Some Runoff Characteristics of a Small Forested Watershed in Northern Idaho

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BENTON CREEK on the Priest River Experimental Forest, Idaho, is one of the few gauged streams flowing from a small, forested watershed in the northern Rocky Mountains, a region of summer drought and heavy winter snows. Over sixteen years of streamflow records from this watershed are summarized here to characterize the runoff from such a stream.

The streamgauging station was installed in 1938 under the direction of Harry T. Gisborne of the Northern Rocky Mountain Forest and Range Experiment Station as a part of a broad investigation of the many factors which might influence fire danger.

Watershed Description

Topography

Benton Creek drains a watershed of 950 acres. The basin as a whole faces west and hence has both north- and south-facing slopes, the south-facing slopes being generally steeper.

The elevation of the watershed varies from 2,660 feet above sea level at the outlet to 5,510 feet at Gisborne Mountain. The median elevation is 3,900 feet (Fig. 1).

Benton Creek first comes to the surface at a deep-seated, constantly flowing spring at an elevation of 4,725 feet, thence flows a distance of 2.02 miles to the gauging dam at the outlet. The grade of the stream averages 19.4 per cent (Fig. 2).

Vegetation

The watershed is almost completely forested by eight cover types as listed below. These are considered to be seral and climax associations of the *Thuja-Tsuga/Pachistima*, *Pseudotsuga/Physocarpus*, and *Picea-Abies/Pachistima* habitat types (Daubenmire, 1952).

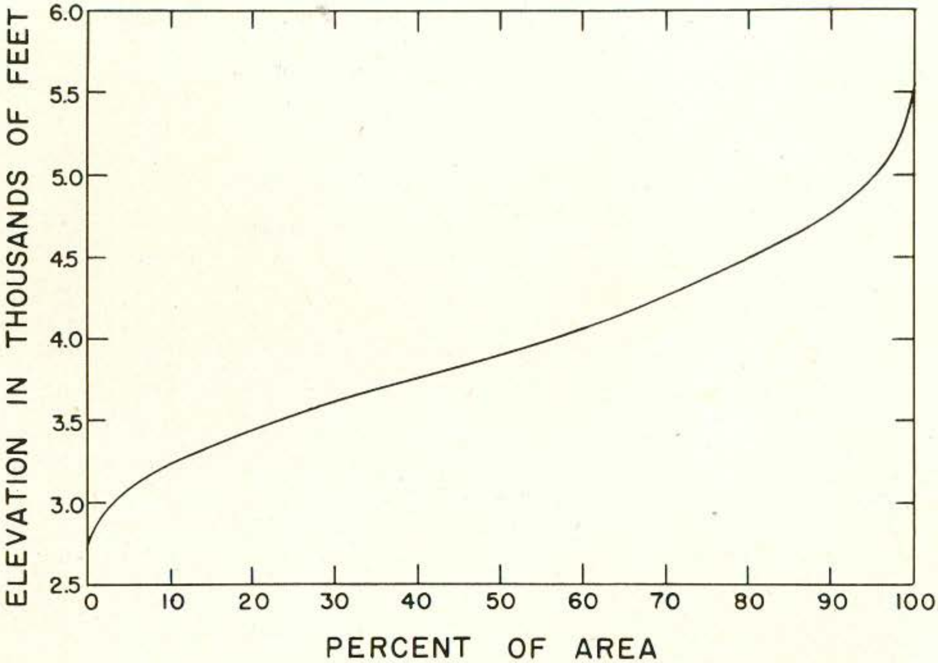

Figure 1. Area-elevation distribution of Benton Creek watershed (area=950 acres).

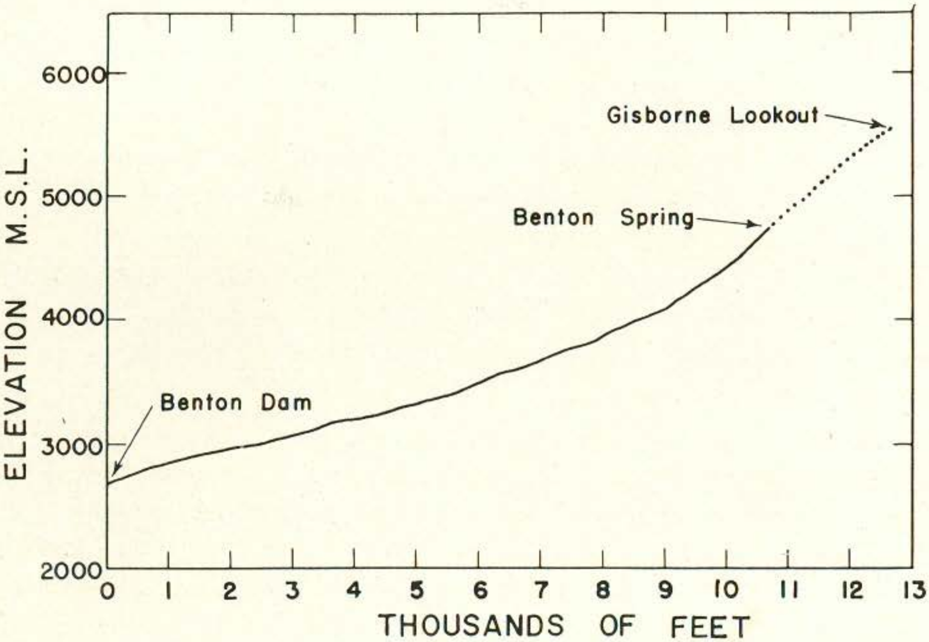

Figure 2. Profile of Benton Creek above gauging dam.

	Acres	Per cent
Western white pine	578	60.9
Western larch—Douglas-fir	95	10.0
Douglas-fir	83	8.7
Ponderosa pine	59	6.2
Western redcedar	50	5.3
Spruce—alpine fir	40	4.2
Lodgepole pine	25	2.6
Western hemlock—grand-fir	16	1.7
Rock	4	.4
	950	100.0

Climate

The long-term climatological station nearest to the watershed is at the headquarters of the Priest River Experimental Forest. This station is located near the lower end of Benton Creek at an elevation of 2,350 feet and about 1.4 miles from the streamgauging station. The average annual precipitation at the headquarters station, based on forty-four years of record, is 30.41 inches.

John R. Mather (1955) of the Laboratory of Climatology, Drexel Institute of Technology, Centerton, New Jersey, computed a theoretical water budget for the headquarters station. This computation was based on records of temperature and precipitation covering the period 1912-1931 and was made in accordance with procedures described by Thornthwaite and Hare (1955). In this "budget" precipitation represents the credit side of the ledger and potential evapo-transpiration the debit side (Fig. 3).

The water year begins October 1, at approximately the time of minimum streamflow. Fall precipitation in excess of evapo-transpiration replenishes the depleted soil-moisture reserve. A surplus of moisture is built up through the winter and early spring that is largely held in the snowpack until the period of snowmelt and runoff.

During the summer, evaporation and transpiration rapidly deplete the stores of soil moisture. As the soil moisture goes below field capacity, the actual evapo-transpiration rate is reduced below the potential. A summation of the amounts by which the actual evapo-transpiration fails to attain the potential represents the moisture deficit. The headquarters record thus indicates the moisture regime of the Benton Creek watershed is characterized by a winter period of surplus water and a summer period of moisture deficit.

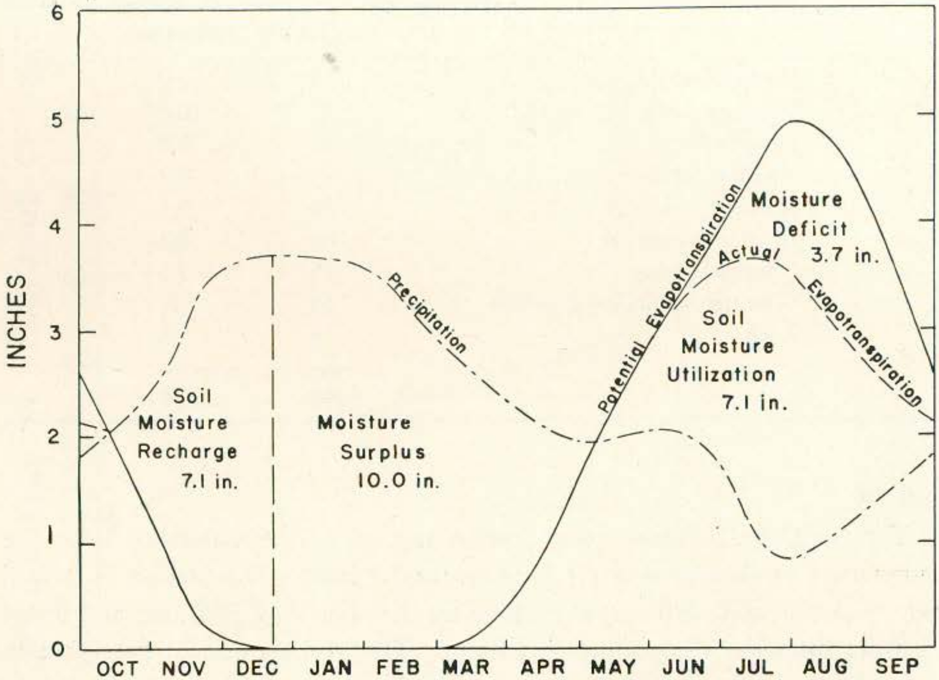

Figure 3. Average water budget for Priest River Experimental Forest Headquarters, Priest River, Idaho (after Mather, 1955).

Streamflow

Instrumentation and Computation

Records of streamflow on Benton Creek were started in January, 1939, and have been obtained continuously since then. The streamgauging station consists of two Cipolletti weirs set in a concrete dam which extends to bedrock on either side. One weir with a 1-foot crest carries this entire flow until the head reaches 0.75 foot, the level of the crest of the second, larger weir. This larger weir has a crest of 10 feet to accommodate the high spring runoff. The water level is measured in a stilling well adjacent to the pond and connected to it by a 4-inch iron pipe. A Stevens water-stage recorder maintains a continuous record of the head at an elevation scale of 1:1 and a time scale of 1 inch to 10 hours horizontally. The chart is changed weekly and its calibration checked with a Boyden hook gauge each time.

The daily volume of flow for the periods 1939 to 1940 and from mid-1948 to 1955 was computed by averaging the rate of discharge at the ends of straight line segments and multiplying by time. During the intervening period, the hourly discharge rates were averaged to obtain the daily rate when the water level was fluctuating and for each four to twelve hours when the level was not fluctuating.

TABLE 1. MEAN DISCHARGE OF UPPER BENTON CREEK WATERSHED AT BENTON CREEK GAUGING DAM, PRIEST RIVER EXPERIMENTAL FOREST, 1939-1955

Water Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Water Year Mean	
	Cubic feet per second per square mile												*c.s.m.*	*Inches*
1938-39	-------	-------	-------	0.196	0.168	0.376	1.265	1.669	0.602	0.308	0.180	0.139		
1939-40	0.177	0.133	0.251	.171	.295	1.415	2.715	1.884	.600	.269	.159	.168	0.686	9.31
1940-41	.173	.194	.323	.390	.404	1.221	1.375	1.518	1.073	.478	.273	.320	.645	8.76
1941-42	.317	.459	1.905	.907	.651	.542	2.240	2.067	1.667	.930	.397	.252	1.028	13.95
1942-43	.213	.386	.330	.236	.293	.486	4.858	2.793	1.746	.799	.352	.205	1.058	14.36
1943-44	.242	.211	.308	.177	.172	.202	.961	1.290	.997	.397	.209	.147	.443	6.01
1944-45	.121	.128	.136	.224	.332	.668	.993	4.968	1.596	.468	.228	.183	.837	11.36
1945-46	.165	.349	.427	.464	.289	.864	3.625	5.279	1.743	.684	.315	.217	1.202	16.32
1946-47	.187	.412	.921	.579	.949	1.645	2.311	2.122	.896	.487	.275	.221	.917	12.45
1947-48	.599	.777	.643	.710	.535	.556	2.940	7.194	3.047	1.236	.601	.351	1.599	21.70
1948-49	.251	.265	.207	.195	.373	.861	4.010	5.975	1.117	.430	.250	.196	1.178	15.99
1949-50	.203	.268	.240	.227	.336	1.261	2.408	6.583	3.791	1.000	.420	.261	1.416	19.22
1950-51	.392	.615	1.967	1.629	2.298	1.163	3.838	4.078	1.127	.475	.281	.226	1.507	20.46
1951-52	.507	.614	1.211	.534	.657	.658	5.858	5.905	1.393	.717	.370	.248	1.556	21.12
1952-53	.188	.215	.189	.696	.925	.768	2.417	4.687	2.230	.709	.372	.239	1.136	15.42
1953-54	.197	.211	.294	.303	.461	.836	1.980	6.395	2.797	.850	.455	.316	1.260	17.10
1954-55	.279	.288	.265	.234	.256	.256	1.077	4.538	4.300	1.246	.508	.334	1.129	15.33
Mean for entire period	.261	.345	.601	.463	.553	.810	2.639	4.056	1.807	.675	.332	.237	1.065	
16-year means:														
c.s.m.	.261	.345	.601	.480	.577	.838	2.725	4.205	1.882	.698	.342	.243	1.100	
inches	.301	.385	.693	.553	.606	.966	3.041	4.848	2.100	.805	.394	.271		14.929

Runoff Characteristics

Annual runoff for the sixteen streamflow years (October 1, 1939 to September 30, 1955) has averaged 14.929 inches, with a standard deviation of ± 4.55 inches (Table 1). A runoff of 6.01 inches during streamflow year 1943-44 was the lowest of record. The greatest runoff—21.70 inches—occurred in streamflow year 1947-48. This range of from 40 to 145 per cent of the mean probably does not represent the extremes that may occur over a longer period of record.

Mean monthly discharges for the period of record show that streamflow tends to rise to a moderate peak in December, to recede in January, to rise again to a major peak in May, and then recede during the summer and fall months. However, there was considerable deviation from this average regime from year to year. In some years there was virtually no winter peak. In some there were two winter peaks. Maximum mean monthly discharges occurred during May in thirteen of the seventeen years of record and during April in the other four years. In all streamflow years except 1939-40 and 1940-41, the mean monthly discharges declined consistently during the summer and fall months following the month of maximum runoff. Minimum mean monthly

TABLE 2. INSTANTANEOUS MAXIMUM DISCHARGES
BENTON CREEK WATERSHED

Year	Date	Discharge *c.s.m.*
1939	May 6	2.815
1940	Mar. 27	4.506
1941	May 18	2.414
1942	May 28	3.979
1943	April 16	10.854
1944	May 24	1.802
1945	May 17	9.091
1946	May 7	9.351
1947	May 9	3.735
1948	May 24	7.642
1949	May 12	12.036
1950	May 14	13.982
1951	May 13	5.945
1952	April 27	16.035
1953	April 28	10.416
1954	May 19	12.208
1955	May 21	9.194
Mean		8.000

TABLE 3. PRECIPITATION AT FOREST HEADQUARTERS, PRIEST RIVER EXPERIMENTAL FOREST, IDAHO

Water Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Total
							Inches						
1939-40	2.48	1.41	6.15	2.18	5.96	3.65	2.65	1.30	0.63	0.55	0.25	2.91	30.12
1940-41	4.23	3.37	4.17	3.25	1.76	1.44	.48	6.24	2.73	.72	1.94	4.69	35.02
1941-42	2.31	3.66	6.66	1.54	1.93	1.80	1.95	4.66	4.06	2.60	.30	.71	32.18
1942-43	2.96	6.02	4.29	3.14	2.09	3.55	2.92	3.15	3.24	.65	1.19	.03	33.23
1943-44	5.25	1.37	2.96	2.48	1.67	.96	2.55	2.42	3.16	.40	.69	1.86	25.77
1944-45	1.49	2.97	2.39	3.88	2.71	5.99	1.59	3.14	1.83	.62	.36	3.15	30.12
1945-46	3.20	4.88	3.70	4.20	3.57	3.50	3.03	1.11	4.21	.42	.41	2.24	34.47
1946-47	2.84	5.52	3.83	3.64	1.75	2.31	1.84	.94	4.24	.47	2.11	2.80	32.29
1947-48	8.31	2.14	2.84	3.09	4.23	1.56	4.51	5.18	4.92	3.43	.91	1.06	42.18
1948-49	1.41	5.03	4.10	.70	6.53	3.65	1.22	1.65	.85	.40	.62	1.76	27.92
1949-50	3.22	4.79	5.01	5.58	3.82	5.57	1.70	.92	3.54	1.26	1.39	.51	37.31
1950-51	8.12	3.62	4.73	5.42	3.51	3.28	.56	1.82	2.31	.91	.61	1.78	36.67
1951-52	8.19	3.89	6.62	5.32	2.14	2.00	1.34	1.04	4.10	.46	.22	.45	35.77
1952-53	.47	1.25	4.84	8.31	2.23	2.32	2.47	2.33	2.88	.09	2.42	.38	29.99
1953-54	.89	3.10	4.40	8.38	3.29	1.92	2.17	1.95	3.31	1.49	2.84	.89	34.63
1954-55	.97	3.31	3.61	2.46	3.33	2.37	4.53	1.60	2.94	2.72	.01	3.19	31.04
16-yr. mean	3.52	3.52	4.39	3.97	3.16	2.87	2.22	2.47	3.06	1.07	1.02	1.78	33.04
44-yr. mean	2.94	3.63	4.25	3.88	2.88	2.67	2.04	2.16	2.39	.93	.97	1.67	30.41

discharges occurred during September in eight of the years of record. During seven other years they occurred in October, and in one streamflow year (1939-1940) the lowest runoff occurred in August, and in 1954-1955 in January.

The minimum flow of record occurred in August of 1941 when the discharge fell to 0.104 cubic foot per second per square mile of drainage area. A maximum instantaneous discharge of 16.035 c.s.m. occurred on April 27, 1952. The latter is about 154 times the minimum but probably does not represent the extremes in discharges to be expected because of the shortness of the record.

Maximum instantaneous discharges occurred sometime in May during thirteen of the seventeen years of record. However, they also occurred as early as March 27 in 1940 and as late as May 28 in 1942 (Table 2), thus indicating that peakflow discharges may occur in any one year over a period of more than sixty days.

Basin Precipitation During Period

The mean annual precipitation as measured at forest headquarters during the sixteen years of measured streamflow was 33.04 inches or 8.65 per cent above the forty-four-year mean (Table 3).

During the period November 15, 1949, to October 9, 1950, twenty-four rain gauges distributed throughout the gauged basin measured the precipitation on the watershed. This number was then reduced to fifteen which were maintained until April 9, 1951. From these records the basin precipitation was computed by the Thiesson method of weighting (Thiesson, 1911). The seventeen-month record was broken into forty-two periods of precipitation approximating storm periods for analysis. The relation of basin precipitation to that at headquarters was determined (1) as a direct ratio for the seventeen-month period, (2) as a regression passing through the origin, and (3) as a regression of the form $Y = a + b X$. All gave very similar results. The regression passing through the origin seemed most appropriate, and its factor of 19.08 per cent higher basin precipitation was selected for further use. The sixteen-year average annual precipitation expanded by this factor is 39.34 inches.

Seasonal Effectiveness of Precipitation

In the Benton Creek watershed there is a striking disassociation of monthly precipitation and runoff (Fig. 4). Through the fall, most of the precipitation is held in the soil. During the winter it is held in the snowpack until the spring melting period. Through the summer period of moisture deficit, its effectiveness in contributing to runoff is negligible. Just how negligible may

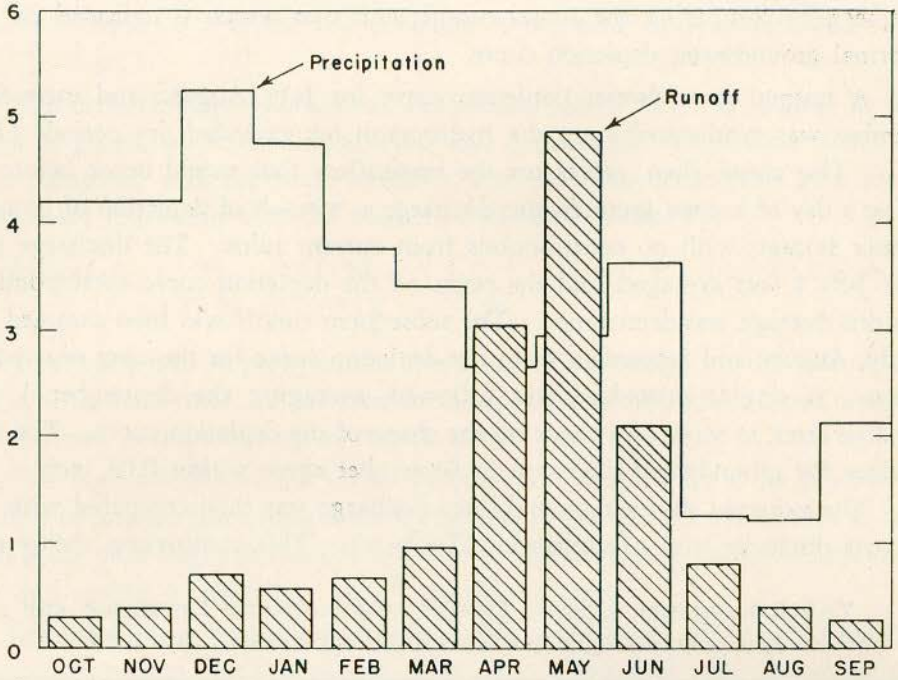

Figure 4. Mean monthly precipitation and runoff, Benton Creek watershed, 1939-1955.

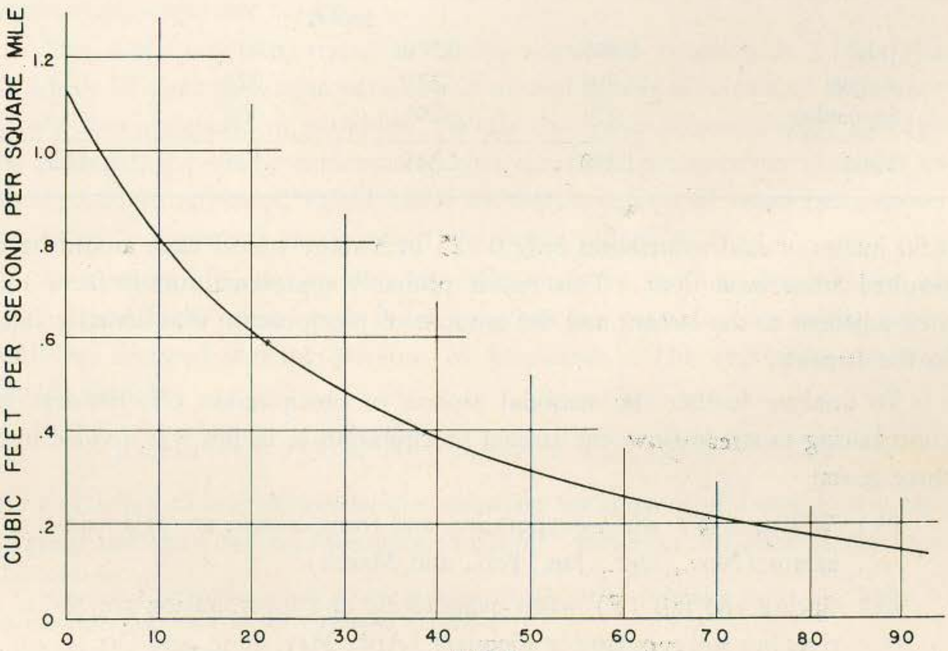

Figure 5. Summer groundwater depletion curve for Benton Creek watershed.

be seen by comparing the actual runoff with that which is indicated by the normal groundwater depletion curve.

A normal groundwater depletion curve for July, August, and early September was synthesized from the hydrograph for extended dry periods (Fig. 5). This curve, then, represents the streamflow that would occur before or after a day of known groundwater discharge as a result of depletion of groundwater storage, with no contributions from current rains. The discharge rate for July 1 was averaged, and the point on the depletion curve corresponding to this average was determined. The subsequent runoff was then summed for July, August, and September from the depletion curve for the next ninety-two days. A similar procedure was followed, averaging the September 1 discharge rates, to serve as a check on the shape of the depletion curve. The two values for groundwater discharge in September agree within 0.01 inch.

The expected summer groundwater discharge was then compared with the actual discharge and precipitation (Table 4). This comparison shows that

TABLE 4. SUMMER RUNOFF, EXPECTED GROUNDWATER DISCHARGE, AND PRECIPITATION FOR BENTON CREEK WATERSHED, 1939-1955

	Runoff (1)	Groundwater discharge (2)	Difference (1)−(2)	Precipitation
			Inches	
July	0.805	0.770	0.035	1.27
August	.394	.370	.024	1.21
September	.271	.205	.066	2.12
Total	1.470	1.345	.125	4.60

4.60 inches of rain contributes only 0.125 inch more runoff than would have resulted from base flow. This excess probably represents runoff from the area adjacent to the stream and the amount of precipitation that actually falls in the stream.

To analyze further the seasonal aspects of precipitation effectiveness in contributing to streamflow, the annual precipitation in inches was divided into three parts:

(1) Winter (W) when evaporation and transpiration are at a minimum (Nov., Dec., Jan., Feb., and March).

(2) Spring and fall (F) when evaporation and transpiration are active, but soil moisture is adequate (Apr., May, June, and Oct.).

(3) Summer (S) when evaporation and transpiration exceed precip-

itation so that the soil moisture is depleted (July, Aug., and Sept.)

A fourth variable—antecedent September runoff (R) in inches[1] as an index to groundwater conditions—was also considered. These four variables were compared with the year's runoff. The equation, determined by a multiple linear regression with the respective standard errors, was:

$$\text{Runoff} = (.983 \pm .132)W + (.722 \pm .109)\,F + (.144 \pm .269)S + (27.92 \pm 7.05)R - 23.56$$

Thus, for each inch of precipitation above or below average for the period, 98 per cent in the winter, 72 per cent in the spring and fall, and 14 per cent in the summer would show up as runoff in that year.

The high coefficient for winter precipitation coupled with the high proportion of annual precipitation occurring during this period shows that snowmelt is the most important source of water for the streams in this area, although fall and spring precipitation play a significant part.

Expressed in dimensionless units of standard deviations (beta coefficients), the net regression coefficients are .935, .778, .060, and .390 respectively.[2] It is of interest to note the relatively small effect of variations in summer rainfall (.060) on annual runoff as compared to the larger effect (.390) of antecedent September runoff.

The coefficient of correlation for the regression equation is .916. That is, about 84 per cent of the variation in annual runoff is related to differences in the four independent variables. While this value is not as high as might be expected, it must be remembered that the three precipitation variables are in themselves estimated values based on the regression of basin precipitation on forest headquarters precipitation and hence subject to error.

Because of the small effect of differences in summer precipitation on yearly runoff, the question is raised whether the variable (S) might just as well be dropped for the purpose of prediction. The regression equation would then be:

$$\text{Runoff} = (.956)W + (.718)F + (.27.32)R - 22.13$$

Its coefficient of correlation before adjusting for degrees of freedom was very slightly less than for the previous equation. However, because of the extra

[1] Antecedent September runoff is the discharge for the month preceding the start (October 1) of the water year used as the dependent variable.

[2] $\beta_{yx} = b_{yx} \left(\dfrac{\delta_x}{\delta_y}\right)$ (Ezekial, 1950, p. 159).

degree of freedom, the adjusted coefficient of correlation was .923 or slightly higher than the previous one.

Applying the latter regression equation to the precipitation averages for forty-four years of record and using the sixteen-year average September runoff, an estimate of the mean discharge for the longer period may be made. This value will be too large because the antecedent term is derived from a period wetter than average. Reducing the antecedent term by the ratio of the runoff so predicted (12.36 in.) to the sixteen-year mean runoff (14.93 in.) and again using the formula, a second estimated "normal" runoff of 11.21 inches is derived. To carry such a process further would be straying from reality. However, this figure should represent the approximate quantity of runoff during the period of climatological records.

The forty-four-year mean annual basin precipitation computed from the forty-four-year mean at forest headquarters, using the basin-station relationship, is 36.21 inches. The expected annual runoff for the same period, as estimated above, is 11.21 inches. The difference, 25.0 inches, presumably represents the mean annual water loss to evapo-transpiration. Expressed as a percentage, this loss amounts to 69 per cent of the precipitation. Compared with a mean annual runoff of 38 per cent during the sixteen-year period of streamflow measurements, the estimated mean annual runoff for the forty-four-year period is 31 per cent of the precipitation.

Diurnal Fluctuations

In addition to the seasonal fluctuations and those caused by summer precipitation, a diurnal variation is pronounced during the summer months. The discharge reaches a maximum in the early morning hours, just at daylight. It then decreases until dark when it starts back up again (Fig. 6). These variations are probably caused by fluctuations in evaporation and transpiration of streamside vegetation.

To get some conception of the magnitude of the diurnal fluctuations, the discharge was computed for several representative days assuming a straight line from peak to peak for each twenty-four-hour period. The volume lost averaged about 1,500 cubic feet per day, or about 2 per cent of the daily discharge. Taking a mean daily rate of potential evapo-transpiration for June, July, and August, of 0.146 inch per day from Figure 3, the area of vegetation necessary to cause a draw-down of 1,500 cubic feet is 123,000 square feet. Dividing by the length of Benton Creek, this amounts to a strip of vegetation about 12 feet wide transpiring at the maximum potential rate.

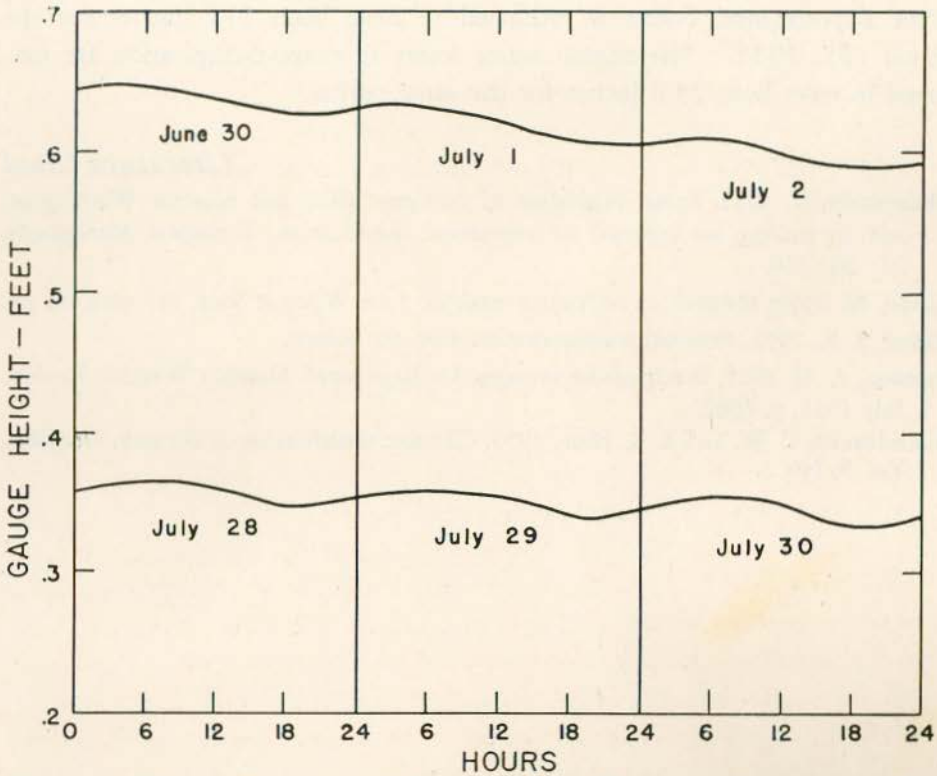

Figure 6. Diurnal fluctuations in hydrograph of Benton Creek at gauging dam for two selected periods, 1953.

Summary

During sixteen years of record on Benton Creek, two thirds of the runoff occurred during April, May, and June. The summer discharge results almost entirely from the depletion of groundwater reserves. During this period of high evapo-transpiration, the effect of summer rains on runoff is negligible. The transpiration of streamside vegetation on sunny days causes a diurnal fluctuation that is quite apparent, though small in magnitude. The fall precipitation brings about a gradual rise in streamflow as it replenishes the depleted soil-moisture reserves. Early winter thaws frequently cause the rate of discharge in December to approach that of the spring runoff. However, these peaks are of short duration.

The annual runoff, expressed as a multiple linear regression, is the sum of 98 per cent of the winter precipitation, plus 72 per cent of the spring and fall, plus 14 per cent of the summer, plus 28 times the antecedent September runoff, minus a constant, 23.6; all in inches.

The average annual runoff from Benton Creek watershed on the Priest

River Experimental Forest is estimated to have been 11.2 inches for the period 1911-1955. The annual water losses to evapo-transpiration are estimated to have been 25.0 inches for the same period.

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