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STREAMFLOW AT WAGON WHEEL GAP, COLO.[1]

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Recently there has appeared under the title above given a preliminary report covering the first stage of the Wagon Wheel Gap Experiment. This experiment, it may be remembered, was planned to show quantitatively the effects of the removal of a forest cover on streamflow and erosion within the drainage basin whence it was removed. Briefly the plan may be outlined as follows: Select two contiguous watersheds similar as to topography and forest cover; observe carefully the meteorological conditions and the streamflow for a term of years under similar conditions of forest cover; then denude one of the watersheds of its timber and continue the measurements as before for such time as may be necessary to determine the effects of the forest destruction upon the time and amount of streamflow, the amount of the erosion, etc.

The outcome of these investigations will be awaited with great interest on the part of the public and the demand for copies of this report will doubtless be far in excess of the number printed. To anticipate this demand as far as practicable this rather full abstract is printed in the belief that it will satisfy the needs of many persons who have an academic interest in the project rather than a technical or professional one. Separates of this abstract can be obtained on application to the Chief of the Weather Bureau, Washington, D. C.

The plan above outlined has been carried out so far as the first stage of the experiment is concerned. The watersheds were selected by the Forest Service of the United States Department of Agriculture near the railroad station of Wagon Wheel Gap, Colo. The geographical coordinates of that station are N. lat. 37° 46′ W., long. 100° 53′. Elevation at the railway station, 8,437 feet above mean sea level.

Figure 1 shows the two watersheds as viewed from a point near the railway station of Wagon Wheel Gap.

On June 30, 1919, 8 years' continuous streamflow observations and nearly 9 years' continuous meteorological observations had been obtained. A consideration of this material showed that while the seasons themselves were more or less different, the one from the other, yet the rainfall-runoff relations on the average were approximately constant, or in cases of rather wide departure the deviations from the mean were easily explainable. It was therefore mutually agreed that one watershed (B) should be denuded. The program of denudation was completed in the autumn of 1920.

OBJECT OF THE PRESENT PAPER.

The object of this discussion is to give a clear idea of the nature of the experiment, the methods followed, the conditions observed to date, and the plan for analyzing the data obtained in the future so as best to bring out faithfully and clearly the effects upon streamflow and erosion which are produced by the denudation of one of the watersheds. Naturally, to be of tangible value, such effects must in some manner be shown quantitatively and statistically. It is especially to be hoped that the present discussion will bring out criticisms from irrigation engineers and others who are particularly interested in matters of water supply from mountainous sources, so that the final study of the results of the projects may succeed in presenting data of the most useful character.

According to the accepted boundary survey, the areas and dimensions of the two watersheds are as shown in Table I. (See also fig. 2.)

TABLE I.

	A	B
Total area..........acres..	222.5	200.4
Extreme length..........feet..	7,300	4,600
Computed mean width...do....	1,328	1,898
Absolute elevations..........	9,373–11,355	9,245–10,952

The greater area of A as compared with B, as above indicated, is of no appreciable import. That which is of importance, in so far as it complicates the relationship of the discharges of the two streams for any short period, is the fact that watershed A is considerably longer and narrower than B, and includes a small area extending to an elevation about 400 feet higher than any part of B. As will be seen later through consideration of the discharge graphs, for the purpose of discharging any single supply of water (such as the fall of a single rain), watershed A might be compared to a narrow trough and watershed B to a fan-shaped collector. The former, on account of its relatively short slopes, is able to deliver the first bulk of a water supply in a relatively short time, and this quick delivery is the basis for a sharp and high flood crest in most cases; yet on account of its length, this area may continue to deliver water to the dams for a long time. By comparison, B delivers its water to the dam after a longer interval, but more largely in one mass, and completes its discharge sooner. Were we ever dealing solely with the water of a single storm or a single period of snow-melting, the relations above set forth might not be difficult to express by a concise formula. But, since the streamflow of any period we may choose to consider is necessarily built up from water contributions of many previous months, it becomes apparent that the watershed differences have introduced a maze of relationships we can not hope to unravel or to give expression to, except

[1] Mo. WEATHER REV. SUPPL., No. 17, Bates, Carlos G., and Henry, Alfred J., pp. 55, figs. 41. Washington, D. C., 1922.

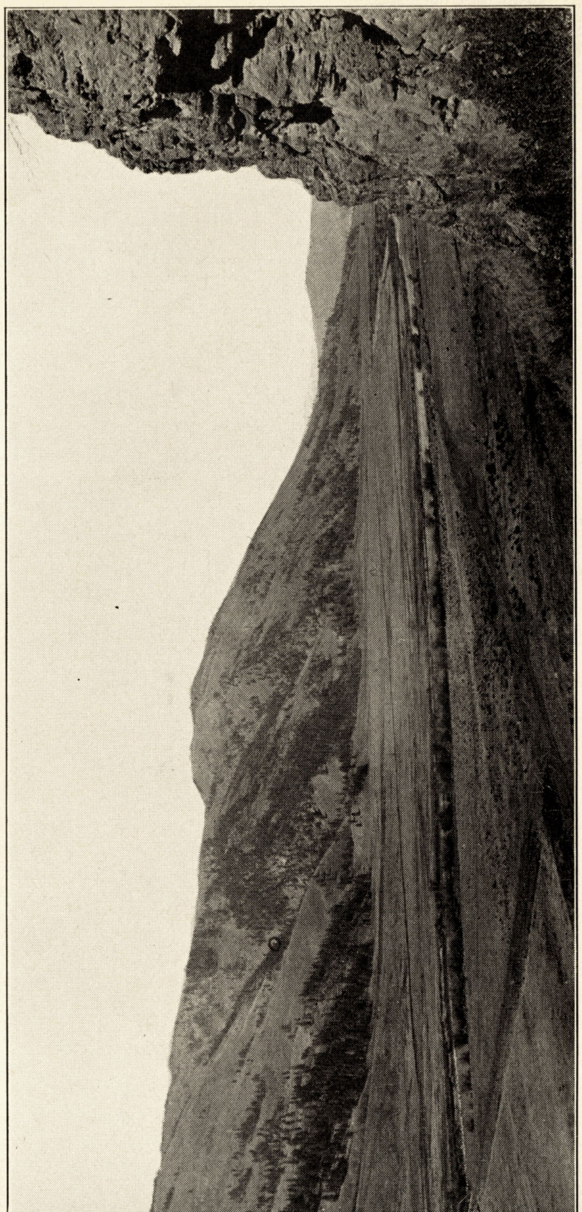

Fig. 1.—Panoramic view of experimental area Wagon Wheel Gap, Colo. Rio Grande in foreground.

in approximate terms. The great difficulties of this situation, of course, could not be foreseen when the watersheds were chosen, nor is it at all certain they could have been avoided, as Nature has nowhere been so kind as to form two objects exactly alike.

Of some slight importance, as it affects snow-melting, is the fact that the main axis of watershed A is almost directly east-west, while that of B is more nearly northeast-southwest. In consequence, the north half or southerly exposure of A contains considerable areas which face squarely the mid-day sun, while on B the corresponding position is very largely an east slope, except for a very small space at the lower end of the watershed. After a very careful survey of the several snow-scale areas, Keplinger (Apr. 1, 1913) computed the mean gradient of watershed A to be 25 per cent and of B 26 per cent; but the mean aspect of all the slopes on A is S. 85 E., while on B it is N. 68 E., a difference of 27 degrees.

Geological formation.—As has been stated, one of the first considerations was that the two areas studied should have similar geological origins, not only because the character of the rock defines the physical character, permeability, and retentiveness of the soil, but also because the present rock *in situ* has the greatest influence on underground water and on the possibility of complete measurement of the water discharged from the areas.

The first geological examination of these watersheds was made by Mr. E. S. Larsen, of the Geological Survey, in June, 1910, or while the first prospecting for the dams was under way. It is regretted that we can not quote here Mr. Larsen's original report, which was entirely reassuring, both as to the uniformity of the structure on the two areas and the probabilities of a structure at the proposed dam sites which would insure a good foundation for the dams and the loss of none of the water which flows away from the areas.

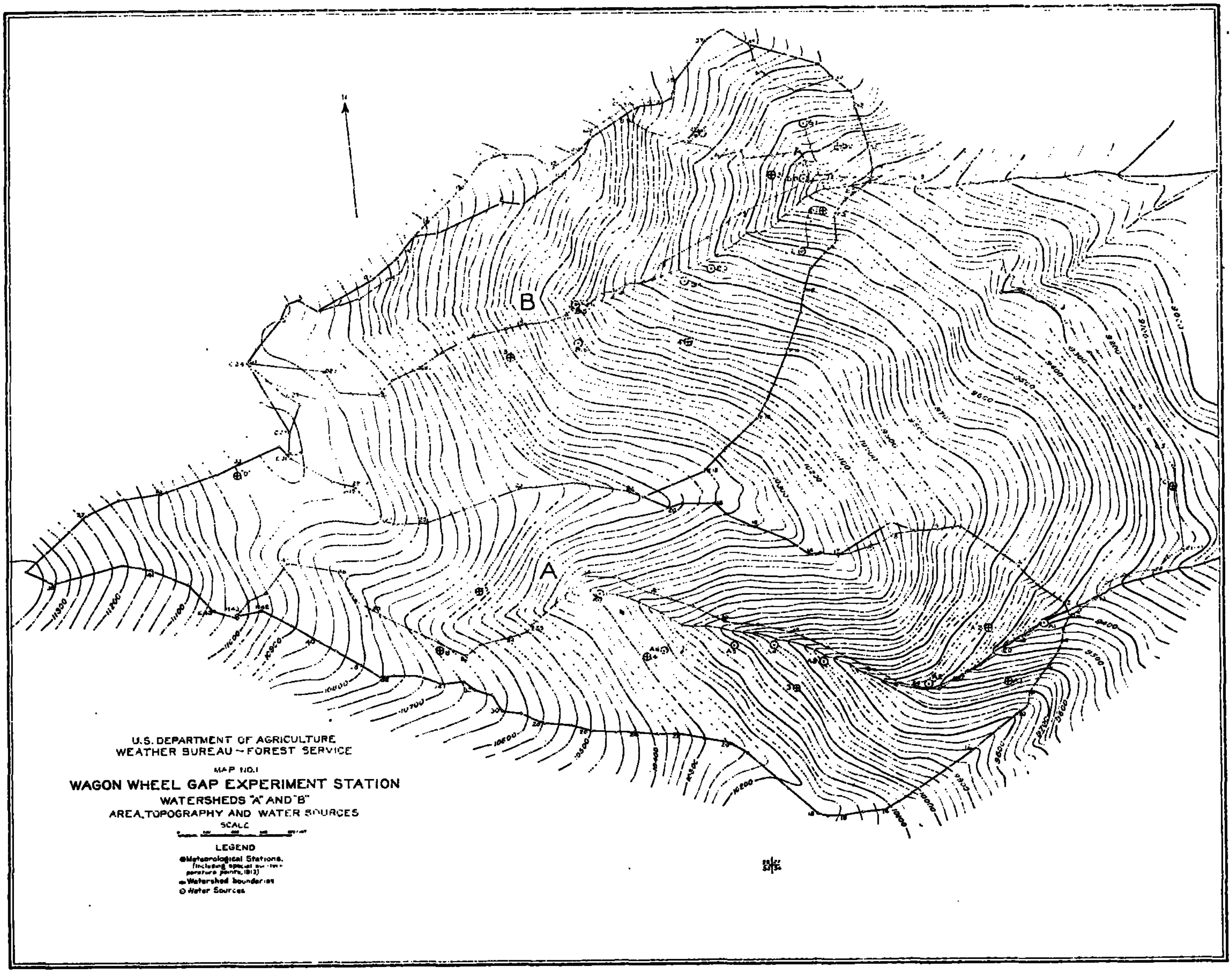

FIG. 2. Area, topography, and water sources.

Description of the forest.—The forest of the two watersheds involved in this study is one fairly typical of the middle zone of the central Rocky Mountains and is characterized by the predominance of Douglas fir.

On account of the character of the soil derived from a fine-grained igneous rock, western yellow pine is practically nonexistent in this locality and does not appear on the lower reaches of the watersheds at all, though in most of the region it would be expected on southerly exposures at this elevation. Such exposures are occupied almost wholly by Douglas fir of good development, but forming open stands. There is everywhere a sprinkling of bristlecone pine, which becomes more numerous at the tops of the slopes and wherever the amount of rock in or on the soil is very great.

The northerly exposures at low elevations are also characterized by fir stands, more dense, of course, than those of the warm slopes. There is everywhere a sprinkling of Engelmann spruce, and with increased elevation the proportion of this species increases, so that at the upper extremities of both watersheds the type is almost pure spruce.

A large part of watershed B, and only slightly less acreage in A, was burned over, as nearly as can be determined, about 1885. While the fire may or may not have run through the stands on the southerly exposures, their open character prevented serious damage, and such areas may be considered to be now in an essentially normal state as regards cover. Much greater damage was done to the north-slope fir stands, on practically all such acreage of watershed B, and in strips on the lower portion of A, while the prime spruce forest at the upper ends of A and B was almost completely destroyed, and a considerable part of this area is not now covered even by aspen, except in occasional clumps.

LOCATION OF OBSERVING STATIONS.

In the beginning it was thought advisable to establish six primary meteorological stations. One is near the office and living quarters and is called the C station; there are two on each of the watersheds, and the last is on the extreme upper portion of A, to represent the higher altitudes of both watersheds, known as the D station.

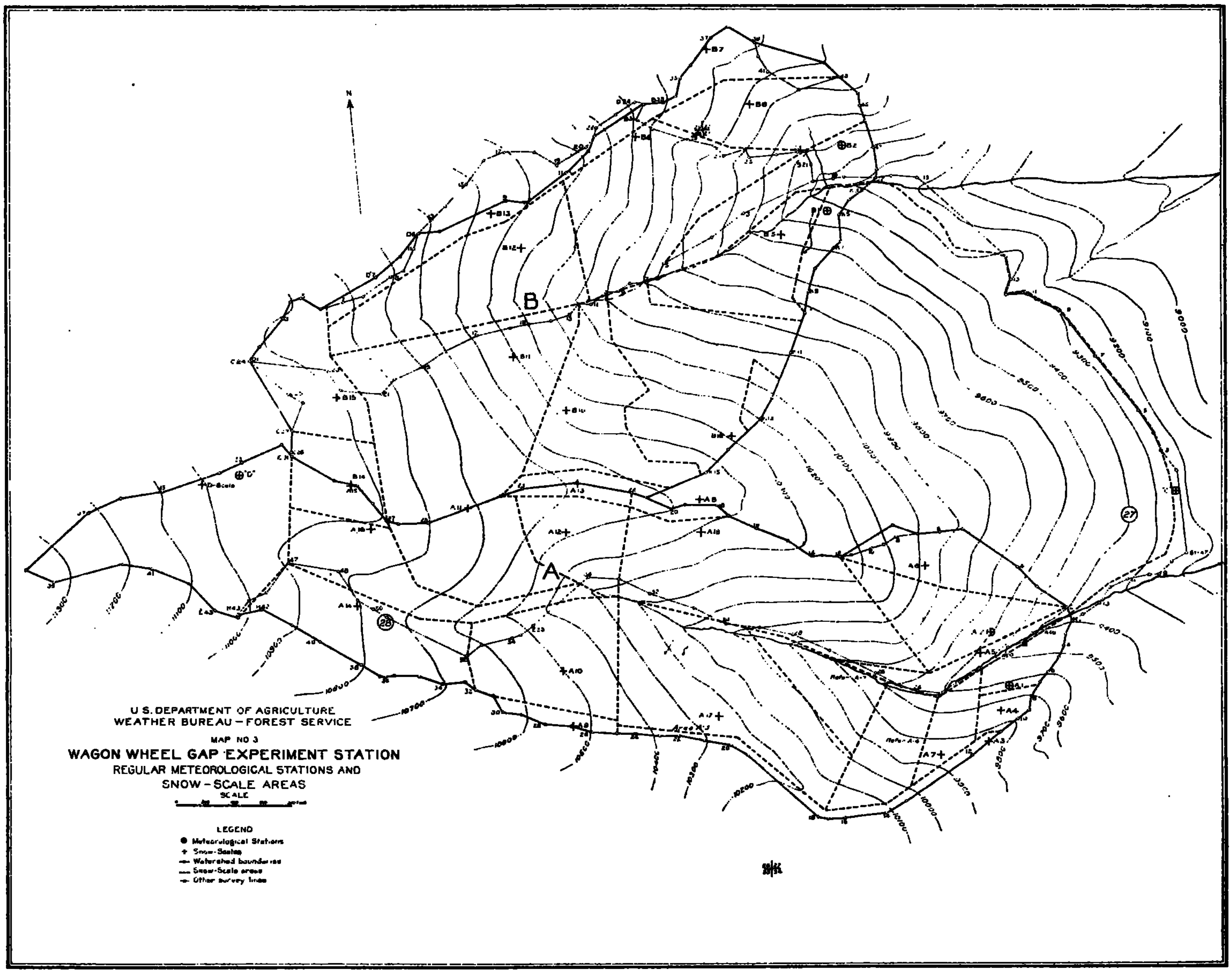

FIG. 5. Meteorological stations, snow scale areas.

The primary stations on both watersheds are situated near the lower boundaries, one on the north slope and the other directly across the ravine in which the stream flows, on the opposite slope. North-slope stations are known as A–1 and B–1, south-slope as A–2 and B–2. The two pairs of watershed stations are the most important, and for this reason the location of these stations was selected with great care, the object being to secure as nearly identical conditions of topography and timber cover as possible. A–1 occupies about the same topographical position in Watershed A as B–1 in Watershed B, and A–2 the same as B–2.

The general topography of the watersheds and the location of primary and secondary stations are shown in figure 5.

Station A–1.—Station A–1 is 700 feet S. 40° W. of Dam A, and 9,601 feet above sea level. The station is on a steep slope, angle 31° 20′, azimuth N. 24° W. Directly west of the thermometer shelter is a large open rock slide. While the surface of the ground at the station has a shallow covering of moss and fir needles, there is very little soil in the ordinary meaning of that term.

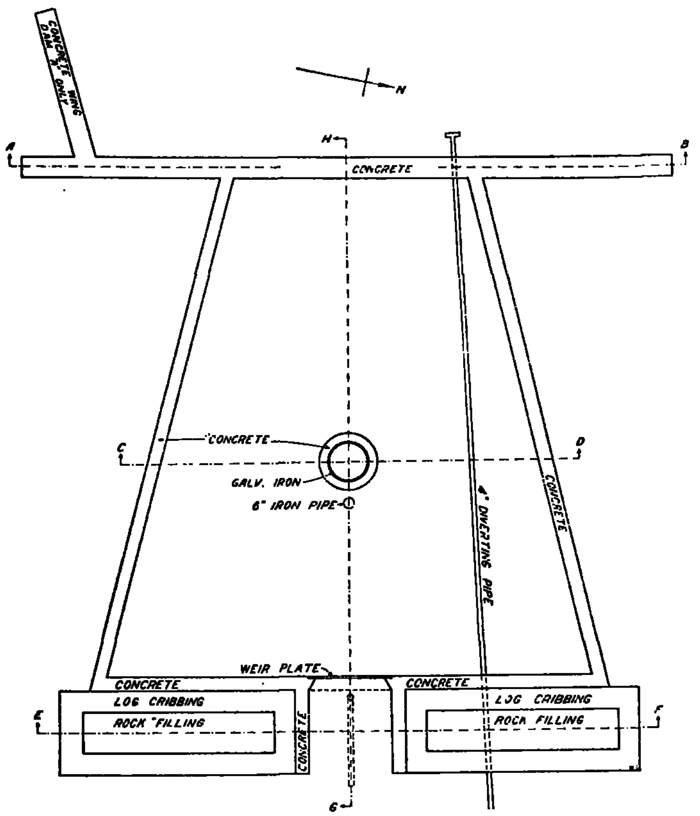

FIG. 6. General plan of dams.

Station A–2.—Station A–2 is located 550 feet N. 80° W. of Dam A. Its elevation above sea level is 9,609 feet. The station is just across stream A from Station A–1, and horizontally distant but 406 feet. The slope is, however, entirely different, the angle being 34° 20′ toward S. 56° E. This station is exposed to the sun nearly all day. The soil is composed of earth and large rock fragments, the rocks weighing, say, 100 to 200 pounds, and being firmly embedded in the earth. Very little humus is found on the ground.

Station B–1.—Station B–1 is located 381 feet S. 30′ W. of Dam B and is 9,426 feet above sea level. The slope of the ground is 37° 30′ toward N. 24° E. The soil is mostly a sandy loam, with broken rock interspersed and with a good cover of fir needles. The station receives but little sunshine in winter.

Station B–2 is situated directly across the ravine, as may be seen from the map, fig. 5. It stands in the same relation to B–1 as does A–2 to A–1.

Station D.—Station D is located near the top of the mountain, elevation 10,949 feet above sea level. This station is in the burned region, and hence the only timber consists of dead trees, standing and fallen. The ground in the vicinity of the station is practically level. The station is exposed to winds from all directions except the west, where it is slightly protected by rising ground.

Station C.—The C station was from the start equipped with a rather complete set of meteorological instruments as follows: Two standard barometers, a barograph, a triple register recording wind direction, velocity, sunshine, and rainfall. A standard Weather Bureau instrument shelter on galvanized-iron supports was installed on a grass-covered east slope, 400 feet north of the office building, and the rain-gage was placed 300 feet farther north in a stand of young aspen. The floor of the instrument shelter is 11.3 feet above ground, the wind vane is 16.9 feet, and the anemometer is 15.6 feet above ground.

Snow scales.—In order to determine the depth and density of the accumulated snowfall of winter, 32 permanent points of measurement were selected, 18 on A and 14 on B. At each point a permanent snow scale or stake 12 feet high was firmly set in the ground. Each scale represents a definite area and the scale reading is applied to the acreage of the area. The location of the snow scales may be seen by references to figure 5.

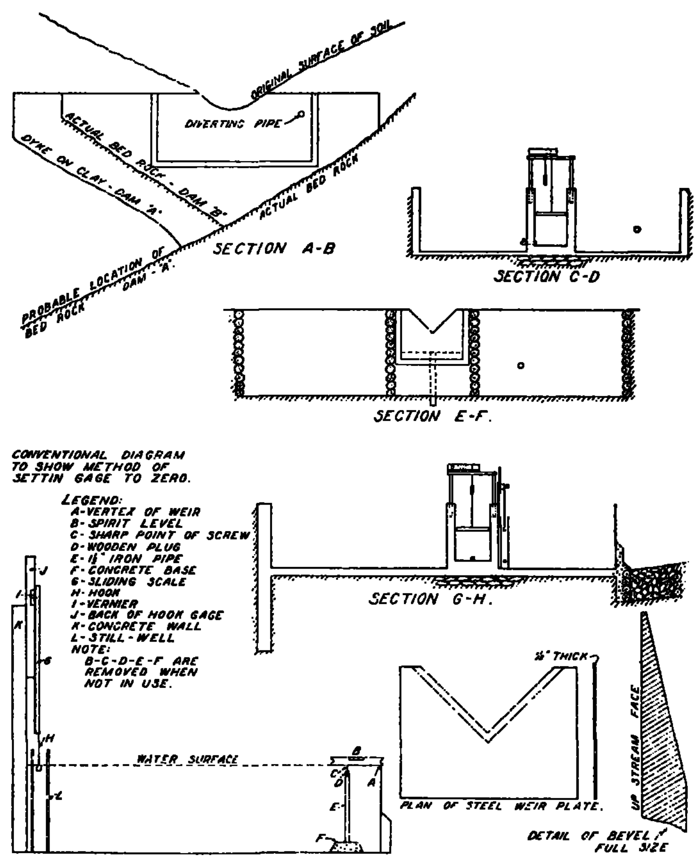

FIG. 7. Details of construction and measuring devices.

Dam construction.—The primary consideration was to construct a wall across either stream channel by means of which both the surface and subflow of the channel could be collected for measurement. This was accomplished, after digging the cross trench down to a solid foundation, by pouring a solid concrete wall to a height at least a foot greater than that of the original stream channel, except at the center of the channel, where a notch was left through which the stream might flow. The thickness of this wall was 8 inches, except at the bottom, where the concrete was allowed to spread out the full width of the trench. The general plan of the dams is shown in figure 6, and additional information is afforded by figure 7 and half-tone figures 8, 9, 10, 11, and 12.

FIG. 3.—Conditions in a young Coniferous stand, typical of much of the upper portion of A.

FIG. 4.—Rather large Douglas fir surrounding thermometer shelter at station A-2.

FIG. 8.—Completed basin at Dam A—from upstream end—column in center still-well, later enlarged for 20-inch float.

FIG. 9.—Completed basin at Dam A—downstream end—with rectangular weirs.

FIG. 10.—Basin at Dam A covered with shelter house for register.

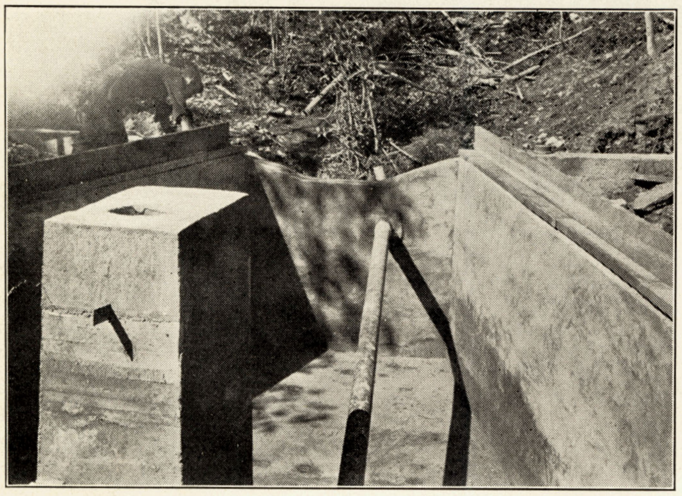

FIG. 11.—Basin at Dam B just ready to cover.

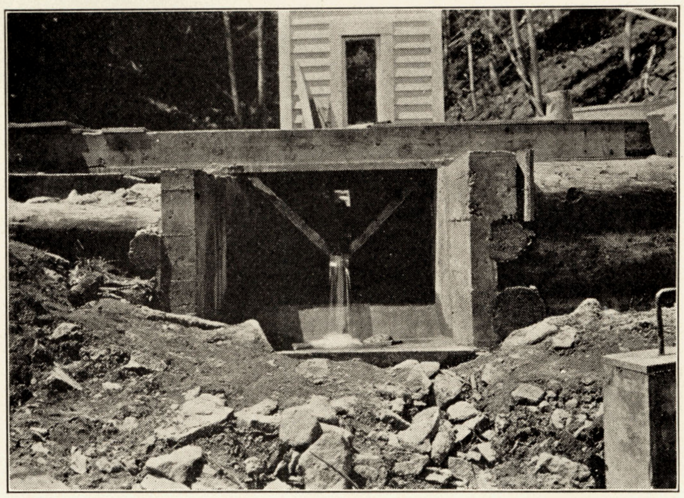

FIG. 12—Triangular weir—Dam B—which replaced rectangular weir of 1911.

THE PROGRAM OF OBSERVATIONS.

The program of meteorological and stream-flow observations as originally adopted was not materially changed during the first stage of the experiment. It involves daily observations, at 9 a. m., at Stations A-1, A-2, B-1, B-2, and C.

In the beginning the north-slope stations of the two watersheds were given the more complete instrumental equipment as follows: Maximum, minimum, dry and wet thermometers, a thermograph, a hygrograph, an anemometer, a standard 8-inch rain gage, a 5-foot snow bin, and a 12-foot snow scale, the latter set permanently into the ground. Later in the experiment a shielded snow gage of the Marvin pattern was added at all of the meteorological stations. Thermometers for determining the soil temperature at depths of 12 and 48 inches were also added on north slopes in 1912. Weekly determinations of soil moisture at all watershed stations were made during the summer months of 1914 to 1919, both inclusive.

The equipment of the south-slope stations in the beginning was limited to maximum and minimum thermometers, a rain gage, and a snow scale. On May 31, 1913, the thermometric readings were discontinued and a little later soil temperatures at 18 and 48 inches were begun. Precipitation was continuously recorded at south slope stations throughout the experiment.

Finally, measurements of depth of snow on the ground *daily* were made at all primary watershed stations except D. Beginning with December of each year, a bimonthly measurement of the depth and density was made at each snow-scale on the watershed until near the beginning of the snow-melting season in the spring, when the measurements were made at three-day intervals in 1912 and 1913. Beginning with March, 1914, and continuing to date, the observations have been at five-day intervals during that period.

At the D station, by reason of its remoteness from the camp, the sheets of the automatic instruments were changed at 6-day intervals and eye readings for check purposes were made on the dates when the sheets were changed. The daily record of wind velocity and of rainfall in the summer were automatically registered in the office at the C station by electrical transmission line.

Stream-flow measurements.—The height of the water in the basin above the V-notch in the weirs was automatically recorded by a Friez water-stage recorder and the instrumental record was checked by the daily reading of a hook gage.

In July, 1911, the rectangular weirs were torn out and triangular weirs installed. The advantages of triangular weirs may be stated as follows: Perfect aeration of nappe; automatic accommodation to all stages, with particular advantage in the case of extremely low stage; an increased amplitude of oscillation of the water surface in the basin at low stage, with consequent increase in the accuracy of the measurements; the use of but one function, height, in the computations; and the elimination of the leading channels from the structural work. These leading channels are difficult to construct with uniform sides, while without them a difficult and doubtful correction for end contraction must be introduced. The weirs are simply steel plates 3 feet by 4 feet and 0.5 inch thick, out of which right-angled notches have been cut. The vertical depth of each notch is 1.5 feet, which gives a maximum capacity of 7 second-feet—seven times greater than the crest of the flood of October, 1911. The faces of the weirs are beveled off for a distance of 2 inches on the downstream side, with a crest width of one-sixteenth inch. The flow of water under gravity over a triangular weir of this form is given by the U. S. Geological Survey as 2.64 times the five-halves power of the head, the flow being expressed in cubic feet per second, and the head being the vertical height in feet of the still water in the pond above the vortex of the weir notch. The above formula is the same as derived by Prof. James Thompson, of Belfast, in the experiment with a trinagular weir of a piece of thin sheet iron.

For the purpose of measuring the height of the water in the basin above the weir notch, a Boyden hook gage, an instrument familiar to engineers, is used. The essential principle of the instrument is that the setting is effected by causing the point of a hook to approach the water surface from the *under* side. The method is so accurate that different observers never vary more than 0.001 foot from the same reading. The Boyden gage is secured to a concrete wall by means of bolts set in the concrete. For the purpose of stilling any waves that may be present, a piece of iron pipe, 6 inches in diameter, the top projecting about 6 inches above the water, is set under the hook gage. The pipe rests unevenly on the concrete bottom of the basin, and to provide further for the free access of water, a half-inch hole was drilled through the side of the pipe 6 inches from the lower end. For the purpose of setting the zero of the hook gage to the level of the weir notch, a special arrangement was devised. A section of iron pipe was embedded in a concrete base weighing some 10 pounds. Into the top of the pipe a wooden plug was driven. A screw hook was then straightened out and one end sharpened to a point. The screw hook was then screwed into the wooden block so that the length of the base pipe and hook was approximately the depth of the water in the basin about a foot back of the weir. The entire apparatus was then set into the basin just back of the weir. By means of a spirit level, one end of which is filed to fit into the weir notch, the point of the screw hook may be finally adjusted to the level of the weir notch. The water in the basin is then adjusted so that the screw hook just pierces the surface. The hook gage may then be set to its zero. The method is simple and accurate, and frequent examinations of the accuracy of the zero may be made without difficulty. A diagram showing the method is appended (fig. 7).

Discharge coefficients.—To obtain the high degree of accuracy required in the stream-flow investigation, it was thought best actually to determine the discharge coefficients rather than to accept the published values. This was particularly necessary because the weirs differ slightly from the Thompson weir in that they had to be made one-half inch thick to provide the necessary strength, while the Thompson weirs were of thin sheet iron. Furthermore, every weir must of necessity be subject to its own departures in construction from a theoretically perfect cutting of the angle, crest width, and level. Also, in placing the weir in position, the concrete may set unevenly, thus throwing the weir slightly out of plumb. For each dam, three tanks made of 16-gage galvanized iron, with iron hoop at the top rim, each tank 4 feet in diameter and 4 feet in depth, were mounted on a platform built far enough below the dam to give the required fall. Over the middle of the platform a galvanized-iron funnel, top 24-inch diameter, tube 6-inch diameter, was suspended in a gimbal or universal joint, so that the lower end of the funnel hung just above the tops of the tanks. The overflow from the weir is conveyed into this funnel through a V-shaped trough, lined with galvanized iron. The method of suspension of the funnel permits the water to be directed into either of the three tanks or into a wooden waste pipe the change being effected in a fraction of a second. The areas of the tanks were determined by taking the circumferences at four heights in each tank with a steel tape, then computing the mean area for that portion of the tank used, allowance being made for the thickness of the iron. To eliminate the error due to irregularity of bottom the tanks were first filled to a depth of about 2 inches and measurements of this height and of the height after the tank was filled were made by means of a hook gage, which was made by transcribing the graduations from a surveyor's rod. The time of beginning and ending a test was determined by use of an ordinary watch. Tests were made by two men, one man making continuous readings of the hook gage in the basin while the second man filled the tanks. Practically all of the tests were made at times of very little fluctuation in the head, and the mean of all hook-gage readings was used as the head. The detailed measurements and computations are too numerous to reproduce. Each individual entry represents a measurement of from 40 to 130 cubic feet of water, most tests having been made with the larger amounts.

THE CLIMATE OF THE WAGON WHEEL GAP AREA.

The geographic location of the Wagon Wheel Gap area, remote from both oceans and in the midst of a rugged mountain area, imposes upon it a climate which partakes of the characteristics both of mountain and continental climates.

Moreover, it lies to the southward of the general path of cyclonic storms, a fact which has an important bearing upon its climate.

AIR TEMPERATURE.[1]

The discussion of temperature is based on daily systematic observations of standard thermometers exposed in the regulation thermometer shelter at the north-slope stations of both watersheds for a period of eight years, 1911 to 1918, inclusive. Daily thermometric observations are also available for the south-slope stations on both watersheds from November, 1910, to May, 1913, a period of 31 months. Thermographs were maintained at north-slope stations and also at the D station for the entire eight-year period and at the G station for the four years, 1914 to 1917. The monthly means as deduced from hourly readings of the thermographs, checked by daily comparisons with the mercurial thermometers in the case of A and B, and weekly comparisons in the case of the D and G stations, are given in Table 1.

TABLE 2.—*Monthly mean temperature, north-slope stations of watersheds A and B.*

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
A	15.6	17.7	24.3	32.4	41.3	51.1	53.6	51.8	45.5	35.9	24.8	14.7
B	14.9	17.3	24.0	32.5	41.5	51.2	53.8	51.8	45.3	35.8	24.3	13.9
D	15.6	17.0	21.2	27.7	36.3	47.5	50.2	49.0	43.0	33.6	24.7	15.1

Considering the north-slope stations as representative of the watersheds, it is at once apparent that the mean temperature of the two watersheds is practically the same. The differences range from 0.8° in December to 0° in August. A is uniformly higher than B, except in the months April to July, inclusive, when it is a small fraction of a degree cooler on the average than B.

The D station, at an elevation of 1,355 feet higher than A-1, and 1,530 feet higher than B-1, has practically the same winter mean temperature as the lower stations, a spring temperature 4° lower, summer about 3° lower, and autumn 1.5° lower. The winter minimum temperatures of the D station are considerably higher than those of the lower levels; hence the equality in the winter means.

South slopes.—The south slope of each watershed is somewhat warmer than the north slope, but the excess in the monthly means is generally less than a whole degree, except that for the cold months, November to March, it may amount to as much as 2° or 3°. The excess in monthly means, south over north slope, is as follows:

	November.	December.	January.	February.	March.
A	2.1	1.8	1.8	1.6	0.6
B	2.5	3.0	2.7	2.6	1.8

This comparison is based upon monthly means that have been derived from the daily extremes instead of the 24-hourly readings as in Table 6. A series of corrections to reduce the means derived from the daily extremes to the true daily means shows that for watershed A the mean temperature, maximum and minimum, divided by 2, gives results that are in excess of the true daily means by amounts varying from 0 in February to 2.1° in August. In general, the corrections for the summer months in both watersheds are the greatest. In the B watersheds small positive and negative corrections offset each other in the mean, with the result that in three months of the year the correction is zero. In the A watershed positive corrections were rarely found in the individual months and not at all in the final means. Further analysis of the excess in monthly mean temperature as above shows that this excess is due to higher maxima on the south slopes of the respective watersheds.

	Excess of maxima on south over north slope (31 months' observations), means for—				
	November.	December.	January.	February.	March.
Watershed A	3.6	3.3	3.4	2.7	0.8
Watershed B	5.3	4.9	5.0	4.4	3.3

The mean minima for the identical periods and slopes are slightly higher for the south than for the north slopes, although the greatest excess for any month does not equal 1°. If we go still further and make an intercomparison between corresponding slopes of the two watersheds we find that the mean temperature, regardless of how obtained, is substantially the same. As illustrating this feature, the monthly means of the daily extremes for the eight full years at the north-slope stations is presented in Table 2.

[1] Degrees Fahrenheit and English units are used throughout this discussion.

TABLE 3.—*Monthly means of the daily maxima and daily minima.*

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual.
WATERSHED A.													
Max......	25.3	28.4	36.4	44.6	54.3	66.6	68.6	67.0	59.7	47.7	36.1	24.2	46.6
Min.......	6.2	7.7	13.7	22.0	29.7	37.5	42.8	40.8	34.6	26.1	15.2	5.8	23.5
WATERSHED B.													
Max......	24.4	27.8	34.9	43.1	53.3	65.6	67.6	65.6	57.9	47.1	35.3	23.3	45.5
Min.......	5.6	7.2	13.5	21.8	29.3	36.9	42.3	40.3	34.1	26.0	14.7	5.1	23.1
D (UPPER PART WATERSHED A).													
Max......	24.9	27.0	31.7	37.3	45.9	58.0	60.7	60.0	53.7	43.8	35.4	24.6	41.9
Min.......	7.5	8.9	12.3	18.9	27.1	37.8	41.8	40.3	34.4	25.1	16.2	7.4	23.1

SOIL TEMPERATURE.

The superficial soil layers receive and absorb incoming solar energy by day and lose heat as outgoing radiation by night. Whenever, therefore, the incoming radiation is in excess of the outgoing, the temperature of the soil rises and in due season reaches an annual maximum, thence receding to the annual minimum in midwinter. As in the case of air temperature, there are also short periods of temporary rises and falls in the temperature of the soil, as well as the more gradual seasonal progression. The magnitude of the accidental changes is largely a matter of the depth below the surface at which measurements are made. In this discussion we are concerned almost wholly with the seasonal changes at a depth of 12 inches, although observations of soil temperatures at a depth of 48 inches are also available. Between 5 and 6 years observations are available for both watersheds, and the D station representing the extreme upper portion of watershed A. The detailed weekly means for both slopes of the two watersheds are given in Table 4.

TABLE 4.—*Weekly mean soil temperature, 12 inches below surface.*

Date.	North slopes, 12 inches.		South slopes, 12 inches.		Date.	North slopes, 12 inches.		South slopes, 12 inches.	
	A.	B.	A.	B.		A.	B.	A.	B.
Jan. 7	19.9	24.0	29.8	26.6	July 1	41.6	46.1	54.7	56.3
14	19.1	23.5	28.6	25.9	8	43.3	47.1	54.8	56.3
21	19.2	23.3	28.4	25.9	16	45.1	48.0	53.7	55.6
28	18.7	23.1	27.7	25.0	23	47.2	48.7	54.2	55.7
Feb. 4	19.1	22.9	28.0	25.4	30	47.9	48.7	53.6	54.8
11	18.7	23.4	27.9	25.8	Aug. 6	48.1	49.3	53.7	55.0
18	18.7	23.5	28.3	26.6	13	47.6	49.3	53.3	54.5
25	19.4	23.7	28.7	27.1	20	47.4	48.3	52.0	53.2
Mar. 4	20.3	24.2	28.6	28.5	27	46.5	48.0	51.8	53.1
11	20.4	24.3	29.1	28.0	Sept. 3	45.5	47.4	51.1	52.4
18	21.1	24.8	31.5	28.9	10	44.4	46.2	50.8	51.5
25	21.3	25.1	31.2	30.7	17	42.3	44.2	48.8	49.8
Apr. 1	22.1	25.8	32.0	32.2	24	38.8	42.4	48.7	49.3
8	23.4	26.8	32.5	33.5	Oct. 1	36.4	40.6	46.7	46.6
15	24.8	28.1	33.4	34.6	8	35.4	39.7	45.8	45.1
22	26.9	29.4	33.8	35.1	15	34.0	37.6	44.1	42.4
29	29.7	30.2	35.4	37.0	22	32.8	35.8	42.5	41.4
May 6	31.6	31.2	36.4	37.5	29	32.3	34.5	41.7	40.0
13	31.8	32.7	38.8	39.7	Nov. 5	31.6	33.3	40.9	39.4
20	32.1	34.2	40.6	42.4	12	31.1	32.7	39.8	37.5
27	32.1	36.2	42.2	43.8	19	29.1	31.0	36.4	34.3
June 3	32.2	38.0	43.7	45.2	26	25.8	29.4	36.4	33.6
10	34.4	39.4	45.0	46.9	Dec. 3	23.2	28.0	35.3	31.9
17	37.2	41.9	49.9	51.8	10	22.6	26.9	33.9	30.1
24	39.5	44.1	52.6	53.8	17	21.3	26.6	32.0	27.7
					24	20.6	24.9	30.3	27.9
					31	20.0	24.2	29.9	26.7

PRECIPITATION.

The precipitation is measured daily at five points within walking distance of the headquarters station, viz, (1) at station C (headquarters), which may be considered as representative of the southern portion of both watersheds, (2) in watershed A and B, respectively, at the slope stations A-1 and A-2, B-1 and B-2, and finally at the D station. Recording rain gages of the tipping-bucket type are in operation during the warm season at stations C and D, and the records from these stations are used to apportion the hourly amounts in both watersheds throughout the 24 hours. The watershed precipitation, midnight to midnight, is determined by taking the larger of the two quantities recorded at the two rainfall stations in each watershed, adding to that quantity the amount of the precipitation at D and dividing the sum by 2.

The watershed precipitation as thus determined is given in table 9. On the average of eight years, watershed A has a mean annual precipitation of 21.02 inches and watershed B of 21.09 inches, or practically the same. The greatest difference in any one year was 1.03 inches, in 1912–13, B having the greater amount.

Colorado being remote from any large body of water and somewhat south of the average path of cyclones, does not at any season receive a generous amount of precipitation. The greatest average for the State, 20 to 25 inches, occurs on the western slope of the Rocky Mountains at altitudes above mean sea level of 10,000 feet and over. While the extreme upper part of both watersheds has an altitude somewhat above 10,000 feet, the situation of the area, with respect to the westerly winds, is not favorable to heavy precipitation, since westerly to northerly winds are descending winds and consequently dry. The precipitation is very nearly equally divided between rain and snow, with the former about 4 per cent greater than the latter; thus, rain 52 per cent and snow 48 per cent.

There is a well-marked rainy season in July and August, at least 55 per cent of the rain falling in those months. Precipitation as rain may occur as early as April and as late as October, although in late spring and early autumn, when beginning as rain, it is quite apt to change to snow before it ends. Snow in considerable amounts may fall in the latter part of September, but the real beginning of the snow season may be fixed as the last week in October. The first snowfall usually disappears by melting and evaporation, and it is not until the temperature during the afternoon hours does not rise above freezing that the snow cover may be said to be permanent for the winter.

Rainfalls of great intensity rarely occur at Wagon Wheel Gap. During the eight years considered, but a single heavy 24-hour rain occurred, viz, on October 5–6, 1911.

Greatest amount of precipitation in 24 hours.—The greatest amount of precipitation that occurred as rain or snow for each month from the beginning of observations to June 30, 1919, is given in Table 5. The data are for the C (headquarters) station. The maximum amounts for the months May to October occurred as rain, for the remaining months as snow. This table clearly shows that heavy rains as much as 2 inches in 24 hours are rare.

TABLE 5.—*Greatest amount of precipitation in 24 hours (inches and hundredths).*

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
1910......	......	......	......	......	......	......	......	......	......	......	0.40	0.20
1911......	0.36	0.63	0.47	0.18	0.31	0.44	0.71	1.27	0.56	2.60	0.36	.67
1912......	.20	.23	.46	.42	.13	.53	.77	.63	.14	.69	.37	.35
1913......	.32	.34	.43	.27	.21	.75	.61	.77	.98	.27	.45	.54
1914......	.83	.40	.30	.22	.60	.67	1.22	.48	.72	.58	.01	.45
1915......	.38	.68	.11	.60	.37	.29	1.00	.73	.88	.25	.92	.78
1916......	.63	.12	.42	.37	.24	.11	1.11	.89	.37	1.03	.16	.24
1917......	.75	.26	.24	.98	.43	.13	.69	.39	.25	.09	.55	.18
1918......	.30	.47	.83	.47	.09	.20	.82	.89	1.04	.36	.85	.58
1919......	.04	.29	.69	.38	.40	.56	......	......	......	......	......	......

Intensity of precipitation.—To present statistics of intensity of precipitation in some detail, the 24-hour precipitation (rain or snow) has been classed according to the scale shown in Table 6. Since, however, the runoff from snow appears at the end of the cold season and is not immediately effective in producing increased streamflow, the *rain only* has been classified in groups according to intensity of the 24-hour amounts. It is considered that rains of 0.10 inch and less in the summer, as a rule, serve merely to replenish losses due to transpiration and evaporation and do not directly effect streamflow. Rains greater than 0.10 inch may be considered effective in producing a slight increase in streamflow, depending, of course, so far as the lower limit of the scale is concerned, upon conditions of soil moisture and other factors. With a saturated soil a precipitation so small as 0.01 inch, will produce a measurable response in streamflow.

The result of this second classification of rains gives the following very interesting results (in hundredths of an inch):

	Average intensity of rains.				
	June.	July.	August.	September.	October.
A........	0.26	0.33	0.30	0.32	0.40
B........	.31	.33	.30	.55	.46

This tabulation shows conclusively that the intensity of the rains is practically the same for each month of the season and substantially the same on both watersheds, with a tendency to be greater on B, at times, than on A.

TABLE 6.—*Intensity of rainfall A (days with total precipitation).*

	Days with—						Total effective rains (days).	Total rainy days, 0.02 inch or more.
	(1) T. to 0.01 inch.	(2) 0.02 to 0.10 inch.	0.11 to 0.30 inch.	0.31 to 0.50 inch.	0.51 to 1 inch.	1 inch and over.		
1912........	42	59	43	13	3	0	59	118
1913........	67	61	36	10	11	0	57	118
1914........	58	67	36	11	9	0	56	123
1915........	50	45	32	13	8	2	55	100
1916........	37	63	32	17	9	1	59	122
1917........	66	58	26	14	5	1	46	104
1918........	77	62	43	12	8	2	65	127

The rainfall intensity has been independently computed by dividing the average monthly precipitation by the average number of rainy days, classing as a rainy day all days with 0.02 inch of precipitation or more.

The results are shown graphically in figure 13, and are explained as follows: The average monthly precipitation (adjusted) is shown by the rectangular figures opposite the respective months. The heavy line in the center of the rectangle represents the average number of rainy days and the shaded portion of the rectangle at the bottom gives the intensity of the precipitation as above indicated. The intensity by this method is somewhat less than when only the so-called effective rains are considered.

Thunderstorms.—Much of the summer rain comes in the form of afternoon thundershowers in July and August. Thundershowers may occur, however, as early as April, before the snow cover has disappeared from north slopes. The amount of rain which falls in these early thundershowers rarely exceeds half an inch, the greater part of which is absorbed by the snow cover. Since the weather associated with April and May thunderstorms generally turns cooler and the precipitation which begins as rain turns to snow, the run-off never assumes flood proportions. The thunderstorm season is from the last half of April to the middle of October, and the months of greatest frequency July and **August.** The average number per season is 70.

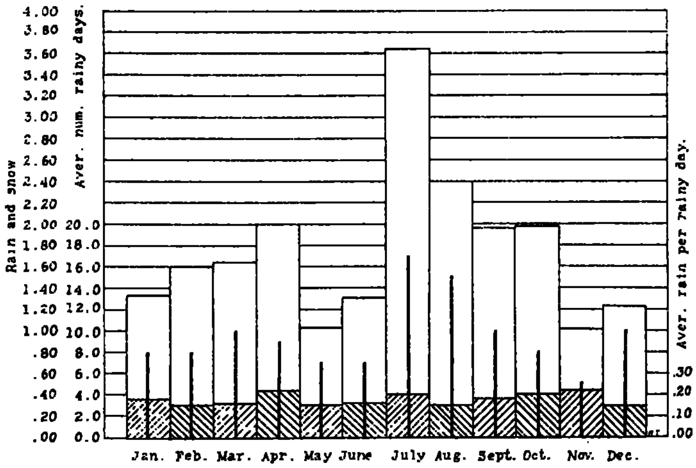

FIG. 13. Intensity of precipitation.

Snowfall.—While the snowfall forms a little less than 50 per cent of the total precipitation, it yields considerably more than 50 per cent of the run-off. The total precipitation in the months November to March, inclusive, is in the form of snow, and the precipitation of April is also 91 per cent snow. While a trace of snow may even fall in the summer months, the real transition months are June with 6 per cent of snow and October with 38 per cent. The snowfall of September is apt to be light, wholly disappearing before the cold-season snowfall sets in. The average depth of snow per season is 113.3 inches, with an equivalent water content of 9.94 inches. The range in depth from year to year is from 149.7 inches in 1916–17 to 80.7 inches in the following year. March, on the average of 9 years, is the month of maximum snowfall, 18.5 inches, with January, 17.9 inches, a close second; when, however, the months are corrected for unequal length, February ranks second with 17.98 inches and January third with 17.54 inches.

TABLE 7.

Watershed A. Average date of disappearance of snow and details of snow scales.				Watershed B. Average date of disappearance of snow and details of snow scales.			
No. of scale.	Direction of slope.	Angle of slope.	Average date of melting.	No. of scale.	Direction of slope.	Angle of slope.	Average date of melting.
	°	° ′			°	° ′	
4	N. 2 E..........	42 00	May 15	1	N. 12 W..........	15 30	May 16
7	N. 2 E..........	25 20	May 10	10	N. 12 W..........	26 50	May 26
1	N. 12 E..........	34 10	May 16	5	N. 6 W..........	26 40	May 11
10	N. 30 E..........	13 50	May 17				
17	N. 40 E..........	21 30	May 11	4	N. 22 E..........	21 50	May 19
14	N. 46 E..........	15 50	May 22	16	N. 26 E..........	16 20	May 20
15	N. 52 E..........	2 00	May 14	15	N. 29 E..........	11 50	May 23
11	N. 72 E..........	16 50	May 13	14	N. 52 E..........	2 00	May 19
				11	N. 66 E..........	22 10	May 12
8	N. 82 E..........	9 30	May 11	13	N. 70 E..........	9 10	May 12
6	N. 82 E..........	33 50	Apr. 26				
9	N. 90 E..........	11 20	May 7	9	S. 84 E..........	10 50	May 16
				8	S. 74 E..........	32 40	Apr. 23
13	S. 84 E..........	10 50	May 13	2	S. 66 E..........	25 30	Mar. 20
5	S. 40 E..........	25 50	Mar. 26	12	S. 52 E..........	21 40	Apr. 6
18	S. 36 E..........	24 50	Mar. 7	6	S. 50 E..........	26 50	Mar. 10
12	S. 32 E..........	23 40	Mar. 16				
2	S. 70 E..........	34 20	Apr. 1	7	Level..........	....	Apr. 24
3	Level..........	....	May 2	D	N. 50 E..........	24 40	May 23
D	N. 50 E..........	24 40	May 23				

Snowfall measurements.—The depth of snowfall and water equivalent, determined by weighing, is observed daily about 9 a. m., at stations C, A-1, A-2, B-1, an B-2. It is determined at six-day intervals at the D station, and the amount for each day is apportioned from the measurements made on the two watersheds. Finally, beginning on March 1, to anticipate the melting season by a few weeks, the depth and density of the snow over the two watersheds is observed at the snow scales or show stakes which were installed at various places on both watersheds. There are 18 snow scales on A and 14 on B. Table 18 is a statement of the details of the location of each scale, to which has been added, for convenience in the discussion, the average date of disappearance of snow at each scale. The arrangement of the table is by slope rather than consecutively by the serial number of the snow scale.

ANALYSIS OF STREAM FLOW.

The general behavior of the streams.—The most casual observation of any of the stream-flow records obtained during periods of rain or melting snow shows the following points: (1) that stream A rises more rapidly than stream B: (2) That the maximum flow of A is reached sooner than that of B, and, therefore, during the early decline of A, stream B may be considerably higher; and (3) that before the flood has fully spent itself A may again attain the higher level, with a secondary and more steady volume of water.

These differences are all explainable by topography.

(1) Stream A receives a larger contribution of the first water falling directly into the stream in the case of rain, or melting along the stream banks in the case of snow, because it has a greater length of stream channel. With either rain or melting snow this advantage may be continued for many days, because the slopes through which the water must drain to reach the stream are both shorter and steeper than those on B. In other words, while B has 200 acres within an average distance of 950 feet of the stream, watershed A has an equal area within 670 feet. Since the flow down these slopes is relatively much slower than the flow in an open channel, it is evident that this width of slope has much more influence on the early flow than the length of the stream.

(2) After stream A has delivered its maximum flow, the longer slopes on B get into action, and not only are they later in delivering, but they may produce a higher flood because the extreme head of the watershed, being relatively near the dam, and hardly more distant from an open channel than the side slopes, delivers almost simultaneously with them. Thus B watershed, having more the shape of a bowl, within a few days of the flood crest may deliver a larger proportion of its total flood waters than A. Whether or not the crest flow on B is as great as on A will depend upon a number of factors, whether, for example, hourly, daily, or decade crests are referred to. A very rapid rise has the effect of amassing a large amount of water in stream A before B is well started, and of creating a higher short-period crest on A. On the other hand, the same rise will permit B to deliver a very large amount in the succeeding 10-day period and may cause a higher decade crest on B. Very different effects may, of course, be produced if the rapid melting of snow occurs after a period of slow melting which has disposed of much of the snow near stream A, since that *near* stream B does not melt so early.

(3) The higher flow of A late in the flood period (which may not be actually much higher when area is considered) is plainly due to the greater length of the watershed, or, in other words, to the slower draining out of the flatter ground more distant from the dam. This upper area, except during the heaviest melting period or in excessive rain, has no surface drainage, and hence its water is long in reaching the stream. The upper section of watershed A may practically be thought of as a separate area, such as does not exist with respect to stream B. It has a stabilizing effect on stream A.

On the other hand, although this is a separate consideration, this high area on watershed A probably contributes little or nothing to the stream in the winter period, when B is actually higher, and considerably higher per unit of area, than A. This high, relatively flat ground has the appearance of becoming very dry in the fall; when once covered with a blanket of snow, since it has no southerly exposures, there is practically no melting for months, and, therefore, although the ground is not frozen to any great depth, there is no water contributed from it.

The streams involved in this experiment are perennial, and after observing that there is melting of snow on south slopes throughout the winter, it is not difficult to calculate that the flow for any ten days, or in fact for any day or hour, is made up (1) of any current precipitation or melting which may reach the streams directly, and (2) of a slower movement of water from the soil. This movement from the soil will vary with each addition to the soil moisture. Its total contribution to the stream for any period will depend not only upon the average amount of moisture in the soil, but upon the distance of that moisture from the stream. Thus the relative amount of moisture at any two points not similarly situated with respect to the stream not only will vary with additions of precipitation, but will depend upon the time since the last addition of moisture.

Each of these variable factors is different for the two watersheds. Any attempt to figure the source of the water, even when we know its volume in the streams, therefore, becomes simply appalling when one considers all of the factors involved; and when it is remembered that the most important of these factors, the accurate measurement of the rainfall or the water contributed from melting snow, is difficult of accomplishment the preparation of a formula which will express streamflow looms up as an impossibility.

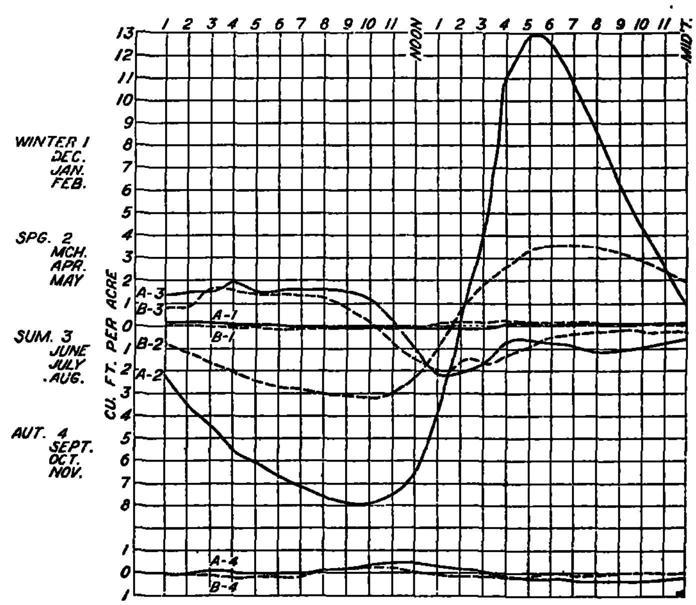

FIG. 14. Diurnal variation in streamflow.

Diurnal variation in streamflow.—The diurnal variation in the flow of the two streams has been computed for the eight years, July, 1911, to June, 1919, and the results have been plotted in figure 14. These curves are both instructive and illuminating—illuminating in that they show more clearly than would otherwise be possible the response of the streams to the meteorological conditions as modified by the physical characteristics of the two watersheds. The several monthly variations have been combined in a seasonal mean, each of which is based on approximately 20,000 observations.

The curve for winter (December, January, and February) is one of very small amplitude, but a weak response to the warm hours of the afternoon can be seen more pronounced on B than on A and the maximum seems to occur at 2 p. m. while on A it is deferred until 5 p. m.

The curve for spring (March, April, and May) is a composite made up of March and April, both of which show a weaker response to the increased insolation than May, the flood month. The dominant feature of the spring or flood curve, since all of the floods except the October rain floods are comprised within it, is the very wide variation of A as compared with B and the fact that the crest of the maximum daily discharge of the afternoon is reached at 3 p. m. and is sharply defined, whereas, the crest of the maximum daily discharge on B is not sharply defined and is reached at 6 p. m. instead of 3 p. m. Doubtless this is due to a greater time being required for concentration of runoff on B than on A, as elsewhere stated.

DISPOSITION OF PRECIPITATION.

Attempt has been made to dispose of the precipitation measured on the A watershed in accordance with the previous analysis. The results appear in Table 8.

TABLE 8.—*Disposition of precipitation, watershed A. Precipitation and run-off observed; interception, transpiration, and evaporation computed.*

Year.	(1) Precipitation.	(2) Run-off.	(3) Interception.	(4) Transpiration.	(5) Evaporation.
	Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*
1912	21.30	8.368	3.61	3.92	5.402
1913	18.63	4.778	3.84	4.14	5.872
1914	22.64	5.629	4.28	4.74	7.991
1915	19.97	5.354	2.59	3.04	8.986
1916	22.71	5.596	4.10	4.28	8.734
1917	22.88	9.644	2.66	2.73	7.846
1918	18.90	3.196	4.28	4.52	6.904
Mean	21.00	6.081	3.62	3.91	7.389
Percentage		29.0	17.0	18.0	36.0

The data in the columns headed "Precipitation" and "Run-off," respectively, were observed; those in the columns headed "Interception" and "Transpiration," respectively, were computed; and finally the column headed "Evaporation" is the difference between the sum of columns 2, 3, and 4 and the figures of column 1. In other words, after diminishing the precipitation by the run-off plus the interception plus the transpiration, the remainder is assumed to represent the loss by evaporation. Inasmuch as run-off, interception, transpiration, and evaporation total 100 per cent and the precipitation is thus completely disposed of, it is obvious that the computed values are inexact unless it be assumed, as it may be without serious error, that the quantity of water in the watershed was the same in the beginning of the year as at the end. As a matter of fact, this amount may vary somewhat from year to year. It is never very large, except as a result of heavy or continued rains. The disposition of the precipitation is graphically presented in figure 15.

STREAM-FLOW PRECIPITATION RELATIONS FOR THE TWO WATERSHEDS.

The remainder of the report is devoted to an attempt to show the relation between precipitation and run-off as influenced by the many factors which enter into the problem and to express these relations graphically in a set of diagrams accompanied by certain precepts which are to control the interpretation of the stream-flow data in future studies. The object of this analysis is, of course, to reach a conclusion as to the best method of determining the most probable run-off of stream B had denudation not taken place. The crux of the experiment lies in the accuracy with which that value is determined.

Stream-flow relations have been analyzed for a number of periods, but space does not permit reproducing the analyses of but three of these periods, (1) for the year, October to October, (2) the spring flood, and (3) the end of the flood period. The arguments, data, and diagrams for these three periods form the concluding part of this abstract and are given verbatim from the full report.[1]

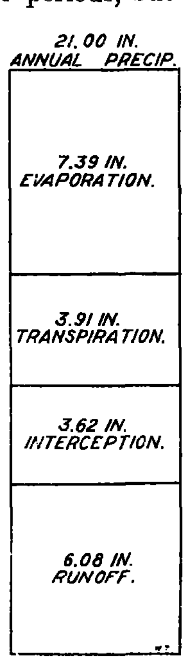

FIG. 15. Disposition of precipitation.

Relations of the streams for whole years.—The precipitation and run-off data for the eight years ending September 30, 1919, are given in Table 9, together with calculations showing the relation of total run-off of each watershed to precipitation.

On the mean amounts of precipitation for the two watersheds for eight years are almost the same, but in individual years they show considerable variation. This raises the question as to whether one watershed may actually receive more precipitation than the other, or whether the differences noted are due solely or largely to peculiarities of gage-catch. No doubt in some summer rains, which in mountainous regions are often very local in character, one watershed may receive more precipitation than the other, and for the whole year 1912–13 it is evidenced by both the precipitation and streamflow records that watershed B must have received appreciably more than watershed A. In the case of winter snowfall, however, since the storms often last for many hours, there is practically no opportunity for differences in the actual fall of the two areas. Yet the winter months show fully as great variations in catch as do the summer months. The conclusion is obvious that differences between the two areas in matters of precipitation are more apparent than real.

In view of these facts, it seems more desirable, as well as simpler, to base all comparisons of streamflow and precipitation on the precipitation of A watershed alone. It might be argued that the average of the two would be even better. The answer is that while discrepancies between the two have, in the past, pretty well evened up over a long period, still there is no assurance, now that watershed B is denuded, that a catch can be obtained, with the greater exposure of gages to the wind, at all comparable to that obtained on A.

The use of the single record can not be seriously objected to when it is considered that at the lower end

[1] A limited number of copies of the full report can be obtained from the Superintendent of Documents, Washington, D. C., at the nominal charge of 50 cents.

of watershed A there is the choice of the better catch of two gages, and this value is averaged with the catch of a third gage at the head of the watershed.

TABLE 9.—*Precipitation and run-off for years beginning Oct. 1.*

Year	Precipitation (inches over watershed).			Run-off (inches over watershed).				Proportion of precipitation appearing as run-off.		$B/A - R/Pa$.
	For the year.		Difference $B-A$.	For the year.		Difference $B-A$.	Ratio B/A	R/Pa.		
	A.	*B.*		*A.*	*B.*			*A.*	*B.*	
1911-12	21.30	21.49	+0.19	8.368	8.367	−0.001	1.000	0.393	0.393	0.607
1912-13	18.63	19.66	+1.03	4.778	5.213	+ .435	1.091	.256	.280	.834
1913-14	22.64	21.84	− .80	5.629	5.551	− .078	.986	.245	.245	.737
1914-15	19.97	19.85	− .12	5.354	5.405	+ .051	1.011	.268	.271	.743
1915-16	22.71	23.13	+ .42	5.596	5.553	− .043	.992	.246	.245	.746
1916-17	22.88	22.78	− .10	9.644	9.839	+ .195	1.020	.422	.430	.598
1917-18	18.90	18.85	− .05	3.196	3.531	+ .335	1.105	.169	.187	.936
1918-19	21.13	21.15	+ .02	6.081	5.968	− .113	.981	.288	.282	.693
Means	21.02	21.09	+ .07	6.081	6.178	+ .098	1.023	.2864	.2916	....
Sums	168.16	168.75	+ .59	48.646	49.427	+ .781	8.186	2.291	2.333	....

The following points with reference to the data of Table 9 are noteworthy:

1. The precipitation is unusually uniform from year to year.
2. The amount of water discharged by stream A varies greatly from year to year, and may be from 17 to 42 per cent of the precipitation.
3. The amount of water discharged by stream B is, on the whole, about 2 per cent greater than that for stream A. This immediately suggests that evaporation must be the less on B, either by reason of the cover conditions or because B has a deeper and better storage reservoir, or both.
4. On closer examination (see diagram A) it is seen that the ratio of B to A total discharge is highest in the years when, either because of relatively low precipitation or other causes, the total streamflow is least. In the case of the year 1912–13 it is probable that the very high ratio B/A is due in part to an actual excess of precipitation on B, and some allowance should be made for this.

The relation of the two streams approaches unity only in years whose precipitation and evaporation tendencies are about normal. On the other hand, B streamflow again tends to become greater than that of A when the total amount discharged by either is unusually great. The two years exhibiting this are 1911–12 and 1916–17. In the former there was a heavy spring flood, as well as a very considerable discharge from October rains. In the second case the flood was unusually large, comprising over 70 per cent of the total run-off for the year.

In such cases it is evident the storage facilities of both watersheds may be filled to capacity, and watershed B, being able to deliver a larger amount of water for streamflow in a given time, naturally makes the better showing.

Although these relations of the two streams do not express themselves as a simple curve, they are so simple that the acceptability of the relations as shown by diagram A can hardly be questioned. On the other hand, the true curve for the data represented by diagram A (fig. 16) is almost impossible to draw. It has, therefore, been sought to express the causes of variation in the ratio B/A, as described above, by introducing another element. The two years of greatest stream discharge were also the two years in which the ratios of discharge to precipitation were highest, while the other extreme of the diagram represents a year in which the relative amount of stream-flow was excessively low. It is, therefore, suggested that the amount of run-off relative to precipitation has a direct bearing on the relation of the two streams for whole years. Whenever the streamflow is *relatively* high (or the evaporation a relatively small percentage of the whole disposal), then the ratio of B to A discharge will be heightened.

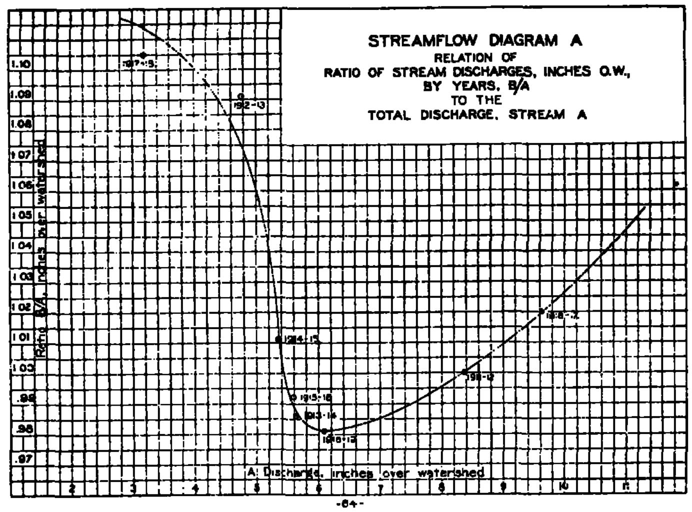

FIG. 16. Streamflow, diagram A.

In the last column of Table 9 the data for diagram AA (fig. 17) have been worked out. The abscissæ are obtained by deducting from the ratio B/A the ratio, in corresponding terms, between the run-off and precipitation

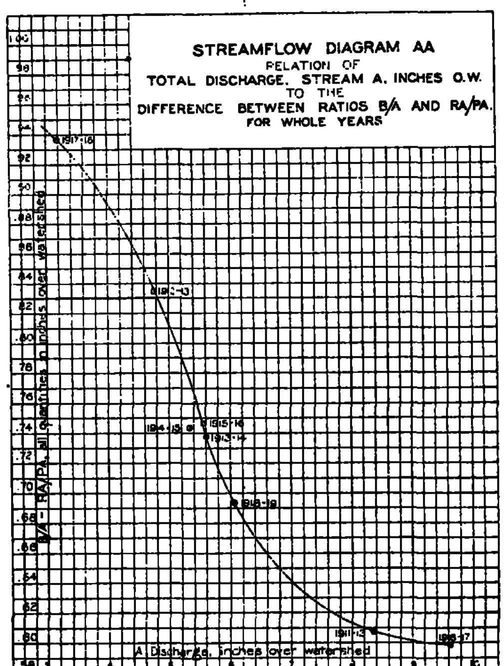

FIG. 17. Streamflow, diagram AA.

of watershed A. The ordinates are, as in diagram A, the run-off in inches of watershed A. The curve might be made straighter, and the relations more fully expressed, by making an even greater allowance for large or small ratio P/R (say one and one-half times), but the use of the straight term P/R brings the data within the range of easy handling. (Figs. 16 and 17.)

The relations may be summarized for reference in the future, as follows:

RULE 1. *Between the extremes of 18 and 23 inches of precipitation, and of 3 and 10 inches of discharge from Watershed A, it is recognized that the ratio of annual discharges, B/A, should never be greater than 1.11 nor less than 0.98, with a mean value of 1.02. The ratio is slightly less than 1.00 only when there is about a normal balance between streamflow and precipitation, represented by 5 or 6 inches for the former and 20 to 22 inches for the latter, and increases either when precipitation and run-off are low, or run-off is very great, due to large volumes in flood. To compute the most probable flow of B, relative to A, for conditions existing prior to denudation, or any year beginning October 1 and ending September 30, the total flow of A will be taken as the guiding condition, in accordance with diagram AA. To the ratio indicated on diagram AA, for a given discharge of A in inches over watershed, will be added an amount, expressed in similar terms, representing the ratio of A run-off to A precipitation for the year. The sum will be the probable ratio of B discharge to A discharge, when both are expressed in inches over the watershed. (For example, if A discharge is 7 inches, and the annual precipitation 20 inches, the indicated ratio is 0.641, and to this must be added seven-twentieths or 0.350, which gives the ratio B/A of 0.991.) The probable error in this method is less than 0.5 per cent of the final result.*

Relations of the streams in the spring flood.—As is shown by figure 12 which gives the average stream discharges by 14-day periods for 1911 to 1917, the rise of the spring flood usually begins in the latter part of March, and the heaviest discharge is usually recorded in the second decade of May. There is a tendency, in spite of variable weather and different amounts of snow, for the culmination of influences to be reached about that time.

In spite of the fact that successive floods show similar characteristics, especially in the general shape of the A and B curves, it has been found impossible to establish any fixed relations between the rates of discharge of the two streams at intermediate stages in the flood. While, as has been stated, stream B lags behind stream A during any rise, the flood as a whole is made up of so many rises and recessions that this relationship usually becomes very complicated before the crest on either stream is reached.

Beginning of the flood.—In Table 10 are presented the data bearing upon the realtions of the two streams at the beginning of the spring flood. The initial date of the flood is taken to be the first day on which the discharge rate of stream A exceeds 0.100 c. f. s. Not infrequently, after a melting period which will produce such a discharge, there occurs colder weather in which the rate for stream A may again fall to 0.100 c. f. s. or less. As neither stream, during the period up to the final rise, is making any net gain, it naturally follows that the relationships during such periods are not those based on the inherent lag of stream B. The latter may have opportunity to overtake stream A before the final and more rapid rise begins. Consequently, it is thought best to consider this period of uncertain or slow melting as a separate stage, even though the volumes of water involved may be very small in comparison with the whole flood volumes.

Table 10 indicates only the initial rises due to snow melting being considered, that there is only slight variation in the ratios B/A for the initial day, and that on the average the relation of the two streams is expressed by unity. On plotting the ratios, however, in relation to the height attained by stream A on this initial day, it is found that there is a fairly consistent relationship. It is probable that the relationship is controlled by the *rate of rise* rather than the head attained by stream A, but we have been unable to find a key which exactly fits the situation.

TABLE 10.—*Conditions at beginning of flood.*

Year.	Initial date.	Discharge on initial date.				
		c. f. s.		Inches O. W.		
		A	B	A	B	Ratio.
1912	Mar. 6	0.102	0.091	0.0109	0.0108	0.991
1913	Apr. 29	.106	.094	.0113	.0111	.983
1914	Apr. 5	.109	.113	.0116	.0135	1.155
1915	Apr. 12	.101	.098	.0108	.0117	1.082
1916	Mar. 10	.108	.096	.0116	.0115	.989
1917	Mar. 29	.119	.092	.0127	.0109	.860
1918	Apr. 23	.108	.092	.0115	.0110	.958
1919	Apr. 4	.107	.094	.0114	.0112	.978
Averages	Mar. 30	.1075	.0962	.01148	.01146	1.000

Year.	Initial date.	Period of uncertain melting.				Discharge on and after highest day.		
		Final date.	Total volume.			Amount.	Number of days.	Amount corrected[1] for number of days.
			A	B	Ratio.			
1912	Mar. 6	Apr. 2	0.2822	0.3082	1.092	0.0852	8	0.0212
1913	Mar. 29	....	....	....	....	....	....	....
1914	Apr. 5	....	....	....	....	....	....	....
1915	Apr. 12	Apr. 17	.0632	.0748	1.183	.0425	4	.0105
1916	Mar. 10	Apr. 7	.3753	.3878	1.033	.2248	18	.0808
1917	Mar. 29	Apr. 8	.1021	.1155	1.131	.1021	11	.0141
1918	Apr. 23	....	....	....	....	....	....	....
1919	Apr. 4	Apr. 11	.0841	.0911	1.082	.0727	7	.0167
Averages	Mar. 30	....	....	....	1.1044	....	....	....

[1] Reduce amount 0.008 for each day, including and following highest day of period.

It is also to be noted that in every listed period following the initial dates, when the streams fell back, the discharge of B exceeded that of A by an amount not varying greatly from 10 per cent. It is practically certain that the relations during such a period depend largely on the opportunity given for stream B to overtake and exceed stream A in delivery. The longer the period after A has reached the highest point, the greater should be the ratio B/A. But this ratio will tend to be lowered, other things being equal, if stream A has reached a relatively high point and discharges a relatively large volume thereafter. The most consistent relationship is found, then, by plotting the ratios B/A for the whole period against the volume discharge of A, with a minus correction for each day elapsed from the highest day to the end of this period of uncertain or suspended melting.

The relations at the beginning of the flood period may be formulated as follows:

RULE 2. *The ratio of B discharge in inches over watershed to the similar discharge for A on the first day of the spring rise in which stream A shows a rate of more than 0.100 c. f. s. is on the average 1.00, but may vary in different years by plus or minus 15 per cent. To determine the suppositional ratio after denudation, reference will be made to the discharge of stream A in c. f. s., and the corresponding value will be read from diagram B (fig. 18).*

RULE 2A. *In the event that the discharge rate of stream A, after the initial date of the flood, should again fall to or below 0.100 c. f. s., the ordinary relationship of the two streams in the early rise, with A leading B, may be reversed, so that on the average B will discharge about 10 per cent more for the whole of such a period. To determine the suppositional ratio B/A for such a period, from the initial day to the day next preceding the final rise above 0.100 c. f. s. (both dates included) in inches over watersheds, reference will be made to the discharge of stream A for that portion of the period beginning with the day of greatest discharge. The computed flow of A in inches over watershed will be reduced 0.008 inch for each day of the period including and following the crest day. The value thus obtained will be referred to diagram BB (fig. 19), from which the ratio B/A for the whole period may be obtained.*

End of the flood.—The relations existing between the two streams at the end of the flood are important, not only in allocating the volume which has been discharged but also because this relation is reflected throughout the summer period.

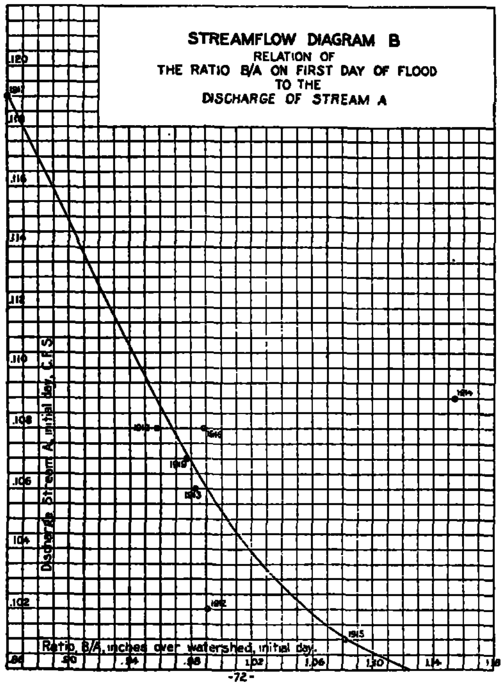

FIG. 18. Streamflow, diagram B.

The end of the flood is taken to be the last day on which stream A has a discharge of 0.150 c. f. s. or more. Should such a discharge occur after a dip below 0.150, it would be allocated to the summer period. One exception has been made in order to give some semblance of character to the very small flood of 1918. Here the crest day showed a rate of only 0.157 c. f. s. for A, the following day 0.148, and the third day 0.151. The last was taken as the closing day of the flood.

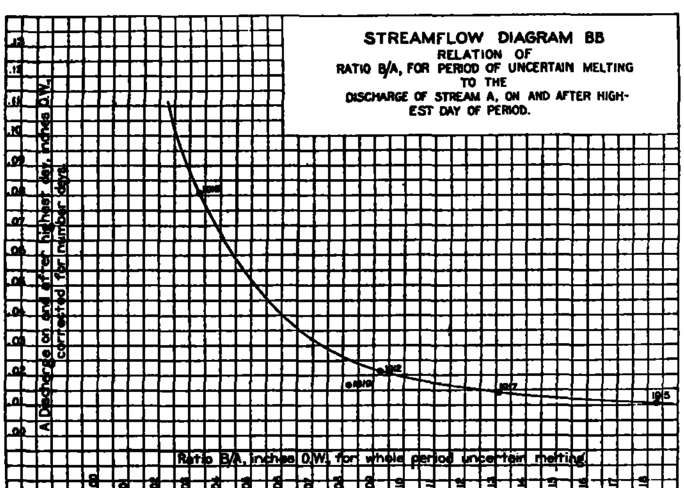

FIG. 19. Streamflow, diagram BB.

In general, the relation between the streams at the arbitrary date is seen to be controlled by the extent to which watershed B has had opportunity to exercise its ability to drain out the surcharge of water from snow melting more rapidly than watershed A. The extent to which this has occurred and the extent of depression of the ratio B/A would, naturally, depend very largely on the length of the draining-out period. On trial, however, it is found better to express this period in volumes discharged rather than in days.

There are four conceivable and rather distinct sets of conditions which produce the relation at the end of the flood:

1. If the flood is exceptionally small, as in 1918, the end of the flood as determined by A discharge rate may occur before stream B has crested, in which event the relation would be a low ratio B/A due to the lag of B during any considerable rise.

2. If the end should occur while B is at or near its crest, the ratio might be higher than unity.

3. From this point on, greater flood volumes will tend to produce lower and lower ratios B/A at the end, by allowing B greater opportunity to drain out, providing only that the melting of snow is fairly continuous, and produces a sharply conical flood crest on stream A.

4. In the event of suspended melting at about the time when stream A has crested (as a result of daily and hourly temperature distribution as affecting snow melting on the two watersheds), there may be a secondary crest on A, a relatively large volume discharged after the primary crest, a much belated and high crest on B, and consequently a high rate B/A maintained to the end of the flood. Naturally, this is more likely to occur in years when there is a large volume of snow to be melted, so that in extension of the remarks under the preceding paragraph there is still a possibility of an increasing ratio B/A with floods of large volume.

The preceding conditions become less confusing and less conflicting in their actual effects if, instead of considering the volume discharged by A as the measure of the opportunity for B to drain out and reach a low position, we consider rather the proportionate discharge of A before and after its crest. The greater the amount discharged by A before its crest the greater will be the accumulated lag of stream B, so that the latter may have a considerable rise to make before it can subside to a subordinate position. Therefore a more logical relation is found between the streams in different years if the opportunity for B's subsidence, as expressed by A volume after its crest, is compared with the opportunity for B's delay as expressed by the volume of A before crest.

In general B holds its highest position at the end of the flood when the rise and fall of A are about symmetrical, being influenced neither by any great amount of belated melting nor by precipitation after the crest. This condition is expressed by approximately a unity ratio, $\frac{\text{A discharge after crest.}}{\text{A discharge before crest.}}$

The ratio B/A at end of flood then steadily decreases if greater opportunity is given for B to drain out, as shown by a *relatively* large A volume after crest. This decrease continues until the ratio of A volume after crest to that before crest is about 2:1. Beyond this point, as represented by the years 1917 and 1913, with their flattened flood crests for stream A, the ratio B/A at end of flood must again rise. Such a flattened crest on A is certain to mean belated melting, which in effect eliminates the opportunity for B to overtake and drain out in advance of A.

In addition to the above-mentioned influences on the relative positions of the two streams at the end of the flood, the amount of precipitation occurring during the period of decline of both streams must have its effect.

Precipitation, especially toward the end of the flood period, tends to increase the ratio B/A. This is especially noticeable in the graph for the year 1913, when, but for continuous rains, the flood would have ended nearly a month sooner, and with a ratio B/A of about 1:1, in spite of the heavy flow after A crest. It is also noticeable in 1912, when there was considerable rain near the end of the flood. That falling earlier is, apparently, united with the water from melting snow, and merely increases the volume of flow after the crest. That falling late probably reaches the streams directly and has an independent effect.

Various methods of correcting for this rain factor suggest themselves, and a number have been carefully gone into. The objection to any direct use of the precipitation record is that the influence of rain is so variable, according to continuity, dryness of the ground at the time, and other conditions. It seems best, therefore, to estimate the possible effect of rain on the final ratio B/A, by noting its effect first on the flow of A. The last one-third of the period of decline for stream A has been chosen as the period in which the influence of rain is most likely to be felt. It is not suggested that earlier rain has no influence, but whatever that influence is, it is likely to be obscured by the later conditions.

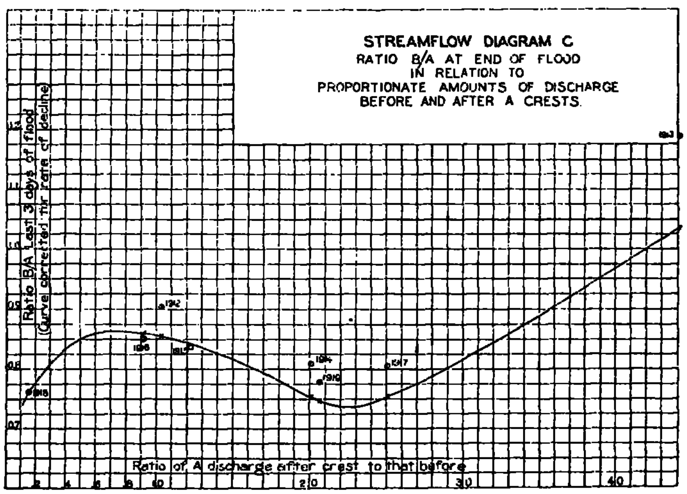

FIG. 20. Streamflow, diagram C.

The rate of decline of stream A in this last-third period affords the best index of the effectiveness of rain. As a basis of comparison, the daily rate of decline for discharges from 0.150 to 0.400 c. f. s., in periods not influenced by rain has been computed. These rates are, of course, influenced by cloudiness, evaporation, etc., and vary a good deal from day to day. Using the mean curve, it is possible to figure up from the rate of 0.150 c. f. s. by adding the daily changes, and to show quite closely what the rate of discharge would have been 15, 20, or 25 days before the rate of 0.150 c. f. s. was reached, if uninfluenced by rain. Thus, in the last 20 days of a flood, the "normal" decline would be from a head of 0.268 to a head of 0.150 c. f. s., or a change of 0.118 c. f. s.

To such a figure as the last, varying according to the length of the period, may be compared the actual decline of any given year. As example, the decline in 1912, for the last 20 days, was 0.074 c. f. s., which, compared with a "normal" of 0.118 c. f. s., gives the ratio 0.626 as expressing the influence of precipitation on the discharge of A. The smaller this decimal, or the greater the effectiveness of the precipitation, the higher the ratio B/A at the end of the flood may be expected to be. It has been found by trial that the influence of precipitation on stream B is about one-seventh more than its influence on A, at this season.

TABLE 11.—*Conditions at end of flood and other conditions relating thereto.*

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Year.	Last day 0.150 c. f. s. or more.	Discharges at end of flood.					Ratio A discharge after crest to that on and before crest.
		Last day, c. f. s.		Last 3 days, O. W.[1]			
		A	B	A	B	Ratio B/A	
						Inches.	
1912	July 19	0.156	0.125	0.0491	0.0443	0.903	1.033
1913	June 28	.157	.105	.0486	.0578	1.188	4.420
1914	July 5	.154	.114	.0502	.0406	.808	2.011
1915	July 4	.150	.112	.0480	.0402	.837	1.227
1916	June 22	.151	.116	.0492	.0417	.850	0.918
1917	Aug. 2	.152	.110	.0488	.0390	.804	2.504
1918	May 8	.151	.102	.0479	.0364	.761	0.158
1919	July 5	.150	.105	.0489	.0380	.777	2.061

		(9)	(10)	(11)	(12)	(13)	(14)	(15)
Year.	Last day 0.150 c. f. s. or more.	Conditions relative to rate of fall of A, last third.						
		Decrease in discharge rate c. f. s.	Number of days.	Full rate decrease this period.	Ratio actual to full decrease.	Ratio plus 6.	Sum divided by 7.	Corrected ratio column.
1912	July 19	0.074	20	0.118	0.626	6.026	0.2466	0.855
1913	June 28	.016	24	.162	.099	6.099	.8713	1.035
1914	July 5	.064	18	.099	.647	6.647	.9496	.767
1915	July 4	.077	15	.076	1.013	7.013	1.0019	.839
1916	June 22	.073	14	.069	1.058	7.053	1.0083	.857
1917	Aug. 2	.101	25	.175	.577	6.577	.9396	.755
1919	July 5	.083	20	.118	.703	6.703	.9576	.744

[1] To avoid possible marked effects of rain on the last day, use the sum for three days, including one before and one after the final day.

RULE 3.—*To determine the suppositional ratio B/A for the last day of the spring flood, when stream A has a discharge rate of 0.150 c. f. s. or slightly more, first compute the volume discharged by stream A up to and including the crest day for A, and the volume after the crest day and including the last day, and express the latter volume as a function of the former. By reference to diagram C (fig. 20), the approximate ratio may then be determined. The ratio indicated by the graph must, however, be corrected according to the extent to which the decline of stream A, in the last third of its declining period, has been influenced by precipitation. From the rate of discharge a given number of days before the end, subtract the rate on the last day; divide this quantity by the normal amount of decline for the given number of days as indicated by the table below; to the quotient add 6 whole units, and divide the sum by 7. This quantity, usually a little less than unity, will be divided into the rato indicated by the graph, to obtain the true ratio for the last day of the flood.*

TABLE 12.—*Normal rate of decline.*

[Days before end of flood.]

Number of days.	Decline (C. F. S.).	Number of days.	Decline (C. F. S.).	Number of days.	Decline (C. F. S.).	Number of days.	Decline (C. F. S.).
1	0.003	9	0.039	17	0.091	24	0.162
2	.007	10	.044	18	.099	25	.175
3	.011	11	.050	19	.108	26	....
4	.015	12	.056	20	.118	27	....
5	.019	13	.062	21	.128	28	....
6	.024	14	.669	22	.139	29	....
7	.029	15	.076	23	.150	30	....
8	.034	16	.083				