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By

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INTRODUCTION

The water that drains from the land into creeks and rivers is called runoff. Supplying many of our basic human needs for water, runoff occurs chiefly as a residual of rainfall after Nature's take - that is, after the persistent demands of evaporation from land and transpiration from vegetation have been supplied.

The streams of the Nation are one of our most valuable replenishable resources. An increasing part of our domestic governmental program, both Federal and State (Hoyt, [1]1943, pp. 290-303), is being devoted to their development for power generation, irrigation, navigation, industrial production, and sanitation.

The annual runoff represents the total flow of a stream and the upper limit of the water potentially available for development; consequently, it forms a convenient unit or base for many hydrologic investigations. Studies of annual runoff in this country go back some 50 or 60 years, but it is only recently that the number of gaging stations has permitted a satisfactory approximation of the distribution and occurrence of runoff in the United States.

Observations of stream flow are regularly made at about 6,000 gaging stations, located on all principal rivers and a large number of their tributaries. The network of gaging stations covers all States, but the density of coverage tends to reflect the value or the volume of the water, so that there are broad areas, chiefly in the West, and small streams, in all parts of the country, where the number of gaging stations is inadequate to give a satisfactory description of the occurrence of runoff.

Because annual runoff is a remainder, it varies to a much greater extent than precipitation. This variability in respect to both place and time emphasizes a need for long-period gaging of numerous rivers. The water resources of the United States can be adequately valuated only by assured continuity in gaging. Continuity is vital because of the possibility that a once-in-a-lifetime flood or drought, for example, may occur during even a short lapse.

The variations in runoff from place to place and from year to year are dominantly associated with corresponding variations in precipitation. Temperature, as it affects the intensity of the evapo-transpirative processes, also has a major influence on the geographic distribution of runoff. Thus an annual

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[1] See page 13 for list of references cited.

precipitation of 20 inches will result in more runoff in a region where the mean annual temperature is 50° F. than in one where the temperature averages 70° F. The geographic distribution of runoff shown on plate 1 therefore reflects to a high degree the variation in climate. Runoff ranges from more than 80 inches in the superhumid rain forest of the Olympic Mountains in Washington to less than a quarter of an inch in the Arizona deserts. Runoff is fairly uniform throughout the humid East in contrast to the extreme diversity with which it occurs in the West. A marked feature of plate 1 is the east-west transition over the Great Plains.

Upon these broad features are superimposed certain anomalies that correspond in the main to effects of geology and topography. Striking examples of these influences will be described.

The collected discharge from a drainage basin is measured at a gaging station in cubic feet per second; however, it has become customary to express volume of runoff in terms of inches of water over the drainage area in order to facilitate comparison with other basins and with rainfall and to simplify other hydrologic studies. The total volume of water discharged, when divided by the drainage area, yields a quotient expressible in inches, which indicates the mean depth contributed by the drainage basin. However, this does not signify that each unit of area drained contributed equally. The depths of runoff contributed by each unit of area may differ because of variations in precipitation over the basin or because of geology and topography. The lines of equal runoff, called isograms of runoff, on plate 1 have been drawn to express, as far as practicable, the areal variation in runoff. The isograms are designed to show the runoff at the place of origin rather than at the point of measurement. On the other hand, the map is intended to show, not the exact amount of runoff to be expected from any area, but the pattern of annual runoff over the United States, the general conformation of which probably remains fairly uniform over long periods of time.

ACKNOWLEDGMENTS

This report was prepared in the Water Resources Division of the Geological Survey under the direction of Carl G. Paulsen, chief hydraulic engineer, with the helpful guidance of R. W. Davenport, chief of the Technical Coordination Branch. Plate 1 is in part a compilation of the work of several engineers in the Water Resources Division: B. R. Colby and R. E. Oltman (1948) are credited with the Missouri Basin, C. D. Bue with the southwestern United States from Texas and Colorado to central California, and H. C. Troxell with southern California. A map of runoff in the Columbia Basin, prepared by C. C. McDonald and H. C. Riggs (1948), was used to modify earlier work by the present writer, and other assistance was obtained from a map published by the Tennessee Valley Authority (1943, p. 16). Information on runoff of streams in the lower Rio Grande Basin was obtained from a report of the International Boundary Commission, United States and Mexico (U. S. Dept. of State, 1940, p. 54).

Acknowledgments are due the engineers and geologists in the many field offices of the Geological Survey who have reviewed the map and have given numerous suggestions for its modification and improvement.

DEFINITIONS

In many writings on this subject, the terms "runoff", "stream flow", and "water yield" are often considered essentially synonymous. However, some hydrologists have found it convenient to distinguish between them about as follows (Davenport, 1946, pp. 876-885):

1. "Runoff" is the discharge of water in surface streams (Meinzer, 1923, pp. 9-16). Current usage associates runoff only with natural sources and effects, excluding those of artificial storage, diversions, and the like.

2. "Stream flow" is the actual discharge in surface streams. It includes runoff modified by artificial causes.

3. "Water yield" is the total outflow from a drainage basin through either surface channels or subsurface aquifers. By inference, therefore, water yield is the surplus of precipitation over evapo-transpiration loss.

Where there is no diversion, regulation, nor other artificial hydraulic effect, stream flow is equivalent to runoff. It is common practice to adjust the observed stream flow to allow for the effects of the simpler forms of diversion or storage and so to compute runoff. It has also become customary to express runoff in units of volume, such as acre-feet or inches, and stream flow in rate of units, such as cubic feet per second.

Where the discharge into or out of a basin through subsurface aquifers is small, then annual runoff is virtually equivalent to water yield and also, with appropriate adjustment for changes in ground and surface storage, equals total precipitation minus evapo-transpiration loss. Annual runoff differs from water yield by the amount of the flow that enters or leaves a drainage basin through any natural course other than on the surface. There is, therefore, no way of measuring yield directly. It can be estimated by adjusting runoff by the amount of the ground-water inflow or outflow, which can be measured under favorable field conditions. In most basins the difference between runoff and yield is small and may be assumed as negligible within the limit of accuracy of measurement. Some outstanding exceptions, however, are pointed out under "Effect of geology and topography."

PREVIOUS MAPS OF ANNUAL RUNOFF

Maps of Annual Runoff in the United States

Systematic stream gaging in the United States had its beginning about 1890. In 1892 F. H. Newell (1894, pp. 149-152), drawing upon very meager data, prepared maps showing annual rainfall and runoff in inches. The map of runoff, probably the first of its kind, was necessarily generalized but developed the main features of the geographic distribution of runoff in the United States quite faithfully. Twenty years later Henry Gannett (1912, pl. 2) published a more detailed map of runoff. Gannett's map was not only based on runoff records but was supplemented by subtracting an estimated "water loss" from precipitation in areas where there were no runoff records. Gannett seems also to have considered the effect of altitude on precipitation and water loss. Prepared in the early days of stream gaging, these maps were pioneer efforts redounding to the credit of their authors but subject to revision on the basis of the more adequate information now available. Gannett's map has been reproduced in many publications, most prominently by Meyer (1928, p. 298); in 1934 it was republished by the Mississippi Valley Committee (Oct. 1, 1934, p. 108).

Later in 1934 the Water Planning Committee of the National Resources Board published a new map (Dec. 1, 1934, pp. 292, 300), showing the "Distribution of average annual runoff in the United States." No record is available to show how it was prepared, but presumably it was based partly on runoff records and, at least in the East, on rainfall with a subtractive water loss. This map also has been republished several times in different forms.

The Water Planning Committee had the powerful advantage of 25 years of additional stream gaging. Its map is many times more detailed than Gannett's, yet it contains some obviously large errors, as in New Mexico, Kentucky, and Florida. Moreover, there are areas where subsequent gagings show Gannett's map to have been more representative than that of the Water Planning Committee.

Recently C. W. Thornthwaite (1944, pp. 686-693) published a map showing runoff in the eastern United States as computed from precipitation and temperature data according to a newly developed technique. On the whole, this map appears to be quite representative, but it deviates from measured runoff in Florida and in Michigan.

Some World Maps of Runoff

Nearly all evaluations of world-wide runoff, precipitation, and evapo-transpiration have been made by European hydrologists. These studies have been based on scant information and are highly generalized. In contrast, hydrologic work in the United States has been directed more toward detailed application to water-resources development, and few presentations of large-scale hydrology have been made despite the comparative wealth of information on which to work.

Beginning with Reclus (1873), who made perhaps the first compilation of the yearly runoff of the world's streams, writers have at intervals attacked the problem of appraising the world budget of precipitation, evaporation, and runoff. The following is a list of references on the subject:

Reclus, Elisée, 1873, The earth, pp. 377-379, Harper & Bro., New York [translated from the French].

Murray, John, 1887, On the total annual rainfall on the land of the globe and the relation of rainfall to the annual discharge of rivers: Scottish Geog. Mag., vol. 3, no. 2, pp. 65-80.

Brückner, Edward, 1905, Balance of water circulation: Soil Rept., vol. 7, no. 3.

Fritzche, R., 1906, Niederschlag, Abfluss und Verdunstung auf den Landflächen der Erde: Zeitschr. Gewässerkunde, Band 7, Heft 6.

Wüst, Georg, 1920, Die Verdunstung auf dem Meere: Inst. Meereskunde Univ. Berlin Veröffentl., neue Folge, Reihe A. Heft 6.

__________, 1922, Verdunstung und Niederschlag auf der Erde: Gesell. Erdkunde Berlin Zeitschr., Hefte 1-2, pp. 35-43.

Kaminsky, A. A., 1925., Data and studies pertaining to the hydrologic cycle: Central Hydrometeorologic Bur News, no. 4, pp. 7-22, Leningrad [in Russian].

Meinardus, Wilh., 1934, Die Niederschlagsverteilung auf der Erde: Meteorolog. Zeitschr., Band 51, Heft 9, pp. 345-350.

_________, 1934, Eine neue Niederschlagskarte der Erde: Petermanns Mitt., Band 80, Heft 1, pp. 1-3.

_________, 1934, Die Areale der Niederschlagsstufen auf der Erde: Petermanns Mitt., Band 80, Heft 5, pp. 141-143.

Halbfass, Wilh., 1934, Der Jahreswasserhaushalt der Erde: Petermanns Mitt., Band 80, Heft 5, pp. 137-140.

For the most part, each of the writers added a little information to that available in previous papers but mainly reworked the earlier data, which were notable only for their scantiness and possible inaccuracies. M. I. L'vovich (1945) attacked the problem anew. He listed the flow of about 500 streams throughout the world as obtained from original published sources insofar as these were available. On the basis of this information, supplemented by estimates made by correlation with rainfall and temperature in ungaged areas, L'vovich prepared what is probably the first world map of runoff. Table 1 is obtained from his report, with conversion from metric to English units.

Table 1.--World distribution of runoff, according to L'vovich

Continent (or other area)	Atlantic slope		Pacific slope		Regions of interior drainage		Total land area	
	Area (thousands of square miles)	Runoff (inches)	Area (thousands of square miles)	Runoff (inches)	Area (thousands of square miles)	Runoff (inches)	Area (thousands of square miles)	Runoff (inches)
Europe (including Iceland)....	3,073	11.7	--	--	661	4.3	3,734	10.3
Asia (including Japanese and Philippine Islands).	4,626	6.4	6,422	11.8	5,273	.66	16,321	6.7
Africa (including Madagascar).	5,110	14.0	2,109	8.6	4,291	.54	11,510	8.0
Australia (including Tasmania and New Zealand).	--	--	1,634	5.5	1,441	.24	3,075	3.0
South America................	6,041	18.7	519	17.5	381	2.6	6,941	17.7
North America (including West Indies and Central America).	5,657	10.8	1,914	19.1	322	.43	7,893	12.4
Greenland and Canadian Archipelago.	1,499	7.1	--	--	--	--	1,499	7.1
Malayan Archipelago...........	--	--	1,012	63.0	--	--	1,012	63.0
Total or average.........	26,006	12.4	13,610	15.5	12,369	.82	51,985	10.5

It will be observed that, according to L'vovich, South and North America are more favored with water than any of the other continents of the world; also, that the area tributary to the Atlantic Ocean is roughly twice that tributary to the Pacific, though the total runoff is only one and a half times as great. Regions of internal drainage total 24 percent of the earth's land surface. The greater part of the area of interior drainage, dominantly arid, is in Asia, Africa, and Australia. The last named is the driest of all the continents.

PREPARATION OF MAP

The runoff map (pl. 1) has been based as far as possible on stream-flow measurements. Not all stream-flow records could be used for this purpose, however. The primary requirements were (1) that the drainage area above the gaging station in question be known, (2) that the flow be not materially affected by diversion or regulation unless data were available for making at least reasonably accurate adjustments, and (3) that at least 5 years of record be available.

Figures of average discharge for the stations that met these requirements were computed for the 25-year period 1921-45. This period was selected because there are enough stations over the country with 25-year records to serve as base stations. Most of the records do not cover all this 25-year period; accordingly, the average runoff for the available period of record was adjusted to the uniform period of 25 years. This adjustment was made by multiplying the average runoff at the short-term station by the ratio that the runoff during this period at a nearby long-term station bore to the runoff during the 25-year period 1921-45. In general, these adjustments were not large. Their effect was most significant where the runoff isograms are widely spaced. Where runoff changes rapidly with distance, as in the Western mountains, the adjustment would shift the isogram by a smaller distance than could be shown on a map of the scale used.

The drainage basins above each gaging station were outlined on tracing paper laid over Geological Survey base maps of the United States, and the figures of average runoff were entered within the basin outlines. The base maps used were those showing drainage and relief.

Wherever possible, opportunity was taken to calculate runoff from partial basin areas and thus define areal variations in runoff more closely. This was done by subtracting the flow at one or more upstream stations from that at a downstream station. It must be recognized that the runoff thus computed for an intervening area commonly represents the difference between two comparatively large quantities and is subject to a relatively large error either in the figures of discharge or in the drainage area. Nevertheless, such subtraction when expressed in terms of discharge per unit of area produces a result that is highly informative in connection with the study of the geographic distribution of runoff.

The runoff isograms were drawn so that the figure plotted would conform to the average runoff in each basin or partial basin. In basins where the runoff varied greatly, the delineation of the isograms was aided by study of the general pattern, by reference to precipitation, or by knowledge of the terrain. In such basins the extremes in runoff may be greatly in error - for example, along mountain crests where they are based necessarily on extrapolation.

By and large, little difficulty was experienced in the East in developing the runoff map from the available stream-flow records. In contrast with the West, the East has a more regular pattern of topography and precipitation, better coverage by precipitation and stream-gaging stations, and fewer streams affected by permanent diversions. Because of extensive irrigation in the Western States, most of the streams are affected by diversions after debouching from the higher altitudes and entering their valley sections, and the stream-flow records are not indicative of the actual runoff from the lower altitudes. Therefore, the usable records are largely concentrated in the headwaters. In order not to limit the use of gaging-station data in the Western States too severely, a number of records were employed even though they were affected by diversions. Notes such as "many small diversions" and "diversions for irrigation" were generally represented by a plus sign after the plotted runoff figure.

There are large areas in the West--notably in Nevada--where no stream-flow records are collected. These areas are generally isolated and sparsely inhabited and have few precipitation records as well. Over a large part of the Southwestern States the isograms were necessarily drawn on the basis of knowledge of the terrain and vegetation and other pertinent information available.

In central and east-central Nevada, for example, is a series of high, narrow ranges, averaging about 100 miles or less in length and running generally north and south. The shrubs and trees on these ranges indicate that the rainfall must average about 20 inches at the 7,000-foot level, increasing to an average of about 35 inches at altitudes of 8,000 to 10,000 feet or more. This deduction is supported by stream-flow records collected on Lamoille Creek near Lamoille, Nev., which has a drainage basin of 25 square miles in the Ruby Mountains. Bailey (1941, p. 192) calls these ranges "humid islands . . . in an arid region."

A geometric scale was advisedly selected for the isograms of runoff. A scale of equal arithmetic intervals, such as is customary in drawing precipitation maps, would have given insufficient detail for use in the arid portions unless an inordinate number of isograms were employed. Previous draftsmen of runoff maps have recognized this problem in a general way, using a smaller interval in the areas of low runoff and a larger interval in the humid areas. The geometric or ratio scale avoids this difficulty altogether. A slight variation occurs in the 1- to 2.5-inch interval in order to facilitate the use of a system of simple fractions in the lower range with a system of multiples of 5 in the upper range. Isograms for 15 and 30 inches have been added in the East to give greater detail.

As is customary with contour maps, interpolations may be made between the isograms of runoff with a maximum error of about half an isogram interval, except in areas such as the Western desert regions where information on runoff is lacking. In the East, where lines of 15-inch and 30-inch runoff have been added, the definition is perhaps within 25 percent.

MEAN RUNOFF, PRECIPITATION, AND EVAPO-TRANSPIRATION IN THE UNITED STATES

Table 2, which is based on planimetered areas within the isograms of runoff in plate 1, was prepared to show the areal distribution of runoff in the United States. It is of interest to note that annual runoff is less than 5 inches in more than half the area of the United States.

Table 2.--Areal distribution of runoff in the United States

Range in runoff (inches)	Area 1/ (square miles)	Percent of total area
0 to 0.25...	306,000	10.1
0.25 to 0.5....	380,000	12.6
0.5 to 1.0....	266,000	8.8
1.0 to 2.5....	413,000	13.7
2.5 to 5......	247,000	8.2
5 to 10.....	258,000	8.5
10 to 20.....	830,000	27.5
20 to 40.....	290,000	9.6
40 to 80.....	30,000	1.0
Total.....	3,020,000	100

1/ Land and water area exclusive of the Great Lakes and coastal waters.

The total volume of runoff is 26,300,000 square-mile inches. Dividing by the total area (3,020,000 square miles) indicates that the Nation-wide runoff in the period 1921-45 averaged 8.7 inches. Calculations based on United States Weather Bureau data indicate that rainfall during that period averaged 30 inches. The difference of 21.3 inches between rainfall and runoff represents evapo-transpiration.

The Bible says that "all the rivers run into the sea," yet about 8 percent of the land area of the United States drains into arid interior basins, where salt or brackish lakes and playas or "sinks", dispose of the water by evaporation and transpiration. The largest of these areas of interior drainage is the Great Basin (215,000 square miles), which discharges no water into the oceans, so that all the precipitation on the basin eventually returns to the atmosphere. The total "runoff" of the Great Basin as computed by planimetering the isograms on plate 1 is 235,000 square-mile inches. Deducting this figure from the total runoff leads to the following computation of the mean evapo-transpiration in the United States (expressed in terms of the whole land area of the United States):

Precipitation = 30 inches
Runoff to the oceans = 8.6 inches
Evapo-transpiration = 21.4 inches

This determination of the mean runoff from the map may be compared with that indicated in table 3 by summation of the flow of the rivers that discharge into the oceans, with proper estimates for unmeasured flow and with deductions for the flow originating in Canada or Mexico.

Table 3.--Summary of estimated flow from the United States to the oceans

Part of drainage system	Description	Area (square miles)	Mean annual flow (cubic feet per second)
1	North Atlantic slope basins	148,000	210,000
2	South Atlantic slope and eastern Gulf of Mexico basins.	284,000	325,000
3, 5, 6, 7	Mississippi River Basin	1,250,000	620,000
5	Hudson Bay basins	48,000	5,000
4	St. Lawrence River Basin	130,000	140,000
8	Western Gulf of Mexico basins	320,000	55,000
9	Colorado River Basin	246,000	23,000
10	Great Basin	215,000	0
11	Pacific slope basins in California	117,000	80,000
12, 13, 14	Columbia River Basin and coastal streams in Oregon and Washington.	262,000	345,000
Total		3,020,000	1,803,000

The total runoff thus measured and estimated amounts to about 1,800,000 cubic feet per second, equivalent to 8.1 inches as compared with 8.6 inches obtained from the map.

This difference may be due to a combination of two factors: (1) incomplete evaluation of the area of interior drainage (noncontributing areas) and (2) evaporation losses from the water surface of the large rivers. The difference is in the expected direction and may be viewed as a confirmation of the computations. However, possible inaccuracies might greatly alter the magnitude of the difference without greatly changing the total value.

EFFECT OF CLIMATE

From one viewpoint, runoff--like soil moisture, evaporation, and other components of the hydrologic cycle--may be regarded as a manifestation of climate. Stream flow is as variable as the weather, but just as climate is integrated weather, so the map of average annual runoff (pl. 1) represents the total result of the day-to-day fluctuations in stream flow. These fluctuations in the main follow the vagaries of the weather to an extent governed by the terrain. In some streams, the variations in flow follow those of precipitation rather sensitively; in others, the flow lags behind the precipitation by periods extending over many months.

Annual runoff is the sum of all the runoff produced by the many rains and snows of

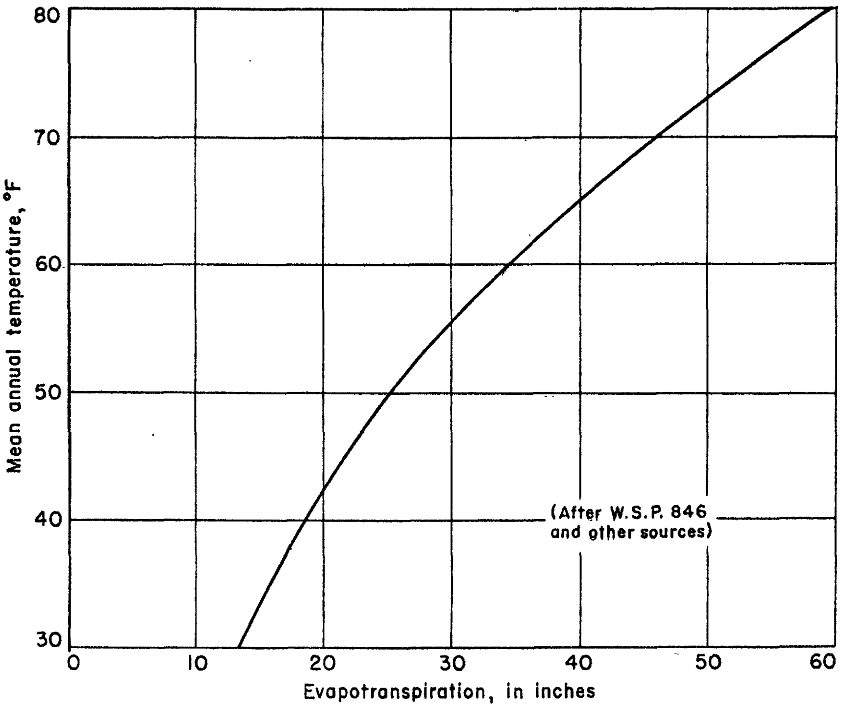

Figure 1.--Relationship of annual evapotranspiration loss in humid areas to temperature.

the year. The amount produced by each storm is highly variable, reflecting, for a given basin, numerous details of volume and intensity of rainfall, temperature, and soil moisture. Runoff also varies from year to year, the variations corresponding to the differences in number and intensity of the storms, but the relative variation in annual runoff is much less than that between storms. However complex the relation between storm rainfall and storm runoff may be, that between rainfall and runoff averaged over long periods of time can be stated in greatly simplified terms.

As noted by Hoyt (1936, pp. 16-17), it was early found that mean annual runoff equals rainfall minus loss due to evaporation from the land surface (including lakes and streams) and the transpiration of vegetation. The total loss, or evapo-transpiration, as it is now commonly called, is governed principally by the temperature and the amount of water available. In humid regions, where there is generally sufficient water to satisfy demands, the mean annual evapo-transpiration is a function chiefly of temperature. Thus the difference between long-term rainfall and runoff in humid regions can be related very closely to temperature (Lloyd, 1938, pp. 423-444; Williams, 1940). Figure 1 shows the relation between mean annual temperature and evapo-transpiration in the eastern United States. This principle has been used in various formulas to compute annual runoff in terms of rainfall and temperature. There are many such formulas (Prior, 1929), designed chiefly for use in humid regions.

A more generalized evaluation may be based on the assumption that any given combination of annual rainfall and temperature is associated with a certain runoff. To make this evaluation, pertinent data for several representative drainage basins in the United States are listed in table 4. Humid and arid, cold and warm regions are represented. The table lists mean precipitation, temperature, and runoff for a concurrent period of years. Also shown is a weighted mean temperature, computed by dividing the sum of the products of monthly precipitation and temperature by the annual precipitation. The quotient gives a mean annual temperature in which the temperature of each month is weighted in accordance with the precipitation during that month. A weighted temperature greater than the mean temperature, as usually computed, indicates that the precipitation is concentrated in the warm months, and vice versa. The difference is a measure of the concentration of precipitation in the warm or cold parts of the year.

(Continued on p. 9)

Table 4.--Mean annual precipitation, temperature, and runoff for selected drainage basins

Stream	Drainage area (square miles)	Period	Mean annual precipitation (inches)	Mean annual temperature (°F)	Weighted mean temperature (°F)	Mean annual runoff (inches)
Mexican Springs Wash at Mexican Springs, N. M.	32.7	1937-41	15.	47.5		0.4
Cannonball River at Breien, N. D.	4,066	1921-45	15.6	42.1	53.5	.61
Churchill River at Island Falls, Sask.	71,000	1929-43	16.	30.	40.2	4.1
S. Fork Palouse near Pullman, Wash.	81.1	1934-40	19.6	47.4	40.1	2.8
Stream A, Wagonwheel Gap, Colo...	0.347	1911-26	21.1	34.0	36.5	6.1
Saline River at Tescott, Kans....	2,820	1920-36	22.1	54.8	63.1	.76
Cajon Creek near Keenbrook, Calif	40.9	1931-43	1/22.8	56.1	48.1	4.5
Elkhorn River at Waterloo, Nebr..	6,900	1921-45	23.0	48.7	57.7	1.7
Deep Creek near Hesperia, Calif..	137	1905-15	1/27.1	51.5	39.	10.0
Strawberry Creek near San Bernardino, Calif.	8.6	1921-41	1/30.9	57.1	49.2	8.0
Washita River near Durwood, Okla.	7,310	1921-45	31.2	60.8	65.	3.2
Kings River at Piedra, Calif. 2/..	1,694	1895-1940	31.4	44.	36.	18.8
Ralston Creek near Iowa City, Iowa.	3.01	1925-35	33.0	50.2	58.1	6.7
Miami River at Dayton, Ohio......	2,513	1924-42	37.0	51.0	53.6	11.5
Neuse River near Clayton, N. C...	1,140	1921-45	45.4	60.3	62.3	13.9
Middle Westfield River at Goss Heights, Mass.	52.6	1922-34	45.6	46.8	46.0	25.9
West River at Newfane, Vt........	308	1920-23;1929-33	46.5	42.3	42.3	25.
Kissimmee River near Okeechobee, Fla.	3,260	1931-42	50.	72.5	76.1	7.3
Little River near Horatio, Ala...	2,690	1931-44	50.7	61.3	61.2	17.3
Elk River at Queen Shoals, W. Va.	1,145	1921-45	51.8	52.0	53.5	24.0
Average of 10 comparable basins in southeastern Alabama 3/	--	1938-47	59.3	66.	66.2	22.7
Amite River near Denham Springs, La.	1,330	1939-47	59.4	67.	67.1	19.5

1/ Computed by H. C. Troxell.
2/ After C. H. Lee in Am. Geophys. Union Trans., 1941, p. 50.
3/ Furnished by R. W. Carter.

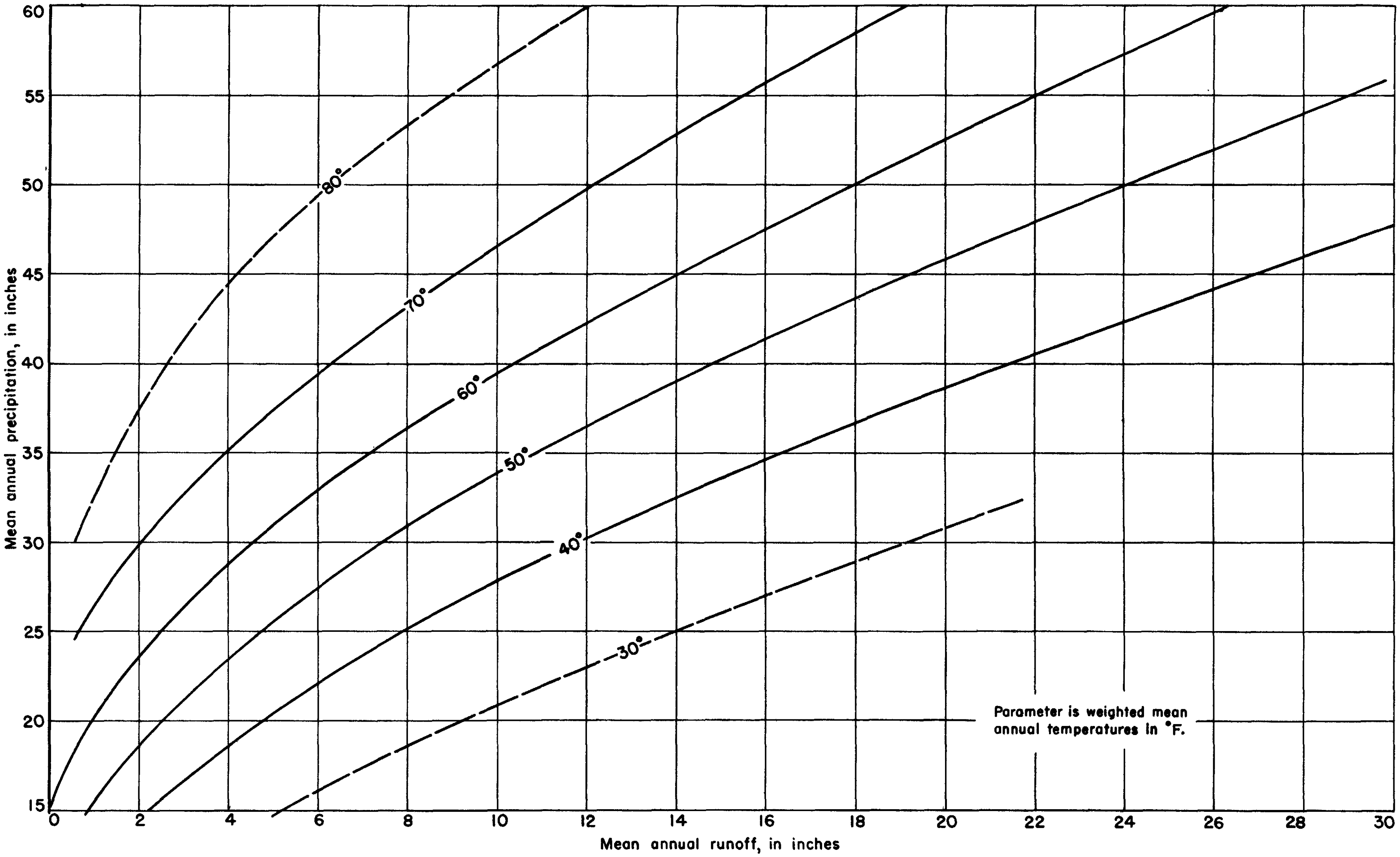

Figure 2.--Relationship of annual runoff to precipitation and temperature.

Figure 2 is a graph that seeks to develop the over-all relation. It illustrates how the runoff for a given annual precipitation decreases as the temperature rises. It also shows that, for a given temperature, runoff increases with precipitation. The numerical difference between precipitation and runoff for a given temperature likewise increases with precipitation, ultimately reaching a constant that represents the limiting or optimum evapo-transpiration, which is here considered as governed primarily by temperature but may be more generally related to such factors as insolation, wind movement, relative humidity, and other climatologic elements.

The energy for evapo-transpiration is provided by the sun, the ultimate source of energy on the earth for maintenance of the hydrologic cycle and the primary generating cause of the atmospheric activities that determine weather and climate (Hand, 1937, p. 415). Climate is customarily measured in terms of precipitation and temperature, but there are certain direct effects of solar radiation on runoff that require consideration. The solar radiation that reaches the ground (insolation) varies with latitude, season, cloudiness, the kind of surface and direction and degree of slope of the land surface. To a large extent the effect of insolation is contained in the temperature factor, but not entirely. A place at a high altitude in a southerly location may have a temperature regimen like that of a more northerly place nearer sea level, yet the insolation at the two places may be entirely different. The same is true with respect to southerly and northerly exposures in mountainous country. It has been observed (Croft, 1944) that drainage basins on north-facing mountainsides produce more runoff than those facing south. The difference is presumably due to the lesser solar radiation and hence lesser evaporation from the snow on the north-facing slopes.

Matthes (1938, p. 662) points out that because of the intensity of solar radiation at high altitudes, wastage of snow by direct evaporation is very great. Therefore, despite low temperatures, only a small part of the snow pack in the Alpine zone of the western mountains, becomes runoff, and figure 2 cannot be expected to apply.

A graph like figure 2 could be used to develop a map of runoff solely from rainfall and temperature data. On the whole, a map based entirely on climatologic data--for example, Thornthwaite's map for the eastern United States (1944, p. 690)--could have much the same appearance as plate 1. The countrywide pattern would be quite similar, but the map would ignore important features associated with local physical conditions.

It is convenient, nevertheless, to use the runoff as determined from climatological data to define what might be called "climatological" or "normal" runoff for a region or place, thus providing a base to which deviations or anomalies can be referred in studying the influence of local physical conditions. This subject is developed further in the next section.

At the risk of overgeneralization, it might be ventured that the conformance between measured runoff and that indicated by the climate is closer in large streams than in small. The effects of diverse drainage-basin characteristics on the flow of small streams are integrated in the flow from large drainage basins. The conformance might also be expected to be greater in humid regions than in arid lands, where the runoff is subject to physical effects that are large in comparison with the low flows. For example, a small depression that may act as a sink or playa in arid country would, in a humid region, become an overflowing lake with only a minor diminution of the flow through it.

A word of caution may be wise. Figure 2 or plate 1 should not be used to estimate runoff from ungaged areas. These illustrations are intended to explain general relations between climate and runoff. Deviations from such relations, associated with strictly local influences that are beyond quantitative appreciation, may be great enough to make their use misleading in any particular engineering problem--especially where a small stream is concerned. The flow of most large streams in the United States is gaged, and the records are readily available in the water-supply papers of the Geological Survey.

EFFECT OF GEOLOGY AND TOPOGRAPHY

The broad effects of geology are manifested in the outlines of the continents and the distribution and relief of the land with respect to the general circulation of moisture and to the sea, the major source of precipitation (Holzman, 1937). The earth's climatic pattern shows prominently the results of the alternation of ocean and continent.

The relief of the land is also a prominent factor in the occurrence of runoff. Matthes (1930, p. 10) has aptly described the Western mountains as the authors of their own climate. The well-known increase in rainfall and accompanying decrease in temperature with altitude produces a marked increase in runoff with altitude at least as high as the snow line (Matthes, 1938, p. 662).

Besides such general physiographic effects there are others that differ regionally or locally depending on the details of the geology. The occurrence of runoff is everywhere conditioned by the geology, but in some places there are anomalies that illustrate the over-all effect unusually well. The physical nature of a drainage basin is reflected in the behavior of the stream flow, the most sensitive characteristic of which is its timing--that is, the time within which the runoff from a storm is discharged from the basin. In some basins the soil mantle and underlying rocks have a large capacity for the penetration and storage of ground water, which is released to the streams at a relatively steady rate. The stream flow, in consequence, may be well sustained during fair-weather periods. On the other hand, the stream flow from basins with a shallow soil mantle upon impermeable rocks may recede rapidly from sharply concentrated flood peaks to low flow, or even no flow, between storms. The slope of a drainage basin may also influence the storage and rate of flow. Except under extreme conditions, however, storage and timing factors appear to have only secondary or indirect effects on the volume of annual runoff.

There are many examples of local variations in mean annual runoff that cannot be accounted for on the basis of climate. Table 5 shows the wide range in runoff observed in pairs of mountain drainage basins with comparable climate in southern California. The contrasts in runoff observed are attributed by Troxell (1948) largely to differences in the absorptive qualities of the mantle rock.

Table 5.--Contrast in runoff between pairs of basins in southern California at comparable altitude and with comparable precipitation

[Data from Troxell, based on period 1896-1948]

Stream	Mean altitude (feet)	Mean precipitation (inches)	Mean runoff (inches)
Cajon Creek	3,900	18.2	3.4
Temecula Creek at Nigger Canyon	3,500	18.2	0.7
West Fork Mohave River	4,000	27.1	8.1
Santa Ysabel River	3,400	29.8	4.7
Crab Creek	6,400	30.6	12.0
Santa Ana River	7,000	29.3	6.6
Deep Creek below Green Valley Creek	6,600	37.5	19.5
Mill Creek	6,600	37.4	13.4

The major effect of geology on annual runoff appears to be twofold. First is the effect on evapo-transpiration. It has been pointed out that evapo-transpiration is in general determined by climate. However, there is another factor, which has been called the evaporation opportunity (Meyer 1928, p. 244). Certain local conditions favor the loss of water; in other places, local physical conditions are such as to protect the water in the ground from loss during the delay between precipitation and runoff. A permeable soil or mantle rock may absorb rainfall with such facility and permit it to percolate to such depths that the stored water is effectively insulated from evaporation and transpiration. The water then reaches the water table and eventually discharges into the streams. An outstanding example of this effect is found in the sand hills of Nebraska. A somewhat similar situation exists on Long Island, where, however, the ground water flows directly to the sea.

A different effect is reported by Troxell (1948, pp. 104-109) for mountain streams in southern California. He shows how drainage basins that he has classified on geologic evidence as most absorptive and retentive produce the lowest annual runoff for a given depth of annual rainfall, and vice versa. Apparently in this region, and perhaps generally in mountainous terrain, basins that are low in absorptive qualities shed rainfall rapidly and store little moisture in the soil for subsequent transpiration. On the other hand, high absorptive qualities, where they occur with high soil-moisture capacity, make a relatively large supply of moisture available for transpiration, and so act to reduce runoff.

The available evidence suggests that generalization may be difficult and that detailed geologic and soil surveys may be necessary to explain the reason for anomalous amounts of runoff in any particular basin.

The second major effect of geology on runoff arises because of a disparity in some places between topographic and phreatic (ground-water) divides. Runoff is ordinarily computed in terms of inches of depth, based on the surface area enclosed by the topographic divide. However sinks and springs in limestone and lava-rock terranes may so modify the drainage system, that the flow in the smaller drainage courses may bear little relation to the local topography (Swinnerton, 1942). The movement of ground water in permeable lava rock may be controlled by the buried pre-lava divides rather than by the present surface. Ground-water piracy may also occur in limestone terrane, where a rapidly advancing solution channel may tap the water originating in another surface drainage basin. Water so pirated appears in the flow of larger, deeply incised streams or as springs. In a regional sense, therefore, the limestone or lava does not necessarily affect the total volume of runoff but only its distribution as between one drainage course and another. Outstanding examples of the effect of limestone terrane on the occurrence of runoff are to be found in Comal County, Tex., in Missouri, and in other places. The east-flowing streams in the Black Hills region of South Dakota lose a large volume of water in passing through the steep gorges leading from the intermontane valleys to the Great Plains beyond. The water disappears into caves and sinkholes in the massive upturned limestone beds that border the crystalline rocks of the Black Hills and that are crossed by outflowing streams (Newton and Jenny, 1880; Brown, 1944). The water thus recharged to the limestone discharges down the dip, but not necessarily in the same basin.

A striking example of the effect of topography and geology on runoff in an arid region is found in the part of the High Plains south of the North Platte River, centering roughly about longitude 102°W., and stretching southward almost to the Pecos River. Plate 1 shows that the runoff from this area is very low, even less than 0.25 inch annually, in a region where the climate would indicate a runoff of nearly 1 inch.

The High Plains are remnants of a great fluviatile plain of Tertiary age that once stretched from the mountains on the west to the Central Lowland. According to Fenneman (1931, p. 14), ". . .the Tertiary mantle is porous and absorbs the surface waters. Thus erosion is prevented or delayed. Beneath this mantle, shale is the commonest rock. Where streams have cut through the upper formation, springs and seepage are common at the contact. . . . The surface produced by this alluviation is as flat as any land surface in nature. Many thousands of square miles still retain this flatness. In the Llano Estacado or Staked Plains of Texas and New Mexico an area of 20,000 square miles is almost untouched by erosion."

A feature of the relief on the High Plains is saucerlike depressions ranging in diameter from a few rods to a mile and in depth from a few inches to 30 or 40 feet. After rains, water collects in these basins and is dissipated by evaporation and by downward percolation to the water table. A few of the deeper basins contain varying amounts of water perennially. In the upper Brazos and Colorado River Basins in Texas and New Mexico nearly 21,000 square miles of the High Plains is considered noncontributing as far as surface outflow is concerned. Because of the flatness and lack of a surface drainage pattern, the High Plains give a nearly optimum opportunity for almost total disposal of precipitation by evapo-transpiration. Annual runoff and ground-water recharge average only a fraction of an inch each (White, 1939, p. 33; White and others, 1946, pp. 387-391); the ground water is discharged at the edges of the High Plains through seeps and springs and by evapo-transpiration.

In describing the hydrology of volcanic terranes, Stearns (1942) states that "hundreds of square miles of the lava plains of Idaho, Oregon, California, and New Mexico have no runoff. In some places runoff is lacking even though rainfall may reach 200 inches annually or 24 inches in a single day. These areas are great sponges and their capacity to absorb runoff is phenomenal. Some of them are densely covered with jungle forests and some are bare, hence vegetation plays virtually no part." The flow of the streams from the mountains that border such lava plains is also absorbed, and they are therefore often called "lost rivers". The water that percolates into the lava reappears in the spring-fed flow of the major streams, where they have cut below the water table. Rivers that drain extensive lava beds are generally characterized by their stability of flow. For example the flow of Deschutes River in Oregon, which drains large volcanic areas, is more stable than any other stream of its size in the United States.

EFFECT OF SIZE OF DRAINAGE AREA

The size of a drainage area in itself does not necessarily affect the annual runoff as expressed in inches. On the other hand, there are important indirect effects. The runoff from small areas tends to reflect more strongly the effects of details of geology or topography than that from large areas. In large basins these variations tend to be compensating, and the runoff tends toward that which is normal for the climate.

Small headwater courses even in humid areas are generally perched above the water table and flow only during rainstorms. In karst, or limestone, terranes the watercourses of intermediate size also are apt to be perched, the water disappearing into sinkholes to reappear in the flow of the deeply incised larger streams. The flow of such intermittent streams represents surficial or perched-water effluent only; the ground-water constituent is essentially lacking.

Runoff from the smaller streams draining the more humid parts of the high mountains in the West, particularly in the Basin and Range province, generally decreases after the streams leave the mountains, owing to percolation into the desert-floor sediments.

Many of these streams are of the quick, "flash-flood" type, their flow consisting almost entirely of storm water. Some reach to the higher snow fields, and the meltwater produces a more sustained flow. In general, the flow of the mountain streams, though perennial in their headwater and middle courses, either actually decreases downstream or increases only slightly as it traverses zones of increasing aridity. Upon debouching from the mountains, most streams are absorbed by the valley fill, become intermittent, and eventually disappear (Babcock, 1942, pp. 49-56). The absorbed water becomes ground water. Before it reaches the major perennial streams the ground-water flow is reduced in amount by evapo-transpiration, by water-loving vegetation in areas of "rising waters," or shallow water table. The larger floods on ephemeral streams in basins of exterior drainage may produce sufficient flow to reach the major permanent streams. The perennial streams are generally entrenched deeply enough so that they receive sufficient ground-water discharge to maintain flow between periods of storm runoff or snow melt.

EFFECT OF VEGETATION

It is difficult to separate the effect of vegetation on annual runoff from that of climate. Ordinarily, vegetation and climate are intimately associated, although varying soil conditions can produce marked vegetal differences in a given climatic province. A normal drainage basin, however, contains upland, valley, and plain soil and vegetal types, so that the effects of vegetal differences on annual runoff are not always identifiable. Vegetation ordinarily influences annual runoff through its effect on the processes of evaporation and transpiration, which include canopy interception, soil evaporation and transpiration, and evaporation from water surfaces. The effects of other factors, too numerous to discuss here, on infiltration capacity are considered important by some hydrologists.

Annual runoff represents the product of all natural climatic, geologic, and biologic factors. Some hydrologists argue that, because annual runoff can be estimated dependably from consideration of climatic and geologic factors alone, vegetation needs no special consideration (Thornthwaite, 1944, p. 689). This position, although confirmed by the experience of many engineering hydrologists, does not seem, from a scientific point of view, to be completely tenable. We have here problems in interdependence that challenge resolution. For example, one might argue with equal propriety that, because it is possible to relate runoff to vegetation, soil, and geology, with residuals too small to be accounted for by climate, therefore the effect of climate should be considered inconsequential.

Perhaps the most feasible method of appraising the effect of vegetation on runoff is by means of artificial changes. To be detectable, the changes made must be abrupt and great. Slow changes such as occur in a gradual transition from sod or forest to cultivated farm are difficult to detect in the ordinary stream-gaging record. On the other hand, complete deforestation in a single season over experimental watersheds has resulted in marked changes in annual runoff. One of the most noted experiments of this kind was that at Wagon Wheel Gap (Bates and Henry, 1928), for which Hoyt and Troxell (1934, pp. 1-111) showed that the annual runoff from the deforested area was 15 percent more than when it was forested. This experiment has been cited frequently, but not all hydrologists are prepared to accept the conclusions. Nevertheless, more recent experiments, notably by Hoover (1944, pp. 969-977), Dunford and Fletcher (1947, pp. 105-110), and Wilm (1948, pp. 547-556), seem to confirm the same general conclusion--that trees transpire sufficiently large quantities of water to reduce the total volume of runoff. The effect of other kinds of vegetation on annual runoff is less evident. There is evidence that the flow from small areas is more responsive to vegetal differences than that from large areas. The literature on the relation of land use and vegetation to runoff is voluminous, and there is no need to dwell on it in this short discussion beyond the observation that the quantitative separation of vegetative from climatologic effects on annual runoff will demand the most careful hydrologic and statistical control.

SUMMARY

Annual runoff from the United States ranges from less than a quarter of an inch in the intermountain deserts to more than 80 inches in the Olympic and Cascade Mountains of Washington and Oregon. The country-wide average is approximately 8.5 inches, which, subtracted from the average precipitation of 30 inches, indicates that evapo-transpiration loss is about 21.5 inches.

The annual discharge of the rivers of the country into the sea averages about 1,800,000 cubic feet per second. About a third of this is carried by the Mississippi River.

The variation in annual runoff is dominantly associated with climate. Runoff is 10 inches or more in the third of the country that has a humid climate; it ranges between 1 inch and 10 inches in the third that has a subhumid or semiarid climate; it is less than 1 inch in the arid third of the country. There are, however, a large number of departures from this generalized pattern.

Runoff is affected by many natural influences besides climate, including geology, topography, and vegetation and other biologic factors. The influence of geology alone may account for doubling or halving the runoff of a given drainage basin that might be considered normal on the basis of climate. To evaluate the influence exerted by these and other yet unidentified factors seems impossible. In view of the complexity of the problem of analysis, there is no substitute for actual records of stream flow, and in view of the relative simplicity of stream gaging, there is no practical reason for any substitute. Records of stream flow are needed to ascertain the nature of the processes that determine the flow and to provide a firm factual base for the accelerating development of the water resources of the country.

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