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HYDRAULIC GEOMETRY OF 12 SELECTED STREAM SYSTEMS OF THE UNITED STATES

By JOHN B. STALL and CHIH TED YANG

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Illinois State Water Survey
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HYDRAULIC GEOMETRY OF ILLINOIS STREAMS

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SUMMARY

Channel characteristics of stream systems have been evaluated for 12 river basins in the humid region of the United States. Basins vary in size from 1532 to 8410 square miles, and river slopes from 1.56 to 107 feet per mile. Each basin was selected as having relatively uniform physiography, but the 12 basins represent widely different physiographic sections of the country.

Discharge, cross-sectional area, width, depth, and velocity of a stream at a particular location in the stream system are each related to the frequency of occurrence of the discharge, F, in percent of days per year, and the drainage area, A_d, in square miles. The resulting five hydraulic geometry equations represent the characteristic interrelationship of these factors throughout the stream system.

The Horton-Strahler laws of channel morphology prove to be valid for these stream systems, regardless of the scale of map used for their determination. Two new laws, the *law of average stream fall*, and the *law of least rate of energy expenditure* are introduced. A theoretical longitudinal streambed profile is computed, as well as an equilibrium profile. The latter, when compared with the actual existing streambed profile, indicates future channel aggradation or degradation.

Stream velocities calculated from hydraulic geometry equations check with the time-of-travel measured in streams by use of dye tracers. Provisional time-of-travel curves for a 140-mile reach of the Sangamon River are shown. Stream velocity and depth as calculated by hydraulic geometry equations can be used to estimate the total capacity of a stream to assimilate wastes.

INTRODUCTION

Since 1895, the Illinois State Water Survey has carried out a full-time program of research and evaluation of the water resources of Illinois including the quantity and quality of water, both surface waters and underground waters. The project reported here is a part of this research and evaluation. Beginning in 1914, a continuing program of measurement of the flows of Illinois streams was undertaken. At about 12 locations in Illinois, there have been continuous measurements of streamflow since 1914. This program has been carried out by the U. S. Geological Survey, which makes the measurements and publishes the results. The State Water Survey has participated in this program as a state sponsor since its inception. The program is carried out on a matching funds basis, in which the state sponsor pays one-half of the cost of the program and the U. S. Geological Survey contributes the other half. In 1970 about 160 continuous-record permanent stream gaging stations were in operation in Illinois under this program.

The streamflow data from these gaging stations have contributed much to the effective development of surface water resources in Illinois. The State Water Survey, as well as other agencies, carries on a continuing analysis of these streamflow data to provide processed results that will be valuable in this resource development. A major study by Stall (1964) has shown how to calculate the yield of an impounding reservoir, and the analysis of streamflow data figured importantly in a major study of potential surface water reservoirs of Illinois by Dawes and Terstriep (1966). Similarly, the amounts of streamflow were associated with the quality of surface water in Illinois in a major study by Harmeson and Larson (1969). The U. S. Geological Survey has provided important generalizations of streamflow data dealing with unit hydrographs (Mitchell, 1948) and floods in Illinois (Mitchell, 1954). Summarized data on flow duration and the duration of high and low discharge have been provided for Illinois streams by Curtis (1969).

An evaluation of the hydraulic geometry of Illinois streams was made in a study by Stall and Fok (1968). In this study, a consistent pattern was evaluated in which the width, depth, and velocity of flow in a stream change along the course of the stream with a constant frequency of discharge. These channel characteristics, termed hydraulic geometry, were shown to constitute an interdependent system which was described by a series of graphs and equations. The success of this earlier study in generalizing these relations has led to the present study of some selected stream systems of the United States. Illinois is a flat prairie state. The streams have relatively low gradients. The present study has been oriented toward the extension of hydraulic geometry relations into parts of this country having more rugged terrain, steeper stream slopes, and greater variation in the total amount of runoff.

The concept of hydraulic geometry was first published by Leopold and Maddock (1953). Here it was suggested that channel characteristics of natural streams are interrelated in a complex manner. The authors showed how the nature of a particular river system can be described quantitatively. They first described this interrelated system as the *hydraulic geometry* of the stream system. These authors gave three principal equations as follows:

$$W = a\,Q^{b} \tag{1}$$

$$D = c\,Q^{f} \tag{2}$$

$$V = k\,Q^{m} \tag{3}$$

where W = width, D = mean depth, V = mean velocity, Q = discharge, and a, b, a, f, k, and m are numerical constants. Leopold and Maddock (1953) showed that these relations, even for stream systems in greatly different physiographic settings, appear to be consistent. The present study set out to provide quantitative evaluation of the hydraulic geometry for a number of different stream systems in various physiographic divisions of the United States, and to investigate the consistency and variability, as well as the numerical value, of the hydraulic geometry constants for a variety of stream systems.

The nature and dynamics of stream systems have been described in a highly readable book by Morisawa (1968). Recent important studies of the hydraulic character of steep, rough stream channels have also been made by Judd and Peterson (1969) and by Morris (1969). These results provide some characterization of hydraulic geometry patterns for streams of this nature. An important contribution to the hydraulics of natural channels has been provided by Barnes (1967) in the form of color photographs and descriptive data for 50 stream channels in the United States for which roughness coefficients are also provided.

Objectives and Scope

The objective of this research project has been to develop the hydraulic geometry relations for 12 stream systems in the United States selected to represent a variety of physiographic and hydrologic conditions. The hydraulic geometry would be described by a set of five equations for each system. This would allow a numerical comparison of the hydraulics of streams between different physiographic regions.

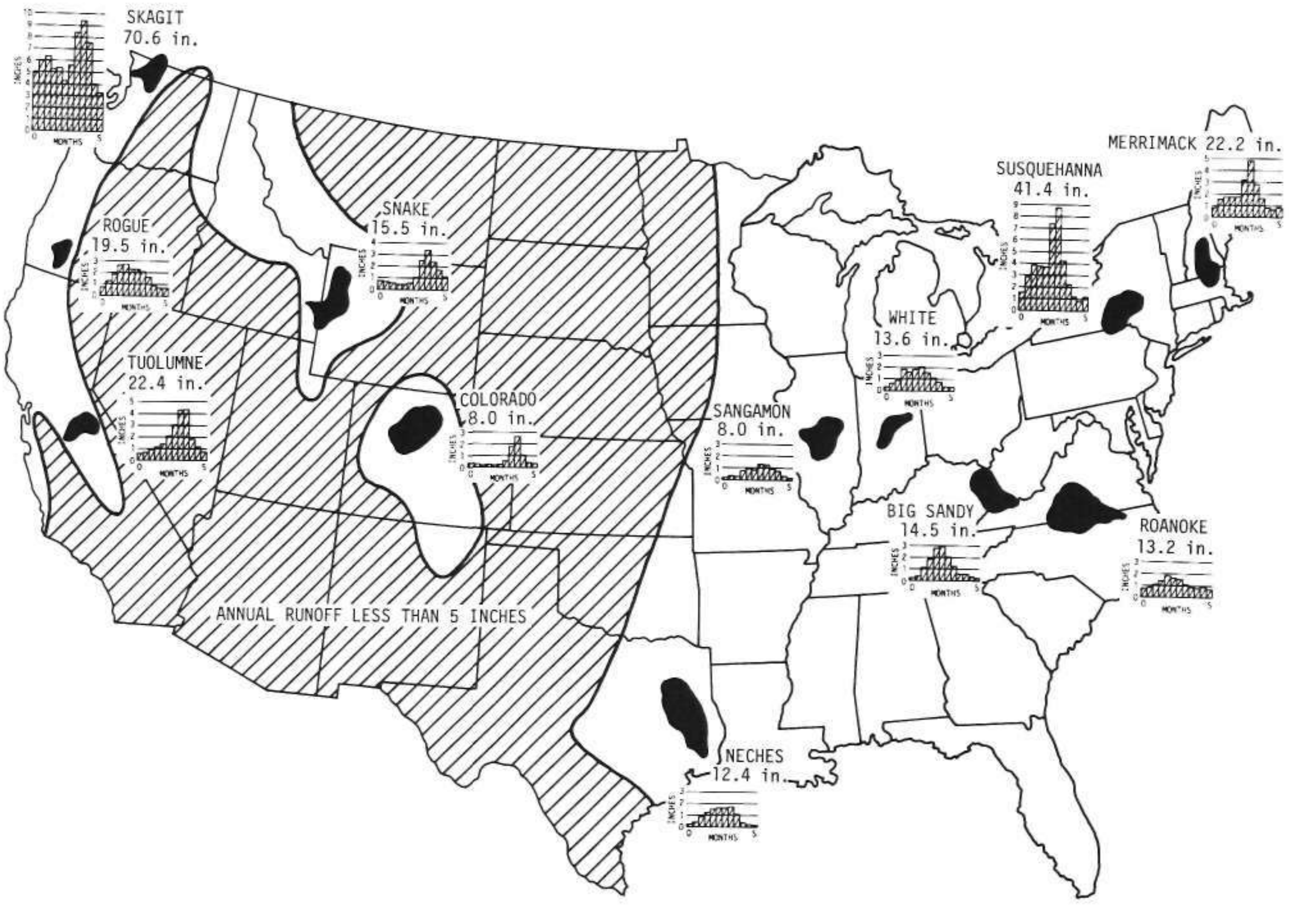


Figure 1. Location of the 12 river basins studied showing annual and seasonal distribution of runoff in inches

From the earlier Illinois study, the Sangamon River Basin was selected as being representative of the hydraulic geometry of Illinois streams. As a part of that study, the hydraulic geometry relations were also developed for the west branch of the White River Basin in Indiana. The White River Basin was deemed slightly different from the Sangamon Basin, so these two basins have been included in the present study. Table 1 gives physical and hydrologic factors for the 12 river basins ultimately selected. The locations of these river basins are shown in the map in figure 1. The generalized river slope in feet per mile, shown in table 1, varies from 1.56 for the Sangamon River in Illinois to 107.6 for the Tuolumne River in California. The drainage areas of the 12 basins range from 1532 to 8410 square miles. The basins were selected in size to be large enough to reveal the consistent patterns of hydraulic geometry and yet small enough that the routine work required for developing the hydraulic geometry factors could be handled adequately during the two-year term of the project. Table 1 also shows the number of stream gages ultimately used in the development of the hydraulic geometry relations, which totals 308 stream gaging stations used in the entire project.

The cross-hatched area in figure 1 is that part of the United States for which annual runoff is less than 5 inches, and this "arid zone" was purposely excluded from the present study. It is believed that in this part of the country, the hydraulic geometry patterns are complex. At a particular time the channel characteristics are highly dependent upon the nature of the last flood and are less likely to represent the result of long-term consistent runoff patterns. The 12 basins studied are all located in the humid regions, and figure 1 gives for each the total annual runoff in inches and the distribution of this annual runoff throughout the water year from October of one year to September of the next year.

Physiography

The physical geography of the United States has been described by Fenneman and Johnson (1964) and by Hunt (1967). Basins selected for this study were contained completely in one physiographic section. Table 2 gives the complete physiographic description for each as provided on the map by Fenneman and Johnson (1964). As can be seen from the descriptions in table 2, the 12 basins provide a great variety of physiographic conditions. Figure 2 shows a general view of the upper Snake River, which is a mountain stream and one of the steeper of the 12 basins studied.

Acknowledgment

The research described in this paper has been carried out by the authors as a part of their regular work at the Illinois State Water Survey under the direction of H. F. Smith, Head of the Hydrology Section, and William C. Ackermann, Chief. Half of the cost of this project has been financed under the matching funds program of the Office of Water Resources Research, U. S. Department of Interior, under a grant to the Water Resources Center of the University of Illinois. Dr. Ben B. Ewing, Director of the Water Resources Center, has been helpful to the authors in carrying out and reporting these research results. Approximately 20 district offices and subdistrict offices of the U. S. Geological Survey have cooperated generously in providing the basic data for this project.

Table 1 Physical and Hydrologic Factors for 12 River Basins

Total relief *(ft)*	Length of main stem *(mi)*	River slope *(ft/mi)*	Annual runoff *(in)*	Drainage area *(sq mi)*	Number of stream gages
Merrimack River at Lowell, Massachusetts					
3180	160	19.9	22.2	4635	28
Susquehanna River near Waverly, New York					
770	185	4.16	41.4	4780	26
Roanoke River at Roanoke Rapids, North Carolina					
2470	278	8 88	13.2	8410	37
Big Sandy River at Louisa, Kentucky					
1510	274	5.51	14.5	3892	19
White River at Spencer, Indiana					
620	185	3.35	13.6	2988	25
Sangamon River near Oakford, Illinois					
415	266	1.56	8.0	5120	18
Neches River at Evadale, Texas					
525	328	1.60	12.4	7951	19
Colorado River at Glenwood Springs, Colorado					
4300	153	28.1	8.0	4560	38
Tuolumne River near LaGrange, California					
11300	105	107.6	22.4	1532	18
Skagit River near Sedro Woolley, Washington					
4500	136	33.1	70.6	3093	39
Snake River near Heise, Idaho					
9350	198	47.2	15.5	5752	20
Rogue River near Central Point, Oregon					
4900	90	54.4	19.5	2053	21

Table 2. Physiographic Description of the 12 Basins as Given by Fenneman and Johnson (1964)

Basin	Map number, Province, and Section		Characteristics
Merrimack	9b	New England, Upland	Dissected and glaciated peneplains on complex structural features, monadnocks
Susquehanna	8c	Appalachian Plateaus, Southern New York	Mature glaciated plateau of moderate relief
Roanoke	4a	Piedmont, Upland	Submaturely dissected peneplain on disordered resistant rocks; moderate relief
Big Sandy	8e	Appalachian Plateaus, Kanawa	Mature plateau of fine texture; moderate to strong relief
White	12d	Central Lowland, Till Plains	Young till plains, morainic topography rare, no lakes
Sangamon	12d	Central Lowland, Till Plains	Young till plains, morainic topography rare; no lakes
Neches	3f	Costal Plain; West Gulf	Young grading inland to mature coastal plain
Colorado	16	Southern Rocky Mountains	Complex mountains of various types, intermont basins
Tuolumne	23d	Sierra Mountains, Sierra Nevada	Block mountain range tilted west; accordant crests, alpine peaks near east side
Skagit	23a	Cascade Mountains, Northern	Sharp alpine summits of accordant height; higher volcanic cones
Snake	18	Middle Rocky Mountains	Complex mountains, mainly anticlinal ranges; intermont basins
Rogue	23b	Cascade Mountains, Middle	Generally accordant summits; higher volcanic cones

Figure 2. Snake River in the region of Moose Falls, Wyoming

Figure 3. Obtaining a discharge measurement by a current meter and wading, at station 8-0391, Ayish Bayou near San Augustine, Texas, in Neches River Basin

This has involved many man hours as well as the costs for copying basic data in their files to be provided to this project for analysis.

The section of the study dealing with the flow duration of streams was carried out by Arie Ben-Zvi , Assistant Hydrologist, a University of Illinois graduate student in Civil Engineering, working under a research assistantship provided by this project. Part-time student assistants who worked on this project include Robert A. Alvey, Terry G. Shaw, Thomas E. Mitchell, Mosen Momen-Nejab, and Douglas W. Hiestand. Other Water Survey personnel assisting in the project were James C. Neill, Statistician, Robert A. Sinclair, who aided in the computer analysis, John W. Brother, Jr., Chief Draftsman, who prepared the illustrations, assisted by William Motherway, Jr., and Mrs. J. Loreena Ivens, Technical Editor, who aided in editing the final report.

DATA

Stream Gaging Stations

All of the data used in this report were collected in the field by personnel of the U. S. Geological Survey as a part of their regular continuing program of streamflow measurement. The general procedure for operating gaging stations has ' been described by Carter and Davidian (1968). There are in 1970 about 8500 such stream gaging stations in the United States. As shown in table 1, data were used from 308 stream gaging stations in the 12 basins. The technique of taking a discharge measurement at a gaging station has been described by Buchanan and Somers (1969) . When the water is shallow, this measurement is often taken by wading the stream as illustrated in figure 3, and measuring the velocity at various points throughout a cross section. The width and cross-sectional area of the stream are also obtained.

In the appendix, figures 17 through 28 provide maps of the 12 basins studied showing the locations of all stream gaging stations used, and tables 14 through 25 list the stream gaging stations by name and identification number. The particular stream gaging stations shown represent only part of the stations that have been in operation in these basins. The selection of the gages used is explained later.

Field records of discharge measurements made by the U. S. Geological Survey were recorded on their Form 9-207. From 50 to 500 measurements were available at each station. Data available for each measurement were the width W, channel cross-sectional area A, average velocity V, and the discharge Q. The average depth D was computed from $D = A/W$ with D being defined as the hydraulic depth.

Hydraulic Rating Curves

The first step in depicting graphically the channel conditions for a reach of stream represented by particular stream gaging stations was the plotting of station hydraulic rating curves. The four parameters A, W, D, and V were plotted on log-log paper versus Q. Figure 4 shows hydraulic rating curves for the gaging station on the Dan River at Danville, Virginia, in the Roanoke River Basin. The points represent actual measurements, and straight lines were fitted to the points by eye to best represent the general relation. The scatter of

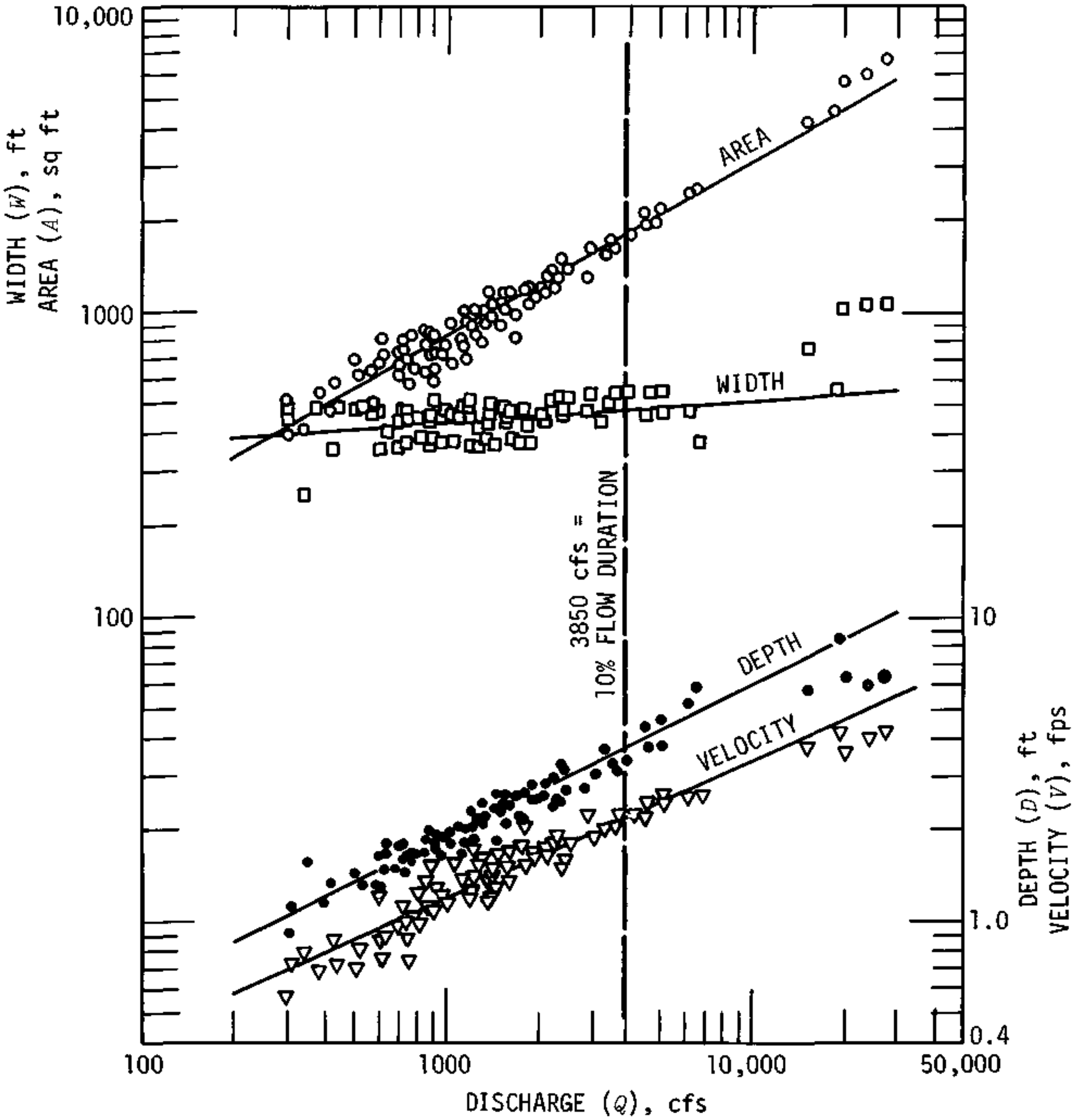


Figure 4. Hydraulic rating curves for gage 2-0570, Dan River at Danville, Virginia, in the Roanoke River Basin

points is due to the variation in local conditions, but the general pattern for the curves is evident. The curves are drawn in such a way as to be consistent. If a vertical section is taken at a given discharge, the values from the curves will satisfy two physical laws the product of width and depth equals area, $WD = A$, and the area times velocity equals given discharge, $AV = Q$.

The vertical dashed line in figure 4 indicates a discharge of 3850 cubic feet per second (cfs). This is the flow that occurs 10 percent of the days each year. As discussed later, the relationships developed in this study were limited to flows at or below this 10 percent duration. Consequently, the relationships derived in this paper are based on the shape of the curves to the left of the dashed line in figure 4. The 10 percent duration flow of 3850 cfs is that which is exceeded about 36 days per year, and is less than bankfull.

In figure 4, there are 89 points representing individual discharge measurements. It was the practice to plot these hydraulic rating curves using data from 50 to 200 discharge measurements during the most recent 10 to 20 years of record. This would generally provide a consistent pattern for the curves such as illustrated in figure 4.

The four straight lines in figure 4 can be represented by equations having the structure of equations 1, 2, and 3. These represent *station* values for these relations and are given as follows

$$W = 268.0\, Q^{0.07} \tag{4}$$

$$D = 0.0636\, Q^{0.49} \tag{5}$$

$$V = 0.0553\, Q^{0.45} \tag{6}$$

$$A = 17.05\, Q^{0.56} \tag{7}$$

METHODS OF ANALYSIS

Comparison of Time

A useful method for describing the time variability of flows at a particular stream gaging station is the flow duration curve. This was described by Foster (1934) and by Lane and Lei (1950), current hydrologic practice is described by Searcy (1959). A duration curve of daily discharge depicts the discharge at the gaging station plotted versus the percent of the days per year that this discharge is equalled or exceeded (a frequency of occurrence F from 0 to 100 percent). Flow frequency in this report has been limited to the range from $F = 0.10$ to $F = 0.90$, that is, the discharges which occur from 10 percent of the days each year to 90 percent of the days each year.

For each basin studied, a tabulation was made of all the stream gaging records available. In each case, there were a few gages with records of 50 to 60 years and a larger number of gages with records of less than 10 years. Consequently, for each basin it was necessary to select the particular gages and the periods of record to be used in this project. Records were not used l) if there was diversion into or out of the basin above the gage in an amount equivalent to 10 percent of the lowest daily discharge of record, and 2) if there was upstream regulation affecting as much as 20 percent of the drainage area of the gaging station. In some cases a portion of the record could be used but a later period of record could not be used because of the diversion or regulation by the above criteria. Even after the stream gaging records were censored in this manner, considerable evaluation of the remaining records was required.

An example of this is illustrated in table 3 which shows the common periods of flow records available for the Rogue River Basin. There is 1 gaging station with a 61-year record, 4 stations have records for the 35-year period 1930-1964, and 11 stations have records for the 3-year period 1947-1949. The locations of all 21 stream gaging stations within the Rogue River Basin are shown in figure 28

Table 3. Common Periods of Flow Records for the Rogue River Basin

Common water years	Length of period *(years)*	Number of stations
1906-1918, 1920-1967	61	1
1911, 1920-1922, 1926-1967	46	2
1930-1964	35	4
1930-1958	29	5
1930-1955	26	6
1939-1964	26	6
1934-1955	22	7
1934-1952	19	9
1934-1949	16	10
1939-1949	11	11
1947-1949	3	11
none	0	21

Table 4. Standard Periods Adopted for Flow Duration Curves

Basin	Water years	Length *(years)*
Merrimack	1919-1964	46
Susquehanna	1925-1967	43
Roanoke	1931-1967	37
Big Sandy	1931-1967	37
White	1933-1967	35
Sangamon	1950-1964	15
Neches	1940-1967	28
Colorado	1911-1960	50
Tuolomne	1926-1967	42
Skagit	1931-1967	37
Snake	1925-1955	31
Rogue	1926-1967	42

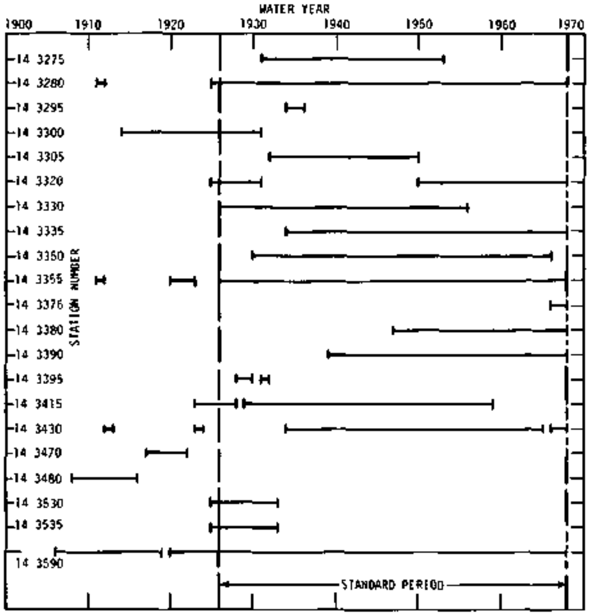


Figure 5. Era of 21 available flow records and standard period adopted, water years 1926-1967 Rogue River Basin

and listed in table 25 in the appendix. Figure 5 shows graphically the era of these 21 available flow records. The location of the gaging stations (figure 28), the era of records available (figure 5), and the length of the common periods of records (table 3) were considered in making a subjective judgment as to the gaging stations that would be used. Generally an attempt was made to use every gage that had at least 3 years of record. In this way, the data used would give the greatest sampling of flow conditions at various locations and for drainage basins of various sizes. In the case of the upper Colorado River Basin this process yielded an excess of gaging stations over those felt required. In this basin 38 gages that gave the best place sampling were selected as shown in the map in figure 24 in the appendix.

On the basis of all of the above considerations, a standard period was selected for each of the river basins to be studied. The standard period for the Rogue Basin is shown graphically in figure 5 and comprises the 42-year period 1926-1967. This standard period was selected to make the maximum use of the long and short records available, as well as to provide a reasonable areal coverage of the basin. The various standard periods adopted for the 12 basins are listed in table 4. These periods range from 28 years for the Neches Basin to 50 years for the upper Colorado Basin, with the exception of the Sangamon Basin. The standard period used for the Sangamon Basin was the 15-year period 1950-1964 described by Stall and Fok (1968), however, this 15-year period is actually representative of a much longer period of 45 to 50 years.

It was believed unnecessary to require identical standard periods for each of the 12 basins. Hydrologic conditions are highly variable in different regions of the United States, and it was felt that each of the standard periods adopted is sufficiently long to provide a good sampling of the range of hydrologic conditions for that basin. Varying the length of these standard periods also provided considerable benefit in making maximum use of the shorter flow records for each basin.

Extending Short Records

In order to make maximum use of the short records available for each river basin, these records were extended synthetically to represent what might reasonably have occurred during the standard period. This is shown by example for the Rogue River Basin. Table 25 in the appendix shows two gaging stations in italics for which daily discharges were available for the entire 42-year standard period. For these index stations, flow duration curves for the standard periods were derived directly from the observed data. The other stations in the basin are called secondary stations and their flow duration curves for the standard period

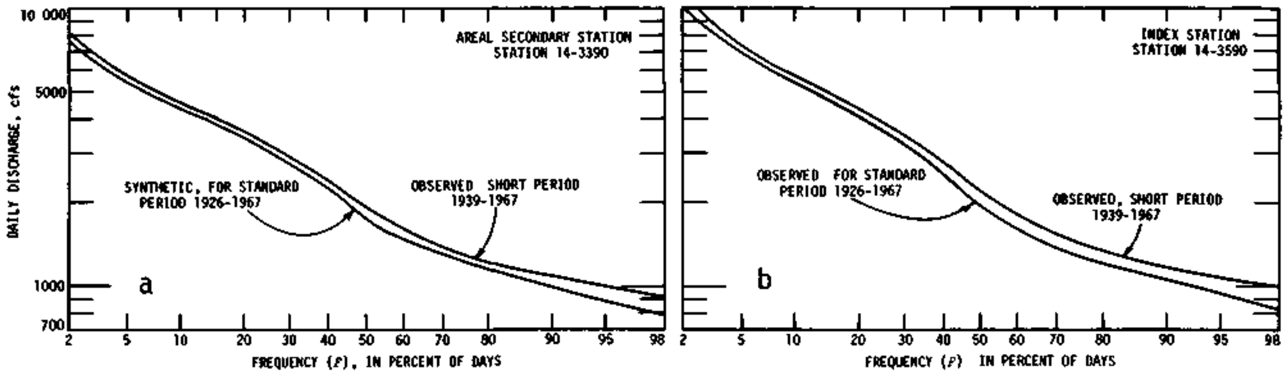


Figure 6. Flow duration curves at an areal secondary station and an index station, Rogue River Basin

are constructed synthetically with the available data. This technique for extending streamflow data has been described by Searcy (1959, 1960), and is exemplified as follows.

In the Rogue River Basin, the record available at station 14-3390 is for the 29-year period, water years 1939-1967, a relatively *short* period. Figure 6a shows a duration curve of daily discharges at this secondary station for this *short* period of record Figure 6b shows flow duration curves at index station 14-3590 for the same *short* period and for the standard 42-year period (1926-1967).

Reading the curves for the index and secondary stations for the concurrent *short* period makes it possible to construct a curve of relation between these two stations. Values of discharge at corresponding values of frequency *F* for the two stations are read and plotted to provide the curve shown in figure 7. Observed discharge values for both stations are given in table 5. These values and figure 7 can then be used to compute synthetic flow values at the secondary station for the standard period of record, as listed in table 5 and plotted in figure 6a.

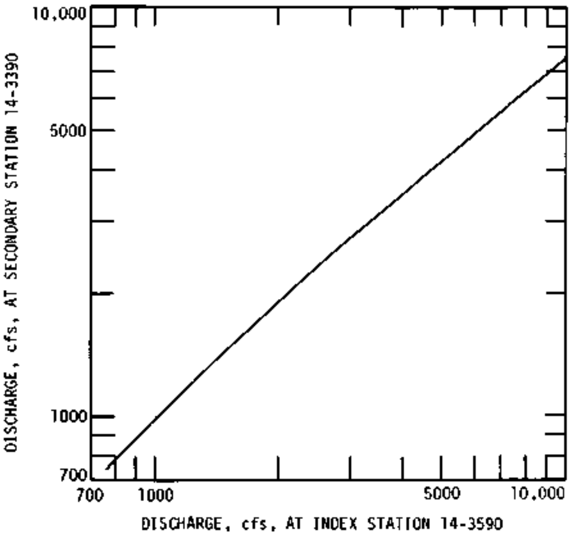


Figure 7. Curve-of-relation of flows at index station and secondary station, Rogue River Basin

Flow duration curves were derived by this process for every station utilized, for the standard period of record for that basin. These curves were used to determine nine values of frequency, from *F* = 0.10, 0.20, 0.30, etc. through 0.90, for each station. These values of discharge *Q* were used in developing the hydraulic geometry relations described later.

Because of the value of the flow duration curve in depicting the general hydrologic regime of a river basin, figure 8 has been developed to show typical flow duration curves for each of the 12 basins studied. Here the

Table 5. Flow Duration Data for Index Station 14-3590 and Secondary Station 14-3390, Rogue River Basin

Frequency F (% of *days*)	Discharge, *cfs*			
	Observed			Synthetic
	secondary station 1939-1967	index station 1939-1967	index station 1926-1967	secondary station 1926-1967
3	7100	9400	8600	6600
5	5800	7400	6900	5450
10	4600	5700	5450	4400
15	4000	4850	4700	3900
20	3600	4300	4100	3450
25	3300	3900	3700	3100
30	3000	3550	3300	2820
35	2700	3150	2950	2550
40	2450	2800	2600	2300
45	2200	2500	2280	2030
50	1990	2200	2000	1800
55	1790	2000	1800	1630
60	1630	1800	1640	1500
65	1510	1650	1530	1400
70	1400	1540	1430	1320
75	1320	1420	1340	1250
80	1250	1330	1240	1160
85	1180	1250	1150	1090
90	1110	1170	1070	1000
95	1010	1070	950	890
97	960	1020	880	830

duration curve shown is for the most downstream gaging station in each basin. Figure 8 indicates that flows in the Skagit River are much higher than those of the other basins and that flows of the Neches are generally the lowest of the 12 studied.

Comparison of Place

To characterize the location of a particular stream gaging station within the stream system, the drainage area above the gaging station has been used. The drainage area in square miles, A_d, is a physical factor which is much used in hydrology. The values of drainage area for each of the stream gaging stations has been determined and published by the U. S. Geological Survey. In the earlier research project on Illinois streams it was found that the drainage area was useful and practical in representing the location of a gaging station within a basin.

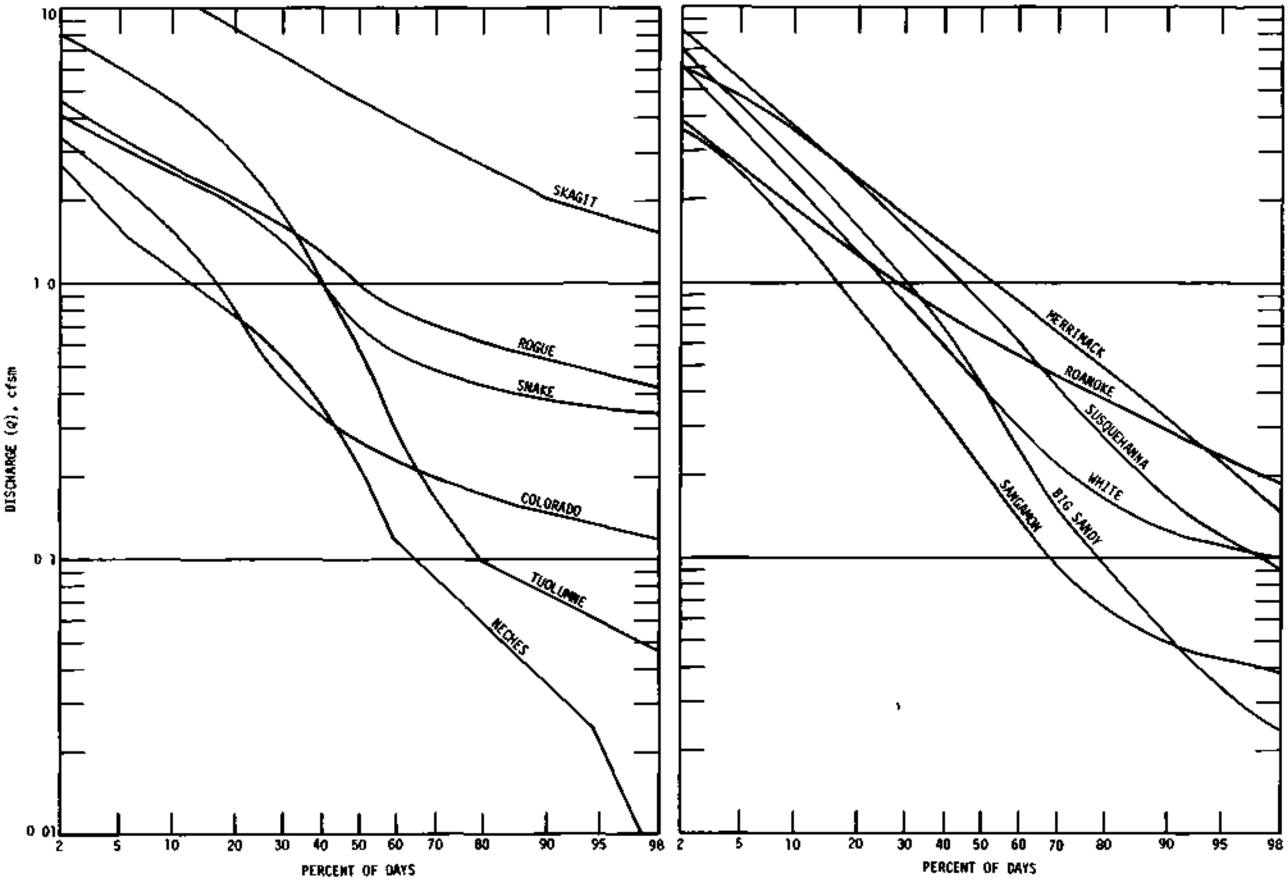


Figure 8. Typical flow duration curves for the 12 basins

Hydraulic Geometry Relations

The hydraulic rating curves as shown in figure 4 for station 2-0750, on the Dan River at Danville, Virginia, in the Roanoke River Basin show the variation in A, V, W, and D as related to the discharge Q. From the flow duration curve for this gaging station, discharges for the nine values of frequency, $F = 0.10$ through 0.90, can be read. These values of discharge Q are shown in table 6, along with the values provided by the curves in figure 4 for cross-sectional area A, velocity V, width W, and mean depth D. These values of A, V, W, and D can of course be computed by using equations 4, 5, 6, and 7, which was the practice in this project. Table 6, then, represents the basic data analyzed to provide hydraulic geometry relations.

Equations

For every river basin studied, a table such as table 6 was prepared for every gaging station. An equation was developed relating each of the five hydraulic geometry factors Q, A, V, W, and D to the two independent variables of flow frequency F and drainage area A_d. This followed the form of the generalized relations shown in the earlier study by Stall and Fok (1968)- An example of this form is provided by figure 9, which shows the relation of discharge Q to F and A_d for the Roanoke River Basin. For clarity, only two curves for values of frequency ($F = 0.10$ and $F = 0.90$) are shown.

Table 6. Hydraulic Geometry Factors Related to Flow Frequency for Station 2-0750, Dan River at Danville, Virginia

Flow frequency F (%)	**Discharge** Q (*cfs*)	**Cross-sectional area** A (*sq ft*)	**Velocity** V (*fps*)	**Width** W (*ft*)	**Mean depth** D (*ft*)
90	760	704	1.07	426	1.66
80	930	789	1.17	432	1.82
70	1100	867	1.26	438	1.98
60	1300	952	1.35	443	2.15
50	1520	1039	1.45	448	2.32
40	1790	1139	1.56	453	2.52
30	2130	1256	1.69	458	2.74
20	2700	1435	1.88	466	3.09
10	3850	1751	2.20	478	3.66

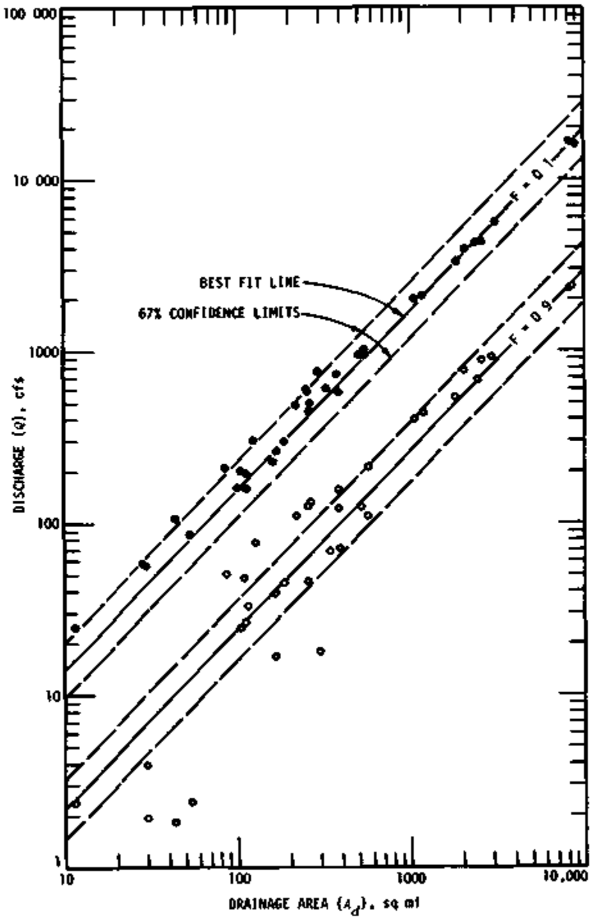


Figure 9. Discharge as related to drainage area for two frequencies showing the 67-percent confidence intervals, Roanoke River Basin

Also shown in figure 9 are the points used to fit these lines. There are 35 individual points defining each curve. Each point is derived from one of the 37 gaging stations used in the Roanoke Basin; the two points not shown in figure 9 lie below 10 square miles. It can be noted that the points cluster around the curve for F = 0.10 more closely than for the lower curve. It is believed that the higher discharges occurring at a frequency of F = 0.10 best represent the *channel forming* discharge.

In this project, nine curves were similarly fitted to the data to represent each of the frequencies from F = 0.10 through F = 0.90. All nine curves were fitted as one total multiple regression to the 37 points that define each curve. The fitting process was carried out mathematically using the natural logarithm of Q as the dependent variable and the values of F and the natural logarithm of A_d as independent variables. A similar mathematical fitting was carried out for the other parameters A, V, W, and D. The result of this process was a set of five hydraulic geometry equations for the Roanoke River Basin. These are:

$$\ln Q = 0.47 - 2.35\,F + 1.05\,\ln A_d \tag{8}$$

$$\ln A = 0.54 - 1.46\,F + 0.92\,\ln A_d \tag{9}$$

$$\ln V = -0.08 - 0.88\,F + 0.13\,\ln A_d \tag{10}$$

$$\ln W = 1.52 - 0.34\,F + 0.54\,\ln A_d \tag{11}$$

$$\ln D = -0.98 - 1.13\,F + 0.38\,\ln A_d \tag{12}$$

in which Q is in cubic feet per second, A_d in square miles, A in square feet, V in feet per second, W and D in feet. The designation In signifies a logarithm to the base e.

The frequency of occurrence F in equations 8 through 12 is limited from 10 to 90 percent of the days. These hydraulic geometry equations are expected to give best results at higher flow rates, as is shown in figure 9 where the best fit is for the upper curve. Complete sets of hydraulic geometry equations for each of the 12 basins are given later in the Results section.

Stream Orders

In the earlier Illinois study, a considerable investigation was made of the consistency of stream orders within Illinois basins. For the present project it was felt desirable to investigate the consistency of the stream orders of the 12 basins. Horton (1945) in a pioneering and comprehensive study of the quantitative morphology of streams described a consistent pattern under which a stream system develops and to which it continually adjusts. He showed that the number of streams, the length of streams, and the slope of streams were all related consistently to the stream order throughout any existing stream system. Later revisions of the Horton stream ordering system were made by Strahler (1957, 1964). Because of the inherent flexibility and the soundness of the Strahler system of stream ordering, it has been used in this report. It provides a means of evaluating numerically the structure of a stream system.

For the complete stream system for each of the river basins studied, the Strahler stream orders were determined and measurements were made of the number of streams, the average length, and the average slope of streams of each order. Where available, the standard 15-minute topographic maps published by the U. S. Geological Survey were used for ordering the stream systems. The scale of these maps is about 1 inch equals 1 mile. According to Strahler (1957), visible unbranched streams shown on the topographic maps in blue were defined as the first-order streams. Where two first-order streams join, a second-order stream begins and so forth. After the entire stream system was ordered, the number of streams in each order were totaled, and the lengths and slopes of streams of the third-order and higher were measured and averaged.

Figure 10 shows the results of the Horton-Strahler relationships for the Rogue River Basin. The solid points in figure 10 are the values derived from a 15-minute topographic map. The straight lines fitted show the linear relationships of stream number, average length, and average slope to the stream order on semilog paper. These relationships show that Horton's law of stream numbers, law of stream length, and law of stream slopes are applicable to this stream system. Similar plots to figure 10 were derived and found to be generally consistent for the 12 river basins.

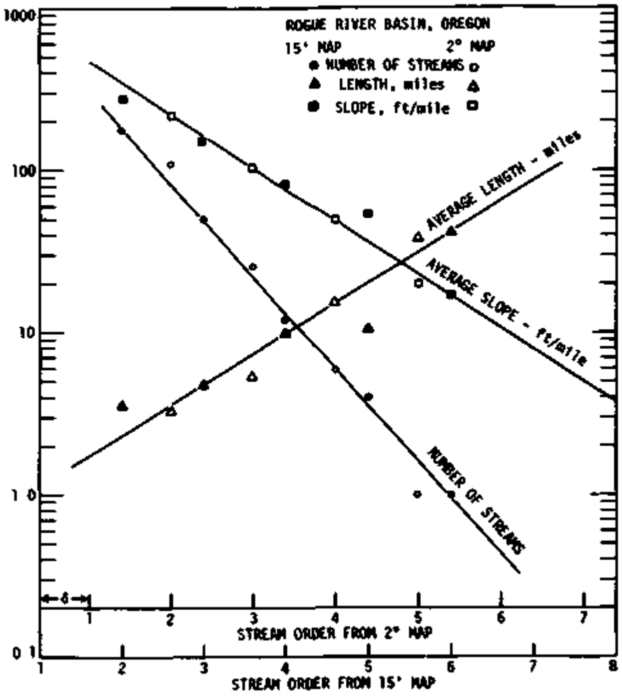


Figure 10. Horton-Strahler relationships for the Rogue River Basin, showing the effect of map scale

Effect of Map Scale

For a number of the basins studied it was not possible to obtain 15-minute topographic maps. The 7 1/2-minute topographic maps were available for some basins, and the 2-degree topographic maps were available for all 12 basins. To make maximum use of all of these maps, the Strahler stream orders were determined on the 2-degree maps for all 12 basins and for the 15-minute and 7 1/2-minute maps for basins where available. A comparison was then made between the Horton relations as devised on various map scales.

The three laws described by Horton (1945), the law of stream numbers, law of average stream length, and law of average stream slope, can be described by equations as follows:

$$\ln N_u = A - Bu \tag{13}$$

$$\ln L_u = C - Du \tag{14}$$

$$\ln S_u = E - Fu \tag{15}$$

where u is the stream order, N_u is the number of u-th order streams, L_u is the average length of u-th order streams, S_u is the average slope of u-th order streams, and A, B, C, D, E, and F are constants. From these three equations the following parameters can be defined:

$$\text{bifurcation ratio of stream number} = e^B = N_u/N_{u+1} \tag{16}$$

$$\text{stream length ratio} = e^D = L_u/L_{u+1} \tag{17}$$

$$\text{stream concavity} = e^F = S_u/S_{u+1} = \frac{Y_u/L_u}{Y_{u+1}/L_{u+1}} \tag{18}$$

where y_u is the average stream fall of u-th order streams.

Figure 10 also shows a horizontal scale for stream order as determined from the 2-degree topographic maps, and the open symbols on the graph represent stream parameters as determined from these 2-degree maps. The straight lines in figure 10 are shown to represent both the solid and open points. This means that the straight lines in figure 10 follow closely Horton-Strahler's straight lines as given in equations 13, 14, and 15. This is true regardless of the scale of the map from which the relationships were obtained.

This consistency in the Horton-Strahler relationships is believed to be a significant result of the present research project. The only difference in Horton-Strahler's relationships from using different scales of maps is the difference in the stream order, 6, as shown by the two horizontal scales in figure 10. This consistency of the structure of the stream patterns of the 12 basins is considered as a valuable element of theoretical support for the idea that hydraulic geometry relations in this study can also be expected to be consistent. Shown later in the Results section in table 13 are the values of the Horton-Strahler parameters as measured from the three scales of topographic maps used Noticeable exceptions to the consistency of these straight line relations were the results for the Skagit, Snake, and Tuolumne River Basins, for which the relations were not as consistent as for the other nine basins studied

River Profiles

Yang (1970) used the analogy between the thermodynamics of a heat system and the hydraulics of a stream system to derive two basic laws governing the formation of a stream network. Absolute temperature in a heat system is analogous to elevation in a stream system, and thermal energy in a heat system is analogous to the potential energy in a stream system.

It was shown by this analogy that under the condition of dynamic equilibrium of a stream system the ratio of the average fall between any two different order streams is unity. This is the *law of average stream fall.* This law requires that, on the average, streams in the same stream system will increase their orders after an equal amount of fall has occurred.

It can be shown also by this analogy that a natural stream will choose its own course of flow such that the rate of potential energy loss per unit mass of water along this course is a minimum compatible with its external constraints. This is the *law of least rate of energy expenditure.* It was shown by this law that river meandering is a basic characteristic of natural streams.

The longitudinal streambed profile of a stream is a plot of elevation versus horizontal distance along the main stem of the stream. The nature of this profile has been discussed by Hack (1957) and by Leopold and Langbein (1962). Yang (1970) introduced a theoretical longitudinal streambed profile for those stream systems that obey Horton's laws of average stream length and average stream slope. That is, Yang's theoretical longitudinal streambed profile is valid only if the average length and average slope in a river basin can be very well represented by equations 14 and 15, as is usually the case. From equations 14 and 15 and the definition of average slope as shown in equation 18, it can be shown that the average fall in the u-th order stream is

$$Y_u = e^{(C+E)-(D+F)u} \qquad (19)$$

Then the total fall measured from the beginning of the first-order stream to the end of n-th order stream should be

$$Z_n = \sum_{u=1}^{n} Y_u = e^{(C+E)} \sum_{u=1}^{n} e^{-(D+F)u} \qquad (20)$$

From equation 14 the total horizontal length measured from the beginning of the first-order stream to the end of the n-th order stream should be

$$X_n = \sum_{u=1}^{n} L_u = e^{C} \sum_{u=1}^{n} e^{-uD} \tag{21}$$

Applying equations 20 and 21 with stream order as a parameter makes it possible to compute a theoretical longitudinal streambed profile. This computed profile from equations 20 and 21 is Yang's theoretical longitudinal streambed profile. Because this profile is based on the entire stream network, it is a more stable and meaningful representation of the channel system than is the actual stream profile of the main channel only.

According to Yang's (1970) law of average stream fall, for any river basin which has reached its dynamic equilibrium condition, the ratio of the average fall between any two different order streams in the same river basin is unity, that is,

$$\frac{Y_u}{Y_{u+1}} = \frac{Y_u}{Y_{u+2}} = \frac{Y_u}{Y_{u+3}} = \ldots = 1 \tag{22}$$

From equations 17 and 18, the stream fall ratio can be defined as the product of stream length ratio and stream concavity. For those river basins which have reached their dynamic equilibrium condition, their stream fall ratios must be unity, that is,

$$e^{D} e^{F} = 1 \tag{23}$$

After substituting equation 23 into equation 20, the total fall measured from the beginning of the first-order stream to the end of the n-th order stream should be

$$Z'_n = ne^{C+E} \qquad (2k)$$

The longitudinal streambed profile calculated from equations 21 and *2k* with stream order as a parameter is Yang's equilibrium profile. Actual longitudinal streambed profiles along the main stem for the 12 river basins have been obtained from topographic maps and are shown later in the Results section in figure 13.

RESULTS

Equations and Graphs

Equations 8 through 12 for the Roanoke River Basin exemplify the primary results of this study. This set of five equations shows the quantitative relation between discharge, cross-sectional area, stream depth, width, and velocity for the various drainage areas within the basin. These equations can be used to compute a generalized value for any of these parameters anywhere within the basin. Results of this type can also be presented graphically.

Figure 11 shows graphically the hydraulic geometry results for the Roanoke River Basin and the Rogue River Basin. For each part of figure 11, the graph at left is for the Roanoke and the graph at the right is for the Rogue. Parts A and B show the relation between discharge, drainage area, and frequency (part A represents equation 8 of this report). Parts C and D show the cross-sectional area, parts E and F the depth, parts G and H the velocity, and parts I and J the width.

The type of information which can be read from the graphs in figure 11 is illustrated as follows. Suppose it is desirable to know within the Roanoke River Basin what the stream channel characteristics might be at a drainage area of 100 square miles during the discharge which occurs 50 percent of the days. Reading part A of figure 11 shows that at a drainage area of 100 square miles and at a frequency of $F = 0.50$, the discharge is about 60 cubic feet per second. Part C of figure 11 shows that for a drainage area of 100 square miles, at a frequency of $F = 0.50$, the cross-sectional area of the stream is about 56 square feet. Part G shows that under such conditions, the mean velocity would be about 1.09 feet per second. Part E then indicates that the average depth under such conditions would be about 1.25 feet, and part I that the stream width under such conditions is about 46 feet. Thus, the use of these five graphs makes it possible to obtain a general estimate as to the stream characteristics any where in the Roanoke River Basin, and this estimate is based upon the consistent patterns of hydraulic geometry as presented in these graphs and by equations 8 through 12. Similar comparative information for the Rogue River Basin can be obtained from the five graphs at the right of figure 11.

The complete results of this study for the 12 basins in the United States are presented in equation form in table 7. A set of equations similar to equations 8 through 12 presents the hydraulic geometry for each of the 12 river basins. It would also be possible to plot these relations graphically for any of the 12 basins by the use of these equations as has been done in figure 11.

The use of equations 8 through 12 or any of the equations in table 7 will be shown by an example. Suppose it is desired to know the cross-sectional area of a stream in the Roanoke River Basin at a location where the drainage area is 10 square miles, at a flow that occurs 90 percent of the days per year. In this case, A_d equals 10 square miles, $F = 0.90$, and the governing expression is equation 9. The hydraulic geometry equation for cross-sectional area in the Roanoke River Basin is

$$\text{In } A = 0.54 - 1.46 F + 0.92 \text{ In } \underset{a}{A_d}$$

so

$$\begin{aligned} \text{In } A &= 0.54 - 1.46(0.9) + 0.92 \ln(10) \\ &= 0.54 - 1.314 + 0.92(2.303) \\ &= 0.54 - 1.314 + 2.119 \\ &= 1.345 \\ A &= 3.84 \text{ square feet} \end{aligned}$$

This value agrees with the plot on figure 11.

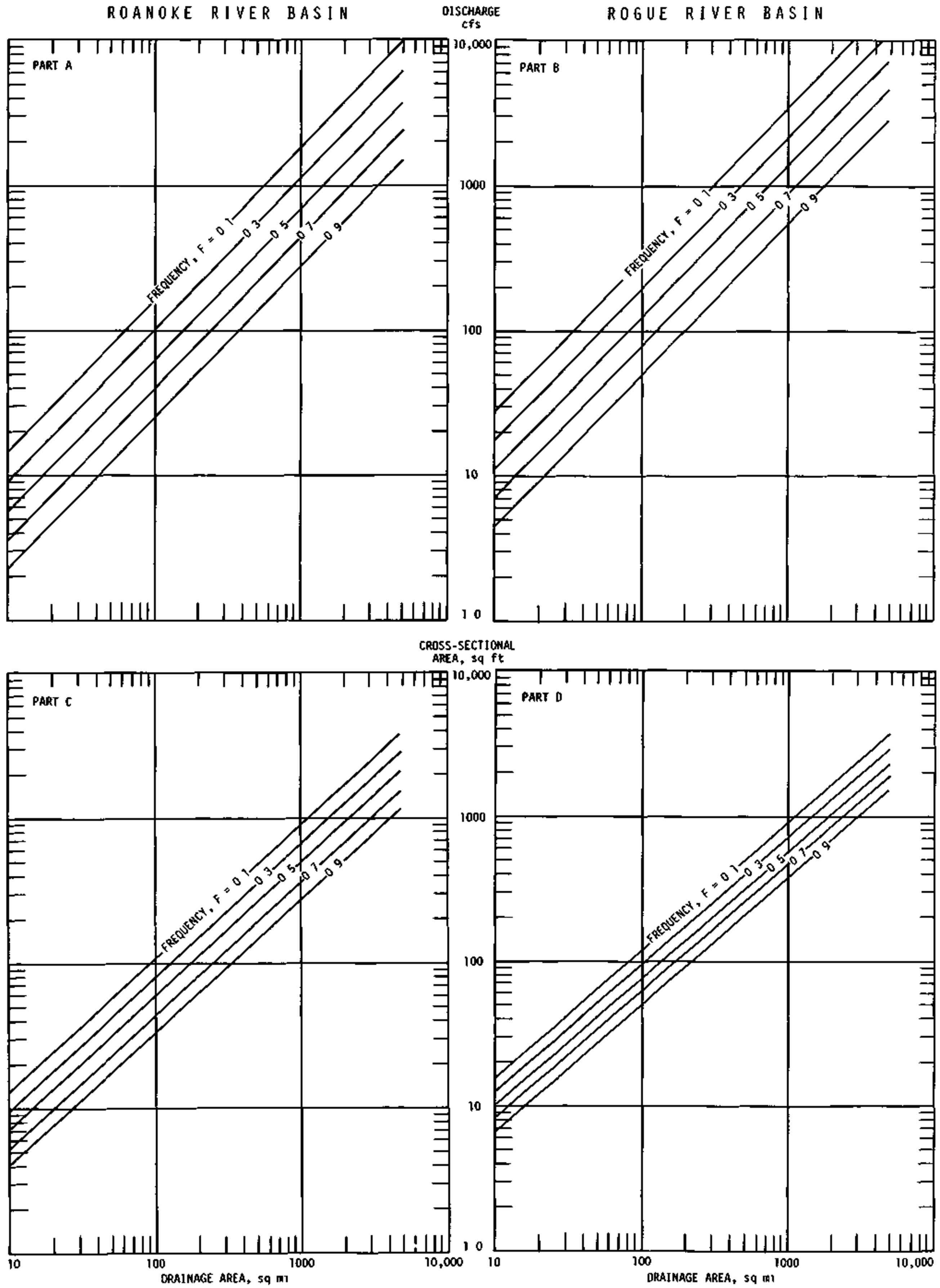


Figure 11 (Parts A-D). Hydraulic geometry results

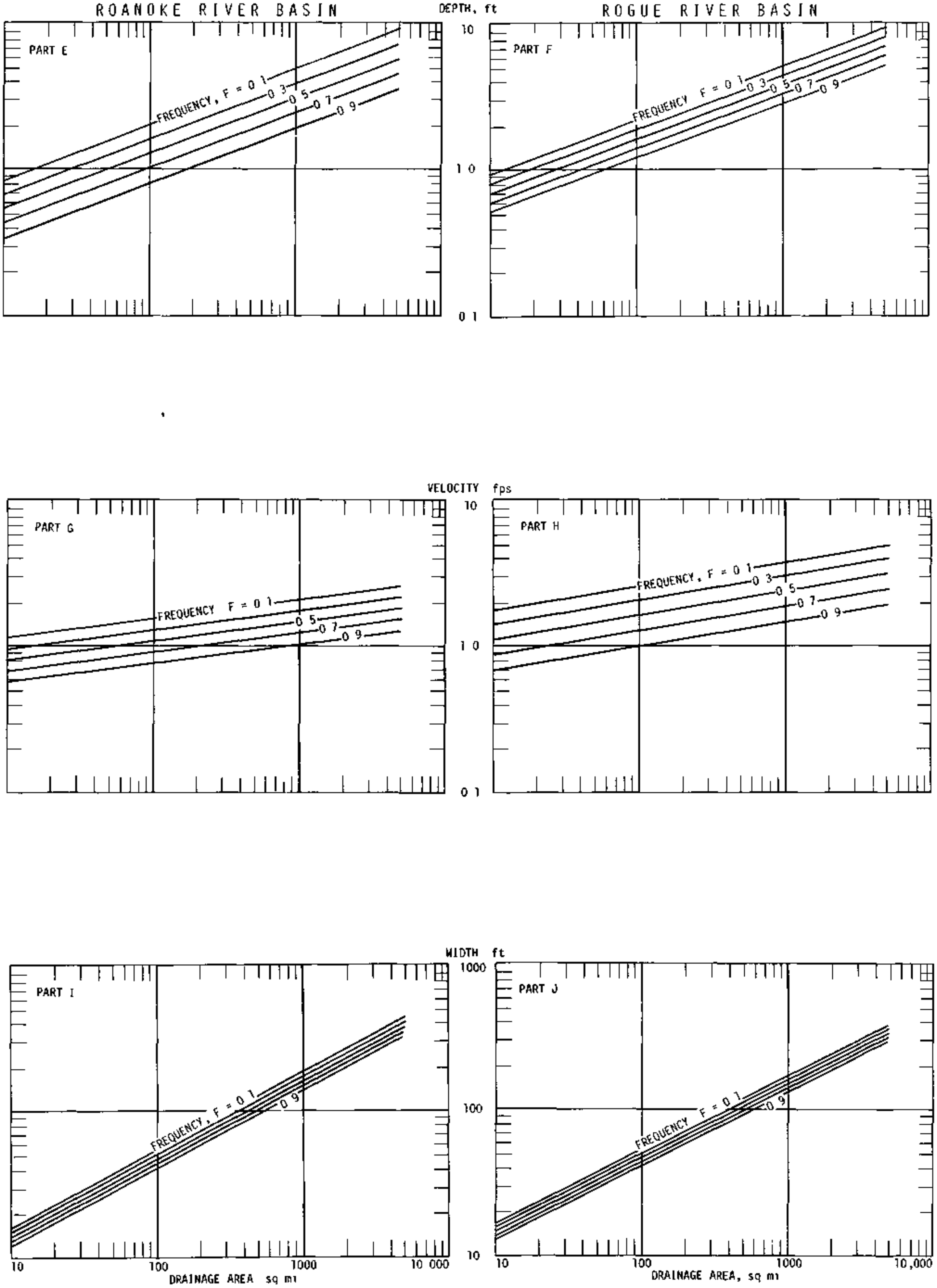


Figure 11 (Parts E-J). Hydraulic geometry results

Table 7. Hydraulic Geometry Equations for 12 River Basins

$$\ln Y = h + iF + j \ln A_d$$

$$Y = Q, A, V, W, D$$

Variable	h	i	j	Variable	h	i	j
Merrimack River Basin				*Neches River Basin*			
Q	1.68	-3.70	1.02	*Q*	0.65	-5.09	1.07
A	1.08	-2.09	0.93	*A*	0.62	-4.05	1.02
V	0.59	-1.60	0.09	*V*	0.03	-1.04	0.04
W	1.77	-0.82	0.56	*W*	1.71	-1.73	0.51
D	-0.68	-1.27	0.37	*D*	-1.09	-2.32	0.50
Susquehanna River Basin				*Colorado River Basin*			
Q	1.48	-3.97	1.05	*Q*	0.84	-3.74	1.01
A	1.12	-2.39	0.91	*A*	0.43	-2.09	0.85
V	0.37	-1.57	0.14	*V*	0.40	-1.66	0.16
W	1.79	-0.92	0.59	*W*	1.07	-0.76	0.60
D	-0.66	-1.47	0.32	*D*	-0.64	-1.33	0.25
Roanoke River Basin				*Tuolumne River Basin*			
Q	0.47	-2.35	1.05	*Q*	1.65	-5.72	1.10
A	0.54	-1.46	0.92	*A*	1.06	-3.74	1.04
V	-0.08	-0.88	0.13	*V*	0.58	-1.97	0.07
W	1.52	-0.34	0.54	*W*	1.70	-1.83	0.59
D	-0.98	-1.13	0.38	*D*	-0.63	-1.91	0.45
Big Sandy River Basin				*Skagit River Basin*			
Q	1.04	-5.38	1.09	*Q*	2.93	-2.88	0.96
A	1.16	-3.47	0.87	*A*	2.35	-1.37	0.75
V	-0.12	-1.90	0.22	*V*	0.57	-1.51	0.21
W	1.94	-1.29	0.50	*W*	2.52	-0.38	0.44
D	-0.78	-2.19	0.37	*D*	-0.17	-0.99	0.31
White River Basin				*Snake River Basin*			
Q	0.79	-4.60	1.05	*Q*	0.37	-2.32	1.05
A	0.56	-3.00	0.95	*A*	0.06	-1.18	0.88
V	0.22	-1.60	0.11	*V*	0.31	-1.14	0.17
W	1.98	-1.33	0.47	*W*	0.99	-0.23	0.57
D	-1.42	-1.67	0.48	*D*	-0.93	-0.96	0.31
Sangamon River Basin				*Rogue River Basin*			
Q	0.30	-5.39	1.10	*Q*	1.08	-2.29	1.05
A	1.19	-4.20	0.87	*A*	0.78	-1.09	0.88
V	-0.89	-1.18	0.23	*V*	0.30	-1.21	0.16
W	1.45	-1.51	0.54	*W*	1.64	-0.33	0.51
D	-0.26	-2.69	0.33	*D*	-0.87	-0.76	0.37

Table 8. Multiple Correlation Coefficient *R* for Hydraulic Geometry Equations

Basin	*Q*	*A*	*V*	*W*	*D*	*W/D*
Merrimack	0.97	0.95	0.78	0.94	0.91	0.64
Susquehanna	1.00	0.99	0.91	0.99	0.97	0.89
Roanoke	0.98	0.97	0.81	0.92	0.92	0.53
Big Sandy	0.99	0.96	0.86	0.90	0.95	0.56
White	0.96	0.93	0.78	0.84	0.85	0.09
Sangamon	0.96	0.95	0.80	0.93	0.91	0.67
Neches	0.95	0.93	0.44	0.88	0.91	0.30
Colorado	0.95	0.96	0.82	0.93	0.81	0.70
Tuolumne	0.90	0.90	0.75	0.87	0.88	0.37
Skagit	0.97	0.96	0.85	0.93	0.90	0.52
Snake	0.96	0.97	0.81	0.97	0.93	0.83
Rogue	0.90	0.91	0.64	0.94	0.83	0.58

The reader may note that the sets of five equations in table 7 for the Sangamon River Basin and for the White River Basin are different from those presented for these two basins in the earlier report by Stall and Fok (1968). The differences are actually minor and are due to the fact that in the earlier study the equations were fitted by eye and in the present study the equations have been fitted by multiple regression on a computer. A graphical plot of the results using the earlier equations and the equations shown in table 7 will show that there is actually only a slight deviation between the two. The results in table 7 were derived mathematically and are consistent with the results for the other 10 basins.

Table 8 gives the values of the multiple correlation coefficient *R* for the hydraulic geometry equations for each river basin as presented in table 7. These correlations give a general idea as to the goodness of fit of each set of equations. For example, table 8 shows that the multiple correlation coefficient *R* for the Roanoke River Basin for the natural logarithm of discharge, In Q, as fitted in equation 8 to the independent variables F and In A_d, has a value of $R = 0.98$. In this case, $R^2 = 0.96$ which, as a simplified interpretation, signifies that 96 percent of the variability in the dependent variable In Q is explained by variations in the independent variables F and In A_d.

Exponents and Coefficients

The general form for hydraulic geometry equations as conceived by Leopold and Maddock (1953) has been presented earlier in equations 1, 2, and 3. These relate width, depth, and velocity of the stream to the discharge through the use of three exponents, b, f, and m. The results of the present project can be expressed in the form of equations 1, 2, and 3 for results at any particular stream gaging station or for an entire river basin. Table 9 gives values of hydraulic geometry exponents b, f, and m as determined at each of the gaging stations used in the Roanoke River Basin. These exponents have been derived from the hydraulic rating curves, such as those in figure 4 for the Dan River at Danville, Virginia, station 2-0750, and the exponents are given in equations 4 through 7. At the bottom of table 9 are the mean values of the exponents and the standard deviations. The results in table 9 give some insight into the inherent variability of the station values of these exponents throughout a river basin.

Table 9. Station Values of Exponents in Hydraulic Geometry of the Roanoke River Basin

Gaging station number	Width b	Depth f	Velocity m	Area $b + f$
2-0538	0.11	0.31	0.58	0.41
2-0545	0.25	0.34	0.41	0.59
2-0550	0.08	0.51	0.42	0.58
2-0551	0.26	0.37	0.36	0.64
2-0560	0.11	0.53	0.36	0.65
2-0584	0.00	0.08	0.92	0.08
2-0595	0.00	0.51	0.49	0.51
2-0605	0.09	0.58	0.34	0.67
2-0615	0.18	0.63	0.19	0.81
2-0625	0.06	0.52	0.42	0.58
2-0640	0.02	0.40	0.57	0.43
2-0655	0.00	0.39	0.61	0.39
2-0660	0.06	0.68	0.28	0.74
2-0665	0.11	0.62	0.27	0.73
2-0685	0.07	0.46	0.47	0.53
2-0697	0.12	0.44	0.44	0.56
2-0700	0.00	0.38	0.62	0.38
2-0705	0.00	0.48	0.52	0.48
2-0710	0.08	0.58	0.32	0.65
2-0715	0.07	0.44	0.49	0.50
2-0720	0.04	0.47	0.49	0.51
2-0725	0.02	0.38	0.60	0.40
2-0730	0.00	0.40	0.60	0.40
2-0740	0.00	0.45	0.55	0.45
2-0745	0.02	0.46	0.52	0.48
2-0750	0.07	0.49	0.45	0.56
2-0751.6	0.35	0.34	0.30	0.69
2-0755	0.08	0.60	0.32	0.68
2-0765	0.16	0.37	0.47	0.52
2-0770	0.14	0.57	0.28	0.72
2-0772	0.34	0.51	0.15	0.86
2-0772.3	0.39	0.41	0.20	0.80
2-0772.4	0.40	0.54	0.07	0.93
2-0775	0.31	0.61	0.07	0.92
2-0796.4	0.17	0.54	0.29	0.71
2-0805	0.00	0.35	0.65	0.35
2-0810	0.11	0.71	0.20	0.81
Mean	0.12	0.47	0.41	0.59
Standard Deviation	0.12	0.12	0.18	0.18

Table 10. Mean Station Values of Exponents in Hydraulic Geometry

		Exponents			
River Basin	**Parameter**	**Width** b	**Depth** f	**Velocity** m	**Area** $b + f$
Merrimack	Mean	0.20	0.35	0.45	0.55
	St. Dev.	0.16	0.15	0.19	0.19
Susquehanna	Mean	0.23	0.37	0.40	0.60
	St. Dev.	0.12	0.10	0.11	0.11
Roanoke	Mean	0.12	0.47	0.41	0.59
	St. Dev.	0.12	0.12	0.18	0.18
Big Sandy	Mean	0.23	0.41	0.36	0.64
	St. Dev.	0.12	0.11	0.13	0.13
White	Mean	0.29	0.36	0.35	0.65
	St. Dev.	0.13	0.10	0.12	0.12
Sangamon	Mean	0.28	0.49	0.23	0.77
	St. Dev.	0.10	0.10	0.10	0.10
Neches	Mean	0.35	0.47	0.18	0.82
	St. Dev.	0.21	0.16	0.26	0.26
Colorado	Mean	0.19	0.36	0.45	0.55
	St. Dev.	0.12	0.11	0.11	0.11
Tuolumne	Mean	0.30	0.34	0.36	0.64
	St. Dev.	0.18	0.09	0.21	0.21
Skagit	Mean	0.13	0.35	0.52	0.48
	St. Dev.	0.08	0.11	0.10	0.10
Snake	Mean	0.11	0.41	0.48	0.52
	St. Dev.	0.07	0.07	0.08	0.08
Rogue	Mean	0.13	0.34	0.53	0.47
	St. Dev.	0.09	0.10	0.13	0.13
Leopold & Maddock, 1953	Mean	0.26	0.40	0.34	0.66
Average values (Leopold et al., 1954, p. 244)					
Midwest	Mean	0.26	0.40	0.34	0.66
Brandywine, Pa.	Mean	0.04	0.41	0.55	0.45
Semi-arid USA	Mean	0.29	0.36	0.34	0.65
158 stations in USA	Mean	0.12	0.45	0.43	0.57
10 stations, Rhine River	Mean	0.13	0.41	0.43	0.54
Mountain streams, 14 stations (Judd and Peterson, 1969)	Mean	0.11	0.48	0.42	0.59

Table 11. Values of Hydraulic Geometry Exponents for 12 Basins Compared with Other Results

Basin	**Width** b	**Depth** f	**Velocity** m	**Area** $b + f$
Merrimack	0.55	0.36	0.09	0.91
Susquehanna	0.56	0.30	0.13	0.87
Roanoke	0.52	0.36	0.12	0.88
Big Sandy	0.46	0.34	0.20	0.80
White	0.45	0.46	0.10	0.90
Sangamon	0.49	0.30	0.21	0.79
Neches	0.48	0.47	0.04	0.95
Colorado	0.59	0.25	0.16	0.84
Tuolumne	0.54	0.41	0.06	0.95
Skagit	0.46	0.32	0.22	0.78
Snake	0.54	0.30	0.16	0.84
Rogue	0.49	0.35	0.15	0.84
Mean	0.51	0.35	0.14	0.86
Standard Deviation	0.05	0.07	0.06	0.06
Midwest Rivers (Leopold & Maddock)	0.50	0.40	0.10	0.90
Theoretical (Leopold 6 Langbein)	0.55	0.36	0.09	0.91

Table 12. Stream Hydraulic Factors for 12 River Basins

(Drainage area = 100 sq mi, discharge of $F = 0.1$)

Basin	**Discharge** Q *(cfs)*	**Cross-sectional area** A *(sq ft)*	**Mean velocity** V *(fps)*	**Width** W *(ft)*	**Mean depth** D *(ft)*
Merrimack	406	173	2.3	71	2.5
Susquehanna	372	159	2.4	83	2.0
Roanoke	159	103	1.5	53	1.9
Big Sandy	250	124	2.0	61	2.0
White	175	103	1.8	55	1.9
Sangamon	125	119	1.1	44	2.7
Neches	159	136	1.1	49	2.7
Colorado	167	62	2.6	43	1.5
Tuolumne	466	239	2.0	69	3.5
Skagit	1168	289	4.0	91	3.2
Snake	144	54	2.7	36	1.5
Rogue	295	112	2.5	52	2.1

Table 10 shows the mean *station* values of these exponents b, f, and m for each of the 12 river basins studied. In each case the standard deviation of the mean value is given. This table provides an insight into the variability of these *station* values for various basins throughout the United States. At the bottom of table 10 are *station* values of b, f, and m as published by others.

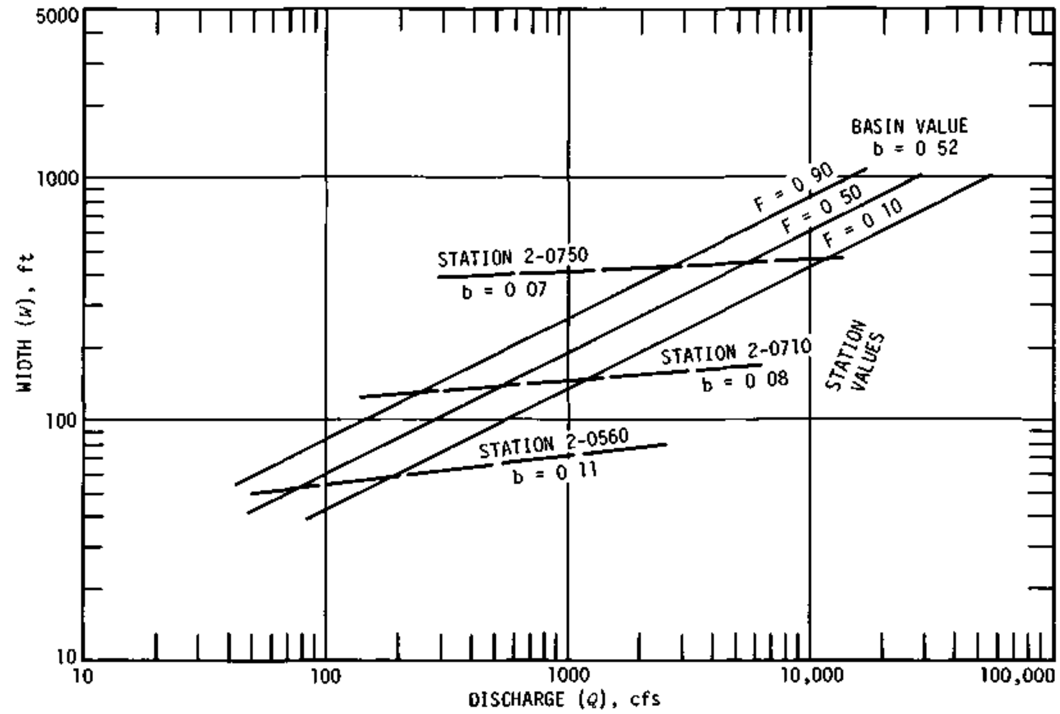
By a similar manipulation, it is possible to derive values of exponents b, f, and m for each entire river *basin.* In this case each set of hydraulic geometry equations from table 7 is rewritten into the exponential form. Table 11 shows the values of the exponents derived in this fashion for each of the 12 *basins* studied, as well as the mean and standard deviation of each. It should be noted from table 11 that the variability of each of these exponents is relatively low. Table 11 also shows comparative *basin* values of these exponents as derived by Leopold and Maddock (1953) for Midwest rivers and the theoretical values as published by Leopold and Langbein (1962).

The hydraulic geometry exponents b, f, and m have been shown as *station* values in tables 9 and 10, and as *basin* values in table 11. The relative meaning of these is illustrated and described in figure 12 for the Roanoke River Basin. The dashed lines in the graph in figure 12 represent the *station* values for three stations; the upper dashed line is for the Dan River at Danville, Virginia, station 2-0750. This is the same line as shown for width in the hydraulic rating curves in figure 4. This line, in both figure 4 and figure 12, is represented by equation 4 as $W = 268.0\ Q^{0.07}$ where the exponent $b = 0.07$. This *station* value of the width exponent b gives the change in channel width at this station, as the discharge increases.

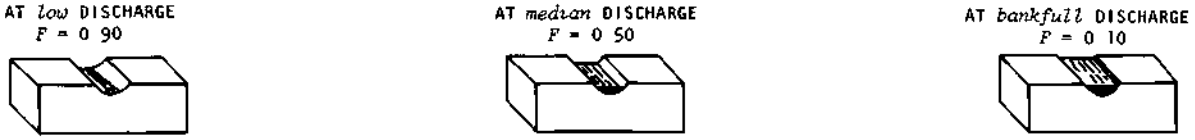
In figure 12 the solid lines represent the *basin* value of the width exponent; here $b = 0.52$ for the Roanoke River Basin as is given in table 11. For a particular flow condition assumed to be steady-state throughout the basin, such as would occur if the discharge at all stations had the same frequency of occurrence F, the *basin* value of width exponent b shows the change in channel width as the discharge increases. And for such a steady-state condition, the discharge increases in a downstream direction.

The diagrams in figure 12 illustrate the differences in the interpretation of *station* values and *basin* values of hydraulic geometry.

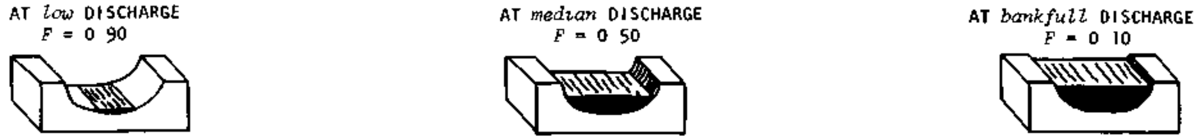
A stream system is the total result of all the gravity and inertial forces involved in the runoff of water from a basin. Progressing downstream within a basin the discharge increases, as does the width, depth, and velocity, as shown and quantified in this report. The downstream increase in discharge is accommodated by increases in the width, depth, and velocity. Changes in these channel characteristics are not fully predictable however. In this project the consistency of the width/depth ratio of the channel was investigated, and its downstream increase was found to be erratic. The width, depth, and velocity of the channel flow are governed by physical laws which also govern the development of the river profile. This report has also shown the predictability of the river profile. There is an ultimate physical control system which specifies the complete stream system. This ultimate understanding of the stream system still escapes specification because of other elements of the rivers energy system which are not yet quantified and proven consistent. These elements include: river meanders, hydraulic friction losses in river bends, changes in bed material and bed regime,



Station values of hydraulic geometry exponents reveal the change in channel width, cross-sectional area, depth, and velocity at a particular gaging station as the discharge changes For example, at an *upstream* station, such as 2-0560



and at a *downstream* station, such as 2-0750



Basin values, or *downstream* values, of hydraulic geometry exponents reveal the change in channel width, cross-sectional area, depth, and velocity at a discharge having a constant frequency For example

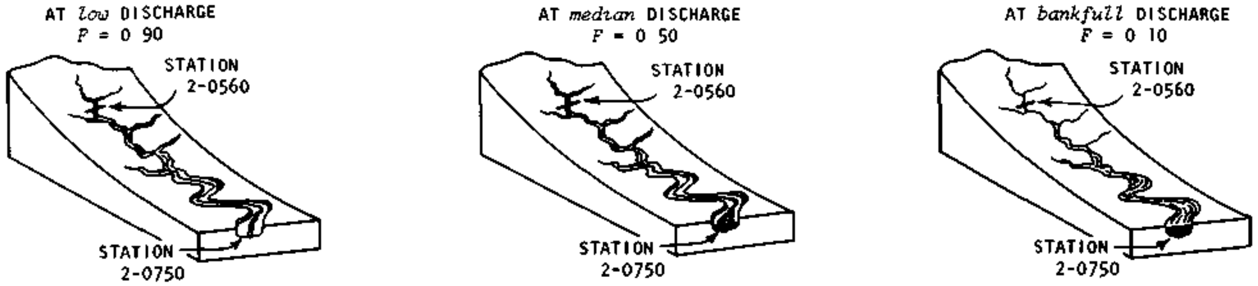


Figure 12. Graphical plot and illustrative diagrams of the differences between the hydraulic geometry exponent b *in the equation* $W = aQ^b$ *for individual* station *values and* basin *values, Roanoke River Basin*

and the hydraulics of the pool-and-riffle flow regime at low flows. Discussions by Leopold, Wolman, and Miller (1954) treat all these important factors and their possible interrelation.

Variation in Stream Parameters

To provide an overall frame of reference for considering the variation in the various hydraulic stream system parameters for the various basins studied, it was decided to inspect the variation of these parameters under a prescribed set of standard conditions. For this purpose a drainage area of 100 square miles and a discharge equivalent to that equalled or exceeded 10 percent of the days per year, $F = 0.10$, were selected. Table 12 presents the computed stream hydraulic factors for each of the 12 river basins under these standard conditions.

Horton-Strahler Parameters

One of the major efforts of this study was the measurement of the Horton-Strahler stream orders and associated parameters for each of the 12 basins. As described earlier, the graph in figure 10 shows how these stream parameters follow Horton's various laws. Table 13 gives the entire stream system parameters as measured from the 2-degree maps and from the available 15-minute or 7 1/2-minute maps, as previously described in this report. The data in table 13 are believed to be an important result of this study. These parameters appear to follow Horton's laws for all basins with the exception of the Skagit, Snake, and Tuolumne Basins, where the deviation was relatively slight and believed to be affected by the physiographic history of each basin.

River Profiles

As described earlier, this project and a study by Yang (1970) have provided a means of computing theoretical and equilibrium profiles for the river basin. This has been done for nine of the 12 basins as shown in figure 13. For the nine basins, the equilibrium profile computed from equations 21 and *2k* is shown by a dashed line, and the theoretical profile computed from equations 20 and 21 is shown as a solid line. The coefficients required to calculate the theoretical and equilibrium profiles by these equations are also given. The actual river profiles as depicted by the plotted points are shown on figure 13 for all 12 river basins. The comparisons among the actual, theoretical, and equilibrium profiles are made only for those river basins which follow both Horton's law of average stream length and law of average stream slope, thus, theoretical and equilibrium profiles were not attempted for the Skagit, Snake, and Tuolumne Basins.

On figure 13, for the nine basins having profile comparisons, the vertical scale shown is the *fall* of the theoretical profile in feet, and this is also used to represent *elevation* in feet for the actual profiles, which would ordinarily progress in the opposite direction (as shown for the Skagit, Snake, and Tuolumne). Also on figure 13, the actual profiles for the Merrimack and Roanoke deviate from their theoretical profiles causing the actual points to plot above the zero on the fall scale. This was allowed for simplicity since this deviation is of minor importance and separate scales of elevation and fall would have been similar.

Table 13. Horton-Strahler Stream System Parameters

Stream order	Number of streams	Average length (*mi*)	Average slope (*ft/mi*)	Stream order	Number of streams	Average length (*mi*)	Average slope (*ft/mi*)
Merrimack River Basin above Merrimack, N. H.							
	2° map				15' map		
3	80	4.13	77.4	3	159	2.98	92.3
4	17	11.9	37.8	4	30	7.58	46.4
5	5	16.3	9.08	5	7	19.2	12.3
6	1	93.5	3.84	6	2	39.9	7.31
				7	1	47.0	2.81
Susquehanna River Basin above Waverly, N. Y.							
	2° map				7 1/2' map		
2	91	4.92	43.3	3	226	3.56	70.0
3	24	12.3	16.1	4	54	8.00	28.6
4	4	42.8	6.06	5	11	21.7	8.94
5	1	60.0	2.34	6	3	39.6	6.79
				7	1	44.8	1.90
Roanoke River Basin above Roanoke Rapids, N. C.							
	2° map				15' map		
2	226	4.64	24.3	3	325	4.01	37.0
3	53	10.8	10.5	4	76	8.83	17.7
4	14	22.2	6.64	5	17	23.2	9.42
5	2	135.7	3.24	6	4	38.6	6.04
6	1			7	2	96.7	2.51
				8	1		
Big Sandy River Basin above Louisa, Ky.							
	2° map				7 1/2^{1} map		
2	123	4.31	37.4	3	436		
3	29	10.9	21.2	4	99	5.44	43.0
4	7	26.8	9.57	5	21	14.3	16.7
5	2	61.2	3.60	6	5	22.9	19.0
6	1			7	2	114.1	4.7
				8	1		

Table 13 (Continued)

Stream order	Number of streams	Average length (*mi*)	Average slope (*ft/mi*)	Stream order	Number of streams	Average length (*mi*)	Average slope (*ft/mi*)
White River Basin above Spencer, Ind.							
2° map				7 1/2' map			
2	62	5.28	13.0	2	531		
3	15	12.2	6.96	3	133	3.97	19.3
4	2	65.2	5.12	4	28	8.49	10.2
5	1			5	6	30.0	4.23
				6	1	65.0	1.83
Sangamon River Basin above Oakford, Ill.							
2° map				15' map			
2	68	6.98	5.23	2	424		
3	20	14.0	4.79	3	103	6.2	9.0
4	5	31.2	2.08	4	26	10.8	4.6
5	2	29.4	0.97	5	5	59.7	1.9
6	1			6	2	31.7	1.6
				7	1	34.6	1.01
Neches River Basin above Evadale, Tex.							
2° map				15' map			
2	192	4.56	11.0	3	212	4.75	11.9
3	38	9.10	5.87	4	43	9.43	6.67
4	8	19.7	2.89	5	9	31.5	2.76
5	2	150.6	1.34	6	2	155.4	1.07
6	1			7	1		
Colorado River Basin above Glenwood Sprvngs, Colo.							
2° map							
2	278	3.19	359.0				
3	58	5.94	189.0				
4	16	15.0	85.0				
5	4	31.1	36.0				
6	2	15.1	23.6				
7	1						

Table 13 (Concluded)

Stream order	Number of streams	Average length (*mi*)	Average slope (*ft/mi*)	Stream order	Number of streams	Average length (*mi*)	Average slope (*ft/mi*)
Tuolumne River Basin above LaGrange, Calif.							
	2° map				15' map		
2	25	7.22	263.9	2	168		
3	7	11.9	190.7	3	41	6.37	250.0
4	1	80.4	74.6	4	12	17.2	224.2
				5	2	30.4	159.9
				6	1	51.4	38.0
Skagit River Basin above Mt. Vernon, Wash.							
	2° map						
3	28	7.16	171.2				
4	7	10.7	56.9				
5	2	43.2	20.5				
6	1	51.2	1.95				
Snake River Basin above Eeise, Idaho							
	2° map						
2	151	4.23	154.7				
3	38	6.99	66.2				
4	8	27.0	37.8				
5	1	126.4	12.7				
Rogue River Basin above Central Point, Ore.							
	2° map				15' map		
2	111	3.34	222.2	2	177	3.59	277.5
3	26	5.56	105.7	3	50	4.74	149.5
4	6	15.5	50.1	4	12	9.9	82.1
5	1	39.2	20.4	5	4	10.7	54.3
				6	1	41.8	17.2

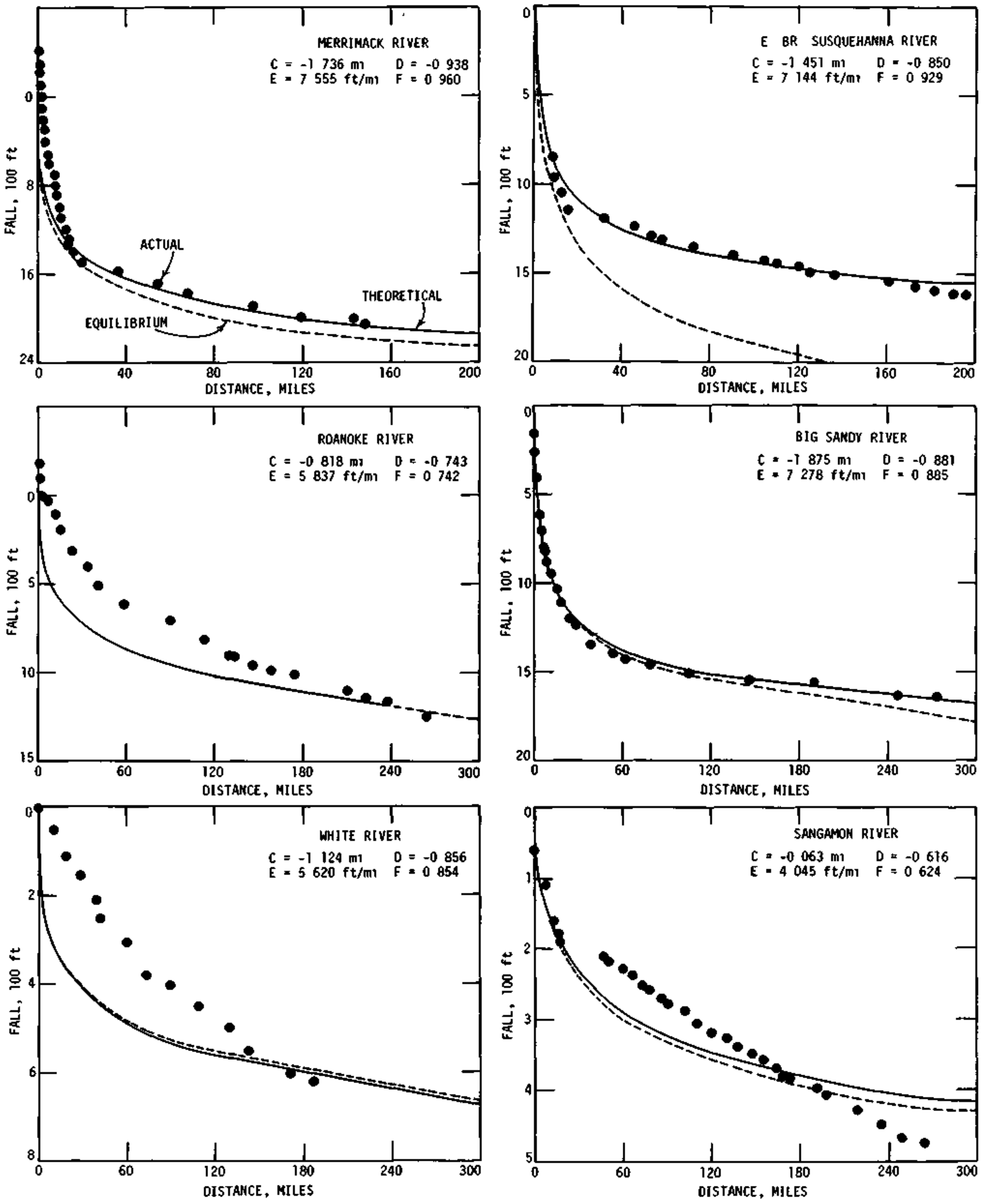


Figure 13. River profiles

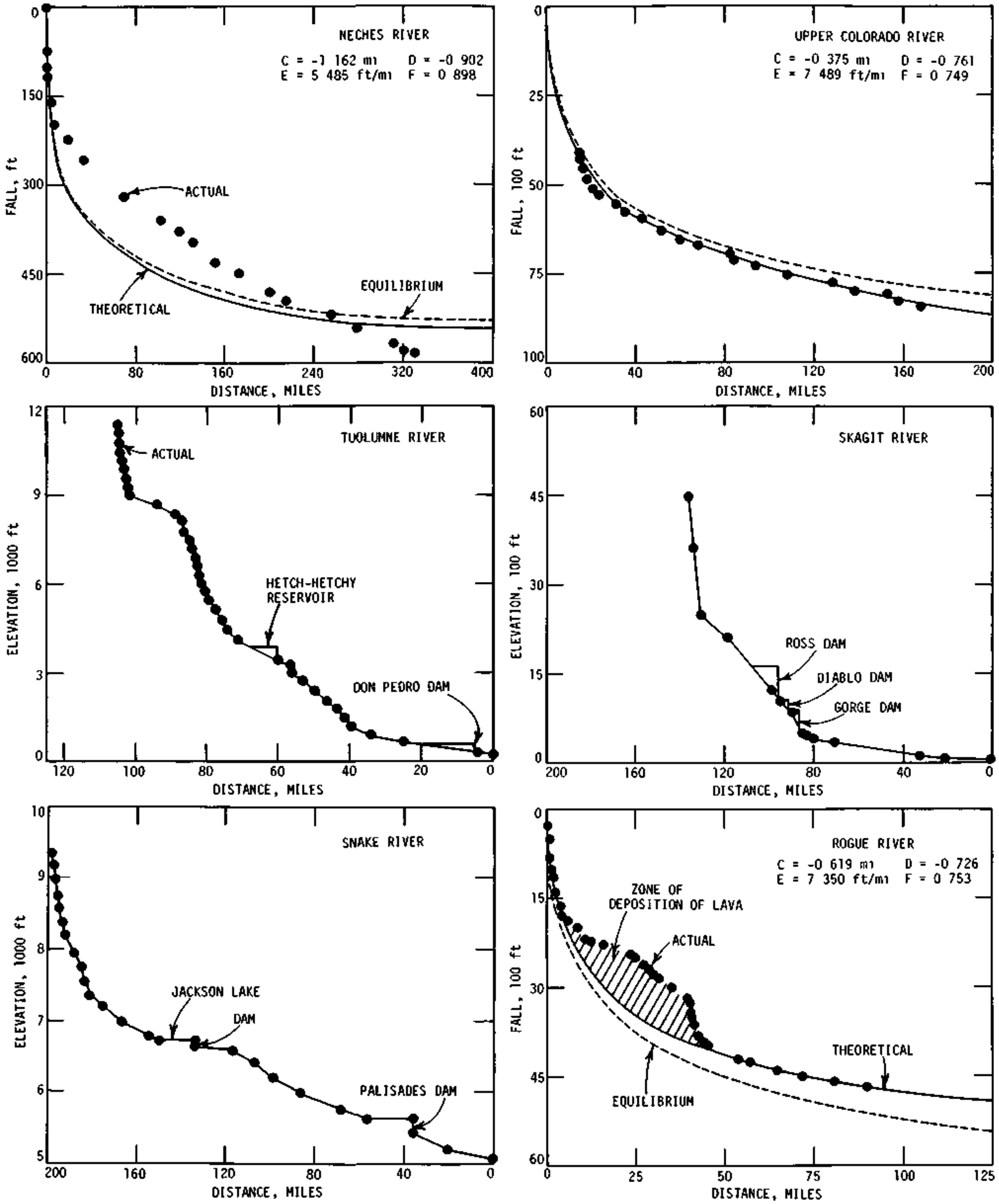


Figure 13 (Continued)

Since Yang's theoretical profile is a representative profile for the river basin as a whole, a certain amount of deviation from the theoretical profile along a particular course of stream should be expected. In spite of this fact, the agreements between the actual profile and the theoretical profile are generally very good, as shown in figure 13. The localized deviation of the actual profile from the theoretical profile is an indication of the presence of either a local geological constraint or a past geological event.

The Rogue River profiles in figure 13 provide an example. The observed streambed profile along the main stem of the Rogue agrees with the theoretical profile in both the upper and lower portions, but not in the middle portion of the stream. Fortunately, because of the volcanic activity near Crater Lake, Oregon, the U. S. Geological Survey has made a thorough study of the geological changes in this area. According to Williams (1956), Crater Lake is the result of volcanic activity of Mount Mazama which took place between 4000 and 7000 years ago. During this period of volcanic activity part of the thick flow of lava went into the Rogue River Valley, and ". . . those that emptied into the valley of the Rogue River did not stop until they had traveled 35 miles. . ." (Williams, 1956). Comparison with the topographic map shows that the deviation of the actual stream profile from the theoretical profile occurs exactly at the place where the lava entered the Rogue River Valley. The horizontal distance of this deviated portion is about 38 miles, which is very close to Williams' 35 miles. The vertical distance indicated between the actual and theoretical profile for the deviated portion may provide a measure of the depth of lava deposition.

When a stream system has reached its maturity, its stream fall ratio should be unity, and the theoretical profile and equilibrium profile should be identical. Since the observed stream fall ratio for the Roanoke River is unity, the river valley, in general, will not aggrade or degrade in the future. However, this does not eliminate the possibility of localized deviation along a particular course of stream from the theoretical profile.

When the stream fall ratio is smaller than unity, the theoretical profile should have a lower elevation than the equilibrium profile, and the stream valley will aggrade in the future to approach the equilibrium profile. Hence, the White, Neches, and Colorado Rivers will aggrade in the future. Conversely, when the stream fall ratio is greater than unity, the theoretical profile should have a higher elevation than the equilibrium profile, and the stream valley will degrade in the future to approach the equilibrium profile. Hence, the Merrimack, Susquehanna, Big Sandy, Sangamon, and Rogue Rivers will degrade in the future. Thus, the actual stream fall ratio of a stream system not only serves as an index of the maturity of the stream system but also indicates in general whether the river valley will aggrade or degrade in the future.

Time-of-Travel

In the earlier report by Stall and Fok (1968), it was found possible to check the velocity equation for the White River Basin by using times-of-travel as measured by dye studies. Since the complete results in the earlier report made available for each principal stream in Illinois an equation relating the velocity of the stream to the flow frequency and drainage area, it was deemed plausible to use these velocity equations to compute estimated times-of-travel for all of the principal reaches of Illinois streams. This was carried out and published by Stall and Hiestand (1969).

Figure 14 illustrates the typical lines of equal velocity in a stream cross section. The average velocity as computed by an hydraulic geometry equation gives the average velocity for this cross section. Theoretical as well as practical studies show that the velocity distribution as shown in figure 14 actually exists in nature. As a consequence, the variation in velocity causes the dispersion of a dye or other contaminant material in a stream. As the material moves downstream it is dispersed and some of the material travels faster than the average velocity. As a generalization it was considered acceptable to use the relation between these relative velocities as

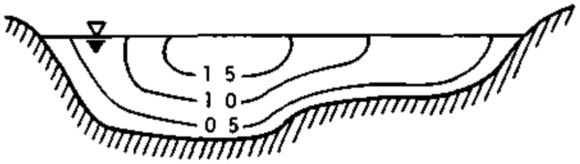


Figure 14. Typical lines of equal velocity in a stream cross section

$$V_l = 1.25 V_p \qquad (25)$$

where V_l is the velocity of the leading edge of the dye and V_p is the velocity of the peak concentration of the dye. This generalization was derived from sets of data from eight separate dye runs available for various streams in Illinois and Indiana, as given by Stall and Hiestand (1969).

Figure 15 shows the computed time-of-travel curves for a section of the Sangamon River in Illinois. These curves were computed by use of the generalized hydraulic geometry equation for velocity as published by Stall and Fok (1968). First, a general solution was made for the average velocity at various points along the course of the main stem of the river for three different flow rates. These were termed *low*, *medium*, and *high* flow, or the flows for a frequency of $F = 0.90$, $F = 0.50$ (median flow), and $F = 0.10$. The average velocities computed in this fashion were then adjusted by the 1 25 factor given in equation 25 to obtain the velocity of the leading edge of the dye or contaminant material. This velocity was used to compute the time-of-travel of a material down the course of the river at these three flow rates

The graphs, such as that shown in figure 15, as checked by dye runs, suggest that at high flows the times-of-travel are accurate, at medium flows they are fairly accurate, and at low flows their accuracy may be poor. Because of the many considerations involved in the hydraulics of a stream at low flows, the curve as shown in figure 15 for low flow represents the fastest time-of-travel that might be expected through this reach of the river. Because of the pooling of the water at low flows, measured travel times are often slower than that shown in figure 15.

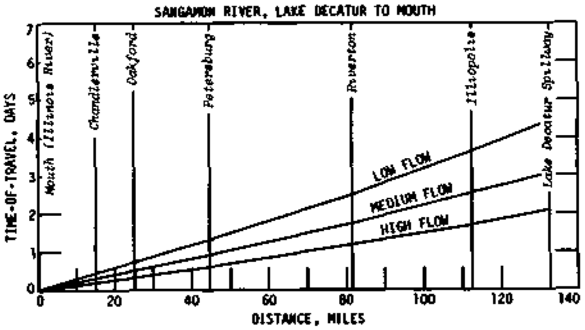


Figure 15. Time-of-travel of the leading edge of a dose of dye or contaminant for a 140-mile reach of the Sangamon River

The use of the results of the hydraulic geometry study to provide time-of-travel graphs for all of the major stream reaches in Illinois is believed to be a valuable application of the results of the earlier research study.

Reaeration Capacity of a Stream

It has been shown by others and by Stall and Fok (1968) that the capacity of a stream to assimilate wastes is dependent on the depth and velocity of the stream at a particular location as well as the amount of discharge. The reaeration capacity of a stream can be computed as follows

$$k_2 = 5.55 \frac{V^{0.5}}{D^{1.5}} \tag{26}$$

where *V* is the mean velocity in feet per second, *D* is the average depth in feet, and *kz* is the reaeration capacity of the stream at a temperature of 20 C. The structure of this equation clearly shows the dominant importance of the average depth and velocity of flow in a stream at a particular location in determining its capacity to reaerate itself.

To determine the total amount of oxygen which the stream can assimilate requires knowing the amount of water in the stream as well as the *kz* value. This computation can be accomplished by

$$A_c = (A\ L\ 5280)\ 2.3\ [k_2\ (3\ 12)\ 10^{-8}] \tag{27}$$

where

A_c = assimilative capacity of a stream reach for each ppm of oxygen deficiency in tons per day
A = cross-sectional area of stream in square feet
L = length of stream reach in miles
kz = reaeration coefficient of stream in milligrams per liter of water per day (to base 10)

The variation in the total load in tons per day which can be assimilated by characteristic or typical streams was calculated for the Roanoke and Rogue River Basins and the results are shown in figure 16. Here, equation 26 has been solved to provide the k_2's for each of the stream orders within these river basins and equation 27 has been solved to provide the total assimilative capacity for all of the streams of various order for these two river basins at a discharge having a frequency of *F* = 0.90. The results have been adjusted to represent the total assimilative capacity available within a typical drainage area of 2000 square miles. For a selected 2000-square-mile basin within the Roanoke River Basin or the Rogue River Basin, the total assimilative capacity of the stream in tons per day at locations having various drainage areas is shown in figure 16.

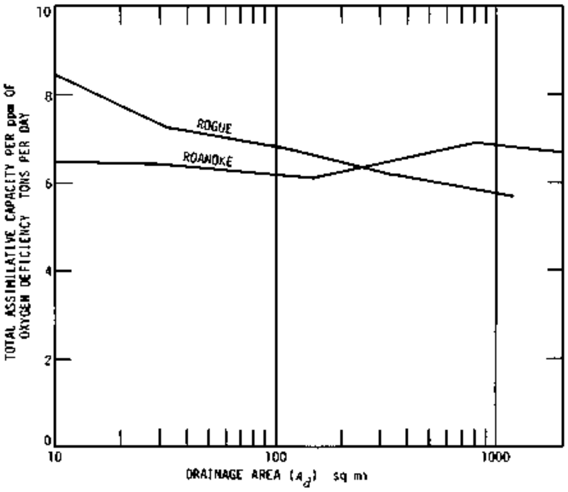


Figure 16. Total assimilative capacity of all streams for two basins (discharge of F = *0.90)*

The use of hydraulic geometry relations can aid considerably in providing a general estimate of the assimilative capacity of a stream system. Although the general answers such as shown in figure 16 are subject to many local variations, this result does provide an overall concept as to the resource available in terms of the total amount of waste that particular stream systems can accommodate.

CONCLUSION

This study has resulted in the following conclusions:

1) The 12 stream systems evaluated do tend to adjust their channels to a consistent pattern which has been numerically specified by the concepts of hydraulic geometry.
2) The pattern holds consistent under the divergent conditions of physiography and hydrology represented by the 12 basins.
3) The sets of five equations for these basins given in table 7 adequately express the hydraulic geometry relationships.
4) Similar patterns can be inferred to exist and could be evaluated in other basins in the humid regions of the United States having relatively uniform physiography. Patterns for basins in arid zones require further study.
5) The results for these 12 stream systems can also be expressed in the form of the hydraulic geometry equations as originated by Leopold and Maddock (1953). The results are compatible with other actual and theoretical results published in this form.
6) The stream systems were shown to follow the Horton-Strahler laws of stream numbers, stream length, and stream slopes. For nine basins the fit was good, and for three basins the fit was fair.
7) The Horton-Strahler laws were found to be consistent regardless of the scale of the map of the stream system.
8) The Horton-Strahler laws allow the computation of a theoretical longitudinal streambed profile based on the nature of all segments of the stream system. This profile is a more stable and meaningful representation of the channel system than the longitudinal profile of the main channel only. Deviations of an actual stream profile from the theoretical is an indication of local geological constraints.
9) Two new laws are proposed to govern stream morphology, the *law of average stream fall* and the *law of least rate of energy expenditure.*
10) The *law of average stream fall* and the Horton-Strahler laws allow an equilibrium streambed profile to be computed. When the equilibrium profile is compared with the actual or theoretical profile, an estimate can be made as to whether this stream system will aggrade or degrade in the future.
11) The equation for stream velocity can be used to provide curves of time-of-travel of a dye or contaminant in a stream. These curves are valid at high and medium flows, but are poor at low flows.
12) Hydraulic geometry equations can be used to provide a general estimate of channel characteristics at any location with the system. Although subject to local variations, this is illustrated to be of value in calculating the capacity of a stream system to assimilate waste loadings.

In 1970 the U. S. Geological Survey operated about 8500 complete-record gaging stations of which 308 were used to provide data for this study. By the use of hydraulic geometry, a broad and useful generalization of these stream gaging data could be made for various stream systems.

The book *Water Facts for the Nation's Future*, by Langbein and Hoyt (1959), is a systematic appraisal of the hydrologic data available in the United States. It states

> "Here it is enough to suggest that one approach to achieving an adequate program is to bridge the gap between available facts and needs of specific problems by means of refined and enlarged knowledge of principles. . . . Given opportunity, gifted investigators can breathe life into raw facts. Moreover, interpretation has a leverage action on the collection of facts. Imaginative review can yield new relationships that can expand the usefulness of the mountains of data already at hand."

In discussing water resources management in Australia, Langbein (1964) stated: ". . . it is facts and knowledge about hydrological interrelationships which are required to make the forecasts of the effects of various alternatives we face. These are the tools administrators and political leaders need to make sound decisions."

Hydraulic geometry provides a set of relations between stream parameters through which a wide and useful expansion of stream measurements has been made.

Hardison (1970), in describing streamlining of data-collection procedures, deals also with overall efficiency in the use of existing data. He notes that every estimate of a streamflow characteristic has an error associated with it, and that regional generalization of streamflow characteristics usually provides an improved estimate by reducing sampling error. This regional generalization of stream channel characteristics is another important result of this project.

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APPENDIX

Table 14. Merrimack River Basin, New Hampshire and Massachusetts

List of 28 gaging stations and periods used for flow duration
All records adjusted to the 46-year standard period, water years 1919-1964
(Index stations shown in *italics)*

USGS number	Drainage area (*sq mi*)	Water years	Station
1-0750	193	1940-1967	Pemigewasset River at Woodstock, N.H.
1-0758	2.94	1964-1967	Stevens Brook near Wentworth, N.H.
1-0760	143	1929-1967	Baker River near Rumney, N.H.
1-0765	*622*	*1904-1967*	*Pemigewasset River at Plymouth, N.H.*
1-0780	*85.8*	*1919-1967*	*Smith River near Bristol, N.H.*
1-0815	1507	1906-1918 1920-1941	Merrimack River at Franklin Junction, N.H.
1-0820	68.1	1946-1967	Contoocook River at Peterboro, N.H.
1-0840	54.8	1925-1967	N. Br. Contoocook River near Antrim, N.H.
1-0845	55.4	1946-1967	Beards Brook near Hillsboro, N.H.
1-0850	368	1940-1967	Contoocook River near Henniker, N.H.
1-0858	5.75	1963-1967	W. Br. Warner River near Bradford, N.H.
1-0860	146	1940-1967	Warner River at Davisville, N.H.
1-0870	129	1919-1920 1928-1940	Blackwater River near Webster, N.H.
1-0880	766	1930-1961	Contoocook River at Penacook, N.H.
1-0890	76.8	1952-1967	Soucook River near Concord, N.H.
1-0895	157	1919-1920 1922-1927 1930-1967	Suncook River at N. Chichester, N.H.
1-0910	104	1941-1967	S. Br. Piscataquog River near Goffstown, N.H.
1-0915	202	1940-1961	Piscataquog River near Goffstown, N.H.
1-0920	3092	1938-1941	Merrimack River near Goffs Falls, below Manchester, N.H.
1-0938	3.60	1964-1967	Stony Brook tributary near Temple, N.H.
1-0940	*171*	*1910-1964*	*Souhegan River at Merrimack, N.H.*
1-0945	107	1936-1967	N. Nashua River near Leominster, Mass.
1-0950	2.28	1947-1948	Rocky Brook near Sterling, Mass.
1-0960	62.8	1950-1967	Squannacook River near W. Groton, Mass.
1-0970	116	1942-1967	Assabet River at Maynard, Mass.
1-0973	12.7	1964-1967	Nashoba Brook near Acton, Mass.
1-0995	405	1938-1967	Concord River below Meadow Brook at Lowell, Mass.
1-1000	4635	1924-1967	Merrimack River below Concord River at Lowell, Mass.

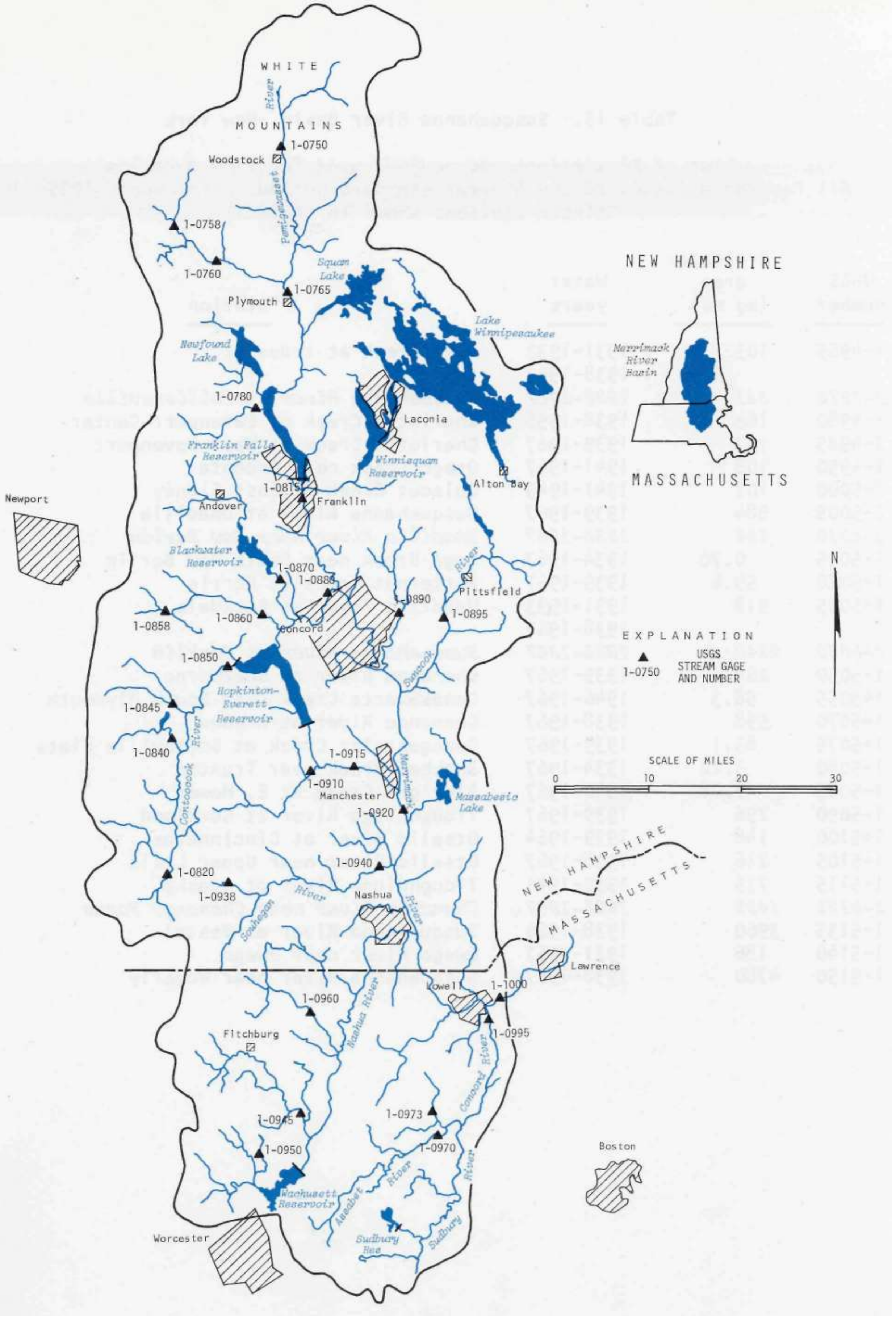

Figure 17. Merrimack River Basin

Table 15. Susquehanna River Basin, New York

List of 26 stations and periods used for flow duration
All records adjusted to the 43-year standard period, water years 1925-1967
(Index stations shown in *italics*)

USGS number	Drainage area (*sq mi*)	Water years	Station
1-4965	103	1931-1932 1938-1963	Oaks Creek at Index
1-4975	*351*	*1925-1967*	*Susquehanna River at Colliersville*
1-4980	163	1938-1956	Charlotte Creek at Davenport Center
1-4985	167	1939-1967	Charlotte Creek at West Davenport
1-4990	108	1941-1967	Otego Creek near Oneonta
1-5000	102	1941-1949	Ouleout Creek at East Sidney
1-5005	984	1939-1967	Susquehanna River at Unadilla
1-5010	*196*	*1925-1967*	*Unadilla River near New Berlin*
1-5015	0.70	1934-1967	Sage Brook near South New Berlin
1-5020	59.6	1939-1967	Butternut Creek at Morris
1-5025	518	1931-1933 1938-1967	Unadilla River at Rockdale
1-5030	*2240*	*1925-1967*	*Susquehanna River at Conklin*
1-5050	264	1939-1967	Chenango River at Sherburne
1-5055	58.3	1946-1967	Canasawacta Creek near South Plymouth
1-5070	598	1938-1967	Chenango River at Greene
1-5075	83.1	1939-1967	Genegantslet Creek at Smithville Flats
1-5080	3.12	1934-1967	Shakham Brook near Truxton
1-5085	7.08	1940-1967	Albright Creek at E. Homer
1-5090	296	1939-1967	Tioughnioga River at Cortland
1-5100	148	1939-1964	Otselic River at Cincinnatus
1-5105	216	1938-1967	Otselic River near Upper Lisle
1-5115	735	1930-1941	Tioughnioga River at Itaska
1-5125	*1492*	*1925-1967*	*Chenango River near Chenango Forks*
1-5135	3960	1938-1966	Susquehanna River at Vestal
1-5140	186	1931-1967	Owego River near Owego
1-5150	4780	1938-1967	Susquehanna River near Waverly

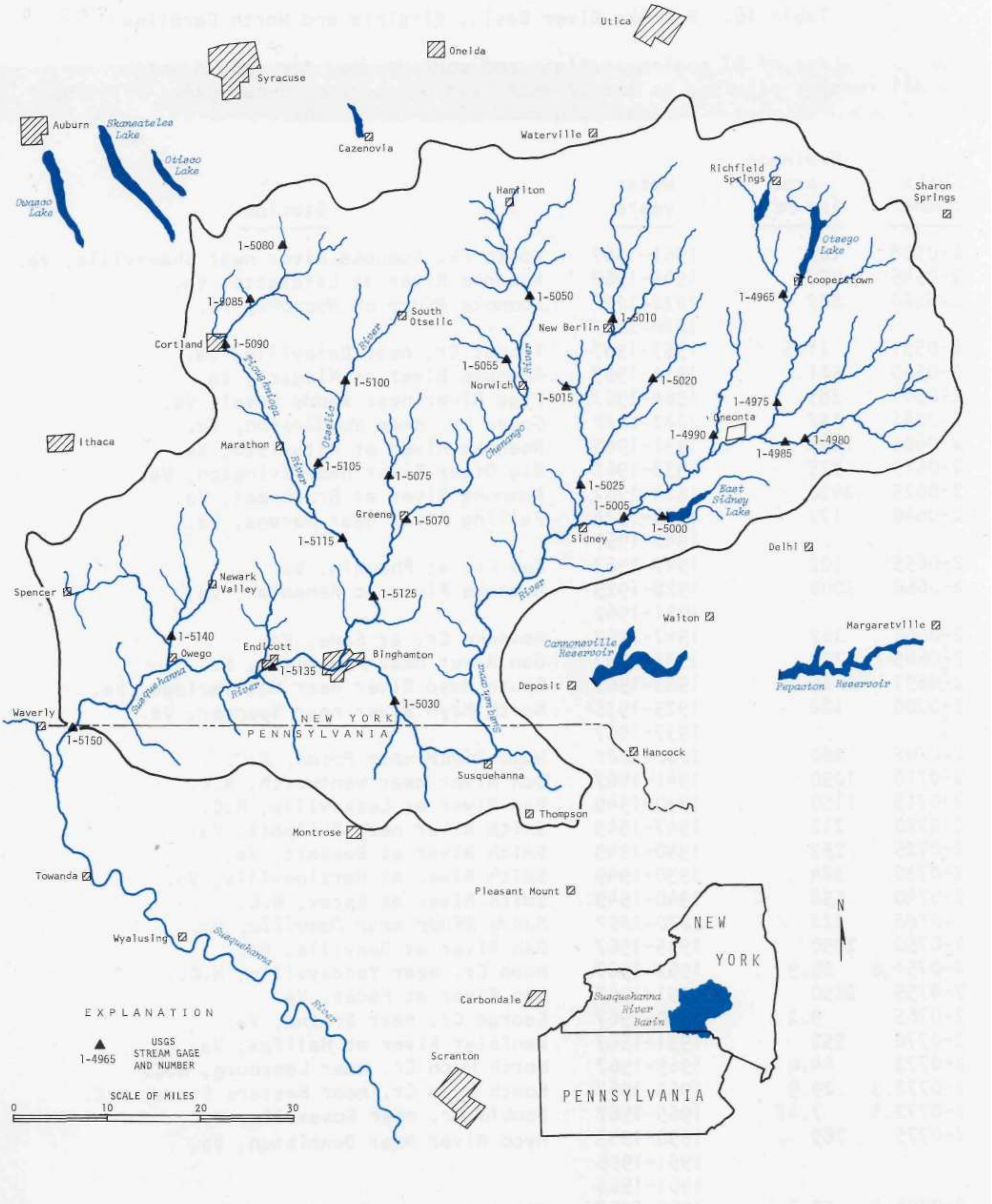

Figure 18. Susquehanna River Basin

Table 16. Roanoke River Basin, Virginia and North Carolina

List of 37 gaging stations and periods used for flow duration
All records adjusted to the 37-year standard period, water years 1931-1967
(Index stations shown in *italics*)

USGS number	Drainage area (*sq mi*)	Water years	Station
2-0538	109	1961-1967	South Fk. Roanoke River near Shawsville, Va.
2-0545	257	1944-1967	Roanoke River at Lafayette, Va.
2-0550	*388*	*1918-1927* *1929-1967*	*Roanoke River at Roanoke, Va.*
2-0551	11.5	1957-1967	Tinker Cr. near Daleville, Va.
2-0560	511	1931-1967	Roanoke River at Niagara, Va.
2-0584	383	1964-1967	Pigg River near Sandy Level, Va.
2-0595	*187*	*1931-1967*	*Goose Cr. near Huddleston, Va.*
2-0605	1802	1931-1962	Roanoke River at Altavista, Va.
2-0615	325	1938-1967	Big Otter River near Evington, Va.
2-0625	2420	1924-1962	Roanoke River at Brookneal, Va.
2-0640	172	1930-1934 1942-1967	Falling River near Naruna, Va.
2-0655	102	1947-1967	Cub Cr. at Phoenix, Va.
2-0660	3000	1928-1929 1951-1962	Roanoke River at Randolph, Va.
2-0665	162	1947-1967	Roanoke Cr. at Saxe, Va.
2-0685	124	1931-1967	Dan River near Francisco, N.C.
2-0697	85.2	1963-1967	South Mayo River near Nettleridge, Va.
2-0700	108	1929-1935 1937-1967	North Mayo River near Spencer, Va.
2-0705	*260*	*1930-1967*	*Mayo River near Price, N.C.*
2-0710	1050	1941-1967	Dan River near Wentworth, N.C.
2-0715	1150	1930-1949	Dan River at Leaksville, N.C.
2-0720	212	1947-1949	Smith River near Philpott, Va.
2-0725	253	1940-1949	Smith River at Bassett, Va.
2-0730	374	1930-1949	Smith River at Martinsville, Va.
2-0740	538	1940-1949	Smith River at Spray, N.C.
2-0745	*113*	*1930-1967*	*Sandy River near Danville, Va.*
2-0750	2050	1935-1967	Dan River at Danville, Va.
2-0751.6	29.9	1962-1967	Moon Cr. near Yanceyville, N.C.
2-0755	2550	1951-1967	Dan River at Paces, Va.
2-0765	9.2	1950-1967	George Cr. near Gretna, Va.
2-0770	552	1931-1967	Banister River at Halifax, Va.
2-0772	44.0	1965-1967	North Hyco Cr. near Leasburg, N.C.
2-0772.3	29.9	1965-1967	South Hyco Cr. near Hesters Store, N.C.
2-0772.4	7.47	1965-1967	Double Cr. near Roseville, N.C.
2-0775	289	1930-1933 1951-1955 1961-1963	Hyco River near Denniston, Va.
2-0796.4	53.3	1962-1967	Allen Cr. near Boydton, Va.
2-0805	8410	1918-1949	Roanoke River at Roanoke Rapids, N.C.
2-0810	8700	1942-1956	Roanoke River near Scotland Neck, N.C.

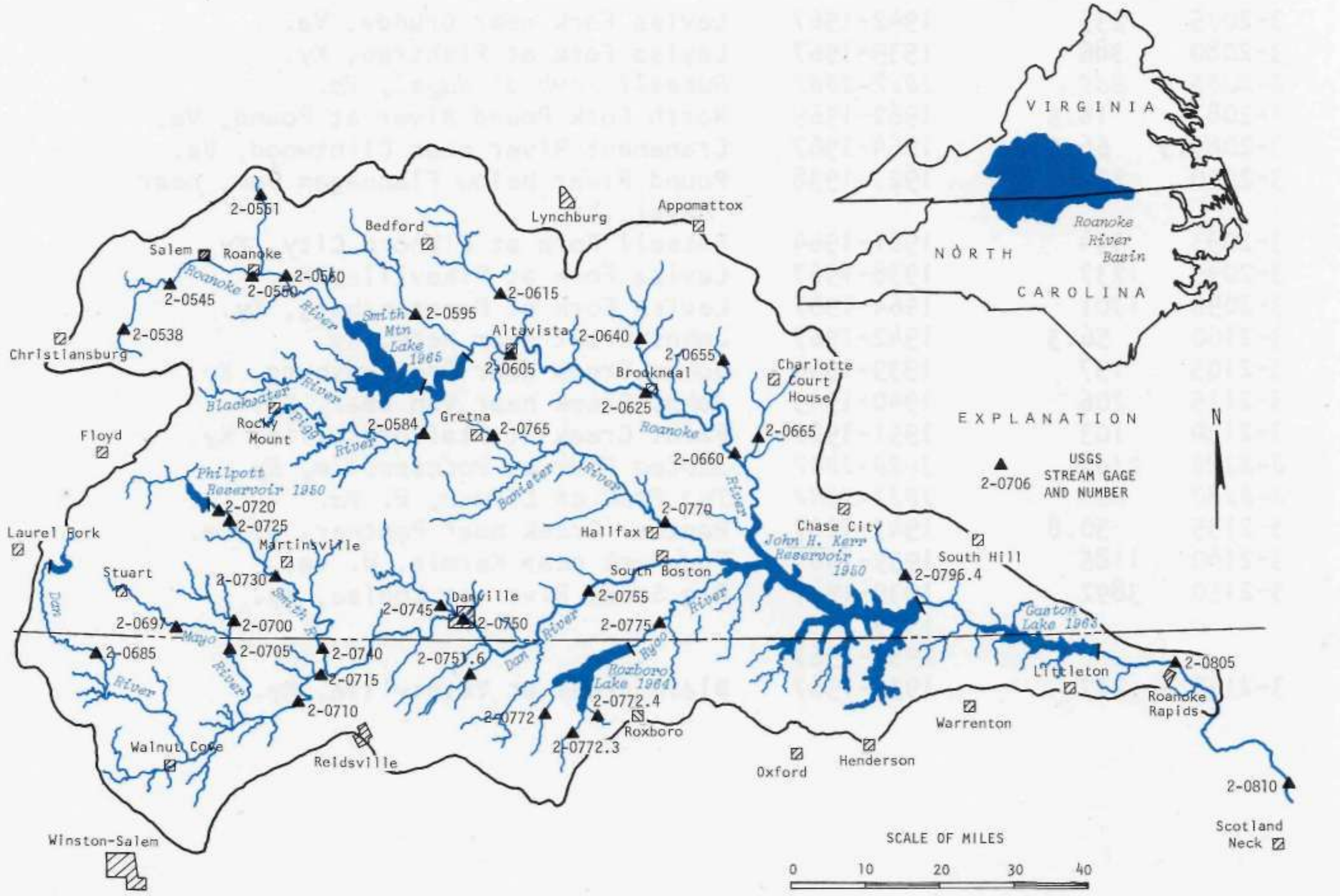

Figure 19. Roanoke River Basin

Table 17. Big Sandy River Basin, Kentucky, Virginia, West Virginia

List of 19 stations and periods used for flow duration
All records adjusted to the 37-year standard period, water years 1931-1967
(Index stations shown in *italics*)

USGS number	Drainage area (*sq mi*)	Water years	Station
3-2075	235	1942-1967	Levisa Fork near Grundy, Va.
3-2080	386	1939-1967	Levisa Fork at Fishtrap, Ky.
3-2085	*286*	*1927-1967*	*Russell Fork at Eaysi, Va.*
3-2087	18.5	1962-1965	North Fork Pound River at Pound, Va.
3-2089.5	66.5	1964-1967	Cranenest River near Clintwood, Va.
3-2090	221	1927-1938	Pound River below Flannagan Dam, near Haysi, Va.
3-2093	554	1961-1964	Russell Fork at Elkhorn City, Ky.
3-2095	1237	1938-1967	Levisa Fork at Pikeville, Ky.
3-2098	1701	1964-1967	Levisa Fork at Prestonsburg, Ky.
3-2100	56.3	1942-1967	Johns Creek near Meta, Ky.
3-2105	197	1939-1940	Johns Creek near Prestonsburg, Ky.
3-2115	206	1940-1949	Johns Creek near Van Lear, Ky.
3-2120	103	1951-1967	Paint Creek at Staffordsville, Ky.
3-2125	*2143*	*1929-1967*	*Levisa Fork at Paintsville, Ky.*
3-2130	*502*	*1931-1967*	*Tug Fork at Litwar, W. Va.*
3-2135	30.8	1947-1967	Panther Creek near Panther, W. Va.
3-2140	1185	1935-1967	Tug Fork near Kermit, W. Va.
3-2150	3892	1939-1947 1949 1951-1967	Big Sandy River at Louisa, Ky.
3-2155	217	1939-1967	Blain Creek at Yatesville, Ky.

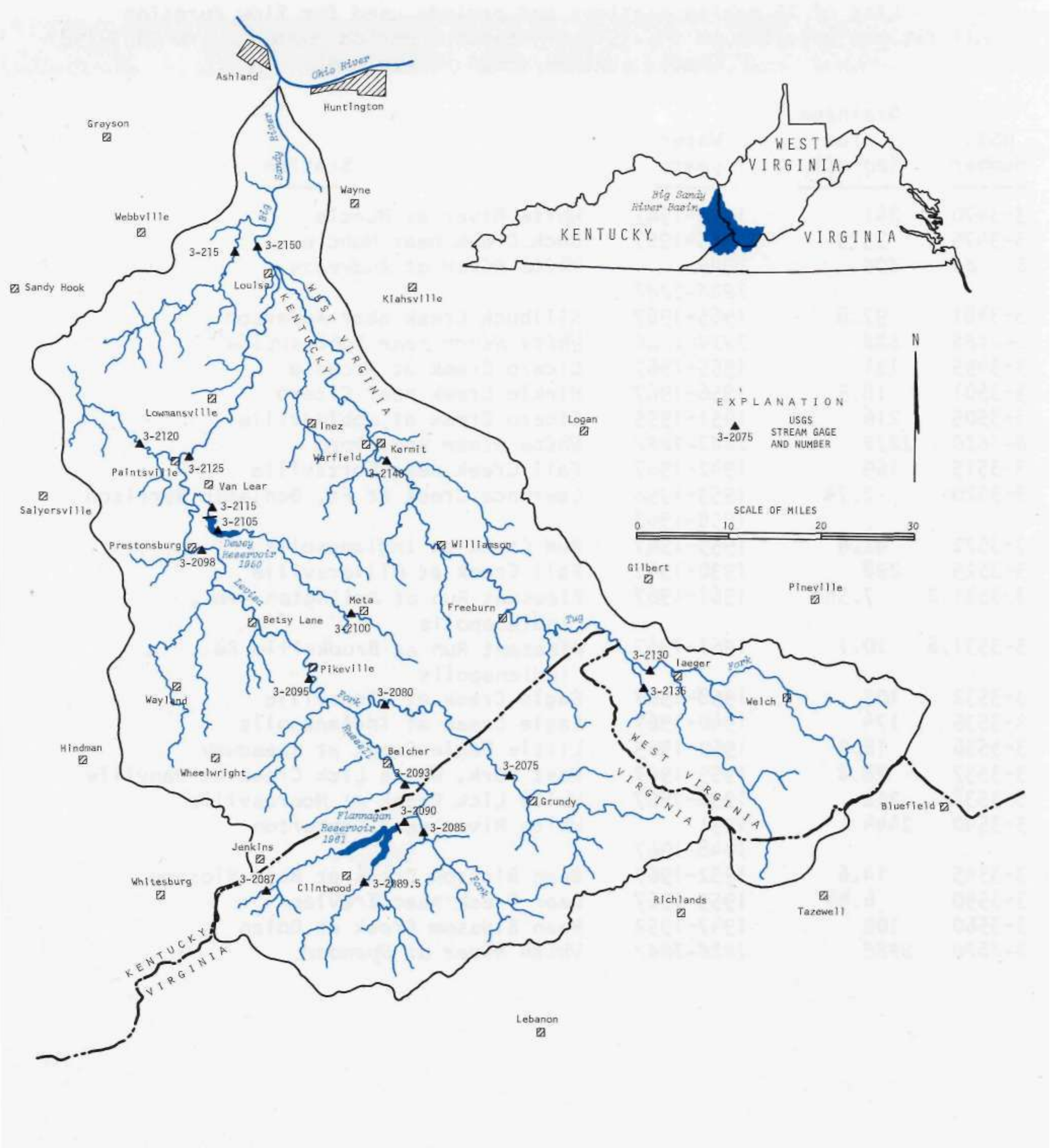

Figure 20. Big Sandy River Basin

Table 18. White River Basin, Indiana

List of 25 gaging stations and periods used for flow duration
All records adjusted to the 35-year standard period, water years 1933-1967
(Index station shown in *italics*)

USGS number	Drainage area (*sq mi*)	Water years	Station
3-3470	241	1933-1967	White River at Muncie
3-3475	35.5	1955-1967	Buck Creek near Muncie
3 80	*406*	*1926* *1933-1967*	*White River at Anderson*
3-3481	97.8	1965-1967	Killbuck Creek near Anderson
3-3485	*828*	*1916-1926*	*White River near Noblesville*
3-3495	131	1955-1967	Cicero Creek at Arcadia
3-3501	18.5	1956-1967	Hinkle Creek near Cicero
3-3505	216	1951-1955	Cicero Creek at Noblesville
3-3510	*1219*	*1931-1967*	*White River near Nora*
3-3515	169	1942-1967	Fall Creek near Fortsville
3-3520	2.74	1953-1956 1958-1967	Lawrence Creek at Ft. Benjamin Harrison
3-3522	42.4	1959-1967	Mud Creek at Indianapolis
3-3525	298	1930-1942	Fall Creek at Millersvilie
3-3531.2	7.58	1961-1967	Pleasant Run at Arlington Ave , Indianapolis
3-3531.6	10.1	1961-1967	Pleasant Run at Brookville Rd., Indianapolis
3-3532	103	1958-1967	Eagle Creek at Zionsville
3-3535	174	1940-1967	Eagle Creek at Indianapolis
3-3536	18.3	1960-1963	Little Eagle Creek at Speedway
3-3537	28.8	1959-1967	West Fork, White Lick Creek at Danville
3-3538	212	1958-1967	White Lick Creek at Mooresville
3-3540	2444	1931 1948-1967	White River near Centerton
3-3545	14.6	1952-1967	Bean Blossom Creek at Bean Blossom
3-3550	6.94	1953-1967	Bear Creek near Trevlac
3-3560	100	1947-1952	Bean Blossom Creek at Dolan
3-3570	*2988*	*1926-1967*	*White River at Spencer*

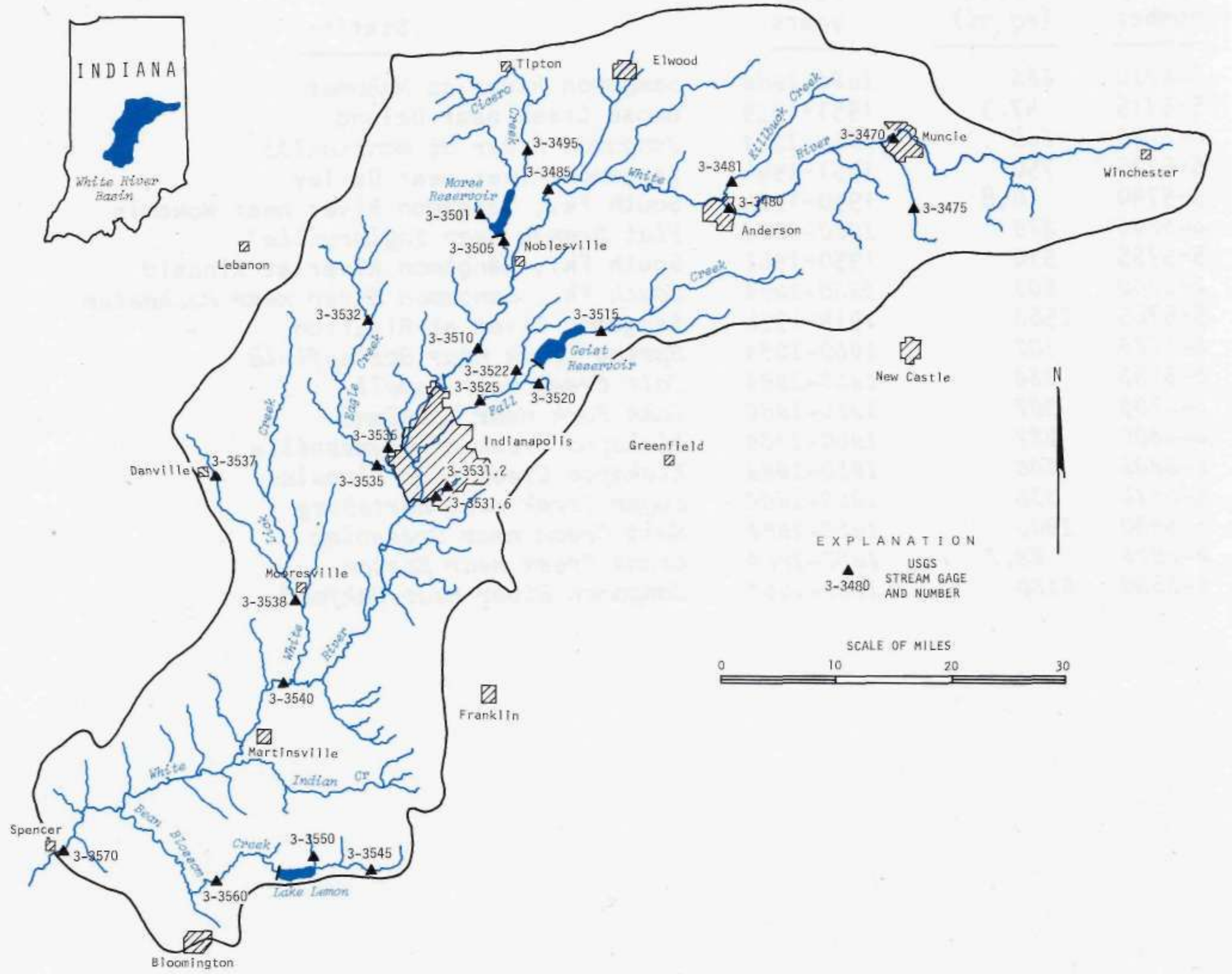

Figure 21. White River Basin

Table 19. Sangamon River Basin, Illinois

List of 18 gaging stations and periods used for flow duration
All records adjusted to the 15-year standard period, water years 1950-1964
(Index stations shown in *italics*)

USGS number	**Drainage area (*sq mi*)**	**Water years**	**Station**
5-5710	*365*	*1950-1964*	*Sangamon River at Mahomet*
5-5715	47.3	1951-1959	Goose Creek near Deland
5-5720	*550*	*1950-1964*	*Sangamon River at Monticello*
5-5725	750	1951-1964	Sangamon River near Oakley
5-5740	10.8	1950-1964	South Fk., Sangamon River near Nokomis
5-5745	*276*	*1950-1964*	*Flat Branch near Taylorville*
5-5755	510	1950-1961	South Fk., Sangamon River at Kincaid
5-5760	*809*	*1950-1964*	*South Fk., Sangamon River near Rochester*
5-5765	2560	1914-1956	Sangamon River at Riverton
5-5775	*107*	*1950-1964*	*Spring Creek near Springfield*
5-5785	*334*	*1950-1964*	*Salt Creek near Rowell*
5-5795	*207*	*1950-1964*	*Lake Fork near Cornland*
5-5800	*227*	*1950-1964*	*Kickapoo Creek at Waynesville*
5-5805	*306*	*1950-1964*	*Kickapoo Creek near Lincoln*
5-5815	*335*	*1950-1964*	*Sugar Creek near Hartsburg*
5-5820	*1800*	*1950-1964*	*Salt Creek near Greenview*
5-5825	*28.7*	*1950-1964*	*Crane Creek near Easton*
5-5830	*5120*	*1950-1964*	*Sangamon River near Oakford*

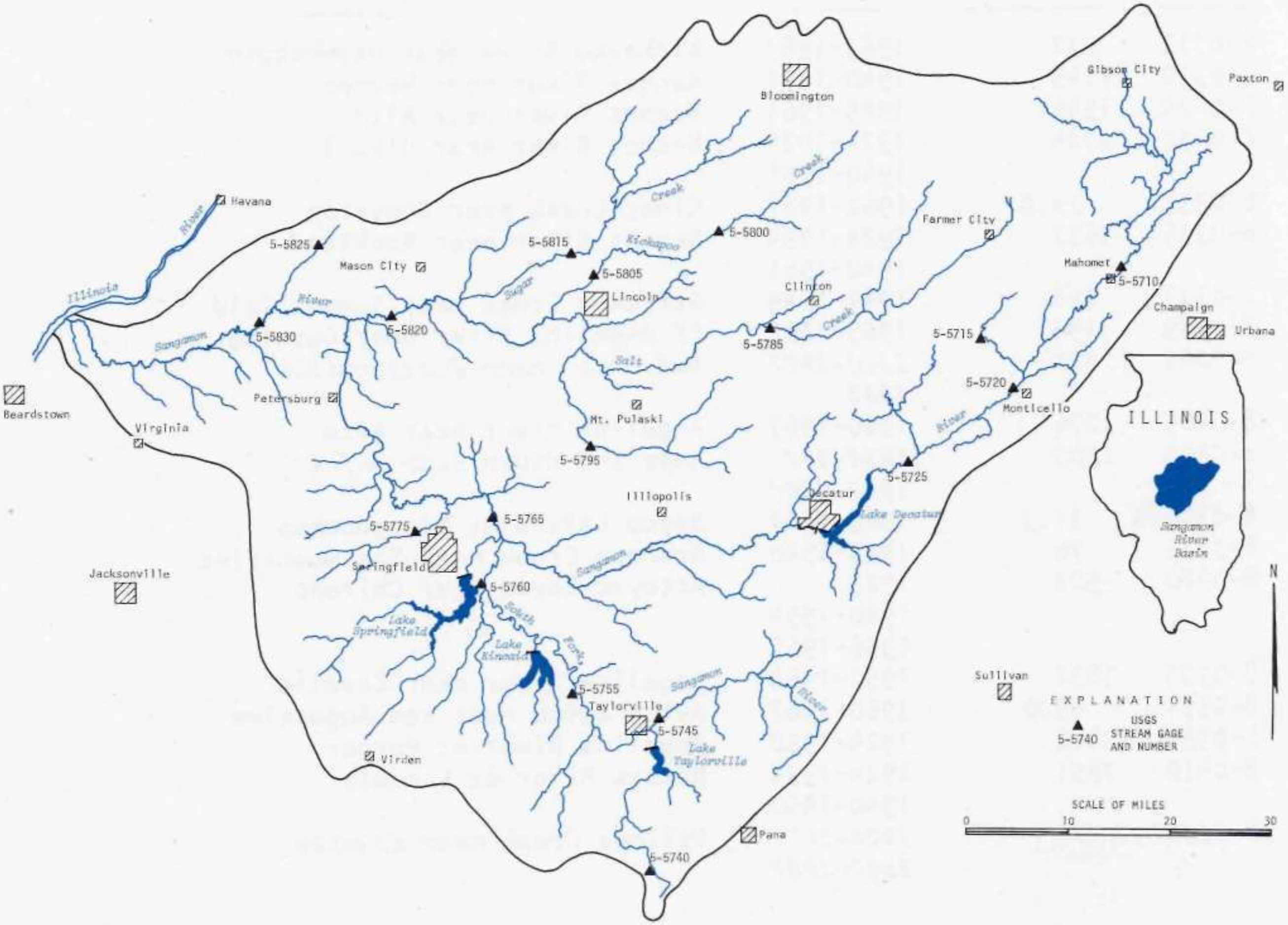

Figure 22. Sangamon River Basin

Table 20. Neches River Basin, Texas

List of 19 stations and periods used for flow duration
All records adjusted to the 28-year standard period, water years 1940-1967
(Index stations shown in *italics*)

USGS number	Drainage area (*sq mi*)	Water years	Station
8-0312	232	1963-)967	Kickapoo Creek near Brownsboro
8-0320	1145	1940-1961	Neches River near Neches
8-0325	1945	1945-1961	Neches River near Alto
8-0330	2724	1924-1925 1940-1961	Neches River near Diboll
8-0333	79.0	1962-1967	Piney Creek near Groveton
8-0335	3637	1924-1934 1940-1961	Neches River near Rockland
8-0337	148	1941-1949	Stricker Creek near Summerfield
8-0339	158	1965-1967	EF Angelina River near Cushing
8-0345	*376*	*1940-1967* *1943*	*Mud Creek near Jacksonville*
8-0365	1276	1960-1967	Angelina River near Alto
8-0370	*1600*	*1924-1934* *1940-1967*	*Angelina River near Lufkin*
8-0370.5	31.3	1965-1967	Bayou LaNana at Nacogdoches
8-0375	76	1939-1940	Arenoso Creek near San Augustine
8-0380	503	1925 1940-1954 1956-1967	Attoyac Bayou near Chireno
8-0385	3892	1952-1964	Angelina River near Zavalla
8-0391	89.0	1960-1967	Ayish Bayou near San Augustine
8-0395	3486	1924-1950	Angelina River at Horger
8-0410	7951	1924-1934 1940-1950	Neches River at Evadale
8-0415	*860*	*1925-1927* *1940-1967*	*Village Creek near Kountze*

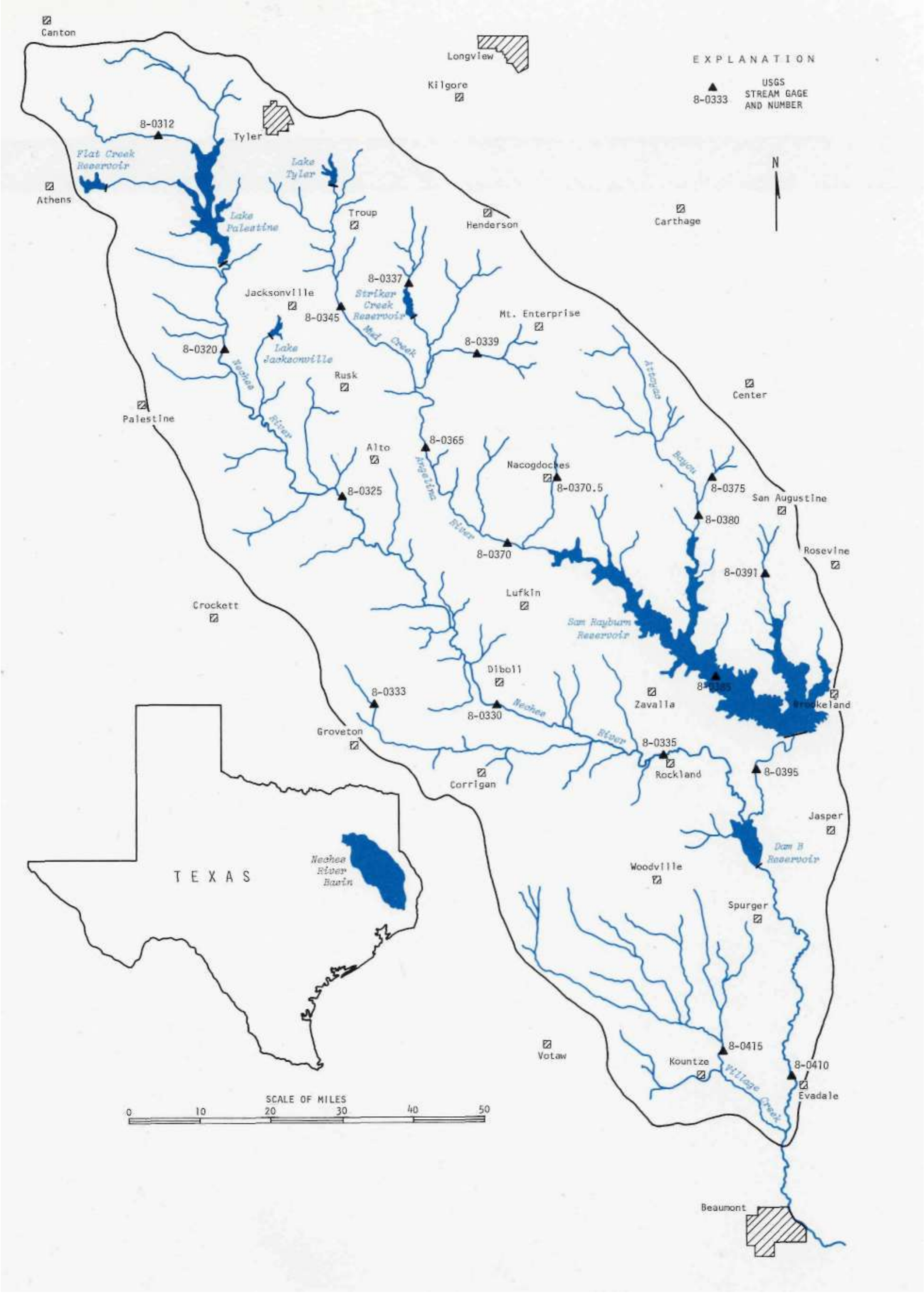

Figure 23. Neches River Basin

Table 21. Upper Colorado River Basin, Colorado

List of 38 gaging stations and periods used for flow duration
All records adjusted to the 50-year standard period, water years 1911-1960
(Index stations shown in *italics*)

USGS number	Drainage area (*sq mi*)	Water years	Station
9-0115	1.3	1951-1955	Little Columbine Creek above Shadow Mountain Reservoir at Grand Lake
9-0195	323	1936-1948	Colorado River near Granby
9-0200	105	1934-1953	Willow Creek near Granby
9-0205	128	1954-1960	Willow Creek above Willow Creek Reservoir
9-0325	50.7	1935-1950	Ranch Creek near Tabernash
9-0330	7.0	1938-1956	Meadow Creek near Tabernash
9-0345	825	1905-1909 1911-1924 1926-1928 1930-1948	Colorado River at Hot Sulphur Springs
9-0365	13.7	1943-1952	Keyser Creek near Leal
9-0375	184	1905-1924 1934-1939	Williams Fork near Parshall
9-0400	76	1938-1943 1954-1966	East Fork Troublesome Creek near Troublesome
9-0405	178	1905 1922-1924 1938-1956	Troublesome Creek near Troublesome
9-0445	1.95	1954-1956	Bemrose Creek near Hoosier Pass
9-0455	5.23	1954-1958	Spruce Creek near Breckenridge
9-0470	*129*	*1911-1960*	*Blue River at Dillon*
9-0505	113	1911-1919 1930-1960	Tenmile Creek at Dillon
9-0520	15.8	1943-1956	Rock Creek near Dillon
9-0525	9.7	1943-1951	Boulder Creek near Dillon
9-0535	511	1944-1962	Blue River above Green Mountain Reservoir
9-0580	2382	1915-1917 1962-1966	Colorado River near Kremmling
9-0587	2.94	1965-1966	Freeman Creek near Minturn
9-0595	86.2	1945-1966	Piney River near State Bridge
9-0605	47.6	1953-1966	Rock Creek near Toponas
9-0609	5.88	1956-1960	Catamount Creek near Burns
9-0610	10	1953-1958	Sunnyside Creek near Burns
9-0635	28.6	1914-1921 1945-1956	Turkey Creek at Red Cliff
9-0645	58.3	1911-1918 1945-1965	Homestake Creek near Red Cliff
9-0675	650	1911-1924	Eagle River at Eagle
9-0680	69.7	1951-1966	Brush Creek near Eagle
9-0700	944	1947-1966	Eagle River below Gypsum
9-0705	4394	1943-1966	Colorado River near Dotsero
9-0725	*4560*	*1900-1966*	*Colorado River at Glenwood Springs*

Table 21 (Continued)

USGS number	Drainage area (*sq mi*)	Water years	Station
9-0755	223	1915-1917	Roaring Fork below Aspen
9-0785	42	1911-1916 1948-1966	North Fork Fryingpan River near Norrie
9-0800	175	1911-1920	Fryingpan River at Thomasville
9-0816	167	1956-1966	Crystal River above Avalanche Creek near Redstone
9-0825	220	1936-1963	Crystal River near Redstone
9-0845	8.0	1946-1947	Fourmile Creek near Carbondale
9-0850	1451	1906-1909 1911-1929	Roaring Fork at Glenwood Springs

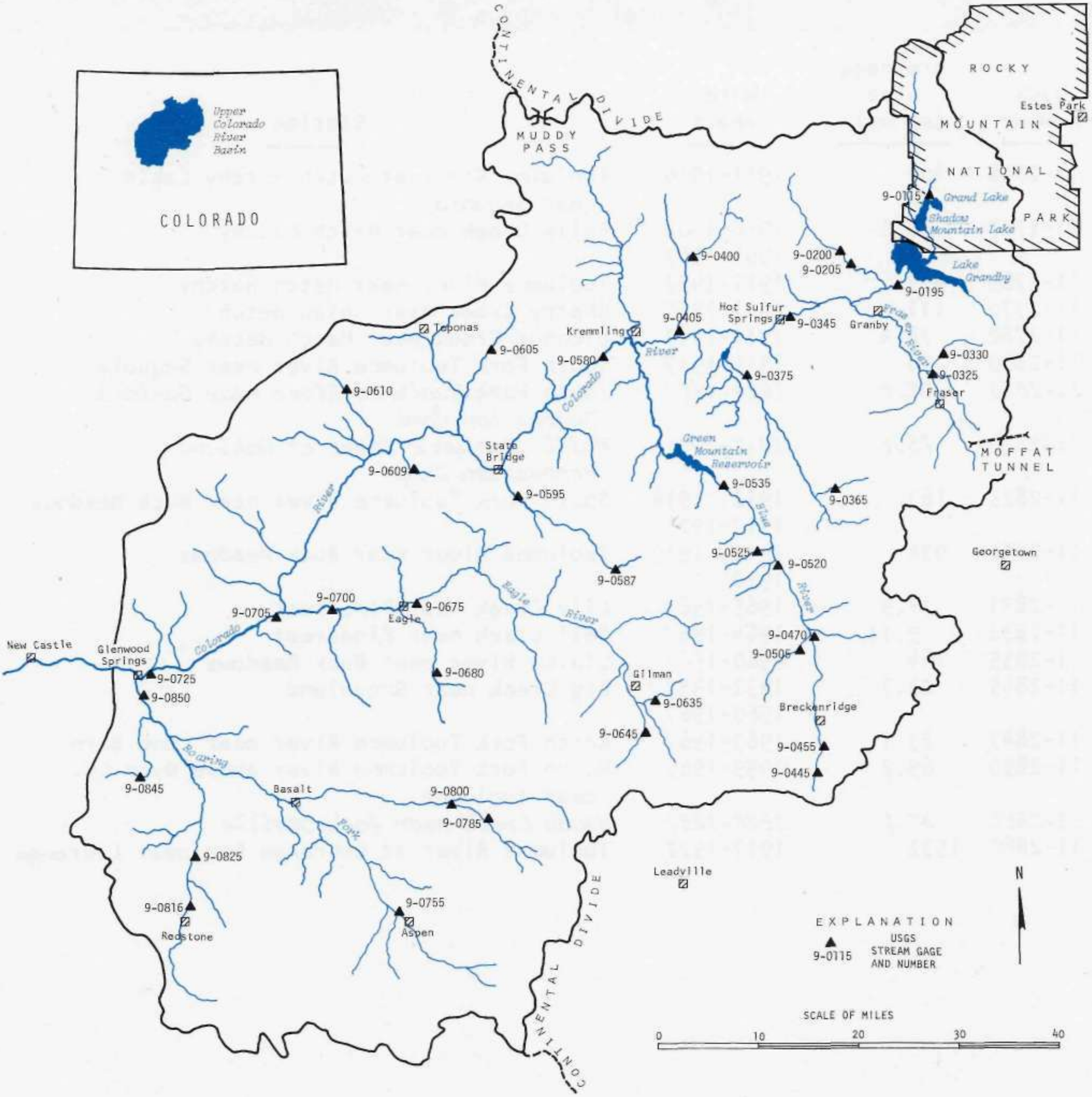

Figure 24. Upper Colorado River Basin

Table 22. Tuolumne River Basin, California

List of 18 stations and periods used for flow duration
All records adjusted to the 42-year standard period, water years 1926-1967
(Index stations shown in *italics*)

USGS number	Drainage area (*sq mi*)	Water years	Station
11-2748	404	1911-1916	Tuolumne River at Hetch Hetchy Cabin near Sequoia
11-2750	46.0	1916-1962 1964-1967	Falls Creek near Hetch Hetchy
11-2765	457	1911-1922	Tuolumne River near Hetch Hetchy
11-2770	111	1911-1955	Cherry Creek near Hetch Hetchy
11-2780	78.4	1911-1917	Eleanor Creek near Hetch Hetchy
11-2800	70	1915-1917	South Fork Tuolumne River near Sequoia
11-2810	*87.0*	*1924-1967*	*South Fork Tuolumne River near Oakland Recreation Camp*
11-2820	*73.5*	*1917-1967*	*Middle Tuolumne River at Oakland Recreation Camp*
11-2825	163	1912, 1914 1917-1921	South Fork Tuolumne River near Buck Meadows
11-2830	934	1911, 1913 1922	Tuolumne River near Buck Meadows
11-2831	11.9	1965-1967	Lily Creek near Pinecrest
11-2832	9.11	1964-1967	Bell Creek near Pinecrest
11-2835	144	1960-1967	Clavey River near Buck Meadows
11-2845	24.7	1932-1933 1960-1967	Big Creek near Groveland
11-2847	23.1	1963-1967	North Fork Tuolumne River near Long Barn
11-2850	69.2	1959-1966	North Fork Tuolumne River above Dyer Cr. near Tuolumne
11-2865	*97.2*	*1926-1967*	*Woods Creek near Jacksonville*
11-2880	1532	1917-1922	Tuolumne River at LaGrange Dam near LaGrange

Figure 25. Tuolumne River Basin

Table 23. Skagit River Basin, Washington

List of 39 gaging stations and periods used for flow duration
All records adjusted to the 37-year standard period, water years 1931-1967
(Index stations shown in *italics)*

USGS number	Drainage area (*sq mi*)	Water years	Station
12-1705	357	1935-1955	Skagit River near Hope, B. C.
12-1710	129	1944-1947	Lightning Creek near Newhalem
12-1715	638	1941-1945	Skagit River above Devils Creek near Newhalem
12-1720	63.2	1941-1948 1963-1967	Big Beaver Creek near Newhalem
12-1725	765	1931-1939	Skagit River near Newhalem
12-1735	206	1949-1956 1963-1967	Ruby Creek below Panther Creek near Newhalem
12-1740	203	1931-1948	Ruby Creek near Newhalem
12-1745	978	1920-1930	Skagit River below Ruby Creek near Newhalem
12-1754	91.7	1958-1962	Thunder Creek below McAllister Creek near Newhalem
12-1755	*105*	*1931-1967*	*Thunder Creek near Newhalem*
12-1760	111	1920-1930	Thunder Creek near Marblemount
12-1770	1100	1918-1922	Skagit River at Reflector Bar near Newhalem
12-1775	22	1934-1967	Stetattle Creek near Newhalem
12-1780	1175	1922	Skagit River at Newhalem
12-1781	27.9	1962-1967	Newhalem Creek near Newhalem
12-1800	50	1944-1950	Bacon Creek near Marblemount
12-1811	2.36	1962-1967	South Fork Cascade River at South Cascade Glacier near Marblemount
12-1812	0.078	1965, 1967	Salix Creek at South Cascade Glacier near Marblemount
12-1820	140	1911	Cascade River near Marblemount
12-1825	*168*	*1929-1967*	*Cascade River at Marblemount*
12-1835	13.2	1945-1947	Jordon Creek at Marblemount
12-1850	76	1918-1920	North Fork Sauk River near Barlow Pass
12-1855	32.7	1918-1920 1930-1931	South Fork Sauk River near Barlow Pass
12-1860	*152*	*1918-1920* *1922* 1929-1967	*Sauk River above Whitechuck River near Darrington*
12-1875	293	1918-1922 1929-1932	Sauk River at Darrington
12-1885	30.4	1944-1946	Big Creek near Mansford
12-1890	335	1939-1949	Suiattle River near Mansford
12-1895	*714*	*1929-1967*	*Sauk River near Sauk*
12-1900	24.5	1944-1947	Jackman Creek near Concrete
12-1915	211	1912-1913 1915 1917-1925 1929-1931	Baker River below Anderson Creek near Concrete
12-1918	8.36	1964-1967	Sulphur Creek near Concrete

Table 23 (Continued)

USGS number	Drainage area (*sq mi*)	Water years	Station
12-1945	55	1945-1948	Finney Creek near Washington
12-1960	10.7	1944-1967	Alder Creek near Hamilton
12-1962	6.56	1964-1967	Day Creek below Day Lake near Lyman
12-1964	32.3	1963-1967	Day Creek near Hamilton
12-1965	34.2	1944-1961	Day Creek near Lyman
12-1990	2970	1918-1922	Skagit River near Sedro Woolley
12-1998	3.56	1963-1967	East Fork Nookachamps Creek near Big Lake
12-2000	20.5	1944-1950 1963	East Fork Nookachamps Creek near Clear Lake

Figure 26. Skagit River Basin

Table 24. Snake River Basin, Wyoming and Idaho

List of 20 stations and periods used for flow duration
All records adjusted to the 31-year standard period, water years 1925-1955
(Index stations shown in *italics*)

USGS number	**Drainage area (*sq mi*)**	**Water years**	**Station**
13-0115	160	1945-1967	Pacific Creek near Moran, Wyo.
13-0119	355	1966-1967	Buffalo Fork above Lava Creek near Moran, Wyo.
13-0120	378	19^{2}»5-1960	Buffalo Fork near Moran, Wyo.
13-0145	622	1945-1955	Gros Ventre River at Kelly, Wyo.
13-0183	10	1963-1967	Cache Creek near Jackson, Wyo.
13-0195	564	1946-1955	Hoback River near Jackson, Wyo.
13-0225	3465	1954-1967	Snake River above reservoir near Alpine, Wyo.
13-0230	448	1954-1967	Greys River above reservoir near Alpine, Wyo.
13-0235	3940	1945-1953	Snake River below Greys River at Alpine, Wyo.
13-0240	47.8	1938-1955	Salt River near Smoot, Wyo.
13-0250	*27.4*	*1943-1967*	*Swift Creek near Afton, Wyo.*
13-0255	115	1947-1949 1962-1967	Crow Creek near Fairview, Wyo.
13-0260	103	1947-1949	Stump Creek near Auburn, Wyo.
13-0295	108	1954-1960	McCoy Creek above reservoir near Alpine, Idaho
13-0300	36.8	1954-1960	Indian Creek above reservoir near Alpine, Idaho
13-0305	59.2	1954-1960	Elk Creek above reservoir near Irwin, Idaho
13-0315	5110	1940-1941	Snake River at Calamity Point near Irwin, Idaho
13-0320	77.1	1954-1967	Bear Creek above reservoir near Irwin, Idaho
13-0325	5225	1950-1955	Snake River near Irwin, Idaho
13-0375	*5752*	*1925-1955*	*Snake River near Heise, Idaho*

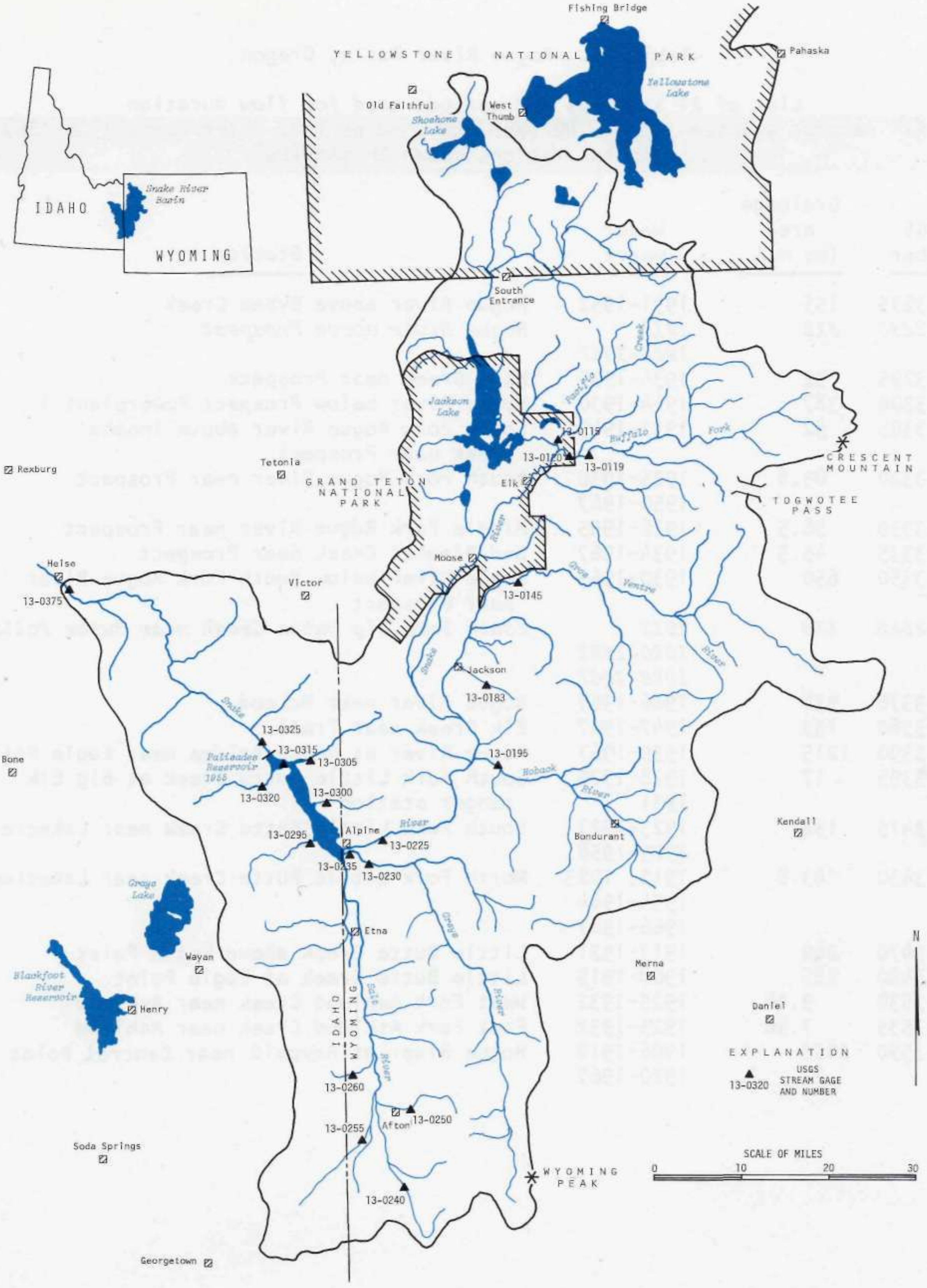

Figure 27. Upper Snake River Basin

Table 25. Rogue River Basin, Oregon

List of 21 stations and periods used for flow duration
All records adjusted to the 42-year standard period, water years 1926-1967
(Index stations shown in *italics*)

USGS number	Drainage area (*sq mi*)	Water years	Station
14-3275	155	1931-1952	Rogue River above Bybee Creek
14-3280	*312*	*1911* *1925-1967*	*Rogue River above Prospect*
14-3295	32	1934-1935	Mill Creek near Prospect
14-3300	387	1914-1930	Rogue River below Prospect Powerplant 1
14-3305	52	1932-1949	South Fork Rogue River above Imnaha Creek near Prospect
14-3320	83.8	1925-1930 1950-1967	South Fork Rogue River near Prospect
14-3330	56.5	1926-1955	Middle Fork Rogue River near Prospect
14-3335	45.5	1934-1967	Red Blanket Creek near Prospect
14-3350	650	1930-1965	Rogue River below South Fork Rogue River near Prospect
14-3355	*138*	*1911* *1920-1922* *1926-1967*	*South Fork Big Butte Creek near Butte Falls*
14-3376	938	1966-1967	Rogue River near McLeod
14-3380	133	1947-1967	Elk Creek near Trail
14-3390	1215	1939-1967	Rogue River at Dodge Bridge near Eagle Point
14-3395	17	1928-1929 1931	South Fork Little Butte Creek at Big Elk ranger station
14-3415	138	1923-1927 1929-1958	South Fork Little Butte Creek near Lakecreek
14-3430	43.8	1912, 1923 1934-1964 1966-1967	North Fork Little Butte Creek near Lakecreek
14-3470	269	1917-1921	Little Butte Creek above Eagle Point
14-3480	285	1908-1915	Little Butte Creek at Eagle Point
14-3530	9.48	1925-1932	West Fork Ashland Creek near Ashland
14-3535	7.96	1925-1932	East Fork Ashland Creek near Ashland
14-3590	2053	1906-1918 1920-1967	Rogue River at Raygold near Central Point

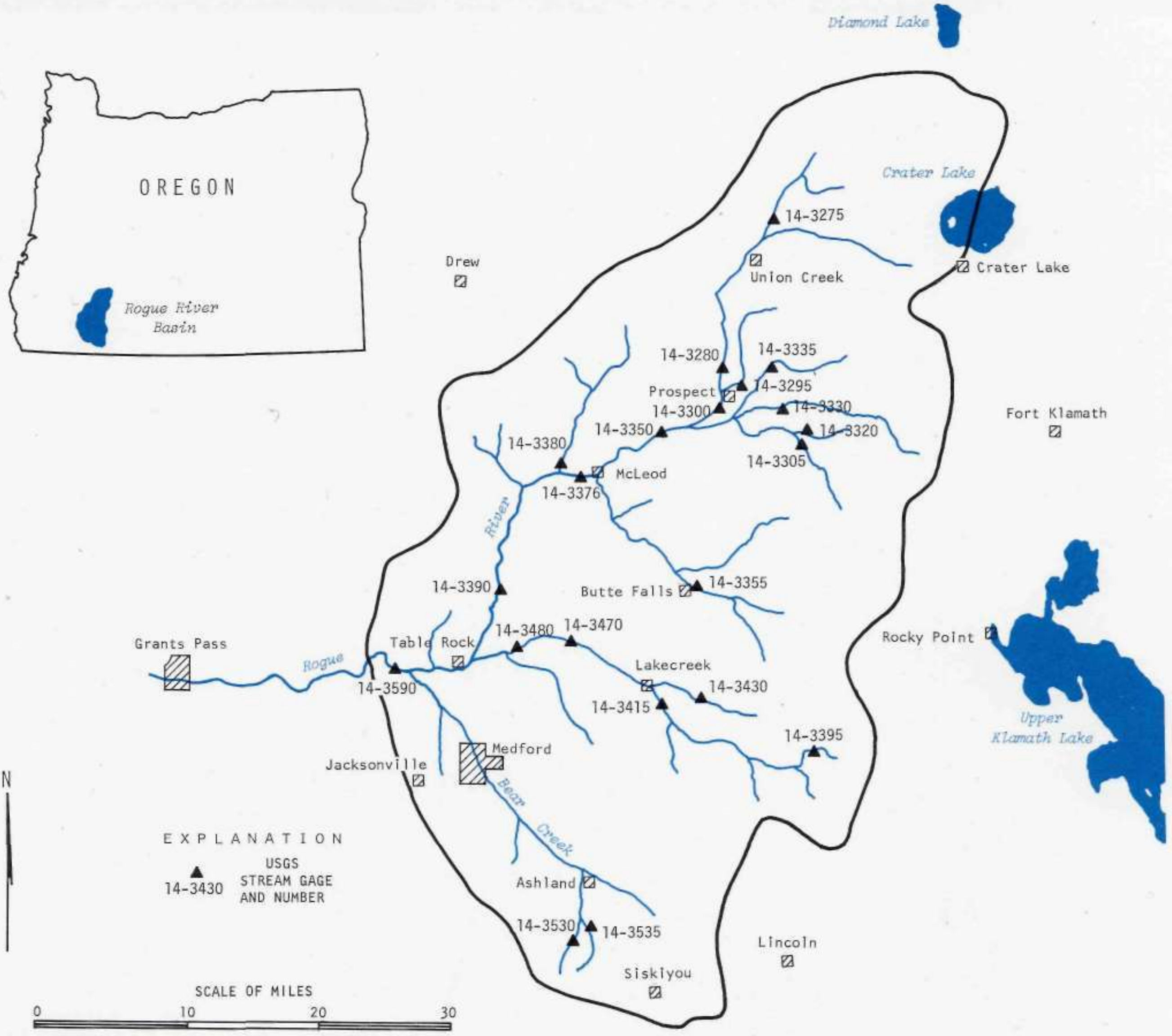

Figure 28. Upper Rogue River Basin