.2 | 1.78 | .042 | .075 | ---- | ---- | ---- |
| 118 | Owego Creek near Owego, N.Y | SNY | 186 | 36.0 | 20.8 | 1.53 | .045 | .069 | ---- | ---- | ---- |
| 119 | Tioga River at Tioga, Pa | (6) | 282 | 34.5 | 16.6 | 1.22 | .065 | .079 | ---- | ---- | .24 |
| 120 | Canisteo River at Arkport, N.Y | SNY | 30.5 | 35.5 | 15.4 | 1.14 | $^{5}$.043 | $^{5}$.049 | ---- | ---- | .20 |
| 121 | Karr Valley Creek at Almond, N.Y | SNY | 27.6 | 35.5 | 15.3 | 1.13 | .025 | .028 | ---- | ---- | ---- |
| 122 | Tuscarora Creek near South Addison, N.Y | SNY | 114 | 35.2 | 12.3 | .91 | .005 | .0045 | ---- | ---- | ---- |
| 123 | Newtown Creek at Elmira, N.Y | SNY | 79.8 | 35.5 | 16.6 | 1.19 | .13 | .15 | ---- | ---- | ---- |

[1] All or most of the drainage area is in the physiographic units indicated.
[2] Median of the minimum annual 7-day flows.
[3] Runoff from natural storage in 30 days following average discharge (summer conditions).
[4] Runoff from natural storage in 30 days following a discharge of 1.0 cfsm (summer conditions).
[5] $Q_{90}$ computed from daily flows.
[6] In northern part of Allegheny Mountain section, adjacent to southern New York section.

the effects on streamflow of such concentrations are greatest for small areas. These same factors apply to a lesser degree to a few other points.

The slope of this relation line differs very slightly from the slope that indicates equal increments of runoff and precipitation. Extension of the relation as a straight line would indicate no runoff when the average precipitation is about 19.5 inches. However, in desert regions, measurable runoff is associated with much smaller amounts of precipitation and this may indicate that the line should curve at lower values of precipitation. Nevertheless the straight line shown probably is very nearly correct for the range involved.

The scatter of points for the southern New York section is greater than that for the Catskill Mountains, but the range in precipitation is sufficient for fair definition of a relation. The relation line shown is parallel to the Catskill Mountains line and slightly below it. The difference in position may not be significant, but relations involving other parameters do show significant differences. The relations defined for these two physiographic units are considered to be reliable indications of the general nature of runoff-precipitation relations in the study area.

Points for the other physiographic units scatter widely, and because of the small ranges in average pre-

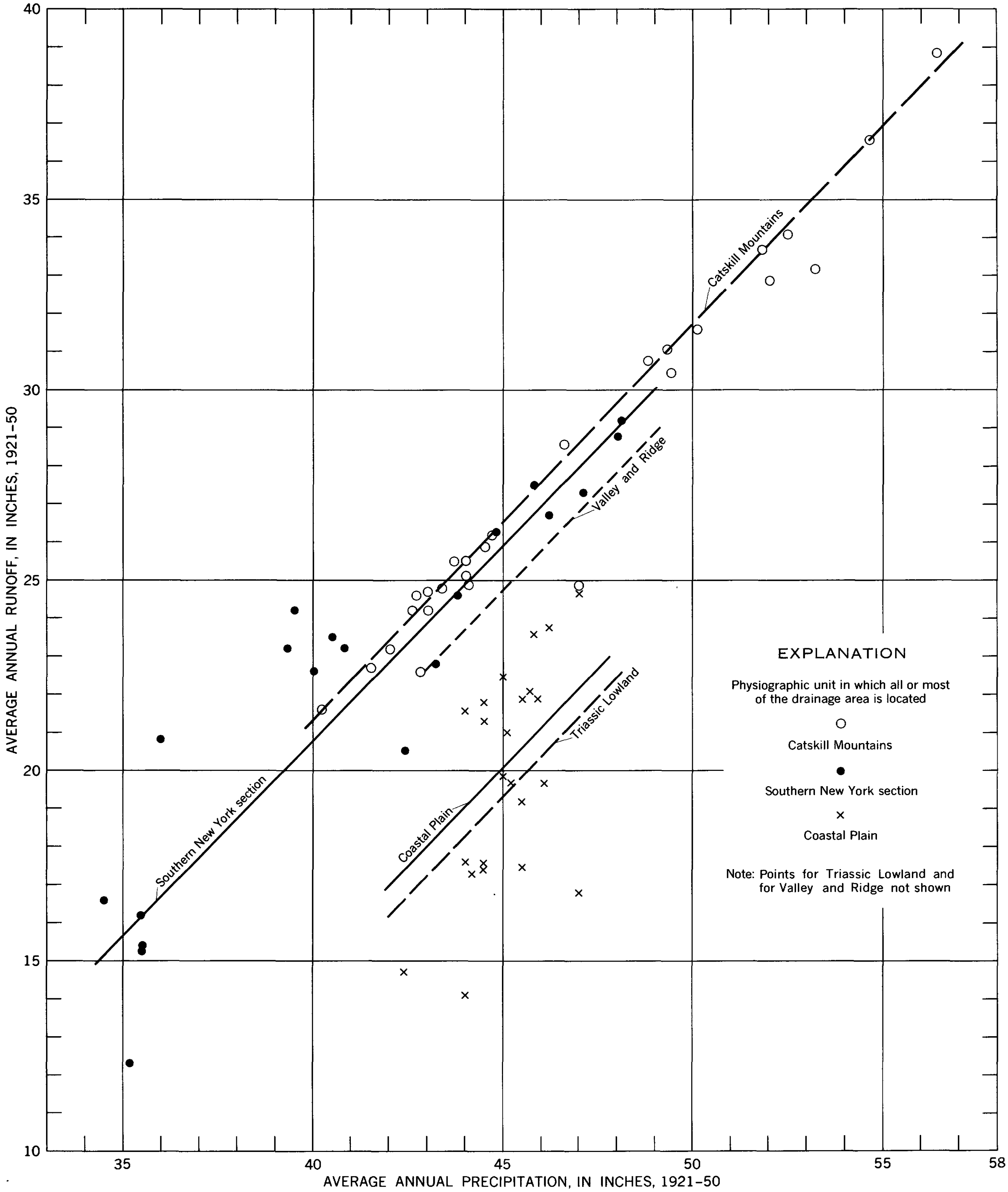


FIGURE 1.—Relations between average annual runoff and precipitation.

cipitation they do not contribute appreciably to definition of the slopes of relation lines. The slopes for all units are assumed to be the same as that for the Catskill Mountains. Lines for three additional units are shown in figure 1 because they are used later in connection with other relations. Points for the Coastal Plain illustrate the great variation that may occur within a single physiographic unit, but points for the remaining units are omitted to avoid confusion.

Vertical differences between lines or points indicate differences in water loss. Losses by evapotranspiration in the southern lowlands are much greater than those in the northern uplands. In the unconsolidated sediments of the Coastal Plain and in some limestone areas, underground outflow is an important part of the total water loss, and areal variations in this outflow probably account for a considerable part of the scatter of Coastal Plain points.

### FLOW-DURATION CHARACTERISTICS

Flow-duration parameters are among the most useful devices for characterizing streamflow. For example: $Q_{50}$, the median discharge, is preferable to the average as an indicator of normal flow and has other advantages for statistical analysis; $Q_{90}$ (the discharge equaled or exceeded 90 percent of the time) is an indicator of low-flow regimen and is well adapted to studies of geological or other terrestrial influences.

Duration curves are generally well defined in the central part of their range and increasingly less well defined toward the extremes because of the smaller number of events corresponding to each increment of discharge. Maximum and minimum values for a period of record correspond to extremes of a duration curve and are subject to erratic variation as the period changes. Although $Q_{90}$ is a good indicator of low-flow characteristics, it is sufficiently far from the low extreme to be relatively stable.

Duration data may be based on daily or monthly discharges. Durations of daily discharge are generally preferred, but because of the expense and time required for their computation they are unavailable for many gaging stations. Durations of monthly discharge may be obtained much more readily and may be nearly as satisfactory as the daily discharge for comparison of some basin characteristics.

In the Delaware River basin there is a well-defined relation between $Q_{90}/Q_a$ (ratio of $Q_{90}$ to the average discharge) obtained from duration curves of daily discharge and $Q_{90}/Q_a$ obtained from curves of monthly discharge (Parker and others, 1963). This relation (fig. 2) forms a basis for estimating from monthly curves the daily flow of 90-percent duration.

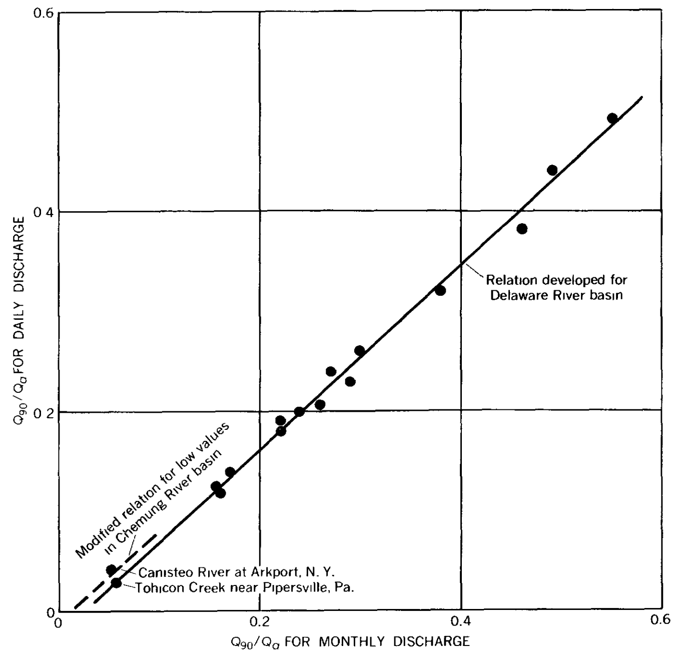


FIGURE 2.—Relations for obtaining daily flow at the 90-percent duration point from monthly flow.

Duration data for daily discharge are available for only 26 of the stations used in this study. Durations of monthly discharge for 12 stations are given by Parker and others (1963), and data for an additional 58 stations (including 4 in the Hudson River basin and 11 in the northern part of the Susquehanna River basin) were computed for this study. Because of the general preference for durations of daily discharge, the monthly data were converted to daily values by means of the relation curve (fig. 2) even though the conversion is an extra source of error in the results. The monthly data are based on records of 10 years or more. Many of these are not adjusted to the standard period (1921–50) because the differences between values for the period of record and the standard period generally are small.

A duration curve of daily discharge for Canisteo River at Arkport, N.Y., was prepared to provide a check on applicability of the relation for the Delaware River basin (fig. 2) to the northern part of the Susquehanna River basin. The departure from the relation line of the point for Canisteo River is about the same as that for some other points. Therefore, it may be concluded that the relation is generally applicable in the northern part of the Susquehanna River basin. However, the modified relation shown in figure 2 was used for low values in the Chemung River basin (pl. 1), as Canisteo River represents that basin better than Tohickon Creek near Pipersville, Pa.

Low values of $Q_{90}$ estimated in this manner should not be used for actual flow studies because of the magnitude of the probable error, but such estimates are considered satisfactory for the present study of the variations in $Q_{90}$.

Flows at several of the stations used in this study were affected by regulation. The values of $Q_{90}$ used are based on unregulated flows or estimated from monthly discharges adjusted for the effects of regulation.

#### RELATIONS BETWEEN $Q_{90}$ AND AVERAGE ANNUAL PRECIPITATION

Relations between $Q_{90}$ and average annual precipitation are shown in figure 3. The available data for four of the physiographic units are plotted in figure 3*A* and for the remaining four in figure 3*B*. Curves developed in one part (shown by solid lines) are repeated in the other (as dashed lines) to facilitate comparisons.

The best defined relations are those for the Catskill Mountains and southern New York section. The points for the Coastal Plain scatter widely for the reasons stated in the discussion of average annual runoff. The three highest points in this group represent stations with much lower water loss than that for the remaining stations in the group. Hence the relation curve was drawn as an approximate average of the points, excepting the top three, and its shape was based partly on the shapes of other curves in the family of curves. Curves for the Valleys and Ridges and the Triassic Lowland also were based partly on the other curves.

No curves are shown for the Great Valley, the New England Upland, or the Piedmont Upland because the points do not define curves. The differences in rock types within the first two units are relatively large, and the range in precipitation for the latter is very small. The New England Upland has a wide range in precipitation, and the curve for the Valleys and Ridges might be considered fairly representative of this unit. Piedmont Upland streams are generally comparable to Coastal Plain streams.

In general, the family of curves shows that for a selected precipitation, high values of $Q_{90}$ are affected more than low ones by a given change in average precipitation; and that in a region of relatively uniform terrestrial characteristics, a given change in average precipitation has more effect at high values of the precipitation than at low ones. These conclusions are consistent with normal expectations of a qualitative nature. Figure 3 provides a semiquantitative indication of the relations.

#### RELATIONS BETWEEN $Q_{90}/Q_a$ AND AVERAGE ANNUAL PRECIPITATION

$Q_{90}$ is sometimes expressed as a ratio to average discharge ($Q_{90}/Q_a$) so that values for different stations will be more nearly comparable.[4] This procedure removes the effects of basin size to the same extent as use of discharge per unit area (the ratio may be computed from either total discharges or discharges per unit area). It also reduces, but does not necessarily eliminate, the effect of differences in average precipitation.

Figure 4 shows relations between the ratio and average precipitation for each of the five physiographic units for which relation curves are shown in figure 3. The quantities involved in this chart are also involved in figures 1 and 3. Therefore, the curves in figure 4 were derived from the preceding figures to assure consistent results. For example, from the relation of figure 1 for southern New York section, 41 inches of precipitation corresponds to 21.8 inches of runoff, which equals 1.61 cfsm. From the corresponding curve in figure 3, $Q_{90}$ is found to be 0.16 cfsm.

$$Q_{90}/Q_a = 0.16/1.61 = 0.099$$

Identical or very similar curves could be developed independently from the data plotted in figure 4, except for the Coastal Plain. The scatter of the points representing this unit is such that they afford little information about the nature of the relation. However, if the slopes of the lines in figures 1 and 3 are correct, the slope of this relation must be as shown. The line fails to average the points because the line in figure 3 does not average all points and figures 3 and 4 contain only about half as many Coastal Plain points as figure 1.

The effectiveness of using the ratio to eliminate effects of areal variations in average precipitation may be judged by comparing figures 3 and 4. The studies of base-flow parameters (which follow) indicate that the true relations for the Catskill Mountains and southern New York section may be somewhat flatter than those shown in figure 4 because areas of high average precipitation are also areas where the geology favors well-sustained low flows.

#### RELATIONS BETWEEN $Q_{90}$ AND AVERAGE ANNUAL DISCHARGE

Average annual precipitation for drainage areas is not always known, particularly in mountainous areas. Consequently, for some studies it may be necessary to correlate low-flow parameters with average annual discharge rather than precipitation. For areas in which a definite relationship exists between runoff and precipitation, such as in the Catskill Mountains, the resulting relations would be very similar to those obtained by correlation with precipitation. However, in areas

[4] The ratio of $Q_{90}/Q_{50}$ might be a better parameter for many purposes because it varies inversely with the numerical value of the slope of a definite segment of the duration curve, but lack of data on $Q_{50}$ prevented investigation of this.

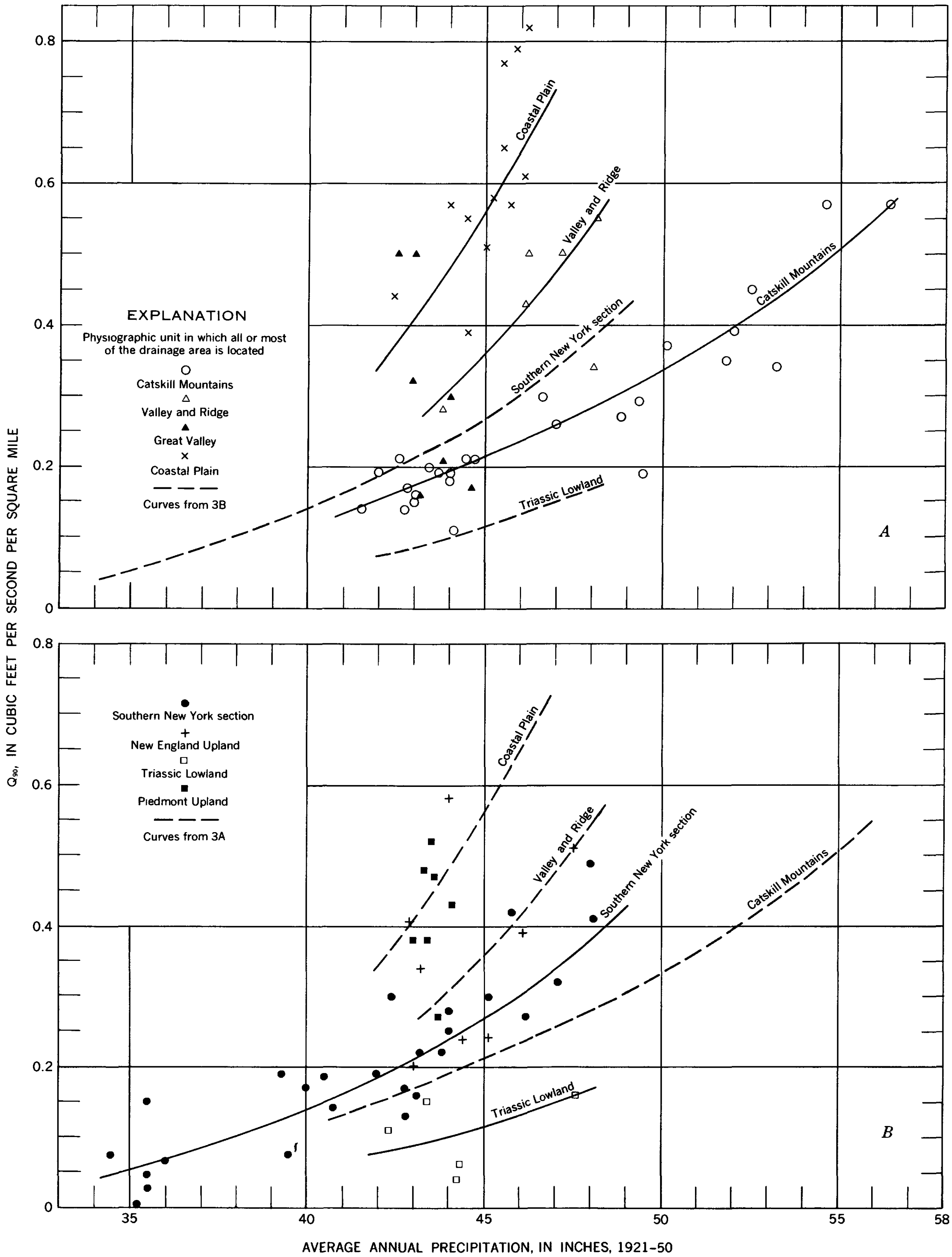


FIGURE 3.—Relations between $Q_{90}$ and average annual precipitation.

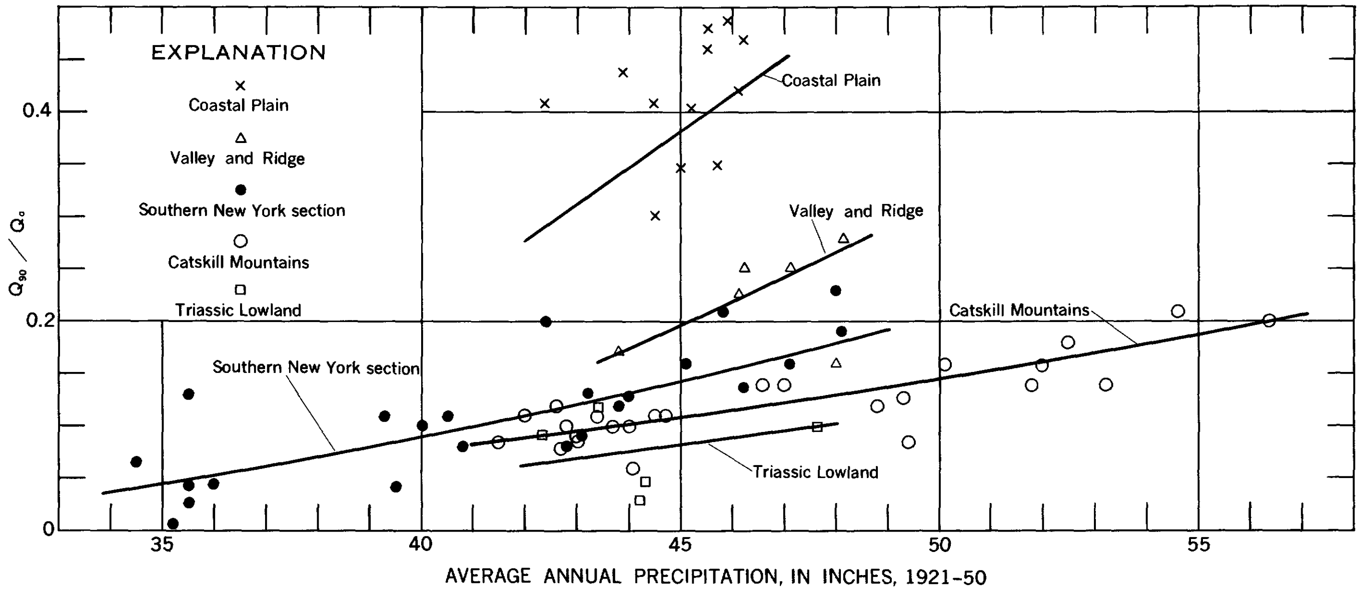


FIGURE 4.—Relations between $Q_{90}/Q_a$ and average annual precipitation.

where the runoff-precipitation relation varies, as in the Coastal Plain, the differences would be appreciable.

Relations between $Q_{90}$ and average discharge for the same five physiographic units that were used in the preceding paragraphs are shown in figure 5. These curves were derived from figures 1 and 3 in the same manner as those in figure 4. In general, the curves are similar to those in figure 3. The greatest difference is in the relative displacement toward the left of the curves for the Coastal Plain and Triassic Lowland because of the high water losses in those units.

### RESIDUAL EFFECT OF BASIN SIZE ON $Q_{90}$

Although expression of discharge in terms of unit area removes most of the effect of basin size, some residual effect on low discharges would be expected because the probability of a drought covering an entire area decreases as the area increases.

The relation curves in figure 3 provide a basis for adjusting $Q_{90}$ to remove most of the effect of differences in average precipitation; and the adjusted values may be used to study relations with other variables, such as basin size.

To make the adjustment, any point that lies on a curve in figure 3 is moved along the curve to the selected value of precipitation. If the point lies between curves, it is moved along a path interpolated between adjacent curves.

Values of $Q_{90}$ adjusted to an average precipitation of 44 inches (the approximate average for Delaware River basin) are listed below and plotted against basin size in figure 6.

*Adjusted values of $Q_{90}$*

| Gaging station index No. | Adjusted $Q_{90}$ (cfsm) | Gaging station index No. | Adjusted $Q_{90}$ (cfsm) |
|---|---|---|---|
| 1 | 0.11 | 36 | 0.17 |
| 2 | .09 | 37 | .21 |
| 3 | .14 | 38 | .24 |
| 4 | .20 | 39 | .19 |
| 23 | .18 | 40 | .16 |
| 24 | .18 | 41 | .22 |
| 25 | .17 | 42 | .16 |
| 26 | .20 | 43 | .25 |
| 27 | .19 | 44 | .19 |
| 30 | .20 | 54 | .19 |
| 31 | .20 | 55 | .21 |
| 33 | .16 | 56 | .20 |
| 35 | .19 | 113 | .24 |

No relation is defined by the plotting of these points, but the range in area is not sufficient for conclusive results. Therefore, in order to extend the range in area and increase the significance of the plot the larger drainage areas of Delaware River at Port Jervis, N.Y., and at Trenton, N.J., were introduced into the analysis. About half of the drainage area at Port Jervis is in the Catskill Mountains and the other half in the southern New York section. Consequently $Q_{90}$ for this station would be expected to plot about halfway between the curves in figure 3 for Catskill Mountains and southern New York section, or 0.025 cfsm above the Catskill Mountains curve at 44 inches on the precipitation scale. The average precipitation on the area is so close to 44 inches that the adjustment is negligible. For the Port Jervis station $Q_{90}$ is 0.28 cfsm and its plotting position on the extended Catskill Mountains curve ($Q_{90}-0.025$) is 0.255 cfsm.

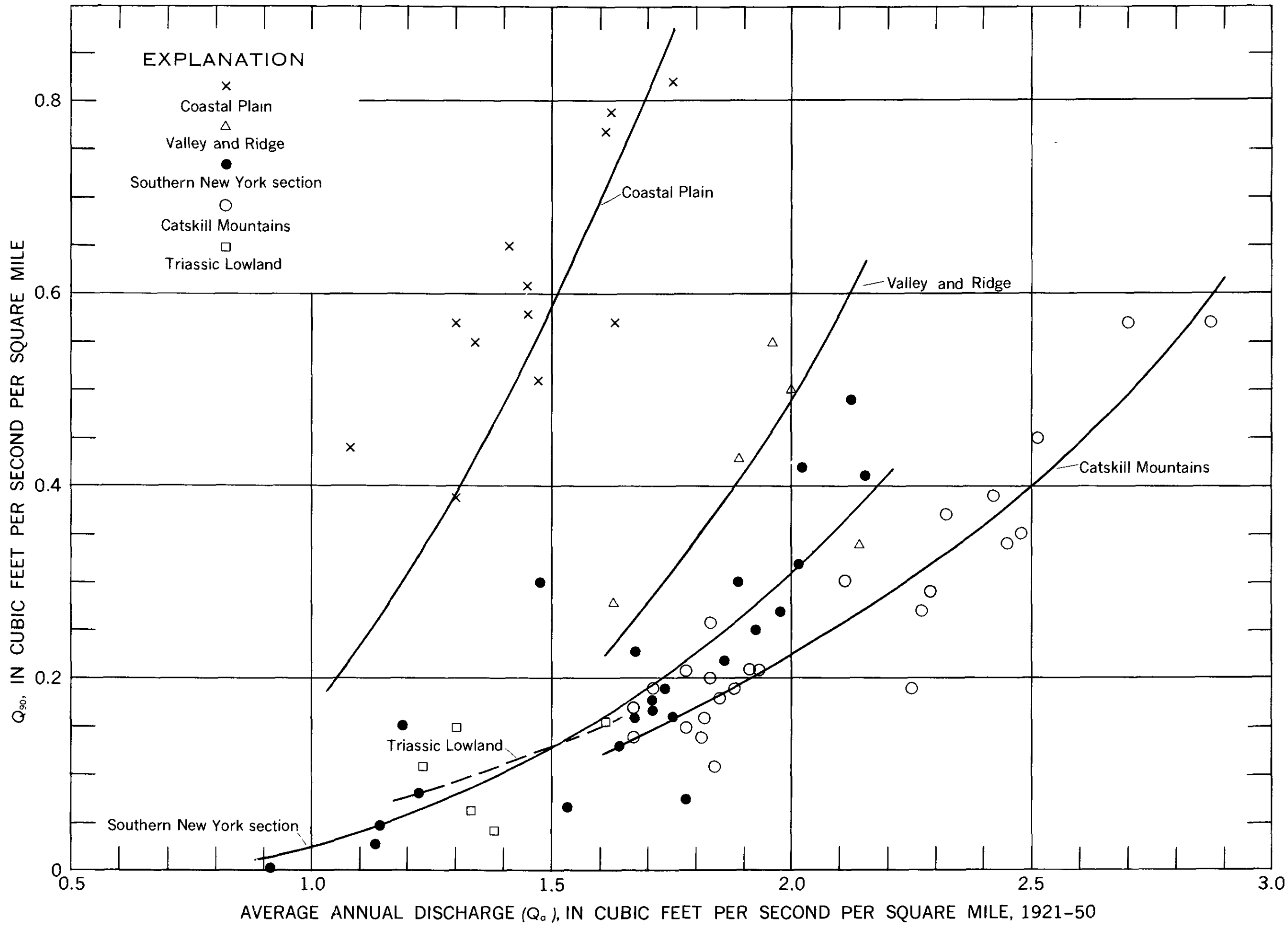


**FIGURE 5.—Relations between $Q_{90}$ and average discharge.**

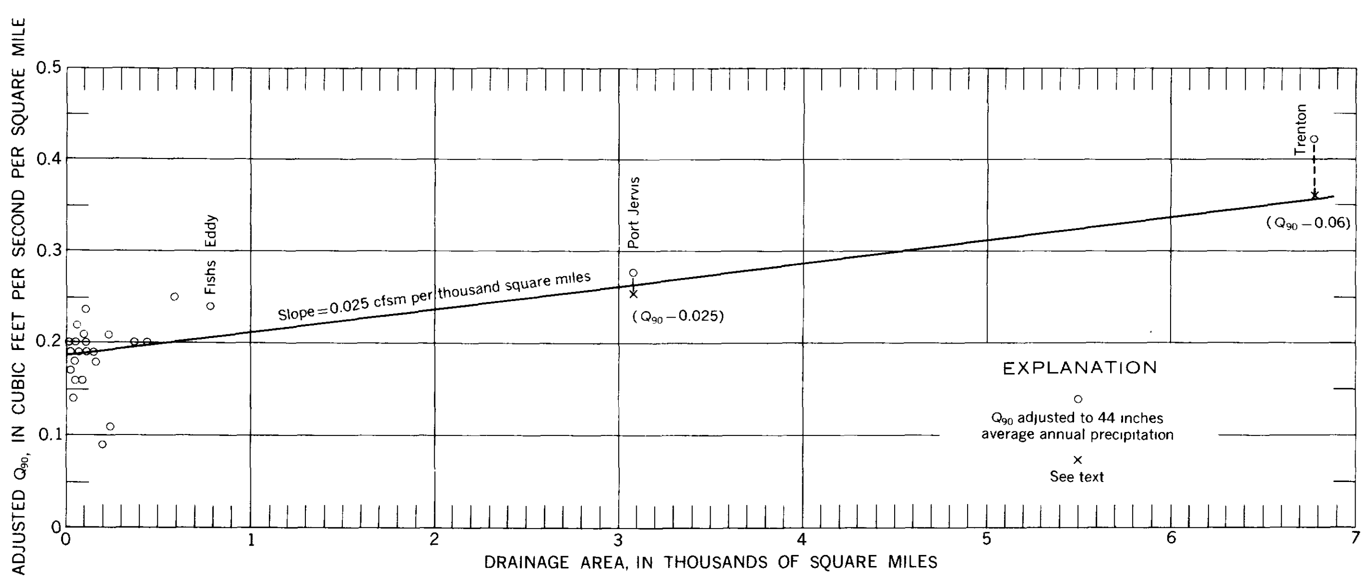


**FIGURE 6.—Residual effect of basin size on $Q_{90}$.**

Most of the area between Port Jervis and Trenton is divided among southern New York section, Valleys and Ridges, Great Valley, and New England Upland. Therefore, at 44 inches the $Q_{90}$ for Trenton would be expected to plot about 0.05 or 0.06 cfsm above the Catskill Mountains curve. The average precipitation for the area above Trenton is 45.5 inches and the estimated adjustment, on the basis of figure 3, is 0.03 cfsm. The adjusted $Q_{90}$ is $0.45-0.03=0.42$ cfsm; and adjusted $Q_{90}-0.06=0.36$ cfsm.

The line in figure 6 represents the estimated relation based on the Catskill Mountains group, Port Jervis and Trenton. Although only two large areas are included, the slope, 0.025 cfsm per thousand square miles, probably indicates the approximate magnitude of the residual effect of basin size. The effect is not significant except where very large differences in area are involved. The relation does not apply to very small areas (under about 10 square miles) where at times the water table may be below the stream channels.

## FLOW-FREQUENCY CHARACTERISTICS

Flow frequencies generally deal with either flood peaks or the annual minimum of the average flows for periods of various lengths, such as 7, 15, 20, or 90 days. Low-flow frequencies are somewhat similar to flow-duration parameters as both relate flow to time, but the frequency parameters are based on average flows for consecutive days, rather than flows equaled or exceeded a given percent of days regardless of order, and are most closely related to occurence of drought.

The medians (recurrence interval equals 2 years) of the minimum annual [5] 7-day flows are compared with

[5] The year used here is a climatic year beginning April 1.

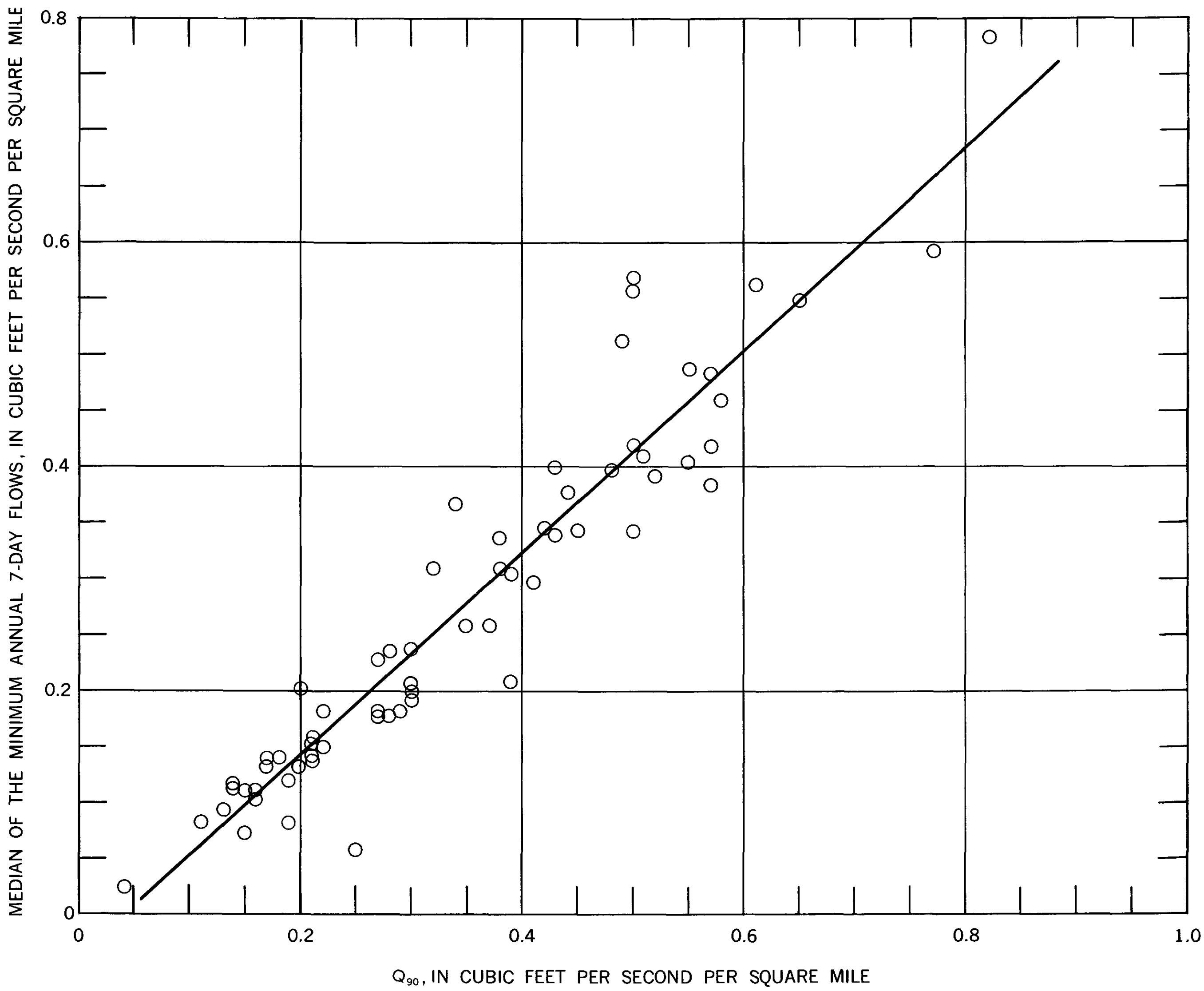


FIGURE 7.—Comparison of minimum 7-day flow and $Q_{90}$.

$Q_{90}$ in figure 7, which shows that there is fair correlation but some marked differences for individual stations. The ratio of the 7-day flow to $Q_{90}$ ranges from about 0.24 to 1.14 and averages about 0.8.

The relation of the minimum 7-day flows to average annual precipitation for the Catskill Mountains streams is shown in figure 8. The relation is similar to that in figure 3. A family of curves roughly similar to those of figure 3 could be developed from the points for the other physiographic units but all except the Catskill Mountains curve would be very poorly defined. Points for the Coastal Plain are shown in figure 8 for illustration but those for the remaining units are omitted.

### BASE-FLOW CHARACTERISTICS

The base flow of streams, derived from depletion of natural storage in the basins, provides a basis for computing parameters that are somewhat different from those previously discussed. Although base flow and base-flow recession curves have been described by many writers, the following discussion is presented to help explain the characteristics of parameters derived from recession curves. The present study is limited to areas of not more than a few hundred square miles.

Consider a drainage basin in which the aquifers are filled to the maximum possible level and then drained to the level of the stream channel at the outlet, or until no drainable water remains, with no precipitation or

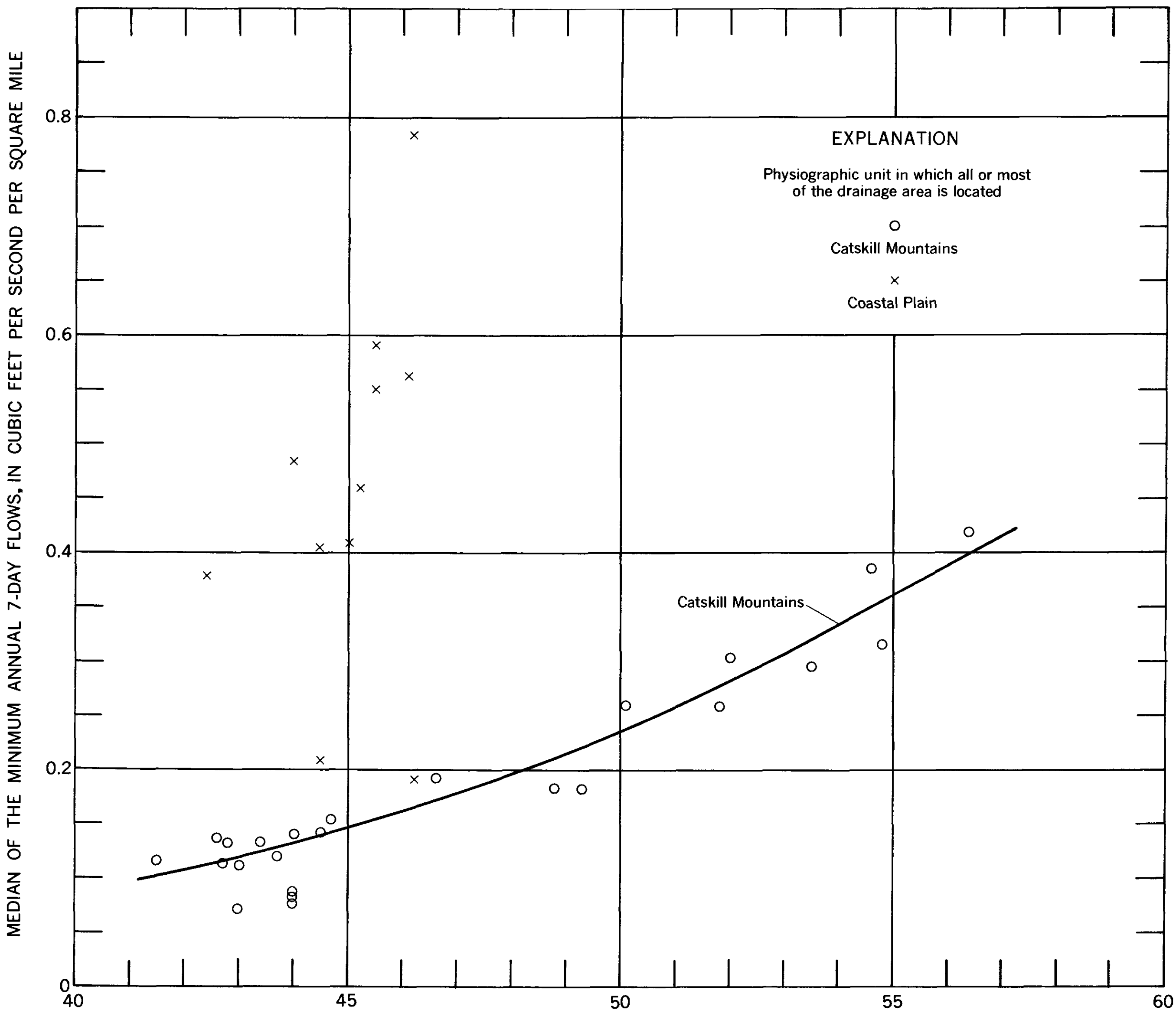


FIGURE 8.—Relations between minimum 7-day flow and average annual precipitation.

other source of ground-water recharge during the period of draining. The recession curve defined between these limits may be called a complete recession curve. It is determined entirely by the drainage characteristics of the aquifers and the surface-drainage system, except for the effects of evapotranspiration of ground water, as described below.

In most basins natural ground-water discharge has two components—evapotranspiration and discharge to streams. The first occurs where the water table or the capillary fringe is within reach of plant roots. The second may be considered as a residual, which, in terms of percent of total ground-water discharge, decreases as loss by evapotranspiration increases. In some areas during droughts, evapotranspiration may account for all natural ground-water discharge, and streamflow may cease.

Evapotranspiration from ground water is affected by depth of the water table and capillary zone below the land surface and the nature of the vegetation. The rate varies both seasonally and areally. In the Delaware River region the seasonal change in evapotranspiration from ground water resembles the seasonal change in total evapotranspiration (Rasmussen and Andreasen, 1959, fig. 19), and the amount in midwinter probably is very small. Maximum rates occur where the water table or capillary fringe are at the surface or within reach of plant roots where vegetation is dense. In basins of little relief, such as some of those in the Coastal Plain, evapotranspiration from ground water may occur over the entire basin. In basins of high relief, particularly those in dissected plateaus, this type of discharge probably occurs chiefly in valleys, adjacent to the streams.

Aside from the effects of evapotranspiration, ground-water discharge to streams is controlled by the subsurface geology and the relation of the water table or piezometric surface to streams.

Thus, winter base-flow recession curves should be good indicators of the hydrologic characteristics of the materials through which ground water moves to the stream channels. Most summer recession curves are affected by evapotranspiration and such curves used in conjunction with winter curves may provide useful information on evapotranspiration from ground water.

Although recession curves have certain inherent advantages for use in comparing terrestrial characteristics of basins, several practical difficulties described below limit their usefulness.

In parts of the Delaware River region it was impossible to define satisfactory winter recession curves because of the scarcity of periods of more than a few days that are unaffected by direct runoff, by delayed runoff from melting snow, or by ice. Consequently, all data listed in this report are for summer conditions.

Sometimes it is difficult to determine which parts of a discharge hydrograph represent base-flow recession. The shapes of individual recessions at a station may vary somewhat because of nonuniformity in the ground-water recharge in different parts of the basin, and a low rate of recharge may not be detectable. Nevertheless, the average, or composite, curve developed from many individual recessions should closely approximate the idealized recession curve, except for the effects of evapotranspiration from ground water.

The complete recession curve postulated above is seldom, if ever, defined. In a region of high precipitation the defined curve might be a segment near the upper end of the complete curve; in a region of low precipitation the defined curve for a basin with identical terrestrial characteristics would be a segment near the low end of the complete curve. A method of relating these segments so that comparable parameters can be derived from them is described in the following paragraphs.

#### METHODS OF RELATING BASE-FLOW RECESSION CURVES

It is common practice to use long-term average discharge or discharge corresponding to a selected percent duration, such as $Q_{50}$, as the initial point for recession curves. However, these discharges and any parameters based on such discharges vary with average precipitation, and consequently, an inherent advantage of recession curves (that of reflecting effects of terrestrial characteristics) is not fully utilized. This suggests the possibility of eliminating the effect of variation in average precipitation by using a selected discharge per unit area as the reference point.

Consider the hypothetical recession curve $AB'$ in figure 9. Assume that segment $AA'$ represents a period of relatively high runoff with average discharge at point $A$, and that segment $BB'$ represents a period of relatively low runoff with average discharge at point $B$. If segment $BB'$ is considered as a separate curve and plotted with average discharge at the initial time it takes the position indicated by $bb'$.

As illustrated in figure 9, the slopes of the curves (approximated by slopes of chords) at points that are in horizontal alinement are identical, and those that are in vertical alinement are not identical. This, of course, follows from the fact that by definition curve $bb'$ is curve $BB'$ moved to the left.

The significance of the diagram is that although curves $bb'$ and $BB'$ might represent recession curves for different gaging stations, the identity, similarity, or dissimilarity of the curves can be established by com-

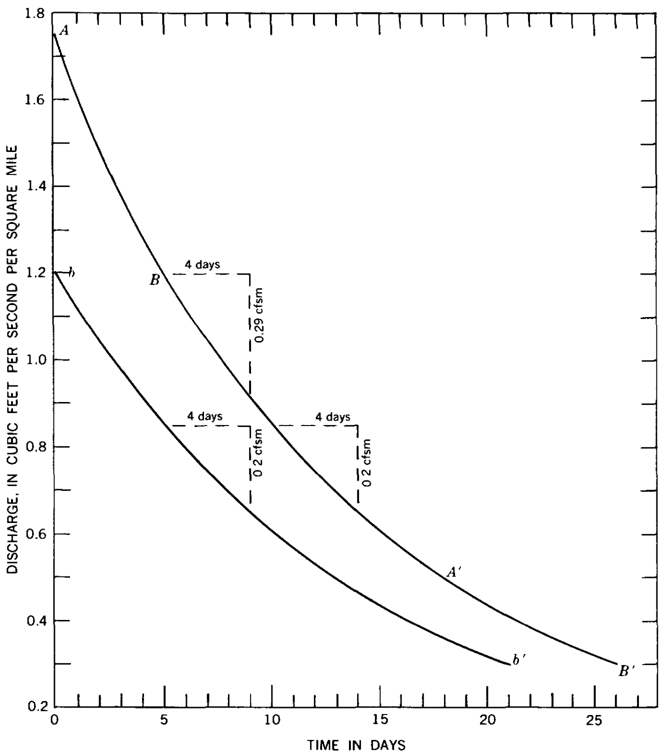


FIGURE 9.—Diagram showing a method of relating base-flow recession curves.

parison of slopes for points in horizontal alinement (represented by a selected discharge per unit area) but not by comparison of slopes for points in vertical alinement (represented by a selected number of days following the occurrence of average discharge). This conclusion also might be anticipated because the location of the time scale is arbitrary and depends on the initial discharge. The location is fixed for two or more curves only when the initial point is a selected discharge per unit area.

This does not mean that recession curves should never be related to average or median discharge. A curve related to median discharge is probably most representative of the flow characteristics at a station and is useful for many purposes. However, if parameters are to be independent of variations in average precipitation, and therefore better adapted to studies of terrestrial characteristics, they must be related to a selected, rather than a variable, discharge per unit area.

Although slope of the recession curve is the most obvious and simply computed parameter, there are some objections to its use. For example, slopes at several points on the curve are required for adequate definition of long recessions with considerable curvature, and use of several figures for one gaging station makes comparisons difficult.

A better basis for comparison of the curves is obtained by integration between specified time limits. The results of this integration, the areas under the curves, represent the runoff from natural storage during the specified time interval. In practice, a summation process is generally substituted for integration in computing the runoff.

The length of period used in these computations may affect the relative magnitudes of the parameters. For example, shallow aquifers in steep terrain might drain rapidly, supplying a large base flow for a short period, but supplying very little after that period; and a thicker aquifier in flatter terrain might drain more slowly but sustain moderate base flow for a long period. Thus, the shallow aquifer would produce the greater runoff for the short period but the thicker one might produce the greater runoff in a longer period.

## RELATIONS BETWEEN BASE-FLOW PARAMETERS AND AVERAGE ANNUAL PRECIPITATION

For computations of runoff from natural storage in this report, the selected time interval is 30 days, which is the longest period for which data from all gaging stations are available. In areas where base flow is well sustained, a longer period would be preferable. The selected discharge of 1.0 cfs per square mile is a convenient figure that is common to the defined segments of the recession curves for all stations and is equivalent to 1.116 inches of runoff in 30 days.

Runoff for two separate 30-day periods was computed; (a) that for the 30 days following occurrence of average discharge ($R_a$), and (b) that for the 30 days following occurrence of a discharge of 1.0 cfsm ($R_{1.0}$). These values are listed in table 1.

Figure 10 shows the variation of summer values of $R_a$ and $R_{1.0}$ with average annual precipitation in the Catskill Mountains. $R_a$ increases rapidly as the precipitation increases because high precipitation produces high average runoff and thus the 30-day segment of the recession curve is located relatively high on the complete recession curve.

As a change in average precipitation does not alter drainage characteristics of basins, values of $R_{1.0}$ should not vary with precipitation if the basins involved have identical terrestrial characteristics. However, assuming that the available recession data represent the idealized curves previously described, figure 10 shows that in the Catskill Mountains high values of $R_{1.0}$ are associated with high average precipitation. Although the slope of the relation line is much less than that for $R_a$, it is steep enough to be significant. This slope might be caused by variations in geologic factors, topography, or evapotranspiration from ground water.

To check the latter possibility, the winer recession data were studied. Such data for the Catskill Mountains are generally less reliable than summer data and

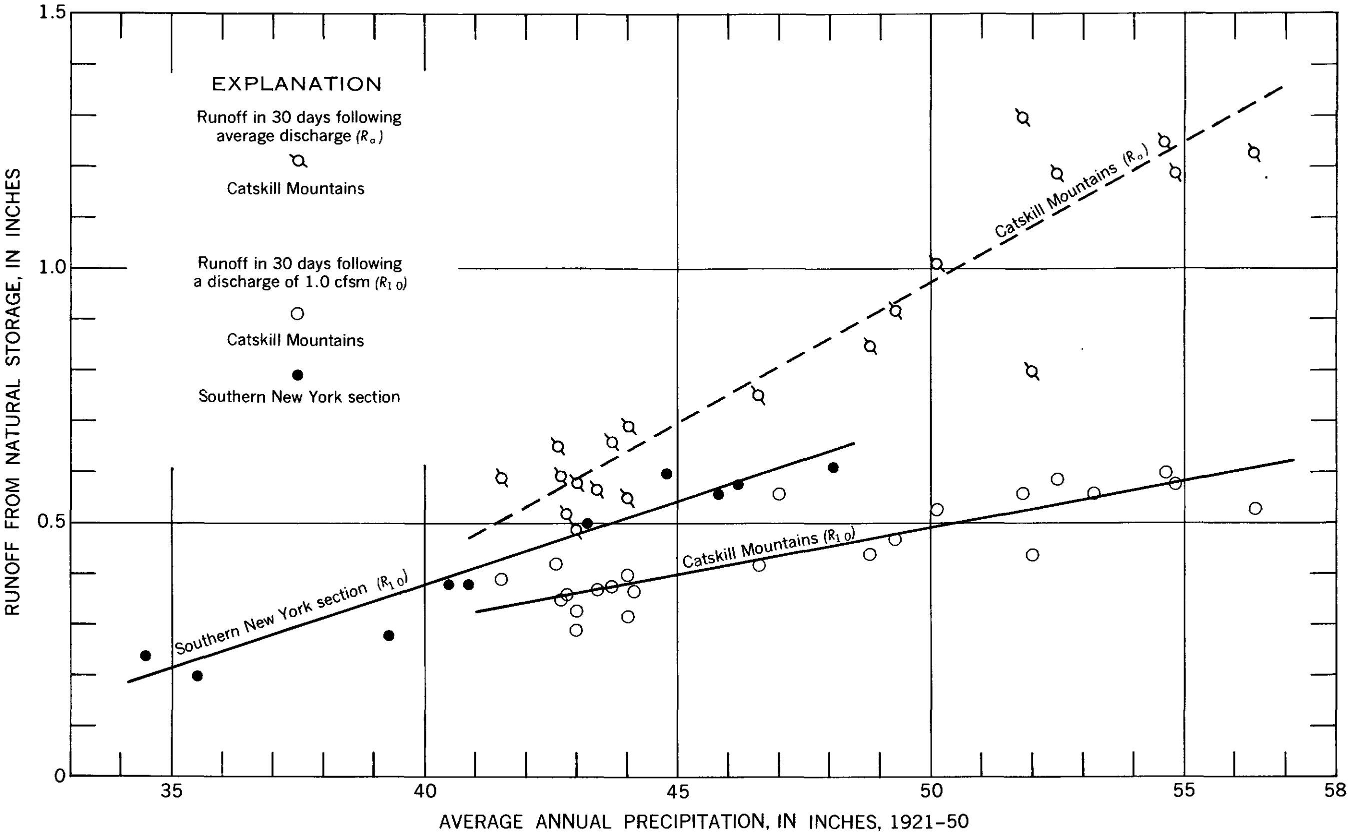


**Figure 10.—Relations between summer runoff from natural storage and average annual precipitation.**

are available for fewer stations. However, the available data indicate that winter values of $R_{1.0}$ plotted against precipitation would define a line (not shown) with nearly the same slope as that shown. Consequently, this slope cannot be attributed to aeral variations in evapotranspiration from ground water and it is concluded that the slope is caused by geologic or topographic factors.

A relation between $R_{1.0}$ and average precipitation for the southern New York section also is shown in figure 10. It has a slope that is somewhat steeper than that for the Catskill Mountains, but the relation is not as well defined and may not represent an average relation for the section. Few data for other physiographic units are available and they indicate no significant correlation. Thus, the available data do not afford an example of the relation for a uniform area in which $R_{1.0}$ does not vary with precipitation.

There are many possible explanations for the variation of $R_{1.0}$ indicated in figure 10. Significant differences occur in rock types (such as proportions of sandstone and siltstone), in valley fill and glacial deposits, in topography, and in depth of weathered material.

Also the length of period (30 days) used in the computations may influence the relative magnitude of $R_{1.0}$. The high relief which occurs in areas of high precipitation favors rapid drainage. In a longer period, such as 60 or 90 days, the rate of runoff from these areas might drop below that from the areas of lower relief and the total runoff might tend to equalize. Not enough information is available to determine which factors cause the variation in $R_{1.0}$ but probably several are involved.

## RELATIONS BETWEEN GEOLOGY AND STREAMFLOW IN A REGION OF COMPLEX GEOLOGY AND RELATIVELY UNIFORM PRECIPITATION

In the preceding pages streamflow parameters were shown to relate to both physiography and average precipitation. Low flows and base flows are related more directly to rock type and structure than to physiography (landform), but the relations are difficult to define quantitatively where drainage basins are underlain by several geologic formations. However, by selecting several drainage basins in a region of nearly uniform average precipitation it was possible to determine semiquantitative relations between geology and low flows. The range in average precipitation is less than 4 inches and the values for most of the basins fall within a range of 2 inches. The effects of this small variation in average precipitation, as indicated by figure 4, are small in comparison with effects of geology and are ignored in this analysis.

The generally unglaciated part of the region south of Blue Mountain was selected for study (pl. 2). Most of the glaciated region was excluded, because the extensive glacial drift has no systematic relation to the underlying rock and therefore tends to mask the effect of the bedrock geology on the streamflow. Although the contrast between the weathered zone and the underlying fresh rock in the area of study may be as great as the contrast between the glacial drift and the underlying bedrock in the glaciated area, the character of the weathered zone probably is reasonably uniform within a given geologic unit.

Twenty-four drainage basins or parts of basins ranging in area from 14.6 to 331 square miles were studied. Streamflow parameters are available for 19 of the basins; the other 5 were included in a total of 19 basins used in an analysis of stream density and land slope as related to geology.

Seven of the basins are wholly or in large part in the Great Valley; parts of seven are in the New England Upland; four are largely or entirely, and one partly, in the Triassic Lowland; seven are in the Piedmont Upland; and five are in the Coastal Plain.

The rocks of the 24 basins or parts of basins are divided into 11 geologic units. In most of the basins the surficial deposits of Quaternary age are thin, inextensive, and relatively unimportant hydrologically; consequently only the pre-Quaternary geology is considered. The 11 units consist of formations, groups of formations having similar lithology, or in one case, two subdivisions of a formation. Ideally, a strictly lithologic classification should be used; however, this is not possible because most of the area is not mapped in sufficient detail.

In relating low flows to geology two principal assumptions are made: Streams in each geologic unit have uniform low-flow characteristics; and the outcrop of each unit is coextensive with the area in which the unit determines the nature of the low flow—that is, the boundaries of the unit are vertical and the thickness is great enough to include all or most of the zone that transmits water to the streams. The first assumption is not valid for units of heterogeneous lithology; the local variations in lithology, structure, and low-flow characteristics may exceed the average differences between many units. However, the assumption is believed to be useful for large areas in which the heterogeneity, itself, may be uniform. The second assumption is approximately true except possibly in parts of the Coastal Plain where the units are only a few tens of feet thick and are gently dipping.

The outcrop areas of the units in the drainage basins were measured by planimeter, and the geology of each basin was classified according to the percentage of the total area underlain by each unit. The physiographic and geologic classifications of the 24 basins are given in table 2 and the areal geology is shown on plate 2.

For each geologic unit the age, lithology, nature of soil and weathered products, and the characteristic structure and the topography of the outcrop are described briefly in table 3. In addition, the physiographic expression of each geologic unit is described quantitatively by two parameters that are believed to have significant relations to low-flow characteristics: (a) Stream density; and (b) land slope. Both these parameters were computed for several of the basins by Langbein and others (1947), but results were not classified according to geology; therefore, in the present study the stream density and land slope for the basins underlain by more than one geologic unit were recomputed by geologic unit. Both parameters were computed by the methods used by Langbein and others and described earlier by Norton (1932, 1945). In order to make the results as nearly comparable as possible, all measurements were made on U.S. Geological Survey 15-minute series topographic maps at a scale of 1:62,500.

Stream density, as used by Langbein and others (1947), is the ratio of stream length (as indicated by blue lines on the topographic maps) to drainage area. Thus defined, stream density is almost always less than drainage density, as used by Strahler (1958) and many other writers, which is the ratio of total channel lengths to drainage area. As pointed out by Morisawa (1957), and Langbein and others (1947), the procedure of measuring only blue lines on the maps introduces an element of inconsistency in the results, because the number and length of blue lines shown on a map vary with several factors, an important one of which is the judgment of the map editor. Although this inconsistency was reduced by using only 1:62,500-scale maps, most of which were made about the same time (about 1885 to 1905), the results given in table 4, and summarized according to geologic unit in table 3, suggest that inconsistencies in the maps mask many of the expected differences in stream density.

The correlation of land slope with geology seems to be much more significant than the correlation of stream density with geology. As shown in table 5, the differences in slope between the Martinsburg shale and the carbonate rocks are much more marked than the differences in stream density, shown in table 4. The differences among the units of Triassic age do not appear

TABLE 2.—*Physiographic and geologic classifications of 24 drainage basins*

| Index No | Name of gaging station | Drainage area (square miles) | Percentage of basin in physiographic unit: Great Valley | New England Upland | Triassic Lowland | Piedmont Upland | Coastal Plain | Percentage of basin underlain by geologic unit: Cretaceous and Tertiary deposits: Sand | Clay and silt | Diabase and basalt | Brunswick formation: Conglomerate and coarse-grained sandstone | Shale and fine-grained sandstone | Lockatong formation | Stockton formation | Shawangunk conglomerate | Martinsburg shale | Carbonate rocks | Crystalline rocks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | Neshanic River at Reaville, N.J | 25.7 | ------ | ------ | 100 | ------ | ------ | ------ | ------ | 1.0 | ------ | 62.9 | 20.3 | 13.8 | ------ | ------ | ------ | ------ |
| 20 | Great Egg Harbor River at Folsom, N.J | 56.3 | ------ | ------ | ------ | ------ | 100 | 100 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ |
| | Delaware River, west side, between Blue Mountain and Easton, Pa.[1] | 244 | 82.9 | 16.2 | 0.9 | ------ | ------ | | ------ | ------ | 0.9 | ------ | | ------ | 3.6 | 52.0 | 33.2 | 10.3 |
| 75 | Little Lehigh Creek near Allentown, Pa | 80.9 | 73.1 | 26.9 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 13.7 | 59.4 | 26.9 |
| 76 | Jordan Creek at Allentown, Pa | 75.8 | 100 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 1.0 | 87.1 | 11.9 | ------ |
| 77 | Monocacy Creek at Bethlehem, Pa | 44.5 | 100 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 36.4 | 62.1 | 1.5 |
| 80 | Saucon Creek at Friedensville, Pa | 26.6 | ------ | 72.3 | 27.7 | ------ | ------ | ------ | ------ | .5 | 20.5 | 6.7 | ------ | ------ | ------ | ------ | 35.6 | 36.7 |
| | Lehigh River between Blue Mountain and Bethlehem, Pa.[2] | 194 | 95.8 | 4.2 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 4.3 | 53.1 | 38.4 | 4.2 |
| 83 | Tohickon Creek near Pipersville, Pa | 97.4 | ------ | ------ | 100 | ------ | ------ | ------ | ------ | 30.6 | ------ | 66.2 | 3.2 | ------ | ------ | ------ | ------ | ------ |
| 86 | Crosswicks Creek at Extonville, N.J | 83.6 | ------ | ------ | ------ | ------ | 100 | 82.2 | 17.8 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ |
| 87 | Neshaminy Creek near Langhorne, Pa | 210 | ------ | ------ | 97.6 | 2.4 | ------ | ------ | ------ | .1 | ------ | 10.4 | 36.7 | 46.6 | ------ | .2 | 3.1 | 2.9 |
| 88 | North Branch Rancocas Creek at Pemberton, N.J | 111 | ------ | ------ | ------ | ------ | ------ | 82.2 | 17.8 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ |
| 91 | Tulpehocken Creek near Reading, Pa | 211 | 90.4 | 9.6 | ------ | ------ | ------ | ------ | ------ | .2 | .8 | ------ | ------ | ------ | 2.5 | 54.2 | 33.7 | 8.6 |
| | Schuylkill River between Blue Mountain and Reading, Pa.[3] | 331 | 92.1 | 7.9 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 6.5 | 62.3 | 23.3 | 7.9 |
| 92 | Perkiomen Creek at Graterford, Pa | 279 | ------ | 17.2 | 82.8 | ------ | ------ | ------ | ------ | 14.8 | 4.9 | 61.6 | 1.5 | ------ | ------ | ------ | 1.1 | 16.1 |
| | Crum Creek at Woodlyn, Pa | 33.3 | ------ | ------ | ------ | 100 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 100 |
| 94 | Ridley Creek at Moylan, Pa | 31.9 | ------ | ------ | ------ | 100 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 100 |
| 95 | Chester Creek near Chester, Pa | 61.1 | ------ | ------ | ------ | 100 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 100 |
| 96 | Oldmans Creek near Woodstown, N.J | 19.3 | ------ | ------ | ------ | ------ | 100 | 92.7 | 7.3 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ |
| 98 | White Clay Creek above Newark, Del | 66.7 | ------ | ------ | ------ | 100 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 5.4 | 94.6 |
| 101 | Red Clay Creek at Wooddale, Del | 47.0 | ------ | ------ | ------ | 100 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 6.2 | 93.8 |
| 102 | West Branch Brandywine Creek at Coatesville, Pa | 45.8 | ------ | ------ | ------ | 100 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 1.5 | 98.5 |
| 103 | Brandywine Creek at Chadds Ford, Pa | 287 | ------ | ------ | ------ | 100 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 7.4 | 92.6 |
| 105 | Salem River at Woodstown, N.J | 14.6 | ------ | ------ | ------ | ------ | 100 | 96.8 | 3.2 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ |

[1] Not including basins of Lehigh River above Bethlehem, Pa., and Saucon Creek above Friedensville, Pa.

[2] Not including basins of Monocacy Creek above gaging station at Bethlehem, Pa., Little Lehigh Creek above gaging station near Allentown, Pa., and Jordan Creek above gaging station at Allentown, Pa.

[3] Not including basin of Tulpehockena Creek bove gaging station near Reading, Pa.

to be significant, except possibly for the conglomerate and coarse-grained sandstone of the Brunswick formation and the diabase and basalt, which have steeper slopes than the other Triassic units. The steeper land slopes of the crystalline rocks in the New England Upland as compared to slopes of the crystalline rocks in the Piedmont Upland illustrate the necessity for restricting comparisons to geologic units within the same physiographic unit.

Hydrologic parameters describing the water yielding and transmitting properties of certain rocks are helpful in evaluating the low-flow characteristics of streams in the areas underlain by these rocks. Although hydrologic characteristics of all the geologic units vary markedly, it is belived that estimates of average coefficients of storage [6] and transmissibility [7] and of the average yields of wells provide a useful basis for comparison. Accordingly, the estimated averages for each unit for which data are available are given in table 3. The estimates are based on information compiled by the U.S. Geological Survey. Because they are based on scanty data, most of the estimates are crude and are used only to evaluate the relative productivity of the aquifers.

The approximate average yield of wells is for wells of several types and is therefore conservatively low; the average for large wells used for municipal or industrial supply is much higher in many of the units. However, a conservative estimate may be most realistic because many reported yields are initial, short-term pumping rates which may greatly exceed yields that can be sustained for long periods.

Observed yields of wells provide only a very rough, and sometimes erroneous, measure of the water-yielding capacity of aquifers. The coefficients of storage and transmissibility are much more valuable but harder to obtain because their accurate determination generally requires pumping tests that are carefully controlled. The necessary data are available for only the sandy aquifer of Cretaceous and Tertiary age in the Coastal Plain and the Stockton formation in the Triassic Lowland. Tests have also been made in the Brunswick for-

[6] The coefficient of storage of an aquifer is a dimensionless ratio representing the volume of water the aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. Under water-table conditions it is approximately equal to the specific yield.

[7] The coefficient of transmissibility indicates the volume rate at which water at the prevailing temperature is transmitted through a section of the aquifer having unit with, under unit hydraulic gradient. The unit used by the Geological Survey is gallons per day per foot.

TABLE 3.—*Physical and hydrological characteristics of geologic units*

| Age | Unit | Lithology | Soils and weathered products | Structure | Physiographic unit | Topography of outcrop | Average stream density of outcrop (mi per sq mi) | Average land slope of outcrop (ft per mi) | Average yields of wells (gpm) | Approximate average coefficient of storage (dimensionless) | Approximate average coefficient of transmissibility (gpd per ft) | [7] $Q_{90}/Q_a$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cretaceous and tertiary | Sand | Several formations consisting largely of unconsolidated to locally semiconsolidated sand and a little gravel, and minor beds of silt and clay. | Deep permeable sandy and silty loams. | Gentle southeastward dips ranging from about 15 to 60 feet per mile. | Coastal Plain | Gently sloping valley sides and nearly flat interstream areas; ridge cappings. | 1.21 | 74 | [1] 30–500 | [1] 0.1–0.3 | [1, 5] 10,000–100,000 | 0.42 |
| | Clay and silt | Several formations consisting of strongly to sparsely glauconitic clay, silt, and minor sand. Interbedded with sand and gravel. | Poorly to moderately permeable clayey and silty soils having fair to poor drainage. | Gentle southeastward dips ranging from about 20 to 60 feet per mile. | Coastal Plain | Steep stream banks and valley sides, gently-sloping interstream areas. | | | 5 | .01 | Very low | .05 |
| Triassic | Diabase and basalt | Dark fine- to medium-grained crystalline rock consisting principally of augite and plagioclase. | Reddish- to yellowish-brown clay and silt, commonly containing irregular fragments of rock as much as several feet in diameter. Soil absent locally. | Sills, flows, and dikes intruding or interbedded with sedimentary rocks of Triassic age. | Triissac Lowland | Steep to gently sloping angular ridges and lines of hills. | 1.59 | 370 | 2 | ---------- | Very low | .02 |
| | Brunswick formation: Conglomerate and coarse sandstone | Moderately to strongly indurated conglomerate consisting of pebbles of quartzite, sandstone, and, locally, limestone in a matrix of red siltstone or claystone; some coarse sandstone. | Reddish-brown silt containing variable quantities of pebbles and cobbles weathered from parent rock. | Gently dipping thick beds. | Triassic Lowland | Rounded hills, generally somewhat higher than adjacent areas underlain by shale and fine-grained sandstone. | 1.39 | 420 | ---------- | ---------- | ---------- | .30 |
| | Brunswick formation: Shale and fine sandstone | Soft red shale, some brownish-red siltstone and fine-grained sandstone, and green, yellow, gray, and purple shale and argillite. Altered to hard dark-gray hornfels adjacent to diabase. | Red, brown, and locally gray silt and silty loam, at many places grading downward into compact clay. Soils thin at many localities; grade downward into weathered soft shale and fine-grained sandstone. | Rather uniform gentle to moderate northwestward dips, commonly interrupted by small high-angle faults and a few large faults. | Triassic Lowland | Softer beds form elongate, parallel valleys between low ridges of harder rocks. Hornfels forms steep slopes adjacent to diabase ridges. | 1.78 | 260 | 70 | [2] .015 | [3] 3,500 | .04 |
| | Lockatong formation | Thick-bedded dark-gray argillite, zones of thin-bedded dark shale, impure limestone and limy argillite. Includes some dark-red argillite and soft red shale in upper part. | Yellowish- to grayish-brown silt, in places overlying varicolored clayey subsoils. Small angular fragments of shale and large blocks of argillite locally abundant. Depth to fresh rock rarely more than a few feet. | Similar to Brunswick formation. | Triassic Lowland | Argillite forms long, straight ridges where interbedded with softer rocks and plateaus where softer rocks are absent. | 1.74 | 250 | 10 | ---------- | [4] 1,000 | .02 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Stockton formation | Yellow to gray arkose, some conglomerate, red to brown sandstone, and soft red shale. | Red, brown, and gray silt, fine sand, and some clay grading downward into soft, weathered sandstone, arkose, and conglomerate. | Similar to Brunswick formation. | Triassic Lowland | Arkose and conglomerate form low ridges; soft red sandstone and shale form intervening valleys. | 1.84 | 230 | 100 | ---------- | [5] 5,000–[4] 10,000 | .12 |
| Silurian | Shawangunk conglomerate. | Hard quartzitic sandstone and conglomerate and a few thin beds of shale. | Bare outcrops or thin sandy soils. | Moderate to steep northward dips. | Valleys and Ridges (Blue Mountain). | Long, narrow, steep-sided ridge. | .38 | 1,200 | ---------- | ---------- | ---------- | ---------- |
| Ordovician | Martinsburg shale | Bluish-gray shale and slate, fine- to medium-grained arkosic sandstone or graywacke, fine-grained calcareous sandstone, limestone, and some red beds and conglomerate. | Thin yellowish- to grayish-brown silt, usually containing abundant fragments of shale; grades downward into yellowish-brown weathered rock within a few feet of surface. | Strongly to moderately folded beds commonly cut by prominent slaty cleavage parallel to axial planes of folds; some faults. | Great Valley | Randomly dissected surface several hundred feet above adjacent limestone lowland and several hundred feet below Blue Mountain. | 1.53 | 530 | 50 | ---------- | ---------- | .04 |
| Cambrian and ordovician | Carbonate rocks | Thick- to thin-bedded limestone, dolomite, magnesian limestone, shaly limestone, and calcareous slate. Includes Cockeysville marble in Piedmont Upland. | Light-brown silty soil grading downward into yellow, brown, or red clay and silt as much as several tens of feet thick. Contact of clay and fresh rock sharp at most places. | Strongly folded and faulted beds which are overturned at many places. | Great Valley, New England Upland, Piedmont Upland, Triassic Lowland (minor). | Gently rolling lowlands surrounded by ridges and uplands formed of more resistant crystalline rocks and Martinsburg shale. | 1.22 | 250 | 200 | ---------- | ---------- | .60 |
| Precambrian and paleozoic | Crystalline rocks | Many types of schist, gneiss, quartzite, phyllite, and associated granitic to ultramafic rocks. | In Piedmont Upland, sandy to clayey regolith as much as several tens of feet thick except along steep valley sides, where outcrops are numerous. In New England Upland, weathered zone usually thinner and in some places replaced by glacial drift. | Metamorphic foliation, lineation, joints, and faults, rather than bedding, are the most important structural elements. | Piedmont Upland and New England Upland. | In Piedmont Upland, moderately to strongly dissected surface. | 2.26 | 460 | 40 | [6] .08 | [4] 1,500–[6] 1,000 | .35 |
| | | | | | | In New England Upland, moderately steep-sided hills and ridges. | 1.13 | 670 | | | | |

1 Range in averages for several aquifers.
2 Based on an estimate by Herpers and Barksdale (1951) for the Newark, N.J., area.
3 Crude rational estimate based on comparison with Stockton formation.
4 Based on specific-capacity data.
5 Based on pumping-test data.
6 Based on an estimate by Olmsted and Hely (1962) for Brandywine Creek basin.
7 Ratio of daily stream discharge equaled or exceeded 90 percent of time to average stream discharge.

TABLE 4.—*Stream density of 19 drainage basins, classified according to geologic units*

[Values in miles per square mile]

| Gaging-station index No. | Drainage basin | Cretaceous and Tertiary deposits | Diabase and basalt | Brunswick formation: Conglomerate and coarse-grained sandstone | Brunswick formation: Shale and fine-grained sandstone | Lockatong formation | Stockton formation | Shawangunk conglomerate | Martinsburg shale | Carbonate rocks | Crystalline rocks: New England Upland | Crystalline rocks: Piedmont Upland | Basin averages |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | Neshanic River | | 0.12 | | 2.14 | 0.98 | 1.31 | | | | | | 1.73 |
| 20 | Great Egg Harbor River | [1]0.96 | | | | | | | | | | | [1].96 |
| | Delaware River, west side, between Blue Mountain and Easton, Pa. | | | | | | | 0.16 | 1.24 | 1.04 | 1.10 | | 1.12 |
| 75 | Little Lehigh Creek | | | | | | | | .75 | 1.23 | 1.09 | | 1.12 |
| 76 | Jordan Creek | | | | | | | 0 | 1.48 | 1.14 | | | 1.44 |
| 77 | Monocacy Creek | | | | | | | | 1.12 | .71 | 1.6 | | .87 |
| 80 | Saucon Creek | | | 1.50 | 1.39 | | | | | 1.89 | .26 | | 1.17 |
| | Lehigh River between Blue Mountain and Bethlehem, Pa. | | | | | | | .25 | 1.20 | .89 | .22 | | 1.00 |
| 83 | Tohickon Creek | | 1.61 | | 1.94 | 1.42 | | | | | | | 1.82 |
| 87 | Neshaminy Creek | | 1.0 | | .81 | 1.87 | 1.85 | | 2.2 | 1.09 | | 2.03 | 1.73 |
| 88 | North Branch Rancocas Creek | [1]1.18 | | | | | | | | | | | [1]1.18 |
| 91 | Tulpehocken Creek | | ([2]) | ([2]) | | | | 1.3 | 1.13 | 1.13 | .64 | | 1.04 |
| | Schuylkill River between Blue Mountain and Reading, Pa. | | | | | | | .29 | 2.18 | 1.51 | 1.36 | | 1.83 |
| 92 | Perkiomen Creek | | 1.61 | 1.34 | 1.82 | .63 | | | | 3.3 | 1.59 | | 1.73 |
| | Crum Creek | | | | | | | | | | | [1]2.44 | [1]2.44 |
| 94 | Ridley Creek | | | | | | | | | | | [1]2.19 | [1]2.19 |
| 96 | Oldmans Creek | [1]1.73 | | | | | | | | | | | [1]1.73 |
| 103 | Brandywine Creek | | | | | | | | | 2.46 | | 2.24 | [1]2.26 |
| 105 | Salem River | [1]1.75 | | | | | | | | | | | [1]1.75 |
| | Formation averages | 1.21 | 1.59 | 1.39 | 1.78 | 1.74 | 1.84 | .38 | 1.53 | 1.22 | 1.13 | 2.26 | |

[1] From Langbein and others (1947).
[2] Included with crystalline rocks.

TABLE 5.—*Land slope of 19 drainage basins, classified according to geologic units*

[Values in feet per mile, given to two significant figures]

| Gaging-station No. | Drainage basin | Cretaceous and Tertiary deposits | Diabase and basalt | Brunswick formation: Conglomerate and coarse-grained sandstone | Brunswick formation: Shale and fine-grained sandstone | Lockatong formation | Stockton formation | Shawangunk conglomerate | Martinsburg shale | Carbonate rocks | Crystalline rocks: New England Upland | Crystalline rocks: Piedmont Upland | Basin averages |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | Neshanic River | | 380 | | 200 | 380 | 350 | | | | | | 270 |
| 20 | Great Egg Harbor River | [1]53 | | | | | | | | | | | [1]53 |
| | Delaware River, west side, between Blue Mountain and Easton, Pa. | | | | | | | 1,600 | 450 | 300 | 730 | | 460 |
| 75 | Little Lehigh Creek | | | | | | | | 600 | 220 | 670 | | 370 |
| 76 | Jordan Creek | | | | | | | 1,600 | 560 | 320 | | | 540 |
| 77 | Monocacy Creek | | | | | | | | 520 | 150 | 550 | | 280 |
| 80 | Saucon Creek | | | 460 | 160 | | | | | 190 | 820 | | 490 |
| | Lehigh River between Blue Mountain and Bethlehem, Pa. | | | | | | | 1,100 | 500 | 260 | 880 | | 470 |
| 83 | Tohickon Creek | | 280 | | 210 | 150 | | | | | | | 230 |
| 87 | Neshaminy Creek | | 160 | | 180 | 240 | 210 | | 370 | 230 | | 340 | 220 |
| 88 | North Branch Rancocas Creek | [1]62 | | | | | | | | | | | [1]62 |
| 91 | Tulpehocken Creek | | ([2]) | ([2]) | | | | 710 | 520 | 210 | 720 | | 420 |
| | Schuylkill River between Blue Mountain and Reading, Pa. | | | | | | | 1,200 | 590 | 260 | 620 | | 560 |
| 92 | Perkiomen Creek | | 420 | 400 | 280 | 180 | | | | 300 | 580 | | 360 |
| | Crum Creek | | | | | | | | | | | [1]480 | [1]480 |
| 94 | Ridley Creek | | | | | | | | | | | [1]410 | [1]410 |
| 96 | Oldmans Creek | [1]150 | | | | | | | | | | | [1]150 |
| 103 | Brandywine Creek | | | | | | | | | 300 | | 460 | 450 |
| 105 | Salem River | [1]140 | | | | | | | | | | | [1]140 |
| | Formation averages | 74 | 370 | 420 | 260 | 250 | 230 | 1,200 | 530 | 250 | 670 | 460 | |

[1] From Langbein and others (1947).
[2] Included with crystalline rocks.

mation, but the standard formulas used to compute coefficients of transmissibility and storage cannot be used because the wells receive water in unknown proportions from both water-table and artesian aquifers (Greenman, 1955, p. 34), and the transmissibility of the fractured rock varies greatly with direction (Herpers and Barksdale, 1951, p. 31). The value given for the Brunswick formation in table 3 is only approximate and is based on a comparison of average well yields of the Brunswick and Stockton formations; it probably represents the average coefficient for all directions in the virtually unconfined zone within 200 or 300 feet of the land surface.

The estimates of coefficient of transmissibility for the crystalline rocks and the Lockatong formation, and the second estimate given for the Stockton formation (table 3) are based on average specific capacities of wells.[8] The coefficient of transmissibility is computed to be very roughly equal to specific capacity times 1,500 by using a modification of a formula developed by Thiem (1906) for determining permeability from the flow into a discharging well under equilibrium conditions, and by assuming water-table conditions. Although inherently less accurate than pumping-test data for individual sites, the specific-capacity data are much more abundant and may therefore provide an estimate of average coefficient of transmissibility of an entire unit that is more accurate than one based on pumping-test data for a few wells. The estimated value for the crystalline rocks agrees reasonably well with values, based on different methods, used in a study of Brandywine Creek basin described by Olmsted and Hely (1962).

Data are insufficient for even rough estimates of the coefficient of transmissibility of the other geologic units; the relative water-yielding capacities of these units can be deduced only approximately from the average yields of wells.

For several geologic units in the study area insufficient information was available to make even crude guesses of the coefficient of storage. Although such estimates have been made for several of these units, some of them apply to the confined or semiconfined zones supplying water to deep wells rather than to the unconfined zone and are not applicable to a study of streamflow. Estimates for the crystalline rocks of the Piedmont Upland were made in a study of the Brandywine Creek basin (Olmsted and Hely, 1962).

In the area shown on plate 2 it is assumed that most of the groundwater discharge to streams is from the zone of water-table fluctuations; the estimated coefficients of storage therefore apply to this zone.

A study was made of the relations between several low-flow parameters and geology in 19 of the 20 basins for which gaging-station index numbers are given in table 2. (Several of the required parameters were lacking for Tulpehocken Creek basin.) Although parameters based on winter base-flow recession should show the best correlation with geology (as explained in the discussion of base-flow parameters) the difficulty in defining accurately the winter base-flow recession of some streams precluded use of these parameters.

It was found that some of the flow-duration parameters used, such as the ratio $Q_{90}/Q_a$ or the ratio $Q_{90}/Q_{50}$, seemed to vary most widely with differences in geology, yet were fairly consistent within each geologic unit. The parameter adopted for this study was $Q_{90}/Q_a$ because it was available for all the basins and other suitable parameters were not.

In estimating an average value of $Q_{90}/Q_a$ for each of the geologic units the first step in the procedure was to calculate the average values for drainage basins underlain entirely or largely by one geologic unit. These averages were weighted according to area of drainage basin. The values for the crystalline rocks in the Piedmont Upland and the sand of the Coastal Plain were determined in this way. Next, the basins underlain wholly or predominantly by two geologic units, but containing different proportions of each, were analyzed, and the values of $Q_{90}/Q_a$ for each unit were calculated by use of simultaneous equations. Values for the carbonate rocks and the Martinsburg shale in the basins in the Great Valley were calculated by this procedure. Next, values for other units in the basins having more heterogeneous geology, particularly the basins in the Triassic Lowland, were estimated by a method of convergent approximations. Trial values were assigned, taking into consideration coefficients of storage and transmissibility and inferred infiltration characteristics of the soils. Finally, minor adjustments were made in the values for all the units, again using convergent approximations. The estimated values thus determined are given in table 3. Values computed from table 3 and the actual values (from streamflow records) of $Q_{90}/Q_a$ for the 19 drainage basins are shown for comparison in the table below.

*Comparison of values computed from table 3 and actual values of $Q_{90}/Q_a$ for 19 drainage basins*

| Gaging-station No. | Drainage basins | $Q_{90}/Q_a$ | |
|---|---|---|---|
| | | Computed | Actual |
| 9 | Neshanic River | 0.046 | 0.047 |
| 20 | Great Egg Harbor River | .42 | .42 |
| 75 | Little Lehigh Creek | .46 | .43 |
| 76 | Jordan Creek | .11 | .11 |
| 77 | Monocacy Creek | .39 | .45 |
| 80 | Saucon Creek | .41 | .35 |
| 83 | Tochickon Creek | .033 | .030 |
| 86 | Crosswicks Creek | .36 | .35 |
| 87 | Neshaminy Creek | .096 | .091 |
| 88 | North Branch Rancocas Creek | .42 | .404 |
| 92 | Perkiomen Creek | .11 | .119 |
| 94 | Ridley Creek | .35 | .30 |
| 95 | Chester Creek | .35 | .31 |
| 96 | Oldmans Creek | .40 | .41 |
| 98 | White Clay Creek | .36 | .39 |
| 101 | Red Clay Creek | .37 | .42 |
| 102 | West Branch Brandywine Creek | .35 | .34 |
| 103 | Brandywine Creek | .37 | .330 |
| 105 | Salem River | .41 | .30 |

The comparison above of computed and actual values of the ratio shows that nearly all of the variation in $Q_{90}/Q_a$ for these areas is associated with differences in rock types.

[8] Specific capacity of a well is defined as the yield per unit of drawdown, generally expressed in gallons per minute divided by the accompanying drawdown of water level, in feet, after a specified period of pumping.

The estimated values of $Q_{90}/Q_a$ are not equally accurate for all units. The best defined values probably are those for the crystalline rocks, the sand of Cretaceous and Tertiary age in the Coastal Plain, the carbonate rocks, the Martinsburg shale, and the shale and fine sandstone of the Brunswick formation; but in some of these units the variation appears to be appreciable. For example, significant variations in the coefficients of storage and transmissibility are known to exist between different sandy formations of the Coastal Plain; such variations undoubtedly are reflected in the low flows. Marked differences also occur in the carbonate rocks and crystalline rocks.

Some of the differences in the values of $Q_{90}/Q_a$ for the geologic units (table 3) might be attributed to differences in land use. However, with two or three exceptions, differences in land use are minor. The outcrops of most of the units are largely cropland, pastureland, and miscellaneous open land including urban and suburban areas; woodland generally constitutes less than 15 percent of the total area. The chief exceptions are the exposures of diabase and basalt, which are almost entirely wooded, and the exposures of crystalline rocks in the New England Upland and the sandy deposits of Cretaceous and Tertiary age in the outer part of the coastal Plain (Great Egg Harbor River basin), which are largely wooded. The area underlain by crystalline rocks in the Piedmont Upland has a slightly higher proportion of woodland than the average; the most extensively wooded areas are ridges underlain by quartzite.

All the values of $Q_{90}/Q_a$ are regarded as approximate averages generally for areas of more than 10 square miles and should not be used when more accurate values for other basins and ungaged areas in the region are required. However, the writers believe that rough estimates of $Q_{90}/Q_a$ and possibly other low-flow parameters can be made by the method described above for fairly large ungaged areas in and near the region of the present study if their geology is known in sufficient detail. Before estimating values of $Q_{90}/Q_a$ for each geologic unit in such areas, it should be ascertained that the topographic characteristics of the outcrops, especially the average land slope and stream density, are similar to those in the area of the present study and that large differences in average precipitation are accounted for. The land-use patterns of these ungaged areas also should be similar to those in the basins studied.

## CONCLUSIONS

This study shows that in the Delaware River region a very large proportion of the areal variation in low-flow characteristics of streams is associated with areal variations in average precipitation and geology, the principal meteorological and terrestrial factors that affect streamflow.

The influence of these two factors is so great that evaluation of effects of less significant factors such as land use is very difficult except in carefully controlled experiments. Relatively small unknown variations in geology or undefined variations in average precipitation (particularly in mountainous areas) might mask the true relation between streamflow and the characteristic in question.

Expression of discharge in terms of unit area removes most—but not all—of the effect of basin size in the relations studied. The residual effect is large enough to be significant only when differences in area are very large (probably more than 1,000 sq mi).

Most common low-flow parameters vary markedly with average precipitation, and this characteristic detracts from their usefulness as indicators of the influence of terrestrial factors in the environment. Parameters based on base-flow recession curves and related to a common discharge per unit area are independent of the areal variations in average precipitation; those based on winter curves are also independent of areal variations in evapotranspiration of ground water. Base-flow parameters are good indicators of the influences of terrestrial factors, but much of this inherent advantage is offset by the practical difficulties of defining base-flow recession curves, particularly winter curves.

In the absence of suitable recession data the ratio $Q_{90}/Q_a$, or a similar flow-duration parameter, probably is the best indicator of influences of terrestrial factors.

The relations between base-flow recession parameters and average precipitation (fig. 10) indicate that regions of high-average precipitation in the Catskill Mountains and the southern New York section of the Appalachian Plateaus are also regions where the geology or topography favors well-sustained base flow. Consequently, the relations between other parameters and precipitation in figures 3 and 4 are affected, and the true relations are somewhat flatter than those indicated.

If the ratio $Q_{90}/Q_a$ that is characteristic of a specific geologic formation can be defined from streamflow data, the results can be applied to other areas in the same formation, provided that the differences in average precipitation are small or accounted for and that certain checks are made to assure similarity of topography.

## REFERENCES

Fenneman, N. M., and others, 1930, Physical divisions of the United States [map]: U.S. Geol. Survey.

Greenman, D. W., 1955, Ground-water resources of Bucks County, Pennsylvania: Pennsylvania Geol. Survey, 4th ser., Bull. W 11, 66 p.

Hely, A. G., Nordenson, T. J., and others, 1961, Precipitation, water loss, and runoff in Delaware River basin and New Jersey: U.S. Geol. Survey Hydrol. Inv. Atlas HA-11 [1962].

Herpers, Henry, and Barksdale, H. C., 1951, Preliminary report on the geology and ground-water supply of the Newark, New Jersey area: New Jersey Dept. Conserv. and Econ. Devel., Div. Water Policy and Supply, Spec. Rept. 10, 52 p.

Horton, R. E., 1932, Drainage basin characteristics: Am. Geophys. Union Trans., v. 13, p. 350–361.

——— 1945, Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology: Geol. Soc. America Bull., v. 56, p. 275–370.

Langbein, W. B., and others, 1947, Topographic characteristics of drainage basins: U.S. Geol. Survey Water-Supply Paper 968–C, p. 125–155.

Morisawa, Marie, 1957, Accuracy of determination of stream lengths from topographic maps: Am. Geophys. Union Trans., v. 38, p. 86–88.

Olmstead, F. H., and Hely, A. G., 1962, Relations between ground water and surface water in Brandywine Creek basin, Pennsylvania: U.S. Geol. Survey Prof. Paper 417–A, p. A1–A21.

Parker, G. G., Hely A. G., Keighton, W. B., Olmsted, F. H., and others, 1963, Water resources of the Delaware River basin: U.S. Geol. Survey Prof. Paper 381, in press.

Rasmussen, W. C., and Andreasen, G. E., 1959, Hydrologic budget of the Beaverdam Creek basin, Maryland: U.S. Geol. Survey Water-Supply Paper 1472, 106 p.

Strahler, A. N., 1958, Dimensional analysis applied to fluvially eroded landforms: Geol. Soc. America Bull., v. 69, p. 279–300.

Thiem, Gunter, 1906, Hydrologische Methoden: Leipzig, J. M. Gebhardt, 56 p.

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