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GEOLOGICAL SURVEY
W. C. Mendenhall, Director

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STUDIES OF RELATIONS OF RAINFALL AND RUN-OFF IN THE UNITED STATES

BY

W. G. HOYT AND OTHERS

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STUDIES OF RELATIONS OF RAINFALL AND RUN-OFF IN THE UNITED STATES

By W. G. Hoyt and others

Foreword

Human relations to the waters of the earth have developed from a simple but very significant status in the haphazard life of primeval man to a complex and often economically limiting status in connection with the present-day activities of a highly organized civilization.

The present wide scope of the uses of water for domestic supply, power development, irrigation, navigation, and recreation and the extensive human activities for protection against floods, drainage of wet lands, control of erosion, and control of pollution are generally accepted as matters of course. It is notable, nevertheless, that the severe drought, which persisted for about 5 years from 1930 to 1934 including the disastrous summer of 1934 has impressed on many people as never before the essential character and the importance of our water resources.

As a consequence the attention not only of Federal and State Governments but of the people as a whole is being turned to an evaluation of water that embraces not only its use and control in the common ways above mentioned but its conservation to a degree and through broad policies never before considered. Heretofore, except of course for the great interest of farmers in rain, the popular and generally recognized interest in water has tended to begin at the time when it has appeared in the surface streams or has become stored in the ground. But the failing streams of drought-affected regions and the disastrous erosive action of waters before they reach well-defined watercourses have notably quickened the regard for the uses and control of water at an earlier stage in the complex cycle through which it passes after its occurrence as rain.

After precipitation, and before it finally reaches well-defined stream channels, water is subjected to the action of numerous agencies, including ground and water-surface evaporation, transpiration in plant and tree growth, infiltration and absorption by the ground, passage through the shallow storage upon ill-drained lands, and surface run-off through systems of trickles and streamlets. The importance of the subtractions from precipitation before it becomes stream flow may be illustrated by statement of the fact that to produce 1 pound of dry vegetable substance of a growing plant several hundred pounds of water is taken up from the soil by the roots of the plant, passes through the growing plant tissues, and then evaporates into the air from the leaf surfaces. Thus to obtain satisfactory crop yields many inches of water over the crop-producing area must be used in this way. It is evident, therefore, that in arid and semiarid regions, and indeed in humid regions in times of drought, the flow of surface streams constitutes a surprisingly small part of the water initially falling as rain.

The conservation of even a small part of the precipitation that under present conditions does not reach the streams may be extremely desirable and important, provided it is practicable and economical. Much more trustworthy information than now available concerning rainfall, run-off, and related factors is desirable for wise planning of water conservation and utilization. There is also need for investigating those factors which are alleged to have caused some regions, within the period of apparent human occupancy, to change at least temporarily in their degree of aridity or humidity.

Early in its consideration of Public Works water projects, the Mississippi Valley Committee realized the great need for more information on the conditions affecting rainfall, run-off, and related factors. It was recognized that to a great extent the available climatic and hydrologic data have never been adequately analyzed with a view to deducing the particular knowledge that would be helpful. Moreover, it was believed that such broad fundamental questions were largely outside the field in which private individuals and institutions could generally be active and hence were especially suited to investigation by an agency or agencies of the Federal Government.

It was with an appreciation of the need and opportunity thus afforded that the present studies were undertaken. The studies were authorized and directed by the Mississippi Valley Committee of the Emergency Administration of Public Works, now the Water Planning Committee of the National Resources Board, and the work was done by the United States Geological Survey. Most valuable and helpful advice has been received from a special committee of the Section of Hydrology of the American Geophysical Union. The objective has been primarily the presentation of facts, generally elementary and basic, as disclosed by observed data or by their simple analysis. It is believed that the results contained in this report present much fundamental information, an understanding of which is essential to adequate long-time planning and execution of projects for the use and control of the water resources of the country.

The Mississippi Valley Committee also found desirable a study of floods and, as a project, that study was combined with the study of the relations of rainfall, run-off, and related factors. Both investigations have been carried forward concurrently with unified control and supervision, yet with the requisite independence of approach to call forth the best efforts of the separate groups at work. The results of the flood study are contained in another report to be published as Water-Supply Paper 771.

Harlan H. Barrows
Herbert S. Crocker
Glen E. Edgerton
Henry S. Graves
Edward M. Markham
Charles H. Paul
Sherman M. Woodward
Harlow S. Person (acting chairman)

Water Planning Committee of the National Resources Board, formerly Mississippi Valley Committee of the Federal Emergency Administration of Public Works.

Authorization

Late in 1933 and during the first few weeks of 1934 members of the scientific staff of the Geological Survey appeared before the Mississippi Valley Committee of the Federal Emergency Administration of Public Works to discuss certain aspects of hydrology, such as floods, droughts, and ground-water conditions, which had been found to be involved in the consideration of the numerous applications for Public Works projects in the Mississippi Valley presented to the committee for study and recommendation. These discussions emphasized the need of studies of available hydrologic and climatologic information, with a view to determining the implications of the data with respect to various questions of planning and design and to placing such information in a form in which it could be used and its value realized.

As a result of these conferences, the Mississippi Valley Committee recommended and obtained from the Public Works Administration late in February 1934 an allotment for studies of this character to be made in collaboration with the Geological Survey, under two headings - (1) the magnitude and frequency of floods and (2) rainfall, run-off, and related factors Formal authorization of the studies by the Geological Survey was contained in a letter of the Federal Emergency Administration of Public Works dated March 6, 1934.

Administration and personnel

Arrangements were made during March 1934 for the studies to be made in the water-resources branch of the Geological Survey under the general administrative supervision of N. C. Grover, chief hydraulic engineer, and under the direct administrative supervision of R. W. Davenport, chief of the division of water utilization. W. G. Hoyt was designated as the responsible head of the studies relating to rainfall, run-off, and related factors. In order to obtain the benefit of their special training and qualifications and to furnish an experienced nucleus for a staff of investigators two engineers and one geologist of the Survey were detailed to the studies. The remainder of the personnel were made up of temporary employees appointed by the Secretary of the Interior from the list of applicants eligible for appointment in connection with projects of the Public Works Administration. The personnel and periods worked up to the time the report was finished, June 30, 1935, are as follows:

Regular employees:

W. G. Hoyt, hydraulic engineer, one-half time, since March 1, 1934.

L. L. Harrold, assistant engineer, since March 8, 1934.

R. C. Cady, junior geologist, part time, since July 1, 1934.

Temporary employees:

Merrill M. Bernard, senior engineer, Crowley, La., part time, April 1, 1934, to May 15, 1935.

A. L. Alin, junior engineer, Portland, Oreg., March 21 to May 2, 1934.

Franklin F. Snyder, junior engineer, Columbus, Ohio, since April 16, 1934.

D. M. Paul, assistant clerk, Odebolt, Iowa, since March 12, 1934.

J. Paul Bowker, assistant clerk (computer), Washington, D. C., since October 24, 1934.

C. E. Kitchin, assistant clerk (computer), Hyattsville, Md., since October 25, 1934.

The division of work has been somewhat as follows:

Merrill M. Bernard has devoted his time almost exclusively to the application of the unit hydrograph and distribution graph to the analysis of flood flows and wrote the discussion "The unit-hydrograph method and storm transposition in flood problems." Mr. Bernard brought to the studies a wealth of original experience in analyzing storm precipitation of high intensity and his knowledge of the unit graph devised by L. K. Sherman and more especially the distribution graph and the pluviagraph devised by himself.

L. L. Harrold in the early part of the studies devoted a large part of his time to the study of ground-water flow, soil moisture, and related matters - subjects which he had been previously investigating. Later he carried on and supervised work of the general computation in connection with precipitation, temperature, and run-off trends and relations.

Franklin F. Snyder, in addition to routine computation, spent a very considerable portion of his time in analyzing the fundamentals of the unit hydrograph, distribution graph, and pluviagraph, methods of presentation, and possibilities of application, and he has prepared much of the text relating to these subjects.

R. C. Cady, as a member of the staff of the ground-water division, devoted much of his time to the determination of ground-water flow from the hydrograph of total stream flow and the study of relations between ground-water flow, water-table level, precipitation, and related factors.

Messrs. Paul, Alin, Bowker, and Kitchin have assisted in general compilations, preparation of charts, and clerical activities.

Advisory coordination

The Water Planning Committee of the National Resources Board and its predecessor the Mississippi Valley Committee maintained contact with the studies through Prof. Sherman W. Woodward, of the University of Iowa, member of the Mississippi Valley Committee, and Prof. Thorndike Saville, of New York University, executive engineer of the Water Resources section. In addition the Section of Hydrology of the American Geophysical Union, at the request of the chairman of the Mississippi Valley Committee, appointed during May 1934 the following engineers and hydrologists as a committee of advisers and consultants:

Wesley W. Horner, consulting engineer, St. Louis, Mo. (chairman).

A. F. Meyer, consulting engineer, Minneapolis. Minn.

G. W. Pickels, professor, University of Illinois, Urbana, Ill.

L. K. Sherman, president, Randolph-Perkins Co., Chicago, Ill.

Roy Towl, mayor, Omaha, Nebr.

J. W. Woerman, senior civil engineer, U. S. Engineer's Office, Chicago, Ill.

R. E. Horton, consulting engineer, Voorheesville, N. Y., was added to this advisory committee in January 1935.

Since May 1934, some of the members of this committee have been in continuous contact with the studies, either personally or through correspondence, and generous acknowledgment is due and here given for the valuable assistance thus rendered.

Observations and recommendations of the committee of the Section of Hydrology have been freely referred to throughout the text of this report, and a statement by the committee is presented as an appendix. All compilations of records and various memoranda prepared by the Geological Survey staff have been made available to the committee members. The material has been the subject of correspondence between the committee members and of conferences and correspondence between certain of the members of the committee and members of the Survey staff.

Nearly all compiled records and memoranda have also been sent to each member of the Flood Protection Data Committee of the American Society of Civil Engineers appointed to advise in the flood studies, the membership of which is as follows:

Gerard H. Matthes, principal engineer, office of the president, Mississippi River Commission, Vicksburg, Miss. (chairman).

Frederick H. Fowler, consulting engineer, San Francisco, Calif.

Robert E. Horton, consulting engineer, Voorheesville, N. Y.

Ivan E. Houk, senior engineer, U. S. Bureau of Reclamation, Denver, Colo.

Charles W. Sherman, consulting engineer, Boston, Mass.

C. W. Kutz, Brigadier-General, U. S. Army (retired). Washington, D. C.

Daniel C. Walser, vice president, Charles B. Hawley Engineering Corporation, Washington, D. C.

Although this committee as a whole has not made definite recommendations with respect to the studies of rainfall in relation to run-off, pertinent comments have been received from individual members.

Acknowledgments

The staff engaged on the rainfall and run-off studies have received encouragement, advice, and criticism from so many sources that full acknowledgment and credit are difficult. Throughout the studies Messrs. Grover and Davenport for the water-resources branch and Professors Woodward and Saville for the Mississippi Valley Committee and the Water Planning Committee have been in close touch with the progress of the work and have been a continuing source of advice and encouragement. In a very large measure the methods of attacking the problems have been developed as a result of the frequent personal contacts, conferences, and exchange of correspondence with members of the committee of the Section of Hydrology, more especially its chairman, Mr. Horner, and Messrs. Sherman, Meyer, and Horton. O. E. Meinzer, chief of the division of ground water, water-resources branch, and members of his staff have made helpful suggestions. Acknowledgment is due the U. S. Weather Bureau, the records of which have been used freely in this report, and special acknowledgment is due J. B. Kincer, chief, Division of Climate and Crop Weather, for his cordial and helpful cooperation.

Previous studies

Among the first attempts in this country to determine the relations between rainfall and run-off were those made in the early 1890's by F. H. Newell, Henry Gannett, and C. C. Babb, of the United States Geological Survey. On the basis of very meager rainfall and run-off data, Newell, in the Fourteenth Annual Report (1892) of the Geological Survey, presented two curves showing the relation between mean annual precipitation and mean annual run-off - one for mountainous regions, the other for streams draining basins having broad valleys. The same report also contains rainfall and run-off maps of the United States. Henry Gannett later prepared more detailed maps of the United States, on one of which were shown lines of equal annual rainfall and on another lines of equal annual run-off. These maps had wide circulation and have been reproduced as late as 1928 (122, fig. 180).* Gannett was among the first of those in the United States to study run-off as a residual of rainfall after losses. Maps similar to those prepared by Gannett but based on much more information have recently been prepared by the Water Resources Section of the National Resources Board and are contained in the report of the Mississippi Valley Committee of the Public Works Administration dated October 1, 1934, and also in the report of the National Resources Board dated December 1, 1934 (obtainable from the Superintendent of Documents, Washington).

C. C. Babb, in 1893 (3), presented curves showing monthly run-off in terms of percentage of annual run-off, the annual run-off being computed as a percentage of the annual precipitation. The year previous, Desmond Fitzgerald presented a paper (39) in which run-off, in terms of a percentage of rainfall, is discussed.

In 1903, George W. Rafter, after many years of study on the problem, presented a report (141) on the relation of run-off to rainfall. He discussed previous studies, including that of C. C. Vermeule in New Jersey. Vermeule (187) in an attempt to express the relation between rainfall and run-off, used a constant plus a percentage for the several months of the year and varied the relation with the mean annual temperature. Rafter presented curves showing the general relation between rainfall and run-off for

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* Numbered citations in parentheses refer to the list of references at the end of this paper.

three periods of the year, designated by him the storage period (December to May), growing period (June to August), and replenishing period (September to November). He drew numerous general conclusions, of which one was as follows (141, p. 81): "There is no general expression giving accurately the relationship of rainfall to run-off. The run-off of a stream is affected by so many complex elements that the data are lacking for final conclusions. Every stream is in effect a law unto itself. An empirical formula may, however, be made which will give for some streams approximately the run-off for a series of years."

D. W. Mead in 1904 brought together in a single treatise (109), for the first time in the United States, information available as of that date on the fundamental phenomena of hydrology. These notes were superseded in 1919 by his complete textbood entitled "Hydrology, the fundamental basis of hydraulic engineering" (111).

In 1914 J. D. Justin (86) expressed the annual run-off by a product consisting of a coefficient (which varied with slope and mean annual temperature) multiplied by the square of the annual rainfall.

A. F. Meyer in 1915 presented a comprehensive paper entitled "Computing run-off from rainfall and other physical data" (121), and in 1917 published his textbook "Elements of hydrology" an enlarged second edition of which was published in 1928 (122). Meyer, like Gannett, considered run-off a residual of rainfall after all losses had been deducted. He established curves by which the evaporation and transpiration from various drainage basins could be determined. Meyer's paper made a great advance over any previous study, in that he undertook to ascertain in rational ways the losses from precipitation after it reaches the ground, in order to determine run-off.

The technical reports of the Miami Conservancy District, published in 1921, especially part 8, "Rainfall and run-off in the Miami Valley" (72), by Ivan E. Houk, presented a great advance in the knowledge of rainfall and run-off relations. Of special interest was Houk's study of absorption rates and the distribution of stream flow into two parts - surface run-off and ground-water run-off - and quantitative analysis of the hydrologic cycle.

Results of studies made by John F. Hayford concerning the relations between rainfall and run-off, under the auspices of the Carnegie Institution of Washington, were published in 1929, 4 years after his death (57). The studies continued over several years and were, so far as known, the most exhaustive yet made in an attempt to express mathematically the factors influencing daily stream flow. Hayford considered stream flow in two parts - "normal stream flow," or that portion derived from ground water, and "flood run-off," or the portion above the normal flow. The results indicated that so many constants must be determined in connection with any drainage basin that the studies are apparently not suited to practical application, although they are of considerable scientific interest.

In 1932 W. T. Collins and Franklin F. Snyder, students at Ohio State University, prepared a thesis (31) in which they derived formulas for expressing the mean monthly flow of certain Ohio streams, using a method of approach similar to that used by Professor Hayford. Reasonable agreement was reached between the computed flow and the observed flow for the particular streams and periods used in determining the several constants.

In 1932 L. K. Sherman (158) presented the idea that surface run-off from rainfall occurring within the same time interval, such as a day or an hour, may be expressed in unit hydrographs having equal bases on the time axis, the ordinates varying with the intensity of the rainfall.

In 1934 Merrill M. Bernard presented a paper (13) which develops certain features of the unit hydrograph and introduces the distribution graph and pluviagraph. The concepts developed by Sherman and Bernard provide a new approach to the analysis of the relation between precipitation and surface run-off.

In 1935 Robert E. Horton gave (70a) an analysis of the hydrograph describing and discussing "the natural processes involved in surface run-off quantitatively and in their natural sequence."

At the end of this report is a bibliography of papers, largely American, discussing relations between rainfall and run-off and related subjects, not including references relating to precipitation or run-off of high intensity. The bibliography is not complete with respect to the extensive and valuable literature on hydrology in foreign countries. Neither is it complete with respect to many articles and discussions which have been presented in the publications of the American Geophysical Union, American Society of Civil Engineers, American Water Works Association, New England Water Works Association, and other organizations, which can readily be found by reference to the indexes of these publications. Many of the authors of these papers have spent the greater part of their professional careers in a study of the intricate problems involved in the hydrologic cycle, and comments on the results of their studies would fill many volumes.

Aims of present study

The preceding brief discussion of previous studies, when read in connection with the partial bibliography, indicates that many minds have been engaged for a period of nearly 50 years in an attempt to determine and express the relations between rainfall and run-off. Although great progress has been made, there are many relations that still remain obscure. Early in the present study it was decided that in the light of prior investigations it was unwise to undertake a broad general study for the purpose of developing empirical formulas for expressing relations between rainfall and mean annual, monthly, or daily run-off. The study was directed, instead, along two rather definite lines of approach - (1) investigation of relations between annual and monthly precipitation, temperature, evaporation, transpiration, direct surface run-off, ground-water run-off, and infiltration as a basis for the quantitative analysis of the hydrologic cycle over broad areas and of trends and changes therein; (2) investigation of relations between storm precipitation and direct surface run-off.

It was felt that the investigations thus outlined would be of immediate value to the Mississippi Valley Committee and its successor the Water Planning Committee in connection with consideration of problems involving the utilization and conservation of water and would also form a logical extension of past hydrologic studies. Such a study would not encroach on the field of experimental research that was being carried on by many organizations and individuals. Rather it would be an attempt to bridge the gap between the small experimental area under controlled and simple conditions and the larger river-system areas of multiple and complex conditions.

It was hoped that the study of trends in the relations disclosed between rainfall and run-off might throw some light on perplexing questions in any broad consideration of hydrologic and climatic factors which had been presented to the Mississippi Valley Committee in the projects submitted to it for consideration and recommendation. It was also the purpose of the study to disclose weaknesses and limitations in the application of the hydrologic and climatologic information and thus to be valuable in connection with the improvement or extension of fact-finding services engaged in collecting these basic data.

Precipitation*

Precipitation, or rainfall, is essentially the source of all water on the earth's surface and hence is commonly considered the starting point of the hydrologic cycle. A very considerable part of the present study has therefore been devoted to the investigation of precipitation with reference to annual and seasonal changes over broad areas, as well as to the study of the relation of precipitation to stream flow. Throughout the study of changes 10-year progressive averages have been generally used, and in the various diagrams the plotted points represent the average of the figures for the 10-year period ending with the year for which the point is plotted. The inherent limitation as to absolute accuracy of precipitation records is recognized and has been kept in mind in an attempt to avoid irrational and unsound use.

Precipitation records have been compiled for the purpose of determining within reasonable limits information concerning (1) possible changes in the precipitation over the continental United States as a whole since 1881; (2) possible changes over broad geographic provinces (a) on an annual basis and (b) on a seasonal basis; (3) possible changes over typical river basins; and (4) relations between annual precipitation and annual run-off.

Changes in precipitation in continental United States

Averages of precipitation by States are available from 1881 to 1934 and are published in Water-Supply Paper 680. There has been a progressive increase in the accuracy of the State averages as a result of the increase in the number of Weather Bureau stations, refinements of methods of recording, and better geographic distribution of the stations used to

* For the most recent map showing distribution of mean annual rainfall in the United States and variations from the mean together with a discussion of precipitation in general see section III of the Report of the Water Planning Committee to the Chairman of the National Resources Board dated November 15, 1934 (obtainable from the Superintendent of Documents, Washington, for $1.00).

compute the State averages. To a greater or less extent, also, similar increases in accuracy are shown by nearly all the basic data used in the present study. The relatively less reliability of the earlier data and greater reliability of the later data should be borne in mind in connection with any conclusions that may be drawn.

Because much of the country has had a period of deficient rainfall during the last few years the question naturally has been raised as to what changes in precipitation, if any, have taken place over the country as a whole during the last 55 years. The following table shows averages, weighted for area, of the mean annual precipitation by successive 5-year periods from 1881-85 to 1926-30 and for the 4-year period 1931-34. The figures were obtained by multiplying the mean annual precipitation computed for 5-year periods in each State by the area of the State in square miles, adding the products, and dividing the sum by the area of the United States in square miles.

Table 1.- Average annual precipitation over continental United States, by 5-year periods

(Area 3,026,719 square miles)

5-year period ending	Precipitation (inches)	Variation from average percent
1885	31.13	+ 6.50
1890	28.92	− 1.06
1895	28.02	− 4.14
1900	29.07	− .55
1905	29.52	+ .99
1910	29.82	+ 2.02
1915	30.24	+ 3.46
1920	29.21	− .07
1925	28.53	− 2.40
1930	29.43	+ .68
1934 (4 years)	27.63	− 5.47
	Average 29.23	

The computed average is probably somewhat small, owing to the inadequate distribution of stations in mountainous areas of the West.

This table seems to indicate that over the United States as a whole the variation shown on the basis of 5-year periods is relatively small when compared with variations for small areas or for individual stations. That the early eighties were, as here appears, years of extremely high precipitation is further indicated by data that follow. The early nineties and the early thirties were dry in many regions. The following study by broad areas indicates that country-wide changes tend to reflect in reduced degree wider departures that occur in different localities.

Changes in annual precipitation, by geographic provinces

In the study of changes in precipitation by basins or States information regarding direction of change and approximate magnitude was desired, rather than information as to amounts over wide areas; therefore, precipitation stations having the longest records in each State were selected as a basis for the analysis. Table 2 lists comparative data for the stations used.

Years of high precipitation

The long-time stations listed in table 2 are shown in figure 1 together with lines drawn to a time scale showing the year of maximum annual precipitation. Only four of the 22 stations for which records are available prior to 1850 - Hanover, N. H.; St. Paul, Minn.; Farmersburg, Iowa; and Cincinnati, Ohio, - recorded years of maximum precipitation prior to 1850, and only two more - Muscatine, Iowa (1851), and Santa Fe, N. Mex. (1854), - recorded years of maximum precipitation during the period 1850 to 1857. The first year in which five or more stations recorded maximum precipitation was 1858, when such records were made at Marietta, Ohio; Marengo and Peoria, Ill.; St. Louis, Mo.; Leavenworth, Kans.; and The Dalles, Oreg. The grouping of five of these six stations in the Central West indicates the probability that 1858 was a year of maximum precipitation in certain parts of that region. From 1859 to 1879 few stations recorded maximum annual precipitation. There was a wide-spread distribution of stations that recorded maximum annual precipitation during the eighties. The following list shows years in which five or more stations recorded maxima:

1882 Evansville, Ind.
Garrison, N. Dak.
Lexington, Ky.
Little Rock, Ark.
Louisville, Ky.
Portland, Oreg.
Spokane, Wash.

1884 Battle Mountain, Nev.
Havre, Mont.
Los Angeles, Calif.
Sacramento, Calif.
San Diego, Calif.
San Francisco, Calif.

1889 Baltimore, Md.
Lynchburg, Va.
New Brunswick, N. J.
Norfolk, Va.
Richmond, Va.

Table 2.- Precipitation at long-time Weather Bureau stations

Station	Period of record	Average annual (inches)	Maximum		Minimum		Maximum 10-yr.		Minimum 10-yr.	
			Year	% of average	Year	% of average	Period ending	% of average	Period ending	% of average
Alabama										
Mobile	1871-1934	61.61	1881	150	1904	64	1885	108	1910	94
Montgomery	1873-1934	51.19	1929	153	1931	67	1924	109	1904	92
Union Springs	1868-1934	50.72	1912	156	1927	59	1909	120	1881	85
Arizona										
Phoenix	1877-1934	7.78	1905	254	1924	39	1914	161	1929	82
Univ. Arizona	1868-1934	11.52	1905	210	1924	44	1884	119	1903	84
Yuma	1870-1934	3.47	1905	329	1928	14	1914	140	1904	57
Arkansas										
Fort Smith	1878-1934	38.85	1890	166	1917	51	1895	118	1919	82
Helena	1874-1934	53.47	1877	151	1918	67	1886	112	1904	86
Little Rock	1878-1934	48.38	1882	156	1924	65	1891	114	1925	90
California										
Indio	1878-1934	3.01	1927	262	1894	0	1921	133	1887	68
Los Angeles	1878-1934	15.23	1884	264	1898	32	1893	134	1903	73
Sacramento	1850-1934	17.95	1884	194	1932	37	1889	121	1932	69
San Diego	1850-1934	10.30	1884	268	1863	29	1893	120	1865	74
San Francisco	1850-1934	22.02	1884	176	1917	41	1887	116	1906 1932	86
Colorado										
Denver	1872-1934	14.05	1909	164	1911	55	1915	116	1904	90
Las Animas	1867-1934	12.41	1923	172	1894	22	1915	121	1897	72
Pueblo	1884-1934	11.67	1921	174	1934	50	1923	116	1934	91
Connecticut										
Canton	1859-1923	51.12	1866	157	1860	68	1872	117	1884	87
Delaware										
Bridgeville	1891-1934	42.78	1906	147	1930	60	1911	108	1918	93
Millsboro	1893-1934	43.90	1934	144	1930	57	1906 1907	107	1918	92
Florida										
Jacksonville	1867-1934	49.74	1885	165	1927	61	1887	118	1918	84
Key West	1870-1934	38.11	1870	183	1893	58	1884	113	1899	91
St. Augustine	1877-1934	47.97	1920	149	1911	66	1886	109	1918	89
Georgia										
Atlanta	1868-1934	48.27	1929	140	1904	69	1889	117	1934	89
Augusta	1869-1934	44.90	1929	164	1933	62	1881	113	1934	91
Rome	1866-1934	49.36	1932	157	1867	64	1920	114	1890	88
Idaho										
Boise	1868-1934	13.10	1871	197	1868	51	1879	121	1933	86
Moscow	1892-1934	23.08	1913	131	1911	48	1903	102	1931	88
Porthill	1890-1934	20.02	1893	193	1929	62	1901	134	1931	101
Illinois										
Chicago	1871-1934	32.86	1883	140	1934	69	1885	121	1901	90
Marengo	1856-1934	33.11	1858	152	1901	59	1885	109	1904	91
Peoria	1856-1934	34.89	1858	153	1910	66	1884	111	1894	91
Indiana										
Evansville	1877-1934	43.16	1882	164	1930	59	1886	115	1933	91
Indianapolis	1867-1934	39.90	1876	145	1934	63	1883	121	1908	91
Lafayette	1880-1934	38.71	1927	142	1914	65	1929	107	1919	89
Iowa										
Dubuque	1851-1934	32.90	1881	168	1894	59	1885	125	1910	87
Farmersburg	1837-1930	31.67	1849	169	1895	58	1885	118	1901	87
Muscatine	1846-1934	36.72	1851	203	1901	58	1858	130	1917	85
Kansas										
Hays	1868-1934	22.91	1878	154	1894	52	1905	116	1896	88
Lawrence	1868-1934	36.38	1915	142	1897	65	1909	110	1934	88
Leavenworth	1836-1934	34.74	1858	172	1864	42	1885	117	1847	83
Manhattan	1858-1934	31.49	1915	161	1860	48	1911	116	1875	85
Kentucky										
Lexington	1858-1934	43.35	1882	146	1930	57	1888	116	1908	85
Louisville	1871-1934	43.26	1882	131	1930	55	1884	115	1934	89
Paducah	1882-1934	46.56	1927	155	1887	59	1934	110	1894	82

Table 2.- Precipitation at long-time Weather Bureau stations.-Continued

Station	Period of record	Average annual (inches)	Maximum		Minimum		Maximum 10-yr.		Minimum 10-yr.	
			Year	% of average	Year	% of average	Period ending	% of average	Period ending	% of average
Louisiana										
Monroe	1886-1934	51.72	1920	154	1899	63	1928	116	1902	86
New Orleans	1870-1934	57.46	1875	149	1899	54	1934	116	1899	82
Shreveport	1872-1934	43.37	1880	154	1899	55	1885	128	1899	86
Maine										
Cornish	1857-1924	46.12	1902	137	1880	73	1902	114	1915	88
Gardiner	1837-1934	43.00	1887	127	1838	70	1859	112	1914	90
Orono	1870-1930	41.80	1926	130	1921	62	1891	116	1923 1924	89
Maryland										
Baltimore	1817-1934	42.56	1889	146	1930	51	1892	120	1872	73
Emmitsburg	1867-1934	43.86	1912	149	1888	59	1920	108	1901	93
Massachusetts										
Boston	1818-1934	40.14	1863	169	1822	68	1870	143	1914	88
Lowell	1826-1934	41.47	1888	143	1914	67	1933	113	1917	81
Michigan										
Detroit	1871-1934	32.05	1880	149	1889	66	1882	118	1891	90
Lansing	1864-1934	31.43	1883	154	1930	59	1885	115	1895	86
Marquette	1872-1934	32.47	1918	129	1925	61	1884	105	1932	92
Minnesota										
Duluth	1871-1934	27.94	1879	162	1910	65	1882	127	1926	89
Minneapolis	1866-1934	27.66	1868	151	1910	42	1876	121	1934	87
St. Paul	1837-1933	27.27	1849	162	1910	37	1874	118	1891	87
Mississippi										
Canton	1883-1934	49.07	1923	139	1924	59	1923	106	1933	93
Columbus	1856-1870 1875-1934	53.93	1932	143	1904	67	1884	110	1910	89
Vicksburg	1840-1853 1872-1934	51.93	1880	162	1924	60	1884	122	1933	88
Missouri										
Hermann	1875-1934	38.50	1927	137	1901	58	1929	107	1887	92
Oregon	1856-1934	35.95	1902	141	1910	59	1905	115	1918	85
St. Louis City	1837-1934	37.44	1858	154	1930	62	1859	128	1908	92
Montana										
Ag. College	1874-1885 1893-1934	18.35	1885	178	1934	57	1885	117	1902	94
Havre	1880-1934	13.90	1884	135	1905	49	1889	103	1913	88
Miles City	1878-1934	13.79	1879	165	1934	40	1915	122	1890	80
Nebraska										
Blair	1868-1934	29.37	1869	162	1934	61	1878	114	1895	83
North Platte	1875-1934	18.39	1915	178	1931	54	1909	116	1901	82
Nevada										
Battle Mt.	1870-1934	6.40	1884	219	1918	38	1892	134	1923	74
Elko	1870-1934	9.51	1904	223	1872	11	1905	159	1880	51
Imlay	1870-1934	5.45	1890	285	1929	31	1927	130	1903	68
New Hampshire										
Hanover	1835-1855 1867-1934	35.25	1843	158	1871	64	1851	127	1884	83
Lakeport	1857-1932	41.54	1888	133	1894	75	1893	109	1930	82
New Jersey										
New Brunswick	1854-1934	45.47	1889	135	1930 1932	72	1874	115	1934	85
New Mexico										
Ag. College	1851-1861 1865-1934	8.57	1905	199	1873	41	1906	125	1880	83
San Marcial	1850-1862 1865-1934	9.13	1859	269	1901	12	1884	123	1901	73
Santa Fe	1850-1934	14.27	1854	174	1917	35	1861	119	1875	88
New York										
Albany	1826-1934	38.38	1871	148	1930	66	1878	113	1914	78
New York	1826-1934	42.99	1859	139	1835	67	1933	116	1840	81
Rochester	1829-1934	32.83	1873	152	1834	52	1878	118	1841	86
North Carolina										
Lenoir	1872-1934	51.44	1901	159	1933	63	1906	108	1934	85
Weldon	1872-1934	45.97	1891	130	1931	62	1896	113	1934	87
Wilmington	1871-1934	46.93	1877	178	1909	59	1885	127	1918	89

Table 2.- Precipitation at long-time Weather Bureau stations-Continued

Station	Period of record	Average annual (inches)	Maximum		Minimum		Maximum 10-yr.		Minimum 10-yr.	
			Year	% of average	Year	% of average	Period ending	% of average	Period ending	% of average
North Dakota										
Devil's Lake	(1870-1890 (1897-1934	18.04	1921	141	1889	58	1905	108	1917	92
Garrison	(1870-1883 (1892-1934	16.38	1882	167	1874	48	1884	107	1877	86
Ohio										
Cincinnati	1835-1934	38.55	1847	169	1901	47	1855	131	1903	84
Cleveland	1871-1934	33.82	1878	158	1934	65	1885	117	1923	87
Marietta	1826-1934	42.25	1858	146	1930	59	1891	110	1901	91
Toledo	1861-1934	32.03	1881	144	1894	67	1870	123	1902	87
Oklahoma										
Lawton	1871-1934	31.53	1905	159	1901	51	1908	116	1918	90
Oklahoma City	1891-1934	31.15	1908	167	1901	51	1927	111	1918	85
Tulsa	1888-1934	37.40	1915	168	1896	64	1929	115	1897	87
Oregon										
Astoria	1854-1934	77.05	1933	148	1884	64	(1880 (1902	110	1931	89
Portland	1872-1934	41.62	1882	162	1929	63	1883	134	1931	85
The Dalles	(1853-1865 (1875-1934	15.72	1858	277	1889	48	1865	165	1931	77
Pennsylvania										
Philadelphia	(1820-1934	40.41	1867	151	1922	72	1874	125	1886	91
Pittsburgh	(1839-1865 1872-1934	36.17	1890	140	1930	63	1873	113	1846	93
Rhode Island										
Providence	1832-1934	39.19	1898	162	1914	75	1895	130	1918	90
South Carolina										
Camden	1850-1934	45.56	1928	183	1879	67	1929	119	1888	85
Charleston	(1738-1765 (1832-1934	45.22	1876	173	1850	52	1879	139	1909	82
South Dakota										
Huron	1882-1934	20.65	1914	146	1925	49	1921	108	1934	75
Rapid City	1888-1934	17.98	1915	151	1931	52	1929	115	1900	79
Yankton	1874-1934	25.30	1881	162	1894	57	1883	114	1934	78
Tennessee										
Clarksville	1854-1934	48.46	1919	152	1918	70	1928	116	1918	93
Knoxville	1871-1934	47.38	1875	156	1930	71	1882	116	1900	93
Texas										
Austin	1856-1934	34.08	1919	190	1917	46	1927	119	1912	82
Brownsville	1871-1934	27.40	1886	219	1917	44	1887	145	1902	64
Galveston	1872-1934	44.77	1900	175	1917	48	1882	119	1898	81
Utah										
Moab	1890-1934	9.41	1918 1927	170	1898	46	1918	121	1904	80
Salt Lake City	1874-1934	16.13	1875	147	1890	64	1915	108	1896 1933	91
Vermont										
Burlington	(1838-1866 (1872-1934	31.61	1897	138	1881	66	1866	112	1888	89
Chelsea	1886-1934	35.78	1897	134	1899	76	1895	112	1917	89
Virginia										
Lynchburg	1872-1934	40.53	1889	150	1930	49	1902	115	1930	82
Norfolk	1871-1934	44.09	1889	160	1930	61	1895	122	1934	83
Richmond	1872-1934	42.02	1889	171	1876	66	1895	117	1885	82
Washington										
Spokane	1882-1934	16.62	1882	156	1929	45	1902	111	1926	77
Walla Walla	1873-1934	17.01	1893	136	1922	66	1902	112	1930	84
West Virginia										
Rowlesburg	1885-1933	48.67	1907	148	1886	39	1914	115	1895	81
Wisconsin										
Milwaukee	1844-1934	30.08	1876	167	1901	62	1878	118	1902	92
Wyoming										
Cheyenne	1871-1934	14.99	1905	151	1876	34	1930	117	1882	65
Lander	1892-1934	12.63	1923	171	1902	57	1924	118	1902	99

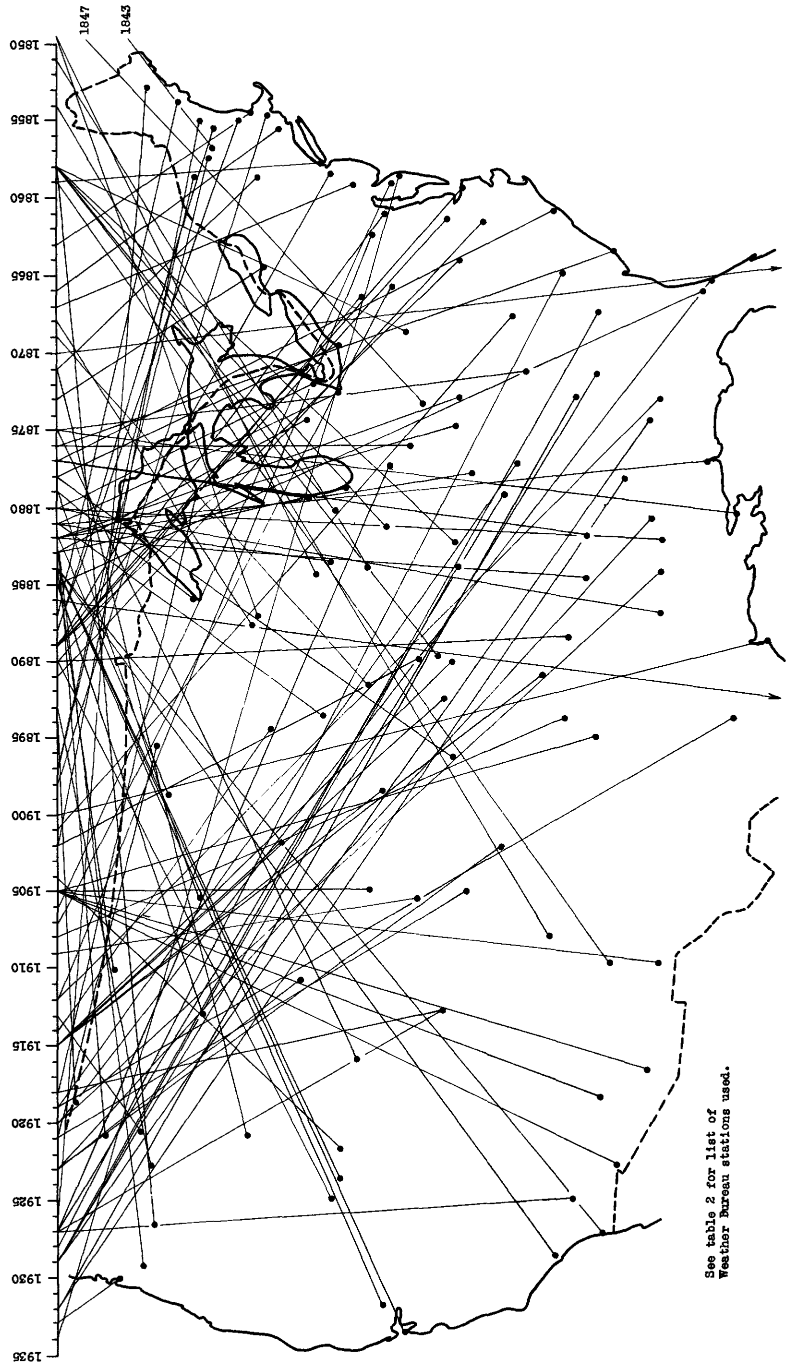

Figure 1.—Year of maximum annual precipitation at selected long-time Weather Bureau stations.

From 1890 to 1904 there are no large groups but 1905, 1915, and 1927 were outstanding wet years, five or more long-time stations having recorded maxima as follows:

1905	Agricultural College, N. Mex.	1915	Lawrence, Kans.
	Cheyenne, Wyo.		Manhattan, Kans.
	Phoenix, Ariz.		North Platte, Nebr.
	University of Arizona, Ariz.		Rapid City, S. Dak.
	Yuma, Ariz.		Tulsa, Okla.
	Lawton, Okla.		

1927	Hermann, Mo.
	Indio, Calif.
	Lafayette, Ind.
	Moab, Utah
	Paducah, Ky.

A study of the characteristics of the precipitation at each of the long-time stations for these long-time maxima would be of interest. For all the stations the average ratio of the maximum to the average annual precipitation is 1.66. Stations at which the ratio is over 1.80 are situated largely in the Southwest.

Periods of high precipitation

The long-time stations listed in table 2 are shown in figure 2 together with a line drawn to the time scale showing the end of the 10-year period of maximum precipitation. The records for a few stations in the Middle Atlantic and New England areas and a few isolated stations elsewhere show that the 10-year maximum period occurred prior to 1880. The 10-year maxima ended at the greatest number of stations during the period 1884 to 1895 and were especially confined to three 10-year periods, as follows:

10 years ending			
1884	Columbus, Miss.	1885	Agricultural College. Mont.
	Garrison, N. Dak.		Chicago, Ill.
	Key West, Fla.		Cleveland, Ohio.
	Louisville, Ky.		Dubuque, Iowa.
	Marquette, Mich.		Farmersburg, Iowa.
	Peoria, Ill.		Lansing, Mich.
	San Marcial, N. Mex.		Leavenworth, Kans.
	University of Arizona, Ariz.		Marengo, Ill.
	Vicksburg, Miss.		Mobile, Ala.
			Shreveport, La.
			Wilmington, N. C.

1895	Chelsea, Vt.
	Fort Smith, Ark.
	Norfolk, Va.
	Providence, R. I.
	Richmond, Va.

During the period 1923 to 1929 there was also a group of stations, located largely in the South and Southeast, that recorded 10-year

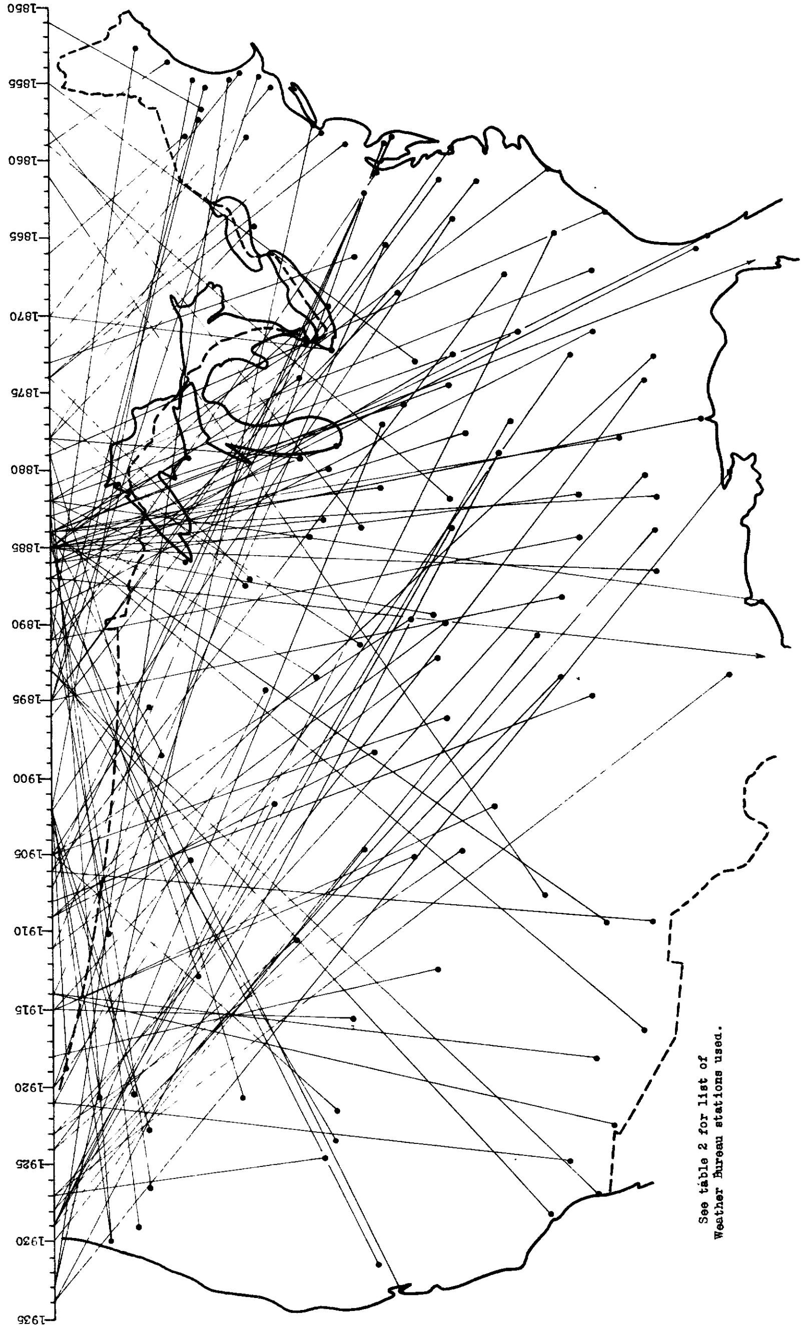

Figure 2.—Year ending 10-year period of maximum precipitation at selected long-time Weather Bureau stations.

maxima. Since 1930 4 stations - Lowell (Mass.), New York, Paduch (Ky.), and New Orleans - have recorded 10-year maxima.

The average ratio of the maximum 10-year period to the mean for all stations is 1.19.

Years of low precipitation

The long-time stations listed in table 2 are shown plotted on figure 3 together with a line drawn to a time scale showing the year of minimum precipitation.

Prior to 1851 six of the 22 stations operating at that time recorded their minimum for the period of record - namely, Boston, Mass., 1822; Rochester, N. Y., 1834; New York City, N. Y., 1835; Gardiner, Maine, 1838; Lowell, Mass., 1846; Charleston, S. C., 1850. These records indicate that in all probability recent droughts in certain parts of the East as regards precipitation may not have been as severe as some that occurred about a century ago.

During the 40-year period 1851 to 1890 only 23 stations recorded minimum annual precipitation. Beginning with 1894 more and more stations recorded their minima, and except in only a few years minima were recorded at one or more stations, with the major grouping as follows:

1894 Dubuque, Iowa
Hays, Kans.
Indio, Calif.
Lakeport, N. H.
Las Animas, Colo.
Toledo, Ohio.
Yankton, S. Dak.

1901 Cincinnati, Ohio.
Hermann, Mo.
Lawton, Okla.
Marengo, Ill.
Milwaukee, Wis.
Muscatine, Iowa.
Oklahoma City, Okla.
San Marcial, N. Mex.

1910 Duluth, Minn.
Minneapolis, Minn.
Oregon, Mo.
Peoria, Ill.
St. Paul, Minn.

1917 Austin, Tex.
Brownsville, Tex.
Fort Smith, Ark.
Galveston, Tex.
San Francisco, Calif.
Santa Fe, N. Mex.

1924 Canton, Miss.
Little Rock, Ark.
Phoenix, Ariz.
University of Arizona
Vicksburg, Miss.

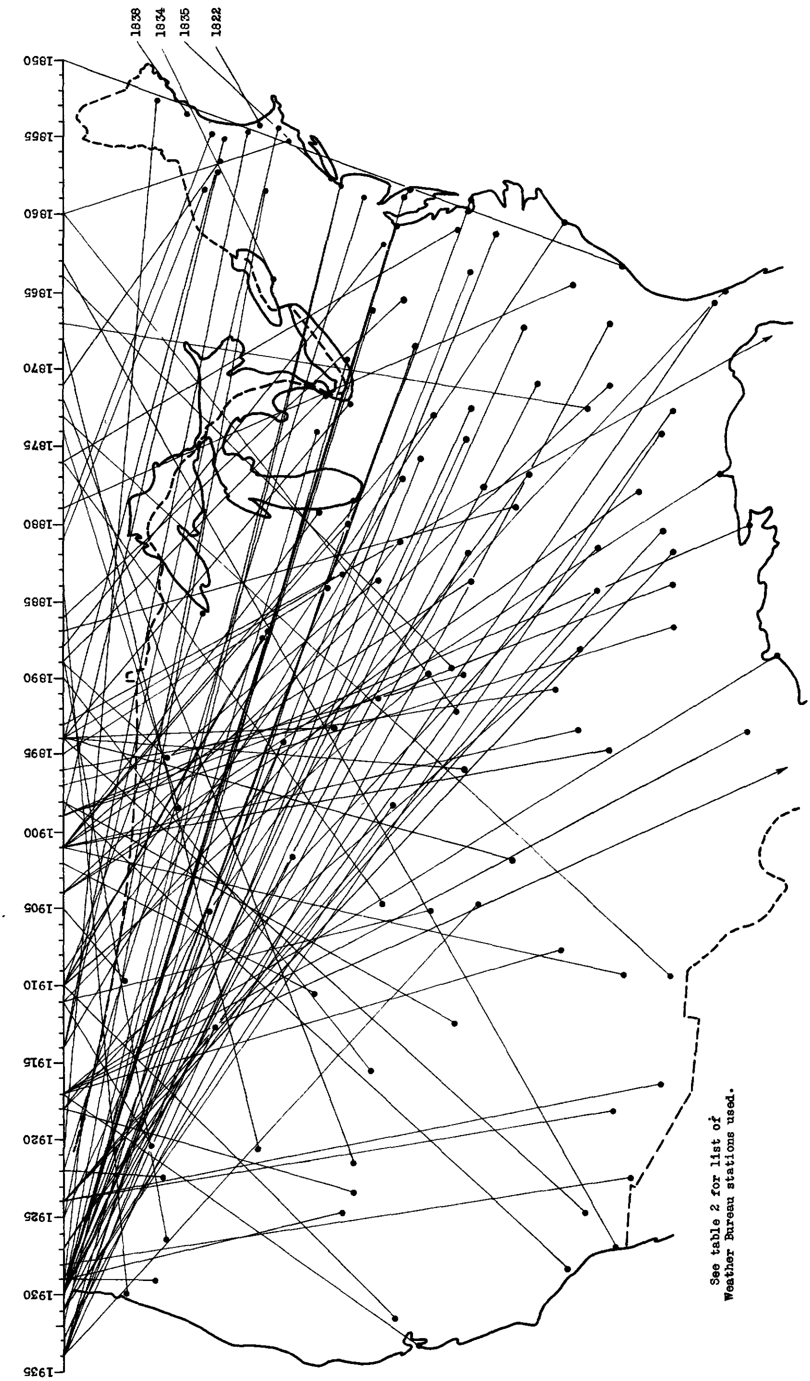

Figure 3.--Year of minimum annual precipitation at selected long-time Weather Bureau stations.

1930	Albany, N. Y. Baltimore, Md. Bridgeville, Del. Evansville, Ind. Knoxville, Tenn. Lansing, Mich. Lexington, Ky. Louisville, Ky. Lynchburg, Va. Marietta, Ohio. Millsboro, Del. New Brunswick, N. J. Norfolk, Va. Pittsburgh, Pa. St. Louis City, Mo.	1931 1934	Montgomery, Ala. North Platte, Nebr. Rapid City, S. Dak. Weldon, N. C. Blair, Nebr. Cleveland, Ohio Chicago, Ill. Indianapolis, Ind. Miles City, Mont. Agricultural College, Mont. Pueblo, Colo.

The average ratio of the annual minima for all stations to the average is 0.56.

Periods of low precipitation

The long-time stations listed in table 2 are plotted on figure 4 together with lines drawn to the time scale showing the end of the minimum 10-year period. Four of the long-time stations recorded minimum 10-year periods prior to 1850 - New York, 1840; Rochester, N. Y., 1841; Pittsburgh, Pa., 1846; Leavenworth, Kans., 1847 - indicating that not only were there individual years of minimum precipitation prior to 1850 but 10-year periods as well. During the 21-year period 1850-70 only one long-time station recorded its 10-year minimum, and from 1871 to 1890 only a few scattered stations. Beginning with 1890 more and more stations recorded their 10-year minima, with an exceptionally large number during the last 4 years. Outstanding 10-year periods were as follows:

10 years ending			
1901	Chicago, Ill. Emmitsburg, Md. Farmersburg, Iowa. Marietta, Ohio. North Platte, Nebr. San Marcial, N. Mex.	1918	Bridgeville, Del. Clarksville, Tenn. Jacksonville, Fla. Lawton, Okla. Millsboro, Del. Oklahoma City, Okla. Oregon, Mo. Providence, R. I. St. Augustine, Fla. Wilmington, N. C.
1902	Agricultural College, Mont. Brownsville, Tex. Milwaukee, Wis. Monroe, La. Lander, Wyo. Toledo, Ohio.	1931	Astoria, Oreg. Moscow, Idaho. Porthill, Idaho. Portland, Oreg. The Dalles, Oreg.
1904	Denver, Colo. Helena, Ark. Moab, Utah. Marengo, Ill. Montgomery, Ala. Yuma, Ariz.	1932	Marquette, Mich. Sacramento, Calif. San Francisco, Calif.

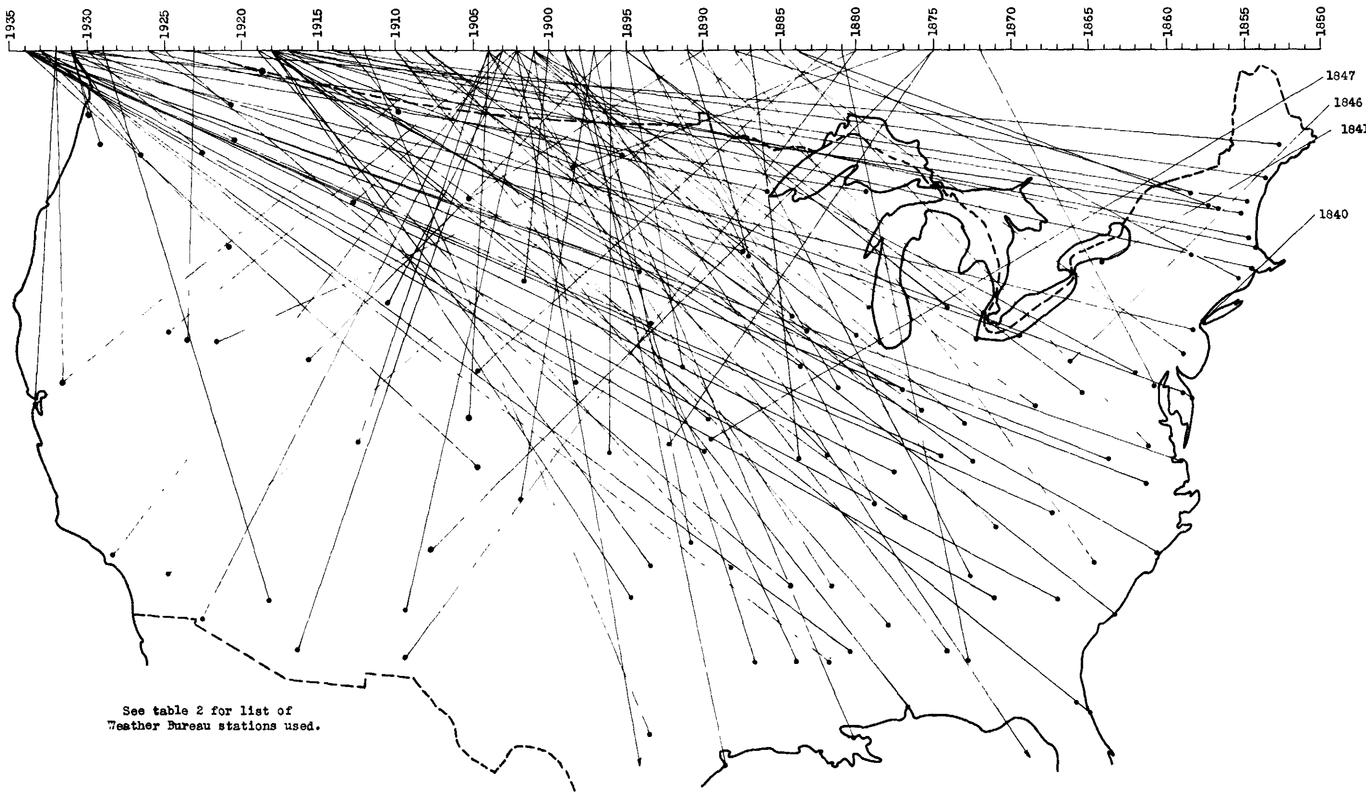

Figure 4.—Year ending 10-year period of minimum precipitation at selected long-time Weather Bureau stations.

10 years ending 1933	Boise, Idaho Canton, Miss. Evansville, Ind. Salt Lake City, Utah. Vicksburg, Miss.
1934	Atlanta, Ga. Augusta, Ga. Huron, S. Dak. Lawrence, Kans. Lenoir, N. C. Louisville, Ky. Minneapolis, Minn. New Brunswick, N. J. Norfolk, Va. Pueblo, Colo. Weldon, N. C. Yankton, S. Dak.

The average ratio of the 10-year minima for all stations to the average is 0.85.

Changes in precipitation, by areas

The preceding discussion indicates that periods of either high or low precipitation occur simultaneously over large areas, and as storms over the United States are known to follow fairly well defined paths it has seemed worth while to investigate whether over large areas precipitation. trends might be related to the same general pattern. This suggested a study in the areal grouping of stations that show similar trends of precipitation.

The progressive 10-year averages for a number of the long-time stations listed in table 2 and for 5 additional stations were plotted and closely compared, and the stations that showed the same general type of variation were then grouped. It was found that these groups embraced stations having much the same geographic location, as follows:

1. North Atlantic group (fig. 6):

   Gardiner, Cornish, and Orono, Maine.
   Lakeport and Hanover, N. H.
   Boston and Lowell, Mass.
   Providence, R. I.
   Canton, Conn.
   Albany and New York, N. Y.
   New Brunswick, N. J.

2. Middle Atlantic group (fig. 6):

   Philadelphia, Pa.
   Baltimore and Emmitsburg, Md.
   Lynchburg, Richmond, and Norfolk, Va.

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3. South Atlantic group (fig. 6):

   Wilmington, Lenoir, and Weldon, N. C.
   Charleston and Camden, S. C.
   Atlanta, Augusta, and Rome, Ga.
   Jacksonville, Key West, and St. Augustine, Fla.

4. Great Lakes group (fig. 7):

   Milwaukee, Wis.
   Marengo, Peoria, and Chicago, Ill.
   Evansville, Lafayette, and Indianapolis, Ind.
   Lansing, Detroit, and Marquette, Mich.
   Marietta, Cincinnati, Cleveland, and Toledo, Ohio.
   Rochester, N. Y.
   Pittsburgh, Pa.

5. Tennessee River group (fig. 7):

   Clarksville and Knoxville, Tenn.
   Louisville, Lexington, and Paducah, Ky.

6. Gulf group (fig. 7):

   Union Springs, Mobile, and Montgomery, Ala.
   Vicksburg and Columbus, Miss.
   New Orleans and Shreveport, La.
   Helena, Fort Smith, and Little Rock, Ark.
   Galveston, Tex.

7. North Central West group (fig. 8):

   St. Paul, Minn.
   Muscatine and Farmersburg, Iowa.
   Blair and North Platte, Nebr.
   Yankton and Huron, S. Dak.
   Devils Lake and Garrison, N. Dak.

8. Central West group (fig. 8):

   Leavenworth, Manhattan, and Hays, Kans.
   St. Louis, Oregon, and Hermann, Mo.

9. South Central West group (fig. 8):

   Austin, Tex.
   Tulsa, Lawton, and Oklahoma City, Okla.

10. Northwest Interior group (fig. 9):

   Walla Walla and Spokane, Wash.
   The Dalles, Oreg.
   Boise, Idaho.
   Elko and McGill, Nev.

11. Northern and Western Plains group (fig. 9):

   Miles City and Havre, Mont.
   Cheyenne and Lander, Wyo.
   Pueblo, Denver, and Las Animas, Colo.

12. Great Basin and Southwest group (fig. 9):

    Salt Lake City, Scipio, and Moab, Utah.
    Phoenix, Yuma, and University Station, Ariz.
    Santa Fe, San Marcial, Fort Wingate-McGaffey Ranger Station, and Agricultural College, N. Mex.
    Indio, Calif.

13. North Pacific coast group (fig. 10):

    North Head, Wash.
    Astoria, Oreg.

14. Central Pacific coast group (fig. 10):

    San Francisco and Sacramento, Calif.
    Imlay and Thorne, Nev.

15. South Pacific coast group (fig. 10):

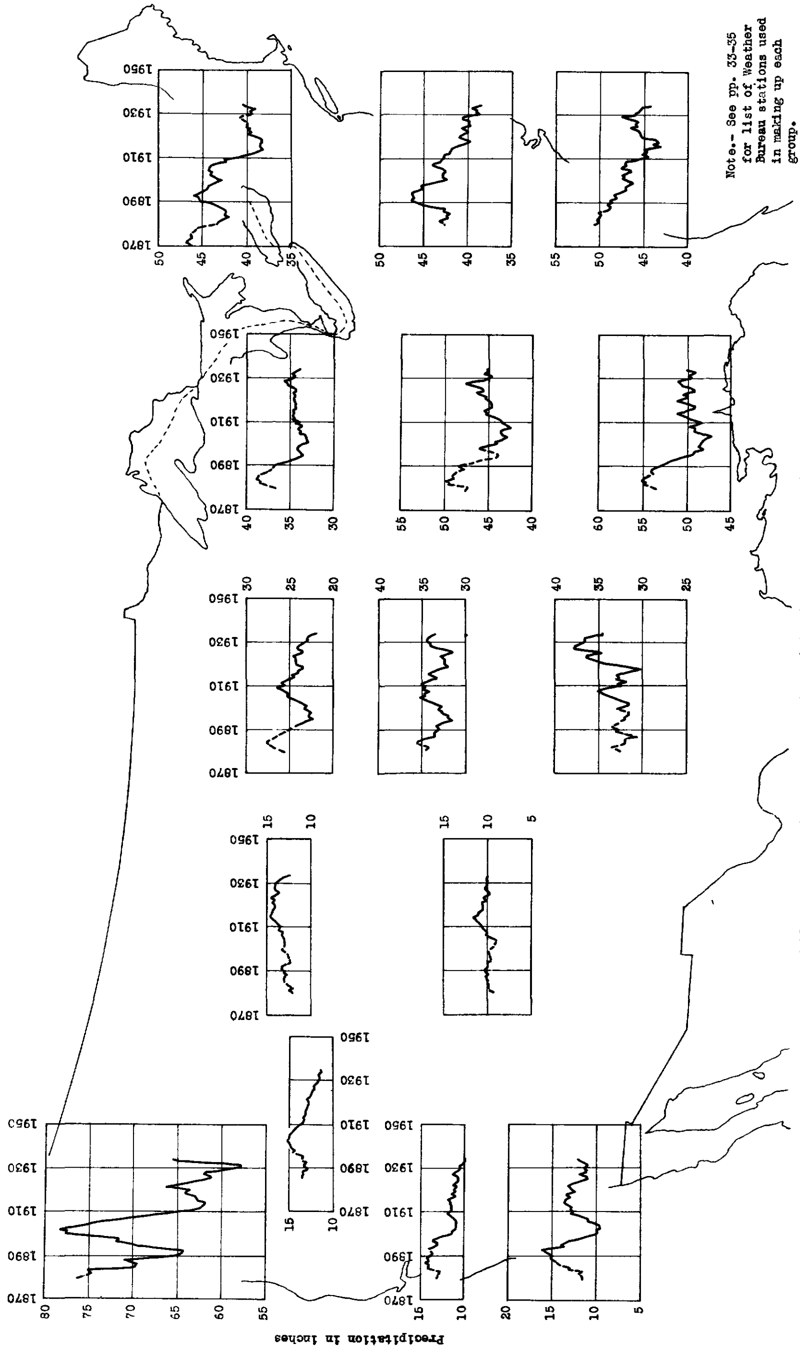
    San Diego and Los Angeles, Calif.

The average of the progressive 10-year averages of the stations in the groups designated above is plotted on figure 5 for annual values and on figures 6 to 10 for annual and seasonal values (December to April, May to August, and September to November). Figures 6 to 10 also show the average precipitation by months for all the stations in each group. That portion of the graphs indicated by a dashed line represents a number of stations less than the total for the group. The figures for these points, however, were adjusted so as to be comparable with the remaining record.

That the average of the 10-year progressive averages for the group of stations shown does not represent the average precipitation over any area is of course recognized, but it is believed to show the direction of periodic trends and the approximate magnitude of changes in each area. The trends indicated are interesting, and consideration of them may indicate areas where climatic conditions seem to be critical and where further detailed study of precipitation is desirable.

The preliminary study of 10-year progressive average annual precipitation leads to the following deductions:

(1) The minimum 10-year period at the exceptionally long-time stations at New York City and Rochester, N. Y., Pittsburgh, Pa., and Leavenworth, Kans., ended in the 1840's (fig. 4). The minimum for any 10-year period since 1850 at these stations has been consistently above these early minima, except New Bedford, Mass. which recorded a low for the 10-hear period ending 1930 that was 15 percent below the minimum 10-year period prior to 1850. The early history of lakes in sections of the West indicates that in the late 1840's their beds were dry and were crossed by emigrant trails (55). Data from the records and diaries of early settlers and travelers as compiled by



Note.- See pp. 33-35 for list of Weather Bureau stations used in making up each group.

Figure 5.—Average of 10-year progressive average annual precipitation for groups of long-time Weather Bureau stations.

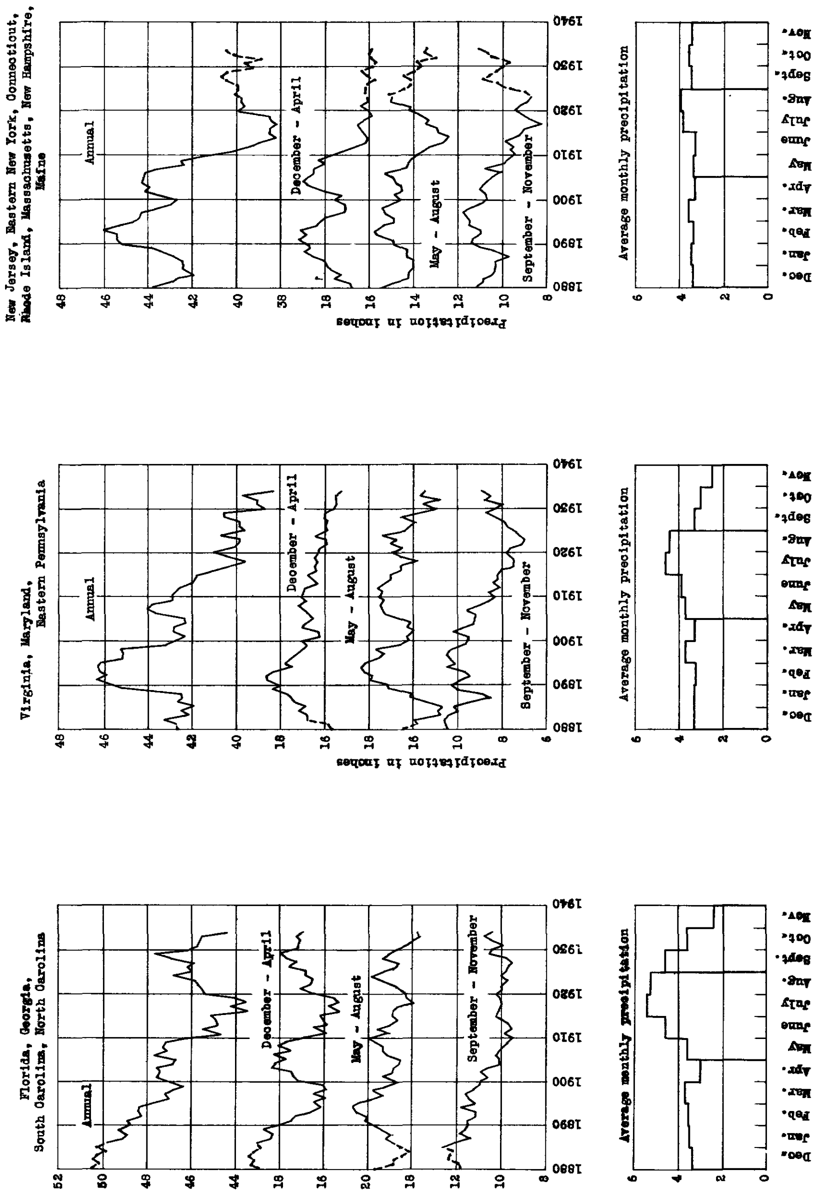


Figure 6.—Average of 10-year progressive annual and seasonal precipitation and average monthly distribution for long-time Weather Bureau stations.

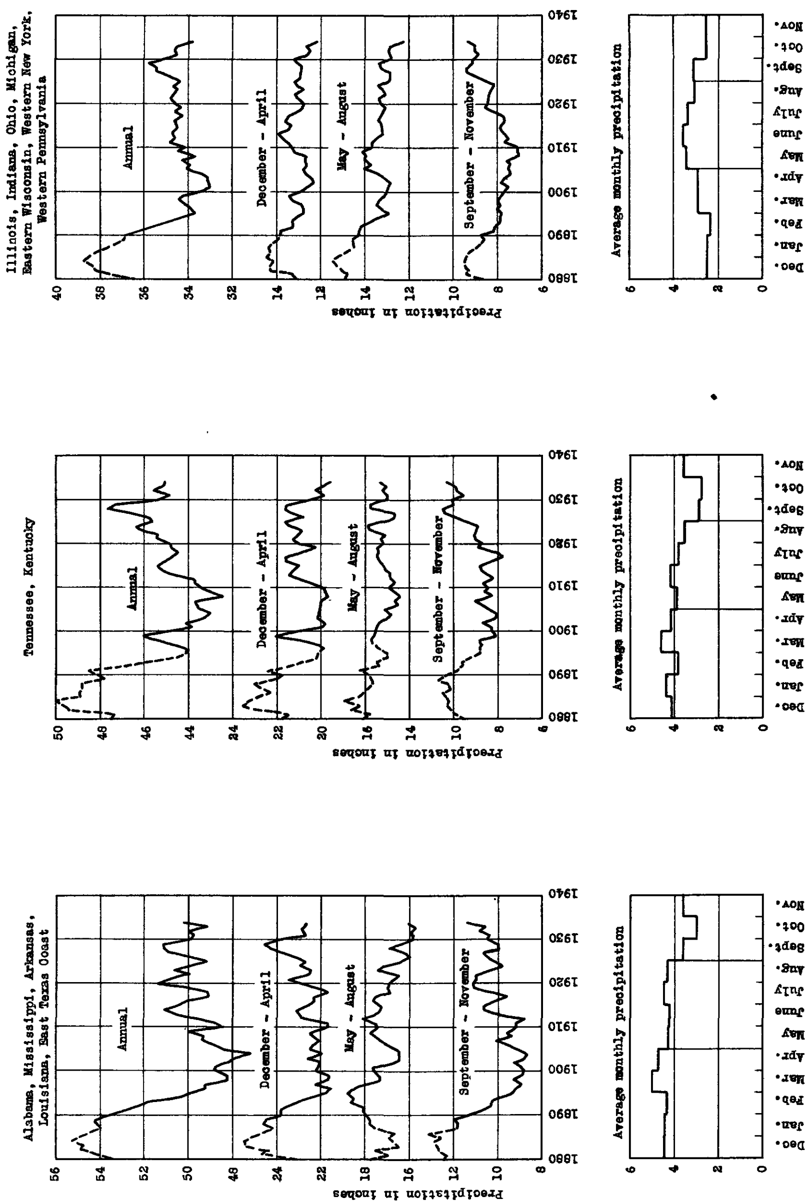


Figure 7.—Average of 10-year progressive annual and seasonal precipitation and average monthly distribution for long-time Weather Bureau stations.

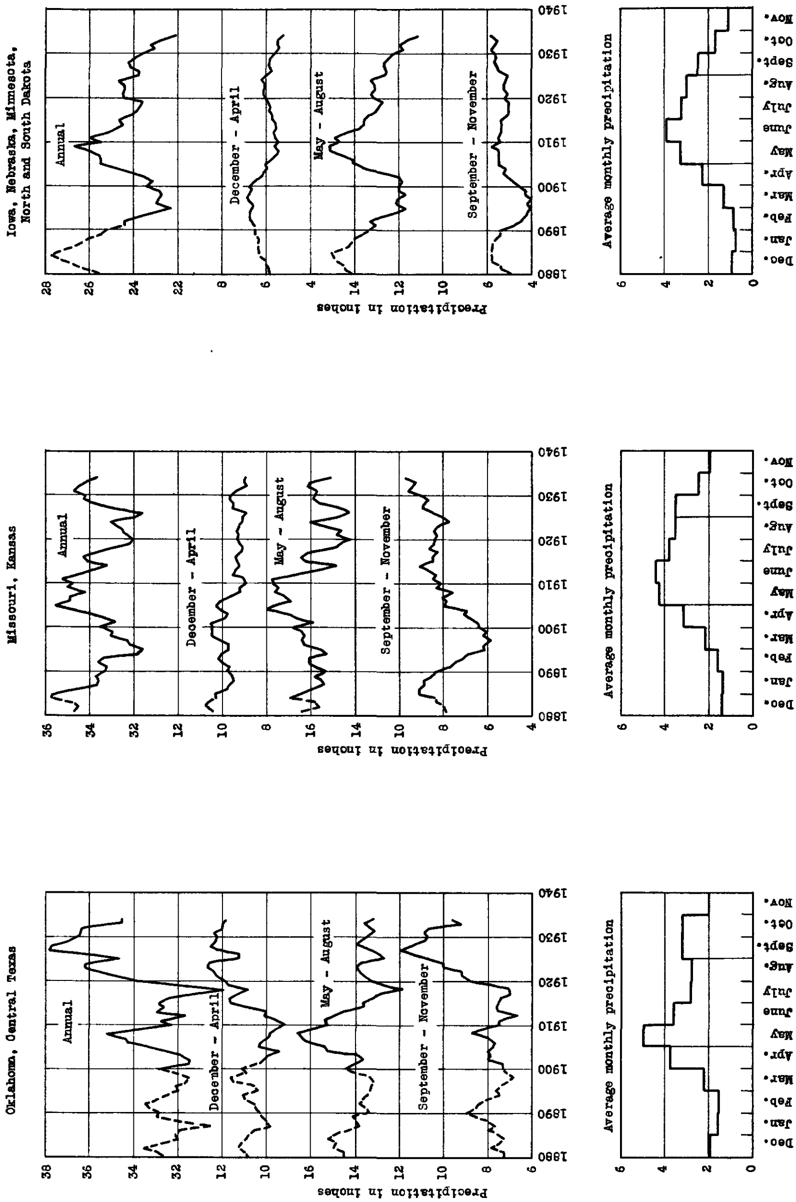


Figure 8.—Average of 10-year progressive annual and seasonal precipitation and average monthly distribution for long-time Weather Bureau stations.

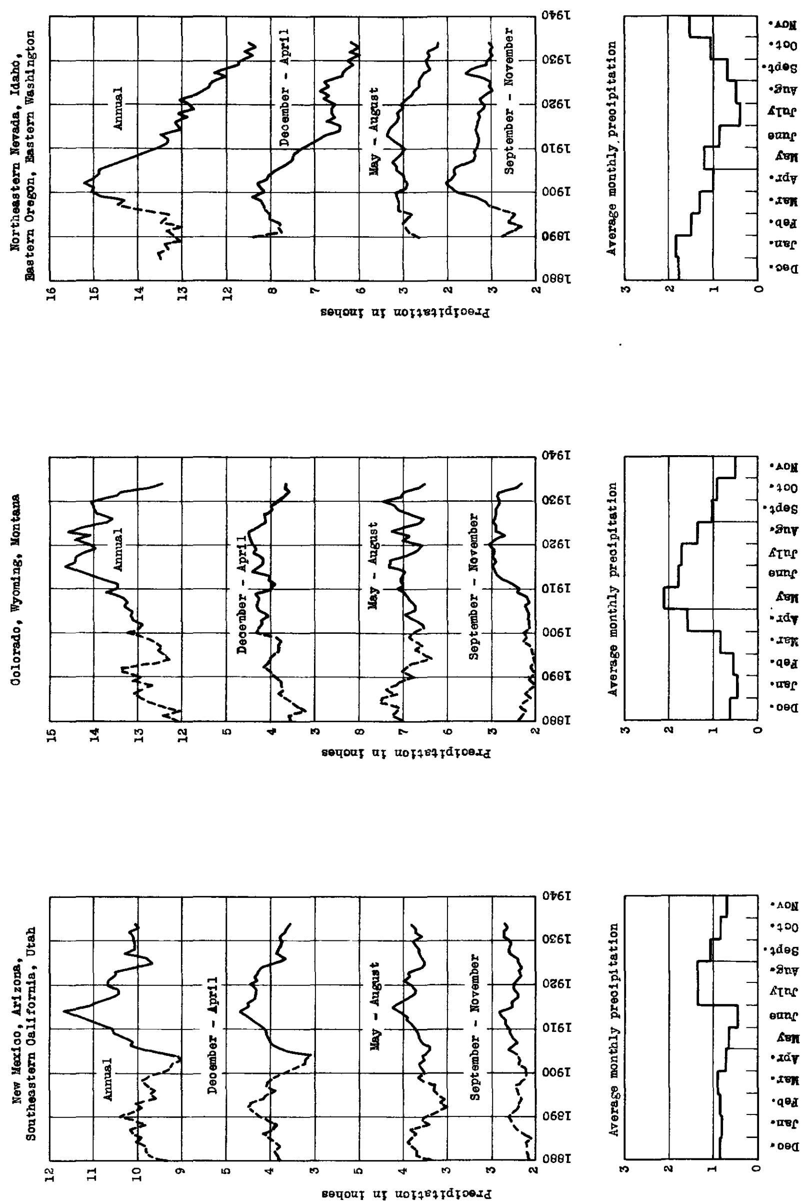


Figure 9.—Average of 10-year progressive annual and seasonal precipitation and average monthly distribution for long-time Weather Bureau stations.

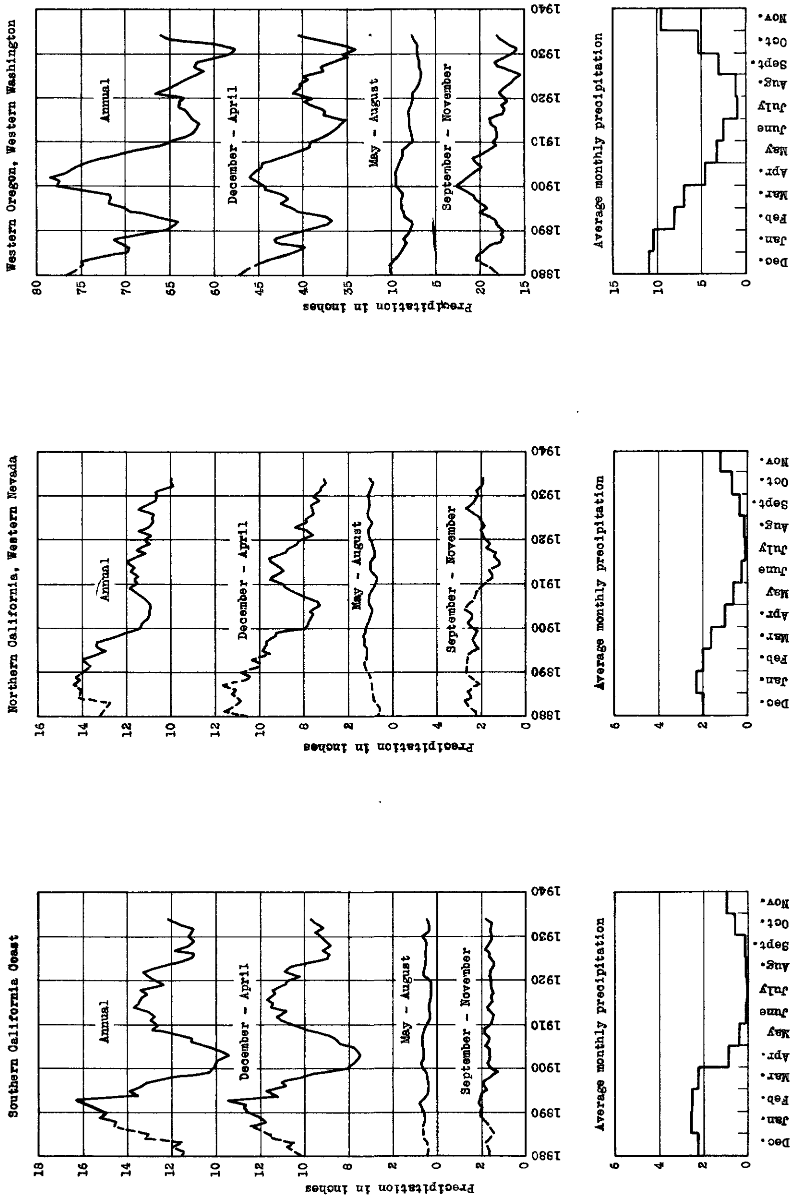


Figure 10.—Average of 10-year progressive annual and seasonal precipitation and average monthly distribution for long-time Weather Bureau stations.

H. B. Lynch (102) indicate a period of deficient precipitation in southern California about 1830 which has not since been surpassed. Composite tree-ring studies in northern California indicate a 5-year period ending in 1850 when tree rings were prevailingly thin (18a). All these evidences seem to point to a severe drought of wide extent about the period 1830 to 1850.

(2) The trend of precipitation for the 30-year period 1850-80 seems to have been generally upward over most of the United States. During this period only a few stations registered minimum 10-year averages (fig. 4). On the other hand, beginning as early as 1855, maximum 10-year averages are noted (fig. 2) culminating in 10-year periods ending in 1886, when 23 out of 98 long-time stations in the United States showed maximum 10-year averages. In no other decade has there been such a grouping of maximum 10-year averages at so many stations. There seems to be little doubt that the average annual precipitation for the 5 years ending in 1885, over a very considerable part of the United States, has not been exceeded during the period 1830-1934. Other periods when in some sections maximum precipitation was recorded were 1902 for stations in the Northwest, 1914-15 for the Central West and Southwest, and 1927, 1928, and 1929 for stations in the Central West and South. These trends are clearly shown on figures 1 to 5.

(3) Beginning about 1894 more and more of the stations recorded minimum 10-year averages (fig. 4). Between 1894 and 1904 37 of the long-time stations recorded 10-year minima. The minima at most of the remaining stations were scattered through the 30-year period 1904-34, with the largest number culminating 10-year lows in 1930, 1931, 1933, and 1934. The long-time stations recording their minimum 10-year average in 1934 were Chicago, Cleveland, Indianapolis, Miles City, Agricultural College (Mont.), and Pueblo.

Insofar as the annual averages of these stations are indicative of annual changes over the respective areas these data indicate that

(1) The persistent downward trend in annual precipitation for the last two or three decades has been generally confined to (a) the Northwest Interior, North Pacific coast, and Central Pacific coast areas, embracing Washington, Oregon, Idaho, Nevada, and central and northern California; (b) the upper Mississippi Valley, embracing parts of North and South Dakota, Nebraska, Iowa, Wisconsin, and Minnesota; and (c) the North Atlantic and Middle Atlantic areas embracing all the New England States, the eastern part of New York, and Pennsylvania, Delaware, Maryland, and Virginia.

(2) The trend in the annual precipitation during the decade ending in 1930 was stationary or slightly upward in the Southwest, Great Basin, Northern and Western Plains, and Great Lakes area and rather decidedly upward in the South Atlantic and Tennessee River areas.

(3) Since 1930 the Northern and Western Plains area has experienced a dropping off, while the North Pacific coast area has turned abruptly upward.

Changes in seasonal precipitation, by geographic provinces

An examination of the seasonal changes in precipitation in certain areas indicates that they did not always correspond to the changes shown in yearly precipitation. For the purpose of examining the seasonal trends over all the areas the monthly averages of all the long-time records at stations used for the yearly trends were combined into three seasons - December to April, May to August, and September to November. These three seasons correspond rather closely over the United States as a whole to the three periods found by experience to be of special significance in the study of hydrology - namely, the replenishing period, September, October, and November, when accretions to soil moisture and ground water commonly occur; the storage period, December through April, when losses are at a minimum; and the growing season, May through August, when evaporation and transpiration are most active, with resulting depletion of soil moisture and minimum recharge to the ground water. As the storm tracks apparently vary by seasons, it is possible that the study of their changes by seasons will tend to disclose some of the reasons for the variations in yearly trends. Changes in seasonal precipitation may also be reflected in significant changes in seasonal run-off which are not disclosed by changes in the annual amounts.

In tables 3, 4, and 5 are shown data by seasons for each areal group of stations.

Changes in winter precipitation

The 10-year progressive averages of the precipitation for the winter season (December to April) shown in figures 6 to 10 and comparisons shown in table 3 indicate that -

Table 3.- Precipitation, December to April, 1871-1934

Area*	Average (inches) 1871-1934	1871-1902	1903-1934	Ratio last 32 years to first 32 years (percent)	Average for 10 years ending 1934 (inches)	Ratio last 10 years (percent) To long time average	To last 32 years
1	17.11	17.92	16.30	91	15.86	93	97
2	16.54	16.98	16.11	95	15.19	92	94
3	17.48	18.30	16.67	91	16.89	97	101
4	13.09	13.11	13.07	100	12.19	93	93
5	21.01	21.25	20.77	98	19.58	93	94
6	23.32	23.80	22.85	96	22.70	97	99
7	5.98	6.29	5.68	90	5.22	87	92
8	9.64	10.12	9.16	91	8.94	93	98
9	11.04	10.48	11.59	111	11.80	107	102
10	7.25	8.12	6.38	79	6.20	86	97
11	3.97	3.90	4.04	104	3.65	92	90
12	3.94	3.83	4.04	105	3.54	90	88
13	41.14	43.60	38.68	89	40.43	98	105
14	8.86	9.70	8.02	83	7.11	80	89
15	10.24	10.11	10.36	102	9.76	95	94

Area*	Maximum 10-year period Inches	Date of ending	Minimum 10-year period Inches	Date of ending	Ratio last 10 years to minimum 10 years (percent)
1	19.20	1891	15.69	1931	101
2	18.64	1892	15.19	1934	100
3	19.38	1883	15.28	1916	111
4	14.56	1885	12.19	1934	100
5	23.55	1883	19.58	1934	100
6	25.45	1884	21.45	1896	106
7	6.92	1897	5.22	1934	100
8	10.74	1882	8.88	1926	101
9	12.72	1923	9.14	1910	129
10	8.43	1890	5.98	1931	104
11	4.48	1922	3.18	1882	115
12	4.72	1914	3.08	1904	115
13	46.90	1880	33.89	1931	119
14	11.66	1881	7.00	1933	102
15	13.55	1893	7.46	1903	131

* Numbers correspond to those of groups listed on pages 33-35.

(1) Except in the Southwest, the average winter precipitation for the last 32 years of record has been less than that for the first 32 years.

(2) Except in the South Central West area and the Northern and Western Plains area, the 10-year average winter precipitation in the 1880's and 1890's was generally at a maximum.

(3) The trend is still downward in several areas, as indicated by the fact that the average for the last 10 years is the same or nearly the same as that for the minimum 10 years.

(4) Insofar as the few stations in the Northwest Interior area may be indicative of the winter precipitation in the adjacent mountain areas, the downward trend is critical, because the economic life of these areas depends to a considerable degree upon the winter precipitation.

Changes in precipitation in growing season

The 10-year progressive averages shown on figures 6 to 10 and comparisons shown in table 4 indicate that -

(1) Except in the Northern and Western Plains area and the Southwest, the average summer precipitation during the last 32 years of record has been less than that for the first 32 years.

(2) Except in the southwest, the trend is generally downward, and in several areas the average for the 10 years ending in 1934 is the same or nearly the same as the minimum for the period of record.

(3) In general the percentage decrease from the first to the last 32 years of record is comparable with the decrease in winter precipitation.

(4) The persistent downward trend is becoming critical in areas such as the upper Mississippi Valley, where the summer precipitation is so large a proportion of the total precipitation.

Changes in fall precipitation

The 10-year progressive averages shown on figures 6 to 10 and comparisons shown in table 5 indicate that for the fall precipitation (September to November) -

(1) There has been a decided reversal from the winter and summer trends.

Table 4.- Precipitation, May to August, 1871-1934

Area*	Average (inches) 1871-1934	Average (inches) 1871-1902	Average (inches) 1903-1934	Ratio last 32 years to first 32 years (percent)	Average for 10 years ending 1934 (inches)	Ratio last 10 years (percent) To long-time average	Ratio last 10 years (percent) To last 32 years
1	14.37	15.04	13.71	91	13.42	93	98
2	16.59	16.60	16.58	100	15.43	93	93
3	19.08	19.35	18.80	97	17.78	93	95
4	13.56	14.08	13.04	93	12.33	91	95
5	15.46	15.73	15.18	96	15.37	99	101
6	17.18	17.52	16.84	96	16.05	93	95
7	13.10	13.29	12.90	97	11.15	85	86
8	16.10	16.57	15.63	94	15.11	94	97
9	13.92	13.98	13.85	99	13.14	94	95
10	2.80	2.99	2.60	87	2.22	79	85
11	6.84	6.83	6.86	100	6.51	95	95
12	3.63	3.46	3.80	110	3.84	106	101
13	8.18	9.02	7.34	81	7.55	92	103
14	.95	.96	.94	98	1.00	105	106
15	.52	.60	.44	73	.45	87	102

Area*	Maximum 10-year period Inches	Maximum 10-year period Date of ending	Minimum 10-year period Inches	Minimum 10-year period Date of ending	Ratio last 10 years to minimum 10 years (percent)
1	15.78	1893	12.41	1914	108
2	18.36	1894	14.64	1885	105
3	20.66	1894	17.70	1933	100
4	15.49	1884	12.33	1934	100
5	16.95	1884	14.38	1908	107
6	18.82	1895	15.64	1933	103
7	15.16	1908-9	11.15	1934	100
8	18.00	1904	14.21	1920, 26	106
9	16.58	1908	11.80	1918	111
10	3.37	1913	2.22	1934	100
11	7.51	1930	6.35	1894	102
12	4.23	1915	3.03	1892	127
13	10.18	1882	6.55	1925	115
14	1.33	1892	.59	1881-82	169
15	.80	1892	.27	1918	167

* Numbers correspond to those of groups listed on pages 33-35.

Table 5.- Precipitation, September to November, 1871-1934

Area*	Average (inches) 1871-1934	1871-1902	1903-1934	Ratio last 32 years to first 32 years (percent)	Average for 10 years ending 1934 (inches)	Ratio last 10 years (percent) To long-time average	To last 32 years
1	10.41	11.02	9.80	89	11.06	106	113
2	9.14	10.15	8.14	80	9.06	99	111
3	10.70	11.35	10.04	88	10.49	98	104
4	8.32	8.31	8.32	100	9.40	113	113
5	9.21	9.36	9.06	97	10.37	113	114
6	10.50	10.86	10.15	93	11.39	108	112
7	5.24	5.02	5.46	109	5.90	113	108
8	8.06	7.40	8.71	118	9.75	121	112
9	8.40	7.98	8.83	111	9.63	115	109
10	3.20	3.19	3.21	101	3.08	96	96
11	2.45	2.22	2.68	121	2.33	95	87
12	2.44	2.32	2.56	110	2.69	110	105
13	18.42	19.20	17.63	92	18.00	98	102
14	2.12	2.45	1.80	74	1.90	90	106
15	1.68	1.80	1.57	87	1.80	107	115

Area*	Maximum 10-year period Inches	Date of ending	Minimum 10-year period Inches	Date of ending	Ratio last 10 years to minimum 10 years (percent)
1	11.80	1897	8.20	1917	135
2	10.59	1882	6.98	1923	130
3	12.62	1885	9.49	1910	110
4	9.52	1884	7.02	1908	134
5	10.71	1889	7.80	1917	133
6	13.02	1886	8.64	1904	132
7	5.90	1934	4.04	1897	146
8	9.75	1934	5.82	1897	168
9	11.98	1927	6.65	1912	145
10	4.04	1902	2.31	1892	133
11	3.08	1920	1.99	1893	117
12	2.83	1914	2.11	1885	127
13	22.48	1900	15.31	1925	118
14	2.75	1883	1.18	1914	161
15	2.17	1892	1.28	1899	141

* Numbers correspond to those of groups listed on pages 33-35.

(2) Except in the extreme East and the extreme West the average for the last 32 years has been above that for the first 32 years.

(3) Except in one area the trend is still upward, the precipitation for the last 10 years being above the average for the last 32 years in all areas except the Northern and Western Plains and, in general, averaging from 20 to 30 percent above the minimum 10-year average.

It is believed that the information disclosed by the study of seasonal trends indicates the great desirability for further study of the subject and the breakdown into months, especially with respect to the upward trend in fall precipitation compared with the generally declining trend in winter and summer precipitation, in order to determine whether more exact knowledge can be developed regarding these interesting relations.

Average monthly precipitation

The graphs of average monthly precipitation shown on figures 6 to 10 are of interest in showing the marked differences in seasonal distribution. Special attention is called to the monthly distribution of rainfall in the interior States, from Missouri, Iowa, and Minnesota westward across the plains to the Rocky Mountains. The source of atmospheric water vapor from which rainfall is derived is evaporation from oceans, lakes, creeks, rivers, swamps, and other wet or moist surfaces, and transpiration by vegetation. Mead states (111, p. 164):

"The precipitation on the continental interior lands is, however, the phenomenon in which the engineers are more generally interested, and the source of this precipitation is derived most largely from moisture that obtains from the continental evaporation, from land surface, and from the surface of rivers, lakes, and swamp areas, and indirectly by the transpiration from animal and vegetable life."

There is a marked similarity between the graphs of monthly precipitation in these areas and the known evaporation and transpiration characteristics. In this connection the uniform rainfall distribution throughout the year in the areas shown for the New England States on figure 6 is of interest. The graph of precipitation in that region bears little if any relation to the probable graph of continental evaporation and transpiration. The thought is suggested that if over broad areas air movements and air temperatures could be taken into consideration, a study of the differences between the precipitation and the moisture put into the air through evaporation and transpiration might throw some light on the probable source or sources of precipitated moisture.

Such a study, if possible, would be valuable in continental areas such as the upper Mississippi River basin and the Red River Basin, where the decline in summer precipitation has been long continued, and where in certain instances steps are being taken to store and retard surface run-off in reservoirs.

Changes in temperature

Joseph B. Kincer (87) presents graphs and tables showing annual and seasonal changes in temperature recorded at several Weather Bureau stations in the United States and in foreign countries. He concludes that "the practically unanimous testimony of these graphs not only establishes the realness of these upward temperature trends but shows that they are operative on an extensive geographic scale."

As a companion to the study of changes in precipitation and a continuation of the studies by Kincer, the 10-year progressive average temperatures have been compiled for groups of stations situated in the 15 areas used in the precipitation study. Figure 11 shows the average of the 10-year progressive averages for the stations in each of 15 groups. Figures 12 to 16 show by groups the plotting of the 10-year progressive averages for each station. The records used are those published in United States Weather Bureau Bulletin W. Since 1889 the same basis of determining the mean annual temperature has been used - namely, the average of the daily maximum readings plus the average of the daily minimum readings divided by 2. Prior to that date they may be on a somewhat different basis. The 10-year progressive average temperature at each station prior to 1889 was recomputed by the methods now used by the Weather Bureau and is shown by a dotted line on figures 11 to 16.

The study of temperature changes as summarized in table 6 indicates that in the country as a whole (a) the average temperatures for the last 32 years of record were greater than those for the preceding 32 years; (b) the average temperature for the 10-year period ending 1934 was nearly 1.4° higher than for the first 32 years of record; (c) the average temperature for the last 10 years was the maximum 10-year average for the period of record; and (d) the average temperature for the last 10 years was 1.9° above that for the 10-year period of minimum temperature, which ended, in

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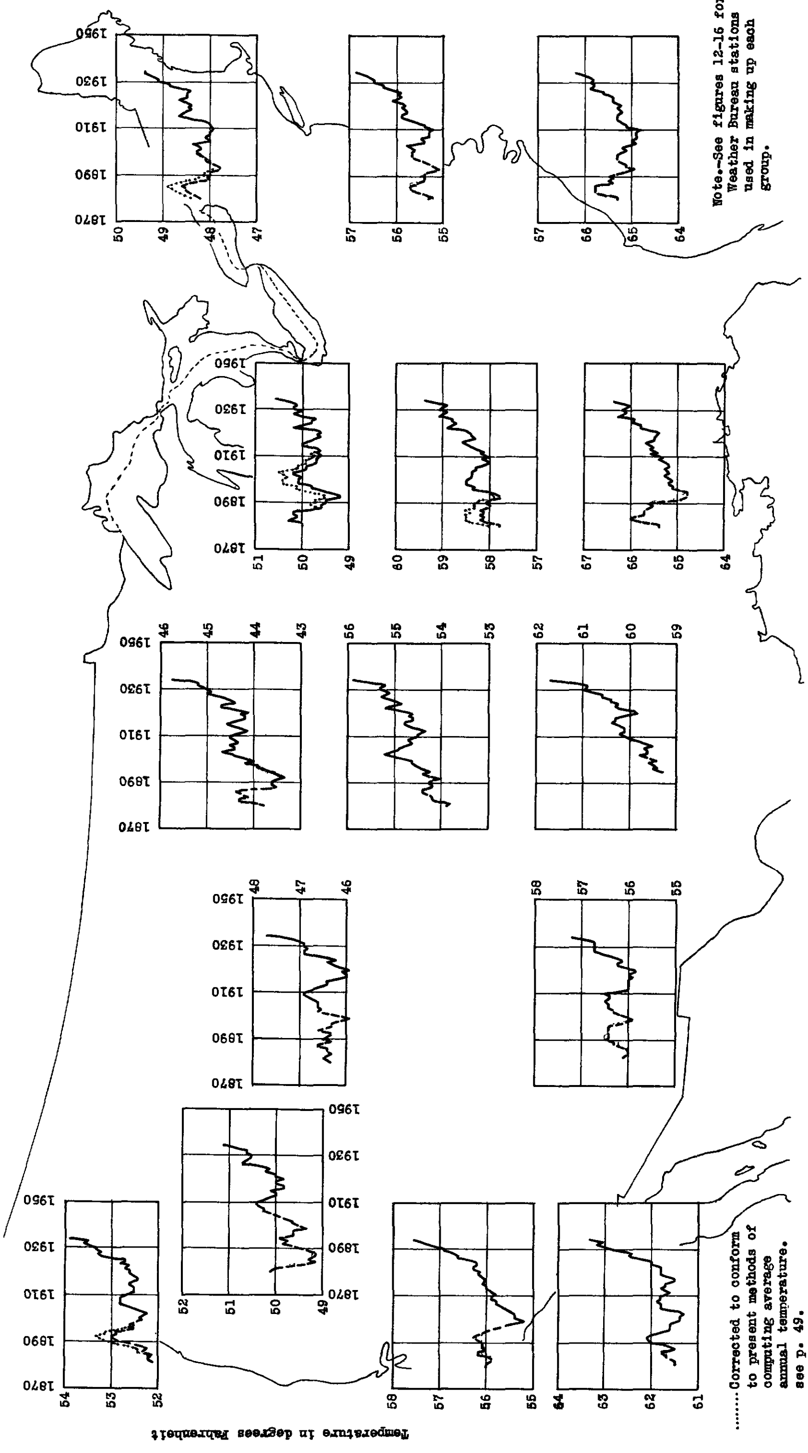


Figure 11.--Average of 10-year progressive average annual temperature for groups of long-time Weather Bureau stations.

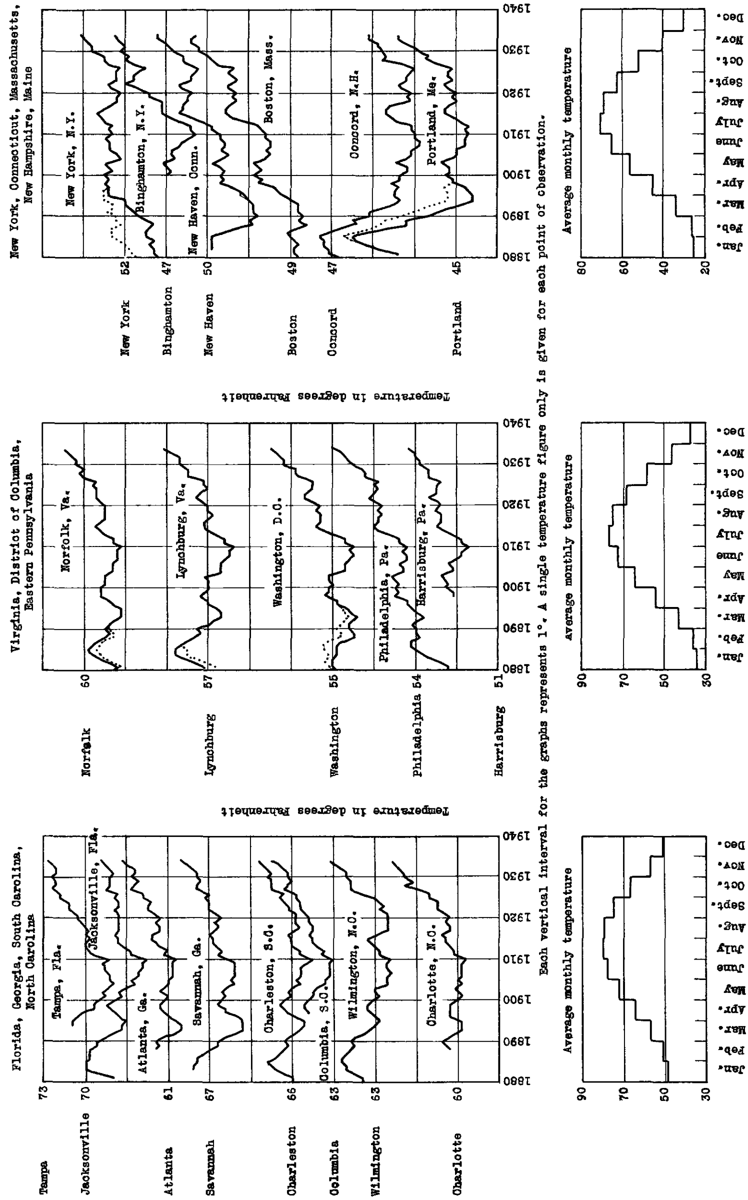
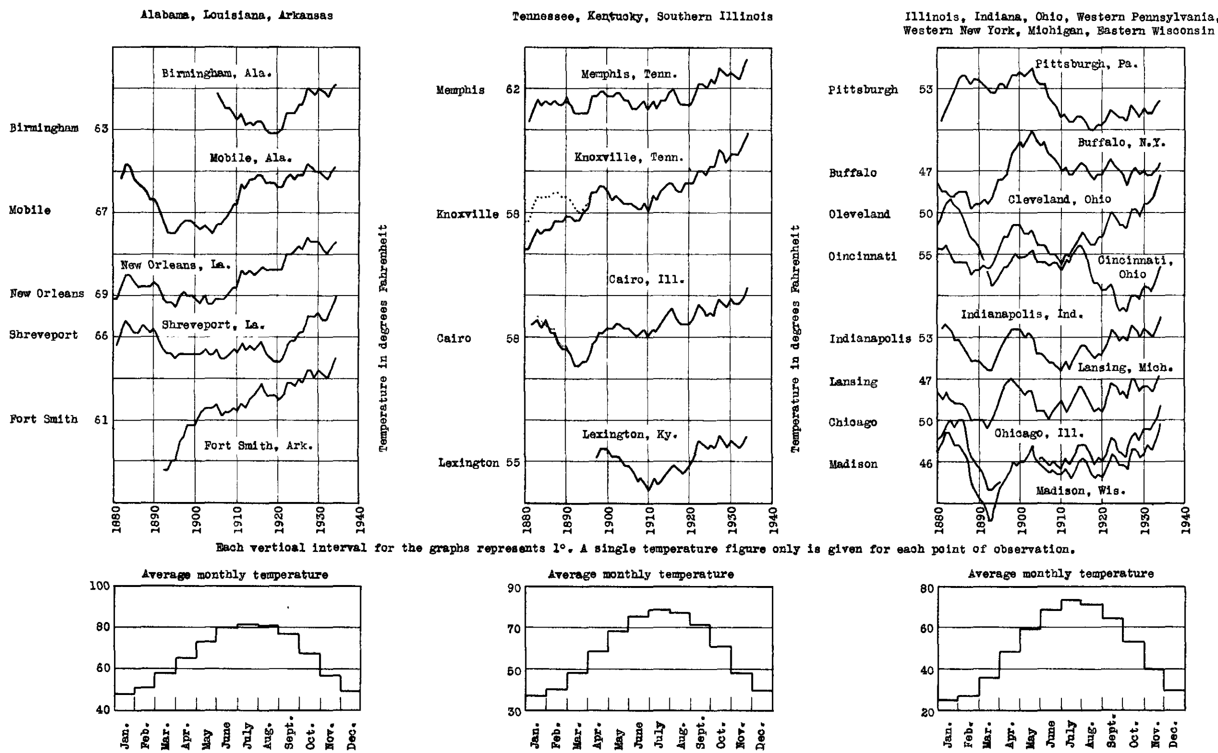


Figure 12.—Ten-year progressive average annual temperature and average monthly distribution for long-time Weather Bureau stations



Each vertical interval for the graphs represents 1°. A single temperature figure only is given for each point of observation.

Figure 13.—Ten-year progressive average annual temperature and average monthly distribution for long-time Weather Bureau stations

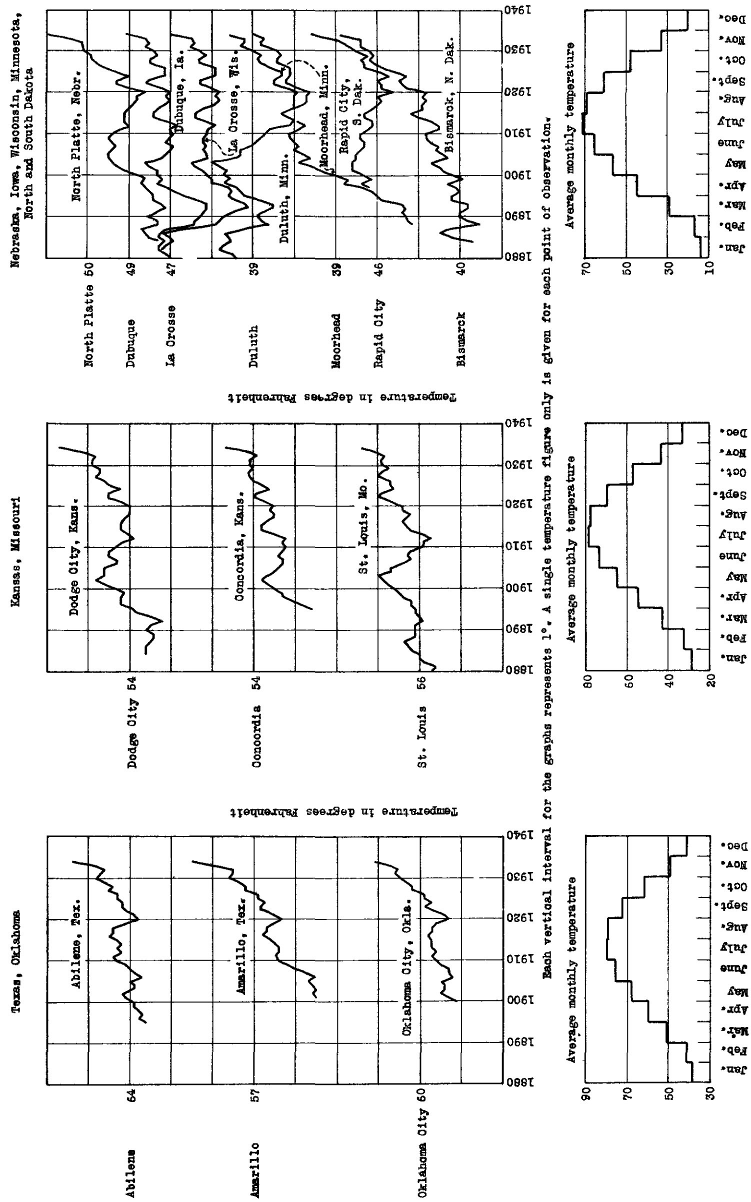


Figure 14.—Ten-year progressive average annual temperature and average monthly distribution for long-time Weather Bureau stations

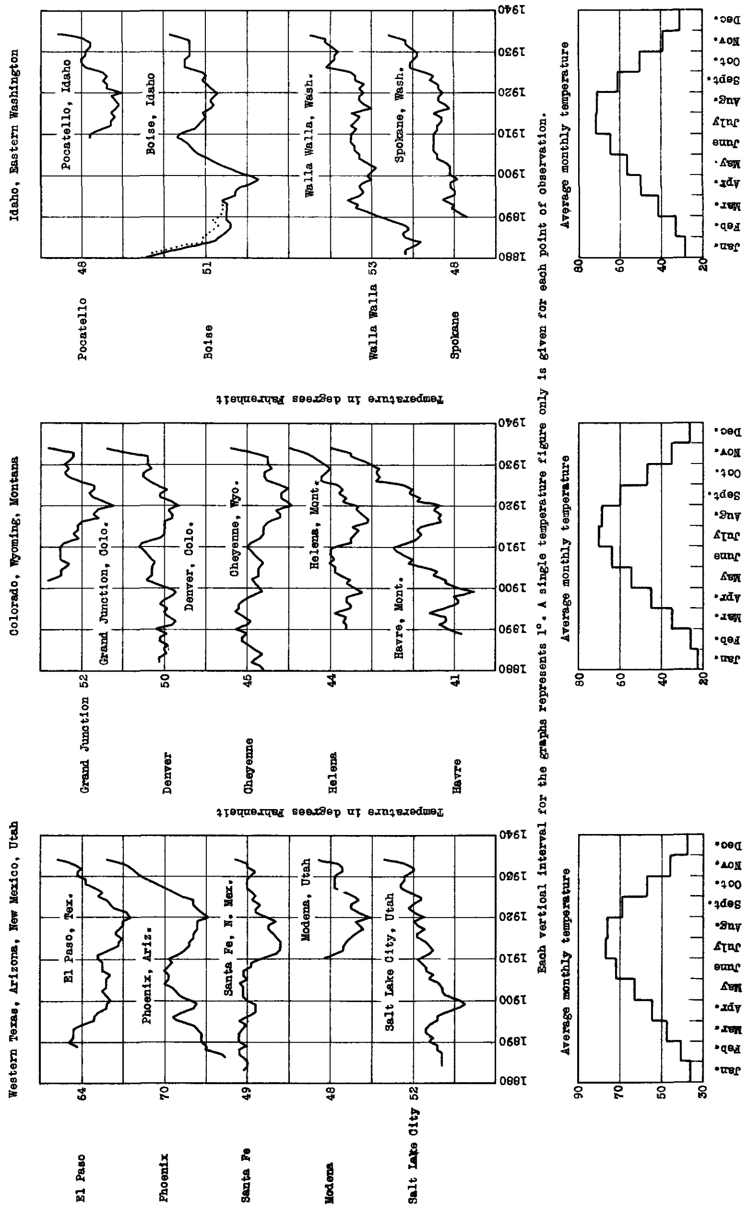


Figure 15.—Ten-year progressive average annual temperature and average monthly distribution for long-time Weather Bureau stations

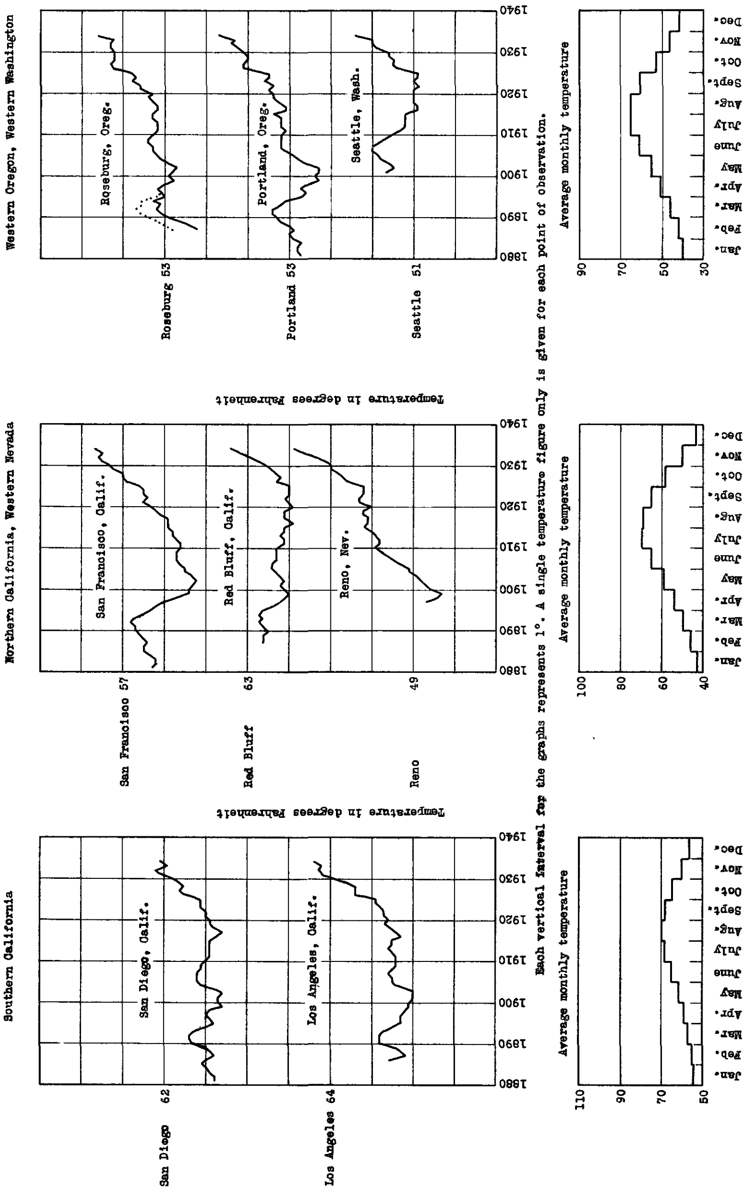


Figure 16.—Ten-year progressive average annual temperature and average monthly distribution for long-time Weather Bureau stations

Table 6.- Annual temperature (°F.) 1871-1934

Area*	1871-1934	Average 1871-1902	1903-34	Increase in last half over first half of period	10-year progressive average ending 1934
1	48.5	48.3	48.7	0.4	49.5
2	55.7	55.4	56.1	.7	56.9
3	65.4	65.3	65.5	.2	66.2
4	50.0	50.0	50.1	.1	50.6
5	58.5	58.3	58.7	.4	59.4
6	65.7	65.6	65.8	.2	66.4
7	44.4	44.0	44.8	.8	45.8
8	54.7	54.3	55.1	.8	56.0
9 **	60.2	59.8	60.8	1.0	61.6
10	50.1	49.8	50.4	.6	51.2
11	46.6	46.4	46.8	.4	47.7
12 #	56.4	56.4	56.5	.1	57.2
13 ##	52.8	52.6	53.0	.4	53.8
14 ##	56.2	55.8	56.6	.8	57.6
15 ##	62.0	61.6	62.3	.7	63.3

Area*	Increase in last 10 years over		Maximum		Minimum		Increase in last 10 years over minimum 10 years
	Long-time average	First half of period	10-year average	Date of ending	10-year average	Date of ending	
1	1.0	1.2	49.5	1934	47.9	1893 1894 1910	1.5
2	1.2	1.5	56.9	1934	55.1	1881 1893 1894	1.8
3	.8	.9	66.2	1934	64.8	1910	1.4
4	.6	.6	50.6	1934	49.4	1892	1.2
5	1.9	1.1	59.4	1934	57.9	1893	1.5
6	.7	.8	66.4	1934	65.0	1895	1.4
7	1.4	1.8	45.8	1934	43.4	1892	2.4
8	1.3	1.7	56.0	1934	53.7	1892	2.3
9	1.4	1.8	61.6	1934	59.4	1895	2.2
10	1.1	1.4	51.2	1934	49.2	1899	2.0
11	1.1	1.3	47.7	1934	46.0	1884	1.7
12	.8	.8	57.2	1934	55.8	1920	1.4
13	1.0	1.2	53.8	1934	52.2	1902	1.6
14	1.4	1.8	57.6	1934	55.2	1899	2.4
15	1.3	1.7	63.3	1934	61.3	1881	2.0

* Numbers correspond to those of groups listed on pages 33-35.
** Record available 1886-1934; divided 1886-1910, 1910-34.
# Record available 1874-1934; divided 1874-1904, 1904-34.
Record available 1872-1934; divided 1872-1903, 1903-34.

general, in the 1890's. Nearly all the stations used in the compilation of records in this report are located in cities where temperatures may be affected by conditions that do not exist in rural areas. Kincer (87) in connection with his study made a long-time comparison between three urban and three rural stations - namely, Lynchburg and Dale Enterprise, Va., Baltimore and Easton, Md., and Philadelphia and West Chester, Pa., - and found the changes at the rural stations were as pronounced as the changes at the nearby city stations. This phase of the question, however, should be given further study, because naturally if the increased temperature trends were confined entirely to urban areas they would have little significance in the problem under consideration. Further evidence that the increased temperature trends are widespread is presented by T. C. Main (103), who found by comparing 20-year progressive averages, increases of 1.0° to nearly 4.0° F. in annual temperature since about 1880 at a group of stations in Alberta and Saskatchewan. In addition to such further studies as may be necessary to determine the extent to which temperature may have increased over broad areas embracing river basins, it is especially desirable in hydrologic studies that a complete breakdown of temperature records be made by seasons and possibly by months. Kincer presents seasonal graphs on the basis of 20-year averages for the two long-time temperature records in the eastern United States. The records at New Haven, Conn., beginning with 1781, and Washington, D. C., beginning with 1817, showed that the largest changes occurred in the fall, winter, and spring and the least in the summer. A similar tendency is shown for Iowa temperature on the basis of 20-year progressive averages beginning in 1892.

Although the temperature study outlined above is far from complete with respect to several phases, it seems to indicate conclusively that there has been an increase in temperature over wide areas in the United States, at least since the 1890's. It also seems reasonably certain that the increased temperatures may have operated with the decreased precipitation to create, in certain sections of the country, a condition that is increasingly unfavorable to the maintenance of water supplies, both in surface streams and in the ground. This condition is especially acute in the upper Mississippi Valley and Red River Valley, where, as will be shown later, the average annual losses through evaporation and transpiration so nearly equal the average annual precipitation that any changs which would tend to increase the losses would materially affect the amount of water available for stream flow and for replenishment of soil moisture and ground water.

Changes in run-off

The basins in which a detailed study of rainfall and run-off has been made are those of the Mississippi, Red, Merrimack, James, Chattahoochee, Tennessee, and Neosho Rivers. In addition the 10-year progressive average annual run-off for the following streams has been compiled and the results plotted on figure 17 for a study in connection with the similar graphs of precipitation and temperature:

Spokane River at Spokane, Wash., 1892-1934.
Willamette River at Albany, Oreg., 1895-1934.
Kings River at Piedra, Calif., 1896-1934.
San Gabriel River near Azusa, Calif., 1896-1934.
Snake River near Moran, Wyo., 1904-1934.
Colorado River at Lees Ferry, Ariz., 1851-1934.

The gage heights on Lake Superior, 1869-1934, were also compiled and plotted.

The run-off records have been corrected for storage. The early records at Lees Ferry were estimated by E. C. La Rue (92a).

A general comparison of the change for the comparatively short run-off records with the long-time precipitation and temperature records indicates clearly, it is believed, that any averages based on the run-off records available in most sections of the country might vary considerably from averages for, say, 100 years. This is a factor which naturally must be given serious consideration in connection with studies or plans based on the available records.

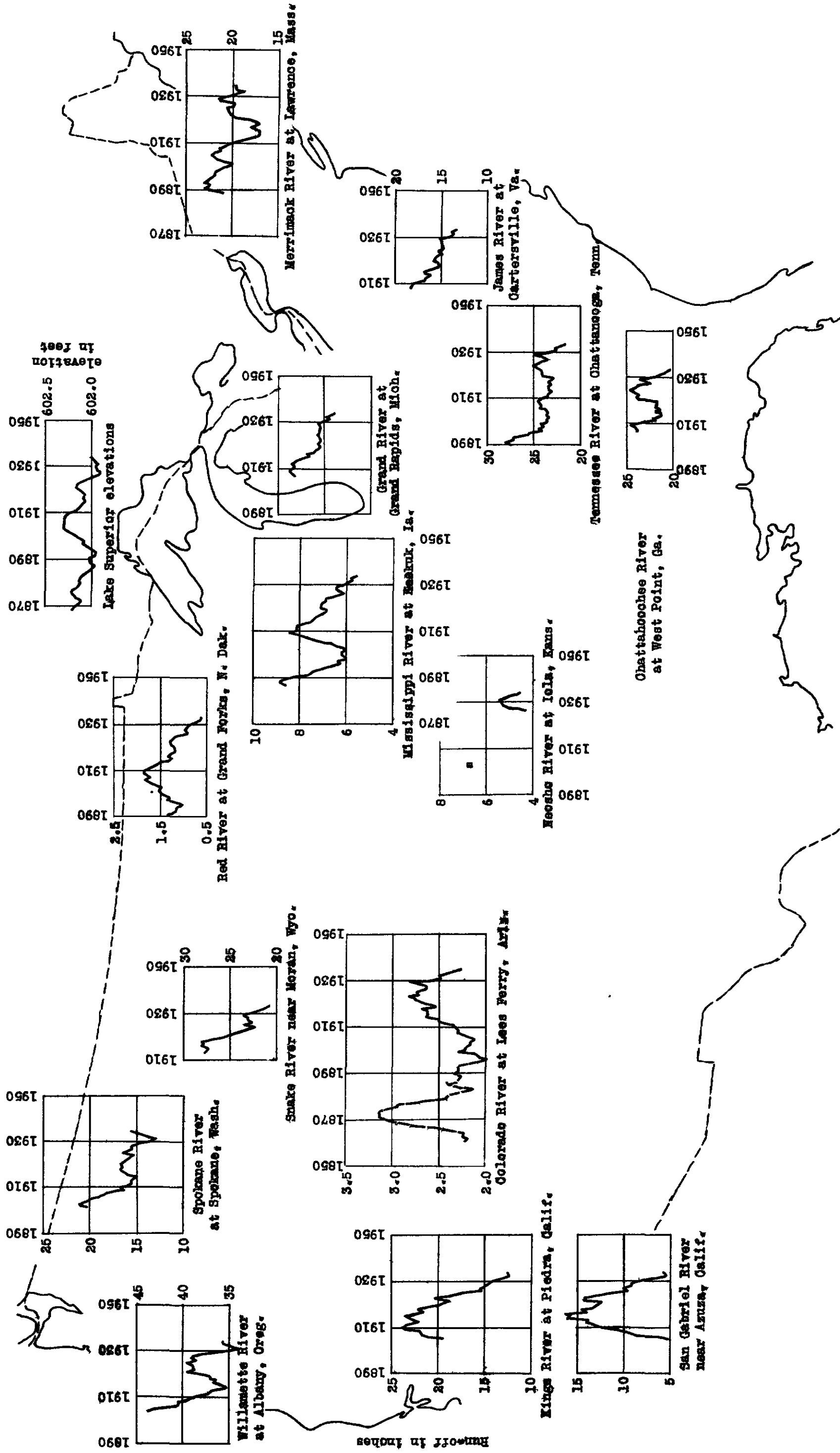


Figure 17.—Ten-year progressive average annual run-off in inches for certain long-time records.

Precipitation, temperature, and run-off, by basins

The changes in the precipitation and temperature already shown by geographic provinces are qualitative rather than quantitative. In the following presentation of the changes in precipitation, temperature, and run-off, by basins, it has been the aim to determine as accurately as possible the magnitude of the several factors. As would be expected, changes within a basin correspond roughly with the changes previously indicated for the particular geographic province or provinces in which the basin may be located.

The correlation of annual rainfall, temperature, and run-off based on long-time averages is necessarily confined to basins where (a) concurrent long-time records are available, (b) the mean annual precipitation and temperature over the entire basin and run-off from the basin have been determined with a fair degree of accuracy, (c) the run-off has not been appreciably changed by storage or diversion, and (d) the precipitation exceeds the combined losses resulting from evaporation and transpiration.

These requirements limit the areas in the United States where studies of this type may be carried on. Many areas in the West cannot be studied, either because the precipitation over the basin as a whole is not accurately known or because storage and diversions are of such magnitude as to affect natural relations materially. Likewise in much of the plains area the annual evaporation and transpiration so nearly equal the annual precipitation that the residual run-off approaches zero.

Records showing annual precipitation, annual temperature, and annual run-off have been made and compiled for the following basins for the periods of record as indicated:

Red River Basin above Grand Forks, N. Dak., 1882-1934.
Mississippi River Basin above Keokuk, Iowa, 1878-1934.
Neosho River Basin above Iola, Kans., 1896-1903, 1918-34.
Merrimack River Basin above Lawrence, Mass., 1880-1934.
James River Basin above Cartersville, Va., 1899-1934.
Tennessee River Basin above Chattanooga, Tenn., 1881-1934.
Chattahoochee River Basin above West Point, Ga., 1897-1934.

As a basis for the preliminary study information for each basin has been compiled and is presented in tables 7 to 21. All precipitation and run-off data are stated in inches over the basin, and all figures are on the basis of the calendar year except those for the Merrimack River Basin, which are on the basis of the year ending September 30.

The precipitation, run-off, and precipitation minus run-off for each basin are presented in the form of graphs on figures 18 to 24.

Red River Basin above Grand Forks, N. Dak.

(Drainage area, 25,500 square miles. Records available, 1882 - 1934)

The Ottertail River, the head of the Red River, rises in the southwest corner of Clearwater County, Minn., at an altitude of about 1,550 feet, and flows south and west to Wahpeton, N. Dak., whence the Red River flows north in a continuous series of short loops, forming the boundary between North Dakota and Minnesota. The basin is very flat, the slope from the sides toward the stream for distances of 5, 10, or 20 miles is usually only a few feet to the mile, in places less than 2 feet to the mile, and the downward slope of the baein to the north is less than 1 foot to the mile, averaging 9 inches to the mile from Wahpeton, N. Dak., about 30 miles north of the southern boundary of the State, to Fargo, and 6½ inches to the mile from Fargo to Grand Forks.

Run-off.- The gage-height record and a few discharge measurements from 1882 to 1901 were collected by the United States Corps of Engineers; since 1901 the United States Geological Survey has maintained the staff gage. The control which consists of clay and silt, shifts slightly, and the stage-discharge relations are affected by ice in winter and aquatic growths in summer.

The winter run-off prior to 1906, with the exception of 1898, 1899, and 1900, was estimated by P. T. Simons, senior drainage engineer, United States Department of Agriculture, who aleo gave a table of monthly run-off from 1882 to 1919 (163). The figures for run-off since 1919 have been taken from the water-supply papers of the United States Geological Survey. All run-off figures are on the basis of the calendar year.

Precipitation.- The precipitation records for 1882 to 1919 were taken from the paper by Simons (163), and those for 1920 to 1923 from a compilation by E. F. Chandler (25); those for 1924 to 1934 were computed by using the arithmetic average of the station records. For the early part of the period of record, when few stations were maintained, Simons calculated separately the average precipitation in each of five subdivisions of the basin and weighted these figures according to their respective areas to get the basin average. The precipitation stations used to compute the basin average were as follows:

Table 7.- Precipitation stations in Red River Basin above Grand Forks, N. Dak.

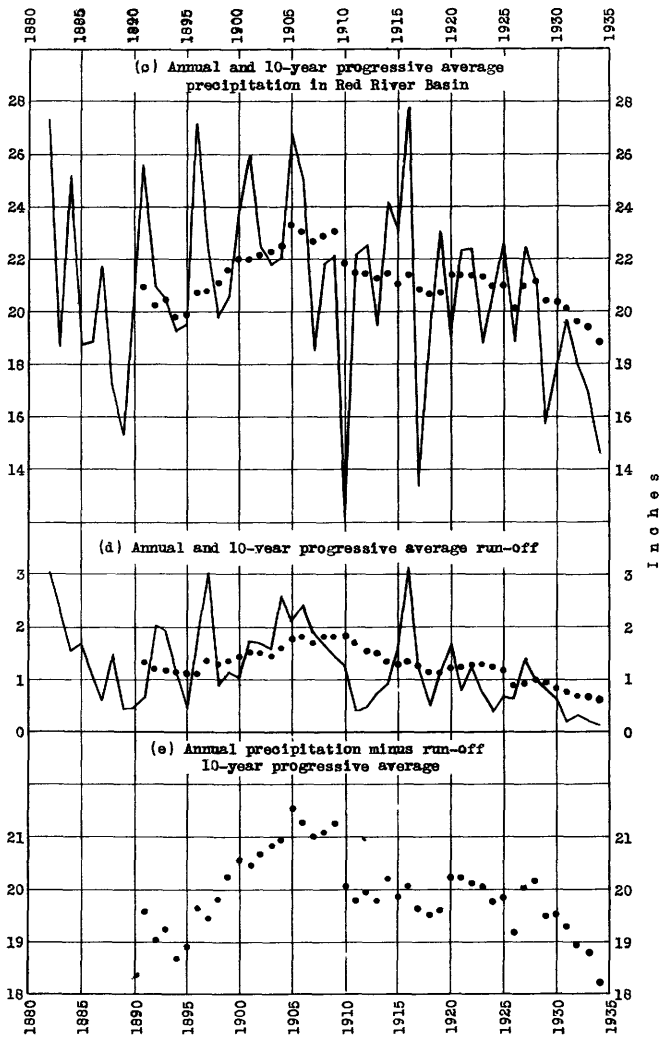
Station	Altitude (feet)	Period of record	Mean annual precipitation (inches)
Minnesota:			
Angus *	870	1920-	18.68
Bemidji *	1,400	1899-1905,1912-	23.88
Campbell *	975	1873-80,1912-	23.74
Crookstown *	888	1890-	20.92
Detroit Lakes *	1,364	1896-	24.84
Fergus Falls *	1,210	1888-	23.96
Fosston *	1,289	1910-	20.12
Gonvick	1,454	1922	19.83
Moorhead *	935	1881-	23.34
Redby *	1,158	1910-	21.84
Thief River Falls *	1,137	1915-	21.32
Wheaton *	1,018	1915-	20.75
North Dakota:			
Amenia *	954	1896-	20.10
Cooperstown	1,428	1890-1907,1915-	17.79
Devils Lake	1,478	1870-90,1897-	18.04
Forman	1,249	1892-	20.72
Grand Forks *	830	1892-	19.49
Hillsboro *	901	1906-	20.35
Larimore *	1,134	1893-	21.13
Lisbon *	1,091	1904-	20.82
McLeod *	1,075	1912-	21.49
Maddock *	1,604	1915-	16.33
Manfred	1,605	1903-	17.55
Mayville *	975	1896-	19.88
Power	1,020	1892-1932	20.94
Sharon	1,516	1924-	19.06
Valley City *	1,245	1905-	18.36
Wahpeton *	962	1892-	21.52

* Station used to compute average basin temperature.

The figures for average annual precipitation over the basin subsequent to 1900, when from 22 to 28 stations fairly well distributed were used, should be fairly accurate. In 1882 there was on the average one station to about 8,500 square miles; in 1930, one to about 910 square miles.

Table 8.- Precipitation, temperature, and run-off data for Red River Basin above Grand Forks, N. Dak.

Year	Precipitation (inches)			Temperature at Moorhead, Minn. (°F.)		Run-off at Grand Forks (inches)			Precipitation minus run-off (inches)		Ratio run-off to precipitation 10-year progressive average (percent)
	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	
1882	27.36	27.36	-	38.4	-	3.06	3.06	-	24.30	-	-
83	18.74	46.10	-	34.1	-	2.22	5.28	-	16.52	-	-
84	25.26	71.36	-	36.4	-	1.56	6.84	-	23.70	-	-
85	18.73	90.09	-	38.0	-	1.70	8.54	-	17.03	-	-
86	18.80	108.89	-	37.7	-	1.04	9.58	-	17.76	-	-
87	21.77	130.66	-	36.4	-	.56	10.14	-	21.21	-	-
88	17.09	147.75	-	36.6	-	1.50	11.64	-	15.59	-	-
89	15.33	163.08	-	40.2	-	.42	12.06	-	14.91	-	-
1890	20.26	183.34	-	38.8	-	.44	12.50	-	19.82	-	-
91	25.62	208.96	20.90	38.9	37.6	.66	13.16	1.32	24.96	19.58	6.32
92	20.97	229.93	20.26	38.5	37.6	2.04	15.20	1.21	18.93	19.05	5.97
93	20.45	250.38	20.43	35.0	37.7	1.93	17.13	1.18	18.52	19.25	5.78
94	19.32	269.70	19.83	40.8	38.1	1.15	18.28	1.14	18.17	18.69	5.75
95	19.55	289.25	19.92	38.5	38.2	.45	18.73	1.02	19.10	18.90	5.13
96	27.20	316.45	20.76	37.7	38.2	1.85	20.58	1.10	25.35	19.66	5.30
97	22.34	338.79	20.81	39.2	38.4	3.05	23.63	1.35	19.29	19.46	6.48
98	19.80	358.59	21.08	40.2	38.8	.89	24.52	1.29	18.91	19.79	6.12
99	20.63	379.22	21.61	39.2	38.7	1.14	25.66	1.36	19.49	20.25	6.29
1900	23.78	403.00	21.97	42.0	39.0	1.02	26.68	1.42	22.76	20.55	6.46
01	26.02	429.02	22.01	41.5	39.3	1.74	28.42	1.53	24.28	20.48	6.96
02	22.46	451.48	22.16	40.7	39.5	1.72	30.14	1.49	20.74	20.67	6.72
03	21.77	473.25	22.29	38.9	39.9	1.59	31.73	1.46	20.18	20.83	6.55
04	22.10	495.35	22.56	38.4	39.6	2.60	34.33	1.60	19.50	20.96	7.09
05	26.92	522.27	23.30	40.1	39.8	2.09	36.42	1.77	24.83	21.53	7.60
06	24.96	547.23	23.08	40.1	40.0	2.46	38.88	1.83	22.50	21.25	7.93
07	18.48	565.71	22.69	37.8	39.9	1.89	40.77	1.71	16.59	20.98	7.54
08	21.84	587.55	22.90	41.6	40.0	1.64	42.41	1.79	20.20	21.11	7.82
09	22.25	609.80	23.06	39.6	40.1	1.41	43.82	1.82	20.84	21.24	7.89
1910	12.21	622.01	21.90	41.9	40.1	1.27	45.09	1.84	10.94	20.06	8.40
11	22.17	644.18	21.52	39.5	39.9	.39	45.48	1.71	21.78	19.81	7.95
12	22.63	666.81	21.53	39.6	39.7	.47	45.95	1.58	22.16	19.95	7.34
13	19.49	686.30	21.30	40.7	39.9	.74	46.69	1.50	18.75	19.80	7.05
14	24.22	710.52	21.52	41.1	40.2	.93	47.62	1.33	23.29	20.19	6.19
15	23.06	733.58	21.13	41.0	40.3	1.57	49.19	1.28	21.49	19.85	6.06
16	27.76	761.34	21.41	37.7	40.1	3.12	52.31	1.34	24.64	20.07	6.26
17	13.41	774.75	20.90	37.4	40.0	1.19	53.50	1.27	12.22	19.63	6.07
18	19.64	794.39	20.68	41.3	40.0	.52	54.02	1.16	19.12	19.52	5.60
19	23.02	817.41	20.76	40.0	40.0	1.18	55.20	1.14	21.84	19.62	5.49
1920	18.81	836.22	21.42	40.8	39.9	1.69	56.89	1.18	17.12	20.24	5.52
21	22.41	858.63	21.44	43.0	40.3	.80	57.69	1.22	21.61	20.22	5.70
22	22.47	881.10	21.43	41.5	40.5	1.27	58.96	1.30	21.20	20.13	6.07
23	18.84	899.94	21.36	41.5	40.5	.70	59.66	1.30	18.14	20.06	6.08
24	20.68	920.62	21.01	39.0	40.3	.38	60.04	1.24	20.30	19.77	5.90
25	22.76	943.38	20.98	41.2	40.3	.71	60.75	1.16	22.05	19.82	5.53
26	18.74	962.12	20.08	40.4	40.6	.64	61.39	.91	18.10	19.17	4.53
27	22.49	984.61	20.99	39.3	40.8	1.41	62.80	.93	21.08	20.06	4.43
28	21.26	1005.87	21.15	42.2	40.9	1.00	63.80	.98	20.26	20.17	4.63
29	15.82	1021.69	20.43	39.0	40.8	.80	64.60	.94	15.02	19.49	4.60
1930	17.95	1039.64	20.34	42.8	41.0	.63	65.23	.83	17.32	19.51	4.07
31	19.67	1059.31	20.07	45.8	41.3	.18	65.41	.77	19.49	19.30	3.84
32	17.94	1077.25	19.62	41.0	41.2	.32	65.73	.68	17.62	18.94	3.47
33	16.50	1093.75	19.38	41.7	41.2	.21	65.94	.63	16.29	18.75	3.24
34	14.67	1108.42	18.78	42.8	41.6	.13	66.07	.60	14.54	18.18	3.19
Total	1108.42	-	-	2107.5	-	66.07	-	-	1042.35	-	-
Av.	20.91	-	-	39.8	-	1.25	-	-	19.67	-	-



Note.— 10-year average plotted at end of period shown thus •

Figure 18.—Relations between rainfall and run-off in Red River Basin above Grand Forks, N. Dak.

Differences in precipitation between one part of the basin and another probably result more from differences in geographic location than from differences in altitude. Such differences show a range from about 24.8 to 16.3 inches on the basis of long-time averages and from about 33.8 to 17.5 inches on the basis of yearly figures. Precipitation generally increases from west to east. The precipitation records are on the basis of the calendar year.

Temperature.- The mean annual temperatures for the period of record at the stations in and adjacent to the basin were averaged and compared with the mean annual temperature recorded at Moorhead and found to be essentially the same. The Moorhead record of annual temperature was therefore used as an approximation of the average annual temperature for the basin. The stations in the basin averaged to compute the normal annual temperature for the basin are indicated in the table of precipitation stations. The temperature records are on the basis of the calendar year.

Mississippi River Basin above Keokuk, Iowa

(Drainage area, 119,000 square miles.
Records available, 1878-1934.)

The Mississippi River rises in an area of small lakes in northeastern Becker County, Minn., at about 1,570 feet above sea level, and flows in a general south and southeast course to Keokuk, Iowa. The major tributaries above Keokuk are the Minnesota, Iowa, and Skunk Rivers from the west and the St. Croix, Chippewa, Wisconsin, and Rock Rivers from the east.

That portion of the basin above St. Paul, an area of 35,700 square miles, is for the most part relatively flat and covered with glacial drift, into which rainfall percolates rapidly. In this part of the basin there are numerous swamps and lakes. The precipitation in this area of 35,700 square miles ranges from an average of about 28 inches a year in the southeastern part to about 23 inches along the northwestern border and averages about 26.5 inches.

The middle portion of the basin, between St. Paul and Le Claire, comprising 52,900 square miles, is also covered with glacial drift. The topography is rougher, however, with increasing slopes toward the river courses. The precipitation on this area averages about 31.2 inches a year.

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The precipitation on the remainder of the Mississippi River Basin above Keokuk, comprising a V - shaped area of 30,400 square miles, covered mostly with alluvial soil, averages 33.0 inches a year.

The fall of the river for about the first 600 miles averages about 1.3 feet to the mile, and the fall in the lower part of the river, from St. Paul to Keokuk, averages between 0.4 and 0.5 foot to the mile.

Run-off.- All the records of flow available for Keokuk prior to 1913 have been based on readings of a gage at the upper lock of the canal, at a place then called "Nashville," now Galland, Iowa, about 8 miles above Keokuk. The gage was founded on a rock and was read twice daily from 1878 to the time when it was drowned out by backwater from the Keokuk Dam, in 1913. The rock bed of rapids below the Nashville gage furnished an excellent control, which is permanent for all stages. Records subsequent to 1913 have been computed as the sum of the flow through the turbines and over the spillways of the power development of Keokuk. All records of flow have been computed and compiled by the Mississippi River Power Co.

There are numerous hydroelectric power developments and several storage reservoirs on the main streams and tributaries, but it is believed that their combined effect on the annual discharge is very small.

Precipitation.- The average annual precipitation ranges from about 25 to 35 inches across the basin. The estimates of annual precipitation over the basin probably increase rather rapidly in accuracy from 1878 to 1900 and should be reasonably accurate and consistent from 1900 to date. Prior to 1900, but more especially prior to 1890, not only were the precipitation stations few but their distribution was poor, especially in Wisconsin. The number of precipitation stations available in determining the annual precipitation over the basin was as follows:

1871 - 18 stations	1910 - 178 stations
1878 - 40 stations	1920 - 178 stations
1890 - 63 stations	1930 - 181 stations
1900 - 144 stations	

The precipitation stations used to compute the basin average were as follows:

Table 9.- Precipitation stations in or near Mississippi River Basin above Keokuk, Iowa

Station	Altitude (feet)	Period of record	Mean annual precipitation (inches)
Illinois:			
Aledo	739	1901-	33.87
Dixon	696	1887,1892-	33.19
Elgin	717	1898-1900,1911-	32.67
Freeport	762	1886-89,1909-	32.69
Galena	603	1896-1901,1928-	32.07
Galesburg	758	1862-71,1885-89 1895-1909,1927-	35.45
Galva	849	1865-69,1873-82,1893-	33.12
Geneseo	639	1873-82,1886-87 1895-1908,1925-	34.55
La Harpe	691	1895-	36.38
Marengo	819	1856-	33.11
Monmouth	763	1894-	34.51
Morrison	670	1896-	34.07
Mount Carroll	817	1887-91,1895-	33.97
Oregon	702	1893-94,1896,1910-	32.17
Paw Paw	928	1913-	32.51
Rochelle	798	1924-	36.15
Rockford	720	1874-	34.64
Sycamore	840	1882-	34.63
Walnut	714	1892-	33.60
Iowa:			
Allison	1,000	1914-	30.72
Amana	721	1876-1915	33.32
Ames	926	1876-	30.58
Baxter	993	1899-1932	31.73
Belle Plaine	866	1876-	34.25
Belmond	1,181	1909-	32.18
Bonaparte	563	1886-89,1891-	33.52
Boone	894	1871-81,1894-	32.88
Britt	1,236	1876,1879-89,1897-	28.14
Burlington	544	1876-82,1897-	36.63
Cedar Rapids	737	1882-	31.22
Charles City	1,015	1875-	31.49
Clinton	595	1865-71,1878--	35.76
Columbus Junction	595	1879-87,1900-	34.15
Davenport	580	1871-	32.14
Decorah	872	1844-46,1878-83,1892-	32.96
Delaware	1,083	1854-58,1875-1921,1930-	33.53
Dubuque	700	1851-	32.90
Elkader	751	1872-1920	32.80
Fairfield	780	1856-59,1876-88 1891-1902,1908-	36.21
Fairport	600	1921-30	35.83
Farmersburg	1,079	1836-1930	31.67
Fayette	1,003	1888-	34.04
Forest City	1,226	1887-89,1894-	29.33
Fort Madison	522	1848-1918	36.58
Grinnell	1,031	1876,1878,1880-83 1888-90,1893-	34.43
Grundy Center	976	1891-	32.86
Hampton	1,142	1877-81,1888-1915,1924-32	33.76
Independence	956	1860-	32.87
Iowa City	733	1857-	36.22
Iowa Falls	1,127	1863-72,1892-	33.85
Keokuk	614	1871-	32.64
Lansing	632	1896-1904,1912-32	32.47
Maquoketa	692	1876,1878-84,1887-90 1892-93,1896-1906 1914-20,1925-	33.62

Table 9.- Precipitation stations in or near Mississippi River Basin above Keokuk, Iowa--Continued

Station	Altitude (feet)	Period of record	Mean annual precipitation (inches)
Iowa--Continued.			
Marshalltown	947	1876-88,1891-	31.99
Mason City	1,148	1887-89,1893-1900,1903-	29.56
Monroe	922	1911-	34.04
Mount Pleasant	730	1876-	34.15
Muscatine	546	1846-	36.72
New Hampton	1,169	1897-	31.74
Northwood	1,222	1896-	33.46
Oelwein	1,036	1923-	32.70
Olin	750	1898-	34.21
Osage	1,163	1876-1916,1925-	30.75
Oskaloosa	835	1876-	31.12
Ottumwa	649	1876,1878-80,1884-86,1894-	33.16
Pella	850	1898-1903,1905-25,1927-28	30.86
Postville	1,192	1891-	33.61
Sigourney	785	1896-	33.18
Stockport	747	1901-	34.34
Tipton	806	1876-80,1891-94,1901-	34.80
Toledo	847	1894-	32.87
Washington	757	1875-	33.14
Waterloo	854	1876-88,1895-	31.21
Waverly	936	1878-81,1887-89,1896-	31.69
Webster City	1,042	1870,1876-81,1885-94 1896-1900,1905-	30.13
Whitten	1,036	1897-1920	31.49
Williamsburg	805	1916-	33.24
Minnesota:			
Albert Lea	1,229	1886,1892-1900,1902-	29.20
Ah-gwa-ohing *	1,336	1908-13,1916,1919-	22.52
Alexandria	1,391	1888-	22.98
Artichoke Lake	1,075	1918-	18.96
Bagley	1,438	1907-16	22.78
Beardsley	1,090	1894-1907,1915-24,1928-	22.56
Bemidji	1,400	1912-19,1922-	23.88
Bird Island	1,039	1885-86,1892-	24.18
Brainerd	1,215	1889,1899-1902,1912-	23.37
Caledonia	1,179	1890-1908,1911-14,1918	32.08
Canby	1,243	1917,1919-24,1926,1929-31	25.34
Cass Lake	1,323	1908-	21.95
Chatfield	975	1914-27	29.81
Collegeville	1,242	1893-	22.88
Detroit Lakes	1,364	1896-	24.84
Fairbault	1,003	1897-98,1900-10,1914-	25.84
Fairmont	1,240	1887-	28.10
Farmington	902	1888-1918,1920-22,1924-	27.23
Fergus Falls	1,210	1888-	23.96
Fort Ripley	1,136	1889-94,1907-	21.30
Glencoe	1,006	1894-1910,1912,1915-17	25.51
Gonvick	1,454	1922-	19.83
Grand Meadow	1,338	1886-	31.66
Hinckley	1,050	1910,1914-15,1917-21	25.85
Hutchison	1,040	1893-99,1917-20	25.54
Itasca State Park	1,500	1912-14,1916-18,1921-	22.61
Lake Crystal	990	1912,1914-15,1917-18	29.61
Leach Lake Dam	1,301	1888-	25.20
Little Falls	1,115	1908-9,1914,1917,1921-	24.24
Long Prairie	1,229	1893-1908,1910,1917	24.26
Lynd	1,175	1893-1927	25.15
Mankato	773	1887-91,1905-	27.79

* Formerly known as State Sanitarium.

Table 9.- Precipitation stations in or near Mississippi River Basin above Keokuk, Iowa--Continued

Station	Altitude (feet)	Period of record	Mean annual precipitation (inches)
Minnesota--Continued.			
Maple Plain	1,023	1892-1907,1915-	29.91
Milaca	1,072	1898-1900,1903-5 1908-9,1917-	25.44
Milan	955	1894	23.23
Minneapolis	918	1856-59,1866-	27.66
Montevideo	900	1890-99,1901-	23.41
Moose Lake	1,085	1899-1902,1904-5,1915-17	27.73
Mora	1,001	1905-	26.47
Morris	1,170	1886-1917,1920-	23.57
New London	1,215	1895-	22.75
New Richland	1,180	1902-6,1908-12,1914-18	29.61
New Ulm	791	1865-77,1894-	29.40
Northfield	916	1882-92	29.94
Ortonville	990	1888-1908	23.60
Park Rapids	1,426	1885-87,1893-	24.65
Pine River Dam	1,251	1887-	25.75
Pipestone	1,710	1899-1903,1906-13 1916,1921-	23.34
Pokegama Falls	1,280	1888-	24.90
Redby	1,158	1910-12,1914-15,1917-	21.84
Red Lake Falls	1,001	1915-21,1923,1925 1927-30,1932-	21.37
Red Wing	680	1886-1919,1931-	29.24
Redwood Falls	1,050	1888-94,1907-11 1916-19,1921-	24.73
Reeds	681	1893-1919,1931-	28.84
Rochester	991	1909-19,1929-	28.16
St. Charles	850	1890-1901,1904-22	30.62
St. Cloud	1,020	1893-1914,1916-18,1921-	26.62
St. Paul	837	1836-1932	27.27
St. Peter	825	1888-91,1894-1909,1912 1914-16,1919-	26.74
Sandy Lake Dam	1,234	1893-1909,1911-	24.99
Stillwater	694	1908,1910-18	29.92
Taylor Falls	759	1908-9,1912-15,1917-	26.27
Tracy	1,403	1888-90,1914-	22.36
Wadena	1,350	1905-6,1921, 1924-28 1931,1934	24.16
Waseca	1,153	1916-	28.04
Willmar	1,133	1893-1900,1917-	24.03
Windom	1,356	1893,1908-10,1914-15,1917	27.30
Winnebago	1,000	1895-1917,1920-	28.30
Winnibigoshish Dam	1,315	1888-	24.67
Winona	700	1886,1893-99,1902-26 1928-29,1931-	30.29
Zumbrota	917	1894-96,1904-10 1912-19,1921-	27.47
South Dakota:			
Brookings	1,628	1889-	20.18
Milbank	1,142	1890-	23.31
Roslyn	1,813	1899-1902,1906-19	21.84
Watertown	1,734	1893,1895-	21.11
Webster	1,841	1896,1899-1903 1906-19,1921-	22.22
Wisconsin:			
Amery	1,070	1922-	26.81
Antigo	1,489	1894-	29.55
Baraboo	854	1892-94,1914-21	33.72

Table 9.- Precipitation stations in or near Mississippi River Basin above Keokuk, Iowa--Continued

Station	Altitude (feet)	Period of record	Mean annual precipitation (inches)
Wisconsin--Continued.			
Barron	1,115	1891-1921	31.36
Beloit	750	1850-	33.18
Big St. German Dam	1,590	1910-	30.19
Brodhead	812	1898-	33.71
Burnett	880	1904-	29.34
Coddington	1,074	1921-	29.90
Crandon	1,650	1891-1903,1907-19	28.01
Danbury	908	1920-	26.45
Darlington	867	1901-5,1910-	32.72
Deerskin Dam	1,683	1910-	29.82
Delevan	920	1887-1903,1907-21	30.65
Dodgeville	1,220	1897-1903,1914-16	31.53
Downing	983	1891-95,1898-	31.49
Eau Claire	800	1891-	32.63
Grantsburg	1,095	1889-90,1892-	30.11
Hancock	1,086	1892-	30.76
Hatfield	973	1894-	30.27
Hayward	1,197	1890-1923	28.69
Hillsboro	980	1891-	32.17
Koepenick	1,681	1891-1918,1920-24	31.54
La Crosse	714	1873-	30.81
Lake Mills	847	1891-	32.84
Lancaster	1,060	1891-1918,1921-	31.58
Long Lake	1,592	1908-	29.31
Madison	974	1869-	31.98
Marshfield	1,250	1913-	31.47
Mather	962	1903-	32.10
Mauston	882	1896-1919,1924-	31.88
Meadow Valley	974	1891-	29.42
Medford	1,420	1890-	32.98
Menomonee Falls	842	1909-15	34.19
Merrill	1,267	1906-	30.88
Milwaukee	681	1841,1844-52,1854-	30.08
Minocqua	1,604	1904-	29.71
Mondovi	738	1908-	31.96
Mount Horeb	1,226	1904-20	34.12
Muscoda	666	1909-19	30.38
Neillsville	1,060	1876-86,1890-	33.26
New Richmond	990	1905-17	29.38
Osceola	806	1891-20	30.72
Park Falls	1,492	1910-	32.98
Portage	809	1889-	31.15
Port Edwards	969	1910-19	32.73
Prairie du Chien	628	1837-45,1891-	30.96
Prairie du Sac	750	1908-	28.50
Prentice	1,551	1898-	31.99
Racine	633	1897-	30.81
Reedsburg	876	1914-19	32.26
Rest Lake	1,600	1910-	30.48
Rhinelander	1,550	1908-	29.67
Richland Center	735	1892,1908,1920-	31.48
River Falls	902	1918-	29.73
Shullsburg	1,019	1906-18	35.77
Solon Springs	1,083	1906-	28.19
Spooner	1,104	1894-	27.54
Stanley	1,082	1903-	33.55
Stevens Point	1,113	1893-	31.94
Sugar Camp Dam	1,580	1910-20	30.03
Tomahawk	1,450	1913-24	31.03
Twin Lakes Dam	1,625	1910-20	27.46
Viroqua	1,281	1890-	33.16
Vudesare	1,600	1908-17	31.72

Table 9.- Precipitation stations in or near Mississippi River Basin above Keokuk, Iowa--Continued

Station	Altitude (feet)	Period of record	Mean annual precipitation (inches)
Wisconsin--Continued.			
Watertown	824	1891-	32.45
Waukesha	864	1892-	31.19
Wausau	1,247	1896-1900,1902-	32.11
West Bend	941	1895-1902,1922-	30.00
Weyerhauser	1,337	1895-96,1907-	31.91
Whitehall	675	1891-92,1895,1897-1906 1910-17,1919-20	30.21
Williams Bay	1,025	1903-	31.96
Wisconsin Dells	900	1922-	30.19
Wisconsin Rapids	1,036	1893-97,1903	30.89

During the period 1871-77, 18 precipitation stations were used; the records for 11 stations in the southern section, controlling 26.2 percent of the area, were averaged, and those for the remaining 7 stations were weighted according to area. The figures for Twin Cities and Duluth were modified according to their relation, during the period 1921-30, to the average for the stations lying within the areas controlled by Minneapolis, St. Paul, and Duluth. The same method was used for the period 1878-85, the records for 29 stations in the southern section, controlling 29.3 percent of the area, being averaged, and those for the remaining 11 stations weighted according to area, Twin Cities, Duluth, and Neillsville being modified as stated above.

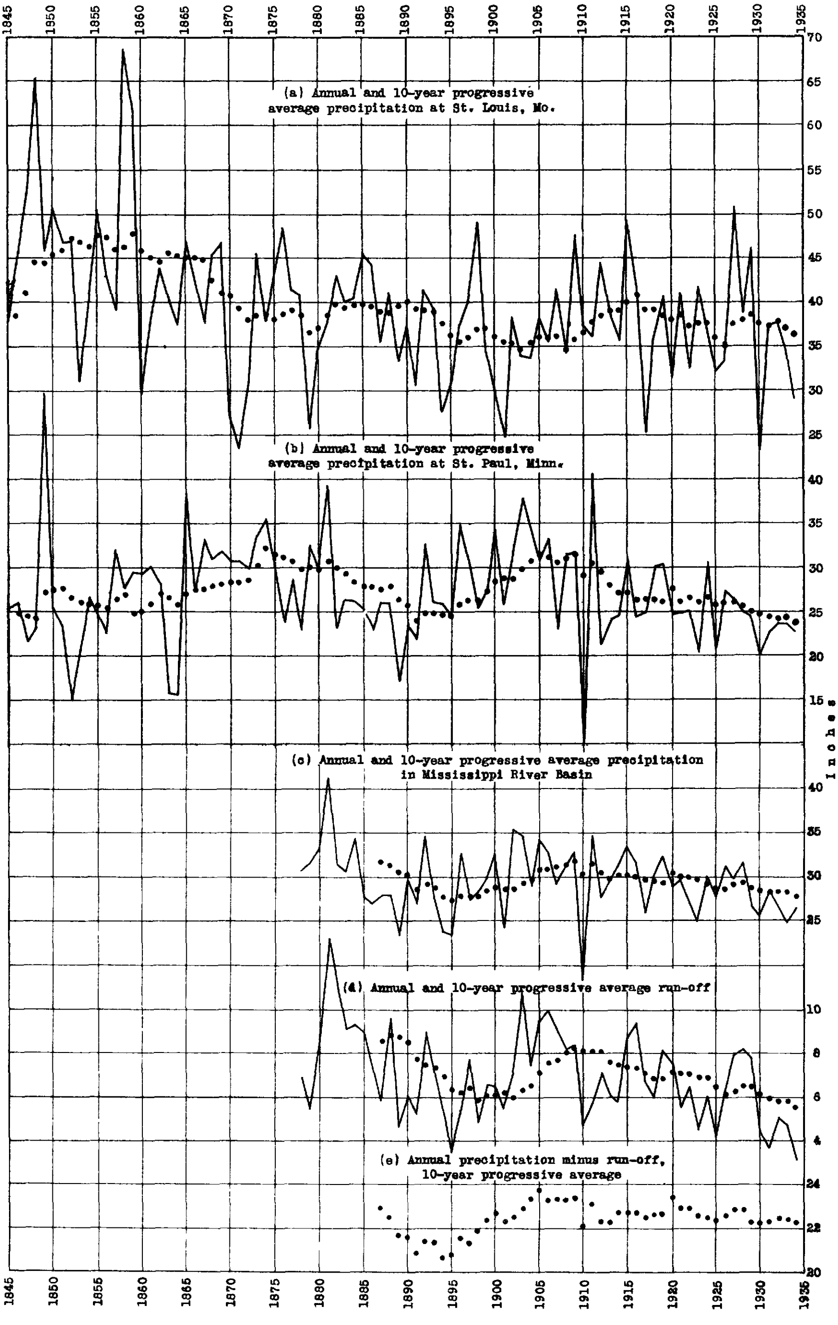
From 1886 to 1934 the records for the stations lying within the boundaries of each State were averaged, and this average was weighted as to that part of the area of the State lying in the Mississippi River drainage basin, in percentage of the area of the basin above Keokuk; from these weighted averages the average annual precipitation for the basin was determined.

Temperature.- Seven stations with long records and well distributed over the basin were selected, and their records were averaged to determine the average annual temperature of the basin. These seven stations are listed in table 11.

Table 10.- Precipitation, temperature, and run-off data for Mississippi River Basin above Keokuk, Iowa

Year	Precipitation (inches)			Temperature * (°F.)		Run-off at Keokuk (inches)			Precipitation minus run-off (inches)		Ratio run-off to precipitation 10-year progressive average (percent)
	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	
1878	30.60	30.60	-	48.6	-	6.96	6.96	-	23.64	-	-
79	31.74	62.34	-	45.4	-	5.49	12.45	-	26.25	-	-
1880	33.15	95.49	-	45.4	-	8.59	21.04	-	24.56	-	-
81	41.28	136.77	-	46.0	-	13.19	34.23	-	28.09	-	-
82	31.49	168.26	-	46.2	-	10.92	45.15	-	20.57	-	-
83	30.47	198.73	-	42.3	-	9.11	54.26	-	21.36	-	-
84	34.33	233.06	-	43.6	-	9.34	63.60	-	24.99	-	-
85	27.82	260.88	-	42.6	-	8.99	72.59	-	18.83	-	-
86	26.96	287.84	-	44.3	-	7.57	80.16	-	19.39	-	-
87	27.92	315.76	31.58	43.5	44.8	5.88	86.04	8.60	22.04	22.98	27.2
88	28.00	343.76	31.32	42.5	44.2	9.61	95.65	8.87	18.39	22.45	28.3
89	23.27	367.03	30.47	45.7	44.2	4.65	100.30	8.78	18.62	21.69	28.8
1890	29.82	396.85	30.14	45.0	44.2	6.16	106.46	8.54	23.66	21.60	28.3
91	26.79	423.64	28.69	45.0	44.1	5.29	111.75	7.75	21.50	20.94	27.0
92	34.76	458.40	29.01	43.8	43.8	9.07	120.82	7.57	25.69	21.44	26.1
93	27.56	485.96	28.72	42.5	43.9	7.20	128.02	7.38	20.36	21.34	25.7
94	23.77	509.73	27.67	47.0	44.2	5.53	133.55	7.00	18.24	20.67	25.3
95	23.56	533.29	27.24	44.5	44.4	3.49	137.04	6.44	20.07	20.80	23.7
96	32.93	566.22	27.84	45.3	44.5	5.41	142.45	6.23	27.52	21.61	22.4
97	27.30	593.52	27.78	45.0	44.6	7.77	150.22	6.42	19.53	21.36	23.1
98	28.46	621.98	27.82	45.8	45.0	4.87	155.09	5.94	23.59	21.88	21.4
99	29.94	651.92	28.49	44.9	44.9	6.65	161.74	6.14	23.29	22.35	21.6
1900	32.87	684.79	28.79	46.7	45.1	6.55	168.29	6.18	26.32	22.61	21.5
01	24.17	708.96	28.53	45.9	45.1	5.55	173.84	6.21	18.62	22.32	21.8
02	35.22	744.18	28.68	45.6	45.3	7.12	180.96	6.01	28.10	22.57	21.0
03	34.65	779.03	29.31	44.4	45.5	10.73	191.69	6.37	24.12	22.94	21.7
04	29.09	808.12	29.84	43.1	46.1	7.49	199.18	6.56	21.60	23.28	22.0
05	34.21	842.33	30.90	44.6	45.1	9.44	208.62	7.16	24.77	23.74	23.2
06	32.83	875.16	30.89	45.6	45.2	9.94	218.56	7.61	22.89	23.28	24.6
07	29.09	904.25	31.07	43.7	45.0	9.01	227.57	7.74	20.08	23.33	24.9
08	31.36	935.61	31.36	46.4	45.1	8.19	235.76	8.07	23.17	23.29	25.7
09	32.79	968.40	31.65	44.6	45.1	8.36	244.12	8.24	24.43	23.41	26.1
1910	18.24	986.64	30.19	46.2	45.0	4.74	248.86	8.06	13.50	22.13	26.7
11	34.53	1021.17	31.22	45.9	45.0	5.75	254.61	8.08	28.78	23.14	25.9
12	27.67	1048.84	30.47	43.5	44.8	7.10	261.71	8.08	20.57	22.39	26.5
13	29.86	1078.70	29.97	46.1	45.0	6.07	267.78	7.61	23.79	22.36	25.4
14	31.04	1109.74	30.16	45.7	45.2	5.77	273.55	7.44	25.27	22.72	24.7
15	33.67	1143.41	30.11	45.3	45.3	8.62	282.17	7.36	25.05	22.75	24.4
16	31.46	1174.87	29.97	43.9	45.1	9.41	291.58	7.30	22.05	22.67	24.3
17	25.89	1200.76	29.65	41.4	44.9	6.76	298.34	7.08	19.13	22.57	23.9
18	29.87	1230.63	29.50	45.6	44.8	5.96	304.30	6.85	23.91	22.65	23.2
19	32.43	1263.06	29.47	45.3	44.9	8.11	312.41	6.83	24.32	22.64	23.2
1920	28.87	1291.93	30.53	45.1	44.8	7.55	319.96	7.11	21.32	23.42	23.3
21	29.53	1321.46	30.03	48.4	45.0	5.48	325.44	7.08	24.05	22.95	23.6
22	26.92	1348.38	29.95	46.5	45.3	6.44	331.88	7.02	20.48	22.93	23.4
23	24.93	1373.31	29.46	45.7	45.3	4.48	336.36	6.86	20.45	22.60	23.3
24	30.27	1403.58	29.38	43.1	45.0	6.03	342.39	6.88	24.24	22.50	23.4
25	27.69	1431.27	28.79	45.3	45.0	4.21	346.60	6.44	23.48	22.35	22.4
26	31.28	1462.55	28.77	44.1	45.1	6.38	352.98	6.14	24.90	22.63	21.4
27	29.73	1492.28	29.15	44.8	45.4	7.92	360.90	6.26	21.81	22.89	21.4
28	31.63	1523.91	29.33	46.0	45.4	8.17	369.07	6.48	23.46	22.85	22.1
29	26.61	1550.52	28.75	43.3	45.2	7.77	376.84	6.44	18.84	22.31	22.4
1930	25.40	1575.92	28.40	46.9	45.4	4.47	381.31	6.14	20.93	22.26	21.6
31	28.64	1604.56	28.31	50.5	45.6	3.62	384.93	5.95	25.02	22.36	21.0
32	26.42	1630.98	28.26	45.6	45.5	5.04	389.97	5.81	21.38	22.45	20.6
33	24.63	1655.61	28.23	46.8	45.6	4.70	394.67	5.83	19.93	22.40	20.6
34	26.57	1682.18	27.86	47.4	46.1	3.12	397.79	5.54	23.45	22.32	19.9
Total	1682.18	-	-	2573.9	-	397.79	-	-	1284.39	-	-
Av.	29.51	-	-	45.2	-	6.98	-	-	22.53	-	-

* Stations used to compute average temperature over the basin are given in table 11.



Note.— 10-year average plotted at end of period shown thus •

Figure 19.—Relations between rainfall and run-off in Mississippi River Basin above Keokuk, Iowa.

Table 11.- Temperature stations in or near Mississippi River Basin above Keokuk, Iowa

Station	Altitude (feet)	Period of record	Mean annual temperature (°F.)
Iowa:			
Dubuque	700	1851-	48.1
Keokuk	614	1872-	52.2
Minnesota:			
Duluth	1,133	1871-	38.0
Moorhead	935	1881-	39.2
St. Paul	837	1820-1932	44.2
Wisconsin:			
La Crosse	714	1873-	46.2
Madison	974	1869-	45.8

Neosho River Basin above Iola, Kans.

(Drainage area, 3,800 square miles. Records available, 1895-1903, 1918-34.)

The Neosho River rises in the north-central part of Morris County, Kans., at an altitude of about 1,500 feet, and flows in a general southeasterly direction to Iola, Kans., a distance of about 120 miles. In this distance the average fall is about 4 feet to the mile. The average width of the basin is about 30 miles. The Neosho River drains a rich agricultural territory which is in a good state of cultivation.

Run-off.- For the period October 12, 1917, to December 31, 1934, a water-stage recorder was located 2½ miles south and 1½ miles west from Iola, Allen County, half a mile below Elm Creek and 8 miles above Owl Creek. From August 1, 1895, to November 30, 1903, there was a staff gage 4 miles downstream from the present location. The drainage area for this early period as printed was 3,670 square miles; the figure 3,800 square miles was considered a correction to the original measurement.

From 1895 to 1903 the United States Geological Survey published daily gage heights, rating table, and a summary of monthly discharges. The records of daily discharge for this period are published in "Surface water of Kansas, 1895-1919," by the State of Kansas Water Commission, 1920. Since October 1917 the United States Geological Survey has published records of daily and monthly discharge. The low-water flow is regulated to a slight extent by dams upstream. The stage-discharge relation for the later period is practically permanent, and the records are considered good. The control for the earlier record was composed of gravel and shifted somewhat, but three to five discharge measurements were made each year to define the rating, and the records were considered fair to good. The records here used are for the calendar year.

Precipitation.- The average annual precipitation over the basin was computed by averaging the annual records at all the precipitation stations in and adjacent to the basin. These stations are listed below.

Table 12.- Precipitation stations in or near Neosho River Basin above Iola, Kans.

Station	Altitude (feet)	Period of record	Mean annual precipitation (inches)
Kansas:			
Bazaar	1,260	1902-3,1905-	31.36
Burlington *	1,010	1894-	36.52
Council Grove	1,234	1909-	30.89
Elmdale	1,195	1925-	30.46
Emporia *	1,138	1881-	33.17
Eskridge	1,412	1907-	35.29
Garnett	1,046	1906-14,1918-	37.95
Herrington	1,328	1918-	31.15
Hesston	1,483	1923-	32.08
Iola	984	1906-	37.65
Lebo *	1,138	1887-	35.59
Le Roy	990	1909-	36.34
Lindsborg	1,333	1911-23,1930-	26.98
Marion	1,310	1908-	31.31
McPherson *	1,495	1877,1889-	30.66
Neosho Rapids	1,092	1906-	33.27
Newton *	1,454	1897-	31.73
Osage City *	1,081	1897-1912,1914-	33.99
Yates Center	1,068	1880-1921,1923-28	35.96

* Station used in 1897 along with Yates Center.

The accuracy of the computed average precipitation probably increases rather rapidly from 1904 to 1908 and is probably good thereafter. Differences in precipitation between one part of the basin and another probably result more from differences in geographic location than from differences in altitude. Such differences showed a range from about 27.0 to 38.0 inches on the basis of the long-time average, and the maximum range in 1912 was from about 21.1 to 47.9 inches. The records are on the basis of the calendar year.

Table 13.- Precipitation, temperature, and run-off data for Neosho River Basin above Iola, Kans.

Year	Precipitation (inches)			Temperature at Wichita, Kans. minus 1° (°F.)		Run-off at Iola (inches)			Precipitation minus run-off (inches)		Ratio run-off to precipitation 10-year progressive average (percent)
	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	
1896	34.09	34.09	-	57.0	-	4.74	4.74	-	29.35	-	-
97	24.76	58.85	-	56.2	-	1.51	6.25	-	23.25	-	-
98	42.49	101.34	-	54.6	-	8.01	14.26	-	34.48	-	-
99	32.49	133.83	-	54.7	-	4.01	18.27	-	28.48	-	-
1900	38.82	172.65	-	56.4	-	5.71	23.98	-	33.11	-	-
01	23.66	196.31	-	56.3	-	3.65	27.63	-	20.01	-	-
02	47.09	243.40	-	54.7	-	12.27	39.90	-	34.82	-	-
03	40.78	284.18	35.52*	54.3	-	12.40	52.30	6.54*	28.38	28.98*	18.4*
04	41.02	325.20	-	55.2	-	-	-	-	-	-	-
05	34.85	360.05	36.01	54.2	55.4	-	-	-	-	-	-
06	32.40	392.45	35.84	54.5	55.1	-	-	-	-	-	-
07	33.45	425.90	36.71	55.6	55.1	-	-	-	-	-	-
08	41.20	467.10	36.58	56.2	55.2	-	-	-	-	-	-
09	39.18	506.28	37.25	55.0	55.2	-	-	-	-	-	-
1910	27.90	534.18	36.15	56.4	55.2	-	-	-	-	-	-
11	27.71	561.89	36.56	56.4	55.3	-	-	-	-	-	-
12	31.67	593.56	35.02	53.3	55.1	-	-	-	-	-	-
13	28.67	622.23	33.81	55.6	55.2	-	-	-	-	-	-
14	29.02	651.25	32.61	56.3	55.4	-	-	-	-	-	-
15	48.74	699.99	33.99	54.4	55.4	-	-	-	-	-	-
16	35.73	735.72	34.33	54.8	55.4	-	-	-	-	-	-
17	24.38	760.10	33.42	53.6	55.2	-	-	-	-	-	-
18	31.32	791.42	32.43	55.4	55.1	1.52	1.52	-	29.80	-	-
19	26.84	818.26	31.20	54.5	55.1	4.37	5.89	-	22.47	-	-
1920	31.63	849.89	31.57	54.8	54.9	1.41	7.30	-	30.22	-	-
21	28.59	878.48	31.66	58.2	55.1	1.79	9.09	-	26.80	-	-
22	39.14	917.62	32.41	56.2	55.4	6.67	15.76	-	32.47	-	-
23	34.75	952.37	33.01	55.9	55.4	5.51	21.27	-	29.24	-	-
24	30.23	982.60	33.14	53.9	55.2	2.67	23.94	-	27.56	-	-
25	29.73	1012.33	31.23	56.3	55.4	1.95	25.89	-	27.78	-	-
26	36.09	1048.42	31.27	55.1	55.4	6.08	31.97		30.01	-	-
27	42.94	1091.36	33.13	55.4	55.6	11.50	43.47	4.35	31.44	28.78	13.1
28	41.12	1132.48	34.11	56.1	55.6	8.78	52.25	5.07	32.34	29.03	14.9
29	34.86	1167.34	34.91	54.0	55.6	7.08	59.33	5.34	27.78	29.56	15.3
1930	27.71	1195.05	34.52	56.2	55.7	2.13	61.46	5.42	25.58	29.10	15.7
31	32.26	1227.31	34.88	58.3	55.7	2.89	64.35	5.53	29.37	29.36	15.8
32	29.41	1256.72	33.91	55.8	55.7	3.24	67.59	5.18	26.17	28.73	15.3
33	25.89	1282.61	33.02	58.9	56.0	1.37	68.96	4.77	24.52	28.26	14.5
34	26.76	1309.37	32.68	58.7	56.5	1.04	70.00	4.61	25.72	28.07	14.1
Total	1309.37	-	-	2169.4	-	70.00#	-	-	479.27#	-	-
Av.	33.57	-	-	55.6	-	4.12#	-	-	28.19#	-	-

* Average of 8 years
\# For the period 1918-34

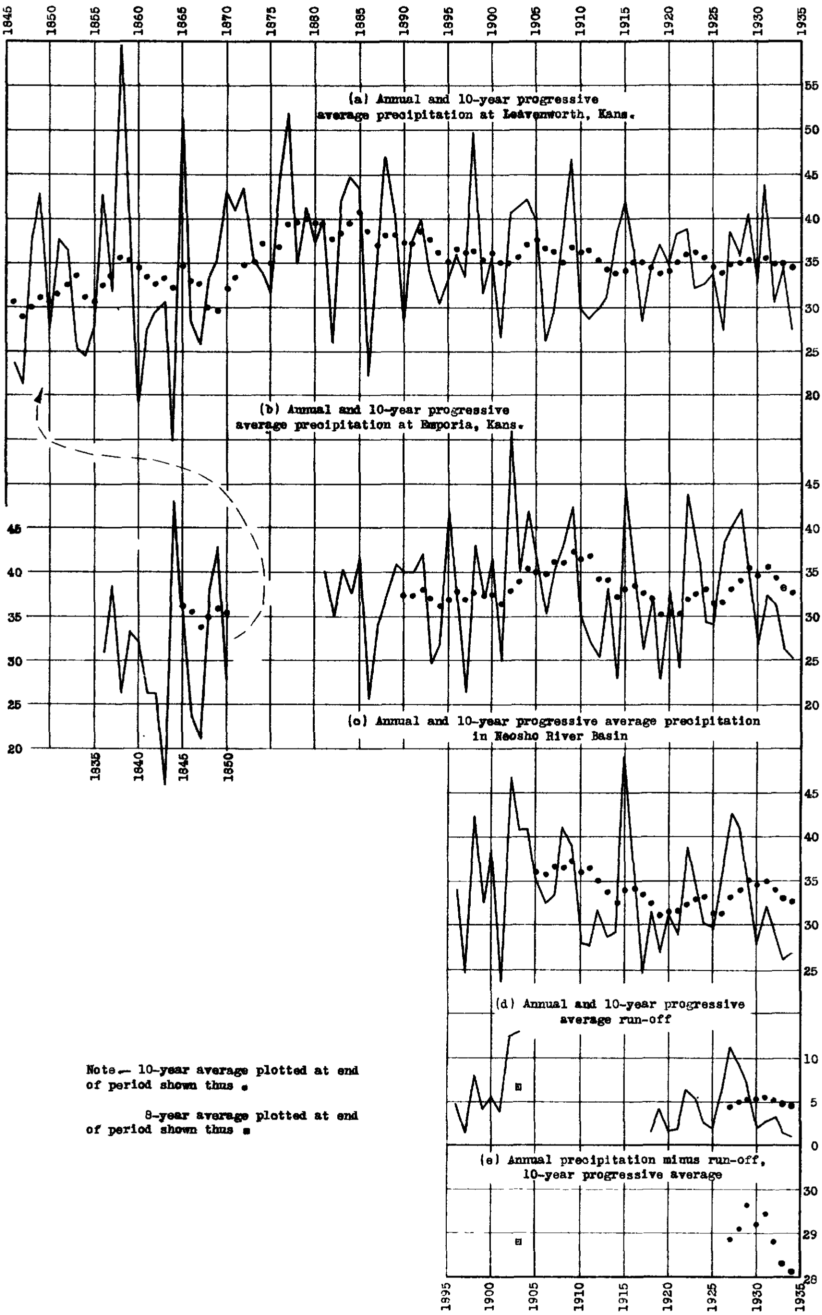


Figure 20.—Relation between rainfall and run-off in Neosho River Basin above Iola, Kans.

Temperature.- The normal annual temperature for the period of record of the stations in and adjacent to the basin was averaged and compared with the normal annual temperature at Wichita and was found to be about 0.8° lower. The annual temperature at Wichita minus 1° was taken as representative of the average annual temperature for the basin.

Merrimack River Basin above Lawrence, Mass.

(Net drainage area, 4,461 square miles.
Records available, 1880-1934.)

The Merrimack River, the fourth largest stream in New England, begins at Franklin, N. H., and is formed by the junctions of the Pemigewasset and Winnepesaukee Rivers, which have drainage areas of 1,085 and 435 square miles, respectively. The Pemigewasset rises in the White Mountains of New Hampshire at an altitude of 5,000 feet and flows 70 miles south to Franklin, with an average slope of 15 feet or more to the mile. The Merrimack flows from Franklin south 40 miles to Manchester, N. H. (altitude 110 feet), then south 30 miles to Lowell, Mass. (altitude 50 feet), and then east 15 miles to Lawrence, Mass. (altitude 40 feet).

The length of the Merrimack and Pemigewasset Rivers above Lawrence is about 155 miles and the average width of the basin about 50 miles. The total drainage area is 4,672 square miles, which includes parts of the basins of the Nashua and Sudbury Rivers and Lake Cochituate from which water is diverted.

The upper part of the basin, in the White Mountains, is largely covered with second and third growth forest and is sparsely settled, but farther downstream the improved areas are more extensive. The topography of the White Mountain district is very rugged, with steep slopes and narrow valleys. From Franklin southward the country becomes more hilly, then rolling.

The lake and pond area amounts to 183 square miles. The largest lake is Lake Winnepesaukee, which has a water area of 72 square miles.

Run-off.- An accurate record has been kept of the flow over the dam and through the wheels and gates of the Essex Co. at Lawrence, Mass., since January 1, 1880. The flow is regulated to some extent by storage in Lake Winnepesaukee. Low-water flow is affected by operation of various power plants above Lawrence. The record is furnished by the Essex Co. and is considered good throughout. The records up to September 30, 1915, are revised and published in United States Geological Survey Water-Supply Paper 415. The records as here used are on the basis of the year ending September 30.

Precipitation.- The figures for monthly and annual precipitation for the basin used here were taken from the water-supply papers. The precipitation as recorded for 1932 was the mean of 33 stations. The precipitation records as herein used are on the basis of the climatic year ending September 30. The following precipitation stations are in or adjacent to the basin.

Table 14.- Precipitation stations in or near the Merrimack River Basin above Lawrence, Mass.

Station	Altitude (feet)	Period of record	Mean annual precipitation (inches)
Maine:			
Hiram	400	1926-29,1931-	40.22
Massachusetts:			
Ashby	1,000	1915-	44.93
Ashland	227	1890-	43.45
Boylston	540	1896-	45.34
Clinton	398	1902-	44.91
Concord *	139	1885-87,1891-	40.61
Cordaville	250	1894-	46.00
Fitchburg *	402	1865-	41.29
Framingham	172	1876-	43.85
Groton	325	1886-1908,1913-	43.34
Haverhill	50	1900-30	38.02
Jefferson	820	1898-1900,1902-5,1907-14 1916-22,1924-	47.49
Lake Cochituate	148	1852-1930	45.27
Lawrence	57	1856-60,1864,1866-67 1869,1871-80,1885-	41.93
Leominster	540	1885-1932	44.08
Lowell *	85	1826-	41.47
Princeton	1,050	1885-91,1897-	45.41
Sterling	555	1897-	43.54
Sudbury	260	1899-	42.34
Wachusett Lake	880	1915-	46.13
Worcester *	625	1841-55,1857-62,1865-71 1876-77,1882-86,1888-90 1893-97,1901-	42.40

* Station used in computing temperature average for basin.

Table 14.- Precipitation stations in or near the Merrimack River Basin above Lawrence, Mass.--Continued

Station	Altitude (feet)	Period of record	Mean annual precipitation (inches)
New Hampshire:			
Bethlehem	1,440	1893-	35.52
Concord *	350	1853,1857,1859-	37.51
Durham	83	1893,1895-	38.73
Franklin *	390	1902-	39.50
Glencliff *	1,650	1910-	40.36
Hanover *	603	1835-55,1867-	35.25
Keene	550	1892-	37.70
Lakeport	500	1857-1933	42.42
Lincoln	1,200	1921-30,1933-	45.73
Manchester	171	1875-	38.65
Nashua *	125	1884-	39.31
Plymouth *	500	1888-1933	39.16

* Station used in computing temperature average for basin.

Temperature.- The average annual temperature for the period of record of each of the stations marked * in the preceding table was averaged and compared with the normal annual temperature at Concord, N. H., and was found to agree so closely that the Concord record has been used to represent the average temperature for the basin. The temperature records as used herein are on the basis of the calendar year.

James River Basin above Cartersville, Va.

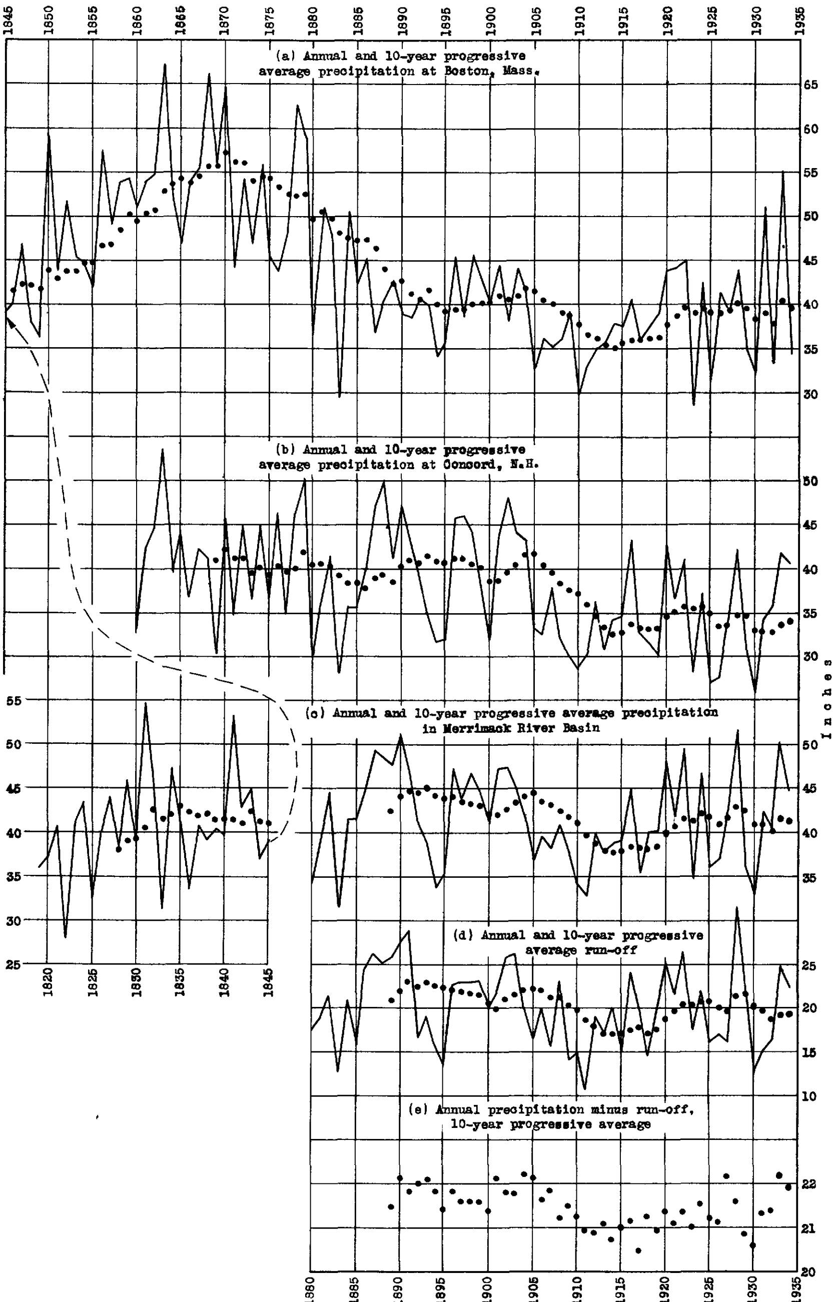
(Drainage area, 6,240 square miles.
Records available, 1899-1934.)

The Jackson River rises on the West Virginia - Virginia State line, flows south 57 miles, and joins the Cowpasture River to form the James River, which flows generally south of east for 187 miles to Cartersville, Va. The average width of the drainage basin is about 50 miles. The western part of the basin lies in the Appalachian and Blue Ridge sections and is rugged to mountainous. The Piedmont section extends from the Blue Ridge tc the Fall Line near Richmond, 50 miles below Cartersville, and is characterized by low hills and broad valleys. Nearly half of the area consists of timber land and wood lots. The basin is primarily an agricultural area.

The Jackson River rises at an altitude of about 2,400 feet and descends to about 1,000 feet where it forms the James River. The James River has an average slope of 5.5 feet to the mile in the mountain section

Table 15.- Precipitation, temperature, and run-off data for Merrimack River Basin above Lawrence, Mass.

Year ending September	Precipitation (inches)			Temperature at Concord, N. H. (°F.)		Run-off at Lawrence (inches)			Precipitation minus run-off (inches)		Ratio run-off to precipitation 10-year progressive average (percent)
	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	
1880	34.57	34.57	-	48.8	-	17.60	17.60	-	16.97	-	-
81	39.54	74.11	-	48.3	-	18.90	36.50	-	20.64	-	-
82	44.53	118.64	-	47.0	-	21.63	58.13	-	22.90	-	-
83	31.38	150.02	-	45.2	-	12.76	70.89	-	18.62	-	-
84	41.61	191.63	-	46.3	-	20.90	91.79	-	20.71	-	-
85	41.53	233.16	-	44.6	-	15.72	107.51	-	25.81	-	-
86	45.03	278.19	-	46.3	-	24.58	132.09	-	20.45	-	-
87	49.28	327.47	-	45.9	-	26.27	158.36	-	23.01	-	-
88	48.59	376.06	-	44.4	-	25.08	183.44	-	23.51	-	-
89	47.57	423.63	42.36	47.7	46.45	25.76	209.20	20.92	21.81	21.44	49.4
1890	51.00	474.63	44.01	45.3	46.10	27.42	236.62	21.90	23.58	22.10	49.8
91	46.84	521.47	44.74	47.0	45.97	28.96	265.58	22.91	17.88	21.83	51.2
92	40.94	562.41	44.38	45.5	45.82	16.42	282.00	22.39	24.52	21.99	50.5
93	38.83	601.24	45.12	41.9	45.49	19.19	301.19	23.03	19.64	22.09	51.0
94	33.72	634.96	44.33	45.7	45.43	15.75	316.94	22.52	17.97	21.82	50.8
95	35.48	670.44	43.73	45.7	45.54	13.60	330.54	22.30	21.88	21.43	51.0
96	47.34	717.78	43.96	45.4	45.45	22.73	353.27	22.12	24.61	21.84	50.3
97	44.01	761.79	43.43	45.6	45.42	23.15	376.42	21.81	20.86	21.63	50.2
98	46.81	808.60	43.25	46.4	45.62	23.14	399.56	21.61	23.67	21.64	49.9
99	44.70	853.30	42.97	45.0	45.35	23.20	422.76	21.36	21.50	21.61	49.7
1900	41.20	894.50	41.99	45.7	45.39	19.77	442.53	20.59	21.43	21.40	49.1
01	47.29	941.79	42.03	45.0	45.19	22.08	464.61	19.90	25.21	22.13	47.4
02	47.59	989.38	42.70	45.2	45.16	26.05	490.66	20.87	21.54	21.83	48.9
03	45.38	1034.76	43.35	45.3	45.50	26.25	516.91	21.57	19.13	21.78	49.8
04	42.10	1076.86	44.19	42.6	45.19	19.82	536.73	21.98	22.28	22.21	49.8
05	37.14	1114.00	44.36	44.6	45.08	16.01	552.74	22.22	21.13	22.14	50.1
06	39.46	1153.46	43.57	45.8	45.12	19.98	572.72	21.94	19.48	21.62	50.4
07	38.20	1191.66	42.99	43.8	44.94	15.42	588.14	21.17	22.78	21.82	49.3
08	40.90	1232.56	42.40	46.3	44.93	23.07	611.21	21.16	17.83	21.23	49.9
09	38.04	1270.60	41.73	45.7	45.00	14.09	625.30	20.25	23.95	21.48	48.5
1910	34.21	1304.81	41.03	46.0	45.03	14.98	640.28	19.78	19.23	21.26	48.2
11	32.96	1337.77	39.60	46.1	45.14	10.65	650.93	18.63	22.31	20.97	47.0
12	40.06	1377.83	38.84	45.2	45.14	19.11	670.04	17.94	20.95	20.91	46.2
13	38.08	1415.91	38.11	47.6	45.37	17.10	687.14	17.02	20.98	21.09	44.7
14	38.83	1454.74	37.79	44.0	45.51	20.09	707.23	17.05	18.74	20.74	45.1
15	38.95	1493.69	37.97	46.9	45.74	15.06	722.29	16.95	23.89	21.01	44.6
16	44.91	1538.60	38.51	45.1	45.67	24.15	746.44	17.37	20.76	21.14	45.1
17	35.60	1574.20	38.25	43.2	45.61	19.71	766.15	17.80	15.89	20.45	46.5
18	40.12	1614.32	38.18	41.1	45.09	14.49	780.64	16.94	25.63	21.23	44.4
19	40.33	1654.65	38.40	46.4	45.16	19.37	800.01	17.47	20.96	20.93	45.5
1920	48.34	1702.99	39.82	45.8	45.14	25.19	825.20	18.49	23.15	21.33	46.4
21	41.77	1744.76	40.70	47.7	45.30	21.60	846.80	19.59	20.17	21.11	48.1
22	49.66	1794.42	41.66	46.1	45.39	26.34	873.14	20.31	23.32	21.35	48.7
23	34.73	1829.15	41.32	45.2	45.15	17.39	890.53	20.34	17.34	20.98	49.3
24	46.47	1875.62	42.09	44.9	45.24	22.00	912.53	20.53	24.47	21.56	48.7
25	36.23	1911.85	41.82	45.8	45.13	16.15	928.68	20.64	20.08	21.18	49.4
26	37.09	1948.94	41.03	43.8	45.00	17.06	945.74	19.93	20.03	21.10	48.6
27	42.42	1991.36	41.72	46.3	45.31	16.15	961.89	19.57	26.27	22.14	46.9
28	51.48	2042.84	42.85	45.9	45.79	31.54	993.43	21.28	19.94	21.57	49.7
29	35.91	2078.75	42.41	45.7	45.72	22.06	1015.49	21.55	13.85	20.86	50.9
1930	33.07	2111.82	40.88	46.9	45.83	12.58	1028.07	20.29	20.49	20.60	49.7
31	42.35	2154.17	40.94	48.0	45.86	15.15	1043.22	19.64	27.20	21.30	48.0
32	40.49	2194.66	40.02	46.9	45.94	16.30	1059.52	18.64	24.19	21.39	46.6
33	50.31	2244.97	41.58	46.3	46.05	24.79	1084.31	19.38	25.52	22.20	46.5
34	44.49	2289.46	41.38	45.5	46.11	22.60	1106.91	19.44	21.89	21.95	47.0
Total	2289.46	-	-	2510.4	-	1106.91	-	-	1182.55	-	-
Av.	41.63	-	-	45.6	-	20.13	-	-	21.50	-	-



Note.– 10-year average plotted at end of period shown thus •

Figure 21.—Relations between rainfall and run-off in Merrimack River Basin above Lawrence, Mass.

of 88 mile and of 2.9 feet to the mile in the Piedmont section to the Fall Line.

Run-off.- The gage is located on the James River between Pemberton and Cartersville, Cumberland County, 1 mile below the mouth of the Willis River. A wire gage was used from January 1899 to July 23, 1903, and a chain gage from July 24, 1903, to June 3, 1927. Since June 3, 1927, a water-stage recorder has been in operation. The daily records are fair to good prior to the installation of the water-stage recorder and good to excellent thereafter.

The flow at Cartersville is regulated to a small extent by nine hydroelectric power plants on the main stream and tributaries, the nearest of which is about 95 miles upstream. The only storage used is the small amount of pondage at the power developments. The records are for the calendar year.

Precipitation.- The annual precipitation over the basin was computed by averaging the annual records at all the fairly well distributed precipitation stations in and adjacent to the basin, which are listed below:

Table 16.- Precipitation stations in or near James River Basin above Cartersville, Va.

Station	Altitude (feet)	Period of record	Mean annual precipitation (inches)
Virginia:			
Blacksburg *	2,100	1892-	41.65
Buchanan	820	1893-95,1904-	41.19
Catawba Sanitarium	2,100	1911-	42.12
Charlottesville	854	1849,1874-78,1882-	43.58
Columbia	246	1899-	41.44
Farmville *	316	1897-1906	41.02
Hot Springs	2,195	1892-	40.35
Lexington	1,060	1869-83,1885-86,1889-	39.30
Lynchburg	681	1872-	40.53
New Canton	300	1894-	41.17
Staunton	1,480	1869-72,1890-1923,1925-	37.68

* Station replaced by another or record discontinued prior to 1911.

Because of the rough topography over the basin, differences in precipitation between one part of the basin and another probably result largely from differences in altitude. The precipitation ranges from about 37.7 to 43.6 inches on the basis of the long-time average, and in one year the range was from 29.4 to 54.1 inches. Records are on the basis of the calendar year.

Table 17.- Precipitation, temperature, and run-off data for James River Basin above Cartersville, Va.

Year	Precipitation (inches)			Temperature at Lynchburg, Va. minus 2.3° (°F.)		Run-off at Cartersville (inches)			Precipitation minus run-off (inches)		Ratio run-off to precipitation 10-year progressive average (percent)
	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	
1899	44.03	44.03	-	54.2	-	18.40	18.40	-	25.03	-	-
1900	40.68	84.71	-	56.1	-	15.56	33.96	-	25.12	-	-
01	54.03	138.74	-	53.4	-	25.06	59.02	-	28.97	-	-
02	41.96	180.70	-	54.5	-	18.87	77.89	-	23.09	-	-
03	44.74	225.44	-	54.1	-	21.52	99.41	-	23.22	-	-
04	32.30	257.74	-	52.5	-	10.21	109.62	-	22.09	-	-
05	44.01	301.75	-	53.8	-	14.75	124.37	-	29.26	-	-
06	47.05	348.80	-	55.2	-	20.20	144.57	-	26.85	-	-
07	44.44	393.24	-	53.7	-	19.65	164.22	-	24.79	-	-
08	45.08	438.32	43.83	54.5	54.2	19.36	183.58	18.36	25.72	25.47	41.8
09	34.20	472.52	42.85	54.6	54.2	16.37	199.95	18.16	17.83	24.69	42.3
1910	39.43	511.95	42.72	54.2	54.1	12.86	212.81	17.89	26.57	24.84	41.8
11	41.39	553.34	41.46	55.7	54.3	12.79	225.60	16.66	28.60	24.80	40.2
12	42.42	595.76	41.51	54.2	54.3	17.73	243.33	16.54	24.69	24.96	39.8
13	45.01	640.77	41.53	56.6	54.5	17.31	260.64	16.12	27.70	25.41	38.8
14	36.59	677.36	41.96	54.6	54.7	14.14	274.78	16.52	22.45	25.45	39.3
15	41.19	718.55	41.68	54.9	54.8	17.10	291.88	16.75	24.09	24.93	40.2
16	37.92	756.47	40.77	54.7	54.8	12.64	304.52	16.00	25.28	24.77	39.2
17	36.56	793.03	39.98	52.5	54.7	13.06	317.58	15.34	23.50	24.64	38.4
18	45.30	838.33	40.00	54.4	54.6	16.95	334.53	15.10	28.35	24.91	37.8
19	42.49	880.82	40.83	55.6	54.7	17.26	351.79	15.18	25.23	25.65	37.2
1920	45.15	925.97	41.40	53.6	54.7	17.26	369.05	15.62	27.89	25.78	37.7
21	32.89	958.86	40.55	57.1	54.8	11.85	380.90	15.53	21.04	25.02	38.3
22	41.67	1000.53	40.48	55.8	55.0	15.77	396.67	15.33	25.90	25.14	37.8
23	37.71	1038.24	39.75	55.4	54.9	12.08	408.75	14.81	25.63	24.94	37.2
24	47.30	1085.54	40.92	53.3	54.7	19.78	428.53	15.38	27.52	25.44	37.7
25	28.84	1114.38	39.58	55.7	54.8	9.86	438.39	14.65	18.98	24.93	37.0
26	39.67	1154.05	39.76	54.7	54.8	13.19	451.58	14.71	26.48	25.05	37.0
27	41.84	1195.89	40.29	55.9	55.2	15.73	467.31	14.97	26.11	25.31	37.2
28	42.94	1238.83	40.05	55.0	55.2	16.90	484.21	14.97	26.04	25.08	37.4
29	44.56	1283.39	40.26	55.2	55.2	18.80	503.01	15.12	25.76	25.14	37.6
1930	21.16	1304.55	37.86	55.7	55.4	7.00	510.01	14.10	14.16	23.76	37.2
31	37.31	1341.86	38.30	56.9	55.4	8.00	518.01	13.71	29.31	24.59	35.8
32	44.21	1386.07	38.55	56.6	55.4	14.84	532.85	13.62	29.37	24.94	35.3
33	38.01	1424.08	38.58	56.8	55.6	15.15	548.00	13.93	22.86	24.66	36.1
34	44.43	1468.51	38.30	55.3	55.8	13.33	561.33	13.28	31.10	25.02	34.7
Total	1468.51	-	-	1977.0	-	561.33	-	-	907.18	-	-
Av.	40.79	-	-	54.9	-	15.59	-	-	25.20	-	-

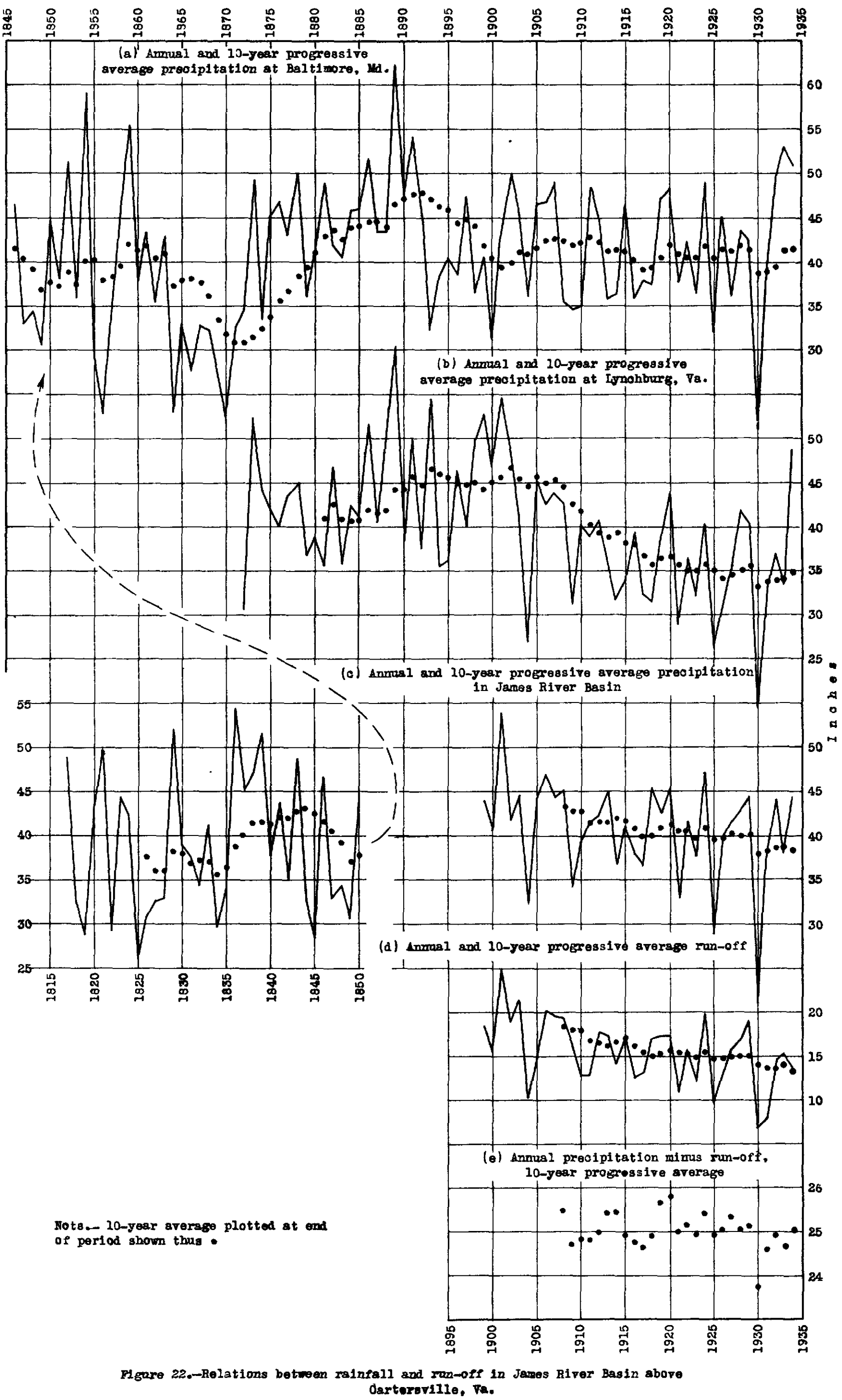


Figure 22.—Relations between rainfall and run-off in James River Basin above Cartersville, Va.

Temperature.- The mean annual temperature for the period of record at the stations in and adjacent to the basin was averaged and compared with the mean annual temperature at Lynchburg and was found to be about 2.3° lower. This amount was then subtracted from the figures of annual temperature at Lynchburg to arrive at the average annual temperature for the basin.

Tennessee River Basin above Chattanooga, Tenn.

The Tennessee River is formed at Knoxville, Tenn., by the junction of the French Broad and Holston Rivers, which rise in western North Carolina and southwestern Virginia and have drainage areas of 5,140 and 3,810 square miles respectively. From Knoxville the Tennessee flows 188 miles in a southwesterly direction to Chattanooga. The headwater area is mountainous country, with altitudes ranging from 3,000 to 6,700 feet. At Chattanooga the altitude is about 620 feet, and the drainage area 21,400 square miles.

The river distance from Chattanooga to the head of the French Broad is about 360 miles, and to the head of the Holston about 385 miles. The average width of the drainage basin is about 85 miles.

The average slope of the Tennessee River from Knoxville to Chattanooga is about 1.0 foot to the mile; that of the French Broad River from its mouth to a point 197 miles above is about 6.6 feet to the mile; and that of the Holston River from its mouth to a point 143 miles above is about 2.5 feet to the mile.

Run-off.- For the period 1874 to 1913, prior to the building of the Hales Bar Dam, the Chattanooga gage record alone was used; from October 22, 1913, to February 28, 1915, and October 1, 1918, to January 5, 1921, the gage record at Bridgeport, Ala., was used; from March 1, 1915, to September 30, 1918, and from January 6, 1921, to June 1930 the Chattanooga gage was used, adjusted by means of the upper and lower gages at Hales Bar Lock and Dam, 33 miles below Chattanooga.

Since July 1930 gage-height records have been obtained from a water-stage recorder just below Hales Bar Lock and Dam, where the drainage area is 22,000 square miles.

Because the stage-discharge relation is not permanent, several rating curves were used, and the low-water records since the completion of Hales Bar Dam, in 1913, may be subject to some error owing to the indirect method of determining the discharge. The run-off records are for the calendar year.

Precipitation.- The accuracy of the annual precipitation records in representing the mean annual precipitation over the basin above Chattanooga is problematic. The accuracy probably increases from 1889 to 1898 and should be fairly satisfactory since 1898. Prior to 1889 the number of precipitation stations was small, but their distribution was fairly uniform over the area. The annual precipitation data prior to 1889 were weighted in relation to area represented, and those subsequent to 1889 were averaged to get the annual precipitation for the basin. The approximate number of precipitation stations used to compute the basin average is as follows:

1885 - 6 stations	1910 - 36 stations
1890 - 15 stations	1920 - 39 stations
1900 - 31 stations	1930 - 38 stations

The following is a list of stations in the basin above Chattanooga used to compute the annual precipitation:

Table 18.- Precipitation stations in or near Tennessee River Basin above Chattanooga, Tenn.

Station	Altitude (feet)	Period of record	Mean annual precipitation (inches)
North Carolina:			
Altapass	2,740	1913-	50.89
Andrews	1,800	1909-33	62.08
Asheville	2,253	1869-78,1889-91,1893-	40.28
Brevard	2,230	1902-34	62.13
Bryson City	2,000	1889-	54.06
Cullowhee	2,100	1910-	43.80
Hendersonville	2,153	1898-	60.13
Highlands	3,350	1879-81,1883-84,1892-	81.44
Hot Springs	1,326	1906-	43.68
Jefferson	2,900	1903-6,1910-	48.86
Linville	3,800	1895-1906	62.72
Linville Falls	3,300	1916-	58.13
Marshall	1,646	1899-	39.40
Montreat	2,600	1917-	53.97
Murphy	1,614	1873-75,1877-82,1889-	58.47
Parker	4,075	1918-	50.15
Waynesville	2,756	1894-	45.57

Table 18.- Precipitation stations in or near Tennessee River Basin above Chattanooga, Tenn.--Continued

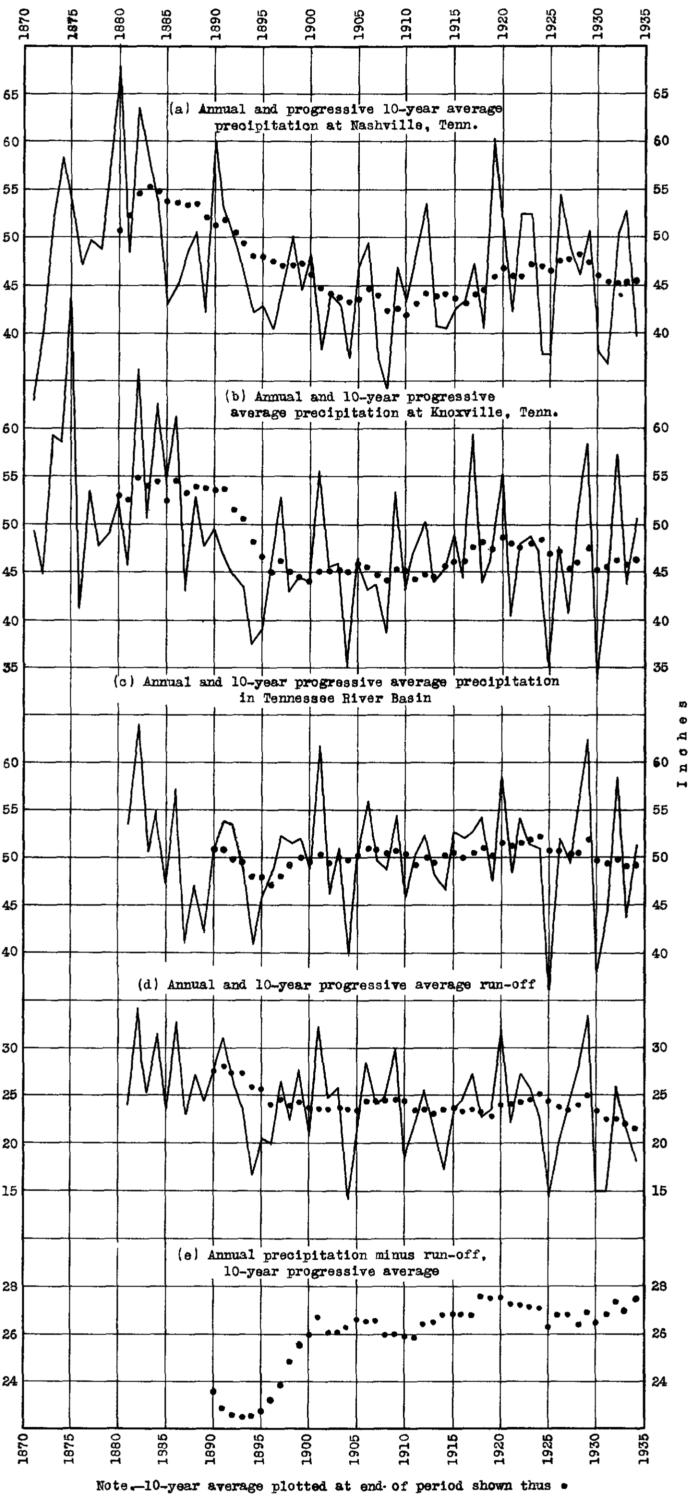
	Altitude (feet)	Period of record	Mean annual precipitation (inches)
Virginia:			
Big Stone Gap	1,966	1891-1911	50.66
Dante	2,000	1917-	48.63
Elk Knob	3,243	1904-19	48.46
Marion	2,145	1884-1911	43.29
Mendota	1,350	1905-	47.81
Saltville	1,770	1896-97,1924-	43.22
Speers Ferry	1,221	1896-1932	49.45
Tennessee:			
Bluff City	1,400	1898-	44.46
Bristol	1,757	1894-1908,1927-32	41.29
Chattanooga	808	1879-	51.61
Clinton	800	1889-91,1893-	52.49
Copperhill	1,624	1914-	54.86
Crossville	1,820	1912-	55.92
Dandridge	1,050	1905-	45.84
Decatur	850	1896-	54.92
Elizabethton	1,575	1869-70,1872 1895-1906,1908-	44.55
Greenville	1,581	1884-1906,1916-19 1921-25,1933-34	43.37
Harriman	841	1891,1893,1895-1911	51.41
Jefferson City	1,117	1910-28	45.75
Johnson City	1,717	1886,1896-1930	44.39
Kingston	751	1889-93,1898-	51.42
Knoxville	977	1854,1871-	47.38
Loudon	816	1889-96,1905-	50.96
Maryville	1,050	1883-85,1888,1898-1912	51.57
McGhee	850	1905-	50.15
Mountain City	2,471	1898-1920	47.07
Newport	1,100	1892-	44.45
Parksville	840	1883-1914,1925-	50.25
Rockwood	725	1889-97,1923-33	52.35
Rogersville	1,150	1886-	44.82
Rugby	1,410	1884,1889-	55.69
Sevierville	900	1906-30	47.94
Springdale	1,058	1889-1909,1911	48.63
Tazewell	1,350	1898-1926	50.45
Tellico Plains	1,000	1897-1908,1927-	53.19

The precipitation records are on the basis of the calendar year.

Temperature.- The mean annual temperaturee for the period of record at the stations in the basin were averaged and compared with the mean annual temperature at Knoxville and were found to be about 2.5° lower; therefore 3° was subtracted from the figures of annual temperature at Knoxville to arrive at the average annual temperature of the basin.

Table 19.- Precipitation, temperature, and run-off data for Tennessee River Basin above Chattanooga, Tenn.

Year	Precipitation (inches)			Temperature at Knoxville, Tenn. minus 3° (°F.)		Run-off at Chattanooga (inches)			Precipitation minus run-off (inches)		Ratio run-off to precipitation 10-year progressive average (percent)
	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	
1881	53.20	53.20	-	56.5	-	23.68	23.68	-	29.52	-	-
82	64.10	117.30	-	56.4	-	34.12	57.80	-	29.98	-	-
83	50.60	167.90	-	55.8	-	25.16	82.96	-	25.44	-	-
84	54.90	222.80	-	55.4	-	31.46	114.42	-	23.44	-	-
85	47.50	270.30	-	53.4	-	23.61	138.03	-	23.89	-	-
86	57.00	327.30	-	53.5	-	32.79	170.82	-	24.21	-	-
87	41.10	368.40	-	55.8	-	23.09	193.91	-	18.01	-	-
88	47.10	415.50	-	55.4	-	27.20	221.11	-	19.90	-	-
89	42.20	457.70	-	55.2	-	24.34	245.45	-	17.86	-	-
1890	51.10	508.80	50.88	57.1	55.4	28.16	273.61	27.36	22.94	23.52	53.8
91	53.93	562.73	50.95	55.2	55.3	31.12	304.73	28.11	22.81	22.85	55.1
92	53.66	616.39	49.91	54.5	55.1	26.28	331.01	27.32	27.38	22.59	54.7
93	48.32	664.71	49.68	55.0	55.0	23.69	354.70	27.17	24.63	22.51	54.7
94	40.68	705.39	48.26	56.1	55.1	16.63	371.33	25.69	24.05	22.57	53.3
95	46.10	751.49	48.12	54.0	55.2	20.48	391.81	26.38	25.62	22.74	52.8
96	48.15	799.64	47.23	56.6	55.5	19.86	411.67	24.09	28.29	23.15	51.0
97	52.34	851.98	48.36	56.1	56.5	26.69	438.36	24.45	25.65	23.91	50.6
98	51.56	903.54	48.80	55.8	55.6	22.22	460.58	23.95	29.34	24.86	49.1
99	51.88	956.42	49.77	55.3	55.6	27.80	488.38	24.29	24.08	25.48	48.8
1900	49.00	1004.42	49.56	56.5	56.5	20.69	509.07	23.55	28.31	26.02	47.5
01	61.68	1066.10	50.34	53.3	55.3	32.25	541.32	23.66	29.43	26.68	47.0
02	46.02	1112.12	49.57	55.2	55.4	24.73	566.05	23.50	21.29	26.07	47.4
03	51.11	1163.23	49.85	54.5	55.3	25.98	592.03	23.73	25.13	26.12	47.6
04	39.85	1203.08	49.77	54.3	55.2	13.95	605.98	23.47	25.90	26.30	47.2
05	50.49	1253.57	50.21	54.8	55.2	21.38	627.36	23.56	29.11	26.65	46.9
06	56.12	1309.69	51.01	55.8	55.2	28.62	655.98	24.43	27.50	26.57	47.9
07	49.49	1359.18	50.72	55.4	55.1	23.99	679.97	24.16	25.50	26.56	47.6
08	48.82	1408.00	50.45	56.1	55.1	25.01	704.98	24.44	23.81	26.01	48.4
09	54.39	1462.39	50.70	55.6	55.2	29.91	734.89	24.65	24.48	26.06	48.6
1910	45.76	1508.15	50.37	54.6	55.0	18.49	753.38	24.43	27.27	25.94	48.5
11	50.51	1558.66	49.26	57.5	55.4	21.90	775.28	23.40	28.61	25.86	47.5
12	52.50	1611.16	49.90	54.4	55.3	25.55	800.83	23.48	26.95	26.43	47.0
13	48.10	1659.26	49.60	56.8	55.5	22.11	822.94	23.09	25.99	26.51	46.6
14	46.55	1705.81	50.27	55.4	55.6	17.36	840.30	23.43	29.19	26.84	46.6
15	52.84	1758.65	50.51	55.7	55.7	23.44	863.74	23.64	29.40	26.87	46.8
16	51.98	1810.63	50.09	55.6	55.7	24.64	888.38	23.24	27.34	26.85	46.4
17	52.67	1863.30	50.41	53.3	55.5	27.44	915.82	23.59	25.23	26.83	46.8
18	53.50	1916.80	50.88	56.2	55.5	22.77	938.59	23.36	30.73	27.52	45.8
19	47.59	1964.39	50.20	57.1	55.7	23.64	962.23	22.73	23.95	27.47	45.2
1920	58.61	2023.00	51.49	54.7	55.7	31.88	994.11	24.07	26.73	27.41	46.8
21	48.26	2071.26	51.26	58.2	55.7	22.04	1016.15	24.09	26.22	27.17	47.0
22	54.10	2125.36	51.42	57.4	56.0	27.27	1043.42	24.26	26.83	27.16	47.2
23	51.35	2176.71	51.75	56.1	56.0	25.97	1069.39	24.65	25.38	27.10	47.6
24	51.12	2227.83	52.20	54.4	55.9	23.63	1093.02	25.27	27.49	26.93	48.4
25	36.17	2264.00	50.54	57.7	56.1	14.60	1107.62	24.39	21.57	26.15	48.3
26	51.89	2315.89	50.53	55.5	56.1	19.96	1127.58	23.92	31.93	26.61	47.4
27	49.56	2365.45	50.22	57.6	56.5	23.99	1161.57	23.58	25.57	26.64	46.9
28	55.38	2420.83	50.40	55.0	56.4	27.94	1179.51	24.09	27.44	26.31	47.8
29	62.41	2483.24	51.89	55.5	56.2	33.46	1212.97	25.07	28.95	26.81	48.4
1930	37.63	2520.87	49.79	56.4	56.4	15.15	1228.12	23.40	22.48	26.39	47.0
31	44.37	2565.24	49.40	58.1	56.4	14.98	1243.10	22.70	29.39	26.70	45.9
32	58.69	2623.93	49.86	57.6	56.4	26.11	1269.21	22.58	32.58	27.28	45.3
33	44.02	2667.95	49.12	58.5	56.6	21.64	1290.85	22.15	22.38	26.98	45.1
34	51.69	2719.64	49.18	57.1	56.9	18.32	1309.17	21.62	33.37	27.57	43.9
Total	2719.64	-	-	3011.0	-	1309.17	-	-	1410.47	-	-
Av.	50.36	-	-	55.8	-	24.24	-	-	26.12	-	-



Note.—10-year average plotted at end of period shown thus •

Figure 23.—Relations between rainfall and run-off in Tennessee River Basin above Chattanooga, Tenn.

Chattahoochee River Basin above West Point, Ga.

(Drainage area, 3,550 square miles.
Records available, 1896-1934.)

The Chattahoochee River rises in the Blue Ridge in White County, Ga., at an altitude of about 4,000 feet, and flows in a southwesterly direction to West Point, Ga., on the Georgia - Alabama State line, at an altitude of about 550 feet. The length of the river above West Point is about 200 miles, and the average width of the drainage basin is 30 miles. From the lower edge of Lumpkin County down to West Point, a distance of about 145 miles, the Chattahoochee River has a fall of 484 feet, an average of about 3.3 feet to the mile.

Run-off.- The original gage, established in July 1896, was a standard chain gage on the downstream handrail of the Montgomery Street Bridge in West Point, Ga. On October 20, 1912, the gage was moved 1 mile upstream, to a point opposite the city pumping plant. A staff gage (0 to 18 feet) was placed on the left bank and was read from the right bank by means of a telescope until January 14, 1920, when the section 0 to 6.7 feet was moved to the right bank. Since January 26, 1925, the gage has been a continuous water-stage recorder in a concrete stilling well on the right bank 500 feet below the West Point waterworks pumping plant. The gage was read to tenths three times daily prior to the installation of the water-stage recorder. The records throughout are considered fair to good. The operation of hydroelectric power plants upstream causes slight diurnal fluctuations at West Point. The run-off figures are on the basis of the calendar year.

Precipitation.- The annual precipitation over the basin was computed by averaging the annual records at all the precipitation stations listed below, located in and adjacent to the basin.

Table 20.- Precipitation stations in or near Chattahoochee River Basin above West Point, Ga.

	Altitude (feet)	Period of record	Mean annual precipitation (inches)
Georgia:			
Atlanta	1,173	1859,1866,1868-	48.27
Canton	894	1879,1892-	52.33
Clayton	2,100	1894-1920,1922-	70.07
Dahlonega	1,519	1885,1894-	61.25
Gainesville	1,254	1875-86,1895-	54.92
Gillsville	1,052	1890-	51.25
Lost Mountain	1,175	1901-19	50.86
Marietta	1,135	1889-98,1920-27	50.20
Newnan	959	1895-	51.12
Norcross	1,025	1911-32	51.33
Tallapoosa	1,150	1897-	51.65
Tocoa	1,050	1892-	57.98
West Point	620	1894-	51.78

Differences in annual precipitation between one part of the basin and another probably result largely from differences in altitude. The range shown by long-time averages is from about 48.3 to 70.1 inches; in one year the range was from 53.4 to 91.6 inches. Precipitation figures are on the basis of the calendar year.

Temperature.- The mean annual temperature for the period of record at the stations in and adjacent to the basin was averaged and compared with the mean annual temperature at Atlanta and was found to be about 0.5° lower. The Atlanta record was therefore taken to represent the average temperature of the basin. Temperature figures are on the basis of the calendar year.

General accuracy of precipitation, run-off, and temperature data

During the periods of record there has unquestionably been a gradual increase in the accuracy of the base data used. In the determination of the mean annual precipitation it has been necessary to base the average during the earlier part of the period on a fewer number of stations than were available during later years. The records in the earlier part of the period have generally been weighted according to area represented. For several basins comparisons were made of the relations both on an annual and on a monthly basis between the straight average of all the stations and the weighted average. In most of these comparisons the differences shown were so small that the straight average has been used in general. Basin trends

Table 21.- Precipitation, temperature, and run-off data for Chattahoochee River Basin above West Point, Ga.

Year	Precipitation (inches)			Temperature at Atlanta, Ga. (°F.)		Run-off at West Point (inches)			Precipitation minus run-off (inches)		Ratio run-off to precipitation 10-year progressive average (percent)
	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	Annual	Accumulated	Progressive 10-year average	Annual	Progressive 10-year average	
1897	50.36	50.36	-	61.8	-	19.07	19.07	-	31.29	-	-
98	59.42	109.78	-	61.5	-	20.37	39.44	-	39.05	-	-
99	49.97	159.75	-	61.6	-	22.80	62.24	-	27.17	-	-
1900	63.81	223.56	-	61.9	-	28.85	91.09	-	34.96	-	-
01	67.02	290.58	-	59.4	-	33.20	124.29	-	33.82	-	-
02	49.05	339.63	-	61.1	-	26.20	150.49	-	22.85	-	-
03	55.04	394.67	-	60.1	-	29.84	180.33	-	25.20	-	-
04	36.03	430.70	-	60.2	-	11.57	191.90	-	24.46	-	-
05	53.71	484.41	-	60.5	-	16.63	208.53	-	37.08	-	-
06	63.75	548.16	54.82	61.1	60.9	28.45	236.98	23.70	35.30	31.12	43.2
07	49.01	597.17	54.68	61.7	60.9	19.52	256.50	23.74	29.49	30.94	43.4
08	52.63	649.80	54.00	61.7	60.9	23.06	279.56	24.01	29.57	29.99	44.4
09	59.55	709.35	54.96	61.4	60.9	28.73	308.29	24.61	30.82	30.35	44.7
1910	45.05	754.40	53.08	60.6	60.8	17.10	325.39	23.43	27.95	29.65	44.2
11	49.94	804.34	51.38	62.9	61.1	16.19*	341.58	21.73	33.75*	29.65	42.3
12	66.64	870.98	53.14	60.1	61.0	30.14	371.72	22.12	36.50	31.01	41.6
13	50.21	921.19	52.65	61.9	61.2	19.77	391.49	21.12	30.44	31.54	40.1
14	48.64	969.83	53.91	61.1	61.3	13.62	405.11	21.32	35.02	32.59	39.5
15	60.04	1029.87	54.55	61.4	61.4	23.25	428.36	21.98	36.79	32.56	40.3
16	50.75	1080.62	53.25	61.4	61.4	22.21	450.57	21.36	28.54	31.89	40.1
17	54.10	1134.72	53.76	59.6	61.2	25.92	476.49	22.00	28.18	31.76	40.9
18	58.02	1192.74	54.29	61.7	61.2	20.41	496.90	21.73	37.61	32.56	40.0
19	58.99	1251.73	54.24	62.2	61.3	27.13	524.03	21.57	31.86	32.66	39.7
1920	70.27	1322.00	56.76	60.0	61.2	33.46	557.49	23.21	36.81	33.55	40.9
21	47.11	1369.11	56.48	63.5	61.3	18.79	576.28	23.47	28.32	33.01	41.6
22	61.17	1430.28	55.93	62.6	61.5	28.03	604.31	23.26	33.14	32.67	41.6
23	56.59	1486.87	56.57	61.4	61.5	23.01	627.32	23.58	33.58	32.99	41.7
24	51.00	1537.87	56.80	60.2	61.4	19.07	646.39	24.13	31.93	32.68	42.5
25	41.26	1579.13	54.93	63.4	61.6	17.77	664.16	23.58	23.49	31.35	42.9
26	52.27	1631.40	55.08	61.0	61.6	18.40	682.56	23.20	33.87	31.88	42.1
27	44.98	1676.38	54.17	63.2	61.9	14.30	696.86	22.04	30.68	32.13	40.7
28	57.33	1733.71	54.10	60.7	61.8	22.08	718.94	22.20	35.25	31.89	41.0
29	78.46	1812.17	56.04	61.4	61.7	37.61	756.55	23.25	40.85	32.79	41.5
1930	43.76	1855.93	53.39	61.5	61.9	17.49	774.04	21.66	26.27	31.74	40.6
31	45.75	1901.68	53.26	63.0	61.8	12.71	786.75	21.05	33.04	32.21	39.5
32	72.96	1974.64	54.44	62.3	61.8	25.65	812.40	20.81	47.31	33.63	38.2
33	42.16	2016.80	53.00	63.2	62.0	18.65	831.05	20.37	23.51	32.62	38.5
34	57.47	2074.27	53.64	61.2	62.1	17.05	848.10	20.17	40.42	33.47	37.6
Total	2074.27	-	-	2335.5	-	848.10	-	-	1226.17	-	-
Av.	54.59	-	-	61.5	-	22.32	-	-	32.27	-	-

* Run-off estimated for 1911

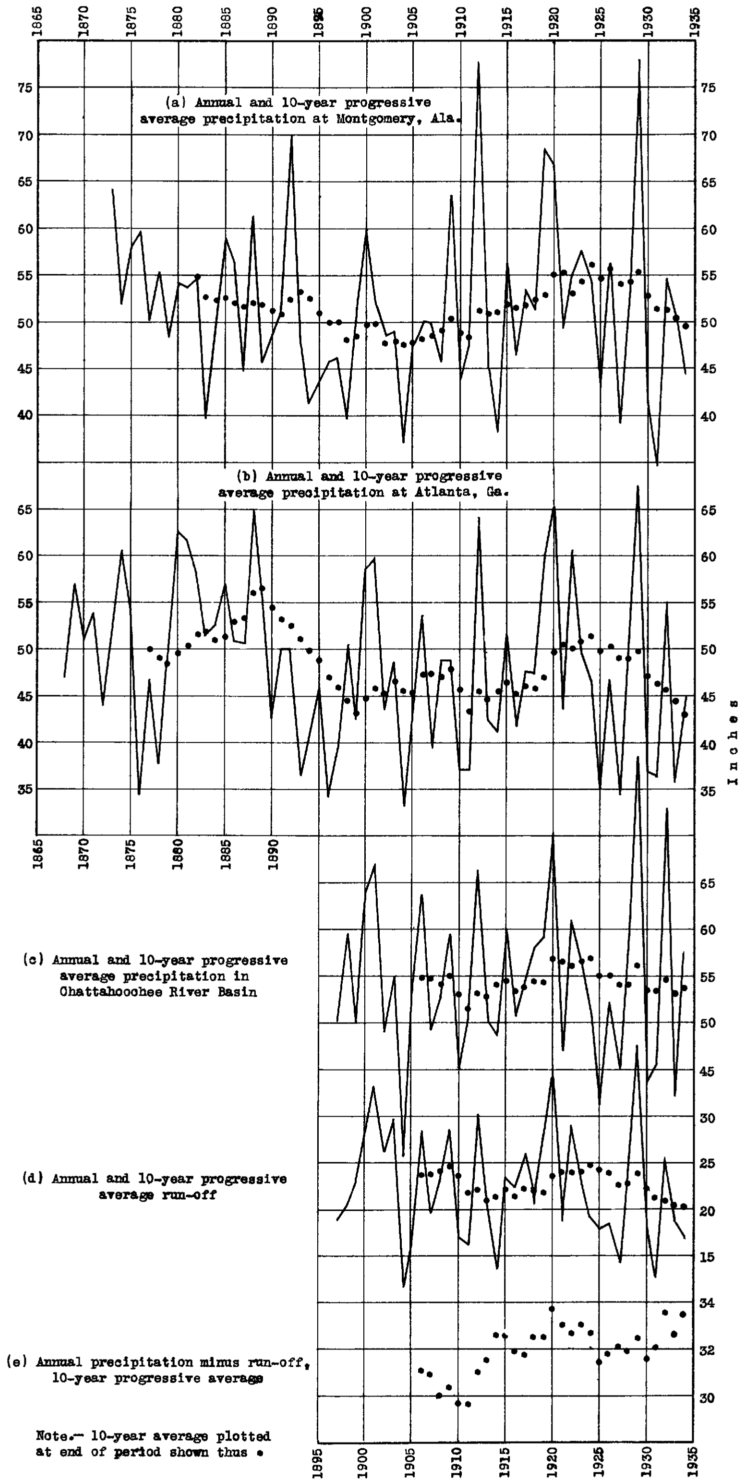


Figure 24.—Relation between rainfall and run-off in Chattahoochee River Basin above West Point, Ga.

in the precipitation based on all the stations can be checked against the trends shown by geographic provinces, and where the data are available figures 18 to 24 also show the mean annual and 10-year progressive annual precipitation for one or two long-time stations within or directly adjacent to the basin.

Whether or not the figures given for the mean annual precipitation represent closely the amounts that fell on the basin is subject to question. For basins in which the precipitation is more a function of geographic location than of altitude the estimates of average precipitation over the basin are believed to be fairly reliable, at least for the later periods. For basins where differences in altitude as well as geographic location affect the magnitude of the precipitation the probability of errors is greater.

In general the estimates of the mean annual temperature have been based on records at a few stations corrected to the mean by comparisons of the average for all the stations in each basin during the later part of the period with the temperature at the base station used.

With respect to the increased temperature in the later years there appears to be little doubt. There is doubt, however, as to the accuracy of the estimates of temperature increases here given. Part of the doubt rests on the belief that the indicated increase at the stations used may not be indicative of the temperatures over the basin. This phase is discussed in the section on temperature. There is also some question as to the accuracy and homogeneity of the record for the periods used. The records of the United States Weather Bureau have been used as given in Bulletin W and other Weather Bureau publications for the period 1889 to 1934, during which the average temperatures have been based on the average of the average daily maxima and average daily minima. For the relatively few records prior to 1889 the figures given in Bulletin W have been corrected, where possible, to conform with the system used since 1889. Such corrections have, in general, changed the 10-year average as compiled from Bulletin W by only 0.2 or 0.3°. Although the temperatures as given may not represent the average temperatures over the basins, especially in the basins having considerable differences in altitude, the indicated changes should at least be fairly representative of changes over the basins.

So far as water stages are concerned the accuracy of the run-off records has probably increased from the beginning of the record at least up to the time when recording gages have been installed. In the matter of stage-discharge relations the accuracy probably increased from the beginning of the record up to about 1910 to 1915, when refined methods of current-meter suspension made possible more accurate determinations of depth and of velocity. In general, however, in spite of probable errors in the base data, the analyses which have been made disclosed few apparent inconsistencies resulting from the data used. In view of the fact that no attempt has been made to recompute or recompile published figures, this consistency is a favorable commentary on the work of the agencies that have collected and compiled the meteorologic and hydrographic data. This does not mean, however, that some of the changes in relations between rainfall and run-off that have been credited to changes in either precipitation or temperature may not be more properly credited to errors in base data or to changes not related to either rainfall or temperature.

The relations between rainfall and run-off, shown in the tables as "ratio of run-off to precipitation", have been determined on the basis of 10-year averages. In some basins the hydrologic cycle may be completed in a much shorter period of time, but Hayford (57) has pointed out, for the small steep Wagon Wheel Gap area in Colorado, that the stream flow on any particular day was influenced by the train of events occurring in the preceding 257 days. If such time elements are involved in a steep basin embracing a few hundred acres, the time required to complete the cycle in all its phases in basins such as the upper Mississippi is probably measurable in years rather than months or days.

In tables 22, 23, and 24 are summarized by basins the basic precipitation, temperature, and run-off data.

Changes in rainfall, by basins

Although the periods of record for the several basins are somewhat different, the presentation allows rough comparisons as between the different basins and also comparisons with the changes as given by areas. Except possibly in the Mississippi, Red, and Tennessee River basins the periods covered by concurrent precipitation, temperature, and run-off records do not embrace early years when, on the basis of long-time records, the precipitation was considerably higher than any included in the basin averages shown in table 22. For example, as shown in figure 21, the precipitation at Boston during the 10-year period ending 1870 was materially above any shown by subsequent periods, and a similar situation is shown with respect to other long-time stations in or near the basins studied. The averages for the Mississippi, Red, and Tennessee River basins include the high precipitation periods of the 1880's, and the average given may be fairly representative of a series of both high and low years. The studies indicate clearly that averages based on records for the last 30 to 40 years in the eastern part of the United States may not embrace periods of maximum precipitation. On the other hand, there seems to be the possibility that in the plains country west of the 100th meridian and also in the Great Basin area (55) records for similar periods do not cover years of prevalent droughts, as shown by the graph of the Colorado River at Lees Ferry, Ariz. (fig. 17). The tables and graphs for the basins studied furnish a convenient record from which those interested may draw their own conclusions with respect to the magnitude of ohanges for different periods.

Changes in temperature, by basins

The temperature changes correspond with the changes previously indicated for areas. All the basins except the Merrimack show higher average temperatures for the last half of the record, and the average for the last 10 years was the highest for the period of record. The average temperature as given, in so far as it reflects the temperature over the basin, is probably too low in basins where there are marked differences in altitude. The changes indicated, however, should represent approximately the changes over the basins.

Changes in run-off, by basins

The apparent changes in run-off are consistent with the indicated changes in the precipitation and temperature. As was to be expected, the average run-off during the last half of the period of record was less than during the first half. Except in the Merrimack River Basin, where the minimum 10-year period occurred in 1918, the average run-off for the 10-year period ending 1934 is the lowest for the period of record. For the

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Table 22.- Average Annual Precipitation

Basin	Period of record	Average (inches)			Ratio last half to first half (percent)	Average for 10 years ending 1934 (inches)	Ratio last 10 years (percent)	
		Whole period	First half	Last half			To long time av.	To first half
Red	1882-1934	20.91	21.76	20.06	92	18.78	90	86
Mississippi	1878-1934	29.61	30.18	28.84	96	27.86	94	92
Neosho	1896-1934	33.58	35.00	32.16	92	32.68	97	93
Merrimack	1880-1934	41.63	42.56	40.70	96	41.38	99	97
James	1899-1934	40.79	42.03	39.55	94	38.30	94	91
Tennessee	1881-1934	50.36	50.34	50.38	100	49.18	98	98
Chattahoochee	1897-1934	54.59	54.20	54.98	101	53.64	98	99

Basin	Maximum year		Maximum 10-year period		Minimum year		Minimum 10-year period		Ratio of last 10 years to minimum 10 years (percent)
	Inches	Year	Inches	Year of ending	Inches	Year	Inches	Year of ending	
Red	27.76	1916	23.30	1905	12.21	1910	18.78	1934	100
Mississippi	41.28	1881	31.65	1909	18.24	1910	27.24	1895	102
Neosho	48.74	1915	37.25	1909	23.66	1901	31.20	1919	105
Merrimack	61.48	1928	45.12	1893	31.38	1883	37.79	1914	109
James	54.03	1901	43.83	1908	21.16	1930	37.86	1930	101
Tennessee	64.10	1882	52.20	1924	36.17	1925	47.23	1896	104
Chattahoochee	78.46	1929	56.80	1924	36.03	1904	51.38	1911	104

Table 23.- Average temperature (°F.)

Basin	Period of record	Average (inches)			Difference last half from first half	Average 10 years ending 1934	Difference last 10 years from	
		Whole period	First half	Last half			Whole period	First half
Red	1882-1934	39.8	38.7	40.8	+ 2.1	41.6	+ 1.8	+2.9
Mississippi	1878-1934	45.2	44.9	46.5	+ .6	46.1	+ .9	+1.2
Neosho	1896-1934	55.6	55.4	56.8	+ .4	56.5	+ .9	+1.1
Merrimack	1880-1934	45.6	45.6	45.6	0	46.1	+ .5	+ .5
James	1899-1934	54.9	54.5	55.3	+ .8	55.8	+ .9	+1.3
Tennessee	1881-1934	55.8	55.3	56.3	+ 1.0	56.9	+ 1.1	+1.6
Chattahoochee	1897-1934	61.5	61.2	61.8	+ .6	62.1	+ .6	+ .9

Basin	Maximum year		Maximum 10-year period		Minimum year		Minimum 10-year period		Difference last 10 years from minimum 10 years
	°F.	Year	°F.	Year of ending	°F.	Year	°F.	Year of ending	
Red	45.8	1931	41.6	1934	34.1	1883	37.6	1891	+ 4.0
Mississippi	50.5	1931	46.1	1934	41.4	1917	43.8	1892	+ 2.3
Neosho	58.9	1933	56.4	1934	53.3	1912	54.9	1920	+ 1.6
Merrimack	48.8	1880	46.5	1889	41.1	1918	44.9	1908	+ 1.2
James	57.1	1921	55.8	1934	52.5	1904	54.1	1910	+ 1.7
Tennessee	58.5	1933	56.9	1934	63.3	1901	65.0	1893	+ 1.9
Chattahoochee	63.5	1921	62.1	1934	59.4	1901	60.8	1910	+ 1.3

Table 24.- Average annual run-off

Basin	Period of record	Average (inches) Whole period	First half	Last half	Ratio last half to first half (percent)	Average for 10 years ending 1934 (inches)	Ratio last 10 years (percent) To Whole period	To First half
Red	1882-1934	1.25	1.57	0.94	60	0.60	48	38
Mississippi	1878-1934	6.98	7.54	6.52	86	5.54	79	74
Neosho	1896-1903 1918-1934	4.12	*	*	*	4.61	*	*
Merrimack	1880-1934	20.13	21.00	19.08	91	19.44	97	93
James	1899-1934	15.59	16.92	14.27	84	13.28	85	79
Tennessee	1881-1934	24.24	25.18	23.30	93	21.62	89	86
Chattahoochee	1897-1934	22.32	22.55	22.09	98	20.17	90	89

Basin	Maximum year Inches	Year	Maximum 10-year period Inches	Year of ending	Minimum year Inches	Year	Minimum 10-year period Inches	Year of ending	Ratio of last 10 years to minimum 10 years (percent)
Red	3.12	1916	1.84	1910	0.13	1934	0.60	1934	100
Mississippi	13.19	1881	8.87	1888	3.12	1934	5.54	1934	100
Neosho	*	*	*	*	*	*	*	*	*
Merrimack	31.54	1928	23.03	1893	10.65	1911	16.94	1918	115
James	25.06	1901	18.36	1908	7.00	1930	13.28	1934	100
Tennessee	34.12	1882	28.11	1891	13.95	1904	21.62	1934	100
Chattahoochee	37.61	1929	24.67	1909	11.57	1904	20.17	1934	100

* The broken record makes it impossible to present comparable data.

basins shown the period of record probably covers the minimum 10-year period of record except for the Neosho River Basin, where as indicated by the Leavenworth record (fig. 20) a lower minimum may have occurred in 1847 or 1869; and for the James River Basin (fig. 22), where a lower minimum during the early seventies is indicated by the Baltimore record.

Relations between rainfall and run-off

The most commonly expressed relation between rainfall and run-off is the ratio obtained by dividing the run-off for a given period by the precipitation for the same period. The concept of run-off thus conveyed is faulty and may be misleading. A sounder concept of the relation is that run-off is a residual of rainfall after the deduction of losses by evaporation and transpiration. However the ratio as commonly derived, properly considered, is of some interest and is presented for the basins studied in tables 8, 10, 13, 15, 17, 19, and 21 by 10-year progressive periods. In figures 25 to 31 are plotted the average annual precipitation against the average annual run-off for each year covered by the period of record, and the total precipitation by 10-year periods against the total run-off for the same 10-year periods.

For the purpose of ready comparison of the relations between rainfall and run-off for the several basins, figure 32 shows to a common scale the average annual precipitation by 10-year periods plotted against the average annual run-off for the same periods. This figure is identical with similar data plotted on figures 25 to 31 with the exception of the scales. The data thus presented disclose several interesting and significant features.

On the basis of the long-time averages it appears that in the Red River Basin a change of 1 inch in annual rainfall is reflected by a change of about 0.3 inch in run-off. On the other hand, in the basins of the James, Merrimack, Tennessee, and Chattahoochee Rivers a change of 1 inch in rainfall is reflected by changes of 0.7 inch to 0.9 inch in run-off. In the Mississippi River Basin a change of 1 inch in rainfall is reflected by a change of about 0.5 inch in run-off.

The transpiration and evaporation as measured by "precipitation minus run-off" as given in tables 8, 10, 13, 15, 17, 19, and 21 and shown graphically in figures 18 to 24 averages about 20 inches for the Red River

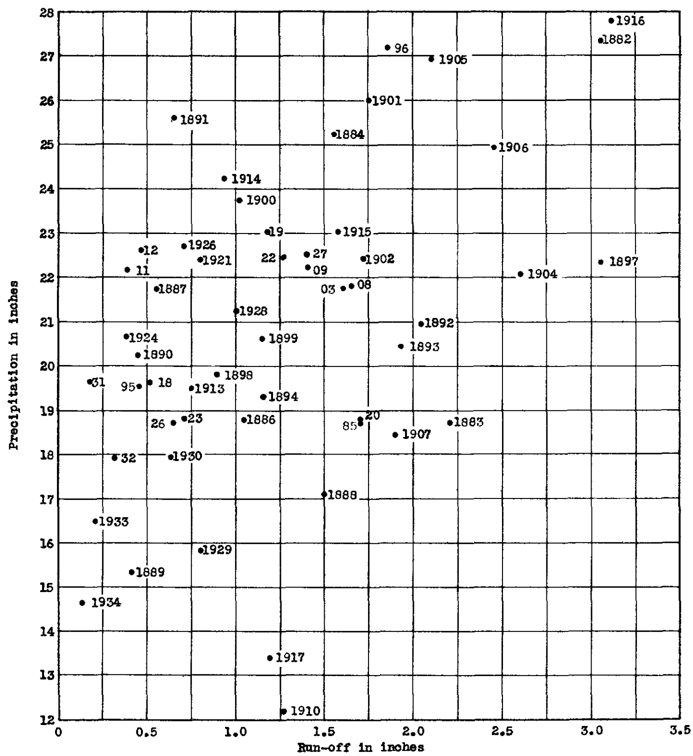

Figure 25a.—Annual precipitation and annual run-off in the Red River Basin above Grand Forks, N.Dak.

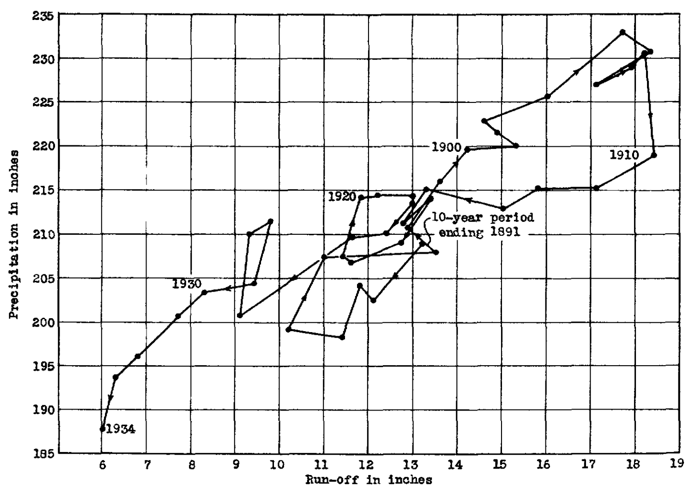

Figure 25b.—Total precipitation and total run-off by 10-year periods in the Red River Basin above Grand Forks, N.Dak.

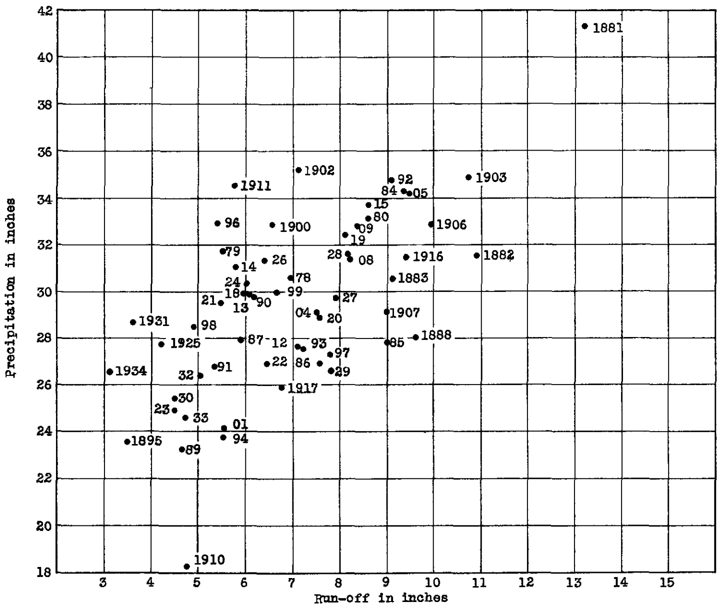

Figure 26a.—Annual precipitation and annual run-off in the Mississippi River Basin above Keokuk, Iowa.

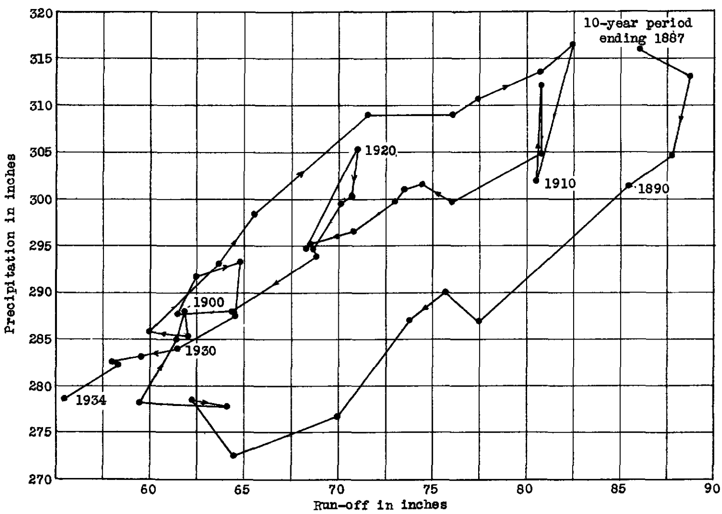

Figure 26b.—Total precipitation and total run-off by 10-year periods in the Mississippi River Basin above Keokuk, Iowa.

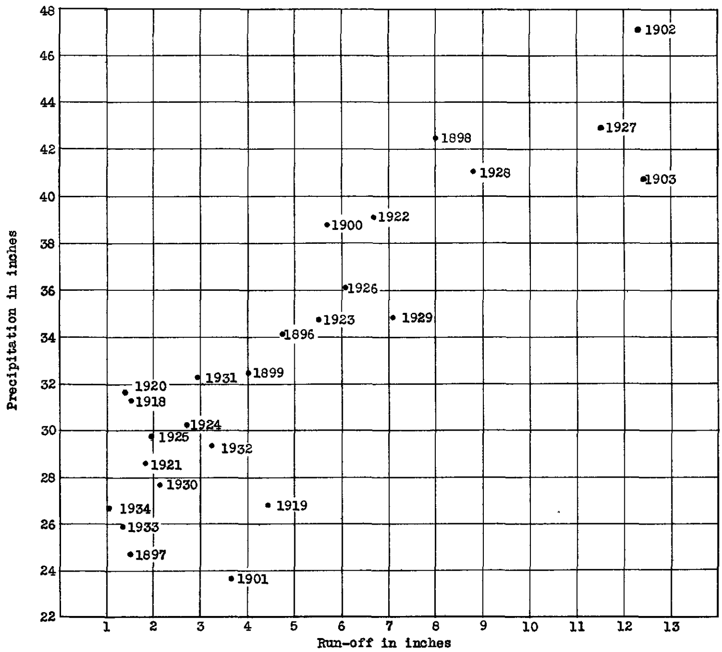

Figure 27a.—Annual precipitation and annual run-off in the Neosho River Basin above Iola, Kans.

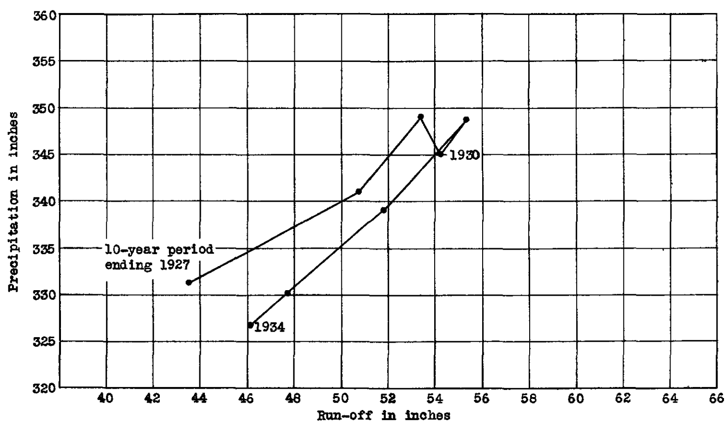

Figure 27b.—Total precipitation and total run-off by 10-year periods in the Neosho River Basin above Iola, Kans.

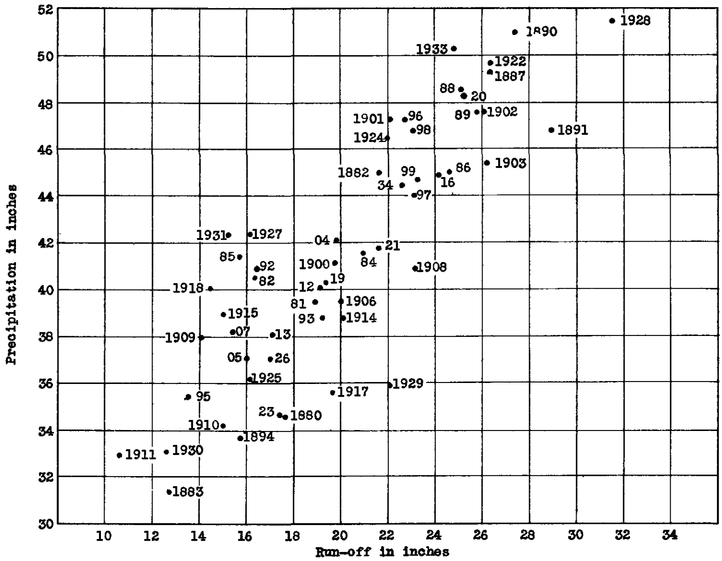

Figure 28a.—Annual precipitation and annual run-off in the Merrimack River Basin above Lawrence, Mass.

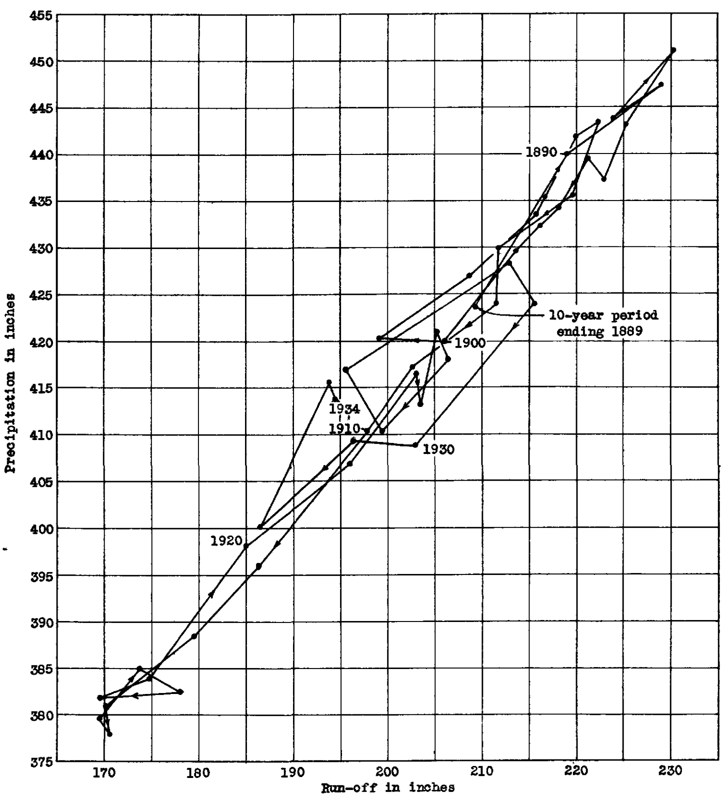

Figure 28b.—Total precipitation and total run-off by 10-year periods in the Merrimack River Basin above Lawrence, Mass.

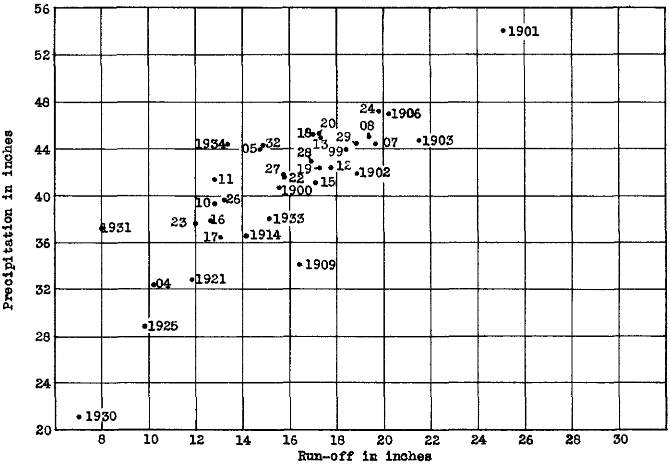

Figure 29a.—Annual precipitation and annual run-off in the James River Basin above Cartersville, Va.

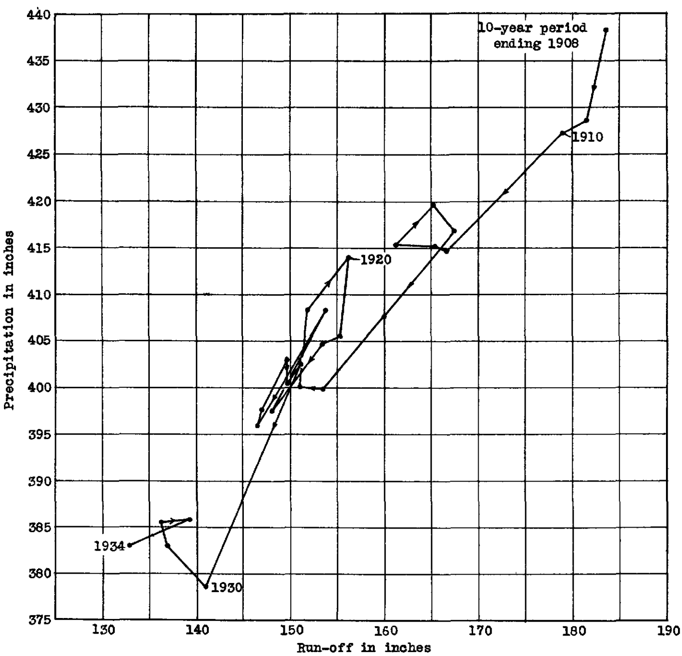

Figure 29b.—Total precipitation and total run-off by 10-year periods in the James River Basin above Cartersville, Va.

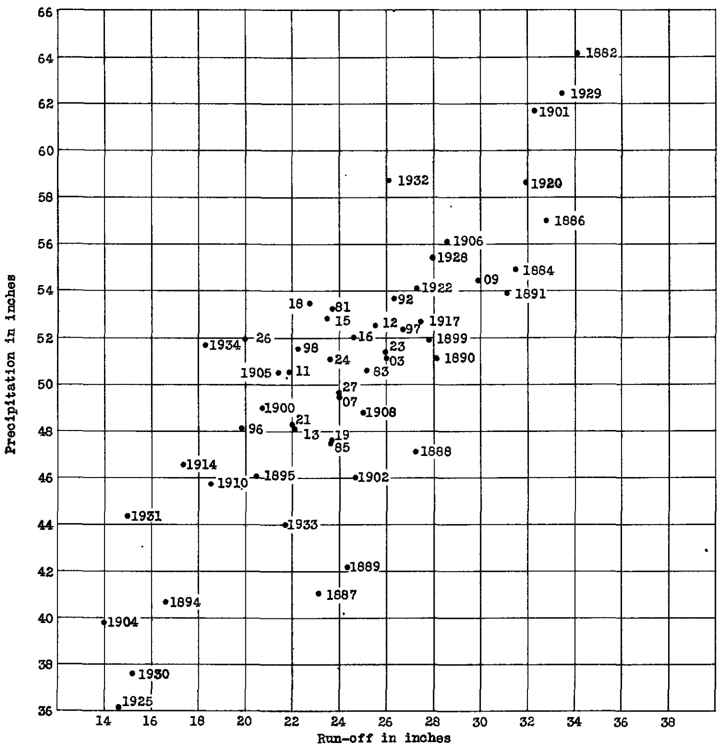

Figure 30a.—Annual precipitation and annual run-off in the Tennessee River Basin above Chattanooga, Tenn.

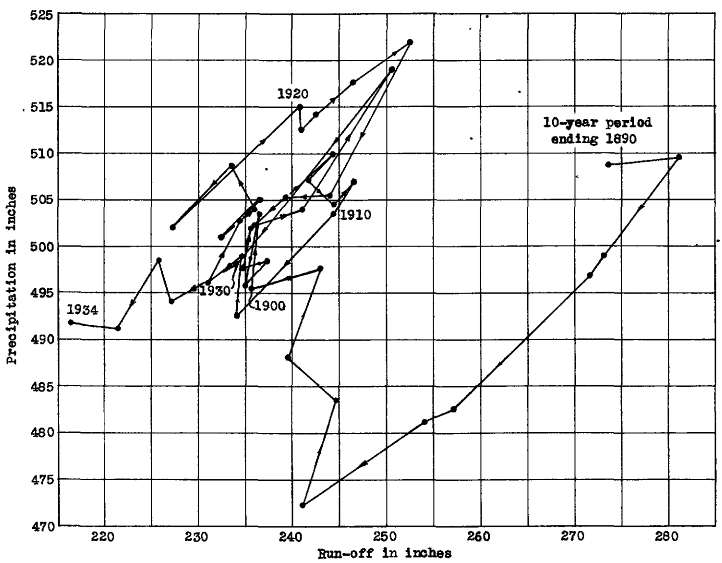

Figure 30b.—Total precipitation and total run-off by 10-year periods in the Tennessee River Basin above Chattanooga, Tenn.

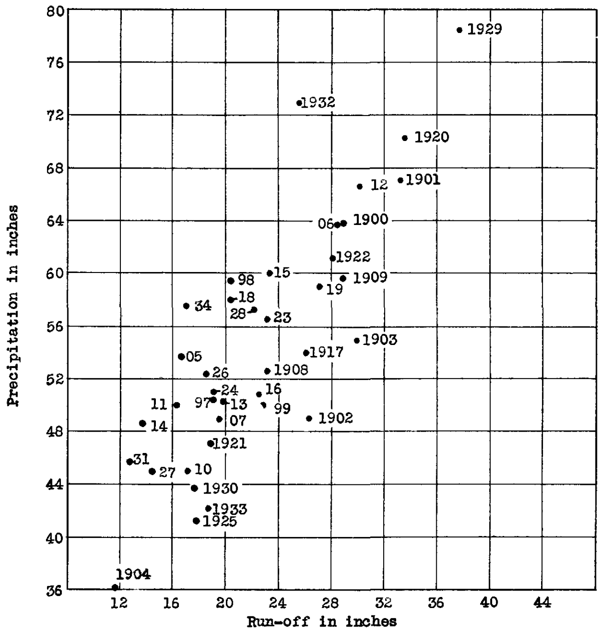

Figure 31a.—Annual precipitation and annual run-off in the Chattahoochee River Basin above West Point, Ga.

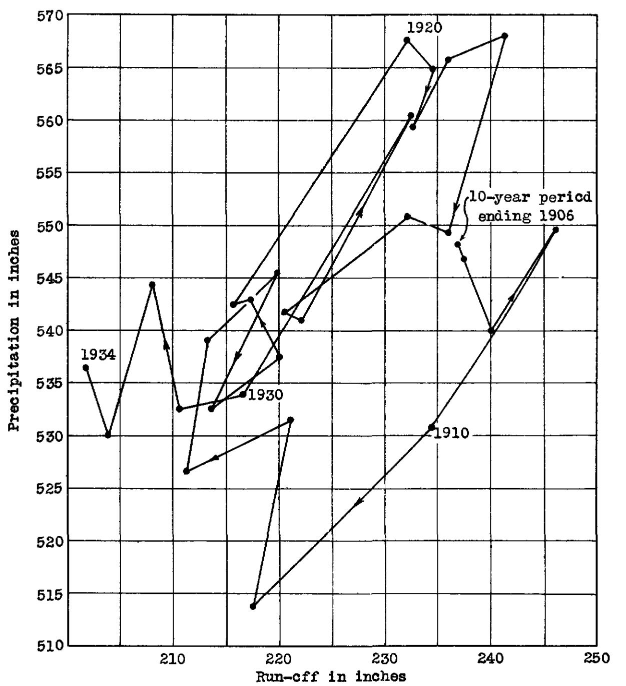

Figure 31b.—Total precipitation and total run-off by 10-year periods in the Chattahoochee River Basin above West Point, Ga.

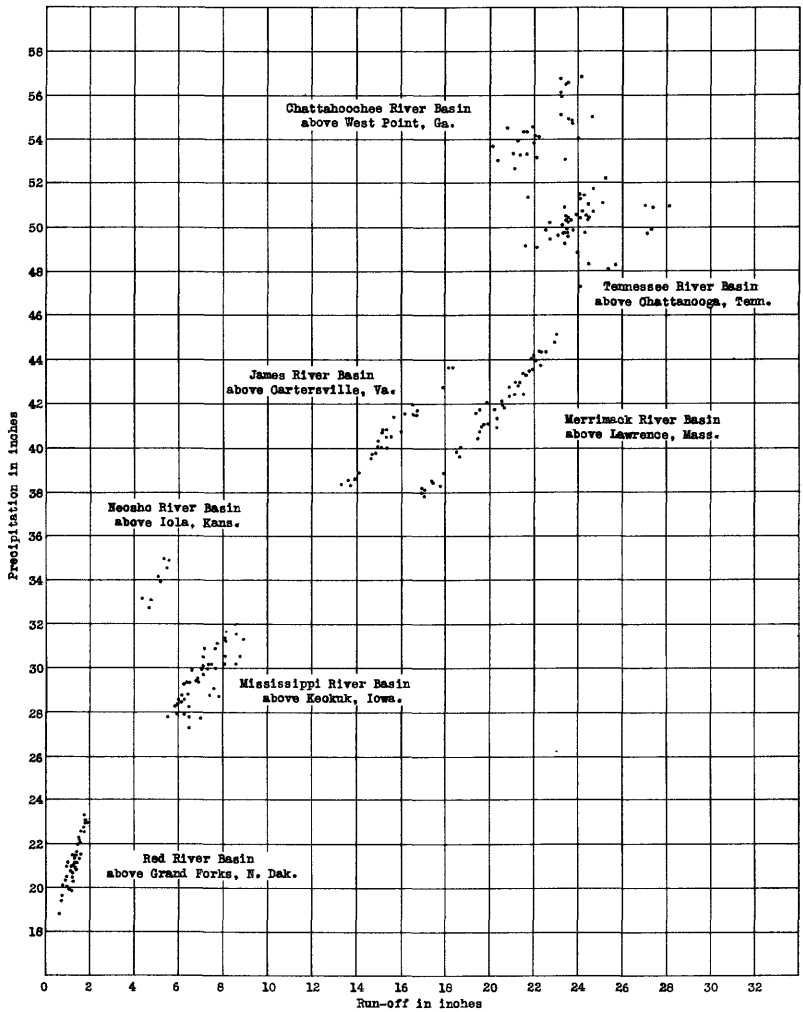

Figure 32.—10-year progressive average precipitation and 10-year progressive average run-off for selected drainage basins.

Basin, 21 inches for the Merrimack River Basin, 23 inches for the Mississippi River Basin, 25 inches for the James River Basin, 26 inches for the Tennessee River Basin, and 32 inches for the Chattahoochee River Basin.

In the Red River Basin the normal loss by evaporation and transpiration is so great that the average annual run-off amounts to less than 10 percent of the average annual precipitation. The average annual precipitation during the last 10 years has apparently been less than the normal demands of transpiration and evaporation. The stream flow that has occurred under such conditions must have resulted mostly from the small amounts of surface run-off resulting from intense rainfall of short duration or melting snow which the ground could not absorb or from seepage from ground water which has escaped the demands of evaporation and transpiration. Figure 25 showing rainfall, run-off, and "precipitation minus run-off" for the Red River Basin, illustrates in a striking manner the fact that during recent years the amount of moisture available in this basin has not been sufficient to satisfy normal evaporation and transpiration demands and that the amount of precipitation that eventually finds its way to the stream has been declining for the last 20 or 25 years.

On the other hand, in the basins of the Merrimack, James, Tennessee, and Chattahoochee Rivers the average precipitation exceeds the normal transpiration and evaporation demands by 20 to 25 inches. There is normally in these basins a large supply of water available for replenishment of ground-water reserves and stream flow. Changes such as have occurred in the precipitation are of less vital concern than they are in areas where there is little or no surplus moisture.

The plotted relations between rainfall and run-off as shown in figures 25 to 31 indicate that except in the Neosho Basin and possibly in the Merrimack River Basin there is a tendency for the points, both annual and 10-year total, indicating the relation during the earlier parts of the record periods, to plot toward the right-hand side of the group of points, and for the points indicating the relation during the later parts of the record periods to plot toward the left-hand side. In other words, the relations thus presented disclose a rather decided tendency for a somewhat smaller amount of run-off for a given amount of precipitation during the later half of the period than during the first half.

This apparent change in rainfall and run-off relations could have resulted from a combination of any or all of the following circumstances:

1. The average precipitation as compiled for the basin during the first part of the period may be less than the amount that fell on the basin, or the observed run-off may be too high. In general it is believed that in so far as the run-off records are concerned, the earlier measurements of flood flows may have had a tendency to overregister rather than underregister, and in so far as the annual averages are based on discharge measurements during high stages, they are probably an overestimate rather than an underestimate. In basins where precipitation is related to altitude the earlier precipitation records probably underestimate the precipitation over the basin. There seems to be the possibility, therefore, that at least a part of the apparent change in the indicated relations may result from errors inherent in the basic data.

2. There may have been a change either in the seasonal distribution of the rainfall or in some other of its characteristics. The preceding analysis of the seasonal precipitation for the long-time Weather Bureau stations indicates that there has been an apparent seasonal change, the fall precipitation trending upward and the winter and summer precipitation trending downward. The same tendency is noted in the seasonal analysis of precipitation by basins, the records indicating a general tendency for a larger proportion of the annual precipitation to occur in the fall during the second half of the period than during the first half. An analysis has not been made to determine whether or not there have been other changes in rainfall characteristics. Just what effect the indicated change would have on run-off is problematic.

3. Changes are supposed to have resulted from man's occupancy. The change in the relations by which less annual run-off has come from the same amount of annual precipitation appears, however, to be somewhat at variance with the opinion frequently expressed. The question arises whether cultivation has not accomplished conservation of moisture for crop production in amount sufficient to overweigh any increased surface run-off that might have been occasioned as a result of agricultural and other activities of man.

4. Increased transpiration and evaporation may have accompanied increased temperatures. With moisture available an increase in temperature would increase transpiration and evaporation. The present studies, however, have not been carried to a point where the losses can be correlated with the indicated increases in temperature.

Stream flow

It is generally understood that run-off, the portion of the precipitation that appears as flow in surface streams, occurs in two ways - namely, (a) as surface run-off, or that part of the precipitation which reaches surface streams by flowing over the surface of the ground and into tributary streams, and (b) as ground-water run-off, or that part of the precipitation which before reaching surface streams has passed through the ground. Ground-water run-off is sometimes termed "seepage flow from ground water" and occasionally "base flow" or "sustained flow."

It is axiomatic that if the greater part of the precipitation runs off the surface of a drainage basin the resulting stream flow will be erratic and irregular and will continue for only relatively short periods of time during and after rains. Little opportunity will be afforded for replenishment of ground-water reserves, and where the run-off is concentrated and erodible material is present erosion will result. On the other hand, if the greater part of the precipitation reaches the stream as seepage from ground water, stream flow will be regular and well sustained through drought periods, and ground-water reserves will be well maintained.

Stream-flow separation

In hydrologic investigations and especially in quantitative studies of factors of the hydrologic cycle, it becomes desirable to separate run-off into its surface and ground-water components. The efforts to make such separation are met with many practical difficulties and complexities. However, some progress has been made by various investigators in the development of methods of separation, and despite the recognized limitations of present knowledge, a brief account of their experience seems appropriate.

First a general contrast may be drawn between the characteristics of surface and ground-water run-off.

Ordinarily, soon after rain falls with sufficient intensity to produce a flow of water across the ground surface, surface run-off begins to appear in the channels of the stream system. Usually, where storage is negligible, not long after the rainfall ceases all such surface run-off is in the channels of the stream system, and within a period ranging from a day or less to a month or more, depending on the size and characteristics of the basin, it has passed out of the stream system. The characteristics of the flow of surface run-off are related to the essential characteristics of the drainage basin and the stream system, including shape of the basin, channel velocities, etc. Many of the features of such basin characteristics are believed to be reflected by the unit hydrograph and the distribution graph, discussed elsewhere in this paper.

On the other hand, the ground-water run-off ordinarily is delayed more or less in passage through the ground, so that the part of the precipitation which takes this course is reflected in stream flow more tardily than the surface run-off, the intervening time involving weeks, months, or even longer.

A customary procedure in estimating ground-water run-off is to present the run-off to be analyzed in the form of a hydrograph of total flow and then undertake to draw a graph to represent the ground-water component of the flow. Any flow above that indicated by the graph of ground-water run-off will then necessarily represent the surface run-off component of the flow. In making such separation full advantage is taken of the knowledge that in general the average annual rate of ground-water run-off is at least equal to the minimum daily rate of discharge of the stream. Above this discharge the determination of the ground-water run-off becomes increasingly uncertain. There is opportunity for the development of a well-defined technique for this determination, but in the absence of such technique the only recourse is to apply the best methods based on experience and science that may be available.

Ivan E. Houk (72) made a separation between ground-water run-off and surface run-off by drawing on the hydrograph of total stream flow "lines representing the rate of ground-water flow . . . so as to pass through the low points only" of the hydrograph. "The endeavor was to draw the line so that the increased flow of tiles immediately after a flood - that is, the drainage of the surface soil - would be included in the surface or flood run-off rather than in the ground-water run-off, since such flow acts more nearly like surface flow than like low-water flow. It was also assumed that no percolation occurs during the growing season."

Meinzer and Stearns (115), in an effort to determine the quantity of ground water that percolated into the Pomperaug River and was carried out of the basin, followed the general method used by Houk. In addition they took into account the probable time element in connection with the passage of the surface run-off out of the basin, and during periods of flood run-off "the curves showing the ground-water run-off were brought up somewhat to meet the descending curve that shows total run-off."

Approximately this same method was used by L. K. Sherman (158) in determining his unit graph of surface run-off. He made the separation under conditions of low ground-water flow uncomplicated by antecedent effects.

One of the major complexities associated with the problem is the consideration of stored surface water in the drainage basin. Although on most streams a large part of the surface run-off appears at the gaging station fairly promptly after the rainfall from which it originates and is shown by a definite rise in the hydrograph of stream flow, there may be in some basins an appreciable amount of surface run-off which is held in storage, either artificially or naturally, in lakes, ponds, reservoirs, and marshes, and which eventually appears at the gaging stations so closely associated with ground-water flow that exact differentiation would require details of information that are rarely if ever available. Also the hydrograph of the peak or rise in stream flow may represent to some extent increased ground-water run-off resulting from recharge to the zones of saturation and increased contributions from those zones.

In the absence of information permitting greater refinement, surface run-off is tentatively regarded in this report as that part of the total run-off that appears systematically and regularly in the stream channel as the rise directly responsive to rainfall or the melting of snow. (For classification of stream rises see 70, p. 455.) The rise probably does not include all surface water, because some of it may be materially delayed by storage in reaching the gaging station. The rise may include some ground water that has been held in ground reservoirs that feed the streams, especially after prolonged intense rainfall, with a responsiveness that is only somewhat less pronounced than that which characterizes surface run-off. This condition may occur especially in basins where perched water tables exist or in tiled areas.

Ground-water run-off as considered in this paper is the estimated seepage flow directly into the stream from the main zone of saturation and from perched water tables. (For definitions of ground-water terms see Meinzer, 113). In view of the approximations involved in the separation of ground-water and surface run-off, a ground-water graph may include some water that has been stored on the surface and may exclude

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some ground water which in the promptness of its reaching the stream channels behaves so much like surface run-off that it is difficult to make a distinction.

There is no question that the occurrence and movement of ground water depends on and is affected by a wide variety of topographic, geologic, and soil conditions. There is also no question that with these conditions constant for any basin, the occurrence and movement of the ground water will vary with meteorologic conditions. In a study of the problems of separating ground-water run-off from surface run-off in a basin of material size it may therefore be desirable and necessary to take into account as many relations and as many flow characteristics as can be developed. Such relations and flow characteristics may include depletion curves, recession curves, recharge curves, unit hydrographs, infiltration and storage factors, together with the effect of meteorologic conditions. The following is a brief summary of some of the observations and methods of investigators who have attempted to ascertain the facts and truths relating to this particular phase of ground water.

Depletion curves

Samuel Hall (53) observed in connection with the recession of stream flow that in "the gently falling and lowest parts of the curve due to percolation discharge, one characteristic is the steady fall, showing not only that the rate of flow decreases but that its rate of decrease also diminishes; in other words, the curve gets flatter from day to day throughout a rainless period," and further, that after additional precipitation "not only has there been a large immediate yield, as shown by a peak, but the stream has gained in staying power. The conclusion drawn is that new supplies of percolation water have increased the amount in storage, with result of increased discharge."

Studies of the fluctuations of the water surfaces in observed wells unaffected by pumping and below the effect of transpiration and evaporation support Hall's observations and indicate that during periods when there is no recharge the decline of the water surface in the well, or the draining out or depletion of the water in the zone of saturation in the vicinity of the well, proceeds at a fairly uniform rate for any given stage of the water table or amount of water in ground storage. It seems reasonable to assume, therefore, that the seepage into the stream from the ground-water supply or the ground-water run-off should also be marked by uniformity except as affected by evaporation and transpiration.

Robert E. Horton (70, pp. 448-449) refers to early observations and presentations of depletion curves of ground-water levels by Maillet in 1903 and D. Halton Thompson in 1921 (180). The methods of these early investigators have been extended to the separation of ground water from surface run-off by Horton and others, and the theory of this separation is presented by Horton (70, pp. 446-460).

Studies of the hydrographs of some streams seem to indicate conclusively that during drought periods, when the stream flow is supplied wholly or in large part by seepage from the reservoir of ground water, the rate of decline for corresponding flow stages and climatic conditions tends to be very nearly the same. In other basins, where water-bearing formations or other conditions may be more complex, the rate in the decline of stream flow during drought periods seems to vary somewhat.

The seepage flow into the streams is supplied from an irregular and interrelated body of water in the ground. It is water that has escaped transpiration and evaporation, the effects of which in many basins are believed to be greatest in the vicinity of stream channels, where the water table is nearest the ground surface. In such localities the effects of evaporation and transpiration may vary greatly from year to year and from season to season, depending upon a variety of conditions. Some investigators have found by extensive observation that marked regularity characterizes the behavior of ground water in relation to season, temperature, and other factors. Horton (70) makes the following statement in regard to what is termed a normal depletion curve in the study of ground-water run-off:

> "For streams where the ground-water level underneath the drainage basin is at a depth beyond the reach of the direct abstraction of plants or vegetation, the normal depletion curves in different years are often nearly identical throughout their common range within the limit of error of observation and excluding the effects of barometric changes, etc., on ground-water flow. The normal depletion curves may differ to a considerable extent in different years or seasons in cases

> where there is a direct abstraction of ground water from the water table by vegetation or evaporation. Even in such cases the differences between summer-season depletion curves in different years is often so small that for practical purposes in separating ground-water and surface run-off, an average normal depletion curve can be used."

Tomihisi Iwasaki (82), by a detailed study of the run-off from a fairly mountainous drainage area of 156 square miles, developed a standard depletion curve and also determined the approximate relation between precipitation and the increment of ground-water and surface run-off and was thus able to build up a hydrograph of total run-off.

It is seemingly permissible in the absence of any better method of approach to utilize in this problem the tendency to regularity that may be detected in a comparison of depletion curves, but the possibility that there may be material deviations from normal depletion curves should not be overlooked. In basins where closely comparable depletion curves can be obtained for different seasons or where the characteristics of depletion curves can be correlated to some degree with climatic or soil conditions, they seem to afford useful and valuable tools in efforts to separate ground-water run-off.

Recession curves

A recession curve, as the term is here used, is the descending limb of a hydrograph of stream flow, including both surface run-off and ground-water run-off, as it recedes from a peak downward to the point of zero surfaoe run-off. Most streams rise more or less frequently to a flood peak and, before subsidence from it has been completed, rise to another peak. For many streams the hydrographs for the winter and early spring are characterized by peaks in such rapid succession that only rarely does the surface run-off have a chance to drain out. Such peaks make the task of drawing a ground-water hydrograph difficult and the results uncertain.

It has been observed that during periods of frequent floods the descending limbs of storm peaks become graded to a higher level than isolated peaks occurring during periods of low flow. Through a study of the descending limbs of hydrographs of storms occurring during the summer, when ground water is low, it may become possible to develop a composite recession curve. Such a composite curve used on the descending limb of a storm hydrograph when ground water is high seems to be valuable in locating the probable intersection of the hydrograph of surface run-off with the hydrograph of ground-water run-off. This method, like the other methods described, has its limitations. In practice it is found that the curvatures of the descending limbs during the summer are somewhat different from those during the winter. It is also found that the descending limb of a storm peak is often affected by rainfall - that is, the rate of descent is not as rapid as the recession would be if there was no rain after the flood peak, and fitting a recession curve to this descending limb results in erroneous estimates of ground-water flow.

Byron E. White (187a), in an original study of relations between rainfall and run-off when there was no snow on the ground and no freezing and thawing, definitely correlated the form and rate of recession of the recession side of the hydrograph with calendar dates and mean atmospheric temperatures. In a letter dated April 29, 1935, he says: "An attempt to determine stream flow on this theory, together with some simple relations between initial flow, an imaginary instantaneous flow, and the mean rainfall on the area, which is described therein, failed to give close results, in part because of insufficient and inadequate rainfall data and in part because of insufficient data regarding other phenomena."

Ground-water levels and accretion

The portion of the precipitation that seeps through the soil into the zone of saturation forms an increment to the ground water in the zone of saturation.

On January 1, 1935, the water surface of more than 3,000 wells was being periodically measured by the United States Geological Survey and cooperating organizations. The publication year by year of the levels thus observed, in a manner similar to the publication of the stream-flow records, is a procedure that is greatly needed. Preliminary studies of precipitation, accretion to the water table, and seepage from the ground-water reservoir into the stream channels have indicated that the relations are involved. In general, information is not available for making an exact correlation, even where many well records are at hand. If however, through a study of well records or of the hydrographs of stream flow some idea can be gained of the rapidity with which accretion to the water table takes place, or the rapidity with which seepage from ground water may increase, such information will be valuable in the determination of the hydrograph of ground-water run-off.

Unit hydrographs

As described more fully in the discussion of the unit-hydrograph method of analyzing surface run-off (pp.123-133) the lengths of the bases of hydrographs of surface run-off of storms of a certain duration, such as an hour or a day, are approximately the same for any given basin. In other words, the interval between the time when the surface run-off from a 1-day storm first reaches a gaging station and the time when all such surface run-off has passed the gaging station appears to be approximately the same, regardless of the storm intensity. Through a study, therefore, of the hydrographs of run-off from appropriately selected storms it is possible to determine the approximate time required for surface run-off to pass out of the basin, and hence, by a study of the hydrograph of stream flow used in conjunction with precipitation records, to determine periods when there is no appreciable surface run-off in the stream or when the hydrograph of total stream flow approximates the hydrograph of seepage flow from ground water.

Much of the information of the unit hydrograph, embodying essential features of the characteristics of the flow from surface-water run-off, is based upon studies of flow at times when uncertainties as to ground-water run-off are relatively small. A carefully derived unit hydrograph unquestionably shows valuable information concerning the characteristics of surface run-off that seemingly may be used in an appropriate way in times of uncertainty, to learn more about the ground-water flow.

Infiltration capacity and storage factors

Robert E. Horton, a member of the Advisory Committee, has suggested that it may be possible eventually, through a knowledge of infiltration capacity, field-moisture deficiencies, and storage factors, defined by him in a recent publication (70a), to determine surface run-off and conversely ground-water run-off.

Meteorologic factors

It is a well-known fact that during rainless periods in the autumn the flow of many springs and streams increases. This increase is usually associated with the end of the growing season and the decline in transpiration losses. A depletion curve of ground-water run-off loses its downward projection under such conditions, and the ground-water run-off presumably increases by an amount approximating the reduction in losses from transpiration. From studies of the relations between the decline in ground-water levels and changes in the rate of ground-water discharge, it has been observed that in certain instances a decline in water levels during a period when evaporation and transpiration are active causes a decrease in the rate of ground-water discharge noticeably smaller than that effected by the same amount of water-table lowering during a period of dormant vegetation. Although effects of other factors could be pointed out, it seems obvious that the problem of separating ground-water run-off from surface run-off requires a consideration of meteorologic conditions. Adolph F. Meyer (122) describes methods whereby meteorologic factors may be used in the determination of the amount of water available for replenishment of soil moisture and recharge to ground water. A discussion of methods devised by Meyer to evaluate evaporation and transpiration losses is given on pages 250 and 251.

Channel storage

O. E. Meinzer, of the United States Geological Survey, has suggested a method whereby ground-water run-off may be directly determined through a study of changes in channel storage. The method requires the determination of the amount of run-off that is held as channel storage at any time. It is based on the hypothesis that as soon as essentially all the direct surface run-off reaches the channel the total amount of direct surface run-off that will pass the gaging station can be calculated from the changes in channel storage. When, during a certain day in which no surface water is added to the stream system, more water is measured at the gaging station than is represented by the changes in channel storage, the excess is attributed to ground-water run-off. Field experiments are now being carried on under the direction of Meinzer to determine changes in channel storage on a small basin near Washington, D. C.

Surface run-off

Quantitative analysis, by basins

The following tables show for typical basins in the United States and for major subdivisions of the Mississippi River above Keokuk, Iowa, an estimate of the mean annual surface run-off expressed in inches and as a percentage of precipitation. All figures are in general based on a 5-year annual average for the period noted and were obtained by subtracting from the total stream flow the ground-water run-off as estimated from a study of the plotted hydrograph of stream flow, using, in part, methods previously discussed. It should be clearly recognized that the estimates given are subject to error. Further refinement in the methods of determination and more exhaustive application of known factors might change the results materially. They are, however, believed to be of sufficient accuracy to make comparisons between typical basins of a very important phase of the hydrologic cycle, and this is a primary purpose of their presentation.

The figures given for the Miami River Basin, Ohio, and for the Pomperaug River Basin, Conn., are based on general straight lines as previously outlined, and the results may not be entirely comparable with the figures given for the other basins.

Table 25.- Average annual surface run-off for typical basins

Basin	Precipitation (inches)	Surface run-off		
		Inches	Percent of total run-off	Percent of precipitation
Red River above Grand Forks, N. Dak. (1928-32)	18.53	0.35	59.3	1.9
Mississippi River above Keokuk, Iowa (1928-32)	28.64	3.36	56.2	11.7
Neosho River above Iola, Kans. (1928-32)	33.07	4.06	82.5	12.3
Merrimack River above Lawrence, Mass. (1928-32**)	40.66	* 9.94	50.9	24.5
James River above Cartersville, Va. (1928-32)	38.04	7.02	53.5	18.5

* Probably too small.
** Years ending September 30.

Table 25.- Average annual surface run-off for typical basins--Continued

Basin	Precipitation (inches)	Surface run-off Inches	Percent of total run-off	Percent of precipitation
Tennessee River above Chattanooga, Tenn. (1901-5)	49.83	15.30	64.4	30.7
Chattahoochee River above West Point, Ga. (1928-32)	59.65	11.59	50.1	19.4
Miami River above Dayton, Ohio# (1894-1919**)	37.07	7.77	65.6	21.0
Pomperaug River above Bennetts Bridge, Conn.## (1914-16**)	44.48	11.90	57.6	26.8

See ref. 72.
** Years ending September 30.
See ref. 115.

Table 26.- Average annual surface run-off for major subdivisions of Mississippi River Basin above Keokuk

Subdivision	Precipitation (inches)	Surface run-off Inches	Percent of total run-off	Percent of precipitation
Minnesota River above Mankato, Minn. (1930-32*)	22.22	0.42	61.0	1.9
Zumbro River above Zumbro Falls, Minn. (1931-32*)	26.35	1.70	48.8	6.5
Maquoketa River above Maquoketa, Iowa (1931-32*)	30.64	2.89	51.5	9.4
La Crosse River above West Salem, Wis. (1928-32*)	30.35	2.64	26.6	8.7
Root River above Houston, Minn. (1931-32*)	27.98	2.42	44.6	8.6
Kickapoo River above Gays Mills, Wis. (1928-32*)	29.67	3.64	40.0	12.3
Rock River above Afton, Wis. (1928-32*)	29.62	3.63	49.0	12.3
Iowa River above Wapello, Iowa (1928-32*)	32.83	4.28	61.1	13.0
St. Croix River above Rush City, Minn. (1928-32*)	25.32	3.76	51.7	14.8

* Years ending September 30.

Table 26.- Average annual surface run-off for major subdivisions of Mississippi River Basin above Keokuk--Continued

Subdivision	Precipitation (inches)	Surface run-off		
		Inches	Percent of total run-off	Percent of precipitation
Pecatonica River above Freeport, Ill. (1928-32*)	31.95	4.77	47.7	14.9
Skunk River above Augusta, Iowa (1928-32*)	35.85	5.47	69.8	15.3
Yellow River above Sprague, Wis. (1928-32*)	29.09	4.87	71.7	16.7
Black River above Neillsville, Wis. (1928-32*)	30.99	7.84	84.1	25.3

* Years ending September 30.

Although basin and precipitation characteristics have not been correlated with these surface run-off estimates, in all probability they would show about the same relations as between these characteristics and flood magnitudes. In other words, the greater the intensity of the precipitation, the more impervious the soil, and the greater the basin slopes the greater will be the direct surface run-off, and vice versa. The estimates, to the extent of their accuracy, represent roughly the amount of water that would be subject to regulation and control operations relating to surface run-off. There is probably a direct relation between the magnitude of these estimates and the magnitude of erosion by water in the respective areas.

Unit-hydrograph analysis of surface run-off

Surface run-off has been defined as that part of the precipitation which reaches surface streams by flowing over the ground and into tributary streams. Once in the stream channel, surface run-off follows the laws governing the flow of water in open channels. The discharge of surface run-off into stream channels simultaneously over basin areas results in pronounced rises in stream levels, followed by periods of decline.

The plotted graph of stream flow, which presents graphically the rises and declines of run-off, has been used by many investigators as a basis for much of the available information regarding the phenomena of surface run-off and the relation of basin characteristics to them.

The Committee on Floods of the Boston Society of Civil Engineers, after a study of New England flood hydrographs, concluded (18) "that a flood hydrograph once determined for a given river, even for an ordinary flood, will serve as a basis for the estimation of greater flood run-off, due to the fact that the base of the flood hydrograph (or time-of-flood period) appears to be approximately constant for different floods." L. K. Sherman (158), in 1932, presented the idea that not only was there a definite total flood period corresponding to a given rainfall for the same drainage area but that surface run-off from rainfalls occurring within the same time interval, such as a day or an hour, will produce hydrographs whose ordinates will vary with the amount of the surface run-off. From the principles set forth by Sherman the hydrograph of surface run-off resulting from rainfall within a unit of time as a day or an hour may be called a "unit hydrograph."

Merrill M. Bernard (13), in 1934, developed certain features of the unit hydrograph, introduced added features of the distribution graph and pluviagraph, and suggested certain relations between rainfall and run-off within the storm period.

The development of unit hydrographs and distribution graphs has been based on a detailed study of the relations between rainfall and run-off as disclosed by hydrographs of stream flow, on the basis of both cumulative experience and scientific analysis. As in many other instances in the development of hydraulic science, reliance is placed to the fullest possible extent on available scientific theory, as well as on the cumulative evidence of general relations disclosed by analysis of experience or experiment. The use of these graphs is still largely in the experimental stage, and theoretically and practically there appear to be limitations of application that have not yet been well defined. Despite a variety of difficulties, the device seems to present a tool of very considerable value for resolving to some extent the complex relations of rainfall and run-off and for advancing the science of hydrology. Consequently in the present investigations considerable time has been given to the investigation of relations between rainfall and surface run-off as disclosed by the unit hydrograph and the distribution graph. These studies have been carried on along three lines - namely, (1) preparation of unit hydrographs for typical drainage basins, (2) general application of the unit-hydrograph method to hydraulic problems, and (3) application of the unit-hydrograph principle to flood studies.

Many rather baffling problems relating to the unit hydrograph have been encountered in these studies, and the following discussion and presentation of the underlying methods of application must be considered more or less provisional.

The unit hydrograph and distribution graph and their preparation

The terms used may be defined as follows:

A unit hydrograph is a hydrograph of surface run-off resulting from rainfall within a unit of time, as a day or an hour.

A distribution graph is a unit hydrograph of surface run-off modified to show the proportional relations of its ordinates in percentage of the total surface run-off.

In theory, at least, it would seem that the principles of the unit hydrograph deal only with surface run-off, and this discussion of the method of its preparation has been predicated on that assumption.

L. K. Sherman (159) describes the basic hypothesis of the unit hydrograph and distribution graph and their preparation as follows:

1. The unit-hydrograph method is a procedure for determining the peak and other rates of surface run-off from a particular basin, by analogy, from an observed rainfall and the corresponding observed hydrograph of surface run-off from the same given basin.

2. The hypothesis upon which the unit-hydrograph method is based is that in a given drainage basin surface run-off from rainfall occurring

in a unit of time will produce hydrographs of approximately equal bases, and the ordinates will vary with the intensity of the net rainfall (net rainfall being rainfall minus infiltration and other losses).

3. The first step in the application of the method to a basin is to find a hydrograph of surface run-off due to an isolated one-day (or unit-time) rainfall from an inspection of daily rainfall and run-off records.

The average daily rates of observed flow for the run-off period are given in the United States Geological Survey water-supply papers. These daily rates of stream flow include both surface run-off and base or ground-water flow. Estimate this base flow. Subtract the base flow from each of the observed flows. Also deduct flow due to antecedent rainfall, if any. This will give the segregated flow or surface run-off due wholly to the rainfall in question. Find the percentage that each day of segregated flow bears to the total segregated flow. These figures will total 100 percent and they form the distribution graph.

Unit hydrographs and distribution graphs have been prepared for a considerable number of rivers in the United States, and typical graphs are shown in figures 33 to 69. The problems and questions outlined below have been considered in connection with their preparation. It should be stated at the beginning that the particular hydraulic problem to be solved by means of the unit-hydrograph theory determines to a great extent the technique used in developing distribution graphs.

For the basins studied the calendar day has been used as the time unit. Basically the problem here discussed is the determination and comparison of the surface run-off resulting from the occurrence of rainfalls of 24-hour duration.

Weather Bureau records coincident with available run-off records are scanned, and all isolated storms that appear from the record to have occurred within a 24-hour period are noted. These storms are then compared with the corresponding run-off records as published in water-supply papers of the United States Geological Survey, and those storms which produced appreciable peaks in the hydrograph of total stream flow are selected as a basis for the preparation of unit hydrographs. The ideal storm would be one of 24-hours' duration coincident with the calendar day and with rainfall of uniform intensity over the basin. Storms that exactly fulfill these requirements seldom, if ever, occur in nature, and only approximations to the ideal can be expected.

It is not necessary to determine the average precipitation over the basin for the unit storm, to derive the resulting distribution graph. However, as an aid in studying variations in the distribution graphs, it is convenient to have at hand the recorded daily precipitation at the available stations. If the unit-hydrograph theory is applied in an intensive study of any particular basin it must be determined whether an average of the station records is satisfactory, or whether some method of weighting is required to obtain average daily depths of precipitation over the basin.

Few of the published records of the United States Weather Bureau indicate whether the recorded precipitation occurred during 1 hour or was well distributed over the 24 hours. A 24-hour storm that does not synchronize with the calendar day will be recorded on two consecutive days. This lack of definite information relative to the length and time relation of storm periods is a decided handicap in analyzing surface run-off, but it is a condition that will be improved as more recording rain gages are installed.

For each unit storm, so called, a hydrograph of stream flow is plotted covering a period that will embrace as a minimum all the time involved in the surface run-off of the storm and at least a month preceding and subsequent to it. The problem now involves the determination of the surface run-off resulting from the storm. The procedure includes the determination of (a) surface run-off resulting from precipitation antecedent to the storm, (b) surface run-off resulting from subsequent precipitation, and (c) ground-water run-off resulting from antecedent precipitation and from the storm itself.

Figure 33 (graph ABCDEF) is a typical hydrograph of stream flow following three storms, the recorded precipitation of which is listed in the following table. The unit hydrograph, table 28, column 5, is the surface flow resulting from the unit storm of June 26.

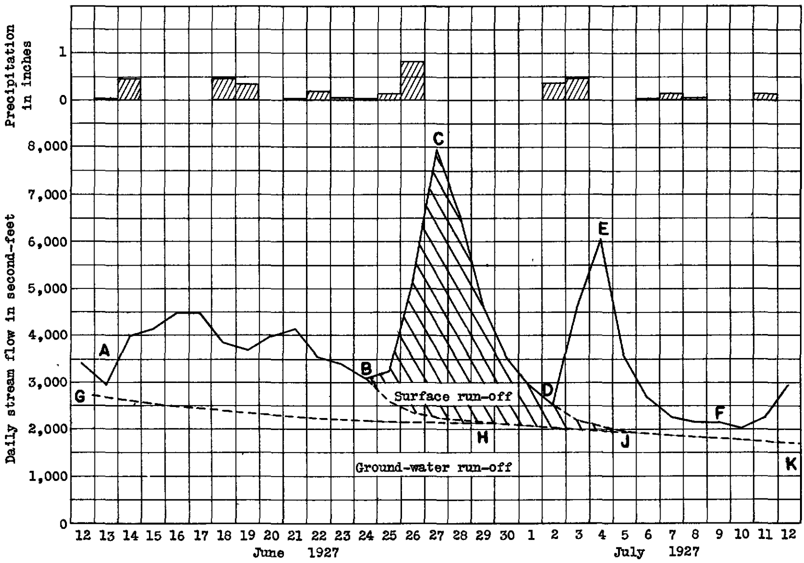

Figure 33.—Unit hydrograph for Muskingum River at Dresden, Ohio.

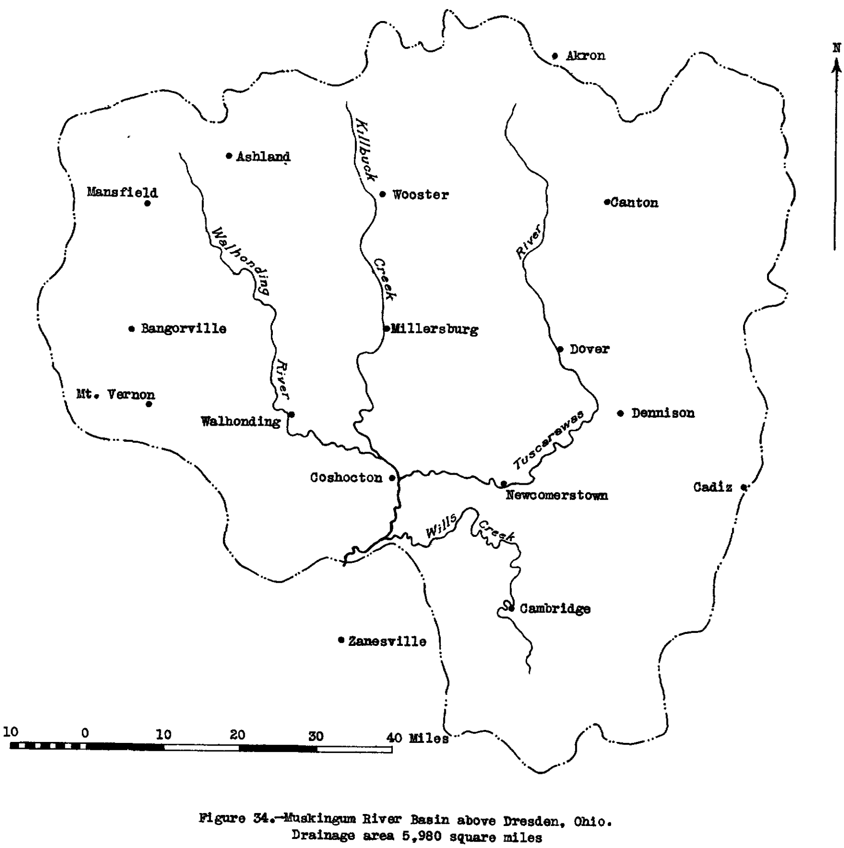

Figure 34.—Muskingum River Basin above Dresden, Ohio.
Drainage area 5,980 square miles

Table 27.- Typical unit-hydrograph storms in Muskingum River Basin above Dresden, Ohio

(Precipitation in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	June 1927									July 1927	
	14	18	19	21	22	23	24	25	26	2	3
Ashland	0.20	0.70	0.10	0.05	0.22	0.20	-	-	0.78	1.20	-
Bangorville	.15	1.03	.05	.08	.33	.05	-	0.29	.08	1.55	0.12
Canton *	.33	-	.90	-	.13	-	-	-	1.11	-	-
Mansfield *	.20	.56	.44	-	.36	.02	-	-	.51	-	2.21
Wooster(no.1)	.18	.24	.10	-	.20	.31	-	.97	.30	.01	.03
Cadiz	.62	.82	-	-	.26	-	-	-	1.32	-	.40
Cambridge	.80	.38	.32	-	.12	-	-	-	.92	.32	-
Coshocton *	.55	.20	.67	-	.05	.07	-	-	.75	-	1.28
Dennison	.60	.45	.13	-	.75	-	-	-	1.59	-	1.18
Dover *	.40	.12	.42	-	.01	-	-	-	1.20	.02	.06
Millersburg	.29	.57	-	-	.16	-	-	.60	.39	1.10	.02
Mount Vernon	.51	.85	-	-	-	-	-	.23	.61	.92	-
Walhonding *	.55	-	.85	-	-	-	0.33	-	.95	-	.42
Zanesville *	.94	.36	.80	-	-	.02	-	-	1.17	-	.50
	6.32	6.28	4.78	.13	2.59	.67	.33	2.09	11.68	5.12	6.22
Average	.45	.45	.34	.01	.19	.05	.02	.15	.83	.37	.44

The hydrograph of ground-water run-off (graph GHJK fig. 33) has been determined by the method described and discussed on pages 111 to 119. The surface run-off from the storm preceding and the storm following the unit storm is determined by the downward extension (graphs BH and DJ) of the hydrograph of total stream flow until it meets the hydrograph of ground water. To the extent that the various assumptions are correct, the cross-hatched area (BCDJH) represents the surface run-off from the unit storm under consideration. The figures for mean daily surface run-off are thus determined and the ratio of each daily figure to the total volume is computed. These ratios in percent constitute the dietribution graph for the particular unit storm under consideration. The following table represents the steps taken:

Table 28.- Derivation of distribution graph

Muskingum River Basin above Dresden, Ohio

(The calendar day on which most of the rainfall occurred is denoted by *.)

Date	Total run-off (second-feet)			Surface run-off from unit storm (col. 2 or 3 - col. 4.) (second-feet)	Distribution graph (col. 5 x 100 ÷ total of col. 5)
	Unit storm	Recession following unit storm	Recession preceding unit storm		
1	2	3	4	5	6
June 24,1927	3,090	-	3,090	-	-
25	3,240	-	2,600	640	3.4
26 *	5,110	-	2,350	2,760	14.5
27	7,990	-	2,250	5,740	30.0
28	6,570	-	2,200	4,370	22.9
29	4,630	-	2,150	2,480	13.0
30	3,540	-	2,100	1,440	7.5
July 1	2,940	-	2,050	890	4.7
2	2,520	-	2,020	500	2.6
3	-	2,200	2,000	200	1.0
4	-	2,050	1,980	70	.4
5	-	1,960	1,960	0	0
				19,090	100.0

Note.- Column 2 corresponds to graph BCD, figure 33; column 3 to graph DJ; column 4 to graph BH; and column 5 to the cross-hatched area.

When the distribution graphs of the different unit storms considered are plotted with respect to the recorded time of the occurrence of the unit storms and with no consideration of a time unit less than 1 day, there is generally a variation in time between the day of recording of the precipitation and the peak run-off.

The average distribution graph for any basin was determined by superimposing the separate graphs to the best fit. From a study of the individual unit storms, the average time between the day of occurrence of the rain and the day of occurrence of the peak of the distribution graph was obtained; this time was then used in synchronizing the day of rain with the composite plot of all the distribution graphs.

In this connection it should be stated that the daily figures for the separate distribution graphs depend in part on the time of recording at the available precipitation stations, whereas the shape of the average distribution graph is independent. In other words, if the precipitation data to be used consist of records made at morning, afternoon, and midnight stations, the synchronization between recorded daily precipitation and resulting mean daily flows is variable.

One continuous rainfall record on or near the basin aids materially in shifting recorded daily depths so as to obtain a good estimate of the precipitation occurring in any 24-hour period that has been synchronized with resulting stream flow.

The average of the peak figures on the separate graphs was used as a basis for determining the one or two peaks for the average graph, and the remaining figures for the average distribution graph were determined from the composite plot of all the graphs. This procedure was necessary, as the scattering horizontally of the peaks on the composite plat made the graphic determination of an average peak value impossible. This difficulty is eliminated where continuous-flow records rather than records of daily mean flow are available.

One of the principal causes for the variation in the time element for the basins studies is believed to lie in the limitations of the basic information, especially with respect to time. Another suggested cause is the position of the center of the storm in the basin with relation to the gaging station. A longer elapsed time is to be expected if the storm centers at a point remote from the gaging station than if it centers at a nearer point. The stage of the river at the time of the storm may also produce a variation. If river stage is high when the unit storm occurs, it is reasonable to expect that the time of occurrence of the peak would be shorter than at a low stage.

In addition to the time variation there is appreciable difference in the percentage for the peak day. Some of this difference is due to the fixed time of beginning and ending the calendar day and is eliminated if continuous records are available. For streams that reach and maintain a high flow for lees than 24 hours, the resulting distribution-graph peak will vary as to whether the period of high flow falls within one calendar day or is divided between two days.

On the other hand, it is entirely conceivable that with continuous discharge records it would be found that owing to variations in storm centers and differences in storm intensities, as close agreement could not be obtained as is indicated from the observed mean daily records, which tend to obscure many important factors.

Differences in intensity and duration of the several unit storms will also modify the peak to some extent, and so will the location and movement of the center of the storm. The more remote storms have a greater opportunity for ironing out, thus producing flatter distribution graphs. Of course, a storm that traveled down the basin would produce the opposite effect.

Before describing problems of application of unit hydrographs and distribution graphs a general discussion based on experiences gained in the group study as well as by others seems desirable. Unquestionably the graphs have their limitations, and likewise it may be shown that some of the necessary assumptions are subject to error. The more clearly the limitations or effect of erroneous assumptions are recognized the greater the value of the graphs will be.

1. In the preparation of unit hydrographs it is necessary to separate ground-water flow from total stream flow, and because, as discussed elsewhere in this report, there seems to be no exact way that the separation can be made, it may be argued that the lack of definiteness imposes a serious limitation on the use of unit hydrographs. To overcome the limitation as far as possible, it is preferable to determine unit graphs from isolated storms that produce large surface run-off and occur when the ground-water flow is small. By so doing the probable errors in the determination of the ground-water flow are small, and the resulting distribution graphs are believed to represent closely the characteristics of surface run-off from that particular basin. As knowledge of the laws governing the flow of surface water and ground water is increased, difficulties incident to their separation will become less and the accuracy of the unit hydrograph in depicting surface run-off should increase.

2. It has been pointed out that "it does not seem entirely safe to assume that the analogy between small and large floods is a rigid one." The special committee of the Section of Hydrology of the American Geophysical Union has concluded that the validity of the unit-hydrograph theory seems strongly supported within practical limits by (a) the general agreement of distribution graphs derived under widely varying rates of rainfall and infiltration by the rainfall and run-off group - Sherman (158), Bernard (13), Smart (167), and others; (b) test by application to the recorded stream flow; (c) studies by the Committee on Floods, Boston Society of Civil Engineers (18); (d) comparative analysis by Sherman (160).

3. Theoretically it would seem that, as a result of differences in channel velocities, the unit hydrograph of a 1-day storm occurring when the river is at a high stage would differ from one derived when the river

is at a low stage. Robert W. Gay, of the United States Engineer Office, Zanesville, Ohio, who has studied the unit graph intensively in connection with Muskingum River projects, in a letter dated February 28, 1935, states: "It is probably true that as the amount of surface run-off per day increases, there are increases in hydraulic radii of the conducting channels of all sizes and corresponding increases in velocities of flow, which would tend to produce shorter run-off periods and apparently controvert to a greater or less extent the basic assumption of 'equal bases' for the graphs from various storms on the watershed. But before discarding the method on this ground, it must be shown that errors arising from the assumptions are sufficiently great to put this method at a disadvantage as compared with others."

The comparative analysis by Sherman (160) indicates that "the hypothesis of direct proportion of ordinates in the unit hydrograph is not accurate for small areas involving only a few acres. The relation rapidly improves in accuracy as the area increases to 2 square miles or more. This is due to the 'ironing out process' with the element of time."

However, W. W. Horner and F. L. Flynt (61) found that the unit-hydrograph theory could be advantageously applied to areas as small as a city block. The data for such application were necessarily refined.

4. The variations in the geographic distribution of rainfall and in the intensities of 1-day storms compared with longer storms impose limitations on the duration and application of graphs. L. K. Sherman has found that "inequality of rainfall distribution over the basin does not materially affect the accuracy of results except under extreme conditions." R. W. Gay (letter dated February 28, 1935) states that "as the path of the storm center is low down, high up, or across the center of the watershed, different graphs will result, the variations in the graphs depending upon the ratio of maximum precipitation to average precipitation and upon the shape and topography of the watershed." Insofar as the study of large floods is concerned, the variations in unit hydrographs are probably not serious, because storms that produce large floods have a tendency to approach uniform distribution.

5. The lack of base data, especially with regard to the time element in connection with the precipitation, is a handicap that undoubtedly will be remedied with time. Precipitation records showing the

beginning and end of all storms and intensities are of great value in connection with unit-hydrograph studies.

6. Unit hydrographs of 1-day storms apparently cannot be obtained in basins where the infiltration capacity exceeds the rainfall or where, as a result of conditions of extreme artificial or natural storage, surface run-off may be materially delayed. Where these conditions are of such magnitude that isolated 1-day storms do not produce appreciable hydrographs of surface flow, it would seem that a time interval longer than a day would have to be used to determine distribution graphs.

These and other problems should be made the basis of much further study.

Unit hydrographs and distribution graphs, by basins

In accordance with a suggestion of the Advisory Committee of the American Geophysical Union, groups of unit hydrographs and distribution graphs have been prepared for typical basins in the central and eastern United States as follows:

Muskingum River at Dresden, Ohio.
Wabash River at Logansport, Ind.
Embarrass River at Ste. Marie, Ill.
Skunk River at Augusta, Iowa.
Susquehanna River at Towanda, Pa.
Delaware River at Port Jervis, N. Y.
French Broad River at Dandridge, Tenn.
Red River near Denison, Tex.

For each of these basins are given below a brief descriptive text accompanied by a map of the basin showing principal streams and the location of the Weather Bureau stations, a table showing the recorded daily rainfall at these stations during the unit storms that have been used, diagrams showing the average precipitation over the basin, hydrographs of stream flow, the estimated ground-water run-off and the distribution graph of surface run-off for the different unit storms and the superimposed distribution graphs, a table showing the distribution graph for each storm and the average distribution graph, and a table showing the approximate precipitation over the basin and the resulting surface run-off.

Muskingum River Basin above Dresden, Ohio

The Muskingum Basin above Dresden, Ohio (fig. 34) is a fan-shaped area of 5,980 square miles. Three principal streams - the Walhonding River, Killbuck Creek, and the Tuscarawas River - flow in a southerly direction to form the Muskingum River about 18 miles above Dresden. Wills Creek enters from the east about 8 miles above Dresden. The northern and western portions of the basin are glaciated, and the remainder has a hilly topography. The river distance from Dresden to the headwaters of the Tuscarawas River (some at altitudes above 1,200 feet) is about 120 miles, and the average gradient is about 2 feet to the mile. The headwater region of the Walhonding River (Mohican Creek) contains areas 1,400 feet or more above mean sea level, and the average gradient of the stream is about 4 feet to the mile. The zero of the gage at Dresden is 693.2 feet above mean sea level.

Daily discharges at this station have been published by the United States Geological Survey since September 1921. The original gage was a chain gage on a heavy steel eyebar suspension bridge half a mile east of Dresden. One reading was taken daily to hundredths. In August 1925 an Au recorder was installed at the same datum 70 feet below the bridge on the right bank. The records are considered good.

Normally about 13 United States Weather Bureau stations are available to determine daily rainfall for the basin. The stations are well distributed within the basin, as shown on figure 34. Table 29 gives the daily precipitation recorded at the various stations for the storms analyzed. These storms produced the unit hydrographs at Dresden shown in figures 35, 36, and 37.

Table 29.- Typical unit-hydrograph storms in Muskingum River Basin above Dresden, Ohio

(Precipitation in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	May 1925				June 1927					
	10	11	16	17	3	4	5	11	13	14
Ashland	0.40	-	-	0.45	-	0.90	-	-	-	0.20
Bangorville	.55	-	0.15	.10	-	2.10	-	-	0.02	.15
Cadiz	.44	0.70	.16	.66	0.14	1.75	-	-	-	.62
Cambridge	.80	.85	.12	.70	.14	.90	-	0.18	-	.80
Canton	-	.98	-	.26	-	1.15	0.64	.15	-	.33

Table 29.- Typical unit-hydrograph storms in Muskingum River Basin above Dresden, Ohio--Continued

(Precipitation in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	May 1925				June 1927					
	10	11	16	17	3	4	5	11	13	14
Coshocton *	-	0.81	-	0.62	0.05	0.75	0.88	-	-	0.55
Dennison	0.41	-	0.71	.37	-	1.45	-	-	-	.60
Dover *	-	.46	-	.80	-	.82	.60	0.07	0.40	.40
Mansfield	.52	-	.04	.02	-	.68	.09	.02	-	.20
Millersburg	.55	-	.39	.16	-	1.69	-	-	-	.29
Mount Vernon	-	-	-	-	-	1.37	-	.12	-	.51
Walhonding *	.10	.30	-	.45	.09	1.58	-	-	-	.55
Wooster(no.1)	.73	-	.19	.05	-	1.05	.01	-	-	.18
Zanesville *	.20	.97	-	.51	.40	.50	.56	.21	-	.92
Average	4.70 .36	5.07 .39	1.76 .14	5.15 .40	.82 .06	16.69 1.19	2.78 .20	.75 .05	.42 .03	6.30 .45

Station	June 1927			July 1927				
	25	26	27	2	3	6	7	8
Ashland	-	0.78	-	1.20	-	-	0.68	-
Bangorville	0.29	.08	-	1.55	0.12	0.02	.22	-
Cadiz	-	1.32	-	-	.40	-	-	-
Cambridge	-	.92	-	.32	-	-	-	-
Canton *	-	1.11	-	-	-	-	.14	0.22
Coshocton *	-	.75	-	-	1.28	-	.10	-
Dennison	-	1.59	-	-	1.18	-	-	-
Dover *	-	1.20	0.02	.02	.06	-	.10	.13
Mansfield *	-	.51	-	-	2.21	-	.41	.01
Millersburg	.60	.39	-	1.10	.02	.03	.11	-
Mount Vernon	.23	.61	-	.92	-	-	-	.04
Walhonding *	-	.95	-	-	.42	.10	-	-
Wooster (no.1)	.97	.30	-	.01	.03	.02	.47	-
Zanesville	-	1.17	-	-	.50	-	.02	.16
Average	2.09 .15	11.68 .83	.02 -	5.12 .37	6.22 .44	.17 .01	2.25 .16	.56 .04

Station	July 1928					
	4	5	6	9	10	11
Ashland	0.10	0.35	-	0.52	-	0.40
Bangorville	-	.66	-	.02	-	.85
Cadiz	-	.86	-	1.12	-	.09
Cambridge	.23	.59	-	.80	-	.70
Canton *	-	.75	0.24	-	0.12	-
Coshocton *	-	.65	.35	.05	.30	-
Dennison	-	.47	-	.43	-	.19
Dover *	-	.33	.10	.06	.38	.03
Mansfield *	.01	.95	.05	-	.63	.06
Millersburg	-	.52	-	.19	-	.08
Mount Vernon	.56	.50	-	.03	-	.13
Walhonding *	-	1.13	-	-	.45	.46
Wooster (no.1)	-	1.33	-	.08	-	.02
Zanesville *	.03	.38	-	-	1.09	-
Average	.93 .07	9.47 .63	.74 .05	3.30 .24	2.97 .21	3.01 .21

Table 29.- Typical unit-hydrograph storms in Muskingum River Basin above Dresden, Ohio--Continued

(Precipitation in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	August 1928					
	4	5	6	8	10	11
Ashland	-	1.26	0.10	-	-	-
Bangorville	-	1.62	-	-	0.01	0.12
Cadiz	-	.30	.71	-	.04	-
Cambridge	-	.30	-	-	-	-
Canton *	-	.02	.89	-	-	.31
Coshocton *	0.15	.05	-	-	.05	-
Dennison	-	.03	.17	0.33	.77	.03
Dover *	-	-	.80	-	-	.26
Mansfield *	-	.11	.80	-	.26	.09
Millersburg	-	.70	.30	-	.35	.12
Mount Vernon	-	1.10	-	-	-	.18
Walhonding *	-	-	.30	-	-	.50
Wooster (no.1)	.10	1.50	.10	-	.04	-
Zanesville *	.24	-	.32	-	-	.73
Average	.49 .03	6.99 .50	4.49 .32	.33 .02	1.52 .11	2.34 .17

Station	June 1929					August 1929		
	7	8	12	13	14	22	23	24
Ashland	-	0.18	0.16	0.10	0.53	0.05	0.04	-
Bangorville	0.28	.27	.18	-	.26	.57	1.45	-
Cadiz	.51	.11	.05	-	.29	.50	.28	0.03
Cambridge	-	.72	-	.68	.35	.52	1.75	-
Canton *	-	.40	-	-	.26	-	.75	.10
Coshocton *	.80	-	-	-	.50	-	1.15	.15
Dennison	-	.58	-	-	.41	.37	.23	-
Dover *	-	.40	-	-	.27	-	.64	.10
Mansfield *	-	.22	.13	-	.31	-	1.55	.04
Millersburg	.03	.27	.10	-	.22	.33	.43	-
Mount Vernon	.41	.43	-	-	.75	.17	.16	-
Newcomerstown *	-	.66	-	.01	.70	.01	1.11	.14
Walhonding *	-	.80	-	-	.49	-	1.37	-
Wooster (no.1)	-	.19	.03	-	.23	.11	.09	-
Zanesville *	-	1.30	-	.29	.23	.04	.92	.48
Average	2.03 .14	6.53 .44	.65 .04	1.08 .07	5.80 .39	2.67 .18	11.92 .80	1.04 .07

Station	August 1932					July 1933				
	17	18	19	26	27	1	2	3	9	10
Ashland	2.50	-	-	0.92	-	-	1.60	-	-	-
Bangorville	-	1.55	-	-	-	-	2.09	-	-	-
Cadiz	-	1.01	-	.04	0.10	0.72	1.80	0.05	-	0.38
Cambridge	-	1.29	-	.02	.17	-	1.26	-	0.17	-
Canton *	-	1.13	0.07	-	.62	-	-	.83	.07	
Coshocton *	-	1.56	-	-	.69	-	-	2.80	-	-
Dennison	.20	2.20	-	.11	.32	-	.57	-	.20	-
Dover *	-	.87	-	-	.78	-	-	1.30	-	.10
Mansfield *	-	2.08	-	-	.69	-	.12	1.77	.02	-
Millersburg	-	.92	-	.07	.01	-	1.49	-	-	-
Mount Vernon	-	2.06	-	.47	-	-	.57	-	.01	-
Newcomerstown *	-	2.48	.28	-	.30	-	-	1.37	.05	-

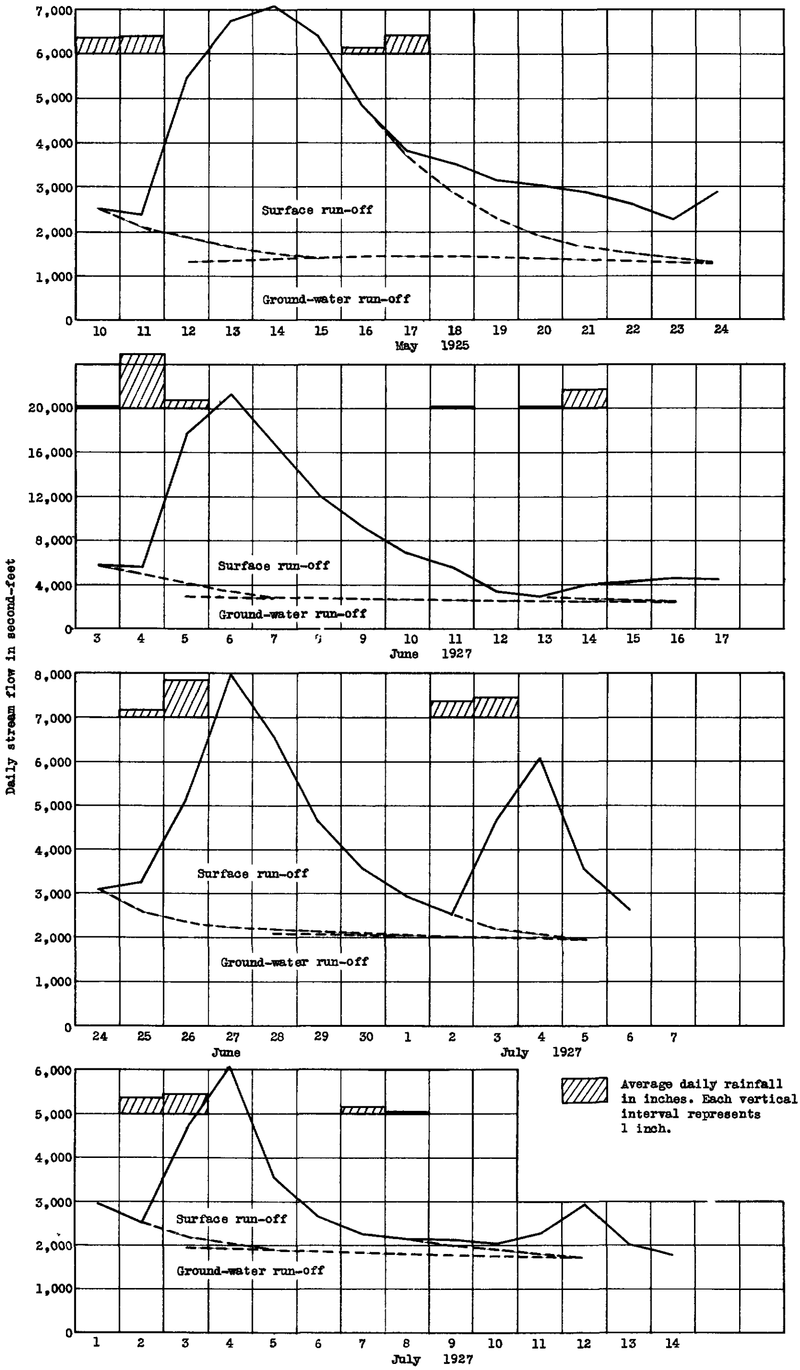

Figure 35.—Unit hydrographs for Muskingum River at Dresden, Ohio.

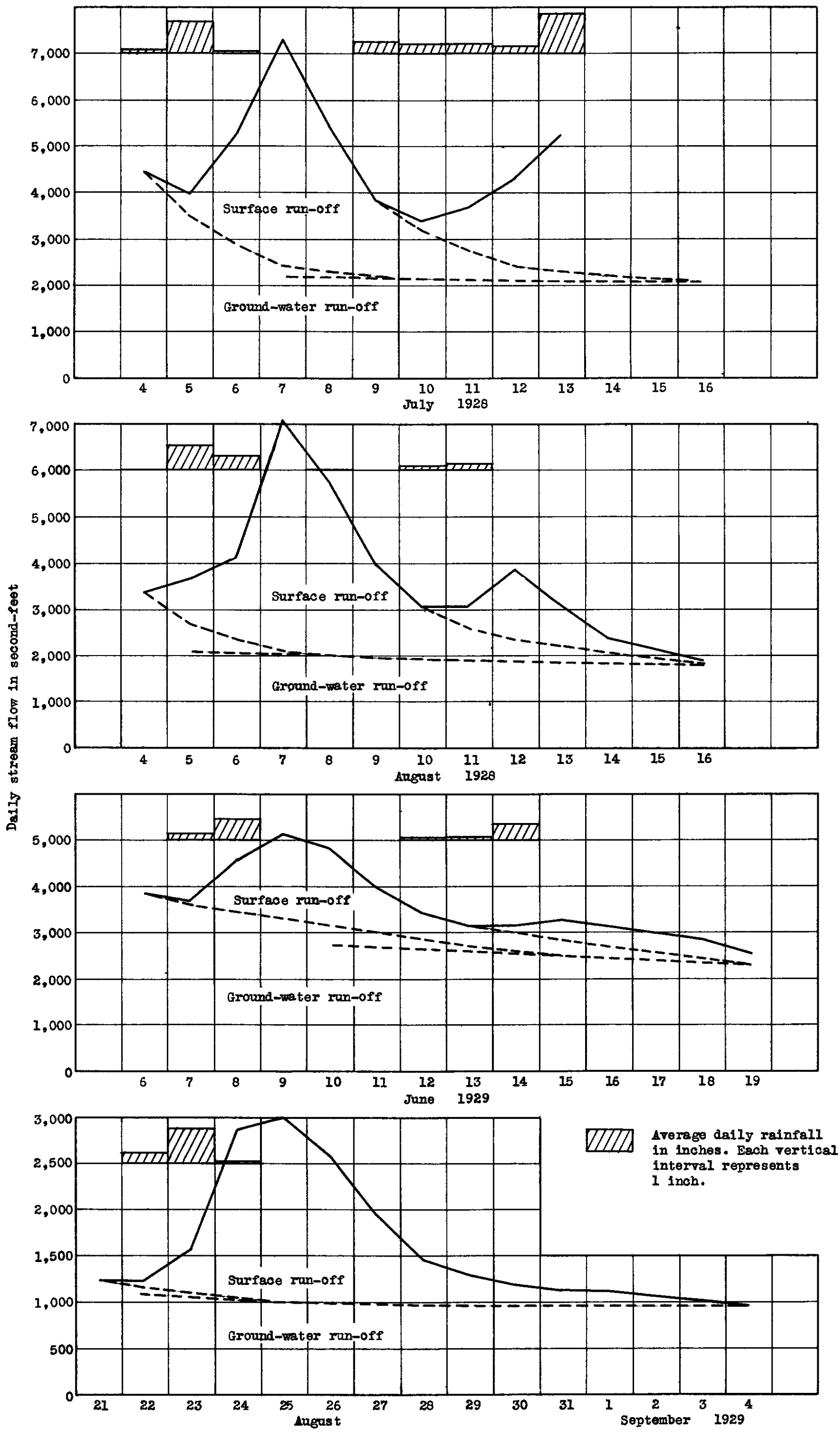

Figure 36.—Unit hydrographs for Muskingum River at Dresden, Ohio.

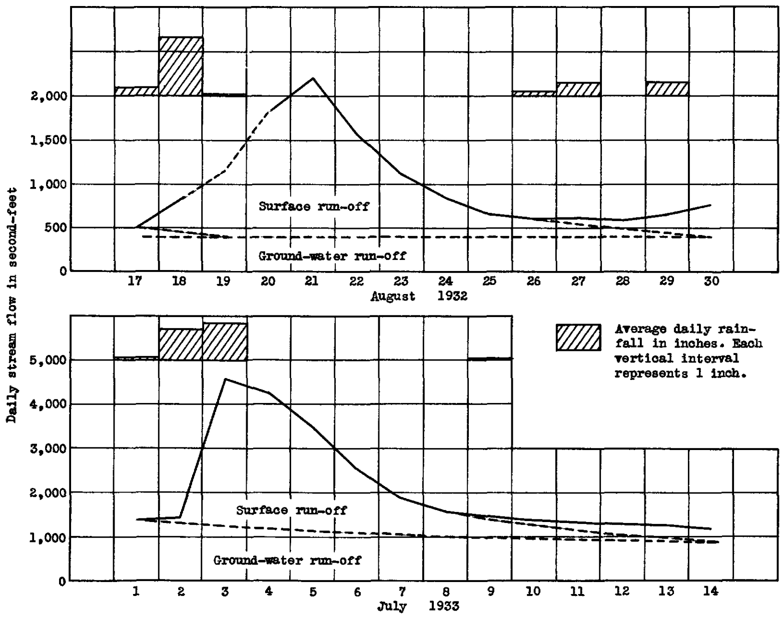

Figure 37.—Unit hydrographs for Muskingum River at Dresden, Ohio.

Table 29.- Typical unit-hydrograph storms in Muskingum River Basin above Dresden, Ohio--Continued

(Precipitation in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	August 1932					July 1933				
	17	18	19	26	27	1	2	3	9	10
Walhonding *	-	0.67	-	-	0.55	-	-	2.10	-	-
Wooster (no.1)	-	1.25	0.05	0.17	.03	-	0.82	.87	0.03	-
Zanesville *	-	.90	-	-	.04	-	-	1.34	-	0.03
	2.70	19.97	.40	1.80	4.30	.72	10.32	12.43	.55	.51
Average	.18	1.33	.03	.12	.29	.05	.69	.83	.04	.03

The storm of May 10-11, 1925, produced the flattest unit hydrograph (and distribution graph) of the group. This is believed to be due mainly to a long light rain. The sharpest unit hydrograph, resulting from the storm of July 2-3, 1927, was the result of poor distribution of rainfall. The greater amounts were concentrated on the Walhonding subbasin, and the resulting distribution graph at Dresden is typical of several distribution graphs that are available for the Walhonding River at Pomerene.

Table 30 gives the surface run-off from the unit storms with an approximation of the precipitation that caused the run-off.

Table 30.- Surface run-off from unit storms, Muskingum River at Dresden, Ohio

Storm	Average of precipitation at stations (inches)	Surface run-off (inches)	Ratio of surface run-off to average precipitation
May 11, 1925	0.75	0.18	0.24
June 4, 1927	1.45	.44	.33
June 26, 1927	.98	.12	.12
July 2, 1927	.81	.06	.07
July 5, 1928	.75	.09	.12
Aug. 5, 1928	.85	.10	.14
June 7, 1929	.58	.05	.09
Aug. 22, 1929	1.05	.05	.05
Aug. 18, 1932	1.54	.05	.03
July 2, 1933	1.57	.08	.05

Table 31 gives the daily percentages of the surface run-off for the ten distribution graphs. The first figure is the percentage for the calendar day on which most of the rainfall occurred; other figures for succeeding days.

Table 31.- Distribution graphs for storms in Muskingum River Basin above Dresden, Ohio

May 11, 1925	1.0	12.5	17.8	19.6	17.5	11.8	8.1	5.1	3.1	1.7	0.9	0.6	0.3
June 4, 1927	.8	19.1	25.4	19.8	13.2	9.4	6.0	4.2	1.1	.5	.3	.2	-
June 26, 1927	3.8	14.2	29.5	22.4	12.7	7.4	5.0	3.1	1.5	.4	-	-	-
July 2, 1927	.0	24.0	39.7	16.3	7.9	4.2	3.3	2.4	1.4	.8	-	-	-
July 5, 1928	3.3	16.1	32.7	21.2	10.8	7.1	4.2	2.0	1.4	.7	.5	-	-
Aug. 5, 1928	6.0	10.9	30.1	22.7	12.3	7.0	4.2	2.8	2.0	1.3	.7	-	-
June 7, 1929	1.3	13.1	23.2	21.9	12.4	7.2	5.6	5.1	3.8	3.2	1.9	1.3	-
Aug. 22, 1929	1.0	5.7	21.8	24.1	18.1	11.5	5.8	3.8	2.6	1.9	1.9	1.2	.6
Aug. 18, 1932	4.6	10.2	19.3	24.4	15.9	9.5	6.0	3.4	2.7	2.0	1.3	.7	-
July 2, 1933	1.0	26.0	24.0	18.3	11.0	6.5	4.4	3.3	2.5	1.7	0.9	.4	-

The superimposed distribution graphs are shown in figure 38. If the two distribution graphs from the storm of May 10-11, 1925, and July 2-3, 1927, are disregarded the range of the remaining graphs is decreased. The average distribution graph determined for the Muskingum River at Dresden is 4, 15, 27, 21, 13, 8, 5, 3, 2, 1, 1 percent.

Wabash River Basin above Logansport, Ind.

The Wabash River rises in the Grand Reservoir, an artificial lake at Celina, Mercer County, Ohio, and flows in a northerly and westerly direction to Logansport, Ind., below which its direction is southwest. The Eel and the Mississinewa Rivers are the principal tributaries above Logansport. The drainage area above Logansport covers 3,830 square miles, is fan-shaped, and is about 90 miles in length and about 40 miles in average width. The length of the Wabash channel above Logansport is about 120 miles. Much of the basin is glaciated. The maximum altitude is 1,285 feet, in Randolph County, Ind.

A chain gage was established in April 1903 on the Cicott Street Bridge at Logansport. The record was discontinued in July 1906. A standard chain gage was established by the State of Indiana in May 1923 at the same location, with its zero 573.8 feet above mean sea level. Records are published by the United States Geological Survey. On March 31, 1927, the Wabash Hydroelectric Co. installed an enamel staff gage on the same bridge, with its zero 2.85 feet above the zero of the State chain gage. The chain gage was read once daily to tenths, and part of the time the staff gage readings to hundredths twice daily were furnished. The records are considered good except for periods of ice effect.

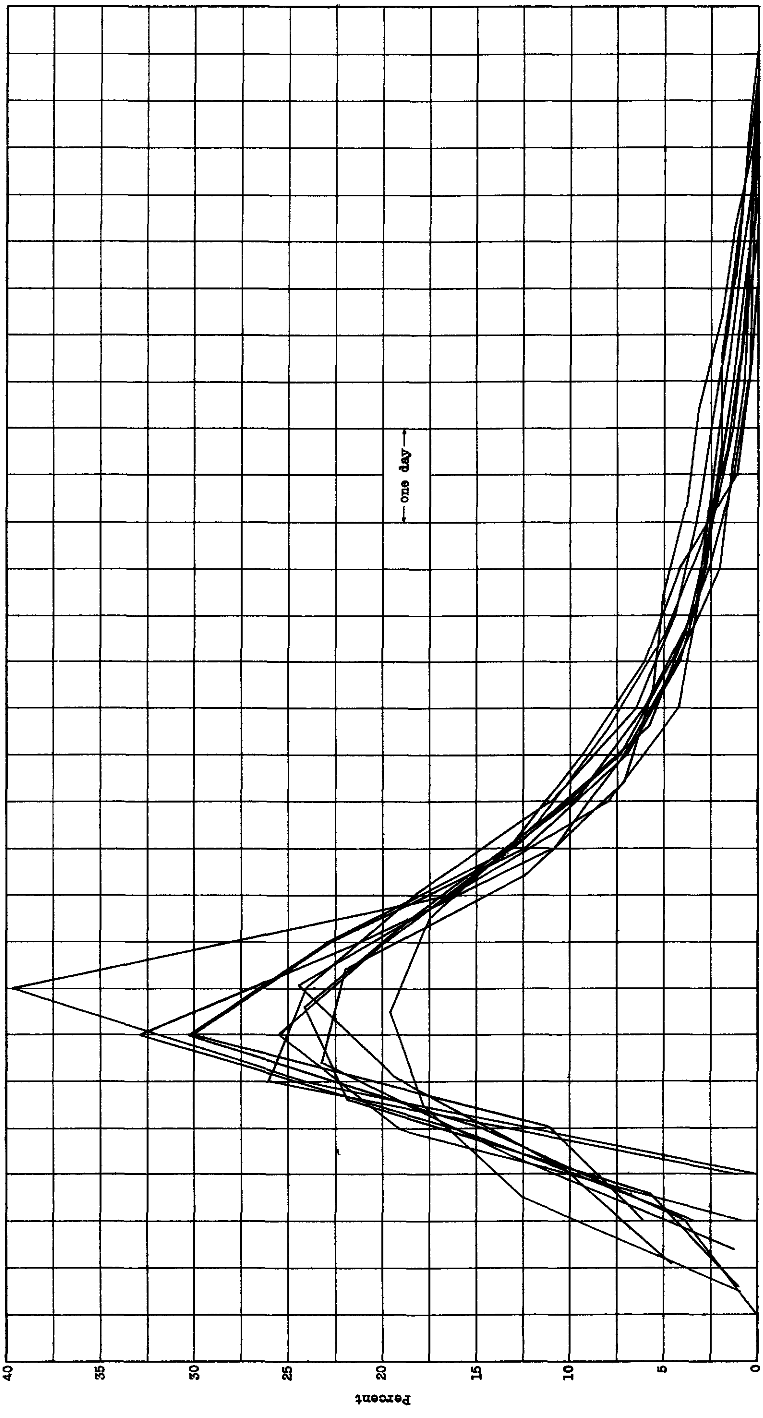

Figure 38.—Superimposed distribution graphs for Muskingum River Basin above Dresden, Ohio.

Normally about 14 stations are available for the determination of daily precipitation. Figure 39 outlines the drainage basin and shows the location of the Weather Bureau stations.

Table 32 gives the daily precipitation recorded at the precipitation stations for the storms that produced the unit hydrographs shown in figures 40 and 41.

Table 32.- Storms studied in connection with unit hydrographs for the Wabash River Basin above Logansport, Ind.

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	July 1925						
	3	4	5	7	8	9	10
Berne	0.05	0.44	0.90	-	-	1.30	-
Bluffton *	-	.20	1.25	-	-	-	0.55
Columbia City	.05	.95	-	-	-	.22	-
Fort Wayne **	.02	.56	-	0.02	-	.24	-
Huntington	.05	1.17	.07	-	-	-	.13
Kokomo	.28	.55	.38	-	-	.15	.54
Logansport *	-	.78	.18	-	-	-	.64
Marion *	-	.64	2.70	-	0.03	-	.42
Rochester **	-	.72	.35	-	.30	-	.18
Wabash *	-	.78	.41	-	-	-	.10
Winona Lake	-	1.43	-	.07	-	.05	1.43
Farmland	.30	.62	-	-	-	-	1.10
Muncie	1.79	.95	-	-	-	.25	1.24
Salamonia	.43	.37	-	.04	-	-	.25
	2.97	10.16	6.24	.13	.33	2.11	6.58
Average	.21	.73	.45	.01	.02	.15	.47

Station	September - October 1925					
	26	27	28	2	3	4
Berne	-	1.35	-	0.68	-	0.17
Bluffton *	-	1.00	0.25	.20	0.28	-
Columbia City	0.97	1.94	-	.12	-	.25
Fort Wayne **	.99	.59	-	.77	.04	.45
Huntington	-	1.57	-	.31	.02	.21
Kokomo	-	1.35	-	.50	.10	-
Logansport *	-	1.50	-	.72	.05	.05
Marion *	-	1.52	-	.13	.12	.12
Rochester *	-	.93	.35	-	.13	.06
Wabash *	-	1.52	.31	.31	.02	-
Winona Lake	-	1.14	-	.02	-	.25
Farmland	1.22	-	-	.52	-	.08
Muncie	-	2.06	-	.43	-	-
Salamonia	-	1.06	-	.43	-	.14
	3.18	17.53	.91	5.14	.76	1.78
Average	.23	1.25	.06	.37	.05	.13

Table 32.- Storm studied in connection with unit hydrographs for the Wabash River Basin above Logansport, Ind.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	August 1929			August 1929			
	2	3	10	13	14	22	23
Berne	0.11	2.04	-	1.03	0.41	-	0.20
Bluffton *	-	3.10	-	-	4.40	0.06	.20
Columbia City	1.25	2.74	0.02	.47	.06	.10	.02
Fort Wayne **	1.06	1.00	.17	.38	-	-	.01
Huntington	.11	3.82	1.47	1.49	-	.03	.18
Kokomo	.20	.04	.20	-	-	.04	.03
Logansport *	-	.58	.08	-	.55	-	.02
Marion *	-	1.09	.10	-	1.18	-	.18
Rochester *	-	1.22	-	-	1.50	.02	.03
Wabash *	-	1.50	1.03	-	2.00	-	.11
Winona Lake	.38	6.25	.01	.51	.55	.09	.01
Farmland *	-	.65	.09	-	2.22	-	-
Muncie	.30	.54	-	-	2.07	-	.56
Salamonia	.04	1.23	.16	.25	1.51	-	.41
	3.45	25.80	3.33	4.13	16.45	.34	1.96
Average	.25	1.84	.24	.30	1.18	.02	.14

Station	June - July 1931						October 1932			
	28	29	30	1	2	5	4	5	10	11
Berne	0.15	1.42	-	-	0.07	0.12	0.88	-	0.80	0.03
Bluffton *	.07	1.63	0.14	-	-	.22	-	1.06	-	.69
Columbia City	.02	.73	-	-	.14	.35	1.32	-	.54	-
Fort Wayne **	-	1.07	-	0.78	.33	.79	1.54	-	.57	-
Huntington	.06	.53	-	-	-	.11	1.57	-	.62	-
Kokomo	-	1.40	-	-	-	.28	1.38	.09	.62	-
Logansport *	-	-	1.15	-	-	-	-	1.04	-	.86
Marion *	-	-	1.26	-	.03	-	1.87	-	.60	.05
Rochester *	-	.05	-	-	-	-	.76	-	1.22	-
Wabash *	-	.23	1.09	-	-	-	-	-	-	.71
Winona Lake	.10	.67	-	-	.07	.42	1.35	.04	1.02	.07
Farmland *	-	.04	.74	-	.87	-	.90	-	1.12	-
Muncie	-	1.00	-	1.09	.04	-	.93	-	.95	-
Salamonia	-	1.88	-	.74	-	.26	.75	-	1.02	.08
	.40	10.65	4.38	2.61	1.55	2.55	13.25	2.23	9.08	2.49
Average	.03	.76	.31	.19	.11	.18	.95	.16	.65	.18

Table 33 gives the surface run-off from the unit storms with the approximate value of the precipitation causing the run-off.

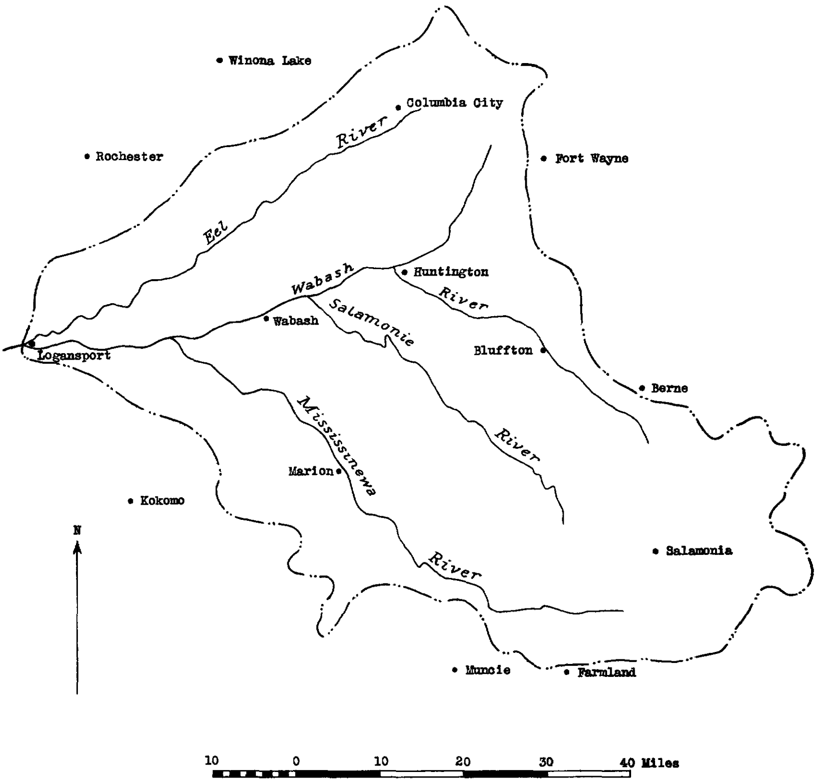

Figure 39.—Wabash River Basin above Logansport, Ind.
Drainage area 3,830 square miles

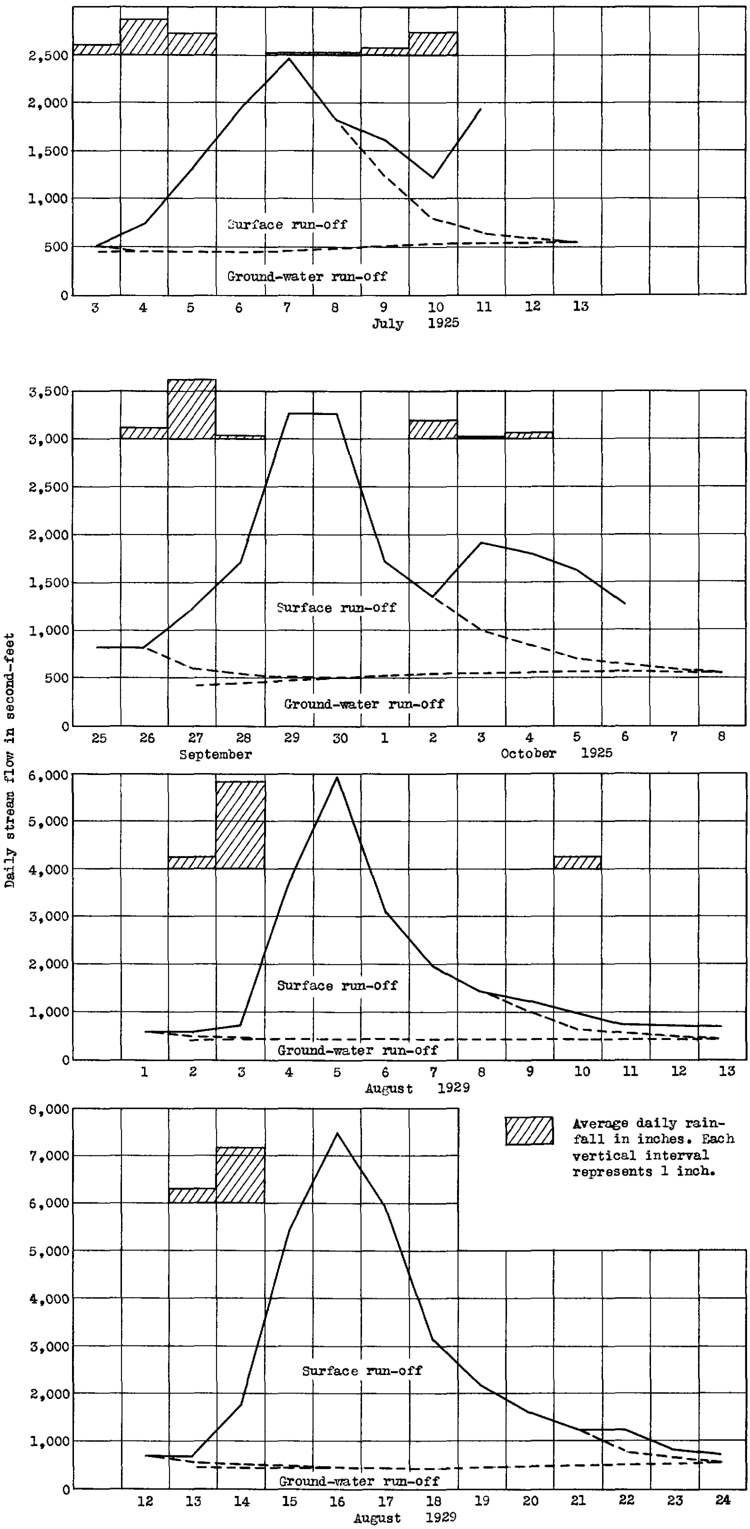

Figure 40.—Unit hydrographs for Wabash River at Logansport, Ind.

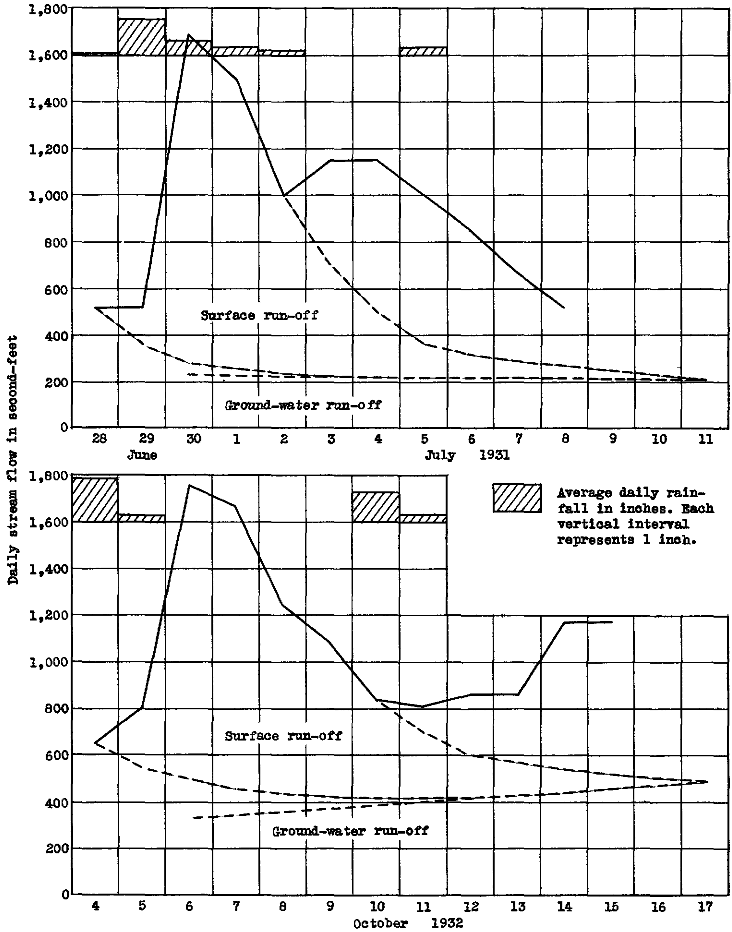

Figure 41.—Unit hydrographs for Wabash River at Logansport, Ind.

Table 33.- Surface run-off from unit storms,

Wabash River at Logansport, Ind.

Storm	Average of precipitation at stations (inches)	Surface run-off (inches)	Ratio of surface run-off to average precipitation
July 4, 1925	1.39	0.07	0.05
Sept. 27, 1925	1.54	.10	.06
Aug. 2, 1929	2.09	.15	.07
Aug. 13, 1929	1.48	.25	.17
June 29, 1931	1.10	.05	.05
Oct. 4, 1932	1.11	.05	.05

Table 34 gives the daily percentages for the six distribution graphs, and figure 42 shows the graphs superimposed. The average distribution graph determined for the station is 3, 12, 27, 24, 14, 9, 5, 3, 2, 1 percent. The first figure is the percentage of surface run-off for the day on which most of the rainfall occurs; other figures for succeeding days.

Table 34.- Distribution graphs for storms in

Wabash River Basin above Logansport, Ind.

July 4, 1925	4.1	12.0	20.7	28.1	18.7	10.4	3.8	1.5	0.7	-	-	-	-
Sept. 27, 1925	5.9	11.4	26.7	26.8	11.6	7.9	4.4	2.8	1.3	0.8	0.4	-	-
Aug. 2, 1929	.7	1.5	21.7	35.9	17.6	9.9	6.4	3.7	1.4	.7	.3	0.2	-
Aug. 13, 1929	.4	4.8	19.5	27.6	21.6	10.6	6.6	4.3	2.8	1.0	.5	.2	0.1
June 29, 1931	3.4	29.8	26.2	15.9	9.9	5.9	3.0	2.1	1.5	1.2	.7	.4	-
Oct. 4, 1932	0	4.8	23.4	23.6	14.9	12.3	7.8	5.2	3.5	2.4	1.5	.6	-

Embarrass River Basin above Ste. Marie, Ill.

The Embarrass River has its source in Champaign County, Ill., just south of Urbana, and flows in a general southerly direction into the Wabash River above St. Francisville. The altitude of the divide near Urbana is 750 feet.

The basin above Ste. Marie (fig. 43) covers 1,540 square miles, is about 80 miles long, and averages 19 miles in width. The average gradient for 40 miles above Ste. Marie is 2 feet to the mile.

The gaging station was established in October 1909 on the Main Street Bridge at Ste. Marie. A standard chain gage was fastened to the handrail on the downstream side of the bridge and was read to hundredths once daily. No records are available from December 1912 to August 1914.

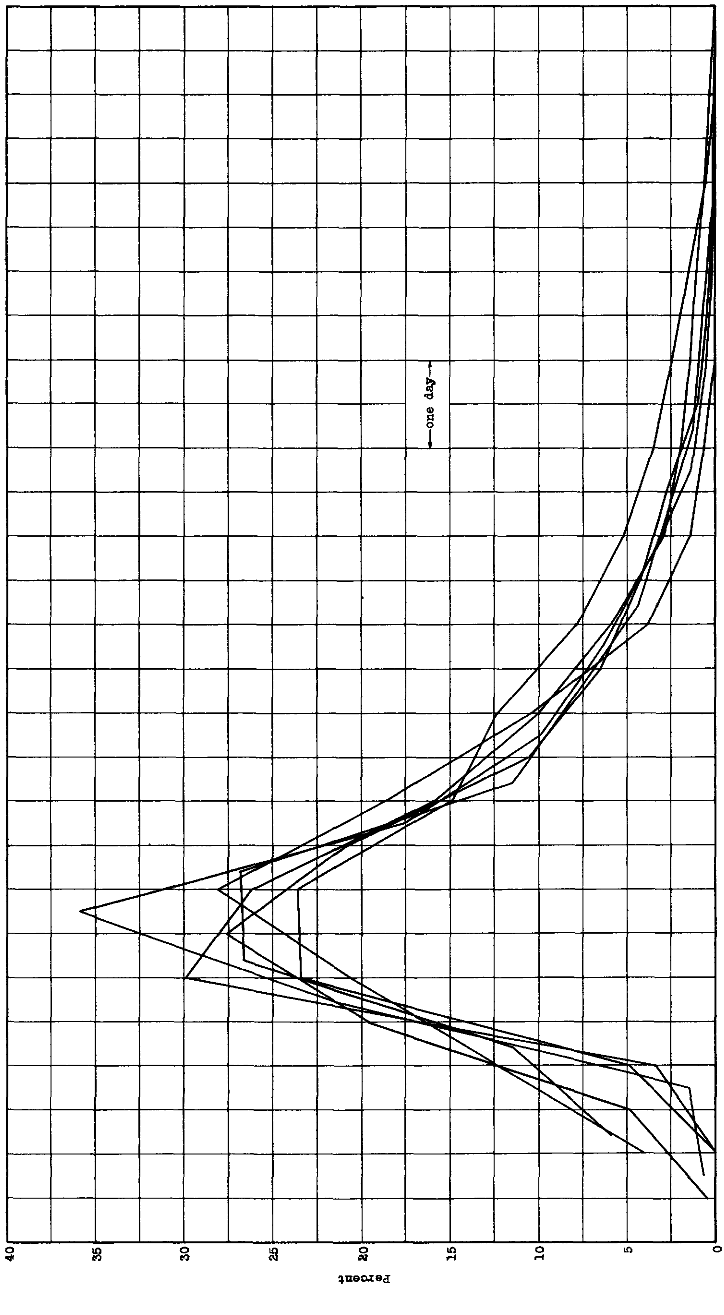

Figure 42.—Superimposed distribution graphs for Wabash River Basin above Logansport, Ind.

The gage was transferred to the new highway bridge in April 1925. The zero of the gage is 447.1 feet above mean sea level. The records are considered good.

Seven precipitation stations of the United States Weather Bureau (see fig. 43) are generally available. If the daily rainfall is to be used extensively the station records should be weighted by some method.

Table 35 gives the daily precipitation recorded at the precipitation stations for the storms that produced the unit hydrographs shown in figures 44 and 45.

Table 35.- Storms studied in connection with unit hydrographs, Embarrass River above Ste. Marie, Ill.

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	June - July 1918					
	24	25	28	29	30	1
Casey	0.04	2.48	1.35	-	0.04	-
Charleston	.03	2.94	1.88	-	.02	-
Effingham *	-	1.10	.44	1.30	-	-
Olney *	-	.62	.50	1.38	-	-
Paris *	-	2.45	.48	.63	-	-
Tuscola	3.79	-	1.27	-	.04	-
Urbana *	-	3.05	.64	.87	-	0.26
	3.86	12.64	6.56	4.18	.10	.26
Average	.55	1.81	.94	.60	.01	.04

Station	May 1920					
	11	12	13	16	17	18
Casey	0.10	2.21	-	0.06	1.41	0.03
Charleston	.08	3.12	-	.10	1.72	.03
Effingham *	-	.77	0.44	-	2.10	.33
Olney *	-	.33	.51	-	1.95	.40
Paris *	-	2.40	.71	-	.80	.38
Tuscola	.02	3.32	-	.10	1.29	.04
Urbana *	.04	1.38	1.04	-	1.15	.08
	.24	13.53	2.70	.26	10.42	1.29
Average	.03	1.93	.39	.04	1.49	.18

Table 35.- Storms studied in connection with unit hydrographs, Embarrass River above Ste. Marie, Ill.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	September 1920						September - October 1921				
	14	15	16	23	26	27	24	25	30	2	3
Casey	-	1.02	0.01	0.01	0.26	0.65	-	0.84	1.19	-	-
Charleston	-	1.94	-	-	-	-	0.02	2.84	.83	0.03	0.04
Effingham *	0.02	-	1.28	.11	-	.08	.27	1.63	.93	.07	-
Olney *	.10		1.58	-	-	-	.82	-	.76	-	.13
Paris *	-	-	.97	-	-	1.08	-	-	-	-	-
Tuscola	-	1.30	-	.04	.13	.54	-	1.98	.71	.01	-
Urbana *	-	-	.67	.02	-	.55	-	.66	.60	-	-
	.12	4.26	4.51	.18	.39	2.90	1.11	7.95	5.02	.11	.17
Average	.01	.61	.64	.03	.06	.41	.18	1.32	.84	.02	.03

Station	June 1929		June 1929					
	7	8	12	13	14	15	18	20
Casey	1.13	-	1.54	0.72	-	-	-	0.09
Charleston	.78	-	1.35	.17	-	-	-	.01
Effingham *	1.00	0.52	1.16	.85	-	-	-	-
Newton *	1.38	-	1.63	.64	0.22	-	0.02	.52
Paris *	1.80	-	.92	.60	.20	-	-	-
Tuscola	.72	-	-	1.25	.12	-	-	.16
Urbana *	.25	-	.92	.05	-	0.32	-	-
	7.06	.52	7.52	4.28	.54	.32	.02	.78
Average	1.01	.07	1.09	.61	.08	.05	0	.11

The superimposed distribution graphs for the Embarrass River above Ste. Marie (fig. 46) show an appreciable variation as a result of having one, two, or three peaks.

The storm of June 25, 1918, though of greater intensity in the upper part of the basin, which would flatten its peak, appears to have lasted about 12 hours, which would counteract the flattening effect. The result is a fairly average distribution graph.

The storm of May 12, 1920, was poorly distributed, with high intensities in the uplands and apparently about 24 hours duration. The result is a flat distribution graph.

The storms of September 15, 1920, and June 7, 1929, appear to have been short and slightly heavier on the lower part of the basin, thus giving high-peaked distribution graphs.

Table 36 gives the surface run-off from the unit storms.

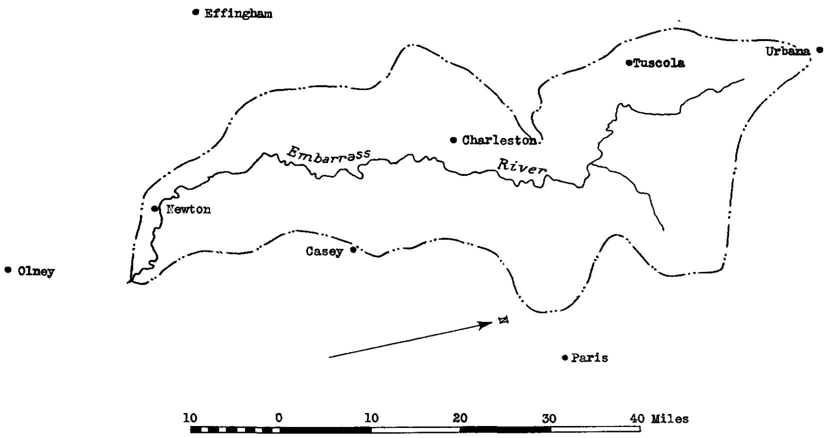

Figure 43.—Embarrass River Basin above Ste. Marie, Ill.
Drainage area 1,540 square miles

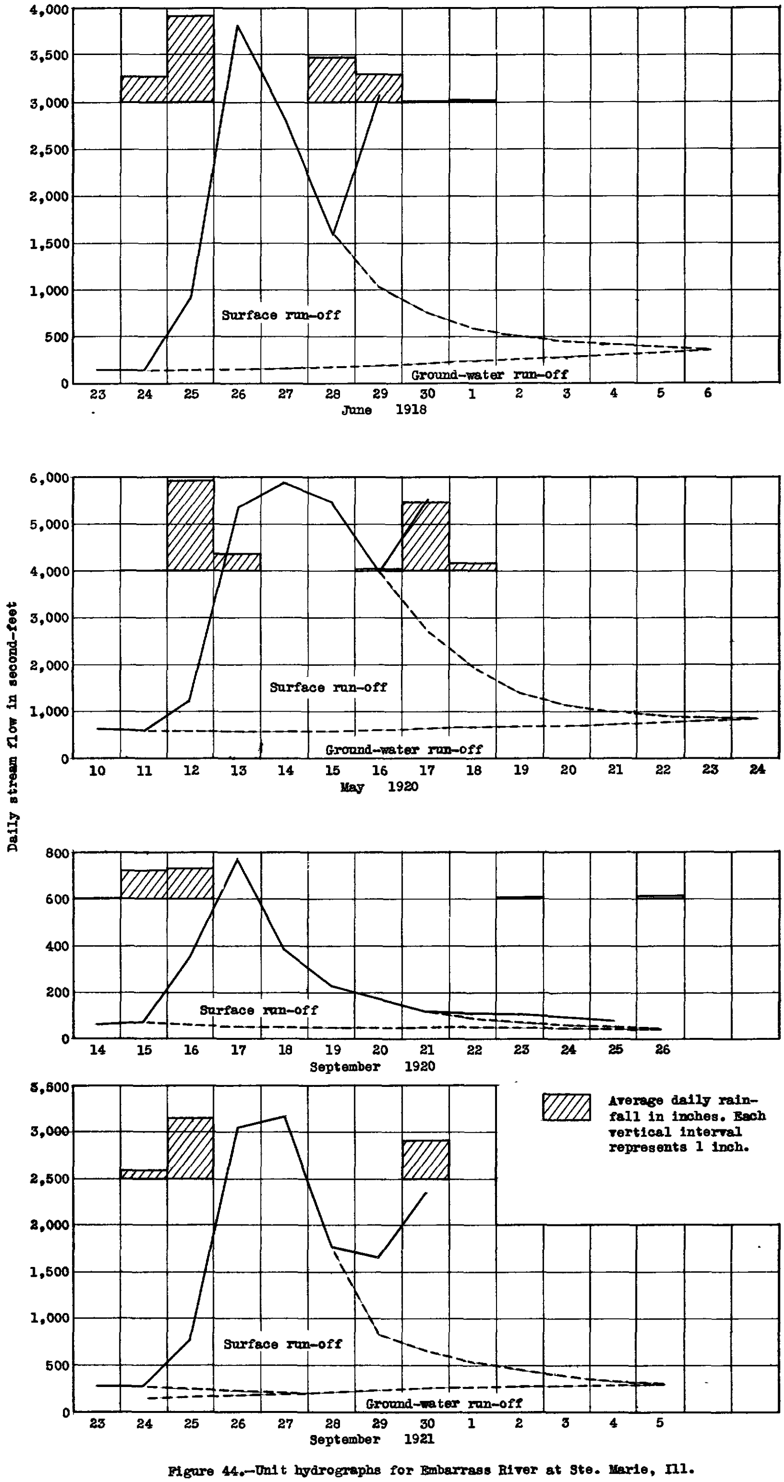

Figure 44.—Unit hydrographs for Embarrass River at Ste. Marie, Ill.

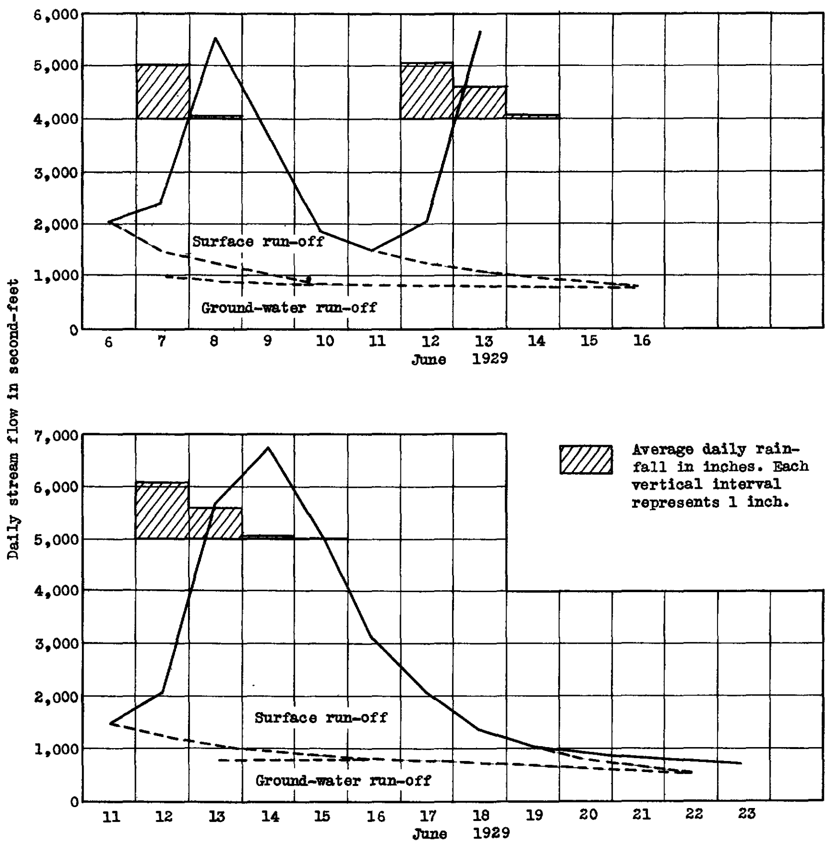

Figure 45.--Unit hydrographs for Embarrass River at Ste. Marie, Ill.

Table 36.- Surface run-off from unit storms, Embarrass River at Ste. Marie, Ill.

Storm	Precipitation (inches)		Surface run-off (inches)	Ratio of surface run-off to weighted precipitation
	Average	Geometrically weighted		
June 25, 1918	2.36	2.86	0.26	0.09
May 12, 1920	2.35	2.79	.58	.21
Sept. 15, 1920	1.26	1.35	.04	.03
Sept. 25, 1921	1.50	1.89	.23	.12
June 7, 1929	1.08	.99	.25	.25
June 12, 1929	1.83	1.66	.49	.30

Table 37 gives the daily percentages for the six distribution graphs, and figure 46 shows the superimposed distribution graphs. An average distribution graph for the stations is 5, 25, 29, 18, 10, 6, 3, 2, 1, 1 percent. The first figure for each graph is the percentage of surface run-off for the calendar day on which most of the rainfall occurred; other figures for succeeding days.

Table 37.- Distribution graphs for storms in Embarrass River Basin above Ste. Marie, Ill.

June 25, 1918	7.1	33.7	24.5	13.2	7.9	5.1	3.2	2.2	1.5	1.0	0.6	-
May 12, 1920	2.8	19.8	22.1	20.3	14.0	8.8	5.4	3.0	1.9	1.0	.6	0.3
Sept. 15, 1920	0	16.6	39.9	18.2	9.7	6.9	3.9	2.4	1.3	.8	.3	-
Sept. 25, 1921	5.5	30.1	31.6	16.5	6.3	4.1	2.8	1.8	1.0	.3	-	-
June 7, 1929	8.8	41.0	25.8	9.4	6.2	3.9	2.6	1.5	.8	-	-	-
June 12, 1929	4.0	22.5	28.5	20.8	11.4	6.4	3.1	1.8	1.0	.5	-	-

Skunk River Basin above Augusta, Iowa

The Skunk River rises at about 1,200 feet above sea level near the northeast corner of Hamilton County, Iowa, in the region of Wisconsin drift. The basin above Augusta (fig. 47) is long and narrow and covers 4,290 square miles. The length of the stream above Augusta is about 270 miles. The basin is about 170 miles long, and the average width is 25 miles. The North Skunk River and Cedar Creek are the principal tributaries and flow in the same general direction as the main stream.

In the upper 130 miles the river drops at an average rate of 3.4 feet to the mile; the 140 miles next above the station has an average gradient of 1.4 feet to the mile. The station at Augusta is about 12 miles

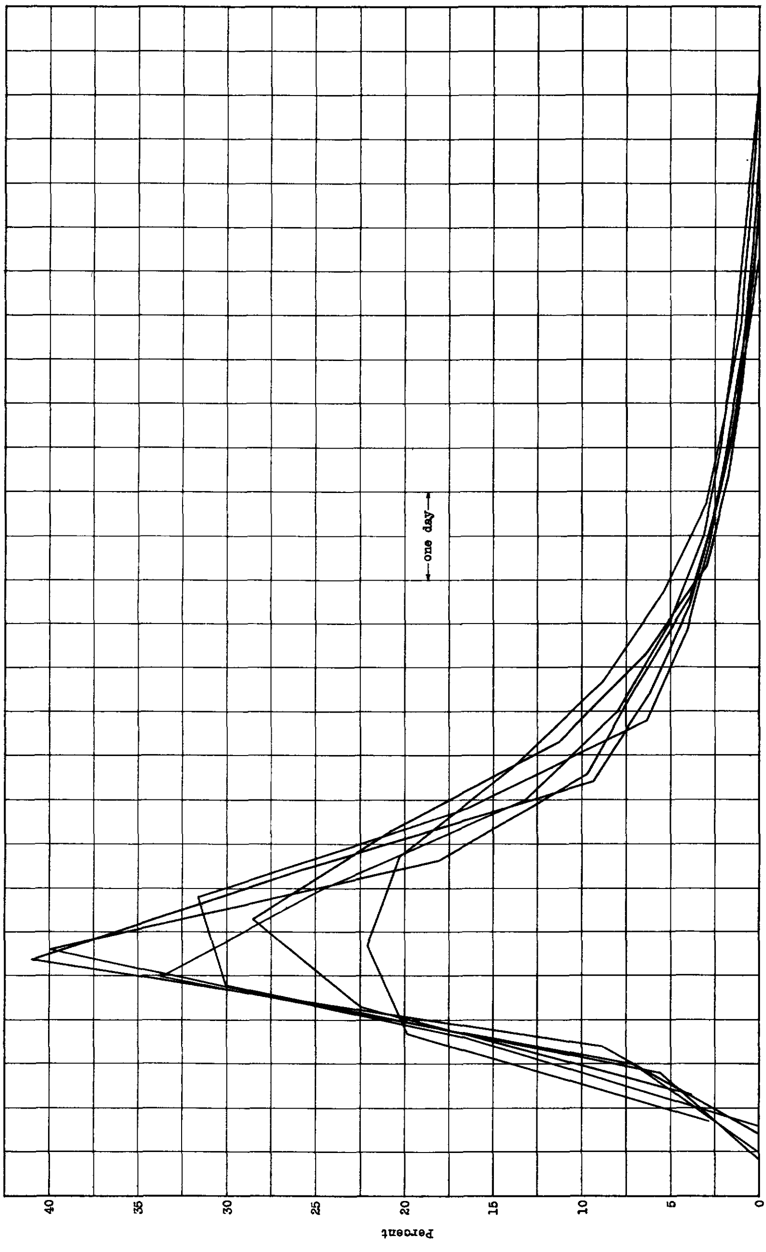

Figure 46.— Superimposed distribution graphs for Embarrass River Basin above Ste. Marie, Ill.

above the mouth, where the river discharges into the Mississippi River pool above the Keokuk Dam.

About 9 percent of the basin is forest, 62 percent is cultivated, and 29 percent is grass land.

The United States Geological Survey chain gage was installed on the highway bridge near Augusta in June 1915. The chain was of iron and the links gave a good deal of trouble. It was replaced by a standard copper chain in July 1919. The gage is read to half tenths once a day. The zero of the gage is 528.6 feet above sea level, Memphis datum. The records are fair with slight regulation at low stages.

Normally 14 or 15 stations are available for the determination of daily precipitation. Figure 47 locates the United States Weather Bureau stations on an outline of the drainage basin.

Table 38 gives the daily precipitation recorded at the Weather Bureau stations for the storms that produced the unit hydrographs shown in figures 48 and 49.

Table 38.- Storms studied in connection with unit hydrographs for the Skunk River Basin above Augusta, Iowa

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	July 1924						
	22	24	25	27	28	29	30
Ames	-	0.15	-	0.25	-	0.16	-
Baxter	-	.30	-	-	0.30	.80	-
Boone *	0.05	.13	-	-	.55	.54	0.04
Grinnell	-	4.40	-	-	.14	.70	-
Monroe	-	.63	-	-	.20	.73	-
Webster City	-	.92	-	.04	-	.90	-
Burlington *	.92	2.27	0.42	-	.03	-	.54
Fairfield	.01	2.53	-	.03	-	.59	.02
Mount Pleasant	.67	3.49	-	-	-	.47	.05
Oskaloosa	-	.75	-	-	1.06	.59	-
Ottumwa	.72	1.10	-	-	.03	.72	-
Sigourney	-	2.70	-	-	.12	1.13	-
Stockport	.22	1.59	-	.05	.07	.66	.39
Washington	1.60	5.80	-	-	-	1.00	.23
	4.19	26.76	.42	.37	2.50	8.99	1.27
Average	.30	1.91	.03	.03	.18	.64	.09

Table 38.- Storms studied in connection with unit hydrographs for the Skunk River Basin above Augusta, Iowa--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	May 1927						
	17	18	19	20	21	22	23
Ames	1.23	0.66	-	0.76	-	0.06	0.92
Baxter	.19	.82	-	.01	-	.15	1.09
Boone *	-	.04	0.55	-	0.56	-	.50
Grinnell	.13	.56	-	-	-	.32	1.18
Monroe	-	.63	-	-	-	.27	1.39
Webster City	1.00	.92	-	.67	-	.05	1.21
Burlington *	.01	.03	2.17	-	-	.06	.64
Fairfield	.01	2.40	-	-	-	.50	.75
Mount Pleasant	.05	1.93	-	-	-	.47	.29
Oskaloosa	-	.36	-	-	-	.39	.64
Ottumwa	-	2.23	-	-	-	.36	.08
Sigourney	.38	.40	-	-	-	.40	.66
Stockport	-	2.56	-	-	-	.28	.19
Washington	.13	.67	-	-	-	.30	.88
	3.13	14.21	2.72	1.44	.56	3.61	10.42
Average	.22	1.02	.19	.10	.04	.26	.74

Station	June 1927						
	2	3	4	7	8	9	10
Ames	-	0.08	-	-	-	0.15	-
Baxter	-	.13	-	0.04	0.61	.24	0.14
Boone *	-	.02	0.08	-	-	1.14	-
Grinnell	0.01	.22	-	.16	.23	-	.20
Monroe	.34	.41	-	-	.55	-	-
Webster City		.03	-	-	-	-	-
Burlington *	-	.15	1.38	-	-	-	.06
Fairfield	.15	1.50	.22	-	-	-	.05
Mount Pleasant	.10	.43	1.95	-	-	-	.12
Oskaloosa	.76	.19	.03	-	.13	-	.03
Ottumwa	.14	.70	.10	-	-	-	-
Sigourney	.55	.72	.08	-	.06	-	-
Stockport	.17	2.00	.18	-	-	-	-
Washington	1.20	.63	1.13	-	.05	-	-
	3.42	7.21	5.20	.20	1.63	1.53	.60
Average	.24	.52	.37	.01	.12	.11	.04

Station	July 1928				
	4	8	9	10	11
Ames	1.10	0.15	-	-	-
Baxter	1.17	.24	-	0.03	0.42
Boone *	1.16	.23	-	.03	-
Grinnell	1.02	.24	-	.02	.03
Monroe	1.22	.22	-	.64	.04
Webster City	.30	.09	-	-	.07
Burlington *	.47	-	0.37	-	.20
Fairfield	2.12	.71	-	-	-
Mount Pleasant	1.46	.32	-	.15	-
Oskaloosa	1.35	.70	-	.33	-

Table 38.- Storms studied in connection with unit hydrographs for the Skunk River Basin above Augusta, Iowa--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	July 1928				
	4	8	9	10	11
Ottumwa	1.01	0.26	-	0.02	0.07
Sigourney	.91	.91	.17	.05	-
Stockport	1.37	.39	-	.03	-
Washington	3.40	.28	.09	1.08	-
	18.06	4.74	.63	2.38	.83
Average	1.29	.34	.04	.17	.06

Station	August - September 1931					June - July 1932				
	30	31	1	2	3	25	26	27	1	3
Ames	0.02	-	0.49	-	0.11	-	0.59	0.02	-	0.89
Baxter	.15	0.03	1.02	-	.08	-	1.14	-	-	.89
Boone *	-	-	.59	-	.04	0.62	.68	.12	-	.75
Grinnell	-	-	1.86	0.07	.07	.03	.32	.09	-	.72
Monroe	-	1.28	-	-	.16	-	.54	.65	-	.79
Newton	.12	.03	1.07	-	.07	.05	.98	-	-	.77
Webster City	-	.03	1.72	-	-	-	.36	-	-	.75
Burlington *	-	-	2.65	.09	-	-	.02	.14	-	.11
Fairfield	.04	.11	3.29	-	.04	-	3.25	-	0.16	2.29
Mount Pleasant	.04	-	1.65	-	.02	-	2.00	.03	.12	1.83
Oskaloosa	-	-	2.99	-	.15	.76	5.45	.07	-	1.02
Ottumwa	-	.38	3.70	-	.15	-	2.28	-	.12	1.67
Sigourney	-	-	2.55	-	-	.65	2.55	-	-	.96
Stockport	-	.04	2.80	-	.05	-	.32	-	-	1.03
Washington	-	-	2.10	-	-	-	2.08	-	-	.92
	.37	1.90	28.48	.16	.94	2.11	22.56	1.12	.40	15.39
Average	.03	.14	1.90	.01	.06	.14	1.50	.07	.03	1.03

Table 39 gives the surface run-off from the unit storms and the approximate value of the precipitation that caused the run-off.

Table 39.- Surface run-off from unit storms, Skunk River at Augusta, Iowa

Storm	Average of precipitation at stations (inches)	Surface run-off (inches)	Ratio of surface run-off to average precipitation
July 24, 1924	1.94	0.75	0.39
May 18, 1927	1.43	.34	.24
June 3, 1927	1.13	.33	.29
July 4, 1928	1.29	.42	.33
Aug. 31, 1931	2.07	.17	.08
June 26, 1932	1.71	.49	.29

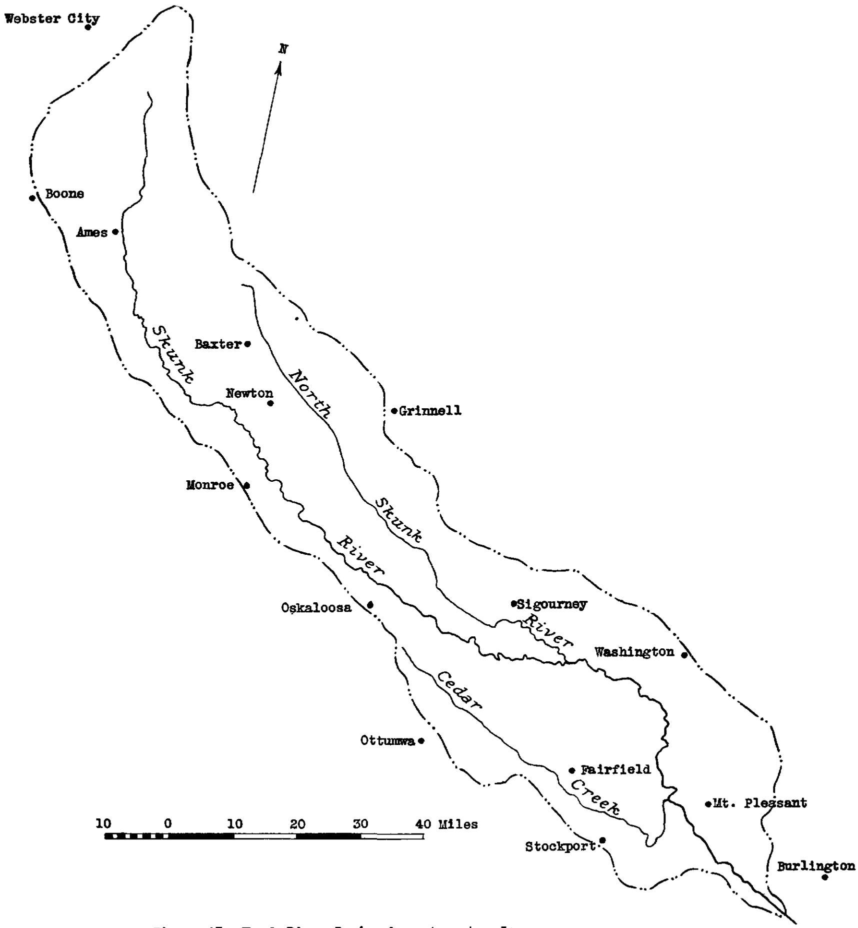

Figure 47.—Skunk River Basin above Augusta, Iowa.
Drainage area 4,290 square miles

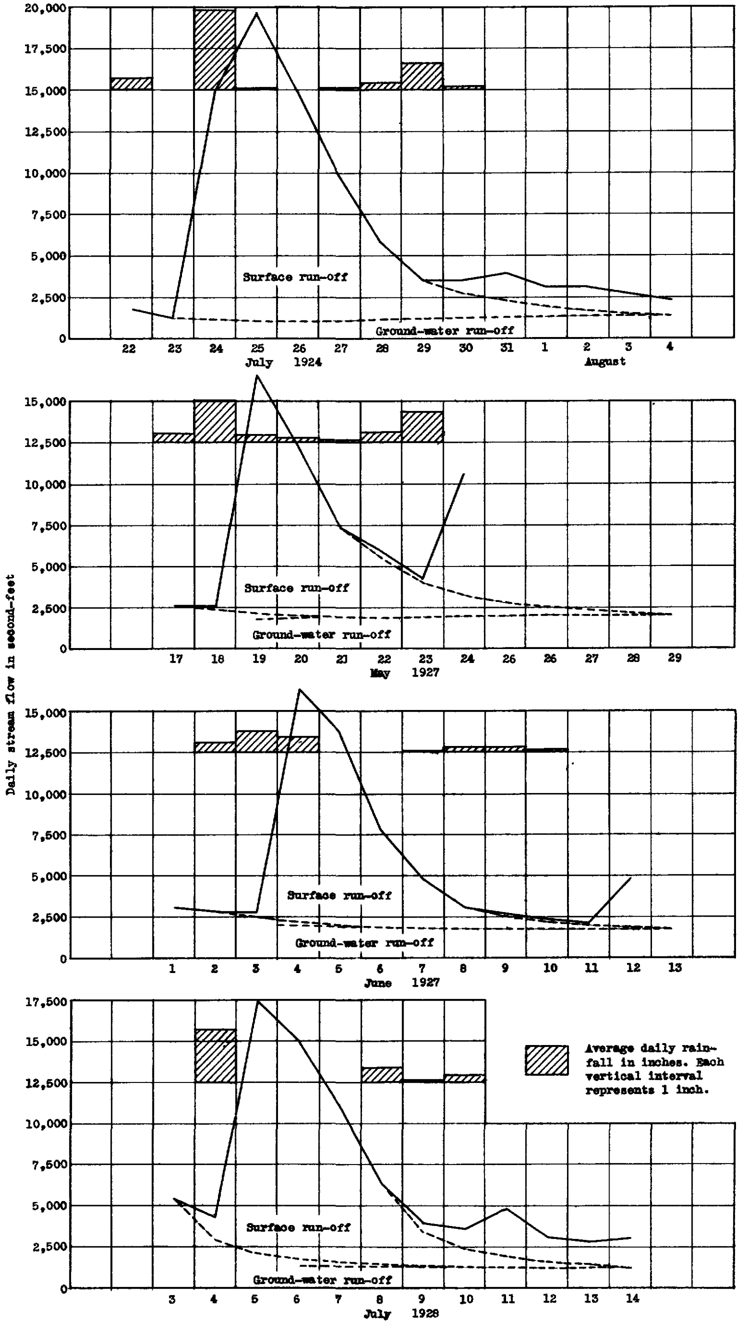

Figure 48.—Unit hydrographs for Skunk River at Augusta, Iowa.

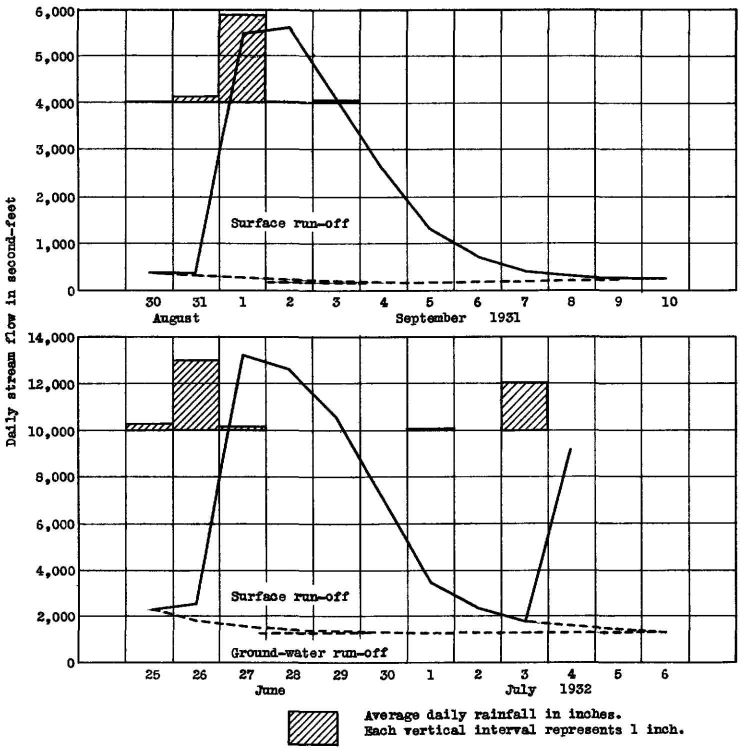

Figure 49.—Unit hydrographs for Skunk River at Augusta, Iowa.

Table 40 gives the daily percentages for the six distribution graphs, and figure 50 shows the graphs superimposed. The average distribution graph determined for the basin is 1, 32, 27, 18, 11, 5, 3, 2, 1 percent. The average graph reflects the long, narrow basin and the tributary drainage. The graph rises rapidly to its peak and then tapers out gradually. The first figure for each distribution graph is the percentage of surface run-off for the calendar day on which most of the rainfall occurred; other figures for succeeding days.

Table 40.- Distribution graphs for storms in Skunk River Basin above Augusta, Iowa

July 24, 1924	21.3	28.7	21.1	13.2	7.0	3.5	2.1	1.5	0.9	0.5	0.2
May 18, 1927	.7	37.2	26.1	13.8	9.2	5.3	3.5	2.0	1.2	.7	.3
June 3, 1927	.9	37.4	31.0	15.5	7.8	3.5	1.9	1.1	.6	.3	-
July 4, 1928	2.6	31.6	27.4	19.4	10.1	4.2	2.3	1.4	.7	.3	-
Aug. 31, 1931	.4	27.6	28.4	20.5	12.6	5.9	2.7	1.1	.6	.2	-
June 26, 1932	1.8	27.3	26.3	21.6	13.6	5.0	2.3	1.1	.7	.3	-

Susquehanna River Basin above Towanda, Pa.

The Susquehanna River rises in Otsego Lake, in the Catskill Mountains, in Otsego County, N. Y., at about 1,193 feet above sea level. It flows in a southerly direction through Otsego, Chenango, and Broome Counties, N. Y., into Susquehanna County, Pa. It then flows in a west northwesterly direction, reenters New York, and flows westward through Broome and Tioga Counties, whence it turns south and again flows into Pennsylvania. The river distance from the State boundary to the Towanda station is about 20 miles. The Chemung River, flowing from the west and draining about 2,500 square miles, empties into the Susquehanna about 13 miles above the station. (See fig. 51.)

The drainage area above Towanda is 7,770 square miles; the length is about 170 miles, and the average width about 46 miles. The stream drops about 500 feet in the 170 miles above Towanda. The zero of the gage is 693.4 feet above mean sea level. The part of the basin in New York is rolling and in places broken country.

Gage heights at the stations have been observed by the United States Weather Bureau since October 1892. The Water Supply Commission of Pennsylvania, in its annual reports, has published discharge measurements and gage heights beginning January 29, 1914, and daily discharge since

Figure 50.—Superimposed distribution graphs for Skunk River Basin above Augusta, Iowa.

October 1918. The stage-discharge relation is probably permanent except as affected by ice.

The gage is a standard chain gage attached to the downstream side of the Bridge Street Bridge at Towanda and read to hundredths twice daily.

The United States Geological Survey has published the records for October 1918 to October 1920 and October 1931 to date. They are considered fair.

About 22 stations are normally available for the determination of daily rainfall. Figure 51 shows the principal drainage and the location of the precipitation stations.

Table 41 gives the daily precipitation recorded at the stations for the storms that produced the unit hydrographs shown in figures 52, 53, and 54.

Table 41.- Storms studied in connection with unit hydrographs for the Susquehanna River above Towanda, Pa.

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	October 1918						
	3	5	6	7	12	13	14
New York:							
Addison	0.30	-	0.88	0.10	0.15	-	0.05
Alfred	.26	-	.19	.14	.30	-	.17
Angelica	.11	-	.15	.07	.27	0.01	.15
Elmira	.02	-	.88	-	.02	-	.09
Haskinville	-	-	-	.38	.23	-	.12
Bainbridge *	.49	-	1.05	.19	-	.09	.02
Binghamton **	.14	0.94	.25	.01	.05	.01	.03
Cazenovia *	.73	-	.45	.14	-	.02	.07
Cooperstown	-	.34	.04	-	.16	.04	-
Cortland	.20	-	.15	.36	.08	.07	.06
De Ruyter	.42	-	.46	-	-	.37	.38
Fishs Eddy	.59	-	-	.14	-	-	-
Newark Valley	.63	.01	.95	-	.05	-	.14
New Berlin	.40	-	.80	-	-	-	.10
New Lisbon	.64	-	.72	.01	.12	-	.07
Norwich *	.58	-	.32	.58	-	.11	.02
Oneonta	.38	-	.19	-	-	.09	-
Roxbury	.38	-	1.31	-	.22	.10	.15
Sherburne *	.25	-	.20	-	-	.05	.05
Ithaca **	.03	.09	.11	-	.04	-	.23
Pennsylvania:							
Lawrenceville	.58	-	.80	-	-	-	-
Montrose	.70	-	1.16	.10	.18	.22	.10
Towanda	.70	-	1.01	.08	.09	-	-
Wellsboro	.86	-	1.28	.16	.15	.02	-
West Bingham	-	-	1.28	1.03	.32	-	-
	9.39	1.38	13.35	3.49	2.43	1.20	2.00
Average	.38	.06	.53	.14	.10	.05	.08

Table 41.- Storms studied in connection with unit hydrographs for the Susquehanna River above Towanda, Pa.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	July 1921							
	12	13	14	15	16	19	20	21
New York:								
Addison	0.06	-	-	1.26	0.05	1.04	0.01	-
Alfred	.09	0.03	-	1.17	-	1.53	.11	-
Angelica	.14	.12	-	1.20	-	1.25	.05	-
Elmira	-	-	0.56	.10	-	.62	.65	-
Haskinville	.10	-	-	.72	-	.73	.18	-
Bainbridge *	.22	-	-	.63	.45	-	.99	0.62
Binghamton **	-	.03	1.14	.73	-	.51	.22	-
Cazenovia *	-	-	-	1.00	-	-	.70	.58
Cortland	-	-	2.40	.36	-	1.04	.12	-
De Ruyter	.31	-	.55	.66	-	.59	1.10	.02
Morrisville	-	-	-	1.65	-	.15	.70	-
New Lisbon	.04	-	.40	2.96	-	.80	.30	.26
Norwich *	.15	-	-	1.40	.30	-	1.20	.24
Oneonta	-	-	-	2.20	-	1.24	-	-
Sherburne *	-	-	-	.89	.64	-	1.20	-
Ithaca **	-	-	.24	1.21	-	.53	.22	-
Pennsylvania:								
Lawrenceville	-	-	-	.70	-	1.40	.25	-
Montrose	-	.34	.20	.22	-	1.00	.25	-
Towanda	.03	-	-	.36	-	.84	.14	-
Wellsboro	-	-	-	.09	-	1.14	-	-
West Bingham	-	-	.40	.41	-	1.43	.05	-
	1.14	.52	5.89	19.92	1.44	15.84	8.44	1.72
Average	.05	.02	.28	.95	.07	.75	.40	.08

Station	April 1923								
	3	4	5	6	8	9	10	11	12
New York:									
Addison	-	0.23	1.05	-	0.01	-	-	0.02	0.12
Alfred	0.10	.21	1.20	-	.03	-	0.02	-	.17
Angelica	.20	.20	1.00	0.02	-	-	.14	-	.15
Elmira **	-	.89	.15	-	-	-	.08	.02	-
Haskinville	.07	.19	.98	-	-	0.02	.10	.12	-
Bainbridge *	-	-	.27	.72	-	.21	-	-	.26
Binghamton **	-	.22	.55	-	-	-	.03	.06	-
Cooperstown	-	.15	.80	-	.05	.03	.20	.15	-
Cortland	-	.03	1.79	-	-	-	-	.06	-
De Ruyter	-	.10	1.72	.05	-	-	-	-	.17

Table 41.- Storms studied in connection with unit hydrographs for the Susquehanna River above Towanda, Pa.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	April 1923								
	3	4	5	6	8	9	10	11	12
New York--Continued:									
New Berlin	-	-	1.25	-	0.05	0.08	0.05	0.13	-
New Lisbon	-	0.09	.77	-	-	-	-	.25	0.04
Norwich *	-	.05	.43	0.62	-	-	-	.13	-
Oneonta	-	-	1.18	-	-	-	-	.15	-
Roxbury	-	-	.75	.10	.10	-	-	.30	.25
Sherburne *	-	.12	.24	.54	-	.05	-	.26	.14
Ithaca **	0.06	1.10	.49	-	.02	-	-	.06	-
Pennsylvania:									
Lawrenceville	-	-	1.20	-	-	-	-	-	-
Montrose	-	-	.84	-	-	-	-	-	-
Towanda	-	.04	.47	-	-	-	-	.02	-
Wellsboro	-	.23	1.02	-	-	-	-	-	-
West Bingham	.12	.20	1.30	-	-	-	.05	-	.15
Average	.55 .02	4.05 .18	19.45 .88	2.05 .09	.26 .01	.39 .02	.67 .03	1.73 .08	1.45 .07

Station	September - October 1924					
	29	30	1	2	7	8
New York:						
Addison	2.00	1.57	-	-	0.15	-
Alfred	2.53	1.45	0.05	-	.10	-
Angelica	2.10	1.12	.05	-	.10	-
Elmira **	-	4.00	-	-	.11	-
Haskinville	2.15	1.56	.06	-	.07	-
Bainbridge *	.14	2.68	1.44	-	-	0.26
Binghamton **	2.04	2.95	-	-	.40	-
Cooperstown	1.96	1.55	-	-	.20	-
Cortland	3.12	.80	-	-	.24	-
Delhi	.30	4.28	.28	-	.07	.07
De Ruyter	1.60	2.82	-	-	.10	.08
Morrisville	.90	2.30	-	-	-	-
New Berlin	.90	2.00	1.20	0.50	-	-
Norwich *	.18	3.34	1.22	-	-	.29
Oneonta	.75	3.52	-	-	.06	-
Roxbury	.23	3.30	.25	-	.03	.11
Sherburne *	1.90	1.80	1.80	-	-	-
Ithaca **	3.14	1.33	-	-	.12	-
Pennsylvania:						
Lawrenceville	1.25	2.90	-	-	.14	.04
Montrose	1.30	2.70	-	-	-	-
Towanda	1.92	2.61	-	-	.05	.03
Wellsboro	1.95	1.75	-	-	.03	-
West Bingham	1.80	1.30	-	-	.10	-
Average	34.16 1.49	53.63 2.33	6.35 .29	.50 .02	2.07 .09	.88 .04

Table 41.- Storms studied in connection with unit hydrographs for the Susquehanna River above Towanda, Pa.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	November 1924						
	21	22	23	24	28	29	30
New York:							
Addison	-	0.18	0.02	0.06	-	0.20	-
Alfred	-	.05	.03	.08	0.02	.08	0.02
Angelica	-	-	-	.15	.03	.05	.05
Elmira **	-	.52	-	-	-	.02	-
Haskinville	-	.20	-	.21	.06	.09	-
Bainbridge *	0.10	1.67	-	-	.10	.03	-
Binghamton **	-	1.27	-	.04	-	.08	-
Cooperstown	.05	1.55	-	.03	-	.20	-
Cortland	-	.98	.03	-	-	.05	.03
Delhi	-	1.73	.45	.06	-	.10	.10
De Ruyter	-	1.37	.08	.12	-	.14	.10
New Berlin	.50	.40	-	-	-	-	.90
Norwich *	-	.73	1.39	.03	-	.15	.10
Oneonta	-	1.56	.15	-	-	.22	-
Roxbury	-	1.45	.08	.06	-	.25	.01
Sherburne *	-	.50	-	-	.15	.05	.06
Ithaca **	.70	-	-	.02	-	.11	-
Pennsylvania:							
Lawrenceville	-	.50	-	.10	-	.10	.05
Montrose	-	.60	.14	-	-	.10	-
Towanda	-	1.01	-	-	-	.07	.05
Wellsboro	-	.35	-	-	-	.08	.06
West Bingham	-	.04	.10	.20	.10	-	.05
	1.35	16.66	2.47	1.16	.46	2.17	1.58
Average	.06	.76	.11	.05	.02	.10	.07

Station	November 1926										
	15	16	17	18	19	20	21	22	23	24	26
New York:											
Addison	-	1.46	-	0.12	0.53	-	-	-	-	-	0.05
Alfred	-	1.27	-	-	.07	0.04	0.04	-	0.02	0.07	.14
Angelica	-	1.10	0.03	.40	.12	-	.03	-	.10	-	-
Elmira **	0.09	2.06	-	.62	-	-	-	-	-	-	.05
Haskinville	-	.62	.06	-	.13	-	-	0.05	-	.04	-
Bainbridge *	.30	.20	1.70	.10	-	-	-	-	-	-	.10
Binghamton **	.01	2.74	-	.56	.02	-	.07	-	-	-	-
Cooperstown	.15	1.05	-	.47	-	.04	.01	.03	-	-	-
Cortland	-	3.15	-	.76	-	-	-	-	-	-	-
Delhi	-	2.30	-	-	.37	-	-	-	-	-	.70
De Ruyter	.03	2.91	-	-	.62	.03	.06	-	.01	.15	.10
Morrisville	.02	2.17	.13	-	.10	-	.10	.05	.02	.05	.09
New Berlin	.30	1.45	-	-	1.02	-	-	-	-	-	-
Norwich *	-	.33	1.44	-	.75	-	.05	-	.06	.05	.01
Oneonta	-	1.95	-	-	.52	-	-	-	-	-	.10
Roxbury	-	2.50	.27	-	.37	-	-	-	-	-	.50
Sherburne *	-	1.50	-	-	.57	-	-	.09	-	-	.14
Ithaca **	-	2.31	-	.40	.10	.03	.05	-	.01	.02	.08

Table 41.- Storms studied in connection with unit hydrographs for the Susquehanna River above Towanda, Pa.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	November 1926										
	15	16	17	18	19	20	21	22	23	24	26
Pennsylvania:											
Lawrenceville	-	1.65	-	-	0.54	-	-	-	-	-	0.07
Montrose	-	2.90	0.15	-	-	-	-	-	-	-	-
Morris Run	0.05	3.24	-	0.39	.45	0.03	-	-	-	-	.14
Towanda	-	2.77	-	.13	.61	-	-	-	-	-	.15
Wellsboro	-	1.75	-	.35	.40	-	-	-	-	-	.15
West Bingham	-	1.37	-	.30	-	.05	0.05	-	0.05	-	.35
Average	.95 .04	44.75 1.86	3.78 .16	4.60 .19	7.29 .30	.22 .01	.46 .02	0.22 .01	.27 .01	0.38 .02	2.92 .12

Station	October 1929						
	1	2	3	4	7	8	13
New York:							
Addison	-	2.05	0.65	-	0.08	-	0.16
Alfred	-	2.00	1.86	-	.16	-	.12
Angelica	-	1.65	1.37	-	.22	-	.11
Elmira **	-	3.00	.05	-	.04	-	.04
Haskinville	-	1.03	1.45	-	.20	-	-
Binghamton **	-	2.99	.33	-	.07	-	.09
Cortland	0.26	1.76	1.26	-	.58	-	.18
Delhi	-	2.13	.35	0.07	.06	0.05	.04
Morrisville	.06	2.08	.60	.15	.48	.05	.26
Norwich *	.14	.10	2.30	.11	.12	.12	.07
Oneonta	-	2.12	.27	.04	.04	-	.09
Roxbury	-	1.40	-	.40	-	.05	-
Sherburne *	.19	.20	2.29	.14	.08	.14	-
Ithaca **	-	2.47	.47	-	.22	-	.16
Pennsylvania:							
Lawrenceville	-	1.85	.60	-	.10	-	.20
Montrose	-	2.13	.47	-	-	-	-
Morris Run	-	2.52	.92	-	-	-	.10
Towanda	-	3.01	.55	-	-	-	.02
Wellsboro	-	2.22	.83	-	-	-	-
Average	.65 .03	36.71 1.93	16.62 .88	.91 .05	2.45 .13	.41 .02	1.64 .09

Table 41.- Storms studied in connection with unit hydrographs for the Susquehanna River above Towanda, Pa.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	April 1930						
	6	7	8	11	12	13	14
New York:							
Addison	0.05	1.05	0.10	-	-	0.26	-
Alfred	.07	.56	.05	-	-	.03	-
Angelica	-	.50	.10	-	0.05	.05	-
Elmira **	.93	.30	-	-	-	.20	-
Haskinville	-	.62	.09	0.06	-	-	0.05
Bainbridge *	-	.81	.31	-	.11	-	.08
Binghamton **	1.01	.60	.16	-	-	.10	-
Cortland	-	1.40	.44	-	-	-	-
Delhi	-	.97	.11	-	.25	-	-
Morrisville	-	1.18	.10	.04	-	-	-
Norwich *	-	1.15	.19	-	.19	-	-
Oneonta	.04	1.18	.04	.02	.12	-	-
Roxbury	-	.85	.07	.20	.04	-	-
Sherburne *	-	.96	.34	-	.07	-	-
Ithaca **	.73	.88	.18	-	-	-	-
Pennsylvania:							
Lawrenceville	-	.52	-	-	-	.10	-
Montrose	.21	1.30	-	-	-	.41	.40
Morris Run	.22	1.08	.08	-	-	.30	-
Towanda	.23	1.49	.02	-	.02	.28	-
Wellsboro	.60	.40	.02	-	-	.25	-
	4.09	17.80	2.40	.32	.85	1.98	.53
Average	.20	.89	.12	.02	.04	.10	.03

Station	June 1930						
	9	10	11	16	17	18	19
New York:							
Addison	0.25	1.26	-	0.26	1.70	0.38	-
Alfred	.09	1.00	-	.25	.55	.50	0.04
Angelica	.12	1.50	0.04	.15	.45	.60	.10
Elmira **	.45	.24	-	.50	1.80	.01	.03
Haskinville	.10	1.23	.05	1.08	.46	.92	-
Bainbridge *	.11	.81	.44	-	-	.08	.80
Binghamton **	.50	.80	-	-	.78	1.87	.05
Cooperstown	.58	.10	-	-	-	.75	-
Cortland	.42	.46	.08	.78	1.74	.72	.24
Delhi	.51	1.02	.08	-	-	.25	.21
Morrisville	.09	.94	.25	.21	1.50	1.16	.52
Norwich *	.08	.75	.49	-	-	.35	.97
Oneonta	.29	.75	.02	-	-	.03	.22
Roxbury	.24	.60	-	-	.27	.25	.12
Sherburne *	.04	.55	.64	-	.03	.32	.47
Ithaca **	.52	1.07	-	1.09	2.49	1.20	.05

Table 41.- Storms studied in connection with unit hydrographs for the Susquehanna River above Towanda, Pa.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	June 1930						
	9	10	11	16	17	18	19
Pennsylvania:							
Lawrenceville	-	.40	1.00	0.10	2.69	0.70	-
Montrose	0.22	1.60	-	-	1.00	.75	.38
Morris Run	.40	1.51	-	.18	.18	.90	-
Towanda	.20	.82	-	-	.33	2.02	.01
Wellsboro	-	1.55	-	-	.32	.52	-
	5.21	18.96	3.09	4.60	16.29	14.28	4.21
Average	.25	.90	.15	.22	.78	.68	.20

Station	October 1932						
	4	5	6	7	11	12	13
New York:							
Addison	0.05	0.70	1.96	-	-	-	0.05
Alfred	.02	.59	1.33	0.03	0.01	0.20	.10
Angelica	.03	.40	1.27	.05	.04	.20	.10
Elmira **	.12	2.10	.49	-	-	-	-
Haskinville	.33	-	1.68	-	-	.20	-
Bainbridge *	-	.60	2.70	.96	-	.04	-
Binghamton **	-	3.59	1.77	-	.05	.02	-
Cooperstown	-	.54	4.85	.04	.08	.12	-
Cortland	-	.30	3.16	-	.03	.46	-
Delhi	-	.73	5.71	.05	-	.01	-
Morrisville	-	1.48	3.49	.02	.15	.08	.08
Norwich *	-	.41	4.04	.90	.11	.05	.25
Oneonta	-	.60	5.09	.06	.02	.08	-
Roxbury	-	.23	6.75	.04	.05	.11	-
Sherburne *	-	.30	2.87	.94	.11	.02	.11
Ithaca **	-	1.14	1.28	-	.03	.11	-
Pennsylvania:							
Lawrenceville	-	.43	2.80	-	-	.10	-
Montrose	-	2.20	2.25	-	-	-	-
Morris Run	.06	.86	2.46	-	.01	.03	-
Towanda	-	2.34	2.65	-	-	.04	-
Wellsboro	.01	1.05	1.61	-	-	-	-
	.62	20.59	60.21	3.09	.69	1.87	.69
Average	.03	.98	2.87	.15	.03	.09	.03

Table 42 gives the surface run-off from the unit storms and the approximate depth of the precipitation that caused the run-off. Figures preceded by * include run-off from melting snow.

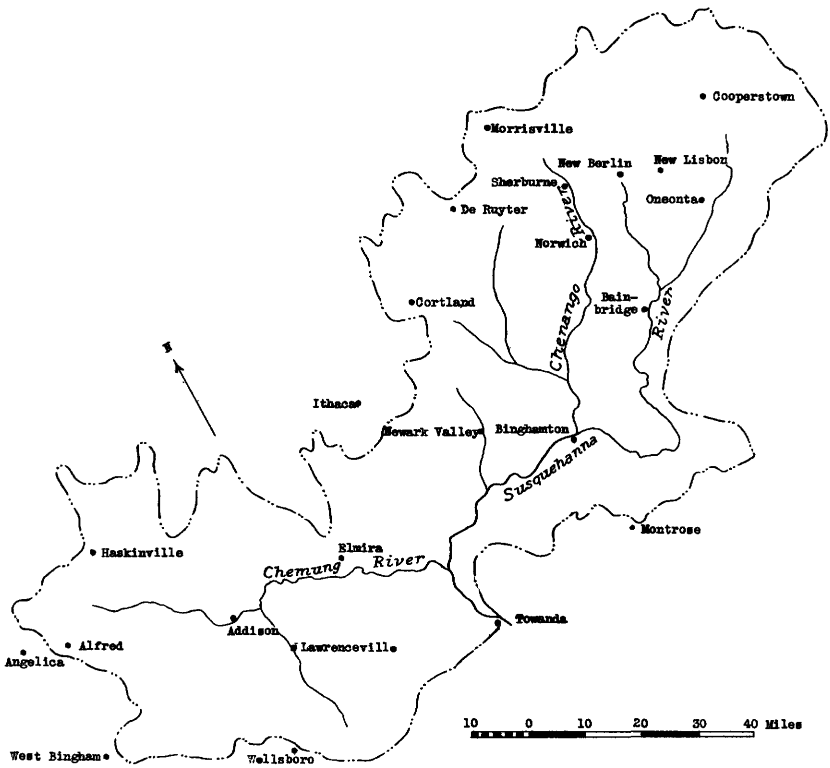

Figure 51.—Susquehanna River Basin above Towanda, Pa.
Drainage area 7,770 square miles

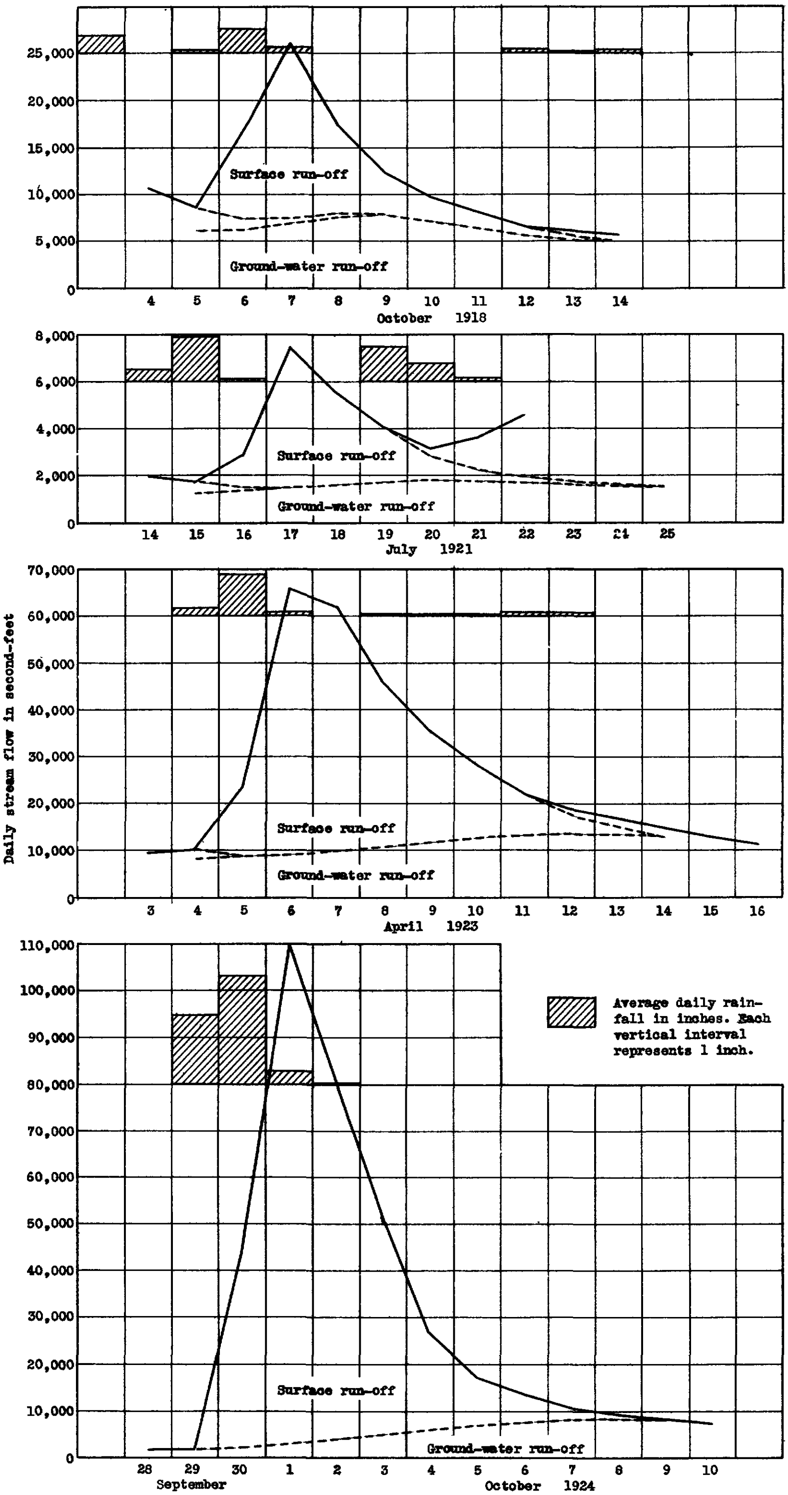

Figure 52.—Unit hydrographs for Susquehanna River at Towanda, Pa.

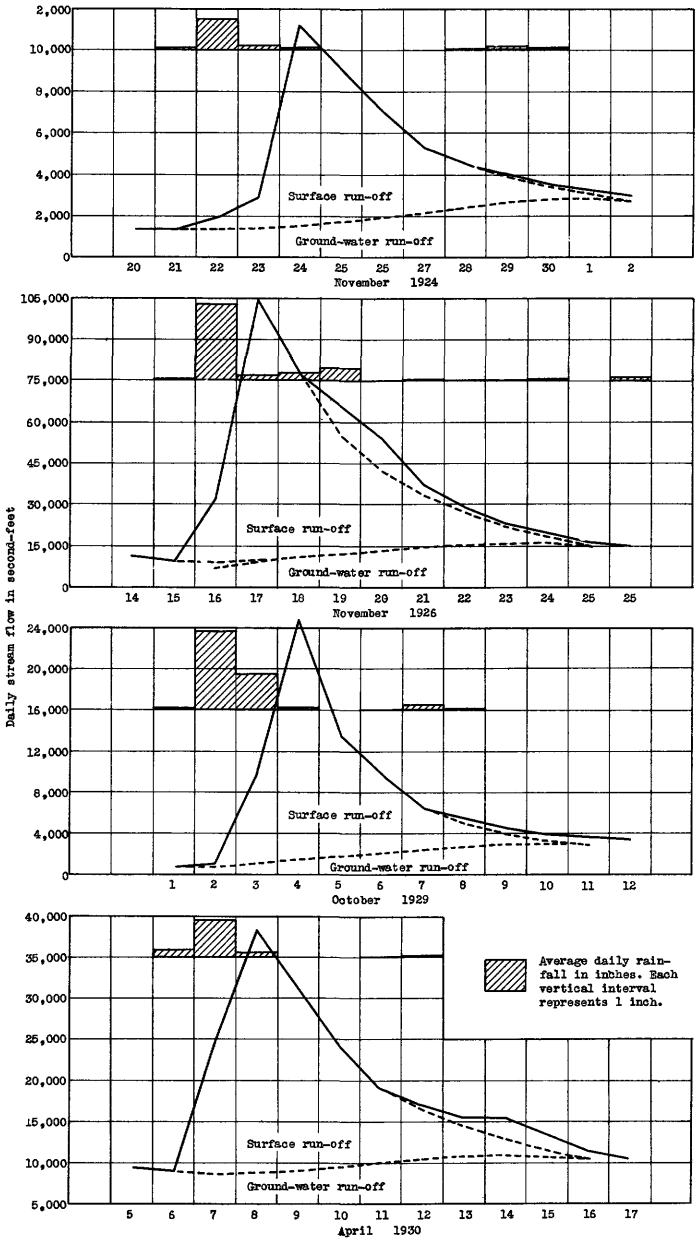

Figure 53.—Unit hydrographs for Susquehanna River at Towanda, Pa.

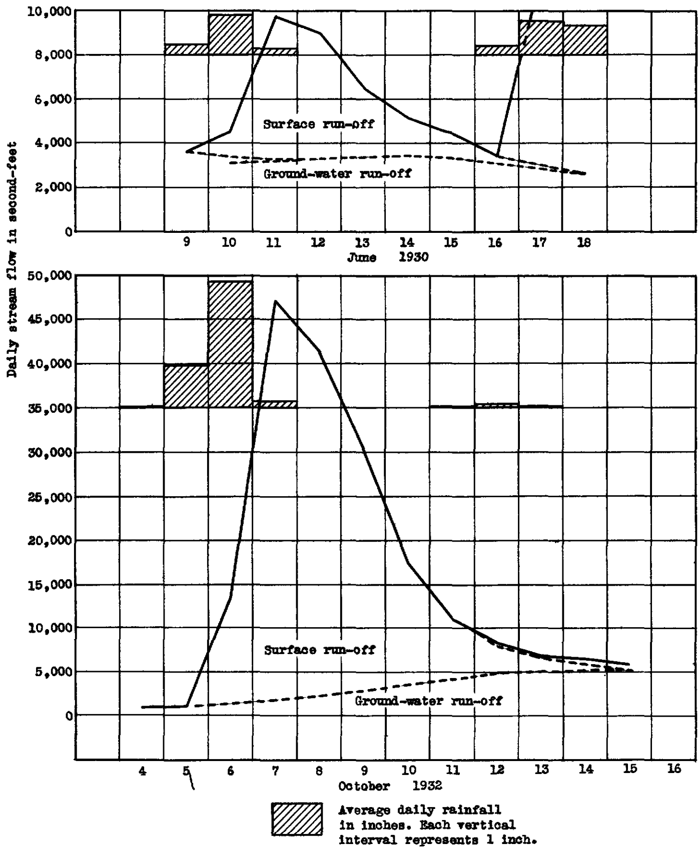

Figure 54.—Unit hydrographs for Susquehanna River at Towanda, Pa.

Table 42.- Surface run-off from unit storms, Susquehanna River at Towanda, Pa.

Storm	Average of precipitation at stations (inches)	Surface run-off (inches)	Ratio of surface run-off to average precipitation
Oct. 6, 1918	0.73	0.22	0.30
July 15, 1921	1.30	.07	.05
Apr. 5, 1923	1.15	* 1.02	.89
Sept. 30, 1924	4.11	1.50	.36
Nov. 22, 1924	.93	.15	.16
Nov. 16, 1926	2.06	* 1.42	.69
Oct. 2, 1929	2.86	.29	.10
Apr. 7, 1930	1.21	.50	.41
June 10, 1930	1.30	.09	.07
Oct. 6, 1932	4.00	.71	.18

Table 43 gives the daily percentages for the 10 distribution graphs, and figure 55 shows the graphs superimposed. The average distribution graph determined for the basin is 12, 33, 24, 15, 8, 4, 2, 1, 1 percent. The first figure of each distribution graph is the percentage of surface run-off for the calendar day on which most of the rainfall occurred; other figures for succeeding days.

Table 43.- Distribution graphs for storms in Susquehanna River Basin above Towanda, Pa.

Oct. 6, 1918	20.1	39.1	19.8	9.6	5.2	3.6	1.9	0.7	-	-
July 15, 1921	0	8.8	38.9	25.5	15.0	6.5	2.9	1.4	0.6	0.4
Apr. 5, 1923	6.8	26.8	24.7	16.6	11.1	7.3	4.1	1.9	.7	-
Sept. 30, 1924	13.8	34.2	24.6	14.8	6.5	3.2	1.9	.8	.2	-
Nov. 22, 1924	1.6	4.6	30.8	23.3	16.4	10.0	6.8	3.9	1.9	.7
Nov. 16, 1926	7.8	32.1	22.5	14.5	9.7	6.4	4.0	2.1	.9	-
Oct. 2, 1929	.6	17.1	38.3	19.3	12.4	6.5	3.6	1.7	.5	-
Apr. 7, 1930	15.5	28.5	21.3	14.1	8.7	5.8	3.5	1.9	.7	-
June 10, 1930	4.5	33.8	29.8	16.2	8.7	4.7	1.6	.7	-	-
Oct. 6, 1932	7.8	30.5	26.1	18.4	9.3	4.6	2.1	.9	.3	-

Delaware River Basin above Port Jervis, N. Y.

The headwaters of the Delaware River lie in Delaware, Greene, and Schoharie Counties, N. Y. The east branch rises at Grand Gorge, in northeastern Delaware County. The west branch has its source in a small lake near the Schoharie and Delaware County line at an altitude of about 1,886 feet. The two branches flow in a southwesterly direction, and the main stream below their junction flows southeast. The drainage area above Port Jervis is 3,070 square miles, the length about 75 miles (river distance

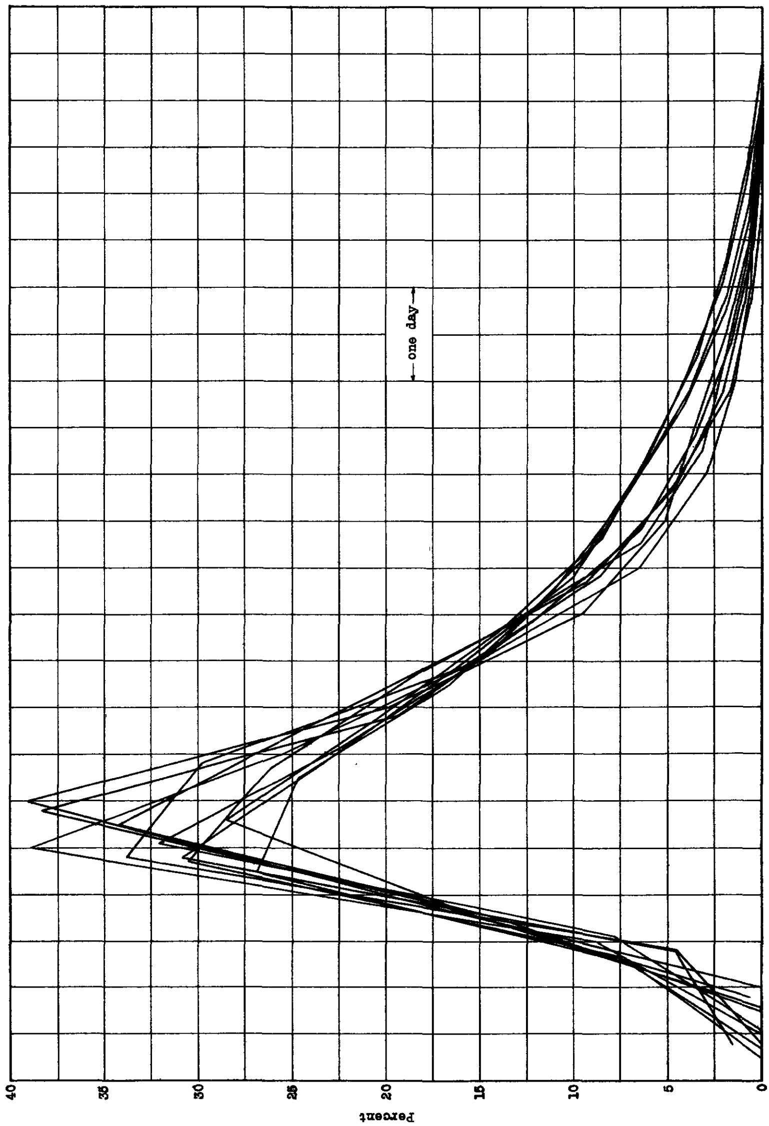

Figure 55.—Superimposed distribution graphs for Susquehanna River Basin above Towanda, Pa.

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140 miles), and the average width about 41 miles. The Mongaup and Lackawaxen Rivers drain the principal subbasins. The gradient of the east and west branches above the junction is about 8 feet to the mile. From Hancock (the junction point) to Port Jervis (75 miles) the average gradient is about 6 feet to the mile.

The original gage, on the toll bridge at Port Jervis, was a chain established by the United States Weather Bureau in October 1904 for the purpose of flood predictions. The gage heights were supplied to the United States Geological Survey for determination of daily discharge.

A vertical and inclined staff gage was installed in June 1914. An automatic recorder was established in August 1928, about 350 feet below the bridge. The zero of the gage is 415.6 feet above mean sea level.

Records are available since October 1904 and are considered good. There are large diurnal fluctuations at medium and low stages, owing to the operation of power plants on tributary streams (12,200,000,000 cubic feet of storage in 1930).

Eight or nine Weather Bureau stations are normally available for the determination of daily precipitation. These stations and the principal drainage are shown in figure 56.

Table 44 gives the daily precipitation recorded at the Weather Bureau stations for the storms that produced the unit hydrographs shown in figures 57, 58, and 59.

Table 44.- Storms considered in connection with unit hydrographs for the Delaware River Basin above Port Jervis, N. Y.

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	October 1917				October 1918				
	28	29	30	31	5	6	7	12	13
New York:									
Bainbridge *	0.42	0.24	1.30	0.57	-	1.05	0.19	-	0.09
Beerston	.68	.30	3.11	-	-	1.42	-	-	-
Jeffersonville	-	.11	1.70	-	-	1.29	-	0.42	.04
Oneonta	-	-	-	-	-	.19	-	-	.09
Port Jervis	.33	.02	1.59	-	-	.54	.14	.09	-
Roxbury	.50	.23	2.40	-	-	1.31	-	.22	.10

Station at Beerston was moved to Walton after October 10, 1918.

Table 44.- Storms considered in connection with unit hydrographs for the Delaware River Basin above Port Jervis, N. Y.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	October 1917				October 1918				
	28	29	30	31	5	6	7	12	13
Pennsylvania:									
Gouldsboro *	0.47	-	1.80	0.60	-	-	-	-	-
Honesdale	.45	-	2.10	-	-	-	-	0.25	-
Scranton **	-	0.05	2.12	-	0.23	0.79	0.11	-	-
	2.85	.95	16.12	1.17	.23	6.59	.44	.98	0.32
Average	.36	.12	2.02	.15	.03	.82	.06	.12	.04

Station	June 1922						April - May 1923			
	2	3	4	5	6	7	28	29	30	1
New York:										
Bainbridge *	0.06	1.00	1.24	-	0.18	0.06	0.30	0.86	-	-
Jeffersonville	.60	1.20	-	0.40	-	-	.55	.88	0.06	-
Oneonta	.48	1.81	-	.18	-	-	1.52	.32	.11	-
Port Jervis	.48	1.34	-	1.03	.12	.03	.49	.52	-	-
Roxbury	.13	1.70	-	.42	.02	-	2.20	.50	-	0.08
Walton	.43	2.41	-	.55	.14	-	1.28	1.04	.16	-
Pennsylvania:										
Gouldsboro *	.26	1.04	1.42	-	.24	-	-	.69	-	.18
Hawley *	-	-	-	-	-	-	-	.87	-	.19
Scranton **	.41	1.80	-	.42	.03	-	1.75	.07	.14	-
	2.85	12.30	2.66	3.00	.73	.09	8.09	5.75	.47	.45
Average	.36	1.54	.33	.37	.09	.01	.90	.64	.05	.05

Station	September - October 1924				
	29	30	1	7	8
New York:					
Bainbridge *	0.14	2.68	1.44	-	0.26
Delhi	.30	4.28	.28	0.07	.07
Jeffersonville	.60	3.80	-	.10	-
Oneonta	.75	3.52	-	.06	-
Port Jervis	1.02	4.33	-	.10	.17
Roxbury	.23	3.30	.25	.03	.11
Pennsylvania:					
Gouldeboro *	.22	4.15	1.72	-	.20
Hawley *	-	2.54	2.22	-	.08
Scranton **	2.00	3.33	-	.08	-
	5.26	31.93	5.91	.44	.89
Average	.58	3.55	.66	.05	.05

Table 44.- Storms considered in connection with unit hydrographs for the Delaware River Basin above Port Jervis, N. Y.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	October 1926						
	5	6	7	10	11	13	14
New York:							
Bainbridge *	0.40	2.00	0.10	-	-	-	-
Delhi	-	2.23	.05	-	-	0.45	-
Jeffersonville	-	1.53	.03	0.10	-	.18	-
Oneonta	.58	1.28	-	.44	-	.40	-
Port Jervis	-	2.00	-	.05	-	.03	-
Roxbury	.03	1.70	.11	.35	-	.30	-
Pennsylvania:							
Gouldsboro *	-	1.35	-	.19	.38	-	.15
Hawley *	-	.93	.03	-	.28	-	.16
Scranton **	.33	.67	.07	.30	-	.13	-
Average	1.34 .15	13.69 1.52	.39 .04	1.43 .16	.66 .07	1.49 .17	.31 .03

Station	October 1927			October 1927				
	3	4	8	12	13	17	18	19
New York:								
Bainbridge *	-	1.70	-	-	1.50	0.40	1.50	1.20
Delhi	-	2.37	0.41	-	.55	.75	.58	1.10
Jeffersonville	-	2.77	.22	-	1.80	.72	1.25	1.69
Oneonta	0.13	1.74	-	-	1.69	.56	1.06	1.41
Port Jervis	1.00	-	.15	1.98	-	1.43	1.70	.10
Roxbury	-	2.85	.37	-	1.66	.36	.78	1.22
Pennsylvania:								
Gouldsboro *	-	2.60	.42	-	2.18	.20	1.60	1.68
Hawley *	-	2.82	.41	-	1.78	.39	.96	2.32
Scranton **	2.60	.29	.34	1.58	.14	.91	1.85	1.11
Average	3.73 .41	17.14 1.90	2.32 .26	3.56 .40	11.30 1.26	5.72 .64	11.28 1.25	11.83 1.31

Station	September 1933					
	3	4	6	7	10	14
New York:						
Bainbridge *	-	0.93	-	0.04	-	1.12
Delhi	0.17	1.44	0.38	.12	-	1.12
Jeffersonville	.80	1.50	-	-	-	.40
Oneonta	.13	.44	.58	.14	-	.85
Port Jervis	.25	1.78	-	.11	0.17	.82
Roxbury	.35	1.22	.74	.25	.03	.88

Table 44.- Storms considered in connection with unit hydrographs for the Delaware River Basin above Port Jervis, N. Y.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	September 1933					
	3	4	6	7	10	14
Pennsylvania:						
Gouldsboro *	0.02	2.51	-	-	0.45	-
Hawley *	.12	2.84	-	-	.36	0.14
Scranton **	.90	.59	-	-	-	1.51
	2.74	13.25	1.70	0.66	1.01	6.84
Average	.30	1.47	.19	.07	.11	.76

Table 45 gives the surface run-off from the unit storms and the approximate precipitation that caused the run-off.

Table 45.- Surface run-off from unit storms in Delaware River Basin above Port Jervis, N. Y.

Storm	Average of precipitation at stations (inches)	Surface run-off (inches)	Ratio of surface run-off to average precipitation
Oct. 30, 1917	2.29	1.34	0.58
Oct. 6, 1918	.91	.28	.31
June 3, 1922	2.23	.80	.36
Apr. 29, 1923	1.54	.56	.36
Sept. 30, 1924	4.79	2.01	.42
Oct. 6, 1926	1.71	.29	.17
Oct. 4, 1927	2.31	.31	.13
Oct. 13, 1927	1.66	.50	.30
Sept. 4, 1933	1.77	.52	.29

Table 46 gives the daily percentages for the nine distribution graphs, and figure 60 shows the graphs superimposed. The average distribution graph determined for the basin is 6, 43, 24, 13, 7, 4, 2, 1 percent. The first figure of each distribution graph is the percentage of surface run-off for the calendar day on which most of the rainfall occurred; other figures for succeeding days.

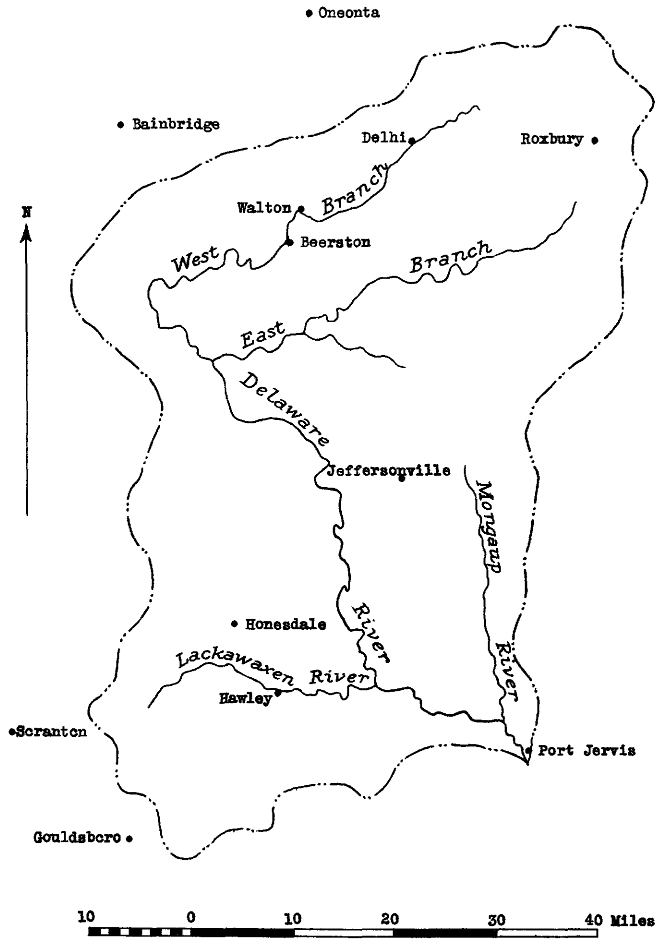

Figure 56.—Delaware River Basin above Port Jervis, N.Y.
Drainage area 3,070 square miles

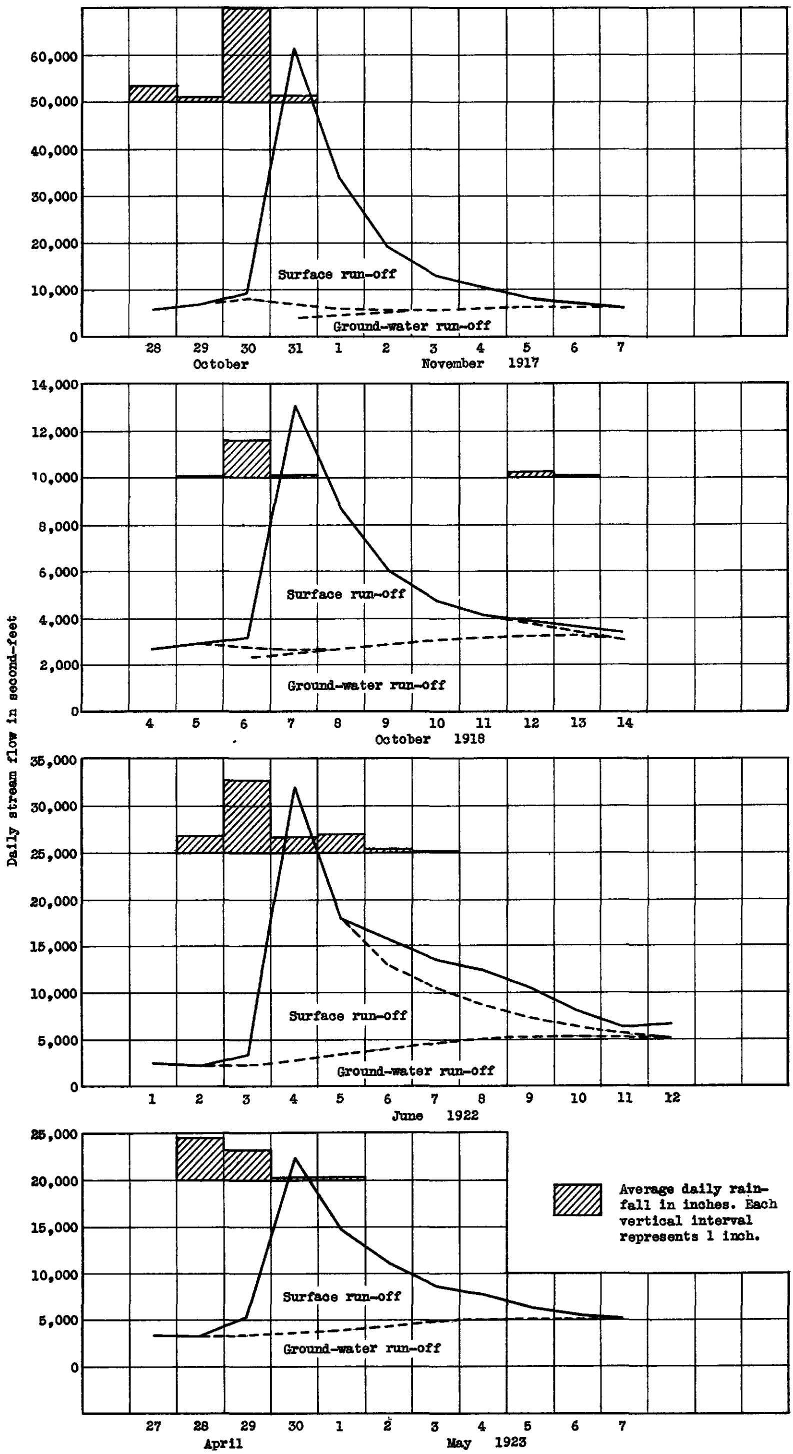

Figure 57.--Unit hydrographs for Delaware River at Port Jervis, N.Y.

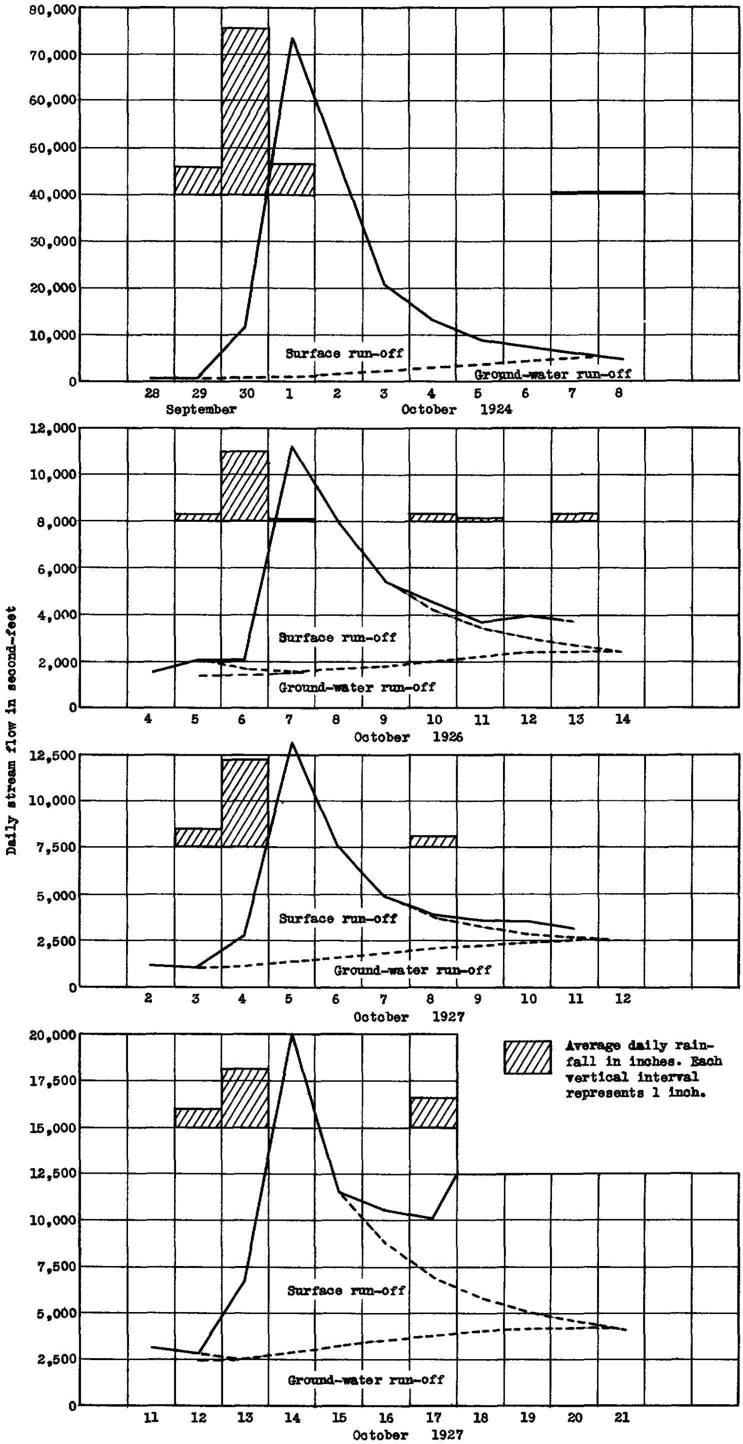

Figure 58.—Unit hydrographs for Delaware River at Port Jervis, N.Y.

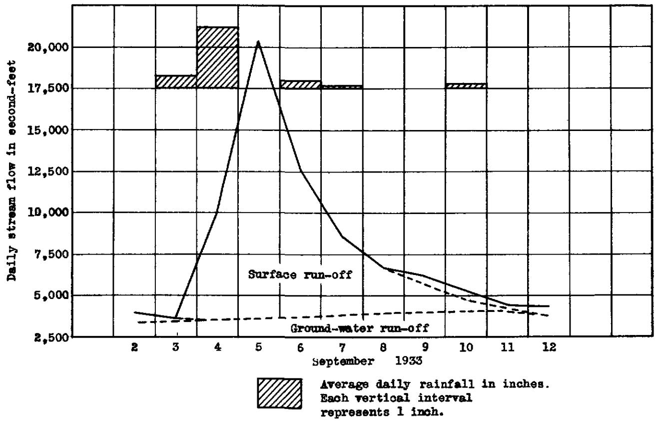

Figure 59.—Unit hydrographs for Delaware River at Port Jervis, N.Y.

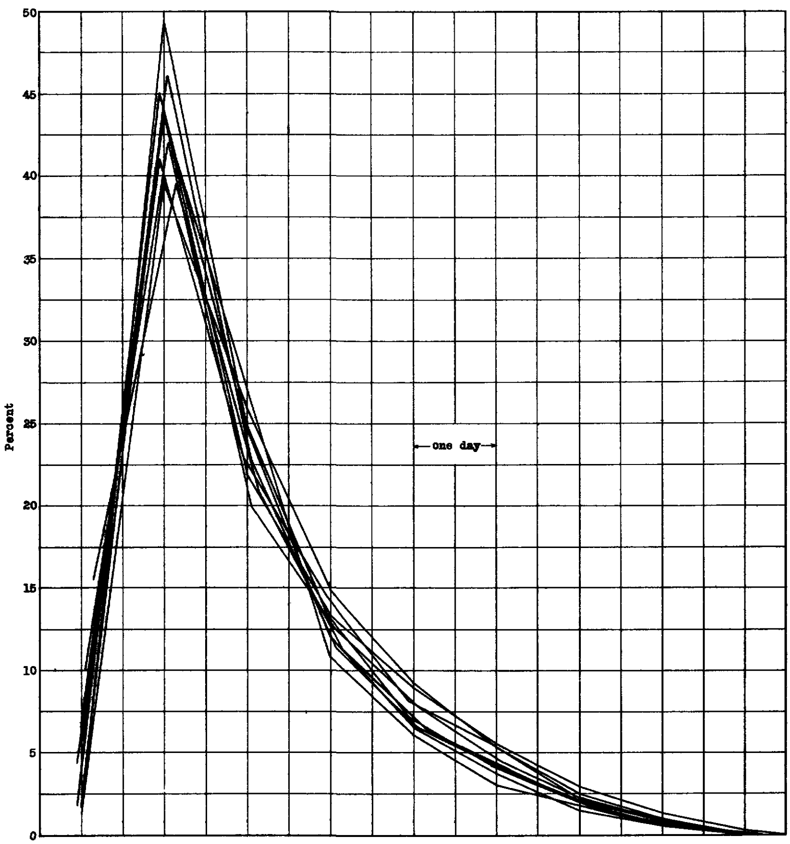

Figure 60.—Superimposed distribution graphs for Delaware River Basin above Port Jervis, N.Y.

Table 46.- Distribution graphs for storms in Delaware River Basin above Port Jervis, N. Y.

Oct. 30, 1917	1.0	49.4	24.7	12.2	6.7	3.8	1.6	0.6	-
Oct. 6, 1918	1.8	45.0	25.5	13.5	7.2	4.2	2.1	.7	-
June 3, 1922	1.7	43.8	21.9	13.4	9.0	5.6	3.0	1.3	0.3
Apr. 29, 1923	4.4	41.0	23.0	14.6	8.1	5.6	2.4	.9	-
Sept. 30, 1924	6.6	43.7	27.2	10.9	6.1	3.1	1.8	.6	-
Oct. 6, 1926	1.4	39.6	25.9	14.9	9.3	5.4	2.5	1.0	-
Oct. 4, 1927	6.1	46.1	22.8	11.5	6.6	4.1	2.0	.8	-
Oct. 13, 1927	10.0	42.0	20.0	12.7	7.8	4.4	2.2	.9	-
Sept. 4, 1933	15.5	39.5	20.9	11.3	6.5	4.0	1.7	.6	-

The individual distribution graphs for the Delaware Basin when superimposed form a more uniform and compact plot than those for any of the other basins studied, although the Delaware is the most rapidly concentrating stream and its distribution graph has the highest peaks of the group studied.

French Broad River Basin above Dandridge, Tenn.

The French Broad River rises in the Blue Ridge in Transylvania County, N. C., near the South Carolina boundary. It first flows in a northerly direction, then northwesterly to the Tennessee Valley, where it turns southwest.

The drainage area above Dandridge is 4,450 square miles, and the length of the river is about 150 miles. The Nolichucky and Pigeon Rivers drain the principal subbasins. The upper 50 miles of the French Broad has an average slope of 3 feet to the mile, the next 50 miles 16 feet to the mile, and the 50 miles above Dandridge 5 feet to the mile. The zero of the gage is 902.8 feet above mean sea level. About 2,800 square miles of the area drained is in North Carolina and consists of high mountainous country with several peaks above an altitude of 5,000 feet. About 50 percent of the area is forest, and the remainder is equally divided between crop and pasture.

The United States Geological Survey has published daily discharges at this station since October 1918. The United States Weather Bureau has obtained gage heights since December 1904. The gage that was used when the Geological Survey records began was painted (1.9 to 35.0 feet) in feet and tenths on the shoreward side of the second concrete pier of the highway bridge. As the gage was difficult to read from the bank, a rowboat was generally used in making a reading once daily. The records are considered fair up to 25,000 second-feet and poor above. A new gage was installed in October 1923 on the right bank; the lower part is a sloping section, and the upper part is a vertical staff gage bolted to the right-bank pier. This gage was set to a datum 0.04 foot lower than the Weather Bureau gage. The records are considered good below 30,000 second-feet and fair above.

A water-stage recorder was installed and has been in use since October 1931. Diurnal fluctuation during low stages is caused by regulation upstream.

The records of daily stream flow are considered poor for the development of any theory connected with the unit hydrograph.

The daily precipitation was obtained by taking the average of 12 to 15 well distributed stations in or adjacent to the basin. The stations and principal drainage are shown on figure 61.

Table 47 gives the daily precipitation recorded at the Weather Bureau stations for the storms producing the unit hydrographs shown in figures 62, 63, and 64.

Table 47.- Storms considered in connection with unit hydrographs for French Broad River Basin above Dandridge, Tenn.

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	August 1921					
	3	4	5	6	7	8
North Carolina:						
Altapass	1.65	0.40	-	-	0.10	-
Asheville **	.51	.41	0.01	-	.49	-
Banners Elk	2.60	.05	-	-	.60	-
Brevard	-	.04	.75	-	.20	-
Cullowhee	1.50	.03	2.10	-	.40	0.05
Hendersonville	-	.50	.43	-	1.50	.10
Hot Springs	1.56	-	-	0.03	.88	.13
Marshall	1.85	.43	-	-	.35	-
Montreat	.70	.06	.02	-	.23	-
Waynesville	-	-	-	-	-	-
Tennessee:						
Dandridge *	.36	.34	.11	.19	-	.24
Greeneville *	.60	1.00	-	-	.72	.26
Newport *	.05	.22	-	-	-	.45
Rogersville *	.12	.29	.04	.16	-	.34
	11.50	3.77	3.46	.38	5.47	1.57
Average	.88	.29	.27	.03	.42	.12

Table 47.- Storms considered in connection with unit hydrographs for French Broad River Basin above Dandridge, Tenn.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	April 1922							
	5	6	10	11	12	13	14	15
North Carolina:								
Altapass	-	1.30	-	-	-	-	-	-
Asheville **	0.57	.67	-	0.26	-	-	-	0.19
Banners Elk	.10	.36	-	.20	-	0.10	-	.41
Brevard	.24	1.56	-	.32	-	-	-	-
Cullowhee	.05	.80	-	.25	-	-	-	.10
Hendersonville	.50	1.51	-	-	0.20	-	-	.16
Hot Springs	.11	.34	-	.30	-	.09	-	.74
Marshall	.12	.70	-	.22	-	-	-	.17
Montreat	.19	1.33	-	.33	-	-	-	.14
Waynesville	.25	.88	0.23	-	-	-	0.17	-
Tennessee:								
Dandridge *	-	.36	-	.14	.07	-	-	.30
Greeneville *	-	.30	-	-	.28	-	-	.17
Newport *	-	.26	-	.10	.16	-	-	.65
Rogersville *	-	.83	.04	.24	.04	-	-	.10
Average	2.13 .15	11.20 .80	.27 .02	2.36 .17	.75 .05	.19 .01	.17 .01	3.13 .22

Station	September 1923						April 1924				
	20	21	22	23	24	25	17	18	19	22	26
North Carolina:											
Altapass	-	0.85	-	1.25	1.10	0.20	0.20	1.00	-	-	0.45
Asheville **	-	.55	-	-	-	-	.41	.45	-	-	.35
Banners Elk	-	.45	-	-	-	-	-	.20	0.30	-	.70
Brevard	-	-	-	-	-	-	-	2.25	-	-	.05
Hendersonville	0.04	4.30	0.04	.24	-	-	.40	1.80	-	-	.10
Hot Springs	.02	.70	-	-	-	-	.12	.52	-	-	.33
Marshall	-	.07	-	.23	-	-	.30	.57	-	-	.35
Montreat	-	1.98	-	-	.18	.20	.13	.90	-	-	.26
Mount Mitchell	-	1.10	.60	-	1.13	1.20	1.57	-	-	-	.55
Waynesville	-	.12	-	-	.01	.19	.10	1.00	-	-	.10
Tennessee:											
Dandridge *	-	.62	-	.05	-	-	-	1.64	.12	0.05	.49
Elizabethton *	-	1.30	-	-	-	-	-	.40	.59	.13	.27
Newport *	-	.78	-	.42	-	-	-	1.15	.15	.09	.48
Rogersville *	-	.33	-	-	-	-	-	1.47	.09	.02	.25
Average	.06 -	13.15 1.01	.64 .05	2.19 .17	2.42 .19	1.79 .14	3.23 .23	13.35 .95	1.25 .09	.29 .02	4.73 .34

Table 47.- Storms considered in connection with unit hydrographs for French Broad River Basin above Dandridge, Tenn.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	October 1927					April - May 1928			
	11	12	13	18	19	27	28	30	1
North Carolina:									
Asheville **	0.20	1.98	-	-	-	0.97	0.20	0.39	0.02
Banners Elk	-	1.76	-	-	-	1.00	.05	-	-
Brevard	-	2.50	-	-	-	1.25	-	-	-
Hendersonville	-	2.08	0.02	-	-	1.34	-	-	.49
Hot Springs *	-	.21	.55	-	-	1.05	.52	-	.30
Linville Falls	-	3.93	-	-	-	.91	.88	-	.08
Marshall *	-	1.05	-	-	-	.70	-	.25	.35
Montreat *	1.02	1.08	-	-	-	.90	.15	-	.52
Mount Mitchell	-	2.10	-	0.10	0.30	1.40	1.10	-	.52
Waynesville	.45	1.15	-	-	-	.25	.85	-	-
Tennessee:									
Dandridge *	-	.23	.67	-	-	.27	.68	-	.11
Embreeville *	-	.10	.63	-	.19	.22	1.03	-	.03
Newport *	-	.23	-	-	.32	.04	1.24	-	.14
Rogersville *	-	.26	.35	-	-	.22	.64	-	.07
	1.67	18.66	2.22	.10	.81	10.52	7.34	.64	2.63
Average	.12	1.33	.15	.01	.06	.75	.52	.05	.19

Station	April - May 1931							
	21	22	23	25	26	27	1	2
North Carolina:								
Altapass	-	1.96	-	-	0.05	-	0.10	-
Asheville **	0.17	1.74	-	-	.14	-	.13	0.03
Banners Elk	1.80	.94	-	-	.30	-	-	-
Hendersonville	.32	1.74	-	0.04	.02	-	.15	.22
Hot Springs	-	1.37	-	-	.48		.10	-
Marshall *	-	1.35	0.10	-	-	0.15	-	.10
Montreat *	.07	2.05	-	.06	.16	-	-	.14
Mount Mitchell	.77	2.25	-	-	.30	-	.37	-
Waynesville	.04	2.32	-	.05	.46	-	.30	.02
Tennessee:								
Dandridge *	-	1.28	-	.16	.72	.08	.03	.04
Embreeville *	-	.98	-	.08	.28	-	-	.12
Newport *	-	1.10	.06	.10	.67	.06	.03	.06
Rogersville *	-	1.10	.05	.12	.45	.01	-	.11
	3.17	20.18	.21	.61	4.03	.30	1.21	.84
Average	.24	1.55	.02	.05	.31	.02	.09	.06

Table 47.- Storms considered in connection with unit hydrographs for French Broad River Basin above Dandridge, Tenn.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning, and stations marked **, where it was measured at midnight.)

Station	September 1931			April - May 1932				
	2	3	4	30	1	8	9	10
North Carolina:								
Altapass	0.62	0.90	-	0.10	2.55	0.05	0.15	0.95
Asheville **	.13	.90	-	1.32	.04	-	.20	-
Banners Elk	-	2.21	-	2.42	-	.25	.64	.70
Hendersonville	.19	.30	-	.59	1.31	.07	.02	.71
Hot Springs	.03	2.15	-	.32	.90	.08	.03	.19
Marshall *	-	.71	0.69	-	1.55	-	.05	.25
Montreat *	-	1.10	.02	1.92	-	-	.03	.40
Mount Mitchell	.45	1.20	-	1.05	2.50	.11	.15	.56
Waynesville	.20	.60	-	.02	1.14	-	.03	.10
Tennessee:								
Dandridge *	-	1.19	-	.09	1.49	-	.67	.35
Embreeville *	-	1.42	.38	-	1.65	-	.30	1.04
Newport *	-	.84	.28	-	1.45	-	.22	.16
Rogersville *	-	1.42	.01	.08	1.23	-	.44	.50
	1.62	14.94	1.38	7.91	15.81	.56	2.93	5.91
Average	.12	1.15	.11	.61	1.22	.04	.23	.45

Table 48 gives the surface run-off from the unit storms and the approximate precipitation that caused the run-off.

Table 48.- Surface run-off from unit storms in French Broad River Basin above Dandridge, Tenn.

Storm	Average of precipitation at stations (inches)	Surface run-off (inches)	Ratio of surface run-off to average precipitation
Aug. 3, 1921	1.44	0.57	0.40
Apr. 6, 1922	.95	.26	.27
Sept. 21, 1923	1.06	.14	.13
Apr. 18, 1924	1.27	.50	.39
Oct. 12, 1927	1.60	.13	.12
Apr. 27, 1928	1.27	.45	.35
Apr. 22, 1931	1.81	.49	.27
Sept. 3, 1931	1.38	.27	.20
Apr. 30, 1932	1.83	.56	.31

Table 49 gives the daily percentages for the nine distribution graphs, and figure 65 shows the graphs superimposed. The average distribution graph determined for the basin is 3, 29, 25, 15, 9, 7, 5, 3, 2, 1, 1 percent. The first figure of each distribution graph is the percentage

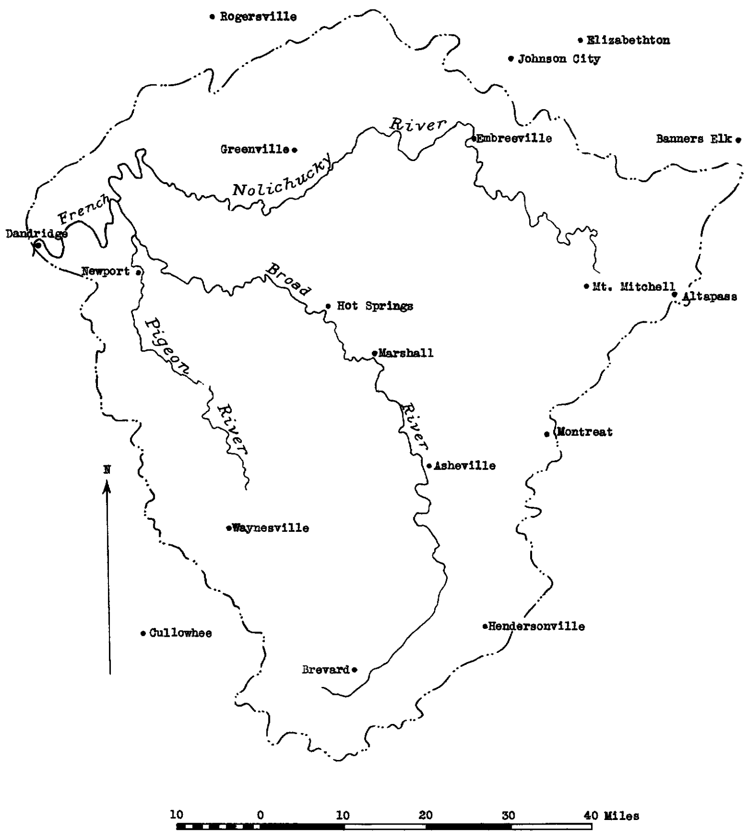

Figure 61.—French Broad River Basin above Dandridge, Tenn.
Drainage area 4,450 square miles

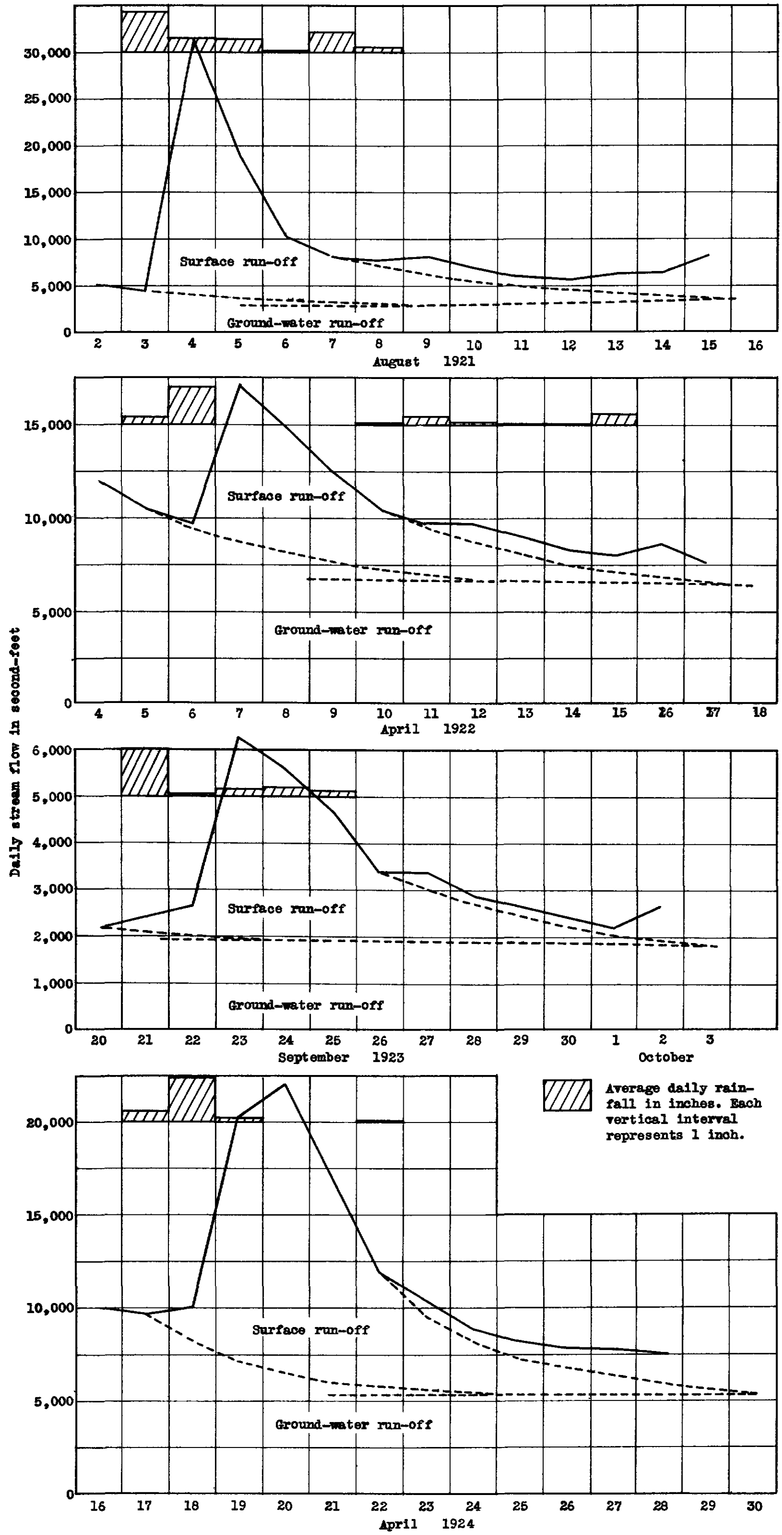

Figure 62.—Unit hydrographs for French Broad River at Dandridge, Tenn.

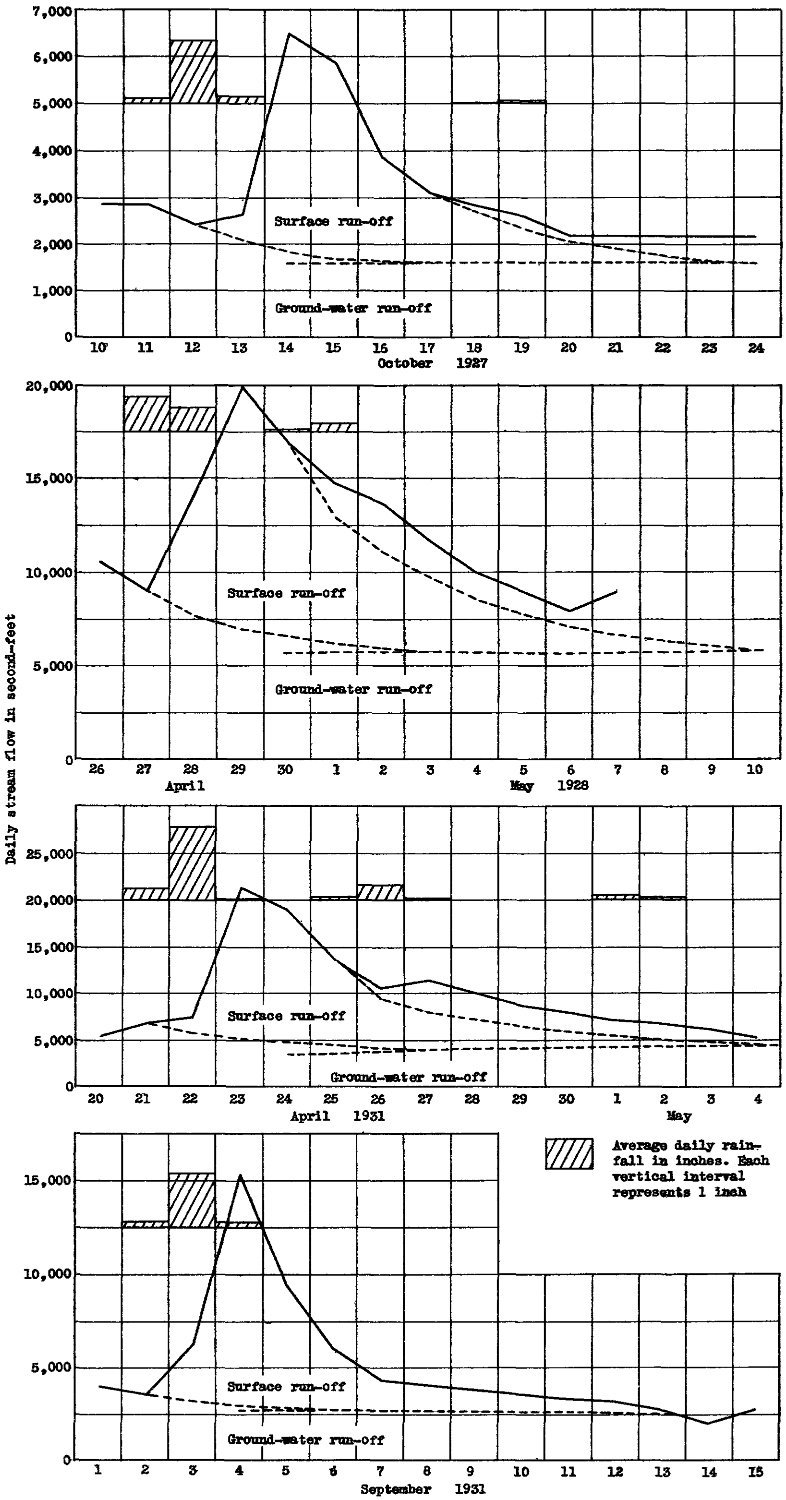

Figure 63.—Unit hydrographs for French Broad River at Dandridge, Tenn.

5955 O—35——13

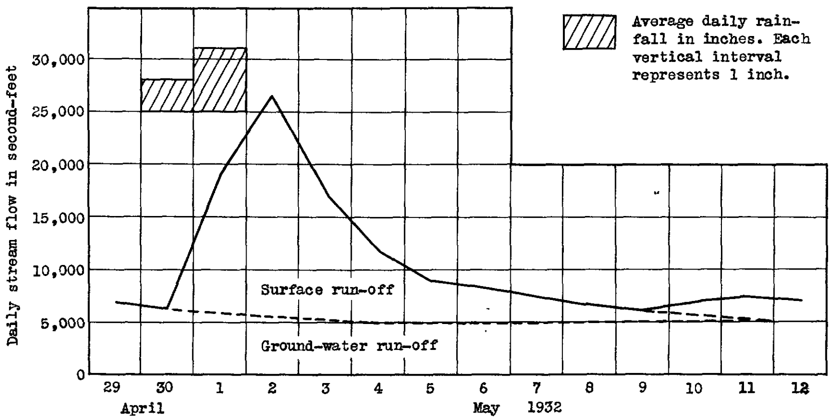

Figure 64.—Unit hydrographs for French Broad River at Dandridge, Tenn.

Figure 65.—Superimposed distribution graphs for French Broad River Basin above Dandridge, Tenn.

of surface run-off for the calendar day on which most of the rainfall occurred; other figures for succeeding days.

Table 49.- Distribution graphs for storms in French Broad River Basin above Dandridge, Tenn.

Aug. 3, 1921	0	40.0	22.2	9.8	7.1	5.7	4.7	3.5	2.7	2.0	1.3	0.7	0.3
Apr. 6, 1922	1.0	26.8	21.6	15.1	10.3	7.8	6.5	4.5	2.7	1.9	1.3	0.5	-
Sept. 21, 1923	1.9	3.8	26.0	22.4	17.1	9.1	6.9	5.1	3.7	2.3	1.1	0.6	-
Apr. 18, 1924	3.0	21.9	26.2	18.5	10.3	6.7	4.6	3.2	2.4	1.7	1.0	0.5	-
Oct. 12, 1927	0	3.3	29.3	26.4	14.0	9.6	6.9	4.6	2.9	1.8	0.9	0.3	-
Apr. 27, 1928	0	11.8	24.1	19.2	12.6	9.6	7.4	5.3	3.9	2.7	1.8	1.2	0.4
Apr. 22, 1931	2.8	27.3	23.8	15.5	8.9	6.5	5.0	3.5	2.6	1.9	1.2	0.7	0.3
Sept. 3, 1931	9.5	39.1	20.7	10.0	4.9	4.2	3.5	2.9	2.3	2.1	0.8	-	-
Apr. 30, 1932	0	19.1	31.0	18.5	10.1	6.2	5.1	3.9	2.5	1.8	1.2	0.6	-

Red River Basin above Denison, Tex.

The Red River heads in eastern New Mexico at an altitude of nearly 5,000 feet and flows a little south of east across the panhandle of Texas, below which it forms the boundary between Oklahoma and Texas, draining areas in both States, but mainly from the north. The drainage area above Denison is 39,400 square miles. The length of the river is roughly 550 miles; the length of the basin is about 400 miles, and the average width about 100 miles. The country is mainly rolling and hilly with some mountainous areas.

The gaging station at Denison was established in October 1923. A standard chain gage was attached to the downstream handrail of the highway bridge 4½ miles northeast of Denison and is read twice daily to hundredths. The control is shifting, and the stage-discharge relation is subject to change. On October 1, 1931, the gage datum was raised 0.22 foot owing to shortening of chain. The records are considered fair, and there are no diversions.

Normally about 35 Weather Bureau stations are available for determining daily precipitation records. These stations are shown in figure 66.

Table 50 gives the daily precipitation recorded at the Weather Bureau stations for the storms producing the unit hydrographs shown in figures 67 and 68.

Figure 66.—Red River Basin above Denison, Tex.
Drainage area 39,400 square miles

Table 50.- Storms considered in connection with unit hydrographs for Red River Basin above Denison, Tex.

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	December 1923							
	10	11	12	13	18	19	21	22
Texas:								
Canyon	0.58	0.17	-	-	0.10	-	0.06	0.04
Chillicothe *	.10	.28	0.59	-	-	0.04	-	-
Clarendon	.10	.25	-	-	.05	-	-	-
Claude	-	.40	-	-	-	-	-	-
Dimmitt	-	.63	-	-	.11	-	-	-
Dundee	.57	.45	.21	-	.01	-	.05	-
Memphis	.06	.15	-	-	.08	-	.08	-
Paducah *	.37	.40	-	-	-	-	.04	-
Plainview	.30	.10	-	-	.36	-	.06	-
Quanah *	-	.23	.27	-	-	-	-	-
Tulia	.48	-	-	-	.02	-	.15	-
Vega *	.49	.76	-	-	-	.06	-	.40
Denison *	.40	1.40	1.82	1.70	-	.38	.40	-
Henrietta *	-	.25	.40	.45	.10	.05	-	-
Sherman *	.70	1.70	1.40	1.59	.05	.37	.33	.36
Oklahoma:								
Ardmore	.14	1.47	1.76	-	-	.07	.03	.16
Chickasha	.10	.73	.82	.15	-	.05	-	-
Marlow	.62	.68	.75	-	.08	-	.05	-
Pauls Valley	.05	1.33	1.42	-	.03	.19	-	-
Ravia	.09	1.25	2.35	-	-	-	.33	.48
Altus	-	.41	.28	-	-	-	-	-
Apache	.29	.84	.36	-	.02	-	-	-
Arapaho	.20	.50	-	-	-	-	-	-
Carnegie	-	.90	.35	-	-	-	-	-
Cloud Chief	-	.42	.31	-	-	-	-	-
Erick	-	.43	.37	-	-	-	-	-
Frederick	.85	.43	-	-	-	.04	-	-
Hammon	-	.40	.18	-	-	.05	-	-
Hobart	-	.39	.27	-	-	.04	-	-
Hollis	-	-	.40	-	-	-	-	-
Lawton	.20	1.05	.50	-	.05	-	-	-
Mangum	-	.70	-	-	-	-	-	-
Walters	-	.31	.36	-	-	-	-	-
	6.69	19.41	15.15	3.89	1.06	1.34	1.58	1.44
Average	.20	.59	.46	.12	.03	.04	.05	.04

Table 50.- Storms considered in connection with unit hydrographs for Red River Basin above Denison, Tex.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	March 1926									
	20	21	22	25	26	27	28	29	30	31
Texas:										
Canyon	0.20	-	-	-	0.16	-	-	1.15	-	-
Childress	-	0.80	-	-	.25	-	-	1.10	-	-
Chillicothe *	-	.95	0.04	-	-	0.12	-	.10	0.30	0.10
Clarendon	.45	-	-	-	-	.13	0.60	.55	-	-
Claude	.52	-	-	-	-	-	-	.40	.60	-
Crowell	1.65	-	-	-	.10	-	-	.55	-	-
Dimmitt	-	.53	.02	-	.20	-	.04	.32	.40	-
Dundee	-	2.20	-	-	-	-	-	.80	-	-
Memphis	-	.55	.15	-	.08	-	.10	1.12	.06	-
Paducah *	.40	-	-	-	.10	.25	-	.35	.22	-
Plainview	-	.58	-	-	.60	-	-	1.25	.10	-
Quanah *	-	1.10	.10	-	.15	-	.60	.65	.15	-
Tulia	-	.47	.02	-	.26	.02	.49	.10	-	-
Vega *	-	.51	.04	-	.05	.10	-	.51	.49	-
Denison *	-	-	1.70	0.20	-	-	-	.30	.28	.54
Henrietta *	-	1.60	.40	.20	-	.05	-	.30	.10	-
Sherman *	-	1.55	.32	.33	-	.05	.02	.05	.40	.18
Oklahoma:										
Ardmore	-	1.14	.39	-	-	-	.14	-	.15	-
Chickasha	-	.74	.15	-	-	-	.08	.72	.14	.39
Marlow	-	1.65	-	-	-	-	-	.30	.10	-
Pauls Valley	-	1.50	.82	-	-	-	.02	.22	.33	.05
Altus	-	-	-	-	-	-	-	1.10	.20	-
Apache	-	.87	-	-	-	-	.05	.95	.43	-
Arapaho	.10	-	-	-	.20	.38	-	.25	.30	-
Carnegie	-	1.40	.10	-	-	-	.15	.60	.30	-
Cloud Chief	-	.85	.07	-	-	-	.10	.40	.40	-
Erick	-	.60	-	-	-	.19	-	.58	.10	.10
Frederick	-	1.73	.10	-	.08	-	-	.37	.50	-
Hammon	-	1.15	.20	-	-	-	.27	.40	.30	.05
Hobart	-	.73	.07	-	-	-	.12	.77	.40	-
Hollis	-	.90	.10	-	.06	-	.05	1.10	.09	-
Lawton	-	1.05	.05	-	-	-	.05	.44	.20	.12
Mangum	-	.81	.23	-	-	-	.10	1.10	.30	-
Walters	-	.81	-	-	-	-	-	.48	.12	-
Wichita National Forest	-	.90	-	-	.14	-	-	.75	.20	-
	3.32	27.67	5.07	.73	2.43	1.29	2.98	20.13	7.66	1.53
Average	.09	.79	.14	.04	.07	.03	.09	.58	.22	.04

Table 50.- Storms considered in connection with unit hydrographs for Red River Basin above Denison, Tex.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	March - April 1929								
	26	27	28	29	4	6	7	8	9
Texas:									
Canyon	1.65	0.35	-	-	-	-	-	-	-
Childress	-	1.35	3.30	-	-	-	-	-	-
Chillicothe *	.07	.94	1.28	0.04	-	-	-	-	-
Clarendon	.13	2.45	.40	-	0.25	-	-	-	-
Claude	-	1.47	.31	-	-	-	-	-	-
Crowell	.25	1.30	.80	-	-	-	-	-	-
Dimmitt	-	1.89	.32	-	.20	-	-	-	-
Dundee	-	-	1.25	-	-	-	0.32	0.24	-
Memphis	1.90	1.65	-	-	.05	-	-	-	-
Paducah *	1.50	1.85	-	-	-	-	-	-	-
Plainview	.04	3.21	.07	-	.10	-	-	-	-
Quanah *	-	1.20	1.90	-	.05	-	-	-	-
Vega *	-	1.15	.75	.04	.01	-	-	-	-
Denison *	-	-	-	.03	-	-	-	.03	0.04
Henrietta *	-	.80	.10	-	-	-	-	-	-
Sherman *	-	-	-	.27	-	0.02	-	.20	1.67
Oklahoma:									
Ardmore	-	.16	.41	-	-	.30	-	.13	.89
Chickasha	-	.57	4.79	-	-	-	1.36	.09	-
Marlow	-	.90	1.55	-	-	-	-	.07	-
Pauls Valley	-	.35	1.26	-	-	-	-	-	.49
Altus	1.51	1.80	-	-	-	-	-	-	-
Apache	.03	2.87	1.30	.02	-	-	1.37	.08	-
Arapaho	-	4.96	.04	-	.04	-	-	-	-
Carnegie	2.10	1.65	-	-	-	-	.27	-	-
Cloud Chief	2.12	3.10	-	-	-	-	-	-	-
Erick	-	3.14	.86	-	.01	-	-	-	-
Frederick	.29	.90	.66	-	-	-	-	-	.05
Hammon	-	2.20	1.35	-	-	-	-	-	-
Hobart	-	3.42	1.87	-	-	-	-	-	-
Hollis	.06	4.54	1.05	-	-	-	-	-	-
Lawton	-	.90	1.70	-	-	-	-	-	-
Mangum	-	1.40	3.50	-	-	-	-	-	-
Walters	-	.42	1.02	-	-	-	-	.17	.34
Wichita National Forest	.10	2.00	1.00	-	-	-	1.20	-	-
	11.75	54.89	32.84	.40	.71	.32	4.52	1.01	3.48
Average	.35	1.61	.97	.01	.02	.01	.13	.03	.10

Table 50.- Storms considered in connection with unit hydrographs for Red River Basin above Denison, Tex.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	June 1930					December 1930				
	13	14	15	16	26	3	4	5	9	10
Texas:										
Canyon	-	-	-	-	-	-	-	-	0.15	-
Childress	-	-	0.15	-	-	-	1.15	1.40	-	0.05
Chillicothe *	-	0.14	1.01	-	-	-	.55	1.69	-	.03
Clarendon	-	-	-	-	-	-	.75	-	.10	-
Claude	-	.25	-	-	-	-	.30	-	-	.27
Crowell	-	-	-	-	-	-	3.60	-	-	-
Dimmitt	-	-	.45	-	-	-	.32	-	-	.20
Dundee	-	2.95	-	-	0.86	-	1.15	-	-	-
Memphis	-	-	1.40	-	-	-	.20	1.00	-	-
Paducah *	-	-	-	-	-	0.75	1.00	-	.06	-
Plainview	-	-	-	-	-	-	.95	-	-	.11
Quanah *	-	-	-	-	-	-	.85	1.50	-	.02
Tulia	-	-	-	-	-	-	-	.31	-	-
Wichita Falls	0.02	.22	1.18	-	-	.03	2.00	.28	-	-
Denison *	-	-	.01	0.09	-	.01	.04	1.07	-	-
Henrietta *	-	1.00	.60	.20	-	.30	1.00	1.50	-	-
Sherman *	-	-	-	-	-	.17	.32	1.52	-	.04
Oklahoma:										
Ardmore	-	-	.20	1.06	-	.10	.90	1.71	-	-
Chickasha	-	.26	.88	-	-	-	.33	1.64	-	-
Marlow	.45	.90	.20	-	-	-	1.97	.50	-	-
Pauls Valley	-	-	1.18	1.14	-	-	2.03	.35	-	-
Altus	-	1.60	-	-	-	-	1.35	.40	-	-
Apache	.13	1.83	.03	.01	.13	-	1.70	.92	-	-
Arapaho	-	.04	-	-	-	-	.60	-	.05	-
Carnegie	-	.91	.32	-	-	-	1.75	.60	-	-
Cloud Chief	.03	.19	.06	-	-	.02	1.14	.26	-	-
Erick	-	-	-	-	-	-	1.00	-	-	-
Frederick	-	.47	2.01	-	-	-	1.60	.76	-	.07
Hammon	-	-	-	-	-	-	.61	-	-	.14
Hobart	-	-	-	-	-	.86	-	.12	-	-
Hollis	-	-	-	-	-	-	2.20	-	-	.08
Lawton	-	1.05	.55	.05	-	-	2.60	.63	-	-
Mangum	-	-	1.20	-	-	-	1.41	-	-	-
Walters	-	3.61	.03	-	.15	-	-	-	-	-
Wichita National Forest	-	.84	-	-	.36	-	.68	.75	-	-
	.63	18.26	11.46	2.55	1.50	2.24	36.05	18.91	.36	1.01
Average	.02	.52	.33	.07	.04	.06	1.03	.54	.01	.03

Table 50.- Storms considered in connection with unit hydrographs for Red River Basin above Denison, Tex.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	January 1932				
	3	4	5	6	12
Texas:					
Canyon	0.22	1.25	-	-	-
Childress	-	.45	0.65	-	-
Chillicothe *	-	.83	.56	-	-
Clarendon	.30	.80	-	-	-
Claude	-	-	.30	-	-
Crowell	.97	.73	-	-	-
Dimmitt	-	.30	.14	-	-
Dundee	-	1.49	-	-	-
Memphis	-	1.30	-	-	-
Paducah *	.61	.66	-	-	-
Plainview	-	.38	.80	-	-
Quanah *	-	.71	.91	-	-
Vega *	-	-	1.21	0.20	-
Wichita Falls	.08	1.60	.04	-	-
Denison *	-	2.00	1.00	-	0.08
Henrietta *	-	1.30	.60	-	.05
Sherman *	.13	1.51	1.15	-	.94
Oklahoma:					
Ardmore	.43	2.25	-	-	.53
Chickasha	.07	1.69	.14	-	-
Marlow	.42	2.35	.07	-	-
Pauls Valley	.67	2.43	.24	-	-
Altus	-	.64	.55	-	-
Apache	.05	1.80	.16	-	-
Carnegie	-	1.28	.50	-	-
Cloud Chief	-	1.09	.33	-	-
Erick	-	.38	.30	-	-
Frederick	.05	1.55	.05	-	-
Hammon	-	.64	.48	-	-
Hobart	-	1.20	.28	-	-
Hollis	-	-	.70	.90	-
Lawton	.05	2.10	.22	-	-
Mangum	.77	1.25	-	-	-
Walters	-	1.70	.30	-	-
Wichita National Forest	-	1.35	.15	-	-
	4.82	39.01	11.83	1.10	1.60
Average	.14	1.15	.35	.03	.05

Table 50.- Storms considered in connection with unit hydrographs for Red River Basin above Denison, Tex.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	April 1932							
	17	18	19	21	22	23	26	27
Texas:								
Canyon	-	0.10	-	-	0.33	-	1.49	-
Childress	0.07	.18	0.28	-	-	0.40	.35	-
Chillicothe *	-	.15	.36	-	-	.51	-	-
Clarendon	.07	-	-	-	.75	-	.47	1.12
Claude	-	-	-	-	.70	-	-	1.02
Crowell	-	-	-	-	.65	-	-	1.15
Dimmitt	-	.05	-	0.17	-	-	-	.74
Dundee	-	.29	-	.44	-	-	-	-
Memphis	.20	-	-	-	.80	-	.30	1.00
Paducah *	-	.11	-	-	.61	-	.18	.88
Plainview	-	-	-	-	-	.78	.02	.49
Quanah *	-	.60	.10	-	-	2.95	-	-
Tulia	-	.23	-	-	-	.65	-	.44
Vega *	-	-	-	-	-	.08	-	-
Wichita Falls	-	-	.23	-	-	.85	-	-
Denison *	-	-	.10	-	-	.90	-	-
Henrietta *	-	-	.15	-	-	.30	-	-
Sherman *	-	-	.08	-	.02	.81	-	-
Oklahoma:								
Ardmore	-	-	2.00	-	-	.15	-	-
Chickasha	-	.13	.23	-	-	.38	-	-
Marlow	-	.08	.50	-	-	.49	-	.76
Pauls Valley	-	.19	.53	-	-	.29	-	-
Altus	-	.74	.38	-	-	.88	-	-
Apache	-	.28	1.50	-	-	.67	-	.01
Carnegie	-	.20	.80	-	-	.25	-	-
Cloud Chief	-	.12	.75	-	-	.38	-	-
Erick	-	-	.45	-	-	1.80	-	.15
Frederick	-	.55	.22	-	-	.36	-	-
Hammon	-	.07	.44	-	-	1.63	-	.31
Hobart	-	.33	.58	-	.84	-	-	.87
Hollis	-	1.00	.13	-	-	.94	-	.11
Lawton	-	.11	.14	-	-	.40	-	-
Mangum	-	1.05	.40	-	-	1.05	-	.10
Walters	-	.25	.47	-	-	.42	-	-
Wichita National Forest	-	.22	.47	-	-	.24	-	-
	.34	7.03	10.29	.61	4.70	18.56	2.81	9.15
Average	.01	.20	.29	.02	.13	.53	.08	.26

Table 50.- Storms considered in connection with unit hydrographs for Red River Basin above Denison, Tex.--Continued

(Precipitation, in inches, measured in the afternoon except at stations marked *, where it was measured in the morning.)

Station	August - September 1932								
	30	31	1	2	4	5	6	7	8
Texas:									
Childress	-	1.90	1.00	0.30	-	-	-	0.28	0.04
Chillicothe *	-	-	1.33	.22	-	-	-	.07	.05
Clarendon	0.12	.08	.15	-	-	-	-	-	-
Crowell	1.35	1.45	-	-	-	-	-	.55	-
Dimmitt	.11	-	-	-	-	-	-	.13	-
Dundee	-	1.23	2.30	-	0.25	-	0.48	.11	-
Memphis	.20	.10	-	.15	-	-	-	-	-
Paducah *	1.50	.50	.20	.06	-	1.30	.26	.22	-
Plainview	.04	-	-	-	-	-	.54	.60	-
Quanah *	-	1.65	1.10	.06	-	-	-	.06	.07
Tulia	.09	.11	-	-	-	-	-	-	-
Vega *	-	.12	.05	.03	-	-	-	-	-
Wichita Falls	.10	.58	1.27	-	-	.16	.85	.16	-
Denison *	-	-	-	-	-	-	.02	-	-
Henrietta *	-	.70	1.05	.40	-	-	.10	.45	-
Sherman *	-	-	-	-	.55	.04	.49	-	-
Oklahoma:									
Ardmore	-	.60	.40	.20	-	-	.61	-	-
Chickasha	-	.09	-	.88	-	-	-	-	-
Marlow	-	.33	-	1.77	-	-	-	-	-
Pauls Valley	-	.07	-	.50	-	-	-	-	-
Altus	-	.33	1.93	.24	-	-	-	-	-
Apache	-	.46	1.43	-	-	-	-	-	-
Carnegie	-	.20	.95	.70	-	-	-	-	-
Cloud Chief	-	.07	.87	-	-	-	-	-	-
Erick	-	.33	.23	.20	-	-	-	-	-
Frederick	-	.08	2.62	.52	-	-	-	-	.04
Hammon	-	.85	.36	.17	-	-	-	-	-
Hobart	-	.53	.41	.17	-	-	-	-	-
Hollis	-	2.40	-	2.40	-	-	-	-	-
Lawton	-	.55	1.00	1.10	-	-	-	-	-
Mangum	-	2.00	.45	.05	-	-	-	-	-
Walters	-	-	.87	-	-	-	-	-	-
Wichita National Forest	.28	1.07	3.00	-	-	-	-	-	-
	3.79	18.38	22.97	10.12	.80	1.50	3.35	2.57	.20
Average	.11	.54	.68	.30	.02	.04	.09	.08	.01

Table 51 gives the surface run-off from the unit storms and the approximate precipitation that caused the run-off.

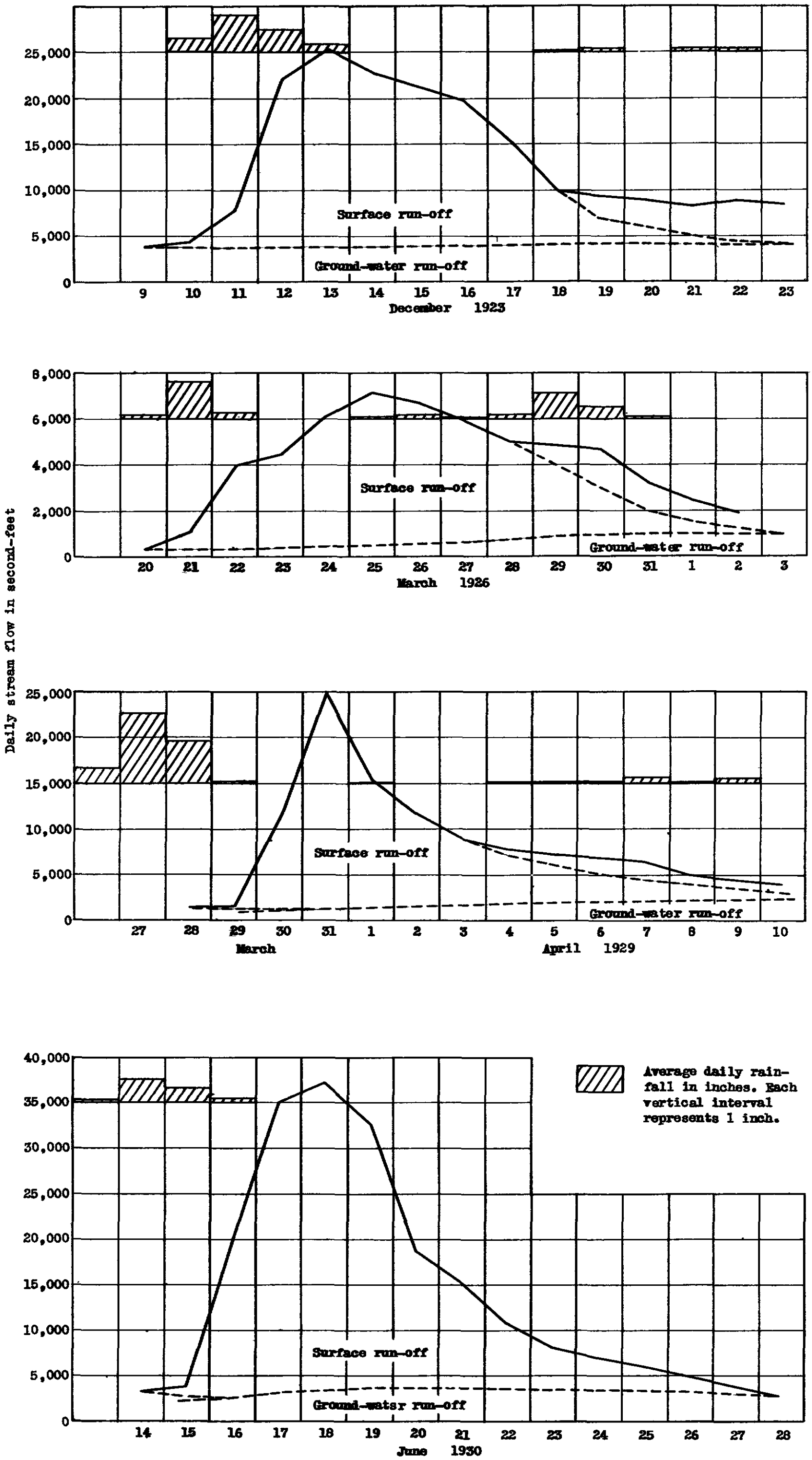

Figure 67.—Unit hydrographs for Red River near Denison, Tex.

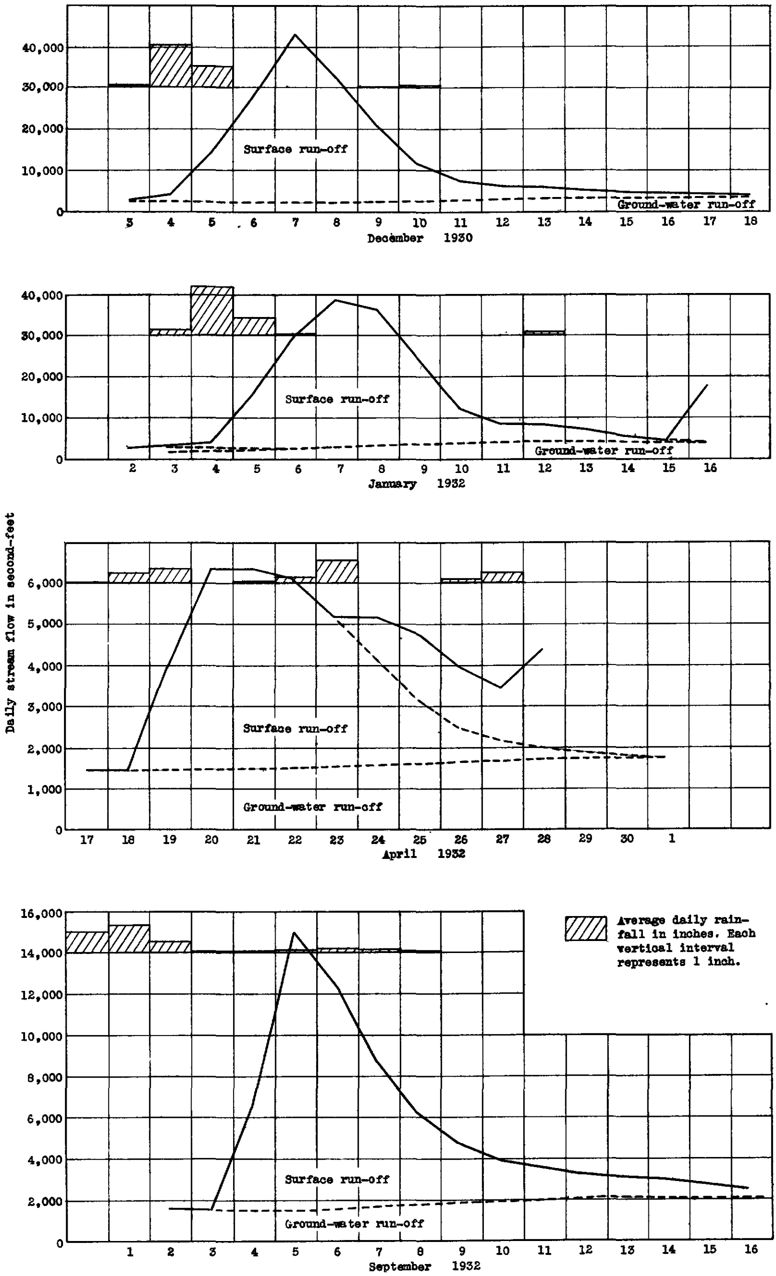

Figure 68.—Unit hydrographs for Red River near Denison, Tex.

Table 51.- Surface run-off from unit storms in
Red River Basin above Denison, Tex.

Storm	Average of precipitation at stations (inches)	Surface run-off (inches)	Ratio of surface run-off to average precipitation
Dec. 10, 1923	1.37	0.11	0.08
Mar. 21, 1926	1.02	.04	.04
Mar. 27, 1929	2.94	.08	.03
June 14, 1930	.94	.15	.16
Dec. 4, 1930	1.63	.15	.09
Jan. 4, 1932	1.67	.14	.08
Apr. 18, 1932	.50	.03	.06
Sept. 1, 1932	1.63	.05	.03

Table 52 gives the daily percentage for the eight distribution graphs, and the graphs are superimposed in figure 69. The average distribution graph determined for the basin is 1, 8, 18, 22, 18, 12, 8, 5, 3, 2, 2, 1 percent. The first figure of each distribution graph is the percentage of surface run-off for calendar day on which most of the rainfall occurred; other figures for succeeding days.

Table 52.- Distribution graphs for storms in
Red River Basin above Denison, Tex.

Storm	1	2	3	4	5	6	7	8
Dec. 10, 1923	0.4	3.5	15.4	18.0	15.8	14.3	13.1	9.7
Mar. 21, 1926	1.7	8.4	9.5	13.1	15.3	14.2	12.2	9.8
Mar. 27, 1929	0	0	.3	11.6	28.2	16.7	12.0	8.3
June 14, 1930	0	.6	10.9	19.9	21.2	18.3	9.4	7.2
Dec. 4, 1930	1.0	8.0	17.0	26.8	19.8	11.9	5.7	2.8
Jan. 4, 1932	1.0	8.2	17.7	23.1	21.5	13.8	5.6	3.0
Apr. 18, 1932	0	10.0	18.4	18.4	17.3	13.7	9.5	5.8
Sept. 1, 1932	0	0	10.1	25.8	21.0	13.6	8.3	5.5

Storm	9	10	11	12	13	14	15	16	17
Dec. 10, 1923	4.9	2.3	1.5	0.7	0.2	0.2	-	-	-
Mar. 21, 1926	7.2	4.8	2.3	1.1	.4	-	-	-	-
Mar. 27, 1929	7.0	4.8	3.6	2.6	2.0	1.4	0.8	0.5	0.2
June 14, 1930	4.4	2.8	2.1	1.7	1.1	.4	-	-	-
Dec. 4, 1930	1.9	1.7	1.1	.9	.5	.4	.3	.2	-
Jan. 4, 1932	2.7	1.9	1.0	.3	.2	-	-	-	-
Apr. 18, 1932	3.2	1.9	1.0	.6	.2	-	-	-	-
Sept. 1, 1932	4.0	3.1	2.5	1.9	1.6	1.1	1.0	.5	-

For practical application of the unit-hydrograph theory, it would seem that the drainage area of the Red River above Denison (39,400 square miles) is too large to work with, except possibly for studying floods due to heavy rainfall of wide extent.

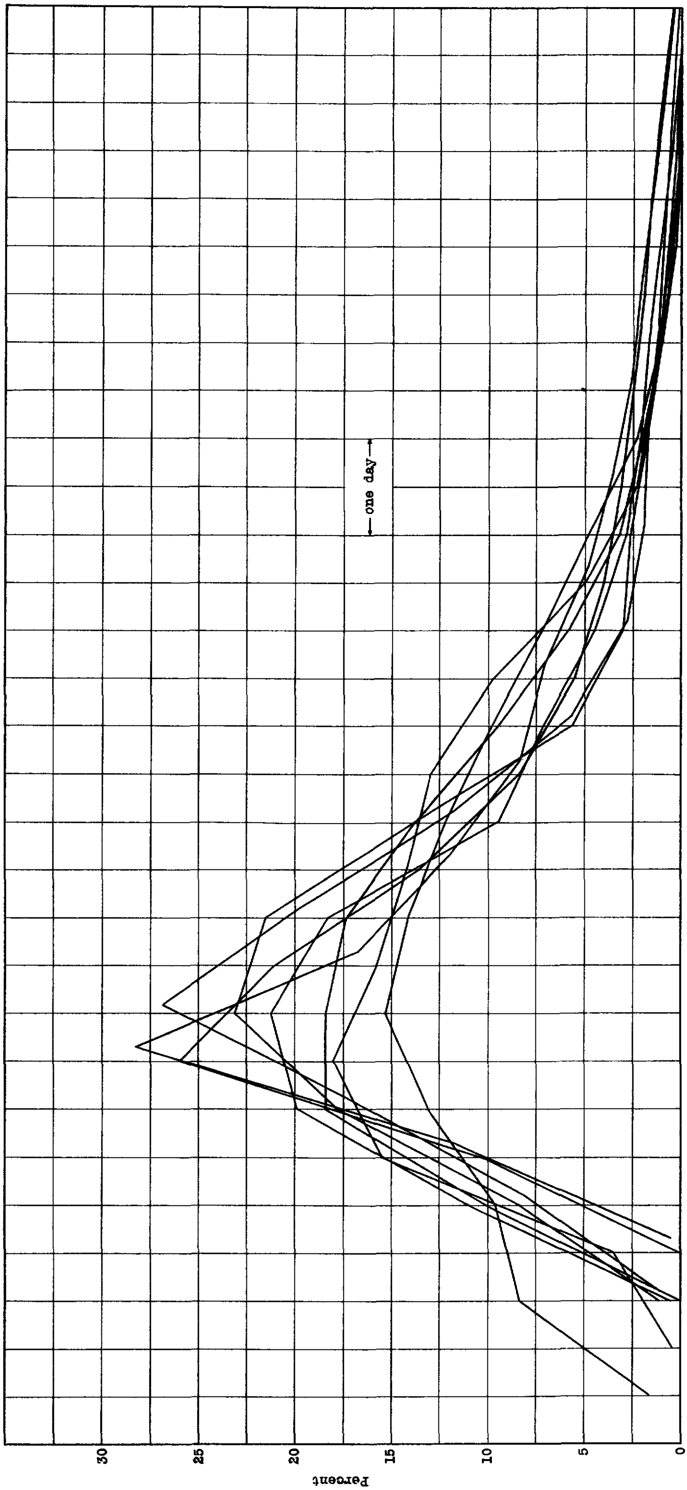

Figure 69.—Superimposed distribution graphs for Red River Basin above Denison, Tex.

Table 53 gives the summary of the average distribution graphs for the eight basins. They are also plotted on figure 70 for graphic comparison.

Table 53.- Average distribution graphs, in percent

Day	Muskingum	Wabash	Embarrass	Skunk	Susquehanna	Delaware	French Broad	Red
1st	4	3	5	1	12	6	3	1
2d	15	12	25	32	33	43	29	8
3d	27	27	29	27	24	24	25	18
4th	21	24	18	18	15	13	15	22
5th	13	14	10	11	8	7	9	18
6th	8	9	6	5	4	4	7	12
7th	5	5	3	3	2	2	5	8
8th	3	3	2	2	1	1	3	5
9th	2	2	1	1	1	-	2	3
10th	1	1	1	-	-	-	1	2
11th	1	-	-	-	-	-	1	2
12th	-	-	-	-	-	-	-	1

The average distribution graphs as obtained for these basins reflect the time of occurrence, synchronization with the calendar day, and other characteristics of most of the unit storms for the respective basin. To the extent that these characteristics are different in the different basins the average distribution graphs presented in table 53 and figure 70 are not strictly comparable - that is, if a unit storm of the same duration and time of occurrence took place on all the basins simultaneously, the percentages of surface run-off on the first day from the several basins would probably not be the same as the percentages given in the table.

The general shape, however, of the various graphs on figure 70 reflects the characteristics of the different basins. No attempt has been made to correlate the graphs with the physical characteristics of the respective basins, except to note that the peak day's percentage of surface run-off varies with the lag or time between peak rainfall and resulting peak run-off. The percentage of run-off on the peak day seems to be an inverse exponential function of the lag, and as the lag is readily ascertainable for any basin, this feature may have significance in further studies.

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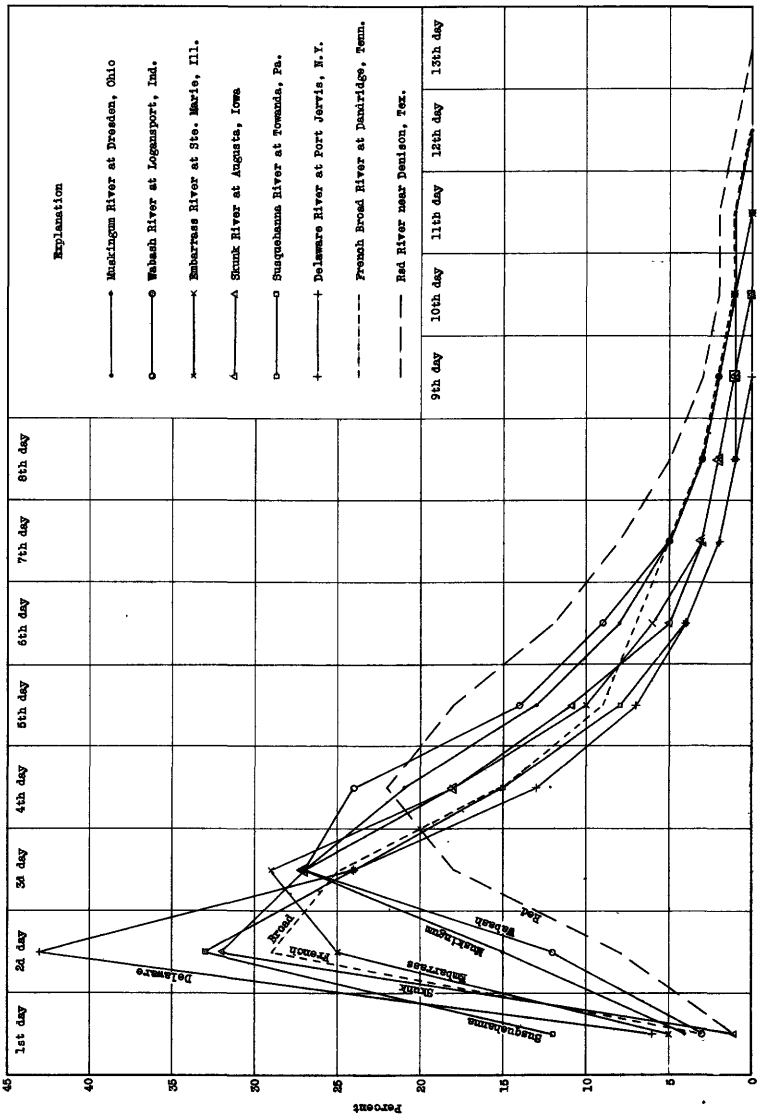


Figure 70.—Average distribution graphs for selected drainage basins.

Application of the unit-hydrograph principle

In the present study the principle of the unit hydrograph has been applied by Merrill Bernard in storm transposition studies and reference is made on page 118, to its use in studies of stream-flow separation. The principle is also being applied by several agencies, principally in connection with flood problems.

The following statement, prepared in the Special Claims Division of the United States District Engineer Office, St. Paul, Minn., Maj. Dwight F. Johns, district engineer, by W. J. Parsons, under the direction of J. A. Grant, describes briefly the use that is being made of unit-hydrograph principles in analyzing surface run-off in connection with operation of pools for navigation on the upper Mississippi River:

> "With the development of operating plans for the 9-foot channel project on the upper Mississippi River, it becomes apparent that complete knowledge of the day-by-day inflow into the pools created by the several dams will be desirable. Furthermore, it appears that operation would be much improved if flood inflow from 2 to 5 days in advance could be estimated. On the main Mississippi River above Minneapolis and on the major tributaries there are stream gaging stations so located as to give sufficient warning of floods from the upper reaches, providing daily reports come in promptly. But the run-off from areas below these gaging stations and the run-off from the minor tributaries where no stations are maintained will be unknown and should be estimated. Accordingly, a study has been made of the feasibility of predicting flood inflow from these areas from the rainfall. The unit-flood (term corresponds to the unit hydrograph) method introduced by Mr. Leroy K. Sherman, which distributes the run-off from each day's rain according to the composite pattern observed in actual simple floods, was recognized as a convenient method of analysis, because of its simplicity and because of its essentially rational basis.
> The day-by-day nature of the desired predictions limited the study to flood flows, and no attempt was made to analyze groundwater inflow, which varies slowly over long period of time. The unit-flood method appears to meet the requirements, because

consistent unit floods have been developed for most of the tributary basins, and complex floods have been reproduced by the addition of the proper unit floods.

"Basin studies made.- Unit floods were developed for each river by reducing to a peak of 100 second-feet all recorded simple floods produced by 1-day rains and such portions of complex floods as were dominated by 1-day rains as the flood rose or fell away from the peak. These simple floods and portions of complex floods were averaged graphically, and a distribution diagram prepared for each stream. Although it is admitted that in this territory the total flood volume is e more uniform function of the rainfall than the peak flow (which is materially influenced by the distribution and short-time intensity of the rainfall), it is believed that this disadvantage is more than overcome by the greater number of floods made available when we reduce floods to one peak rather than one volume. On some streams, where only scanty records exist, no simple 1-day floods have been reported, and entire reliance had to be placed on a unit flood built up from portions of complex floods.

"Flood run-off has been considered to be that portion of the hydrograph above a straight line connecting the fairly uniform flow before and after the flood. This base line for run-off generally rises on a gradual slope. Although it is realized that the flood run-off under this assumption, includes that portion of the inflow from ground water, which responds quickly to the rainfall, sufficient information is not available to segregate this inflow, and the influence of abnormal ground-water conditions will be ignored. This study is limited to periods of flood flow and no attempt has been made to extend the predictions into low-flow periods, when the influence of the inflow from ground water would become important.

"Within the total area under consideration there were available a total of 190 floods, produced by rainfall alone, for which daily average discharges were published by the United States Geological Survey and during which daily rainfall and temperature records were published by the United States Weather

Bureau. On an average there were records of about 20 floods per stream, but in some instances only 5 to 10 were available.

"Rainfall-run-off relations were developed for each stream so that, in the large majority of floods, predicted values were within 20 percent of the total observed flood volumes. In these studies it was necessary to use complex as well as simple floods. the complex floods being subdivided into unit floods. The final rainfall-run-off relation was represented by a series of three curves defining a narrow belt. These maximum, mean, or minimum curves should be used as indicated by the season or the record of the preceding flood.

"Data which should be available.- The proposed plan of operation will use 25 fairly well distributed United States Weather Bureau stations, which should report daily at 8 a.m. to a central office. In addition, these stations will make immediate reports of rainfall which exceeds intensities of 1 inch in 24 hours. The stations are distributed so that at least three are in or adjacent to each drainage basin.

"It is planned to use 11 United States Geological Survey gaging stations located near the mouths of the major tributaries, which will report gage heights daily, at 8 a.m., to the central office.

"Daily prediction forms.- A compilation sheet has been prepared for each tributary basin showing all pertinent data and curves, such as the rainfall-run-off relation curves and formulae, average base flows, seasonal factors, forms for computing the average rainfall, and forms for building up flood flow from unit floods. One of these sheets should be filled out each morning during the flood season, and a predictio' prepared for the desired number of days in advance. This should be accomplished in the following order: (a) Compute the average rainfall over the river basins; (b) compute the total volume of flood run-off, using formula and curve; (c) distribute the total flood volume produced by each day's rainfall according to the distribution diagram; (d) estimate the base flow from the run-off prior to the flood; and (e) obtain the total run-off on each day by adding the contributions from the several sources of supply to the base flow.

"The predicted run-off should be corrected from day to day in the following manner: Compare the predicted run-off for the beginning of the day (as computed on the preceding day) with the reported run-off. If these values differ by more than the allowable departure, compute a correction factor C from the formula

$$C = \frac{\text{Observed run-off - estimated base flow}}{\text{Estimated run-off - estimated base flow}}$$

Daily contributions from all previous floods should then be multiplied by C, and the total flood run-off volume of the next unit-flood taken from the next higher curve if C is more than 1 or the next lower curve if C is less than 1."

The United States District Engineer office at Zanesville, Ohio, and engineers of the Muskingum Watershed Conservancy District have made use of the unit-hydrograph principle in connection with studies in the Muskingum River Basin. Engineers connected with the Tennessee Valley Authority are using the principle in studies relating to the determination of possible flood run-off and also for the purpose of forecasting run-off for a period of several days in advance. In the latter study continuous hydrologic and climatologic data are being used, whereas most of the other studies to date have been confined to daily averages.

The value of the unit-hydrograph principle in analyzing surface run-off will depend on the extent to which the principle is found applicable to areas and problems of various kinds. The principle seems especially applicable to analysis of rainfall and surface run-off that is of practical value where detailed knowledge of hydrology is important, as in (a) manipulation of storage on large systems of river development for power and water supply; (b) obtaining definite knowledge of run-off characteristics of urban areas; and (c) analysis of potentialities of drainage basins for producing floods and (d) forecasting flood crests.

Method of application of the unit-hydrograph principle.- By definition, a unit hydrograph is a hydrograph of surface run-off resulting from rainfall within a unit of time, as a day or an hour, and a distribution graph is a unit hydrograph of surface run-off modified to show the proportional relations of its ordinates, in percentage of the total surface run-off.

If a distribution graph has been prepared for a basin by methods described in the foregoing pages and if the 24-hour depth of rainfall is known, the problem is the determination of the hydrograph of the resulting surface run-off. L. K. Sherman describes the method as follows:

"First multiply the given 24-hour rainfall depth by a coefficient (or percentage) of run-off. This will give the depth d on the area in question. Multiply d by 26.89M (M = drainage area in square miles); this gives the total run-off expressed in cubic feet per second for a 24-hour period. The aforesaid figure, multiplied in turn by each daily percentage of the distribution graph will give the ordinates N_1, N_2, N_3, etc., for the average rate of run-off in cubic feet per second for each 24-hour interval of the run-off period. They form the required hydrograph of run-off."

In some problems, such as that of using the unit-hydrograph principle as a means of forecasting flood stages, on the basis of continuous records rather than average rates of run-off, the unit graph as presented by Sherman in his original discussion (158), seems more adaptable than the distribution graph. The unit graph may be defined as the unit hydrograph modified so that the total surface run-off of the unit graph represents a depth of 1 inch over the drainage basin. This is accomplished by dividing the unit-hydrograph ordinates in second-feet by the total surface run-off in inches.

Merrill M. Bernard (13) uses the distribution graph to distribute total rainfall expressed either as depth in inches over the area or as flow in second-feet, which, when presented in the form of a hydrograph, shows the hypothetical stream flow if all the precipitation had appeared as surface run-off. He designates such a hypothetical hydrograph a "pluviagraph." In the problem under consideration the given rainfall (expressed either as depth over the area or as second-feet) would have been multiplied in turn by each daily percentage of the distribution graph to form a pluviagraph, or graph of 100 percent rainfall and run-off. The pluviagraph figures are then multiplied by a coefficient of run-off to determine the hydrograph of surface run-off.

When the surface run-off from a rain lasting several days is considered the distribution-graph percentage is applied to each day's rainfall and the results are summed as shown in table 54.

Regardless of whether (a) a coefficient or percentage of run-off is applied to the recorded rainfall, (b) a deduction is made from the rainfall as recorded on the basis of infiltration loss, or (c) a coefficient of run-off is applied to the pluviagraph, the accuracy of the hydrograph of surface run-off thus obtained will depend, as stated by Sherman, "largely on the ability of the engineer or hydrologist to determine the proper infiltration loss or coefficient of run-off. Until improved quantitative or mechanical procedure is established, it is important that one who applies the simple unit-hydrograph methods (or any rainfall method) be familiar with the basic factors affecting infiltration and run-off."

If Sherman's method of approach is followed the engineer or hydrologist must determine the coefficient of run-off or deductive factor to apply to the daily rainfall, so that the adjusted figures when distributed by means of the distribution graph, or unit graph will give a hydrograph of surface run-off. In Bernard's method a coefficient of run-off must be selected for each storm period which, when applied to the pluviagraph of total rainfall as distributed by the distribution graph, will give a hydrograph of surface run-off. Only surface run-off is obtained by either method.

The advisory committee of the American Geophysical Union has recommended that steps be taken to

(1) Derive and publish a set of distribution graphs for several typical basins throughout the country.

(2) Derive and publish flood hydrographs compiled from possible hypothetical storms of known rainfall frequency upon the several basins.

(3) Continue the studies of flood run-off due to actual storms in these basins and also include similar studies on other basins. The flood-hydrograph studies should develop the different seasonal characteristics.

The Flood Protection Committee of the American Society of Civil Engineers has recommended that steps be taken to

(4) Compare for several basins the maximum surface run-off from known storms with the pluviagraph figures.

(5) Compare for one basin the maximum surface run-off with the pluviagraph figures at several gaging stations for the same storm.

Studies in connection with recommendation No. 1 are outlined in the preceding discussion. The distribution graphs thus developed have been used by Mr. Bernard in the following section to compare the known surface run-off with pluviagraph figures as recommended under No. 4 and thus arrive at probable run-off coefficients, which he has used to make estimates, in accordance with recommendation No. 2, of the probable surface run-off that would have resulted if certain outstanding storms had centered in a critical position over certain basins.

The unit-hydrograph method and storm transposition in flood problems relating to great storms in the Eastern and Central United States

By Merrill Bernard

The idea of superposing storms of unusual magnitude upon drainage basins for the purpose of estimating flood flow is not new. The results have not always been satisfying because of the question whether it would be physically possible for the given storm to be simulated on the drainage basin and also because of the difficulty of taking into account the effect of drainage-basin characteristics on run-off when translating the records of a storm in one basin into terms of flood flow in another basin.

All flood formulas that include storm rainfall as a factor entail the idea of storm superpositon. Their use involves what is really transposition of synthetic storms to the point of application, often for great distances from the basin or basins on which the originator evolved his empirical relationships. The method herein presented involves a limited transposition of storms and the application of the unit-hydrograph principle which, through its distribution graph, gives determinate value to the effect on surface run-off of such basin characteristics as area, shape, general slope, and arrangement of stream system.

Flood coefficients

This study utilizes the approximate proportionality between the ordinates of the hydrograph of flow from surface run-off and the ordinates of the pluviagraph, or graph of 100 percent run-off. The ratio between the greatest ordinate of the hydrograph of surface run-off and that of the pluviagraph is taken as the "flood coefficient." Although this ratio or "flood coefficient" is not an average coefficient for the flood period, it insures agreement between the observed and computed peak values, with only a slight sacrifice in agreement between the actual and computed hydrographs.

The determination of the flood coefficient becomes largely a mechanical procedure after the distribution graph for the basin is made available through the various steps described on pages 124-133.*

The steps taken in the development of the coefficient for the Susquehanna River at Towanda, Pa., are illustrated in table 54. They are as follows:

(a) Compute, for the storm and flood period selected, the average daily rainfall depth over the basin. Where rainfall stations are comparatively numerous and well distributed, the arithmetic average is acceptable. Where stations are few and poorly distributed each station record should be weighted by geometric proportioning. Average daily rainfall is listed by date in column 2.

(b) The distribution graph of the drainage basin is listed in column 3.

(c) The rainfall for each day is multiplied by the items of the distribution graph and listed in a column. The product of the rainfall and the first item of the distribution graph is placed in column 4 opposite the date on which the rainfall occurred, with the following products opposite succeeding dates. The next day's rainfall is treated in the same manner and placed in column 5, and so on. If there is rain on every day for a long period, at least as many columns are necessary for the distribution of the rainfall as there are items in the distribution graph being used. This procedure is shown in columns 4 to 10.

(d) The daily increments in columns 4 to 10 are summed horizontally, and the totals are listed in column 11 as the pluviagraph values, or 100 percent run-off, expressed in inches on the drainage basin, and are converted to second-feet in column 12.

(e) Observed stream flow is listed by date in column 13.

(f) Base flow, or ground-water run-off, is estimated from a plotted hydrograph of observed flow (see pp. 111-119) and listed by date in column 14.

(g) Flow from surface run-off (column 15) is obtained by deducting base flow from observed stream flow.

* It is to be noted that the distribution graphs used by the writer in the development of flood coefficients took slightly different daily percentages than those presented on pages 141, 148, 155, 163, 176, 181, 190, 207, owing to minor changes and refinements of the distribution graphs in their final presentation.

Table 54.- Development of a flood coefficient for Susquehanna River above Towanda, Pa.

Date (1933)	Average daily rainfall (inches)	Distribution graph* (percent)	Distributed daily rainfall - 100 percent run-off** (inches)							Pluviagraph (100 percent run-off) (col. 4 to 10) Inches	Pluviagraph Sec.-ft.	Observed stream flow (sec.-ft.)	Ground-water flow (sec.-ft.)	Surface run-off (sec.-ft.)	Flood coefficient "C"
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Aug. 17	0.03	16	0.005	-	-	-	-	-	-	-	-	-	-	-	-
18	.06	37	.011	0.013	-	-	-	-	-	-	-	-	-	-	-
19	.15	23	.007	.030	0.024	-	-	-	-	-	-	-	-	-	-
20	-	12	.004	.018	.055	-	-	-	-	-	-	-	-	-	-
21	-	6	.002	.010	.035	-	-	-	-	0.047	9,810	1,140	-	-	-
22	.74	3	.001	.005	.018	0.118	-	-	-	.142	29,700	1,200	1,100	100	0.037
23	.69	2	-	.002	.009	.274	0.111	-	-	.396	82,700	2,070	1,200	870	.011
24	1.44	1	-	.001	.005	.170	.255	0.231	-	.662	138,300	38,600	1,400	37,200	.269
25	.25	-	-	.001	.003	.069	.189	.532	0.040	.824	172,200	65,100	1,800	63,300	# .368
26	.04	-	.006	-	.001	.045	.063	.332	.092	.559	116,900	34,900	2,200	32,700	.280
27	.05	-	.013	.008	-	.022	.040	.173	.057	.313	65,400	19,400	2,700	16,700	.255
28	.03	-	.009	.019	.005	.015	.021	.066	.030	.185	38,600	14,600	2,800	11,800	.287
29	-	-	.005	.012	.011	.007	.014	.043	.015	.107	22,400	10,200	2,900	7,300	.326
30	-	-	.003	.006	.007	-	.007	.028	.008	.060	12,500	7,560	3,000	4,560	.365
31	-	-	.002	.002	.004	-	-	.014	.005	.027	5,640	6,150	-	-	-
Sept. 1	-	-	.001	.002	.002	-	-	-	.003	-	-	-	-	-	-
2	-	-	.001	.001	.001	-	-	-	-	-	-	-	-	-	-

* Unrevised distribution graph.
** Columns 4 to 10 do not include distributed rainfall occurring before Aug. 17 or after Aug. 30.
\# Ratio of maximum daily ordinates used as flood coefficient.

(h) The ratios of the surface run-off to the pluviagraph are noted in column 16. The ratio of the maximum values is taken as the flood coefficient.

On figures 71 to 77 are plotted for the maximum observed floods for selected rivers during the nonwinter period the observed rainfall, the distributed rainfall in the form of a pluviagraph, and the hydrograph of surface run-off. There is also indicated the ratio (c) between the maximum surface run-off (maximum day) and the peak pluviagraph value. A computed hydrograph of surface run-off is also shown, obtained by multiplying the pluviagraph value by the flood coefficient.

The flood coefficients are found to change somewhat consistently with the seasons, indicating that temperature is an important factor. Other factors causing changes probably relate to differences in vegetal cover. The intensity and distribution of the rainfall within the storm period, regardless of the season, may also affect the flood coefficient.

The coefficients of the greatest floods for the different seasons are compared graphically in figure 78, and their magnitudes show, for each basin studied, a seasonal trend. Flood coefficients are not shown for the months of December, January, February, and March for basins where they might be materially affected by snow run-off.

It was found that in most basins the particular month of the year having the greatest flood within the period of record was also the one of greatest monthly run-off and always a month of considerable rainfall. It was also found that, with only few exceptions, the principal phase of the flood occurred toward the middle or end of an extended wet spell, indicating a reduction of the infiltration and absorptive capacity of the ground. Although in many basins a higher degree of saturation of the ground may have been possible, the coefficients shown in figure 78 seem the best evidence obtainable from the comparatively short records available as to what a maximum value might be in a particular month or season for the selected rivers.

Storm rainfall studies of the Miami Conservancy District

In March 1913 a storm that centered in western Ohio produced a disastrous flood on the Miami River throughout most of its length. Corrective steps were taken almost immediately after the flood to protect the

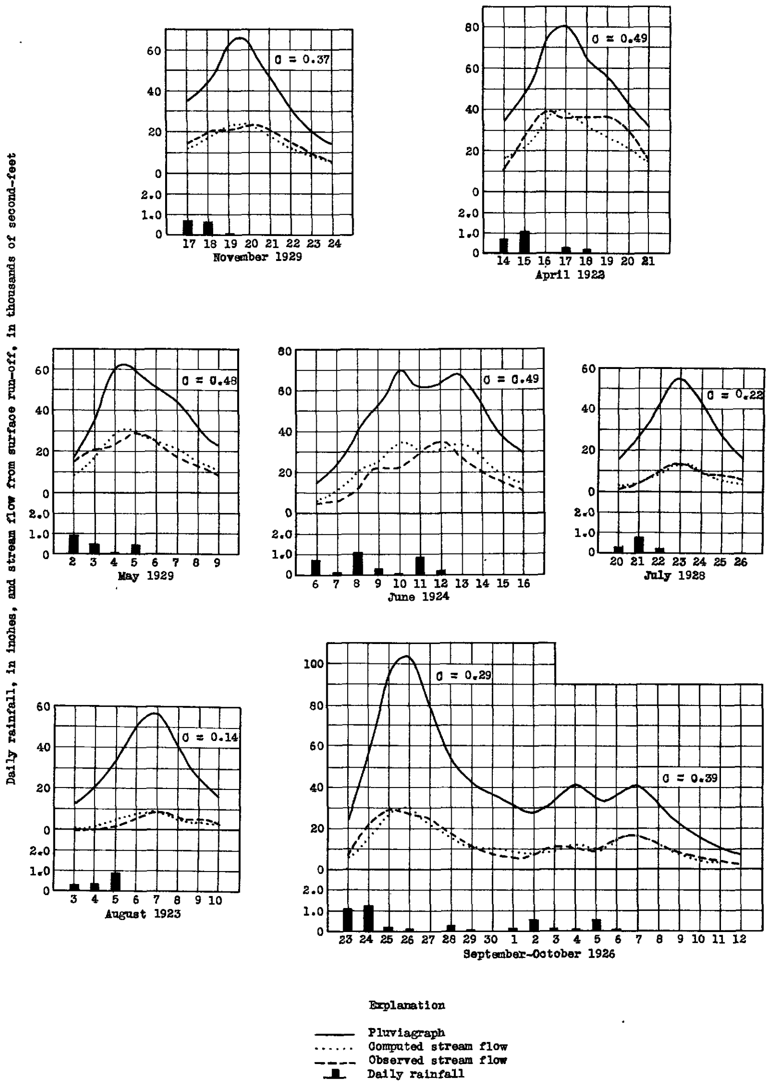


Figure 71.—Flood hydrographs and flood coefficients (C) for Muskingum River at Dresden, Ohio.

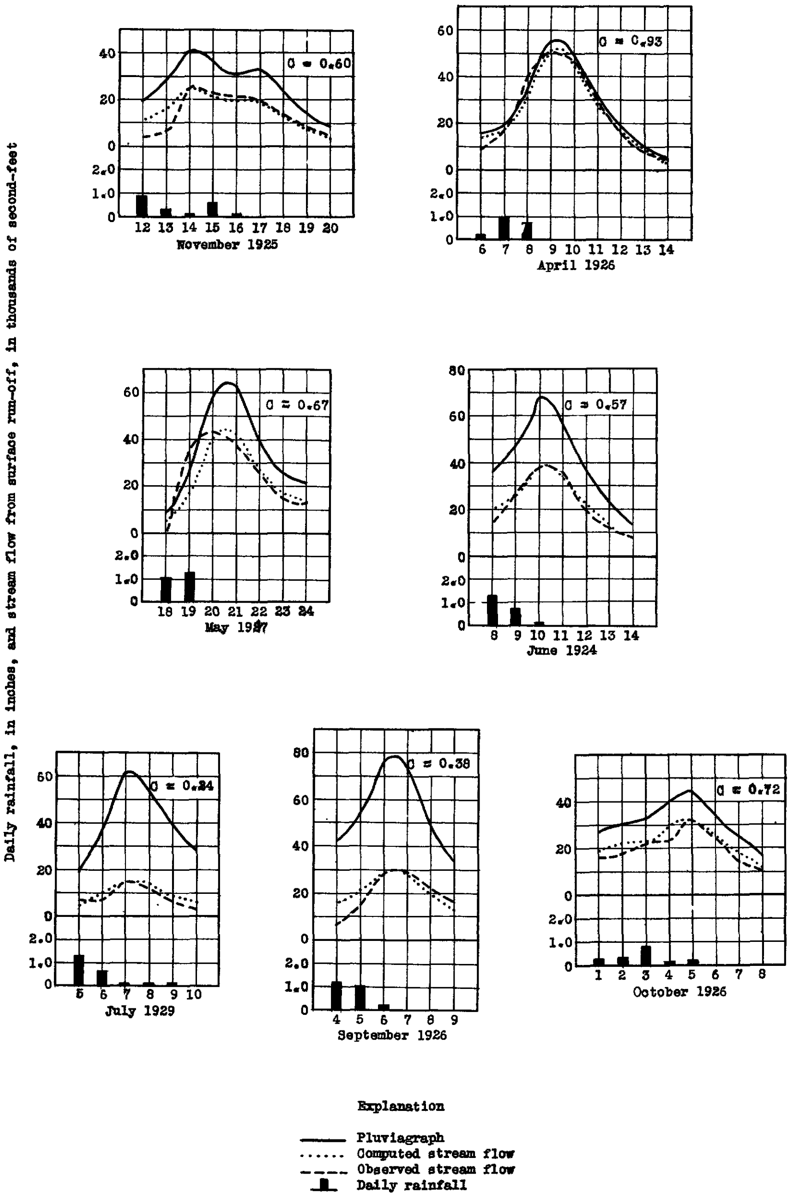


Figure 72.—Flood hydrographs and flood coefficients (C) for Wabash River at Logansport, Ind.

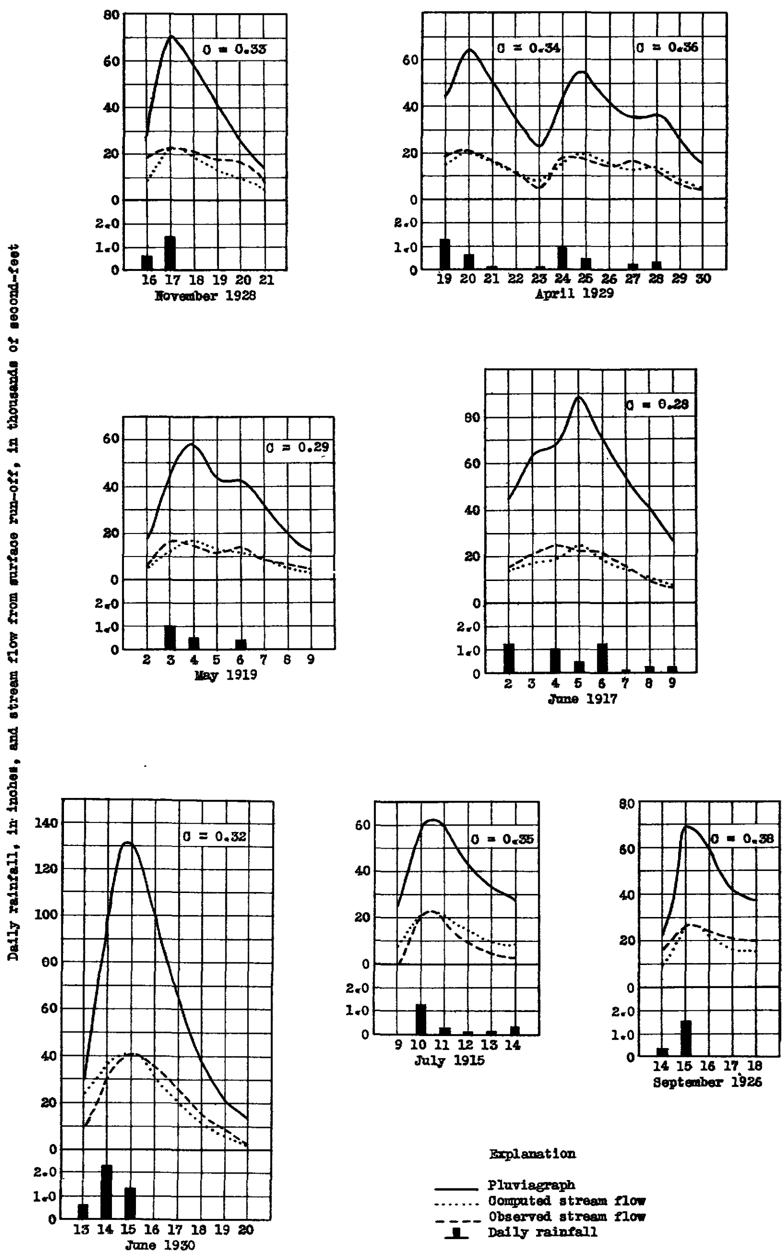


Figure 73.—Flood hydrographs and flood coefficients (C) for Skunk River at Augusta, Iowa.

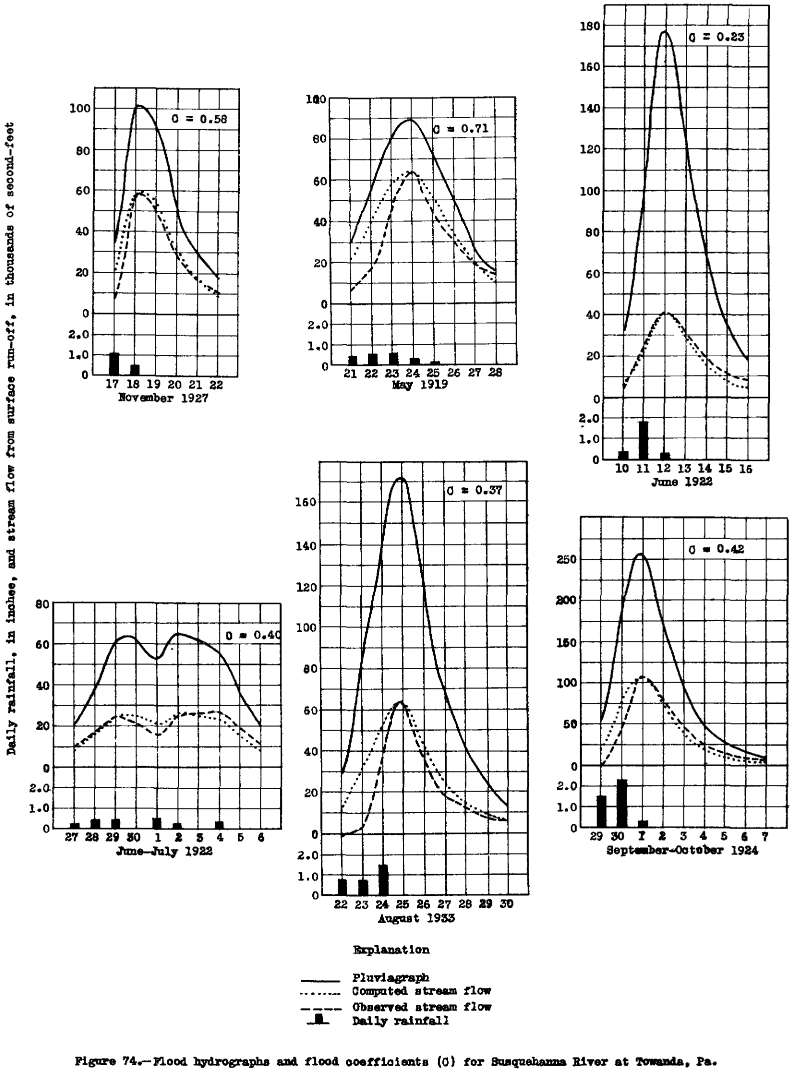


Figure 74.—Flood hydrographs and flood coefficients (C) for Susquehanna River at Towanda, Pa.

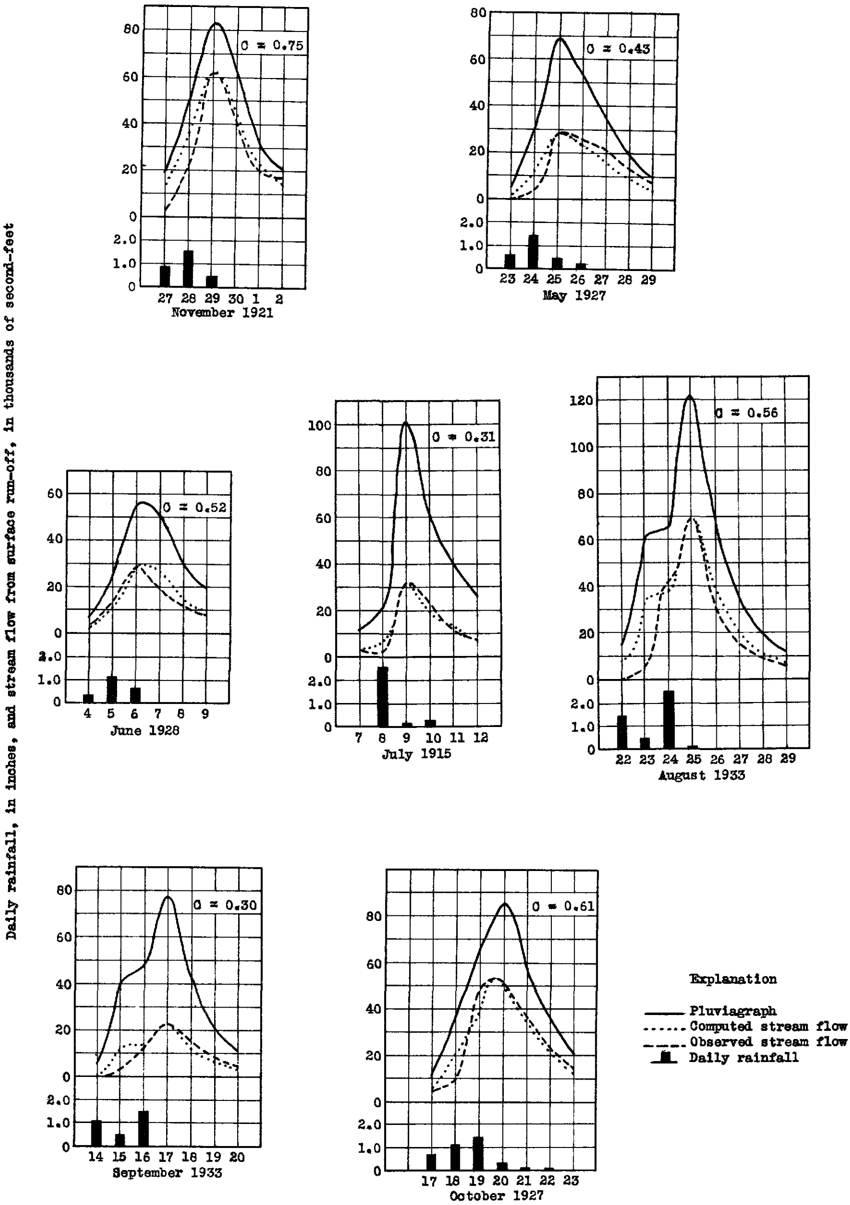


Figure 75.—Flood hydrographs and flood coefficients (C) for Delaware River at Port Jervis, N.Y.

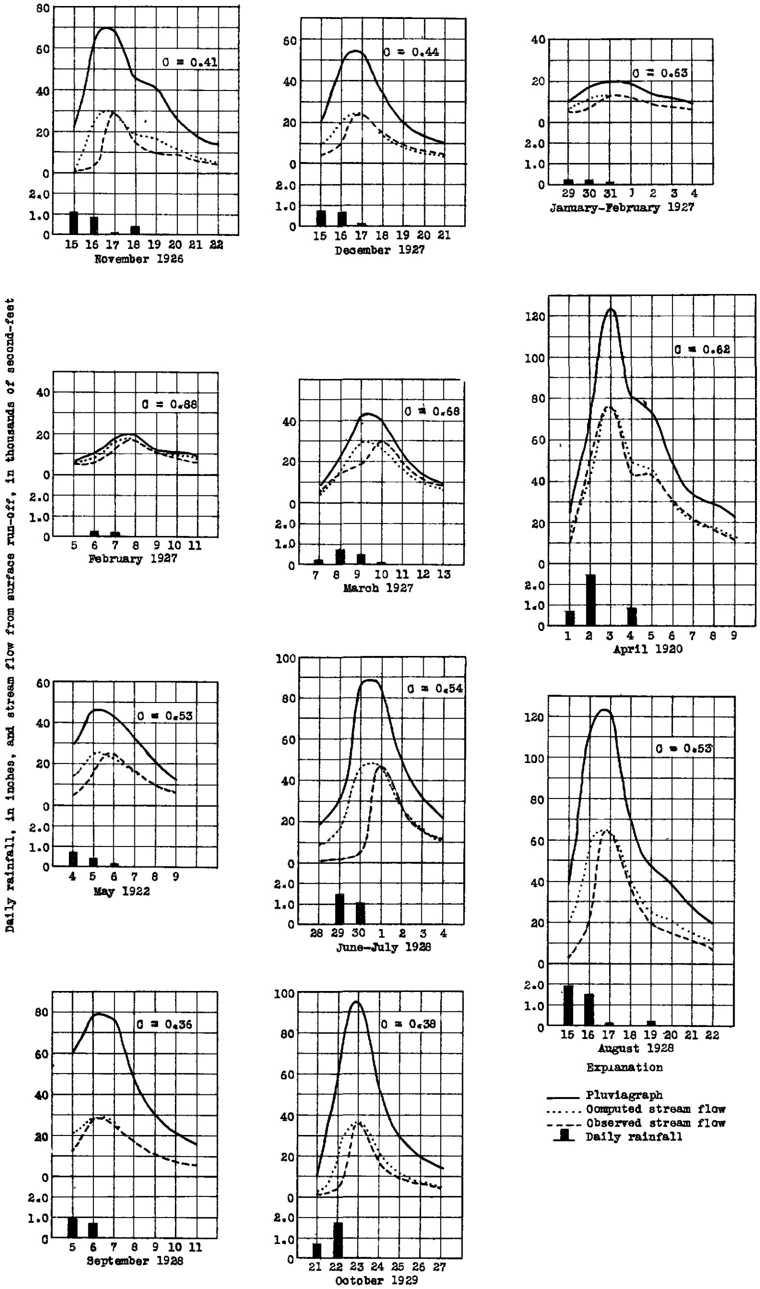


Figure 76.—Flood hydrographs and flood coefficients (C) for French Broad River at Dandridge, Tenn.

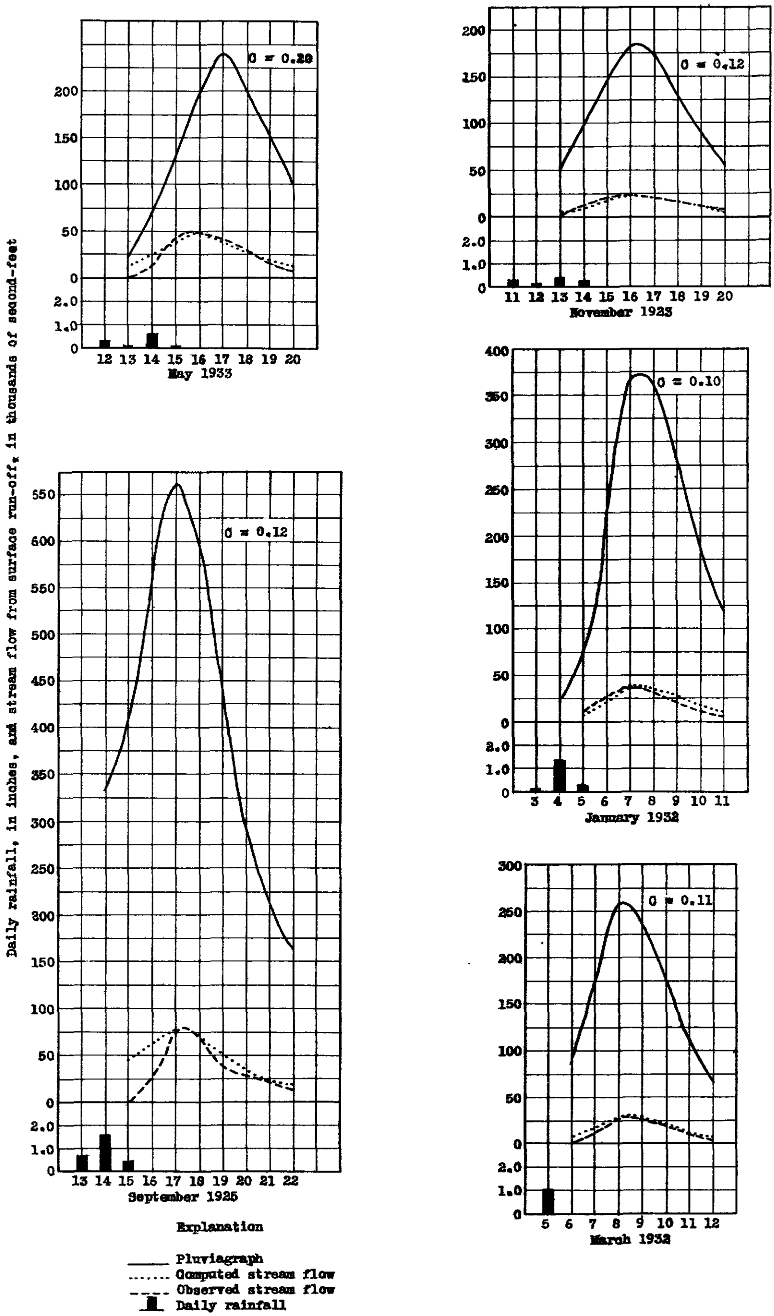


Figure 77.—Flood hydrographs and flood coefficients (C) for Red River near Denison, Tex.

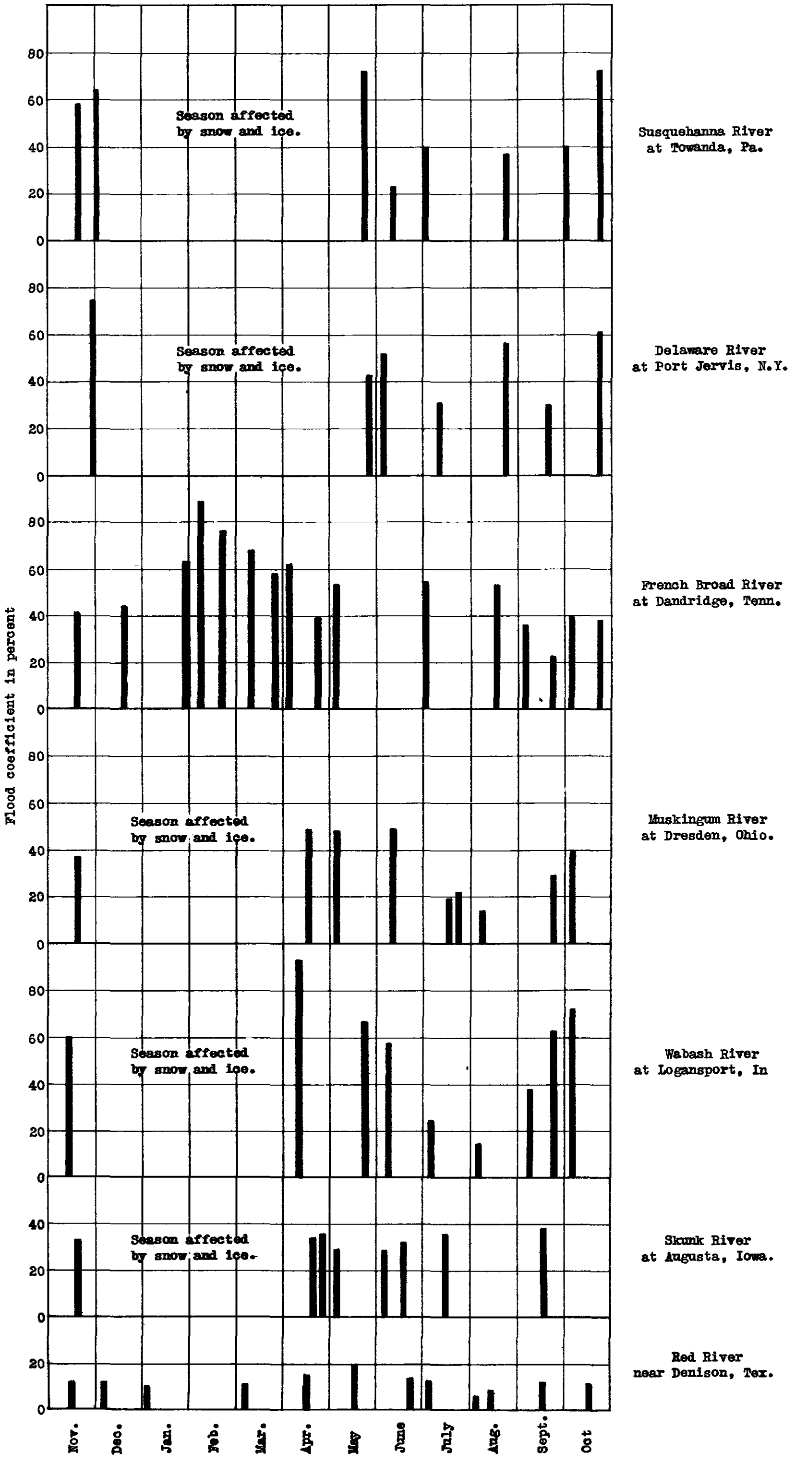


Figure 78.—Flood coefficients for selected drainage basins.

region against a recurrence of such a catastrophe. As a preliminary to the design of adequate flood protection works for the Miami Valley, an extensive research and analysis of rainfall data was made. This analysis, covering the whole of the eastern United States and complete to 1916, was published by the Miami Conservancy District (123). This report is now in the course of revision by the Conservancy District. The storms of such areal extent that they embraced at least five precipitation stations recording 6 inches or more of rainfall in 3 days are compared and classified on the basis of the fifth highest 3-day rainfall. This value is referred to as the storm index.

In the original report 160 notable storms were listed, plotted, and analyzed. The Conservancy District has since analyzed 90 storms occurring between 1916 and the end of 1931, making available for the present study detailed information regarding the 250 greatest storms visiting the eastern United States during the period 1892-1931.

A summarized classification of these storms is as follows:

Storm index (inches)	Number of storms greater than index
16	2
15	4
12	10
11	18
10	32
9	59
8	95
7	172
6	246

There is little doubt that as time passes storms will occur that will tend to increase all maxima and have the effect of moving inland charted isohyetals of excessive rainfall depths such as are presented in the isopluvial maps of the report cited (123), as well as in figure 79. This figure shows a sufficient number of storm indexes plotted at their approximate storm centers to determine the position of isohyetals enveloping areas having storms of equal or greater index. This illustration is noticeably similar to the isopluvial charts of the Miami Conservancy District report.

Storm transposition

The purpose of this study is to outline a refined method of estimating flood flow from storm rainfall and to direct attention to a fuller use of available storm data. The superposed storms are not to be accepted as "limiting" storms, but as actual great storms, which, having visited the vicinity, could have, with reasonable likelihood, shifted slightly and centered in a critical position on the particular basin of interest.

An examination of figure 79 indicates that storms having indexes of 8 to 12 inches have occurred at widely different points in the central and upper Mississippi Valley. The superposition of certain storms on any basin within the region encompassed by them seems logical. Mountainous topography, however, creates an entirely different situation. Storms centering on the windward slope of great mountain barriers cannot justifiably be shifted to basins lying on the leeward side.

Without involving questions of magnitude or frequency, valuable information may be gained by considering the superposition of a known storm in a critical position on a basin. The storm selected for use should not have its center so far removed from the basin as to cast doubt on the assumption that the storm could, with reasonable probability, have centered on the basin.

The method followed superposes in a critical position upon a map of the basin the pattern of the storm, pictured as isohyetals of equal rainfall depth for the storm period. The selection of a critical position entails the assumption of the position that would produce the greatest average depth of rainfall on the basin. As a rule this position is reasonably obvious. In a more detailed study the storm is centered on one or more of the subbasins having characteristics highly conducive to the production of floods. In such a study it is necessary to deal with all subbasins separately, synchronizing their flows in accordance with the indications of experience to the nearest practicable time unit. The present study considers only the position producing the greatest average depth over the basin.

The pattern or map of the storm having been fixed in critical position, the rainfall stations are treated as if the storm actually occurred in this locality and position. The rainfall depths are listed by date, properly weighted, and combined to give average daily rainfall over the basin throughout the storm period. All antecedent rainfall contributing surface run-off to the flood is included in the study.

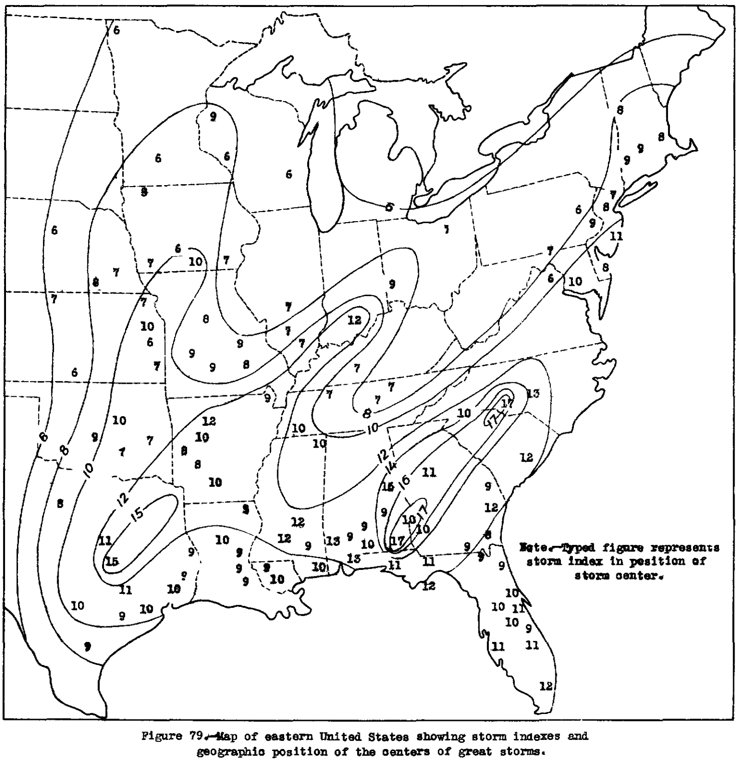


Figure 79.—Map of eastern United States showing storm indexes and geographic position of the centers of great storms.

Figure 49 of the Miami Conservancy report (123) shows the seasonal occurrence of the great storms embraced by the report. The 90 storms occurring since 1916 require, to some extent, revision of the chart. This can also be said of figures 50 to 57 of the report, which show the geographic position of the storms by seasons. In the northern group there were certain seasons in which it would seem, from the experience disclosed by the record, that it was practically impossible for a storm of any considerable magnitude to develop, the possible explanation being deficiency in air moisture occasioned by prevailing low temperatures.

Of the seven basins analyzed, the four appearing in the table below and shown in figure 80 were selected to demonstrate the unit-hydrograph method of determining flood flow. The study has used the division of the year into seasons suggested in the Miami Conservancy report, the quarters beginning on November 1, February 1, May 1, and August 1. The quarters in which no qualifying storm has visited the locality are then eliminated from consideration in each basin, and it is assumed that the superposed storm could have occurred in any of the other seasons. The seasons in which, it is assumed, the superposed storm could have occurred, based on figures 50 to 57 of the Miami report, are as follows:

Basin	Gaging station	Quarters	Months
Delaware River	Port Jervis, N. Y.	3d and 4th	May 1 to Oct. 31
French Broad River	Dandridge, Tenn.	3d and 4th	May 1 to Oct. 31
Wabash River	Logansport, Ind.	2d, 3d, and 4th	Feb. 1 to Oct. 31
Skunk River	Augusta, Iowa	3d and 4th	May 1 to Oct. 31

For each of these basins the maximum flood coefficient for the season in which the storm occurred is also the maximum for any other season in which it is considered possible for the storm to have occurred. This coefficient has been used for estimating the probable surface run-off of each storm in the superposed position.

Tables 55, 56, 57, and 58 give flood coefficients for the months of probable storm occurrence in each of the four basins.

Table 55.- Flood coefficients for Delaware River at Port Jervis, N. Y.

Date	Maximum pluviagraph value (second-feet)	Maximum daily surface run-off (second-feet)	Flood coefficient
Third quarter:			
May 25, 1927	68,700	29,600	0.43
June 6, 1928	55,800	29,200	.52
July 9, 1915	101,200	31,700	.31
Fourth quarter:			
Aug. 25, 1933	* 121,800	* 68,500	.56
Sept. 17, 1933	77,500	23,300	.30
Oct. 20, 1927	85,400	51,900	* .61

* Maxima.

Table 56.- Flood coefficients for French Broad River at Dandridge, Tenn.

Date	Maximum pluviagraph value (second-feet)	Maximum daily surface run-off (second-feet)	Flood coefficient
Third quarter:			
May 4, 1932	45,700	25,500	0.53
June 30, 1928	88,000	47,500	* .54
Fourth quarter:			
Aug. 17, 1928	* 122,000	* 64,500	.53
Sept. 2, 1928	106,000	22,000	.23
Sept. 7, 1928	79,000	29,000	.36
Oct. 1, 1929	82,000	30,500	.39
Oct. 23, 1929	95,000	36,000	.38

* Maxima.

Table 57.- Flood coefficients for Wabash River at Logansport, Ind.

Date	Maximum pluviagraph value (second-feet)	Maximum daily surface run-off (second-feet)	Flood coefficient
Second quarter:			
Mar. 22, 1927	72,600	* 51,700	0.71
Mar. 31, 1924	55,000	35,000	.84
Apr. 8, 1926	54,900	50,800	* .93

* Maxima.

Table 57.- Flood coefficients for Wabash River at Logansport, Ind.--Continued

Date	Maximum pluviagraph value (second-feet)	Maximum daily surface run-off (second-feet)	Flood coefficient
Third quarter:			
May 21, 1927	63,700	42,700	0.67
June 10, 1924	67,700	38,400	.57
July 6, 1929	61,600	15,000	.24
Fourth quarter:			
Aug. 3, 1926	69,800	9,500	.14
Sept. 3, 1926	* 76,600	29,300	.38
Sept. 25, 1926	50,200	31,000	.63
Oct. 7, 1926	44,500	32,000	.72

* Maxima.

Table 58.- Flood coefficients for Skunk River at Augusta, Iowa

Date	Maximum pluviagraph value (second-feet)	Maximum daily surface run-off (second-feet)	Flood coefficient
Third quarter:			
May 4, 1919	58,000	16,500	0.29
June 5, 1917	87,500	24,500	.28
June 15, 1930	* 130,500	* 41,000	.32
July 11, 1915	50,000	20,000	.35
Fourth quarter:			
Sept. 15, 1926	78,500	26,000	* .38

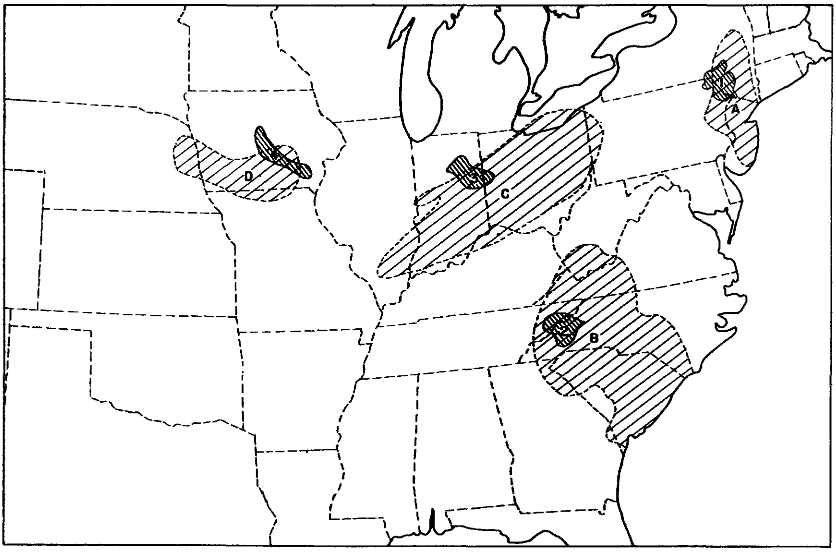
* Maxima.

Storm superposition

Figure 80 shows the outlines of the four basins and the area embraced by four major storms.

Delaware River Basin above Port Jervis, N. Y.

Storm A, of October 8-11, 1903, occupied the 22d position in order of magnitude of storms over the eastern United States and ranked 3d among the northern storms, with a storm index of 10.66. It centered at



Explanation

1 Delaware River Basin above Port Jervis, N.Y.
2 French Broad River Basin above Dandridge, Tenn.
3 Wabash River Basin above Logansport, Ind.
4 Skunk River Basin above Augusta, Iowa

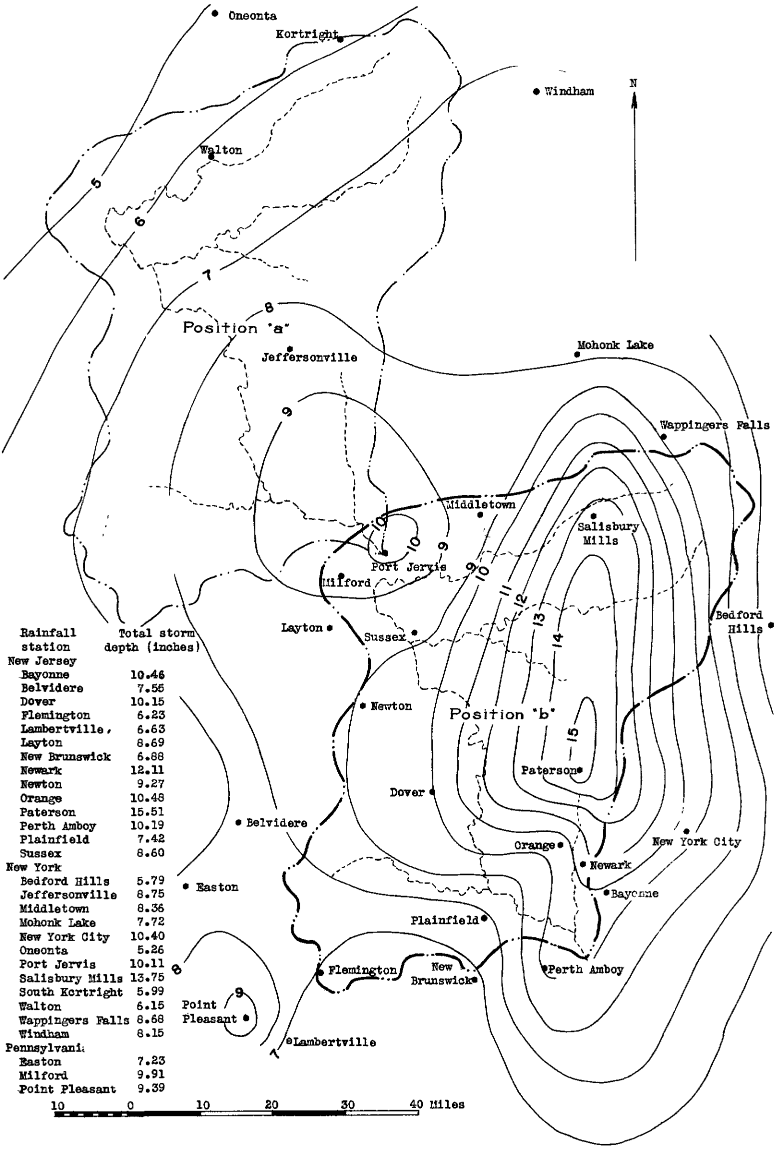
A Storm of October 8-11, 1903
B Storm of July 15-16, 1916
C Storm of March 24-26, 1913
D Storm of August 25-28, 1903

Figure 80.—Map of eastern United States showing location of storm areas relative to selected drainage basins.

Paterson, N. J., and enveloped the Delaware Basin above Port Jervis, N. Y. An average depth of about 8 inches of rainfall fell on this basin during the storm, developing a flood peak at Port Jervis that is still the greatest of record (U. S. Geol. Survey Water-Supply Paper 726, p. 216, 1932). This storm is considered in the two positions shown in figure 81. Position a is that in which the storm actually occurred. The flood pluviagraph has been constructed by applying the distribution graph for the basin to the weighted daily rainfall shown in figure 82. The flood hydrograph of surface run-off shown in figure 82 has been obtained by applying a flood coefficient of 0.61, the highest developed in the possible seasons (3d and 4th quarters, table 55) to the daily ordinates of the pluviagraph. The computed maximum daily flow is 142,800 second-feet. This figure is consistent with the estimated instantaneous peak of about 155,000 second-feet for this flood (U. S. Geol. Survey Water-Supply Paper 726, p. 216, 1932). The storm was next considered in position b, under which the greatest possible average depth of rainfall over the basin was developed. Obviously this involves the question whether it would be consistent with topographic and other controlling conditions for this storm to occur in the transposed position. By weighting the daily rainfall at the stations in their new positions and applying the distribution graph for the basins and the same flood coefficient a maximum daily discharge of 187,000 second-feet was computed. To the extent that the various assumptions are correct, if the storm of October 1903 had centered 80 miles to the northwest it would have produced a maximum daily discharge of 187,000 second-feet at Port Jervis.

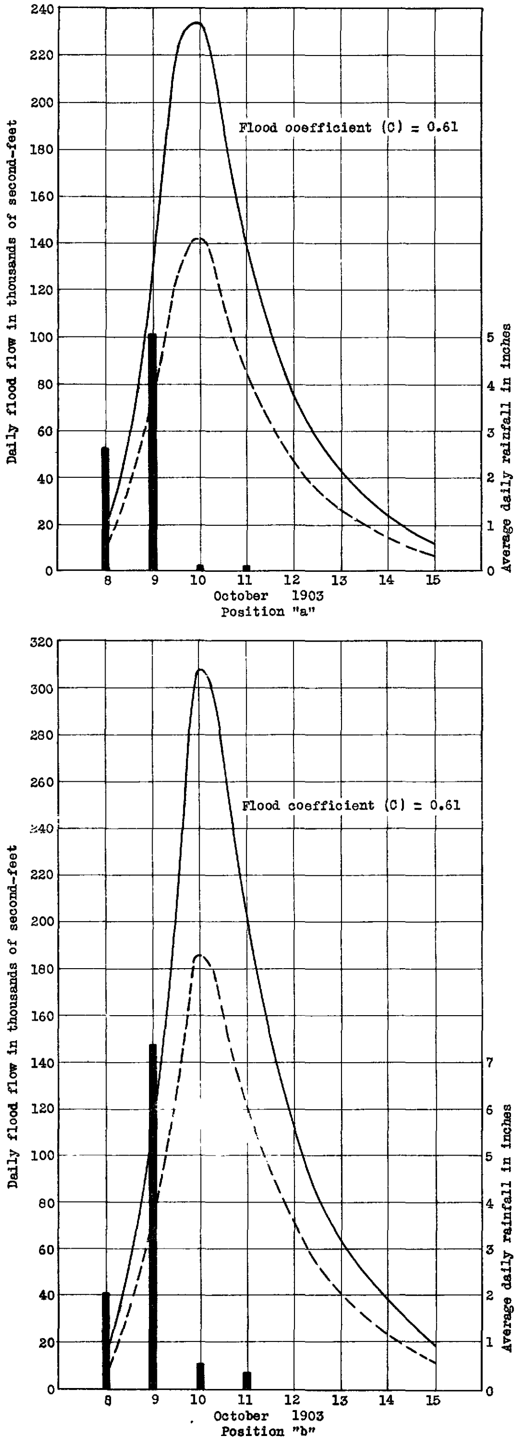
French Broad River Basin above Dandridge, Tenn.

Storm B, of July 15-16, 1916, centered at Altapass, N. C., with one of the highest single-station 24-hour rainfall depths on record. With a storm index of 16.77 inches, it was the 2d largest of storms over the eastern United States. The excessive rainfall was confined principally to the eastward slopes of the Blue Ridge but averaged more than 5 inches over the French Broad Basin above Dandridge, Tenn. The storm's position is shown in figure 83. The pluviagraph was based on recorded precipitation. The highest flood coefficient developed within the record period for the seasons in which it is assumed that such a storm could have occurred was



Rainfall station	Total storm depth (inches)
New Jersey	
Bayonne	10.46
Belvidere	7.55
Dover	10.15
Flemington	6.23
Lambertville,	6.63
Layton	8.69
New Brunswick	6.88
Newark	12.11
Newton	9.27
Orange	10.48
Paterson	15.51
Perth Amboy	10.19
Plainfield	7.42
Sussex	8.60
New York	
Bedford Hills	5.79
Jeffersonville	8.75
Middletown	8.36
Mohonk Lake	7.72
New York City	10.40
Oneonta	5.26
Port Jervis	10.11
Salisbury Mills	13.75
South Kortright	5.99
Walton	6.15
Wappingers Falls	8.68
Windham	8.15
Pennsylvania	
Easton	7.23
Milford	9.91
Point Pleasant	9.39

Figure 81.—Storm of October 8-11, 1903, with relative location of Weather Bureau stations and the Delaware River Basin above Port Jervis, N.Y., in its actual position ("a") and shifted so as to give a maximum average depth of rainfall on the basin (position "b").



Average distribution graph

Day	Percent
1 a/	6
2	43
3	24
4	13
5	7
6	4
7	2
8	1
	100

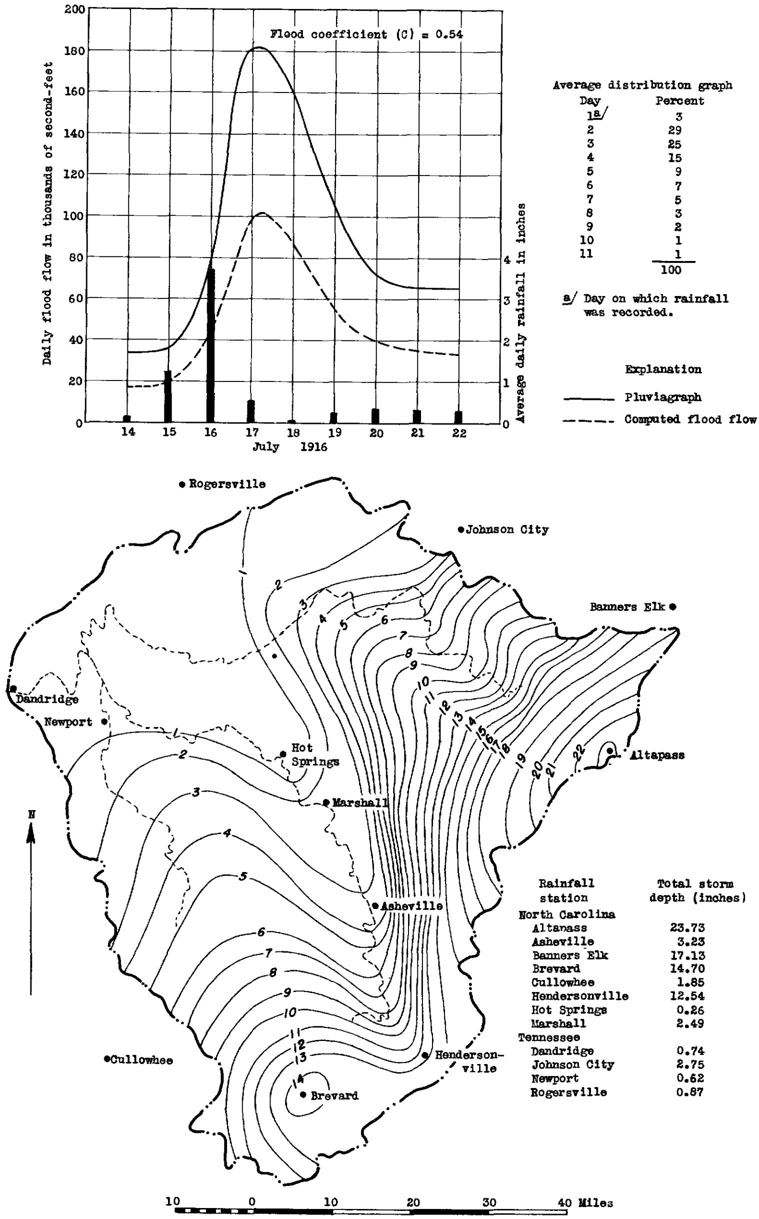
a/ Day on which rainfall was recorded.

Explanation

——— Pluviagraph

– – – – Computed flood flow

Figure 82.- Delaware River at Port Jervis, N. Y., pluviagraphs and hydrographs of computed flood flow resulting from storm of October 8-11, 1903, in its actual position ("a") and shifted so as to give a maximum average depth of rainfall on the basin (position "b").



Average distribution graph

Day	Percent
1a/	3
2	29
3	25
4	15
5	9
6	7
7	5
8	3
9	2
10	1
11	1
	100

a/ Day on which rainfall was recorded.

Rainfall station	Total storm depth (inches)
North Carolina	
Altapass	23.73
Asheville	3.23
Banners Elk	17.13
Brevard	14.70
Cullowhee	1.85
Hendersonville	12.54
Hot Springs	0.26
Marshall	2.49
Tennessee	
Dandridge	0.74
Johnson City	2.75
Newport	0.62
Rogersville	0.87

Figure 83.—Storm of July 15-16, 1916, in its actual position on French Broad River Basin above Dandridge, Tenn., and resulting pluviagraph and hydrograph of computed flood flow.

0.54. This coefficient, applied to the pluviagraph, produced the estimated flood hydrograph of surface flow shown in figure 83, with a maximum of 98,400 second-feet. A stage of 21.0 feet was recorded on July 17, 1916, by the United States Weather Bureau. This stage corresponds to a flow of 100,000 second-feet based on an extension of the rating curves from 16.1 feet to 21.0 feet. Because of differences in topography it is not considered feasible to center this storm on the French Broad River Basin.

Wabash River Basin above Logansport, Ind.

Storm C, of March 24-26, 1913, centering in eastern Indiana and western Ohio, caused the disastrous flood on the Miami River. With a storm index of 8.98 inches, it is the 9th largest of the northern storms. This storm has been used by various investigators to estimate probable flood discharge for many areas. By the method outlined in this study, the surface flood flow that would have resulted had this storm centered critically on the Wabash River above Logansport, Ind., has been computed and is shown graphically in figure 84. The figure also shows the storm superposed over the basin in such a position as to produce the maximum average depth of rainfall. The stations listed on the basin map are located relative to the storm and not to the basin area. The high flood coefficient, 0.93, is substantiated by those developed in this season on the Muskingum River above Dresden, Ohio, and a coefficient of over 0.90 was developed during the storm of March 1913 on the Miami River above Sidney, Ohio.

Skunk River Basin above Augusta, Iowa

Figure 85 shows storm D, of August 25-28, 1903, the 30th in order of magnitude of storms over the eastern United States and the 4th largest of the northern storms, superposed in critical position on the Skunk River Basin above Augusta, Iowa. The maximum flood coefficient of 0.38 is applied to the computed pluviagraph to give the estimated flood hydrograph of surface run-off shown in the figure. This graph indicates a maximum daily discharge of 118,300 second-feet, or 28 second-feet per square mile.

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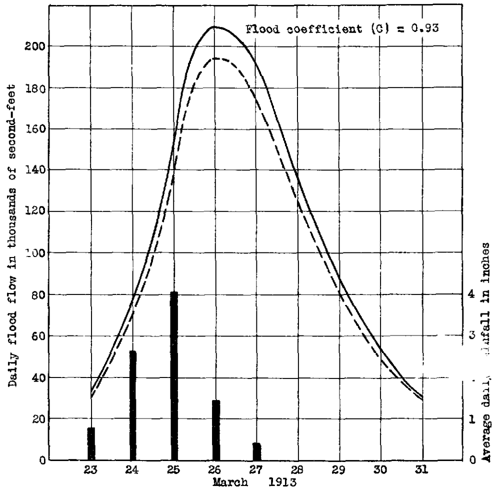
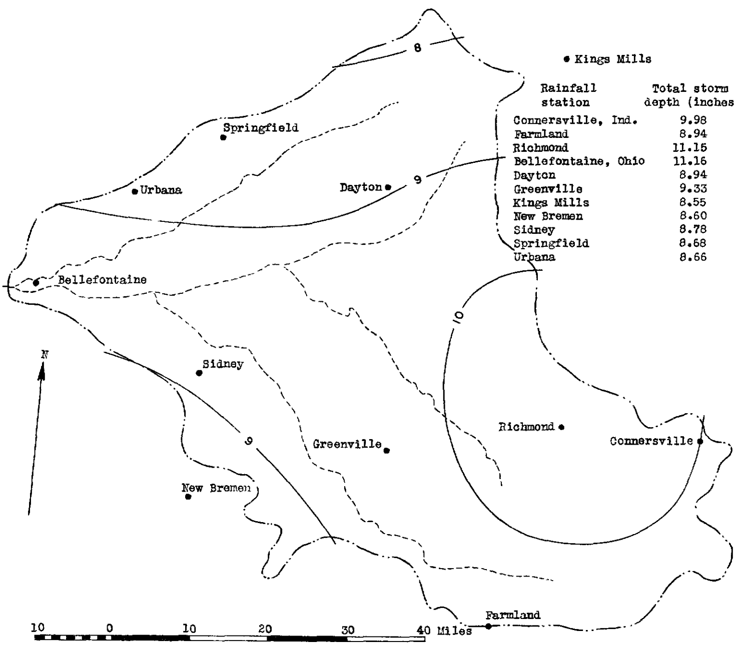


Average distribution graph

Day	Percent
1[a]	3
2	12
3	27
4	24
5	14
6	9
7	5
8	3
9	2
10	1
	100

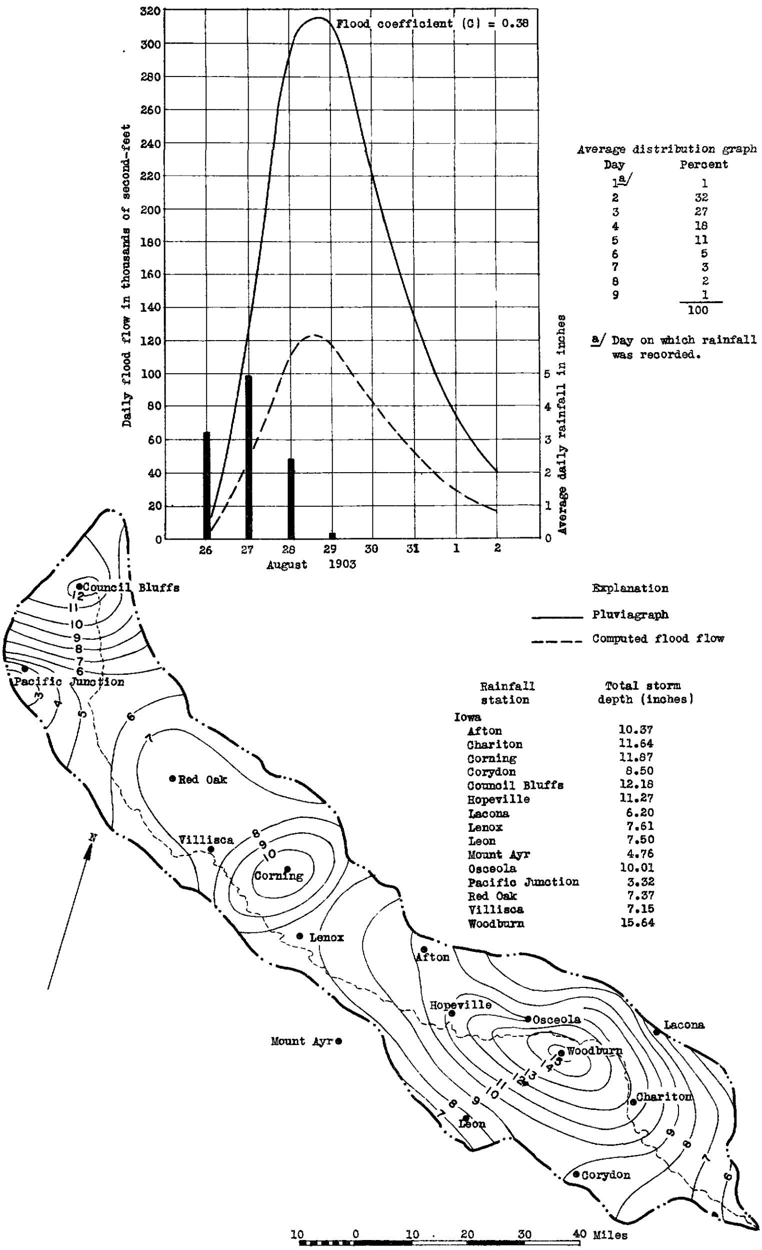
[a] Day on which rainfall was recorded.

Explanation
——— Pluviagraph
- - - - Computed flood flow



Rainfall station	Total storm depth (inches)
Connersville, Ind.	9.98
Farmland	8.94
Richmond	11.15
Bellefontaine, Ohio	11.16
Dayton	8.94
Greenville	9.33
Kings Mills	8.55
New Bremen	8.60
Sidney	8.78
Springfield	8.68
Urbana	8.66

Figure 84.—Storm of March 24-26, 1913, with relative location of Weather Bureau stations superposed on Wabash River Basin above Logansport, Ind., and resulting pluviagraph and hydrograph of computed flood flow.



Average distribution graph

Day	Percent
1 a/	1
2	32
3	27
4	18
5	11
6	5
7	3
8	2
9	1
	100

a/ Day on which rainfall was recorded.

Rainfall station	Total storm depth (inches)
Iowa	
Afton	10.37
Chariton	11.64
Corning	11.87
Corydon	8.50
Council Bluffs	12.18
Hopeville	11.27
Lacona	6.20
Lenox	7.61
Leon	7.50
Mount Ayr	4.76
Osceola	10.01
Pacific Junction	3.32
Red Oak	7.37
Villisca	7.15
Woodburn	15.64

Figure 85.—Storm of August 25-28, 1903, with relative location of Weather Bureau stations superposed on Skunk River Basin above Augusta, Iowa, and resulting pluviagraph and hydrograph of computed flood flow.

Floods influenced by snow

As previously stated the present study excludes an analysis of storm run-off during winter periods, when, as a result of run-off from melted snow, appreciable floods may be produced by light rainfall accompanied by marked rises in temperature. Under these conditions the hydrograph of stream flow may show peaks exceeding peak pluviagraph values and so-called "flood coefficients" exceeding unity.

The analysis of several hydrographs of run-off associated with melting snow, however, has disclosed an interesting and apparently significant fact. It was found that run-off from winter rainfall, augmented by melting snow and ice, responded satisfactorily to the daily "proportioning" of the distribution graph developed from normal rainfalls. In other words, the run-off from the melted snow and ice seemed to be distributed in the same proportions as the run-off from rain.

Conclusion

This special study has been intended primarily to examine the possibilities of storm superposition as a means of determining flood flow, and it is realized that further refinements may be practical and essential to the ultimate development of this method. The study is intended to direct attention to the possibility of a fuller use of available storm data, rather than to indicate that such storms are to be taken conclusively as limiting storms for their respective localities. Use of such storms as a basis for estimating flood flow should be made with caution and with appreciation of their significance, and the impression should not be created that the estimated results are necessarily to be accommodated by any contemplated design.

Ground-water run-off

In the preceding pages some of the problems in connection with the separation of ground-water run-off and surface run-off are discussed, together with a quantitative analysis of surface run-off and its characteristics as disclosed by unit hydrographs. The following discussion relates to the disposal of that part of the precipitation which either is lost through evaporation and transpiration, is accumulated in the ground as soil moisture or ground water, or flows out of the basin as ground-water run-off.

The following tables show for typical basins in the United States and for major subdivisions of the Mississippi River Basin above Keokuk, Iowa, an estimate of the mean annual ground-water run-off expressed in inches and as a percentage of "precipitation minus surface run-off." All figures are, in general, 5-year annual averages and were obtained through a study of the plotted hydrographs of total stream flow, in part by methods described on pages 111-119.

As was pointed out in the discussion of the quantitative analysis of surface run-off, these estimates are subject to error. To the extent that the estimates of ground-water run-off are too large the estimates of surface run-off are too small, and vice versa. These estimates are rough approximations of the amount of infiltration that eventually reaches stream channels. They represent on an annual basis that part of the stream flow which is dependable, as compared with erratic and often destructive surface run-off.

As noted elsewhere, the figures given for the Miami River, Ohio, and the Pomperaug Basin, Conn., are based on a general straight-line separation, and the results may not be entirely comparable with the figures given for the other basins. However, where comparisons have been made between annual estimates of ground-water run-off based on straight lines connecting the low points of hydrographs and estimates based on other methods the differences have generally not exceeded 10 percent on an annual basis, the straight-line method giving the smaller result.

Table 59.- Ground-water run-off for typical basins in the United States

Basin	Precipitation (inches)	Precipitation minus Surface run-off (inches)	Ground-water run-off		
			Inches	Percent of total run-off	Percent of "Precipitation minus Surface run-off"
Red River above Grand Forks, N. Dak. (1928-32)	18.53	18.18	0.24	40.7	1.3
Mississippi River above Keokuk, Iowa (1928-32)	28.64	25.28	2.62	43.8	10.4
Neosho River above Iola, Kans. (1928-32)	33.07	29.01	0.86	17.5	3.0
Merrimack River above Lawrence, Mass. (1928-32*)	40.66	30.72	## 9.59	49.1	31.2
James River above Cartersville, Va. (1928-32)	38.04	31.02	6.09	46.4	19.6
Tennessee River above Chattanooga, Tenn. (1901-5)	49.83	34.53	8.44	35.6	24.5
Chattahoochee River above West Point, Ga. (1928-32)	59.65	48.06	11.55	49.9	24.0
Miami River above** Dayton, Ohio (1894-1919*)	37.07	29.30	4.08	34.4	13.9
Pomperaug River above# Bennetts Bridge, Conn. (1914-16*)	44.48	32.58	8.76	42.4	26.9

* Years ending September 30.
** Ref. 72.
\# Ref. 115.
\## Probably too large.

Table 60.- Ground-water run-off for major subdivisions of Mississippi River Basin above Keokuk, Iowa

Subdivision	Precipi-tation (inches)	Precipi-tation Surface run-off (inches)	Ground-water run-off		
			Inches	Percent of total run-off	Percent of "Precipi-tation minus Surface run-off"
Minnesota River above Mankato, Minn. (1930-32*)	22.22	21.80	0.27	39.0	1.2
Black River above Neillsville, Wis. (1928-32*)	30.99	23.15	1.48	15.9	6.4
Skunk River above Augusta, Iowa (1928-32*)	35.85	30.38	2.37	30.2	7.8
Zumbro River above Zumbro Falls, Minn. (1931-32*)	26.35	24.65	1.78	51.2	7.2
Yellow River above Sprague, Wis. (1928-32*)	29.09	24.22	1.92	28.3	7.9
Iowa River above Wapello, Iowa (1928-32*)	32.83	28.55	2.72	38.9	9.5
Maquoketa River above Maquoketa, Iowa (1931-32*)	30.64	27.75	2.73	48.5	9.8
Root River above Houston, Minn. (1931-32*)	27.98	25.56	3.00	55.4	11.7
Rock River above Afton, Wis. (1928-32*)	29.62	25.99	3.78	51.0	14.5
St. Croix River above Rush City, Minn. (1928-32*)	25.32	21.56	3.51	48.3	16.3
Pecatonica River above Freeport, Ill. (1928-32*)	31.95	27.18	5.24	52.3	19.3
Kickapoo River above Gays Mills, Wis. (1928-32*)	29.67	26.03	5.47	60.0	21.0
La Crosse River above West Salem, Wis. (1928-32*)	30.35	27.71	7.28	73.4	26.2

* Years ending September 30.

Soil moisture

As is shown in the quantitative analysis of ground-water run-off in tables 59 and 60, only a relatively small part of the "precipitation minus surface run-off" eventually appears in the stream as seepage from ground-water. Although it is known that the portion which does not eventually appear as stream flow, either surface or underground, represents the amount of water that is either evaporated or transpired, the exact processes involved are complex. One important phase of these hydrologic processes is, however, related to soil moisture and changes therein.

O. E. Meinzer (113) defines soil water as moisture in "the part of the lithosphere, immediately below the surface, from which water is discharged into the atmosphere in perceptible quantities by the action of plants or by soil evaporation."

G. E. Condra (31a) defines soil moisture as "the capillary phase of ground-water accumulation" and states that "because of its bearing on agriculture, it is perhaps our most economically important resource. There is drought when and where soil moisture fails during the growing season."

In addition to being one of the most important phases of the hydrologic cycle from the viewpoint of the agriculturist, it is of particular interest to the hydrologist. Information regarding the characteristics of changes in soil moisture is desirable in connection with the determination of run-off coefficients for use in studies of flood, drought, and erosion problems, and in the application of methods, such as Meyer's, for computing stream flow from meterologic information.

Field experiments by Houk in Ohio and by Taylor and others in California give valuable information concerning changes in soil moisture over small areas. Whether such information can be obtained over larger areas, other than through detailed field observations, presents an interesting question. Houk, in his study of rainfall and run-off in the Miami Valley (72), made a quantitative analysis of the components of the hydrologic cycle, month by month. He presents for the Mad River Valley above Wright, Ohio, for the years 1915 to 1919, graphs showing by months the rainfall, flood run-off (surface run-off), ground-water run-off, soil absorption, percolation and evaporation. The method used by Houk in obtaining the ground-water run-off and the flood run-off is described on page 112, of the present report. His so-called "retention" (storage, absorption, and evaporation) was obtained by subtracting the run-off from the precipitation. The soil absorption was estimated on the basis of plot experiments. It was "assumed that there is a variation of 5 inches in the amount of moisture during the year; that the soil reaches its driest condition sometime late in the summer, during August or September; that it gradually fills with moisture during the months of September, October, November, and December; and that this remains saturated until late in the spring, when it begins to dry out due to transpiration and increased soil evaporation. In drawing percolation curves it was assumed that percolation ceases about the time the soil begins to dry out in the spring and does not begin until late in the fall, about the time the surface soil becomes saturated."

A somewhat different method of approach was used in the present study. The "precipitation minus surface run-off" having been determined as an approximate representation of the amount of water which either is absorbed by the soil or remains on the surface in some form of storage, it is possible to obtain, by the use of the Meyer curves of evaporation and transpiration, an approximation of the soil-moisture changes plus accretion to ground water. The objection may be raised that inasmuch as the evaporation, transpiration, surface run-off, and amount of accretion to the ground water cannot be determined accurately, the derived changes in soil moisture may have little relation to the facts. It is evident that errors in the determination of these factors may be of such magnitude as to cast doubt on the accuracy of the results. To the extent, however, that the results are demonstrated to be reasonable, as by comparison with observations relating to soil-moisture conditions, they may throw some light on this phase of the hydrologic cycle. When the data now being collected in great quantity at the numerous projects being carried on by the Soil Conservation Service, Forest Service, United States Geological Survey, and other agencies become available, greater refinement in the methods of quantitative analysis may be developed. A summary and brief discussion of the analyses that were made in the present study with reference to the investigation of soil moisture is given below.

The average precipitation and temperature were determined month by month over several drainage basins in the upper Mississippi Valley, from Weather Bureau records. The evaporation from water surfaces in the basins studied was assumed to be so small that it could be neglected. The evaporation from land areas and transpiration were based on curves developed by

Adolph F. Meyer (122, 2d ed., fig. 272, p. 456, and fig. 164, p. 263), using the method described (idem, pp. 455-458) as follows:

> "The author's evaporation curve.- The variation of evaporation from land areas with changes in seasons, monthly mean temperature, and monthly mean rainfall, based on the author's study of the subject, is summarized in the evaporation curve of figure 272.
>
> "In the fall, when the monthly temperature reaches 20°, practically all the precipitation occurs as snow; consequently, evaporation for temperatures below 20° is no longer dependent on precipitation after the ground has been covered with snow, but entirely on temperature. Full evaporation, corresponding to the given monthly temperature, is usually possible throughout the winter. After the temperature rises above 20°, in spring, the evaporation again depends largely on available moisture, as determined mainly by precipitation. Nevertheless, a considerable constant evaporation is still possible, irrespective of precipitation, because a certain quantity of snow and ice is almost always present on the ground while the monthly temperature ranges from 20° to 35°. After the snow has disappeared, there will still be a relatively large constant evaporation, irrespective of the rainfall, unless the winter precipitation has been distinctly deficient.
>
> "A gradual reduction in the constant evaporation has been assumed for the summer. It is realized, of course, that the constant evaporation during the summer depends, in a measure, on the rainfall of each previous month. In making detailed computations of evaporation losses, the constant evaporation is readily varied by one or two tenths of an inch, in accordance with apparent variations in storage. On some watersheds, when the fall precipitation is very low and the temperature remains above 30°, the right-hand portion of the curve is used for January and sometimes also for February - that is, when the storage is practically exhausted and there is no snow on the ground, the constant of evaporation otherwise used practically vanishes, and the evaporation is entirely proportional to the rainfall. In the same way, when the fall rains are copious and the ground-water supply is abundant, a constant of evaporation one or two tenths higher than that given by the curve may be used to advantage.
>
> "The portions of the limiting curve below temperatures of approximately 35° represent evaporation from snow and ice surfaces. At the higher temperatures the limiting curve represents values somewhat less than the evaporation from shallow water. The quantity evaporated out of each inch of rainfall becomes less and less as the monthly precipitation increases, varying more rapidly at the lower than at the higher rates of precipitation.
>
> "To the values of evaporation, in inches of depth per month, as taken off the curve, a coefficient must be applied to reduce these quantities to actual evaporation from the given watershed. This coefficient ranges from about 0.95 to 1.25 for most watersheds of the Northwest and for similar ones elsewhere. Very sandy watersheds may require a coefficient as low as 0.60, and very impervious flat watersheds may require a coefficient in excess of 1.25. The coefficient to be used depends on topography, vegetal cover, soil, subsoil, humidity, and wind. An extremely high coefficient of evaporation (in excess of 1.25) would result from flat topography devoid of vegetation, moderately pervious, shallow soil underlain with impervious subsoil or rock, low humidity, and high wind velocity. An extremely low coefficient (less than 0.95) would result from rugged topography, bare scanty soil underlain with rock, high humidity, and low wind velocity or extremely sandy soil. Between these limits the usual working values will be found. With a little experience, one can select coefficients for different watersheds with considerable accuracy.

"The author's transpiration curve.- The base values for total transpiration, in inches of depth, during the growing season on any given watershed, are selected with reference to the character of the vegetation and the length of the growing season on that watershed, giving consideration also to available sunshine. In the following computations a normal seasonal transpiration of about 9 inches has been assumed for small grains, grasses, and other agricultural crops, 8 to 12 inches for deciduous trees, 4 inches for evergreen trees, and 6 inches for small trees and brush. The normal monthly distribution of this total seasonal transpiration is based mainly on temperature. To obtain actual transpiration in any given month, however, the values taken from the transpiration curve (fig. 164, p. 263), after being multiplied by a coefficient, must be further modified on the basis of available moisture. Where precipitation minus evaporation for a given month is insufficient to meet the normal plant requirements for that month, the ground water is drawn on to a varying extent, depending on the character of the root system of the given vegetation, the depth and character of the soil, and the quantity of surface-soil storage, as determined by the precipitation minus losses for previous months."

Although the study covered the entire period from 1916 to 1934 there is given in table 61 for the Skunk River Basin, Iowa, for the period October 1927 to September 1932, (1) observed precipitation over the basin; (2) observed temperature; (3) computed transpiration over the basin; (4) computed evaporation over the basin; (5) the surface run-off determined from a study of the hydrograph of total flow; (6) "Precipitation minus surface run-off" which in basins like this one, where the surface run-off is rapid, represents evaporation and transpiration, a small amount of surface storage, and the infiltration month by month. In column 7 is given the difference between "Precipitation minus surface run-off" and the total computed transpiration and evaporation. The plus sign indicates that the demands of transpiration and evaporation were less than the supply during that month and that there was either an increase in soil moisture or an accretion to the water table, or both, by about the amount indicated. The minus sign indicates that the current water supply was less than the combined demands of evaporation and transpiration and that there was a draft either on soil moisture or on the ground water, or both, by about the amount indicated.

The monthly accretion to ground water (column 8) was estimated by applying the average ground-water depletion curve to the estimated hydrograph of ground-water flow at both the beginning and end of the month, and designating the area bounded by the hydrograph and the two depletion curves to the point of their intersection as "ground-water accretion" for the month under study. With these estimates (column 8) it is

Table 61.- Observed and estimated meteorologic and hydrologic data for Skunk River Basin above Augusta, Iowa

Month	Precipitation (inches)	Temperature (°F.)	Transpiration (inches)	Evaporation (inches)	Surface run-off (inches)	Precipitation minus surface run-off (inches)	Column 6 minus columns 3 and 4 (inches)	Total accretion to ground water (inches)	Changes in soil moisture (inches)	Ground-water run-off (inches)
	1	2	3	4	5	6	7	8	9	10
1927										
Oct.	5.08	57.8	1.00	2.08	0.51	4.57	1.49	0.20	+1.29	0.12
Nov.	1.14	41.8	0	.41	.04	1.10	.69	0	+ .69	.07
Dec.	1.16	24.3	0	.38	.14	1.02	.64	.11	+ .53	.03
1928										
Jan.	.18	26.1	0	.48	.21	– .03	–.51	0	– .51	.09
Feb.	2.18	31.0	0	.83	.96	1.22	.39	.27	+ .12	.15
Mar.	1.66	40.0	.05	.78	.24	1.42	.59	.21	+ .38	.24
Apr.	2.61	46.8	.40	1.14	.28	2.33	.79	.29	+ .50	.29
May	1.95	64.2	1.30	1.20	.09	1.86	–.64	0	– .64	.13
June	6.81	66.7	1.50	3.25	.54	6.27	1.52	.35	+1.17	.09
July	4.71	76.0	2.30	2.86	1.03	3.68	–1.48	.07	–1.55	.24
Aug.	6.54	74.7	2.10	3.43	.94	5.60	.07	.12	– .05	.24
Sept.	3.59	62.6	1.40	1.86	.37	3.22	–.04	.07	– .11	.17
Oct.	3.93	56.5	1.00	1.61	.36	3.57	.96	.64	+ .32	.24
Nov.	4.32	41.4	0	1.20	1.28	3.04	1.84	.79	+1.05	.48
Dec.	1.17	31.3	0	.30	.85	.32	.02	0	+ .02	.55
1929										
Jan.	2.42	13.7	0	.31	.12	2.30	1.99	0	+1.99	.21
Feb.	1.25	18.1	0	.50	.16	1.09	.59	.11	+ .48	.15
Mar.	2.07	43.4	.20	.93	2.73	– .66	–1.79	.86	–2.65	.36
Apr.	5.30	53.0	1.00	2.14	2.18	3.12	– .02	.76	– .78	.60
May	2.13	59.6	1.30	1.20	.29	1.84	– .66	0	– .66	.55
June	2.70	69.0	1.50	1.72	.15	2.55	– .67	0	– .67	.25
July	5.06	75.7	2.20	2.96	.47	4.59	– .57	.12	– .69	.14
Aug.	2.70	72.4	1.60	1.67	.16	2.54	– .73	0	– .73	.11
Sept.	4.01	64.6	1.40	1.98	.07	3.94	.56	.06	+ .50	.07
Oct.	3.34	53.2	.70	1.31	.07	3.27	1.26	.15	+1.11	.09
Nov.	1.41	34.6	0	.36	.16	1.25	.89	.17	+ .72	.14
Dec.	.53	28.4	0	.16	.02	.51	.35	0	+ .35	.12
1930										
Jan.	1.69	14.8	0	.35	.01	1.68	1.33	0	+1.33	.07
Feb.	.98	37.2	0	.59	.59	.39	– .20	.44	– .64	.19
Mar.	.99	38.4	0	.59	.11	.88	.29	0	+ .29	.26
Apr.	2.78	53.3	.80	1.35	.13	2.65	.50	.10	+ .40	.14
May	3.18	62.8	1.40	1.75	.21	2.97	– .18	.25	– .43	.21
June	7.45	71.0	2.10	3.74	1.99	5.46	– .38	.46	– .84	.23
July	1.20	78.6	2.30	1.04	.09	1.11	–2.23	0	–2.23	.17
Aug.	1.98	75.6	1.70	1.35	.02	1.96	–1.09	0	–1.09	.04
Sept.	2.50	68.9	1.30	1.46	.02	2.48	– .28	0	– .28	.02
Oct.	2.22	52.2	.50	.90	.04	2.18	.78	0	+ .78	.02
Nov.	1.94	42.8	0	.60	.02	1.92	1.32	0	+1.32	.01
Dec.	.97	28.0	0	.28	.08	.89	.61	0	+ .61	.01
1931										
Jan.	.59	31.4	0	.54	.01	.58	.04	0	+ .04	.01
Feb.	.18	36.8	0	.42	.03	.16	– .26	.08	– .35	.04
Mar.	2.45	36.2	0	.94	.05	2.39	1.45	.05	+1.41	.04
Apr.	3.30	52.3	.70	1.51	.37	2.93	.72	.20	+ .52	.11
May	3.08	58.4	1.20	1.56	.04	3.04	.28	0	+ .28	.08
June	4.05	76.5	2.20	2.48	.38	3.67	–1.01	.08	–1.09	.08
July	3.61	80.2	2.40	2.41	.22	3.39	–1.42	0	–1.42	.05
Aug.	3.56	74.6	1.90	2.10	.05	3.51	– .49	0	– .49	.02
Sept.	7.21	72.4	2.10	3.50	.40	6.81	1.21	.12	+1.09	.04
Oct.	4.19	59.0	1.10	1.77	.29	3.90	1.03	.20	+ .83	.16
Nov.	5.96	48.8	.40	1.62	1.55	4.41	2.39	1.01	+1.38	.20
Dec.	2.84	37.1	0	.72	1.07	1.77	1.05	.30	+ .75	.59
1932										
Jan.	1.56	30.0	0	.70	1.53	.03	– .67	.33	–1.00	.49
Feb.	.75	34.0	0	.55	.28	.47	– .08	.53	– .61	.45
Mar.	1.53	29.7	0	.70	.38	1.15	.45	.33	+ .12	.52
Apr.	1.49	50.3	.50	.83	.08	1.41	.08	0	+ .08	.40
May	4.03	64.0	1.50	2.13	.41	3.62	– .01	.33	– .34	.32
June	6.95	74.2	2.20	3.66	.84	6.11	.25	.34	– .09	.30
July	4.70	77.4	2.50	2.90	.75	3.95	–1.45	0	–1.45	.31
Aug.	7.93	73.8	2.20	3.90	.92	7.01	.91	.40	+ .51	.17
Sept.	1.45	65.0	1.50	.85	.01	1.44	– .91	0	– .91	.16

possible to correct the figure shown in column 7 to show the changes in soil moisture only. This amount is shown in column 9. The estimated ground-water run-off is listed in column 10. These data show quantitatively some of the factors in the hydrologic cycle.

Figure 86 shows graphically for the Skunk River Basin for the period October 1926 to September 1932, by months, the rainfall, temperature, evaporation, transpiration, surface run-off, ground-water run-off, and changes in soil moisture. These changes have been accumulated for the replenishing and storage period, which has been taken as the period from September 1 through April 30, and for the growing period, from May 1 through August 31. These indicated changes in soil moisture are the plus or minus differences between precipitation and the sum of the evaporation, transpiration, surface run-off, and accretion to ground water. The graph either represents the accumulated errors in the determination of these items or is an approximate representation of the changes in soil moisture.

Although various steps in the method of analysis are open to criticism, in that they are not subject to an exact mathematical solution, the results seem reasonable and represent, at least in a general way, the average magnitude of several elements of the hydrologic cycle in the Skunk River Basin.

A comparison was made between the computed changes in soil moisture and the general summary of concurrent climatologic conditions for this basin as reported by the Weather Bureau. A summary of the outstanding results is given below:

(1) Beginning about May 1, there is an indicated depletion in soil moisture that generally continues through August. Years in which the indicated depletion is more than about 4 inches, or months in which such depletion is excessive, are described by the Weather Bureau as drought periods, so far as vegetative growth is concerned.

(2) Months during the growing season when either no net change or an increase instead of a decrease in soil moisture is indicated are invariably described by the Weather Bureau as generally cool, wet months in which cultivation was difficult on account of wet soils and crop growth was generally retarded.

(3) In general, beginning with the heavy September rains, there is an apparent increase in soil moisture. Fall months that do not show

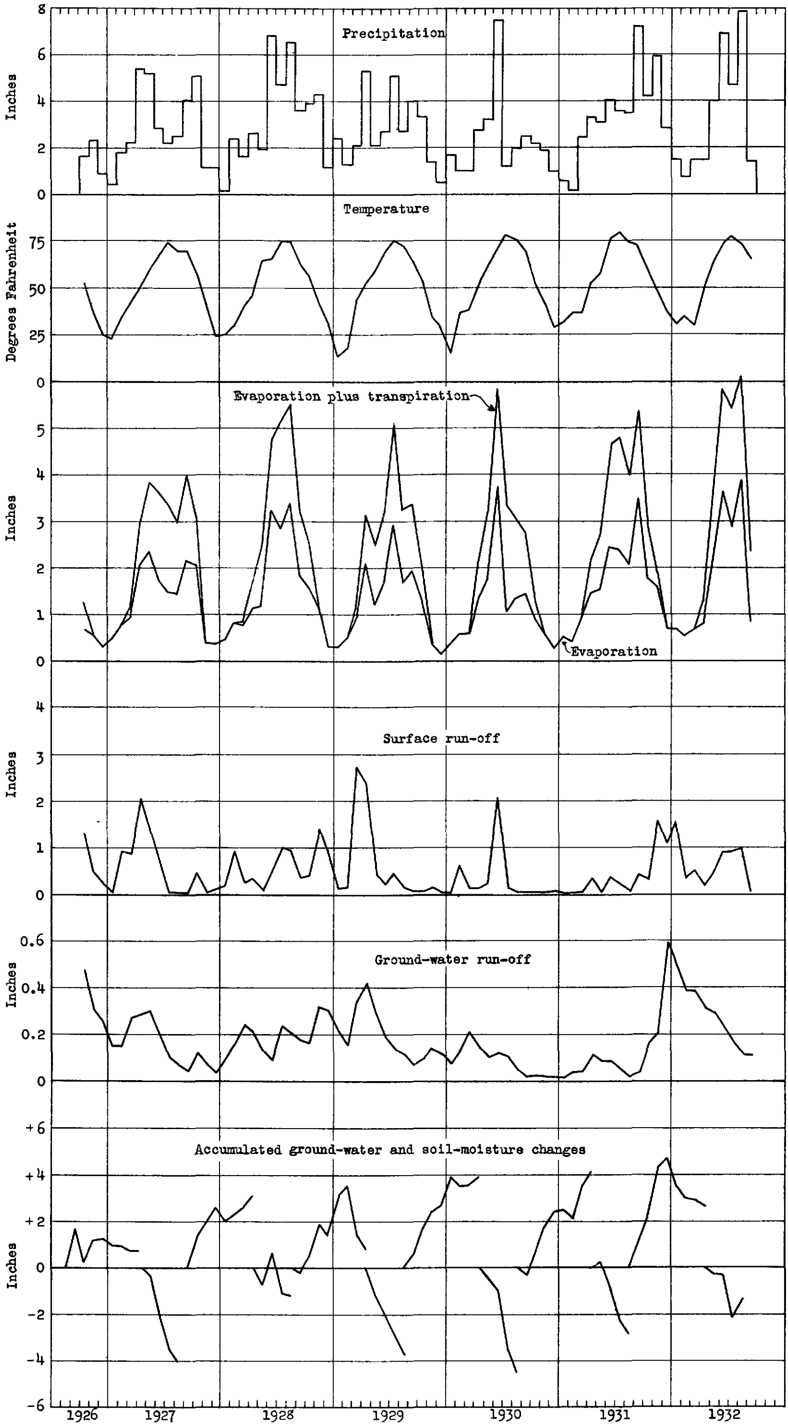


Figure 86.—Observed and estimated meteorologic and hydrologic data for Skunk River Basin above Augusta, Iowa, 1926-32.

such trends are described by the Weather Bureau as being unusually warm and dry.

(4) Spring months in which an unusual amount of soil moisture is shown to have accumulated are described by the Weather Bureau as being cool and wet and accompanied by delayed planting.

Studies similar to that already outlined for the Skunk River Basin were made on the Black River and Rock River Basins, in Wisconsin. In figure 87 the computed changes in soil moisture for these three basins were plotted against the precipitation and temperature on a monthly basis, and a comparison showed a considerable degree of uniformity. Although no great amount of accuracy is claimed for these curves, they illustrate a phase of the hydrologic cycle that is of the greatest importance to the farmers and are believed to represent roughly the information that would be obtained if the combined experience of successful farmers in this area were translated into specific data.

These curves are especially notable as indicating that in the areas studied with the surface run-off taken into consideration, an average monthly precipitation of $6\frac{1}{2}$ to 7 inches is required during July to hold the soil moisture constant. An examination of the Weather Bureau records indicates that when this amount of precipitation occurs in July, the surface soil is generally too wet for satisfactory cultivation. Consequently, from the viewpoint of the farmer the most satisfactory conditions would seem to prevail when normal drafts on soil moisture occur, providing drying of the surface soil sufficient to permit cultivation.

Run-off during drought periods

From the beginning of climatic records in the United States until about 1930 widespread droughts were infrequent, the major droughts in the humid areas having occurred during 1894, 1895, 1901, and 1910. During 1930, however, there was one of the most widespread droughts on record, followed by deficient precipitation over extensive areas in 1931, 1932, and 1934. These droughts have naturally raised questions as to their effect and as to what can be done to provide against losses from their recurrence.

In conformity with the suggestions of the advisory committee of the American Geophysical Union, only preliminary studies have been made of run-off during drought periods and its relations with rainfall

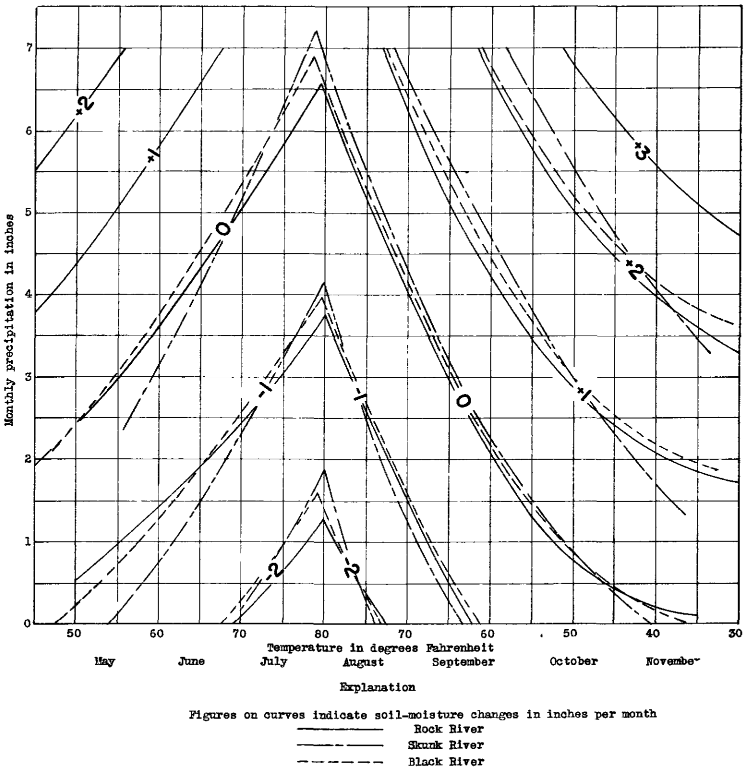


Figure 87.—Estimated relations between mean monthly precipitation, temperature, and soil-moisture changes in inches per month in Rock, Skunk, and Black River Basins.

or deficiency of rainfall. These studies have included (a) comparison of deficiencies in run-off, which during such drought periods is largely ground-water run-off, with deficiencies in rainfall and excesses in temperature, and (b) plotting of hydrographs of the annual minimum stream flow for periods of record on representative streams.

Comparison of deficiencies in ground-water run-off with deficiencies in rainfall

The study of deficiencies in ground-water run-off compared with deficiencies in rainfall was based on the assumption that if two severe droughts of equal intensity have occurred many years apart and at the same season of the year, the minimum flow, being supplied mainly from ground water, would be less and the rate of decline of the stream flow greater in the later drought if there had been a material lowering of the water table in the drainage basin during the intervening period. On ths other hand, it was assumed that if for fairly comparable drought conditions as respects rainfall and temperature there was an indication that the decline in stream flow was no more rapid and the minimum contribution of ground water to the stream no less in the later drought, the state of depletion of the ground-water supply was probably no more severe. Although during drought periods it seems well established that stream flow in basins with no artificial storage is supplied in a large part by seepage from ground water, no exact correlation seems possible between the ground-water conditions considered in detail over large areas and the seepage flow therefrom appearing in the stream.

Ground-water experts agree that when the water table in a basin is high the seepage flow from the ground water will tend to be greater than when it is low, and vice versa. It appears, therefore, that if the minimum stream flow of a region is found to be the lowest in many years, it may be inferred that the water table is probably also correspondingly low. As the relation between ground-water run-off and the ground-water conditions as marked by water levels in wells is complex and not well defined, deductions as to ground-water conditions from a study of low-water run-off are necessarily qualitative and at present, at least, more or less open to question. In this connection the following quotation from the report of David G. Thompson, chairman of the Committee on Underground Water of the Section of Hydrology of the American Geophysical

Union (179a), is of value in calling the attention of hydrologists and others to the complexities of ground water:

> "Only those who have studied in detail the fluctuations of the ground-water levels and the factors producing them appreciate the errors that may result from inadequate observations and erroneous interpretations. Although much detailed information has been gathered in regard to fluctuations of ground-water levels, and some of it is in print, comparatively few hydrologists appear to be informed on the subject, to know the variety of factors that produce fluctuations or the complexity of the resulting ground-water movements. There is little realization of the magnitude or rapidity of fluctuations that may result from seasonal or secular differences in rainfall, from differences in geologic conditions, in relief, and depth at which the water lies, from differences in artesian and nonartesian conditions, from heavy pumpage in highly permeable formations or small withdrawals for domestic use in poorly permeable formations, and from changes in atmospheric pressure and other factors. The variety of fluctuations of the ground-water levels that have been revealed by automatic recorders installed on wells during the past 15 years has been amazing, and such records serve to emphasize the fact that conclusions as to secular changes in ground-water levels based on any information except actual measurements in wells may be quite erroneous."

A comparison has been made between the run-off, rainfall, and temperature during drought periods on the Red River at Grand Forks, N. Dak.; the Black River at Neillsville, Wis.; the Rock River at Afton, Wis.; the Skunk River at Augusta, Iowa; and the Mississippi River at Keokuk, Iowa. Several different methods of analyzing the run-off and the precipitation, or lack of it, during drought periods were tried, and a comparison was made of the deficiencies in rainfall and run-off and excess in temperature - factors that seem to be the most illuminating.

In tables 62 to 66 are given the observed precipitation, temperature, and run-off for each month during drought periods, together with the averages and departures for each basin. The tables also show, so far as possible, the estimated ground-water flow for each period of drought.

Table 62 gives data for the Red River Basin for three outstanding drought periods, 1889-90, 1910-13, and 1929-31. During the first drought a deficiency of 5.05 inches in precipitation accumulated in 5 consecutive months, and by the end of 14 months the accumulation had reached a total of 8.79 inches. In 5 consecutive months of the second drought a deficiency of 5.77 inches had accumulated, and for the remainder of the drought the precipitation averaged a little more than the general average. In the third drought a deficiency of 5.68 inches had accumulated in 4 consecutive months; at the end of 16 months had reached a total of 8.60 inches, and at

Table 62.- Drought data for Red River Basin above Grand Forks, N. Dak.

Month	Temperature at Moorhead, Minn. (°F.)			Precipitation over the basin (inches)			Run-off at Grand Forks (inches)			Estimated ground-water run-off (inches)
	For month	Average	Departure	For month	Average	Departure	For month	Average	Departure	
1889										
April	45.2	40.6	+ 4.6	1.09	1.72	- 0.63	0.09	0.29	- 0.20	-
May	52.0	55.1	- 3.1	1.89	2.69	- .80	.05	.18	- .13	-
June	63.7	64.4	- .7	1.18	3.68	- 2.50	.03	.14	- .11	-
July	66.8	68.1	- 1.3	2.32	2.98	- .66	.03	.13	- .10	-
August	68.6	66.1	+ 2.5	2.11	2.57	- .46	.02	.07	- .05	-
September	54.3	58.2	- 3.9	3.68	2.04	+ 1.64	.02	.06	- .04	-
October	43.6	44.5	- .9	.02	1.31	- 1.29	.02	.06	- .04	-
November	24.8	27.1	- 2.3	.24	.80	- .56	.02	.05	- .03	-
December	20.0	11.5	+ 8.5	.52	.60	- .08	.02	.04	- .02	-
1890										
January	-.9	3.8	- 4.7	.32	.56	- .24	.02	.03	- .01	-
February	4.8	8.1	- 3.3	.39	.59	- .20	.02	.03	- .01	-
March	18.2	22.7	- 4.5	.30	.75	- .45	.02	.09	- .07	-
April	44.6	40.6	+ 4.0	.59	1.72	- 1.13	.08	.29	- .21	-
May	48.0	55.1	- 7.1	1.26	2.69	- 1.43	.04	.18	- .14	-
June	67.6	64.4	+ 3.2	5.37	3.68	+ 1.69	.06	.14	- .08	-
July	69.2	68.1	+ 1.1	2.35	2.98	- .63	.05	.13	- .08	-
August	62.7	66.1	- 3.4	2.77	2.57	- .20	.03	.07	- .04	-
September	54.6	58.2	- 3.6	1.88	2.04	- .16	.02	.06	- .04	-
October	44.8	44.5	+ .3	2.54	1.31	+ 1.23	.03	.06	- .03	-
November	32.6	27.1	+ 5.5	.24	.80	- .56	.04	.05	- .01	-
December	18.8	11.5	+ 7.3	.17	.60	- .43	.03	.04	- .01	-
1910										
June	69.1	64.4	+ 4.7	1.26	3.68	- 2.42	.09	.14	- .05	.05
July	71.4	68.1	+ 3.3	1.57	2.98	- 1.41	.04	.13	- .09	.03
August	65.4	66.1	- .7	1.09	2.57	- 1.48	.02	.07	- .05	.02
September	57.7	58.2	- .5	2.19	2.04	+ .15	.02	.06	- .04	.02
October	50.4	44.5	+ 5.9	.70	1.31	- .61	.02	.06	- .04	.01
November	24.0	27.1	- 3.1	.48	.80	- .32	.02	.05	- .03	.01
December	11.8	11.5	+ .3	.51	.60	- .09	.01	.04	- .03	-
1911										
January	-.6	3.8	- 4.4	.92	.56	+ .36	.01	.03	- .02	-
February	9.2	8.1	+ 1.1	.73	.59	+ .14	.01	.03	- .02	-
March	31.2	22.7	+ 8.5	.34	.75	- .41	.03	.09	- .06	-
April	42.8	40.6	+ 2.2	2.01	1.72	+ .29	.08	.28	- .21	-
May	58.0	55.1	+ 2.9	4.01	2.69	+ 1.32	.07	.18	- .11	.04
June	69.2	64.4	+ 4.8	3.41	3.68	- .27	.08	.14	- .06	.04
July	67.8	68.1	- .3	2.58	2.98	- .40	.03	.13	- .10	.02
August	64.4	66.1	- 1.7	2.57	2.57	0	.02	.07	- .05	.01
September	55.9	58.2	- 2.3	2.44	2.04	+ .40	.02	.06	- .04	.01
October	43.5	44.5	- 1.0	1.27	1.31	- .04	.02	.06	- .04	.01
November	17.2	27.1	- 9.9	.96	.80	+ .16	.02	.05	- .03	-
December	15.6	11.5	+ 4.1	.51	.60	- .09	.02	.04	- .02	-
1912										
January	-6.2	3.8	-10.0	.32	.56	- .24	.01	.03	- .02	-
February	11.0	8.1	+ 2.9	.22	.59	- .37	0	.03	- .03	-
March	20.6	22.7	- 2.1	.38	.75	- .37	.01	.09	- .08	-
April	46.0	40.6	+ 5.4	2.36	1.72	+ .64	.08	.29	- .21	.04
May	56.6	55.1	+ 1.5	4.02	2.69	+ 1.33	.08	.18	- .10	.04
June	63.0	64.4	- 1.4	2.25	3.68	- 1.43	.05	.14	- .09	.04
July	68.6	68.1	+ .5	3.82	2.98	+ .84	.03	.13	- .10	.02
August	64.4	66.1	- 1.7	3.93	2.57	+ 1.36	.03	.07	- .04	.02
September	54.6	58.2	- 3.6	3.87	2.04	+ 1.83	.04	.06	- .02	.02
October	46.0	44.5	+ 1.5	.52	1.31	- .79	.06	.06	0	.03
November	32.4	27.1	+ 5.3	.14	.80	- .66	.03	.05	- .02	-
December	17.6	11.5	+ 6.1	.62	.60	+ .02	.02	.04	- .02	-
1913										
January	1.0	3.8	- 2.8	.47	.56	- .09	.01	.03	- .02	-
February	7.5	8.1	- .6	.16	.50	- .43	.01	.03	- .02	-
March	19.0	22.7	- 3.7	.94	.75	+ .19	.01	.09	- .08	-
April	47.8	40.6	+ 7.2	1.01	1.72	- .71	.31	.29	+ .02	-
1929										
June	64.0	64.4	- .4	1.15	3.68	- 2.53	.06	.14	- .08	.04
July	71.5	68.1	+ 3.4	1.65	2.98	- 1.33	.04	.13	- .09	.02
August	69.8	66.1	+ 3.7	1.10	2.57	- 1.47	.02	.07	- .05	.02
September	54.8	58.2	- 3.4	1.69	2.04	- .35	.01	.06	- .05	.01
October	47.6	44.5	+ 3.1	2.63	1.31	+ 1.32	.02	.06	- .04	.01
November	24.8	27.1	- 2.3	.78	.80	- .02	.02	.05	- .03	.02
December	12.2	11.5	+ .7	.81	.60	+ .21	.01	.04	- .03	.01

Table 62.- Drought data for Red River Basin above Grand Forks, N. Dak.-Continued

Month	Temperature at Moorhead, Minn. (°F.)			Precipitation over the basin (inches)			Run-off at Grand Forks (inches)			Estimated ground-water run-off (inches)
	For month	Average	Departure	For month	Average	Departure	For month	Average	Departure	
1930										
January	0.3	3.8	− 3.5	0.32	0.56	−0.24	0.01	0.03	−0.02	0.01
February	23.0	8.1	+ 14.9	1.48	.59	+ .89	.01	.03	− .02	0
March	27.0	22.7	+ 4.3	.26	.75	− .49	.18	.09	+ .09	.02
April	46.3	40.6	+ 5.7	1.20	1.72	− .52	.17	.29	− .12	.05
May	53.4	55.1	− 1.7	4.03	2.69	+1.34	.14	.18	− .04	.04
June	65.0	64.4	+ .6	2.26	3.68	−1.42	.05	.14	− .09	.04
July	73.6	68.1	+ 5.5	1.45	2.98	−1.53	.03	.13	− .10	.02
August	72.2	66.1	+ 6.1	1.08	2.57	−1.49	.01	.07	− .06	.01
September	58.8	58.2	+ .6	1.07	2.04	− .97	.01	.06	− .05	.01
October	43.6	44.5	− .9	1.86	1.31	+ .55	.01	.06	− .05	.01
November	30.4	27.1	+ 3.3	2.02	.80	+1.22	.01	.05	− .04	.01
December	19.8	11.5	+ 8.3	.23	.60	− .37	.01	.04	− .03	.01
1931										
January	19.6	3.8	+ 15.8	.17	.56	− .39	.01	.03	− .02	.01
February	26.2	8.1	+ 18.1	.31	.59	− .28	.01	.03	− .02	.01
March	27.7	22.7	+ 5.0	.93	.75	+ .18	.02	.09	− .07	.01
April	44.6	40.6	+ 4.0	.53	1.72	−1.19	.05	.29	− .24	.02
May	53.2	55.1	− 1.9	2.15	2.69	− .54	.03	.18	− .15	.02
June	69.0	64.4	+ 4.6	3.71	3.68	+ .03	.02	.14	− .12	.01
July	72.5	68.1	+ 4.4	3.27	2.98	+ .29	.01	.13	− .12	.01
August	67.6	66.1	+ 1.5	2.55	2.57	− .02	.01	.07	− .06	0
September	64.9	58.2	+ 6.7	1.74	2.04	− .30	0	.06	− .06	0
October	50.5	44.5	+ 6.0	2.52	1.31	+1.21	.01	.06	− .05	0
November	33.0	27.1	+ 5.9	1.31	.80	+ .51	.01	.05	− .04	0
December	21.2	11.5	+ 9.7	.21	.60	− .39	.01	.04	− .03	0
1932										
January	11.4	3.8	+ 7.6	.49	.56	− .07	.01	.03	− .02	.01
February	13.2	8.1	+ 5.1	.58	.59	− .01	.01	.03	− .02	.01
March	17.8	22.7	− 4.9	.59	.75	− .16	.05	.09	− .04	.01
April	43.6	40.6	+ 3.0	2.17	1.72	+ .45	.17	.29	− .12	.02
May	57.0	55.1	+ 1.9	2.90	2.69	+ .21	.04	.18	− .14	.02
June	68.9	64.4	+ 4.5	2.35	3.68	−1.33	.02	.14	− .12	.01
July	72.1	68.1	+ 4.0	1.96	2.98	−1.02	.01	.13	− .12	.01
August	70.7	66.1	+ 4.6	2.42	2.57	− .15	0	.07	− .07	0
September	58.8	58.2	+ .6	1.30	2.04	− .74	0	.06	− .06	0
October	41.2	44.5	− 3.3	2.05	1.31	+ .74	0	.06	− .06	0
November	25.3	27.1	− 1.8	.74	.80	− .06	0	.05	− .05	0
December	11.5	11.5	0	.19	.60	− .41	0	.04	− .04	0
1933										
January	11.9	3.8	+ 8.1	1.07	.56	+ .51	0	.03	− .03	0
February	7.4	8.1	− 0.7	.37	.59	− .22	0	.03	− .03	0
March	28.0	22.7	+ 5.3	.84	.75	+ .09	.04	.09	− .05	0
April	41.4	40.6	+ 0.8	1.61	1.72	− .11	.10	.29	− .19	.01
May	56.8	55.1	+ 1.7	3.40	2.69	+ .71	.03	.18	− .15	.01
June	72.8	64.4	+ 8.4	2.28	3.68	−1.40	.02	.14	− .12	.01
July	73.7	68.1	+ 5.6	1.77	2.98	−1.21	.01	.13	− .12	0
August	69.5	66.1	+ 3.4	1.33	2.57	−1.24	0	.07	− .07	0
September	63.2	58.2	+ 5.0	1.30	2.04	− .74	0	.06	− .06	0
October	42.6	44.5	− 1.9	.60	1.31	− .71	0	.06	− .06	0
November	25.4	27.1	− 1.7	.89	.80	+ .09	0	.05	− .05	0
December	7.2	11.5	− 4.3	1.36	.60	+ .76	0	.04	− .04	0
1934										
January	13.8	3.8	+ 10.0	.28	.56	− .28	0	.03	− .03	0
February	15.4	8.1	+ 7.3	.11	.59	− .48	0	.03	− .03	0
March	24.2	22.7	+ 1.5	.48	.75	− .27	.02	.09	− .07	0
April	42.4	40.6	+ 1.8	.80	1.72	− .92	.07	.29	− .22	.01
May	63.6	55.1	+ 8.5	.91	2.69	−1.78	.02	.18	− .16	.01
June	66.2	64.4	+ 1.8	3.96	3.68	+ .28	.01	.14	− .13	0
July	72.5	68.1	+ 4.4	1.66	2.98	−1.32	.01	.13	− .12	0
August	67.5	66.1	+ 1.4	1.73	2.57	− .84	0	.07	− .07	0
September	53.5	58.2	− 4.7	1.27	2.04	− .77	0	.06	− .06	0
October	49.6	44.5	+ 5.1	2.08	1.31	+ .77	0	.06	− .06	0
November	34.2	27.1	+ 7.1	.50	.80	− .30	0	.05	− .05	0
December	11.0	11.5	− .5	.43	.60	− .17	0	.04	− .04	0

Note.- Zero represents run-off less than 0.01 inch.

the end of 24 months the total accumulation had reached 9.42 inches. During each growing season of the next 3 years, 1932, 1933, and 1934, the precipitation was deficient in amounts ranging from about 3 to 5 inches. During the drought of 1889-90 a deficiency in run-off of 1.45 inches had accumulated in 21 consecutive months; during the drought of 1910-13 a deficiency of 1.45 inches in 21 consecutive months and 1.94 inches in 34 months; and during the drought of 1929-31 a deficiency of 1.56 inches in 21 consecutive months and 1.88 inches in 31 months. The monthly run-off subsequent to March 1930 has been continuously deficient up to the end of the record under consideration, December 1934. The ground-water flow, exclusive of frozen periods, reached a minimum of practically zero during the drought of 1929-31. The temperature affecting the amount of transpiration (over 40°) was on the average during 1929-31 about 0.2° a month lower than that during the period 1932-34, 1.2° a month higher that that of the drought period of 1910-13, and 3.1° a month higher than that of the drought period of 1889-90.

Table 63 gives data for the Black River Basin for two outstanding drought periods, 1917-18 and 1930-31. During the earlier drought a deficiency of 4.10 inches in precipitation accumulated in 8 consecutive months, although in the second and sixth months the precipitation was slightly more than average. In the drought of 1930-31 a net deficiency of 5.55 inches in precipitation accumulated in 8 consecutive months, the fourth month having an excess of 0.85 inch, and by the end of 14 months the accumulated deficiency had reached 9.63 inches. During each growing season of the next 3 years, 1932, 1933, and 1934, the precipitation was deficient in amounts ranging from about 3 to 10 inches. Deficiency in run-off for the drought period of 1917-18 began 2 months earlier than deficiency in precipitation and by the end of 10 consecutive months amounted to 3.88 inches. The run-off during the drought period of 1930-31 was deficient for 16 consecutive months, accumulating a total deficiency in that time of 8.48 inches, and in a 10-month period similar to that of the drought of 1917-18 the deficiency in run-off amounted to 6.85 inches. For the years 1932, 1933, and 1934 the maximum accumulation of deficiency in run-off amounted to 3.06, 4.47, and 2.66 inches respectively. The temperature during the period 1930-31 that would affect the amount of transpiration (over 40°) was on the average about 4.5° a month higher than that during the drought of 1917-18. The ground-water run-off, exclusive of months of freezing temperature, reached lower amounts in the later drought than in the earlier.

Table 63.- Drought data for Black River Basin above Neillsville, Wis.

Month	Temperature at Wausau, Wis. (°F.)			Precipitation over the basin (inches)			Run-off at Neillsville (inches)			Estimated ground-water run-off (inches)
	For month	Average	Departure	For month	Average	Departure	For month	Average	Departure	
1917										
July	68.4	68.4	0	4.23	3.56	+0.67	0.12	0.35	-0.23	0.07
August	61.8	66.0	-4.2	5.30	3.54	+1.76	.11	.39	-.28	.06
September	56.0	58.9	-2.9	2.34	3.92	-1.58	.08	.46	-.38	.06
October	36.3	47.2	-10.9	2.86	2.41	+.45	.38	.49	-.11	.12
November	34.8	32.2	+2.6	.23	2.04	-1.81	.24	.66	-.42	.11
December	10.4	19.1	-8.7	.55	.97	-.42	.07	.20	-.13	.03
1918										
January	4.0	14.2	-10.2	1.12	1.23	-.11	.01	.15	-.14	.01
February	13.2	15.1	-1.9	1.30	1.21	+.09	.01	.18	-.17	.01
March	34.2	28.0	+6.2	1.34	1.58	-.24	1.64	1.84	-.20	.19
April	39.9	43.8	-3.9	2.16	2.64	-.48	1.13	2.95	-1.82	.32
May	56.9	55.2	+1.7	7.68	3.47	+4.21	2.94	1.18	+1.76	.18
June	62.4	64.7	-2.3	2.72	5.45	-2.73	1.57	1.31	+.26	.08
1930										
July	71.4	68.4	+3.0	2.09	3.56	-1.47	.29	.35	-.06	.11
August	70.2	66.0	+4.2	1.59	3.54	-1.95	.05	.39	-.34	.02
September	60.8	58.9	+1.9	3.11	3.92	-.81	.03	.46	-.43	.02
October	46.2	47.2	-1.0	3.26	2.41	+.85	.25	.49	-.24	.09
November	36.4	32.2	+4.2	1.80	2.04	-.24	.22	.66	-.44	.08
December	20.8	19.1	+1.7	.35	.97	-.62	.09	.20	-.11	.07
1931										
January	22.3	14.2	+8.1	.53	1.23	-.70	.10	.15	-.05	.05
February	27.0	15.1	+11.9	.60	1.21	-.61	.06	.18	-.12	.04
March	30.4	28.0	+2.4	1.46	1.58	-.12	.19	1.84	-1.65	.09
April	45.7	43.8	+1.9	1.12	2.64	-.52	.65	2.95	-2.30	.21
May	54.0	55.2	-1.2	1.40	3.47	-2.07	.22	1.18	-.96	.14
June	68.8	64.7	+4.1	5.98	5.45	+.53	.76	1.31	-.55	.07
July	72.6	68.4	+4.2	2.25	3.56	-1.31	.11	.35	-.24	.05
August	66.8	66.0	+.8	2.95	3.54	-.59	.02	.39	-.37	.02
September	65.4	58.9	+6.5	5.76	3.92	+1.84	.13	.46	-.33	.05
October	51.9	47.2	+4.7	2.70	2.41	+.29	.20	.49	-.29	.10
November	40.0	32.2	+7.8	4.70	2.04	+2.66	1.93	.66	+1.27	.14
December	28.0	19.1	+8.9	1.06	.97	+.09	.44	.20	+.24	.25
1932										
January	21.3	14.2	+7.1	2.64	1.23	+1.41	.80	.15	+.65	.24
February	18.5	15.1	+3.4	1.87	1.21	+.66	.49	.18	+.31	.25
March	21.6	28.0	-6.4	.89	1.58	-.69	1.92	1.84	+.08	.28
April	42.0	43.8	-1.8	2.32	2.64	-.32	3.15	2.95	+.20	.29
May	55.3	55.2	+.1	4.16	3.47	+.69	1.29	1.18	+.11	.23
June	67.8	64.7	+3.1	3.86	5.45	-1.59	.22	1.31	-1.09	.07
July	70.5	68.4	+2.1	2.67	3.56	-.89	.11	.35	-.24	.04
August	69.1	66.0	+3.1	3.74	3.54	+.20	.07	.39	-.32	.03
September	58.0	58.9	-.9	1.39	3.92	-2.53	.05	.46	-.41	.04
October	43.5	47.2	-3.7	1.08	2.41	-1.33	.05	.49	-.44	.02
November	28.1	32.2	-4.1	2.31	2.04	+.27	.10	.66	-.56	.04
December	17.5	19.1	-1.6	2.34	.97	+1.37	.22	.20	+.02	.02
1933										
January	23.6	14.2	+9.4	1.88	1.23	+.65	.34	.15	+.19	.04
February	12.4	15.1	-2.7	1.27	1.21	+.06	.31	.18	+.13	.09
March	27.5	28.0	-.5	.97	1.58	-.61	1.63	1.84	-.21	.16
April	42.1	43.8	-1.7	3.23	2.64	+.59	2.19	2.95	-.76	.19
May	57.2	55.2	+2.0	4.29	3.47	+.82	1.04	1.18	-.14	.12
June	73.8	64.7	+9.1	2.44	5.45	-3.01	.32	1.31	-.99	.03
July	73.7	68.4	+5.3	1.66	3.56	-1.90	.02	.35	-.33	.01
August	66.4	66.0	+.4	1.76	3.54	-1.78	.02	.39	-.37	.01
September	63.1	58.9	+4.2	2.37	3.92	-1.55	.01	.46	-.45	.01
October	43.4	47.2	-3.8	1.89	2.41	-.52	.03	.49	-.46	.01
November	29.2	32.2	-3.0	.63	2.04	-1.41	.05	.66	-.61	.02
December	18.0	19.1	-1.1	.98	.97	+.01	.05	.20	-.15	.03
1934										
January	22.4	14.2	+8.2	1.30	1.23	+.07	.10	.15	-.05	.04
February	14.6	15.1	-.5	.25	1.21	-.96	.06	.18	-.12	.04
March	27.0	28.0	-1.0	1.78	1.58	+.20	.23	1.84	-1.61	.04
April	43.2	43.8	-.6	2.52	2.64	-.12	3.10	2.95	+.15	.10
May	64.3	55.2	+9.1	1.03	3.47	-2.44	.12	1.18	-1.06	.09
June	70.2	64.7	+5.5	6.16	5.45	+.71	.37	1.31	-.94	.03
July	74.3	68.4	+5.9	1.98	3.56	-1.58	.04	.35	-.31	.03
August	66.2	66.0	+.2	3.38	3.54	-.16	.04	.39	-.35	.01
September	58.4	58.9	-.5	8.10	3.92	+4.18	2.02	.46	+1.56	.04
October	50.2	47.2	+3.0	3.32	2.41	+.91	1.07	.49	+.58	.10
November	37.5	32.2	+5.3	4.86	2.04	+2.82	2.66	.66	+2.00	.17
December	16.3	19.1	-2.8	1.65	.97	+.68	.50	.20	+.30	.22

Table 64 gives data for the Rock River Basin for three outstanding drought periods, 1918-19, 1930-31, and 1933-34. During the first drought a deficiency of 7.24 inches in precipitation accumulated in 8 consecutive months, and by the end of 15 months the accumulation had reached 7.94 inches. In the second drought a deficiency of 7.37 inches in precipitation accumulated in a similar 8-month period, and by the end of 14 months the accumulation had reached 11.09 inches. During the drought of 1933-34 a deficiency of 7.48 inches in precipitation accumulated in 8 consecutive months and 13.11 inches by the end of 15 months. The run-off during all three droughts was below normal for 16 consecutive months, a deficiency of 6.79 inches accumulating in 1933-34, 6.51 inches in 1930-31, and 4.25 inches in 1918-19. The temperature during drought of 1930-31 that would affect the amount of transpiration (over 40°) was on the average about 0.4° a month higher than that of 1933-34 and 2.5° higher than that of 1918-19. The flow from ground-water was less in the drought of 1933-34 than in that of the two earlier drought periods.

Table 65 gives data for the Skunk River Basin for three outstanding drought periods, 1917-18, 1930-31, and 1933-34. The three droughts were generally similar, the first accumulating a deficiency of 10.10 inches in precipitation in 10 consecutive months, the second a deficiency of 9.59 inches in 12 months, and the latest a deficiency of 18.80 inches in 15 months. The run-off during the drought of 1930-31 and 1933-34 was deficient for 14 and 19 consecutive months, accumulating a deficiency of 5.76 and 8.84 inches respectively. In the drought of 1917-18 there was an excessive amount of run-off during the 11th month, but the first 10 months accumulated a deficiency of 3.91 inches, and at the end of 14 months the accumulated deficiency was 4.92 inches. The greatest difference was in the temperature affecting the amount of transpiration (more than 40°), the earlier drought having temperatures about average and the last two droughts having temperatures averaging 3.5° and 4.0° a month respectively greater than the average.

Table 66 gives data for the upper Mississippi River Basin for three outstanding drought periods, 1894-96, 1910-11, and 1930-32. During the drought of 1894-96 a deficiency of 7.11 inches in precipitation accumulated in 4 consecutive months, and by the end of 22 months the accumulated deficiency had reached 13.88 inches. During the drought of 1910-11 a deficiency of 7.63 inches in precipitation accumulated in 5 consecutive months, and by the end of 16 months the accumulation amounted to 12.16 inches. In

Table 64.- Drought data for Rock River Basin above Afton, Wis.

Month	Temperature at Madison, Wis. (°F.)			Precipitation over the basin (inches)			Run-off at Afton (inches)			Estimated ground-water run-off (inches)
	For month	Average	Departure	For month	Average	Departure	For month	Average	Departure	
1918										
June	65.9	67.2	− 1.3	2.09	3.95	− 1.86	0.61	0.64	− 0.03	0.34
July	70.3	72.1	− 1.8	2.02	2.90	− .88	.34	.47	− .13	.27
August	72.6	69.8	+ 2.8	2.12	3.04	− .92	.26	.42	− .16	.24
September	55.9	62.4	− 6.5	1.61	4.29	− 2.68	.25	.43	− .18	.25
October	52.9	50.3	+ 2.6	2.82	3.05	− .23	.27	.51	− .24	.26
November	39.4	35.2	+ 4.2	1.81	2.15	− .34	.30	.53	− .23	.27
December	31.4	22.8	+ 8.6	2.18	1.39	+ .79	.25	.53	− .28	.25
1919										
January	24.1	16.7	+ 7.4	.33	1.45	− 1.12	.25	.42	− .17	.24
February	23.7	19.1	+ 4.6	1.94	1.26	+ .68	.23	.56	− .33	.22
March	33.2	30.6	+ 2.6	2.37	2.08	+ .29	.31	1.35	− 1.04	.27
April	45.8	45.4	+ .4	3.22	2.84	+ .38	.86	1.54	− .68	.38
May	55.2	57.6	− 2.4	3.01	3.29	− .28	.79	.87	− .08	.43
June	71.2	67.2	+ 4.0	3.40	3.95	− .55	.44	.64	− .20	.29
July	74.8	72.1	+ 2.7	3.01	2.90	+ .11	.28	.47	− .19	.24
August	69.0	69.8	− .8	1.71	3.04	− 1.33	.26	.42	− .16	.22
September	64.2	62.4	+ 1.8	6.62	4.29	+ 2.33	.28	.43	− .15	.22
October	50.2	50.3	− .1	5.54	3.05	+ 2.49	.77	.51	+ .26	.30
November	32.6	35.2	− 2.6	2.64	2.15	+ .49	.75	.53	+ .22	.36
1930										
July	72.8	72.1	+ .7	2.53	2.90	− .37	.30	.47	− .17	.22
August	72.5	69.8	+ 2.7	1.67	3.04	− 1.37	.22	.42	− .20	.18
September	63.8	62.4	+ 1.4	3.21	4.29	− 1.08	.22	.43	− .21	.17
October	48.1	50.3	− 2.2	2.09	3.05	− .96	.25	.51	− .26	.19
November	39.0	35.2	+ 3.8	.72	2.15	− 1.43	.19	.53	− .34	.15
December	24.4	22.8	+ 1.6	.63	1.39	− .76	.22	.53	− .31	.18
1931										
January	26.1	16.7	+ 9.4	.91	1.45	− .54	.22	.42	− .20	.18
February	31.4	19.1	+ 12.3	.40	1.26	− .86	.23	.56	− .33	.17
March	31.7	30.6	+ 1.1	1.95	2.08	− .13	.29	1.35	− 1.06	.21
April	48.0	45.4	+ 2.6	1.34	2.84	− 1.50	.35	1.54	− 1.19	.21
May	54.9	57.6	− 2.7	2.23	3.29	− 1.06	.23	.87	− .64	.17
June	71.4	67.2	+ 4.2	3.80	3.95	− .15	.16	.64	− .48	.13
July	75.8	72.1	+ 3.7	2.05	2.90	− .85	.13	.47	− .34	.10
August	70.8	69.8	+ 1.0	3.01	3.04	− .03	.12	.42	− .30	.09
September	68.4	62.4	+ 6.0	6.25	4.29	+ 1.96	.17	.43	− .26	.10
October	54.9	50.3	+ 4.6	3.97	3.05	+ .92	.29	.51	− .22	.18
November	44.8	35.2	+ 9.6	5.12	2.15	− 2.97	.64	.53	+ .11	.25
December	33.0	22.8	+ 10.2	1.63	1.39	− .24	.88	.53	+ .35	.41
1932										
January	25.9	16.7	+ 9.2	1.49	1.45	+ .04	.86	.42	+ .44	.45
February	27.1	19.1	+ 8.0	1.02	1.26	− .24	.61	.56	+ .05	.35
March	24.4	30.6	− 6.2	1.33	2.08	− .75	.70	1.35	− .65	.33
April	44.6	45.4	− .8	.64	2.84	− 2.20	.69	1.54	− .85	.31
May	58.6	57.6	+ 1.0	2.51	3.29	− .78	.38	.87	− .49	.29
June	70.4	67.2	+ 3.2	3.18	3.95	− .77	.24	.64	− .40	.18
July	73.7	72.1	+ 1.6	3.00	2.90	+ .10	.16	.47	− .31	.11
August	71.2	69.8	+ 1.4	2.00	3.04	+ 1.04	.09	.42	− .33	.07
September	61.9	62.4	− .5	.42	4.29	− 3.87	.08	.43	− .35	.06
October	48.0	50.3	− 2.3	3.83	3.05	+ .78	.14	.51	− .37	.09
November	32.0	35.2	− 3.2	1.60	2.15	− .55	.16	.53	− .37	.09
December	22.4	22.8	− .4	1.58	1.39	+ .19	.23	.53	− .30	.12
1933										
January	30.8	16.7	+ 14.1	.89	1.45	− .56	.29	.42	− .13	.19
February	18.9	19.1	− .2	.93	1.26	− .33	.31	.56	− .25	.22
March	31.0	30.6	+ .4	2.69	2.08	+ .61	.44	1.35	− .91	.25
April	44.1	45.4	− 1.3	3.17	2.84	+ .33	1.86	1.54	+ .32	.38
May	57.9	57.6	+ .3	8.06	3.29	+ 4.77	2.22	.87	+ 1.35	.51
June	76.0	67.2	+ 8.8	2.91	3.95	− 1.04	.90	.64	+ .26	.34
July	73.6	72.1	+ 1.5	3.92	2.90	+ 1.02	.43	.47	− .04	.24
August	69.6	69.8	− .2	2.31	3.04	− .73	.27	.42	− .15	.18
September	67.2	62.4	+ 4.8	3.28	4.29	− 1.01	.22	.43	− .21	.13
October	49.0	50.3	− 1.3	1.72	3.05	− 1.33	.19	.51	− .32	.13
November	34.0	35.2	− 1.2	.58	2.15	− 1.57	.21	.53	− .32	.13
December	23.4	22.8	+ .6	1.08	1.39	− .31	.20	.53	− .33	.13
1934										
January	26.6	16.7	+ 9.9	.76	1.45	− .69	.27	.42	− .15	.15
February	18.5	19.1	− .6	.31	1.26	− .95	.16	.56	− .40	.10
March	29.1	30.6	− 1.5	1.63	2.08	− .45	.22	1.35	− 1.13	.11
April	45.8	45.4	+ .4	1.58	2.84	− 1.26	.62	1.54	− .92	.25
May	65.7	57.6	+ 8.1	2.08	3.29	− 1.21	.25	.87	− .62	.17
June	73.1	67.2	+ 5.9	2.61	3.95	− 1.34	.11	.64	− .53	.08
July	75.3	72.1	+ 3.2	3.25	2.90	+ .35	.09	.47	− .38	.05
August	69.4	69.8	− .4	1.94	3.04	− 1.10	.07	.42	− .35	.04
September	60.6	62.4	− 1.8	3.99	4.29	− .30	.13	.43	− .30	.05
October	53.8	50.3	+ 3.5	1.84	3.05	− 1.21	.11	.51	− .40	.06
November	41.6	35.2	+ 6.4	6.86	2.15	+ 4.71	.25	.53	− .28	.08
December	20.2	22.8	− 2.6	1.05	1.39	− .34	.49	.53	− .04	.20

Table 65.- Drought data for Skunk River Basin above Augusta, Iowa

Month	Temperature at Davenport, Iowa (°F.)			Precipitation over the basin (inches)			Run-off at Augusta (inches)			Estimated ground-water run-off (inches)
	For month	Average	Departure	For month	Average	Departure	For month	Average	Departure	
1917										
July	75.8	75.3	+ 0.5	2.01	3.44	- 1.43	0.26	0.48	- 0.22	0.15
August	71.2	73.1	- 1.9	2.01	3.78	- 1.77	.10	.35	- .25	.07
September	63.7	65.6	- 1.9	3.33	4.76	- 1.43	.14	.49	- .35	.05
October	43.9	53.7	- 9.8	1.71	2.63	- .92	.04	.48	- .44	.04
November	42.2	39.0	+ 3.2	.20	2.07	- 1.87	.04	.45	- .41	.03
December	18.2	27.1	- 8.9	.68	1.21	- .53	.03	.34	- .31	.02
1918										
January	10.0	21.8	- 11.8	1.06	1.04	+ .02	.01	.34	- .33	.01
February	26.8	24.9	+ 1.9	1.15	1.10	+ .05	.32	.44	- .12	.06
March	44.8	36.1	+ 8.7	.31	2.11	- 1.80	.24	.97	- .73	.14
April	45.6	49.9	- 4.3	2.83	3.25	- .42	.12	.87	- .75	.09
May	66.2	61.3	+ 4.9	7.20	3.48	+ 3.72	.71	.75	- .04	.08
June	70.2	70.5	- .3	6.93	5.18	+ 1.75	2.24	1.08	+ 1.16	.28
July	74.1	75.3	- 1.2	2.70	3.44	- .74	.38	.48	- .10	.17
August	76.8	73.1	+ 3.7	3.32	3.78	- .46	.22	.35	- .13	.07
September	58.9	65.6	- 6.7	2.35	4.76	- 2.41	.18	.49	- .31	.07
October	56.1	53.7	+ 2.4	3.00	2.63	+ .37	.05	.48	- .43	.05
November	42.2	39.0	+ 3.2	2.02	2.07	- .05	.07	.45	- .38	.04
December	35.5	27.1	+ 8.4	1.68	1.21	+ .47	.11	.34	- .23	.04
1919										
January	27.8	21.8	+ 6.0	.18	1.04	- .86	.14	.34	- .20	.04
February	28.2	24.9	+ 3.3	2.56	1.10	+ 1.46	.23	.44	- .21	.05
March	40.0	36.1	+ 3.9	2.75	2.11	+ .64	1.35	.97	+ .38	.33
April	51.0	49.9	+ 1.1	4.78	3.25	+ 1.53	.98	.87	+ .11	.43
1930										
July	78.6	75.3	+ 3.3	1.20	3.44	- 2.24	.26	.48	- .22	.17
August	75.6	73.1	+ 2.5	1.98	3.78	- 1.80	.06	.35	- .29	.04
September	68.9	65.6	+ 3.3	2.50	4.76	- 2.26	.03	.49	- .46	.02
October	52.2	53.7	- 1.5	2.22	2.63	- .41	.06	.48	- .42	.02
November	42.8	39.0	+ 3.8	1.94	2.07	- .13	.03	.45	- .42	.01
December	28.0	27.1	+ .9	.97	1.21	- .24	.09	.34	- .25	.01
1931										
January	31.4	21.8	+ 9.6	.59	1.04	- .45	.02	.34	- .32	.01
February	36.8	24.9	+ 11.9	.18	1.10	- .92	.06	.44	- .38	.04
March	36.2	36.1	+ .1	2.45	2.11	+ .34	.10	.97	- .87	.04
April	52.3	49.9	+ 2.4	3.30	3.25	+ .05	.48	.87	- .39	.11
May	58.4	61.3	- 2.9	3.08	3.48	- .40	.12	.75	- .63	.08
June	76.5	70.5	+ 6.0	4.05	5.18	- 1.13	.46	1.08	- .62	.08
July	80.2	75.3	+ 4.9	3.61	3.44	+ .17	.27	.48	- .21	.05
August	74.6	73.1	+ 1.5	3.56	3.78	- .22	.07	.35	- .28	.02
September	72.4	65.6	+ 6.8	7.21	4.76	+ 2.45	.44	.49	- .05	.04
October	59.0	53.7	+ 5.3	4.19	2.63	+ 1.56	.45	.48	- .03	.16
November	48.8	39.0	+ 9.8	5.96	2.07	+ 3.89	1.75	.45	+ 1.30	.20
December	37.1	27.1	+ 10.0	2.84	1.21	+ 1.63	1.66	.34	+ 1.32	.59
1932										
January	30.0	21.8	+ 8.2	1.56	1.04	+ .52	2.02	.34	+ 1.68	.49
February	34.0	24.9	+ 9.1	.75	1.10	- .35	.73	.44	+ .29	.45
March	29.7	36.1	- 6.4	1.53	2.11	- .58	.90	.97	- .07	.52
April	50.3	49.9	+ .4	1.49	3.25	- 1.76	.48	.87	- .39	.40
May	64.0	61.3	+ 2.7	4.03	3.48	+ .55	.73	.75	- .02	.32
June	74.2	70.5	+ 3.7	6.95	5.18	+ 1.77	1.14	1.08	+ .06	.30
July	77.4	75.3	+ 2.1	4.70	3.44	+ 1.26	1.06	.48	+ .58	.31
August	73.8	73.1	+ .7	7.93	3.78	+ 4.15	1.09	.35	+ .74	.17
September	65.0	65.6	- .6	1.45	4.76	- 3.31	.17	.49	- .32	.16
October	51.4	53.7	- 2.3	2.46	2.63	- .17	.13	.48	- .35	.09
November	35.8	39.0	- 3.2	1.73	2.07	- .34	.25	.45	- .20	.08
December	26.4	27.1	- .7	1.83	1.21	+ .62	.93	.34	+ .59	.08
1933										
January	36.4	21.8	+ 14.6	1.10	1.04	+ .06	.64	.34	+ .30	.19
February	25.2	24.9	+ .3	.35	1.10	- .75	.20	.44	- .24	.13
March	37.4	36.1	+ 1.3	3.00	2.11	+ .89	.24	.97	- .73	.14
April	49.6	49.9	- .3	1.30	3.25	- 1.95	.91	.87	+ .04	.32
May	62.2	61.3	+ .9	6.09	3.48	+ 2.61	2.25	.75	+ 1.50	.46
June	79.6	70.5	+ 9.1	2.67	5.18	- 2.51	.51	1.08	- .57	.29
July	77.6	75.3	+ 2.3	1.95	3.44	- 1.49	.19	.48	- .29	.09
August	72.8	73.1	- .3	3.20	3.78	- .58	.16	.35	- .19	.05
September	72.1	65.6	+ 6.5	4.23	4.76	- .53	.17	.49	- .32	.03
October	52.4	53.7	- 1.3	1.61	2.63	- 1.02	.04	.48	- .44	.03
November	38.8	39.0	- .2	.24	2.07	- 1.83	.02	.45	- .43	.02
December	30.0	27.1	+ 2.9	.88	1.21	- .33	.02	.34	- .32	.02

Table 65.- Drought data for Skunk River Basin above Augusta, Iowa-Continued

Month	Temperature at Davenport, Iowa (°F.)			Precipitation over the basin (inches)			Run-off at Augusta (inches)			Estimated ground-water run-off (inches)
	For month	Average	Departure	For month	Average	Departure	For month	Average	Departure	
1934										
January	30.8	21.8	+ 9.0	0.99	1.04	− 0.05	0.04	0.34	− 0.30	0.02
February	23.8	24.9	− 1.1	.60	1.10	− .50	.04	.44	− .40	.02
March	35.1	36.1	− 1.0	.90	2.11	− 1.21	.05	.97	− .92	.02
April	51.3	49.9	+ 1.4	1.52	3.25	− 1.73	.08	.87	− .79	.03
May	70.2	61.3	+ 8.9	1.14	3.48	− 2.34	.02	.75	− .73	.02
June	79.4	70.5	+ 8.9	2.74	5.18	− 2.44	.04	1.08	− 1.04	.02
July	80.6	75.3	+ 5.3	2.93	3.44	− .51	.09	.48	− .39	.02
August	73.1	73.1	0	2.05	3.78	− 1.73	.01	.35	− .34	.01
September	63.4	65.6	− 2.2	5.71	4.76	+ .95	.03	.49	− .46	.01
October	58.0	53.7	+ 4.3	1.25	2.63	− 1.38	.02	.48	− .46	.01
November	45.3	39.0	+ 6.3	6.05	2.07	+ 3.98	.16	.45	− .29	.02
December	23.4	27.1	− 3.7	.62	1.21	− .59	.18	.34	− .16	.07

Table 66.- Drought data for Mississippi River Basin above Keokuk, Iowa

Month	Temperature* (°F.)			Precipitation over the basin (inches)			Run-off at Keokuk (inches)		
	For month	Average	Departure	For month	Average	Departure	For month	Average	Departure
1894									
June	70.9	66.6	+ 4.3	2.70	4.31	- 1.61	0.91	0.89	+ 0.02
July	74.4	61.4	+ 3.0	.67	3.61	- 2.94	.33	.80	- .47
August	71.5	69.2	+ 2.3	1.17	3.36	- 2.19	.20	.47	- .27
September	63.7	61.5	+ 2.2	3.17	3.54	- .37	.25	.42	- .17
October	50.0	49.3	+ .7	2.84	2.26	+ .58	.23	.50	- .27
November	29.5	34.0	- 4.5	1.15	1.50	- .35	.27	.45	- .18
December	28.6	20.8	+ 7.8	.89	1.08	- .19	.23	.32	- .09
1895									
January	10.5	14.4	- 3.9	1.07	1.03	+ .04	.16	.29	- .13
February	13.9	17.7	- 3.8	.52	1.05	- .53	.14	.31	- .17
March	31.1	30.1	+ 1.0	.54	1.60	- 1.06	.44	.69	- .25
April	50.7	45.2	+ 5.5	1.56	2.51	- .95	.31	1.02	- .71
May	58.6	57.3	+ 1.3	3.66	3.62	+ .04	.43	1.01	· · .58
June	67.5	66.6	+ .9	3.50	4.31	- .81	.44	.89	- .45
July	69.8	71.4	- 1.6	3.27	3.61	- .34	.41	.80	- .39
August	70.6	69.2	+ 1.4	2.70	3.36	- .66	.28	.47	- .19
September	65.2	61.5	+ 3.7	3.39	3.54	- .15	.22	.42	- .20
October	44.8	49.3	- 4.5	.44	2.26	- 1.82	.29	.50	- .21
November	31.9	34.0	- 2.1	1.55	1.50	+ .05	.21	.45	- .24
December	23.3	20.8	+ 2.5	1.28	1.08	+ .20	.16	.32	- .16
1896									
January	19.3	14.4	+ 4.9	.79	1.03	- .24	.14	.29	- .15
February	23.3	17.7	+ 5.6	.56	1.05	- .49	.21	.31	- .10
March	27.3	30.1	- 2.8	1.51	1.60	- .09	.29	.69	- .40
April	49.3	45.2	+ 4.1	5.48	2.51	+ 2.97	.38	1.02	- .64
May	63.6	57.3	+ 6.3	5.33	3.62	+ 1.71	1.20	1.01	+ .19
June	68.0	66.6	+ 1.4	3.70	4.31	- .61	1.02	.89	+ .13
July	71.0	71.4	- .4	3.37	3.61	- .24	.51	.80	- .29
August	70.0	69.2	+ .8	2.60	3.36	- .76	.40	.47	- .07
September	57.2	61.5	- 4.3	3.63	3.54	+ .09	.27	.42	- .15
October	46.1	49.3	- 3.2	2.66	2.26	+ .40	.25	.50	- .25
November	26.2	34.0	- 7.8	2.50	1.50	+ 1.00	.35	.45	- .10
December	25.7	20.8	+ 4.9	.69	1.08	- .39	.39	.32	+ .07
1910									
March	48.0	30.1	+ 17.9	.18	1.60	- 1.42	.91	.69	+ .22
April	49.2	45.2	+ 4.0	2.20	2.51	- .31	.81	1.02	- .21
May	53.9	57.3	- 3.4	2.46	3.62	- 1.16	.63	1.01	- .38
June	69.5	66.6	+ 2.9	1.36	4.31	- 2.95	.42	.89	- .47
July	73.4	71.4	+ 2.0	1.82	3.61	- 1.79	.25	.80	- .55
August	69.4	69.2	+ .2	3.11	3.36	- .25	.21	.47	- .26
September	60.9	61.5	- .6	2.84	3.54	- .70	.23	.42	- .19
October	53.3	49.3	+ 4.0	.99	2.26	- 1.27	.23	.50	- .27
November	29.4	34.0	- 4.6	.70	1.50	- .80	.21	.45	- .24
December	19.5	20.8	- 1.3	.58	1.08	- .50	.14	.32	- .18
1911									
January	15.9	14.4	+ 1.5	.94	1.03	- .09	.17	.29	- .12
February	24.4	17.7	+ 6.7	1.68	1.05	+ .63	.56	.31	+ .25
March	37.1	30.1	+ 7.0	.90	1.60	- .70	.39	.69	- .30
April	44.7	45.2	- .5	2.32	2.51	- .19	.40	1.02	- .62
May	62.3	57.3	+ 5.0	3.90	3.62	+ .28	.42	1.01	- .59
June	71.1	66.6	+ 4.5	3.37	4.31	- .94	.52	.89	- .37
July	71.6	71.4	+ .2	3.69	3.61	+ .08	.25	.80	- .55
August	67.5	69.2	- 1.7	4.25	3.36	+ .89	.40	.47	- .07
September	60.8	61.5	- .7	4.98	3.54	+ 1.44	.36	.42	- .06
October	46.9	49.3	- 2.4	4.76	2.26	+ 2.50	.93	.50	+ .43
November	26.2	34.0	- 7.8	2.00	1.50	+ .50	.77	.45	+ .32
December	26.1	20.8	+ 5.3	1.87	1.08	+ .79	.58	.32	+ .26
1930									
July	74.0	71.4	+ 2.6	2.41	3.61	- 1.20	.45	.80	- .35
August	73.3	69.2	+ 4.1	1.54	3.36	- 1.82	.23	.47	- .24
September	62.7	61.5	+ 1.2	3.27	3.54	- .27	.19	.42	- .23
October	47.7	49.3	- 1.6	2.14	2.26	- .12	.23	.50	- .27
November	37.3	34.0	+ 3.3	1.97	1.50	+ .47	.20	.45	- .25
December	23.8	20.8	+ 3.0	.45	1.08	- .63	.19	.32	- .13

* Stations used to compute average temperature over the basin are given in table 11.

Table 66.- Drought data for Mississippi River Basin above Keokuk, Iowa-Continued

Month	Temperature* (°F.)			Precipitation over the basin (inches)			Run-off at Keokuk (inches)		
	For month	Average	Departure	For month	Average	Departure	For month	Average	Departure
1931									
January	25.7	14.4	+ 11.3	0.44	1.03	- 0.59	0.19	0.29	- 0.10
February	31.5	17.7	+ 13.8	.48	1.05	- .57	.23	.31	- .08
March	31.8	30.1	+ 1.7	1.67	1.60	+ .07	.23	.69	- .46
April	48.4	45.2	+ 3.2	1.55	2.51	- .96	.31	1.02	- .71
May	55.3	57.3	- 2.0	2.37	3.62	- 1.25	.27	1.01	- .74
June	71.3	66.6	+ 4.7	4.17	4.31	- .14	.26	.89	- .63
July	75.5	71.4	+ 4.1	2.32	3.61	- 1.29	.33	.80	- .47
August	70.2	69.2	+ 1.0	2.99	3.36	- .37	.16	.47	- .31
September	67.9	61.5	+ 6.4	4.77	3.54	+ 1.23	.22	.42	- .20
October	54.7	49.3	+ 5.4	3.06	2.26	+ .80	.31	.50	- .19
November	42.0	34.0	+ 8.0	4.33	1.50	+ 2.83	.45	.45	0
December	31.1	20.8	+ 10.3	1.38	1.08	+ .30	.66	.32	+ .34
1932									
January	22.1	14.4	+ 7.7	1.61	1.03	+ .58	.63	.29	+ .24
February	23.7	17.7	+ 6.0	.94	1.05	- .11	.40	.31	+ .09
March	23.8	30.1	- 6.3	1.37	1.60	- .23	.59	.69	- .10
April	45.9	45.2	+ .7	1.73	2.51	- .78	.89	1.02	- .13
May	59.2	57.3	+ 1.9	3.53	3.62	- .09	.67	1.01	- .34
June	69.9	66.6	+ 3.3	3.82	4.31	- .49	.52	.89	- .37
July	73.5	71.4	+ 2.1	3.20	3.61	- .41	.38	.80	- .42
August	71.4	69.2	+ 2.2	4.30	3.36	+ .94	.28	.47	- .19
September	60.8	61.5	- .7	1.50	3.54	- 2.04	.20	.42	- .22
October	46.6	49.3	- 2.7	1.92	2.26	- .34	.17	.50	- .33
November	30.8	34.0	- 3.2	1.76	1.50	+ .26	.19	.45	- .26
December	19.2	20.8	- 1.6	1.43	1.08	+ .35	.22	.32	- .10

* Stations used to compute average temperature over the basin are given in table 11.

the drought of 1930-32 a deficiency of 3.64 inches accumulated in 4 consecutive months and a total of 8.67 inches in 14 months. The run-off during the first drought period was deficient for 22 consecutive months, the accumulated total being 6.42 inches, and by the end of 29 months the accumulated deficiency amounted to 6.96 inches. During the second drought a deficiency of 2.87 inches accumulated in 10 consecutive months, and at the end of 18 months the accumulation amounted to 5.18 inches. In the third drought a deficiency of 7.15 inches in run-off accumulated in 30 consecutive months. The temperature affecting the amount of transpiration (over 40°) during the drought of 1930-32 averaged about 0.6° higher than in 1910-11 drought and about 0.7° higher than in 1894-96.

Ground-water levels

The advisory committee of the American Geophysical Union in a report to the Water Planning Committee, dated February 12, 1935, suggested, among other things, "a study of the laws governing the ground-water supply to streams and the relation of ground-water levels to ground-water flow. This is important because ground water is the only source of supply to streams without surface storage during drought periods. Also in case of many crops, such as alfalfa, ground water is the principal source of moisture utilized by vegetation during drought periods when soil moisture is deficient."

In this connection a comparison of deficiencies in precipitation with decline of ground-water levels made in the Platte Valley in central Nebraska by Leland K. Wenzel, of the United States Geological Survey, is of interest. The results of this study are briefly outlined in the following statement prepared for the press, dated April 1, 1935. In connection with this statement it should be noted that water is pumped from wells for irrigation during the summer in the area east of Kearney, and hence the water-level fluctuations shown in the accompanying figure are not wholly caused by natural conditions. The part of the Platte Valley where irrigation is practiced with water diverted from the Platte River is somewhat separated from the part of the valley east of Kearney by a restriction in the valley, and it is believed that the effect of surface-water irrigation west of Kearney on the fluctuations of the water table in the area to the east is negligible.

"The water levels in about 100 wells in the Platte River Valley between Grand Island and Cozad, in central Nebraska, have been measured periodically since October 1930 by the United States Geological Survey in cooperation with the Conservation and Survey Division of the University of Nebraska. In October 1934 the water levels in these wells stood from 1 to 8 feet lower than in October 1930, thus indicating a general decline of the ground-water table throughout this part of the Platte Valley. It has been greatest in parts of the valley between Cozad and Kearney, ranging from 4 to 8 feet in an area north of Cozad and Lexington and from 3 to 4 feet in an area on the north side of the valley from Lexington to and beyond Kearney. This decline has been caused principally by subnormal precipitation, together with the relatively small amount of surface water available for irrigation, and thus for seepage to the ground-water table, in the last 4 years. N. H. Darton, of the United States Geological Survey, made an investigation in 1896 of the geology and ground-water conditions of southeastern Nebraska. The ground-water level in the vicinity of Lexington was then 20 to 22 feet below the land surface. At the present time it is only 7 to 10 feet below the land surface and hence is still from 10 to 15 feet above the level of 1896. The net rise since 1896 doubtless has been caused by seepage of water diverted from the Platte River for irrigation. In years when only comparatively little water flows in the irrigation ditches--as during the last 4 years--the seepage is small, and therefore rather large declines of the water table occur. Rises of 1 to 4 feet of the water level in wells near Lexington were recorded in the fall of 1934, when surface water once more flowed in many of the canals near the city.

"East of Kearney the decline of the ground-water table has in general been less than west of Kearney. From Kearney to Shelton and south of Alda it has in general ranged from 2 to 3 feet, and in the vicinity of Wood River it has been less than 2 feet. The decline east of Kearney was smaller chiefly because the water table had not been built up prior to 1930 to any great extent by surface-water irrigation and also, perhaps, because east of Kearney the ground-water level is sustained to a greater extent by underflow from the northwest. Such decline as occurred was due chiefly to subnormal precipitation but in small part to the considerable quantity of ground water that was pumped for irrigation.

"A special study was made of the fluctuation of the water levels in 20 observation wells between Grand Island and Kearney and their relation to the precipitation. The results are shown in the accompanying graphs (figure 88). One hydrograph shows the average water level at the end of successive 3-month periods from January 1931 to January 1935 in 14 wells in which the water levels stand more than 10 feet below the land surface. Another hydrograph similarly shows the average water levels in 6 wells with water levels less than 10 feet below the surface. The wells of the second group are in the same stretch of the Platte Valley as those of the first group but are nearer the river, where the water table is not far below the surface. A third graph shows the accumulative departure from normal precipitation as compiled from the records at Grand Island and Kearney since January 1, 1931.

"The water levels in the wells of the second group in general rise and fall more than the water levels in the wells of the first group. This more active fluctuation is due to the following causes: Recharge from precipitation occurs more frequently where the water table is shallow and thus larger rises of the water level result. On the other hand, the roots of more plants draw water directly from the zone of saturation where the water table is shallow, and consequently larger declines of the water level occur in the growing season. Changes in the level of the Platte River cause similar changes in the water levels in wells close to the stream, but the river has small effect on the water levels in wells farther away. In the winter and spring of 1931, 1933, and 1934 the average rise was less than 1 inch in the wells with deeper water level but more than 1 foot in the wells with shallow water level. The decline of the water levels in the summer and fall was likewise greatest in the shallow-water wells. Consequently in the last 4 years the net decline was nearly the same in each group.

"In the first half of 1932 there were rather large rises of the water levels in all the wells in the Platte Valley, as indicated by the hydrographs. The cause of this rise is apparent from the curve showing accumulative departure from normal precipitation. From October 1931 to April 1932 the average precipitation recorded at Grand Island and Kearney was slightly above normal, and consequently considerable water percolated into the ground and was added to the ground-water reservoir in this recharge period. As a result the water level did not reach as low a level

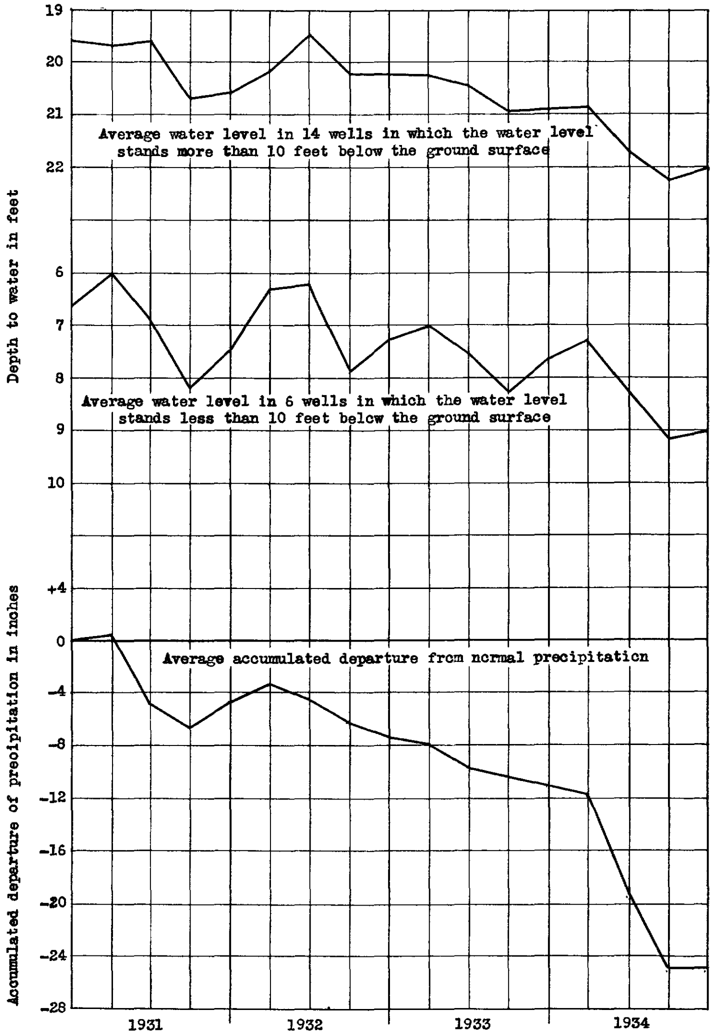


Figure 88.—Hydrographs of the average water levels in observation wells in the Platte Valley between Grand Island and Kearney, Nebr., and the accumulated departure from normal precipitation since January 1, 1931, recorded at Grand Island and Kearney, by 3-month periods

in 1932 as it did in 1931. Since July 1932 the precipitation has been about 22 inches below normal--a deficiency equivalent to almost one year's normal precipitation--and the water level in the valley has suffered annual net declines. It may reasonably be expected that future years of greater precipitation will again raise the ground-water levels."

Comparison of graphs of minimum flow

The comparison of the graph of minimum flow of the major basins studied should be of interest, especially if the relations between general ground-water conditions in the basins and the seepage flow therefrom are eventually determined. In figure 89 is plotted (plotted points are shown connected for purpose of illustration) for the period of record the annual minimum average daily discharge for 7 consecutive days, not including the frozen period, for the major basins studied, except for the Merrimack River Basin, for which annual minimum monthly flows are plotted. The records have not been corrected for storage and no attempt has been made to determine the effect, if any, of storage operations or channel improvements on the minimum flows.

From the records as they stard some general observations can be made. For the relatively short records for the Red, James, and Chattahoochee Rivers, the trend in 7-day minimum flows seems to be somewhat downward. The longer time record for the Mississippi River above Keokuk shows a decided downward trend in 7-day minima since 1930, but in three years - 1894, 1910, and 1925 - the minimum was almost as low as in 1930. The Merrimack monthly minima have trended generally upward since 1911, with an early low recorded in 1883. The Tennessee River minima have trended upward since 1925, when the minimum was the lowest for the period of record, although approached in the earlier years 1881, 1883, and 1904. Zero flow was recorded on the Neosho River in 1896, 1897, 1920, and 1934.

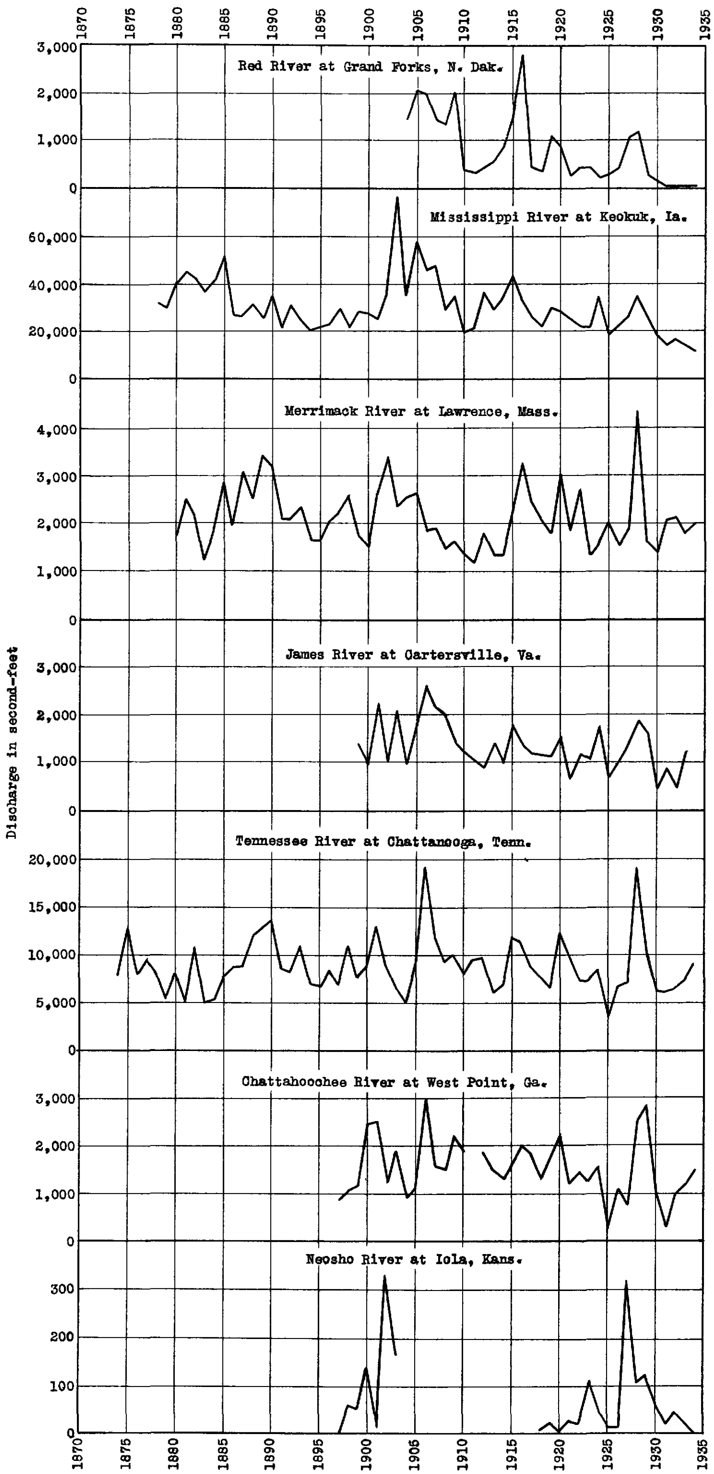


Figure 89.—Minimum annual average daily discharge for 7 consecutive days not including frozen periods. Figures for Merrimack River are minimum annual average monthly discharge.

APPENDIX

Report of Advisory Committee of Section of Hydrology of the American Geophysical Union to the Water-Planning Committee of the National Resources Board

Gentlemen:

The Advisory Committee of the Section of Hydrology of the American Geophysical Union, which at your request has maintained an advisory status with the Geological Survey with regard to studies of the relations of rainfall and run-off, has now in hand a progress report in this matter which, we understand, has been prepared for publication as a water-supply paper.*

The committee wishes to offer its commendation of the very useful work done by the engineers and hydrologists of the Geological Survey. The report is a record of progress made in exploratory studies of certain phases of the relations of rainfall and run-off and the factors that affect these relations. It should be understood that this report is in no sense to be considered a record of completed, exhaustive research into the subject. Many parts of the report suggest pertinent questions concerning aspects of the data presented, which are not answered and not answerable at this time.

The proposed publication offers more or less simple representations and tentative analyses of basic hydrologic data and should be of value to those who seek knowledge of these subjects. The compilation will enable students of the subjects involved to have the benefit of the information collected, and its publication offers an opportunity for hydrologists, meteorologists, and others to review and criticize the methods used and the results obtained. One of the principal benefits hoped to be derived from the report is the stimulation of such review and criticism. Studies such as are here described, when supplemented by other similar studies or when carried to a point where definite changes, trends, and relations can be disclosed and reasonably accurate conclusions drawn, should be of value in connection with the preparation of plans and measures

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* Refers to this paper.- W. G. H.

for the conservation of water resources. The committee cautions readers against the use of any of the material apart from its accompanying text.

The Advisory Committee approves the publication of this material at this time. During the progress of the studies the committee has suggested items of study and also alternate methods of approach in many problems. It has recommended that some specific studies undertaken be abandoned, because the basic data available did not appear to be sufficiently complete or accurate for the purpose. It should be understood that in recommending publication of the material at this time the committee is not necessarily committed to the approval of the procedures used as the best methods for particular studies, nor in any way committed to an approval of tentative conclusions which may appear to be expressed in the report.

Although rainfall and run-off are the most obvious and most widely observed factors of the hydrologic cycle, the records of reliable observation of these phenomena are comparatively short and afford a meager basis for satisfactory conclusions.

Few continuous records of precipitation and temperature and no records of stream flow are now available for any part of the United States for periods of 100 years or more.

The variations in precipitation, temperature, and run-off that are presented in the report cover a relatively short period of time, and no attempt has been made to extend the records by use of tree rings, lake levels, glacial changes, timber-line movements, or similar studies. No attempt has been made to determine whether the apparent changes are a part of long-time cyclic variations or are indications of permanent changes. The important thing is the fact that during a period of less than 100 years changes of sufficient magnitude to affect human occupancy have apparently occurred in meteorologic and hydrologic conditions in certain parts of the United States. Whether any part of the changes noted may have resulted from man's occupancy is an open question. In one instance the data presented suggest that possibly conditions could be improved through man's efforts. The committee feels, however, that much more research will be needed before it can be definitely asserted that over the basins studied man's occupancy has caused measurable changes either in meteorologic conditions or stream flow. It is possible, however, that when the data presented are used in conjunction with other studies, or when the present studies are carried to completion, definite reasons can be disclosed for the various changes, and in that event it can be definitely determined whether or not over large areas man can reasonably undertake remedial measures.

The Advisory Committee calls attention to the resolution of the American Geophysical Union at its annual meeting in Washington on April 25, 1935. This resolution points out the fact that the study of hydrologic phenomena and its application to the conservation and utilization of water resources is a work that is divided among a number of different bureaus and departments of the Federal Government, and that at the present time there is no correlating authority or agency for uniting in a systematic manner the work of these Federal agencies, and therefore the American Geophysical Union recommended and urged that there be established a permanent agency with authority to direct and correlate the work of all these separate agencies engaged in matters pertaining to the utilization of the nation's water resources.

The Advisory Committee endorses the aforesaid resolution and furthermore recommends that in the event of further investigations in the application of hydrology, all such future work be under the direction and supervision of such a centralized correlating agency, to be established; that such agency be vested with the necessary power and authority to insure a correlated work; and that the aforesaid correlating agency have authority to assign to the various bureaus and departments specific studies for which they may be best equipped.

In the attached supplementary notes the committee is indicating certain specific matters that might be restudied to advantage, and other methods of approach that for certain problems seem desirable.

This report was prepared and concurred in by a subcommittee consisting of Messrs. Horner, Horton, Meyer, and Sherman. The other members of the committee, Messrs. Pickels, Towl, and Woermann, although cooperating in the studies, have not had opportunity to review the proposed water-supply paper in its present form of compilation.

Respectfully submitted.

ADVISORY COMMITTEE,

AMERICAN GEOPHYSICAL UNION

June 12, 1935

By Wesley W. Horner, Chairman.

Supplementary notes

Work of the committee

The seven members of the committee have maintained contact with the studies of the Geological Survey since their appointment in May 1934. To a considerable degree discussion of material between members of the Advisory Committee and between them and the active staff on this project of the Geological Survey has been maintained by correspondence. During the first 6 months of the work the correspondence was supplemented by frequent conferences between Mr. Hoyt and others, on the one hand, and Messrs. Horner and Sherman, of the committee, on the other.

In order to expedite the work of the Advisory Committee, a subcommittee was formed, consisting of Messrs. Horner, Meyer, and Sherman, and to this subcommittee was added Mr. R. E. Horton in January 1935. On January 18 three members of the subcommittee met with Mr. G. M. Matthes, chairman of the Committee of Flood Protection Data, for the discussion of certain material of common interest to the two committees; thereafter, a memorandum report was rendered to the Water-Planning Committee. On April 22, 1935, the four members of the subcommittee met with Mr. Hoyt and his assistants for a full-day session in Washington. At this time, the studies contained in the proposed water-supply paper were nearing completion. The material was analyzed in detail, and the members of the Advisory Committee offered definite suggestions as to policy, as to differences in procedure, and as to specific details or apparent defects in the basic data.

After the material had been assembled in final form, but prior to complete editing, the subcommittee met in Chicago on June 12, 1935, and again reviewed the results of all the studies undertaken. This report of the Advisory Committee will be considered its final report on the present exploratory studies, to be published as Water-Supply Paper 772.

Detailed comments on matter contained in the water-supply paper

To amplify the statements on pages 19 and 20 it should be made clear that during the progress of the studies the Advisory Committee came to appreciate more and more the deficiencies of the fundamental data on which the studies undertaken had to be based. It had been hoped that exploratory studies in the various fields might develop derived information of real present value, and that the results of the studies would permit tentative conclusions by both hydrologists and economists which would be useful in connection with present national planning. Although these hopes could not be fully realized, because of deficiencies in the fundamental data, the studies contained in the present report indicate fields for further study for which present basic data may be considered reasonably adequate, and they also indicate desirable modifications in methods of collecting basic data. With respect to the last item, the Advisory Committee calls attention to the report now being made to the Water-Planning Committee by a special committee on standards and specifications for hydrologic data, with which some of the members of the Advisory Committee have been associated. Because the improvement and standardization in the collections, compilations, and publication of basic data are there discussed in detail and definite recommendations are made with regard to them the Advisory Committee refrains in general from further recommendation on these subjects herein.

With regard to the material on page 19 the Advisory Committee wishes to make clear its understanding that although the studies contained in the main report may not be considered "broad general studies", yet in many phases they deal with relations of mass values, such as rainfall, run-off, and temperature on annual, 5-year, and 10-year bases. At the committee's suggestion, seasonal values have been developed in certain of the studies. To the extent that mass values are involved, detailed fundamental relationships are obscured, and the committee wishes at this point to call attention to the extreme benefit that would result from specific studies of the relations of rainfall and run-off with regard to smaller areas, high intensities, and short times of occurrence, such as definite storm periods. Owing to the greater simplicity of conditions and the possibility of their control in part, studies of run-off from small drainage basins are better adapted to the determination of the underlying laws and principles of run-off phenomena than studies of larger drainage basins.

In the studies of natural phenomena, such as precipitation, temperature, and run-off, 10-year progressive averages have been used extensively in the report. The committee believes that on the whole 5-year moving averages, with the result plotted for the third year, give a better indication of trends than 10-year moving averages. If 10-year moving averages are used and are plotted on the tenth year they tend to obscure trends and make the moving averages appear in conflict with the annual averages. If 10-year averages are used it appears best to have the average value plotted as the middle point of the series instead of the end.

The material presented in table 1 (p. 21) is of great interest. However, in view of studies presented in other sections of the report with regard to changes in precipitation by geographic provinces and by basins, table 1 and the statements on page 21, appear to need further analysis and discussion. For example, figure 1 indicates a general downward trend of precipitation except in certain southern and west-central provinces and in a portion of the southwestern area. In view of the definite decrease in precipitation as indicated in figure 1 and as shown more specifically in certain tables, there appears to be a necessity for harmonizing the two studies.

The study of precipitation trends by seasons in fifteen geographic areas is a presentation of material of the first importance and material that may be used by hydrologists for further analysis. The committee considers it unfortunate that these studies have of necessity had to be based to so great an extent upon precipitation data collected at the so-called "first order stations." At many of these stations the gages have been subject to change in location and exposure and in particular, to more than one change in height above the ground surface, generally to the roof of a higher building. On this account it is possible that the trend at some of these stations will indicate a decreasing annual precipitation, when as a matter of fact the data may be affected by decreased catch of gage.

Much of the work on trends of hydrologic data presented in the paper is based on annual values. The committee feels that although annual values are useful in various ways there are certain respects in which such values alone are either inadequate or may be deceptive, and that in future studies, involving trends or changes in conditions, a seasonal basis should in general be used, with the data for a growing season presented separately from those for the remainder of the year. Aside from the obvious advantage of this plan in relation to agriculture, it segregates the summer data which are less subject to basic errors than those for the winter season, and inasmuch as the greater part of the run-off for many drainage basins occurs in the winter season, such a segregation is necessary if the results are to be applied to summer conditions.

The committee particularly commends the study of trends and of relationships by basins and recommends that the future studies, insofar as possible, be carried out along drainage-basin lines.

The committee recommends that in future research relations between rainfall and run-off should not be studied or expressed as ratios or percentages, but should be indicated by differences between rainfall and run-off, or so-called "water losses", which are indicative of what is called the "consumptive use" characteristic of the particular basins.

The report contains tabulations showing the segregation based on a 5-year annual average for certain periods noted and obtained by subtracting from the total stream flow an estimated ground-water run-off obtained through a study of the plotted hydrograph of stream flow, in part by methods discussed in the report. Certain exceptions are made as to the straight-line methods used on the Miami and Pomperaug Basins.

The committee calls attention to the qualification as to the accuracy of the results obtained, contained on page 120 where it is stated: "It should be clearly recognized that the estimates given are subject to error. Further refinements in the methods of determination and more exhaustive application of known factors may change the results materially." The committee believes that the character of the material presented in subsequent tables is of such importance as to justify a further attempt to organize the technique of ground-water separation in accordance with the most scientific methods now possible, and it would suggest that the values presented in these tables be considered tentative only and that the studies on which they are based should be renewed and revised at the earliest possible opportunity.

Many additional studies are in progress, and better methods for the separation of ground-water stream flow are being developed. When these methods are applied to the records for which a separation of stream flow was made in this report, material differences will undoubtedly be shown, but it is nevertheless appreciated that the existing information indicates striking differences in the characteristics of the various drainage basins listed, and for purposes of comparison the results are believed to be of value.

In the opinion of the committee the methods used are not subject to error sufficient to invalidate their application to the separation of ground-water stream flow in the use of the unit-graph method.

The committee's statements with relation to the tables on pages 120-122 apply equally to tables on ground-water run-off on pages 246 and 247.

A considerable part of the ground-water flow included in the tabulated values is necessarily derived from flow during the winter season. To the extent that values of winter flow are derived from estimates and not from measurements, the possible error in total annual quantity is increased. The development of winter depletion curves by the making of more extensive actual measurements on northern streams during periods when there is no surface run-off is strongly recommended.

With regard to the statement on page 245, the committee is of the opinion that quantitative values of ground-water run-off which may eventually be developed by scientific application of the best possible methods may vary from the values given on pages 246 and 247, in some instances by more than 10 percent, and that the variation may be in either direction.

The committee feels that the work presented by Merrill Bernard relating to the possibility of transposing flood producing storms by means of the unit hydrograph is a useful contribution in making flood estimates. In such applications it is necessary to be fully acquainted with the geographic and meteorologic conditions of the areas involved.

REFERENCES

The following list of references, largely American, to relations between rainfall and run-off and related subjects does not include articles on run-off of high intensity, such references being included in U. S. Geological Survey Water Supply Paper 771.

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