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ESTIMATES OF STREAMFLOW CHARACTERISTICS FOR SELECTED SMALL STREAMS, BAKER RIVER BASIN, WASHINGTON

By J. R. Williams

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METRIC (SI) CONVERSION FACTORS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound units	By	To obtain SI units
inch (in.)	2.540	centimeter (cm)
foot (ft)	0.3048	meter (m)
acre	4,047.	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)

<u>National Geodetic Vertical Datum of 1929 (NGVD):</u> A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "<u>Mean Sea Level.</u>"

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ABSTRACT

Regression equations were used to estimate streamflow characteristics at eight ungaged sites on small streams in the Baker River basin in the North Cascade Mountains, Washington, that could be suitable for run-of-the-river hydropower development. The regression equations were obtained by relating known streamflow characteristics at 25 gaging stations in nearby basins to several physical and climatic variables that could be easily measured in gaged or ungaged basins. The known streamflow characteristics were mean annual flows, 1-, 3-, and 7-day low flows and high flows, mean monthly flows, and flow duration. Drainage area and mean annual precipitation were the most significant variables in all the regression equations. Variance in the low flows and the summer mean monthly flows was reduced by including an index of glacierized area within the basin as a third variable. Standard errors of estimate of the regression equations ranged from 25 to 88 percent, and the largest errors were associated with the low-flow characteristics.

Discharge measurements made at the eight sites near midmonth each month during 1981 were used to estimate monthly mean flows at the sites for that period. These measurements also were correlated with concurrent daily mean flows from eight operating gaging stations. The correlations provided estimates of mean monthly flows that compared reasonably well with those estimated by the regression analyses.

INTRODUCTION

Background

Over 80 percent of the electricity in the State of Washington is obtained from hydropower, practically all generated by large powerplants that make use of relatively high-head dams with large storage capacities (Boese and Kelley, 1981). Almost all sites suitable for a large powerplant have been developed. If additional hydropower is to be used to help meet projected energy needs in this State, it will have to be obtained, at least in some part, from the many small, steep streams that drain the Cascade Range.

The amount of energy available at a potential hydropower site is directly proportional to the volume of water available and the distance through which it can fall. In 1981, the U.S. Geological Survey, in cooperation with the State of Washington Department of Ecology, began an investigation to estimate streamflow characteristics at selected sites in the Cascade Range that could be suitable for run-of-the-river hydropower development. As a part of that investigation, eight sites in the Baker River basin and vicinity were chosen for this study (fig. 1).

Purpose and Scope

The purpose of this report is to present methods that can be used to estimate streamflow characteristics at selected sites in the Baker River basin, based on basin characteristics, a few discharge measurements, and streamflow records from nearby gaging stations. The report presents and compares the results obtained from several methods of estimation. Although the area for this study is relatively small, the methods used for estimating streamflow characteristics there could perhaps also be applied to the entire Cascade Mountain Range. It would take additional studies in other areas to determine the accuracy of similar estimates in those areas.

DESCRIPTION OF THE STUDY AREA

The Baker River drains an area of 297 square miles of rugged, mountainous terrain and flows into the Skagit River at Concrete, Washington (fig. 1). Elevations in the basin range from about 174 feet at Concrete to 10,773 feet at the summit of Mount Baker.

Mount Baker is an extensively glacierized volcano that continues to have some thermal activity within its crater. Winter precipitation in the basin falls mainly as snow, and the basin has 63 glaciers covering an area of 13 square miles. The southern and eastern flanks of Mount Baker are drained by the Baker River and its tributaries.

The Baker River basin has 39 lakes and ponds with a total surface area of 7,466 acres. Lake Shannon and Baker Lake, both manmade reservoirs, account for more than 96 percent of this total. The remaining 37 lakes and ponds, all above 2,500 feet altitude, range in size from 0.2 to 45.8 acres (Drost and Lombard, 1978).

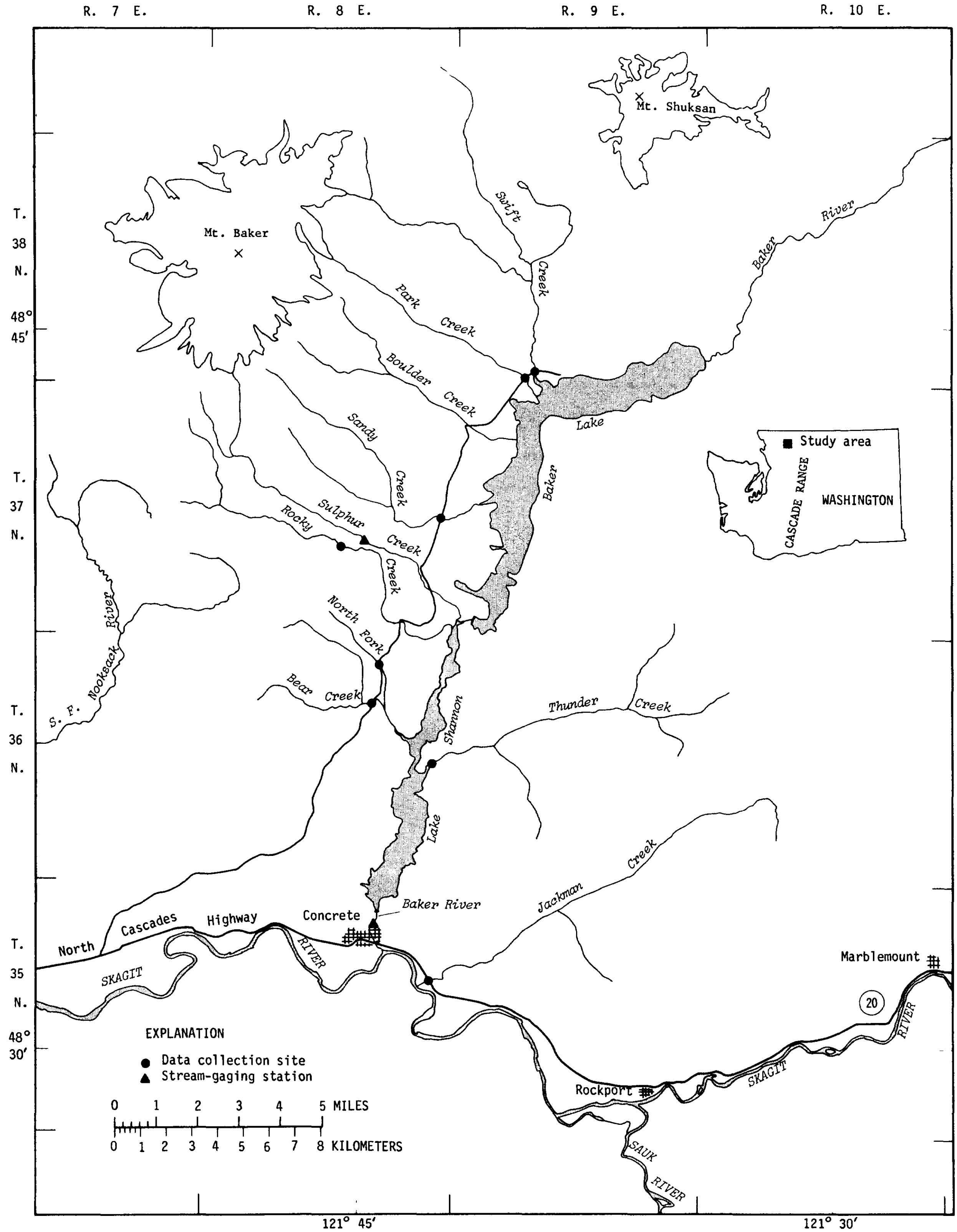

Figure 1.--Location of the the study area, including data-collection sites and stream-gaging stations.

ESTIMATES OF STREAMFLOW CHARACTERISTICS

Data Available

Continuous streamflow records have been gathered at seven gaging stations in the Baker River basin and vicinity. A listing of these gaging stations and their periods of record through the 1981 water year is given in table 1. Whereas five of the seven stations are on small streams, only two of the five have more than 1 year of record and only one of the two has more than 4 years of record.

TABLE 1.--Gaging stations in the Baker River basin and vicinity

Station name and Geological Survey number	Period of record (calendar years)
Jackman Creek near Concrete (12190000)	1943-47
Sandy Creek near Concrete (12191000)	1953-54
Baker River below Anderson Creek near Concrete (12191500)	1910-25; 1928-31; 1955-59
Sulphur Creek near Concrete (12191800)	1963-73; 1981-
Bear Creek near Concrete (12192000)	1953-54
North Fork Bear Creek near Concrete (12192500)	1953-54
Baker River at Concrete (12193500)	1910-15; 1943-

Continuous streamflow records also have been collected for many years at many sites in the river basins west of the Cascade Range crest, both north and south of the Baker River basin. Including two stations in the Baker River basin, there are 25 gaging stations in those areas that have a mean drainage-basin elevation greater than 1,200 feet and for which 10 or more years of unregulated streamflow data have been collected. For each of these gaging stations, statistical streamflow characteristics have been computed using data through the 1979 water year. The computed statistics include monthly and yearly mean flows, daily mean high and low flows, and flow-duration values. The 25 gaging stations used in this study are listed in table 2.

The gaging station Sulphur Creek near Concrete (12191800), which operated from 1963 to 1973, was re-installed in January 1981 for this study. The only other active gaging station in the basin is the Baker River at Concrete (12193500), where streamflow is regulated. Discharge measurements were made at eight additional sites in the basin for the study (see fig. 1) during the 1981 and 1982 water years. Measurements were made at about midmonth of every month, beginning in December 1980. The results of these measurements are listed in table 3.

TABLE 2.--Gaging stations used in this report

Station name and Geological Survey number	River basin	Complete years of record
Pilchuck River near Granite Falls (12152500)	Snohomish	14
South Fork Stillaguamish River near Granite Falls (12161000)	Stillaguamish	51
Jim Creek near Arlington (12164000)	---do---	18
Squire Creek near Darrington (12165000)	---do---	19
Deer Creek at Oso (12166500)	---do---	13
North Fork Stillaguamish River near Arlington (12167000)	---do---	51
Pilchuck Creek near Bryant (12168500)	---do---	26
Big Beaver Creek near Newhalem (12172000)	Skagit	14
Ruby Creek below Panther Creek near Newhalem (12173500)	---do---	15
Thunder Creek near Newhalem (12175500)	---do---	49
Stetattle Creek near Newhalem (12177500)	---do---	48
Newhalem Creek at Newhalem (12178100)	---do---	18
South Fork Cascade River at South Cascade Glacier (12181100)	---do---	18
Salix Creek at South Cascade Glacier (12181200)	---do---	12
Cascade River at Marblemount (12182500)	---do---	51
Sauk River above White Chuck River near Darrington (12186000)	---do---	56
Suiattle River near Mansford (12189000)	---do---	11
Baker River below Anderson Creek near Concrete (12191500)	---do---	21
Sulphur Creek near Concrete (12191800)	---do---	10
Alder Creek near Hamilton (12196000)	---do---	28
Day Creek near Lyman (12196500)	---do---	18
East Fork Nookachamps Creek near Big Lake (12199800)	---do---	10
North Fork Nooksack River below Cascade Creek near Glacier (12205000)	Nooksack	42
South Fork Nooksack River near Wickersham (12209000)	---do---	45
Skookum Creek near Wickersham (12209500)	---do---	21

TABLE 3.--Discharge measurements made at data-collection sites

Stream	Location	Drainage area in square miles	Date	Discharge, cubic feet per second
Jackman Creek	SE 1/4 NW 1/4 sec. 13, T.35 N., R.8 E., at road crossing, 2 miles upstream from mouth, and 2 miles southeast of Concrete	23.9	12-16-80	462
			1-15-81	74.4
			2-18-81	569
			3-17-81	67.8
			4-16-81	142
			5-16-81	157
			6-11-81	223
			7-17-81	54.4
			8-15-81	22.8
			9-19-81	19.2
			10-18-81	71.5
			11-19-81	172
			12-16-81	135
Swift Creek	At road crossing, 1,000 feet upstream from mouth when Baker Lake is normal full elevation, 5 1/2 miles north of Upper Baker Dam	36.3	12-17-80	560
			1-15-81	125
			2-17-81	1,190
			3-16-81	158
			4-15-81	168
			5-15-81	448
			6-11-81	584
			7-15-81	408
			8-14-81	314
			9-20-81	114
			10-15-81	222
			11-18-81	424
			12-16-81	193
Park Creek	At road crossing, 1,000 feet upstream from mouth when Baker Lake is normal full elevation, 5 1/2 miles north of Upper Baker Dam	11.3	12-17-80	121
			1-15-81	27.8
			2-18-81	220
			3-16-81	41.6
			4-15-81	53.4
			5-15-81	109
			6-10-81	254
			7-15-81	178
			8-14-81	325
			9-20-81	63.2
			10-15-81	79.5
			11-18-81	126
			12-16-81	50.0

TABLE 3.--Discharge measurements made at data-collection sites--continued

Stream	Location	Drainage area in square miles	Date	Discharge, cubic feet per second
Sandy Creek	At road crossing, 1 mile upstream from mouth when Baker Lake is normal full elevation, 2 1/2 miles north of Upper Baker Dam	10.8	12-17-80	139
			1-15-81	40.7
			2-18-81	329
			3-17-81	36.2
			4-16-81	75.6
			5-16-81	76.8
			6-10-81	167
			7-16-81	64.7
			8-14-81	60.4
			9-19-81	27.6
			10-16-81	47.8
			11-19-81	119
			12-16-81	70.6
Rocky Creek	At old road crossing, 3.7 miles northwest of Upper Baker Dam, and 1 mile downstream from crossing of road to Wanlick Creek	7.54	12-15-81	141
			1-14-81	7.80
			2-16-81	273
			3-16-81	14.5
			4-15-81	5.96
			5-15-81	61.6
			6-10-81	141
			7-15-81	18.8
			8-14-81	51.0
			9-19-81	21.4
			10-15-81	13.0
			11-18-81	64.6
			12-15-81	15.7
Bear Creek	In SE 1/4 sec.10, T.36 N., R.8 E., at road crossing, 1/2 mile upstream from North Fork and 5 1/2 miles north of Concrete	10.0	12-17-80	113
			1-15-81	24.6
			2-17-81	600
			3-17-81	26.0
			4-16-81	83.9
			5-16-81	45.5
			6-11-81	107
			7-16-81	19.9
			8-15-81	8.0
			9-20-81	5.54
			10-16-81	35.6
			11-19-81	83.5
			12-16-81	73.2

TABLE 3.--Discharge measurements made at data-collection sites--continued

Stream	Location	Drainage area in square miles	Date	Discharge, cubic feet per second
North Fork Bear Creek	In SW 1/2 sec.2, T.36 N., R.8 E., at road crossing 1 mile upstream from mouth and 6 1/2 miles north of Concrete	1.22	12-17-80	33.3
			1-16-81	7.68
			2-17-81	150
			3-17-81	8.52
			4-16-81	25.0
			5-16-81	14.6
			6-11-81	29.8
			7-16-81	7.27
			8-15-81	2.26
			9-20-81	1.33
			10-16-81	10.8
			11-19-81	30.5
			12-16-81	24.6
Thunder Creek	NW 1/4 NE 1/4 sec.24, T.36 N., R.8 E., 1/4 mile upstream from Lake Shannon, 4 1/2 miles northeast of Concrete	22.4	12-16-80	610
			1-14-81	72.4
			2-18-81	437
			3-17-81	67.6
			4-16-81	128
			5-16-81	166
			6-11-81	230
			7-16-81	61.3
			8-15-81	25.7
			9-19-81	19.3
			10-18-81	63.9
			11-19-81	161
			12-16-81	114

Methods of Analysis

Three methods were used to estimate various streamflow characteristics. All characteristics discussed in this report were estimated from regression equations based on the relation of a given streamflow characteristic to selected basin characteristics. Three regression techniques, (1) step-forward, (2) step-backward, and (3) maximum correlation coefficient analysis, were used in developing the equations. Mean monthly discharges were also estimated from two methods that use discharge measurements at the ungaged sites.

Multiple Regression

Streamflow characteristics for the small ungaged streams in the Baker River basin were estimated from multiple regression of basin characteristics with streamflow characteristics for long-term gaging stations in nearby basins. The regression equations were defined by the historical data from the 25 gaging stations listed in table 2.

The gaging stations that were used for the regression analyses were selected in accordance with the purpose of the study--to determine the feasibility of hydropower development. The criteria for selection were as follows:

1. Each gaging station had to have 10 or more complete years of daily streamflow record.
2. Each gaging station was in the mountains (minimum mean basin elevation of 1,200 feet was used). The electric power that can be developed is dependent on both the volume of water and the fall that can be obtained at any site. Gaging stations in the lowlands, therefore, were not used.
3. Each gaging-station record was for natural flow; that is, no manmade regulation of the flow.
4. Only one gaging station was used for a stream. When several gaging stations on the same stream would have qualified, the station farthest upstream was used.

The periods of record for the 25 gaging stations used in the regression analyses varied considerably between stations (see table 2). Some ran for 10 years in the 1920's and 1930's, for instance, and others ran for 10 or 15 years in the 1960's and 1970's. Others may have run for 50 years or more. This variety in the periods of record for the stations provides regression estimates that are generally independent of data from any specific set of years at any one station.

The relations between various streamflow characteristics (dependent variable) and the physical and climatic characteristics of the drainage basins (independent variables) were determined by multiple-regression analyses. A log-linear relation between a streamflow characteristic and the basin characteristics was selected as the model form, and the logarithms of all variables were used in the regressions. The model equation is one commonly used in regionalization and is of the form:

$$\log Z = \log a + b_1 \log X_1 + b_2 \log X_2 \ldots b_n \log X_n,$$

or (1)

$$Z = a\, X_1^{b_1}\, X_2^{b_2}\, X_3^{b_3} \ldots\ldots X_n^{b_n} \quad ,$$

where Z is the dependent streamflow characteristic, X_1, X_2,.....X_n are independent basin characteristics, a is the regression constant, and b_1, b_2,.....b_n are regression coefficients for the appropriate basin variables.

Several techniques for multiple-regression analysis were applied to the data in this study in order to determine the equation that would provide the "best" estimates of each streamflow characteristic, considering both the accuracy of the estimate and the complexity of the relation equation.

A technique called "step-forward analysis" was first used. It begins by finding the one independent variable that produces the highest correlation coefficient with the dependent variable. It then picks from the remaining independent variables the one most effective in reducing variance of the dependent variable, adds it to the first, and derives the equation using the two independent variables. Variables are thus added to the model one by one until all are used. Once an independent variable is in the model, it stays, even though the introduction of a new independent variable can make a previously included independent variable superfluous because of a high correlation between it and other independent variables now in the regression.

A technique called "step-backward analysis" also was used. This technique begins by calculating statistics for an equation including all the independent variables. Then the independent variables are deleted from the model, one by one, beginning with the independent variable showing the smallest contribution. The steps are continued until the model using the most significant independent variable is left.

The third technique used is called "maximum correlation coefficient analysis." This technique determines the "best" one-independent-variable equation, the best two-independent-variable equation, and so forth. Unlike the other two techniques, this one does not necessarily keep the previous independent variables in the equation as additional independent variables are added. For example, it is possible that the "best" four-independent-variable equation may not contain all of the independent variables used in the "best" three-independent-variable equation.

Application of these techniques showed that two independent variables, drainage area and precipitation, were by far the most significant. For example, the regression analysis using all the independent variables to estimate the annual mean flow at the 50-percent exceedence probability produced the following equation:

$$Q = 0.91\ (DA)^{0.99}\ (P)^{0.39}\ (GL)^{0.86}\ (S)^{0.01}\ (F)^{0.25}\ (SN)^{-0.10}\ (SL)^{-0.06}\ (EL)^{0.26} \quad (2)$$

where:
DA = drainage area,
P = mean annual precipitation,
GL = glacier factor (see p. 19 for definition),
S = storage,
F = forest cover
SN = mean annual snowfall
SL = main channel slope
EL = mean basin elevation

This equation had a multiple-correlation coefficient of 0.992.

An equation for estimating the same flow characteristic using only the variables drainage area and precipitation has a multiple-correlation coefficient only slightly smaller, at 0.990. This equation was

$$Q = 1.04\ (DA)^{0.98}\ (P)^{0.41}.$$

The flow of streams that contain glaciers in their drainage areas remains higher during the summers than the flow of streams that do not have glaciers in their drainages. Glacier-fed streams will often rise during periods of hot, dry weather when nonglacial streams are falling. As expected, the glacier factor (see p.) did improve the standard error of estimate when used as an independent variable in the regressions for estimating low flows and mean monthly flows for the spring and summer months. Most of the equations finally selected for estimating flow characteristics used only the two independent variables drainage area and precipitation, although some for low flows did include the glacier factor.

The scope of this study precluded the use of other independent variables that had not been computed previously. Ground-water storage, however, can significantly affect streamflow, especially lower flows, and future studies of streams in the Cascade Range should attempt to take that into account. Parameters that should be tested might include, for example, channel and valley shape indices and geologic factors such as the extent of consolidated and unconsolidated materials.

The drainage-basin and climatic characteristics computed for each of the 25 gaging stations and used as independent variables in this study are listed in table 4 and described as follows:

TABLE 4.--Indices for basin and climatic characteristics used in multiple regressions

Station number	Drainage area in square miles (DA)	Annual precip-itation (inches) (P)	Glacier factor (1.0 minus percent glacier) (GL)	Storage (percent area of lakes) (S)	Forest cover, (percent of basin) (F)	Annual snow-fall in inches (SN)	Channel slope, in feet per mile (SL)	Mean basin elevation, in feet (EL)
12152500	54.5	68	1.0	0.19	96	25	46	1,500
161000	119	106	1.0	.09	94	40	46	2,600
164000	46.2	91	1.0	.88	92	25	132	1,400
165000	20.0	100	.992	.01	70	45	308	2,530
166500	65.9	89	1.0	.01	98	30	101	2,540
167000	262	83	.998	.01	92	40	33	2,300
168500	52.0	64	1.0	2.49	91	20	75	1,290
172000	63.2	74	.961	.01	76	540	115	4,400
173500	206	77	.990	.05	79	465	194	5,700
175500	105	129	.858	.11	61	340	257	5,800
177500	22.0	88	.977	.46	84	500	560	5,000
178100	27.9	125	.996	.31	77	360	578	4,140
181100	2.36	154	.467	.05	1	600	876	6,240
181200	.078	150	1.0	.01	67	500	36	5,390
182500	168	131	.958	.17	78	360	156	4,400
186000	152	139	.990	.14	81	315	125	3,700
189000	335	132	.965	.16	74	425	96	4,500
191500	211	126	.938	.72	69	390	89	3,900
191800	8.36	125	.856	.01	90	400	667	3,960
196000	10.7	58	1.0	.01	99	25	203	1,280
196500	34.2	77	1.0	.65	88	20	143	2,310
199800	3.56	60	1.0	.01	62	30	435	2,700
205000	105	109	.939	.20	71	690	106	4,300
209000	103	92	1.0	.30	84	35	58	3,000
209500	23.1	93	1.0	.10	90	25	334	3,020

1. Drainage area, DA, in square miles, as measured by planimeter from available U.S. Geological Survey quadrangle maps.
2. Mean annual precipitation over the drainage basin, P, in inches, as determined by the grid method from the isohyetal map prepared by the U.S. Weather Bureau (1965).
3. Glacier factor, GL. This factor is determined by first computing the proportion of the drainage basin area that is covered by glacier ice and then subtracting this value from unity. For a basin containing no glacier, the factor would be 1.0.
4. Storage, S, expressed as the percentage of the drainage area occupied by lakes and ponds, as determined by planimeter. A minimum value of 0.01 percent is used.
5. Forest cover, F, expressed as the percentage of the drainage area covered by forests, as determined by the grid method from a colored topographic map. A minimum value of 1 percent is used.
6. Mean annual snowfall over the drainage basin, SN, in inches,as estimated from data from snow courses and weather records.
7. Main channel slope, SL, in feet per mile. This is the average slope of the stream channel between points that are 10 and 85 percent of the distance along the main channel between the desired site and the upstream drainage divide.
8. Mean basin elevation, E, in feet above sea level, determined by superimposing a rectangular grid over the contour map of the drainage area and averaging the elevations at the intersections of the grids. The grid should provide at least 25 values.

Other Methods

The two other methods used to estimate discharges use the relation between the discharges from current-meter measurements at the ungaged sites and daily or monthly discharges at a nearby gaging station in a drainage basin with a similar geologic and climatic setting. Both methods use discharge measurements that were made about mid-month at the eight ungaged sites for the 13 month period from December 1980 to December 1981. In the first method the discharges measured at the ungaged sites were correlated with the concurrent daily mean discharges at the gaging station. The equations that resulted from the correlation was applied to mean monthly discharges at the gaging stations to provide an estimate of the mean monthly discharge at the ungaged site.

In the second method, monthly means for each month in 1981 were computed by a method proposed by Riggs (1969). The Riggs procedure is based on the assumption that the ratio of concurrent daily mean flows of two streams near the middle of a month equals the ratio of their means for that month (Riggs, 1969). Calculations of the estimated monthly mean flows at the ungaged sites were made by multiplying the measured flow at the ungaged site by the ratio of the monthly mean flow to daily mean flow at a gaging station. A visual inspection of data plots revealed no seasonal variation in the relations between discharges at gaged and ungaged sites.

The following gaging stations were used to obtain the estimates for the eight stream sites:

12167000 North Fork Stillaguamish River near Arlington for Jackman, Bear, and North Fork Bear Creek.
12177500 Stetattle Creek near Newhalem for Swift Creek.
12186000 Sauk River above White Chuck River near Darrington for Sandy Creek.
12205000 North Fork Nooksack River below Cascade Creek, near Glacier for Rocky and Park Creeks.
12209000 South Fork Nooksack River near Wichersham for Thunder Creek.

The gaging stations listed above were all operating during the period January 1981 to December 1981. They were selected on the basis of high correlation of the discharges measured at each stream site to the concurrent daily mean flow at the respective gaging stations. The records from three other gaging stations (Sulphur Creek, Newhalem Creek, and Thunder Creek near Newhalem) were also tested for use in making the estimates, but their correlations with the eight sites were poor, and they were not used. Similar correlations, but in the form of linear regressions of monthly mean flows estimated at each stream site and recorded at each gaging station identified in table 7 for January 1981 to December 1981, were used to estimate the mean monthly flows at each stream site.

Results of Study

Regression of basin characteristics

The regression relations that were selected for estimating various streamflow characteristics are listed in table 5. The list includes equations for computing mean annual flows, high flows, low flows, mean monthly flows, and flow-duration data. The multiple-correlation coefficients and the average standard errors of estimate are given for each relation.

The standard error of estimate is a range of error such that an estimate by the regression equation is within this range for about two of three gaging stations and within twice this range for about 19 of 20 gaging stations. The standard error of estimate is, therefore, an indicator of the accuracy of the regression equations.

The standard errors of estimate are largest for the low-flow relations, possibly because of the undefined ground-water storage differences between basins, which, in turn, results from the differences in geology. It is expected that future studies of this kind in the Cascade Range may be able to define the geologic factors partially and thereby reduce the size of the standard errors of estimate for low flows.

Discharges have been computed with the regression equations listed in table 5 for the eight stream sites in this study. These computed discharges are shown in table 6.

TABLE 5.--Regression relations for estimating various streamflow characteristics

Streamflow characteristic	Regression equations[1] (Q, in cubic feet per second)	Average standard error, in percent	Multiple correlation coefficient
Mean annual flow (Probability of being exceeded):			
10 percent	$Q = 1.58(DA)^{0.98}(P)^{0.37}$	27	0.99
50 ---do--	$Q = 1.04(DA)^{0.98}(P)^{0.41}$	27	.99
90 ---do--	$Q = 0.57(DA)^{0.97}(P)^{0.50}$	29	.99
Low flow (50-percent probability of not being exceeded):			
1-day	$Q = 0.000085(DA)^{0.98}(P)^{2.05}(GL)^{1.95}$	71	.94
3-day	$Q = 0.000082(DA)^{0.98}(P)^{2.06}(GL)^{1.89}$	70	.94
7-day	$Q = 0.00009(DA)^{0.97}(P)^{2.06}(GL)^{1.91}$	68	.94
Low flow (10-percent probability of not being exceeded):			
1-day	$Q = 0.000013(DA)^{1.00}(P)^{2.35}(GL)^{1.88}$	88	.92
3-day	$Q = 0.000014(DA)^{1.00}(P)^{2.35}(GL)^{1.77}$	88	.92
7-day	$Q = 0.000012(DA)^{1.00}(P)^{2.38}(GL)^{1.87}$	87	.92
High flow (50-percent probability of being exceeded):			
1-day	$Q = 88(DA)^{0.94}(P)^{-0.11}$	48	.97
3-day	$Q = 39(DA)^{0.94}(P)^{0.0063}$	41	.98
7-day	$Q = 16(DA)^{0.93}(P)^{0.14}$	34	.98

TABLE 5.--Regression relations for estimating various streamflow characteristics--continued

Streamflow characteristic	Regression equations[1] (Q, in cubic feet per second)	Average standard error, in percent	Multiple correlation coefficient
Mean monthly flow:			
October	$Q = 1.06(DA)^{0.98}(P)^{0.38}$	45	.97
November	$Q = 21(DA)^{1.00}(P)^{-0.25}$	46	.98
December	$Q = 100(DA)^{1.08}(P)^{-0.66}$	58	.97
January	$Q = 220(DA)^{1.04}(P)^{-0.83}$	64	.96
February	$Q = 380(DA)^{1.04}(P)^{-0.97}$	61	.96
March	$Q = 290(DA)^{1.10}(P)^{-1.00}$	57	.97
April	$Q = 15(DA)^{1.03}(P)^{-0.21}(GL)^{1.82}$	37	.99
May	$Q = 0.16(DA)^{0.98}(P)^{0.90}(GL)^{1.21}$	40	.98
June	$Q = 0.0042(DA)^{0.97}(P)^{1.70}(GL)^{-0.036}$	51	.97
July	$Q = 0.00028(DA)^{0.97}(P)^{2.17}(GL)^{-1.11}$	66	.96
August	$Q = 0.00087(DA)^{1.02}(P)^{1.74}(GL)^{-2.40}$	61	.96
September	$Q = 0.058(DA)^{1.00}(P)^{0.86}(GL)^{-2.08}$	43	.98
Flow duration (probability of being exceeded):			
95 percent	$Q = 0.00078(DA)^{1.07}(P)^{1.50}$	71	.93
90 ---do--	$Q = 0.0031(DA)^{1.07}(P)^{1.25}$	61	.96
75 ---do--	$Q = 0.15(DA)^{1.09}(P)^{0.52}$	40	.98
70 ---do--	$Q = 0.32(DA)^{1.10}(P)^{0.38}$	38	.98
50 ---do--	$Q = 1.09(DA)^{1.05}(P)^{0.26}$	33	.99
25 ---do--	$Q = 1.21(DA)^{0.99}(P)^{0.43}$	31	.99
10 ---do--	$Q = 2.61(DA)^{0.94}(P)^{0.42}$	29	.99

[1] DA, drainage area; P, mean annual precipitation; GL, glacier factor.

TABLE 6.--Discharge estimates from regression relations for selected streamflow characteristics at eight stream sites

Streamflow characteristic	Computed discharge estimates, in cubic feet per second, for:							
	Jackman Creek	Swift Creek	Park Creek	Sandy Creek	Rocky Creek	Bear Creek	N.F. Bear Creek	Thunder Creek
Mean annual flow (probability of being exceeded):								
10 percent	200	310	102	98	69	84	11	190
50 ---do--	170	260	81	80	56	68	8	160
90 ---do--	130	200	67	65	46	54	7	120
Low flow (50-percent probability of not being exceeded):								
1-day	29	44	13	16	12	10	1	27
3-day	30	46	13	16	13	10	1	28
7-day	32	48	14	18	14	11	1	30
Low flow (10-percent probability of not being exceeded):								
1-day	20	31	9	11	8	7	1	19
3-day	20	32	10	12	9	7	1	19
7-day	21	33	10	12	9	7	1	20
High flow (50-percent probability of being exceeded):								
1-day	1,000	1,500	510	490	350	470	65	980
3-day	800	1,200	390	380	270	350	49	750
7-day	620	920	300	300	220	270	38	580
Mean monthly flow:								
October	140	210	71	67	47	61	7	130
November	150	230	71	67	47	66	10	140
December	140	220	57	55	38	59	6	130
January	120	180	50	48	33	53	6	110
February	110	160	44	42	29	48	5	100
March	86	130	33	31	21	36	4	80
April	140	200	47	57	42	60	7	140
May	250	370	110	120	92	99	13	240
June	270	440	160	160	110	99	13	250
July	170	290	130	110	72	58	8	160
August	79	140	71	49	31	28	3	74
September	81	140	61	45	28	31	4	75

TABLE 6.--Discharge estimates from regression relations for selected streamflow characteristics at eight stream sites--continued

Streamflow characteristic	Computed discharge estimates, in cubic feet per second, for:							
	Jackman Creek	Swift Creek	Park Creek	Sandy Creek	Rocky Creek	Bear Creek	N.F. Bear Creek	Thunder Creek
Flow duration probability of being exceeded):								
95 percent	27	45	15	14	10	9	1	25
90 ---do--	33	55	17	17	12	12	1	31
75 ---do--	55	88	26	25	17	20	2	51
70 ---do--	62	100	29	27	18	23	2	58
50 ---do--	100	170	49	47	32	41	4	98
25 ---do--	210	330	110	100	72	86	11	200
10 ---d0--	370	560	190	180	130	160	22	350

The drainage area (DA), precipitation (P), and glacier factor (GL) that were used to compute the streamflow characteristics by the regression equations are listed as follows:

Creek	DA	P	GL
Jackman	23.9	110	1.0
Swift	36.3	115	.959
Park	11.3	125	.833
Sandy	10.8	125	.956
Rocky	7.54	125	1.0
Bear	10.0	100	1.0
N.F. Bear	1.22	100	1.0
Thunder	22.4	110	1.0

Correlation using discharge measurements

The relation equations for correlations of measured discharges at the eight stream sites with concurrent daily mean flows at nearby operating gaging stations are shown in table 7 with their correlation coefficients and standard errors. Estimates of mean monthly flows for the eight stream sites are shown in table 8 as obtained from the equations in table 7, using mean monthly flows for the indicated gaging stations.

Flows at none of the eight stream sites correlated best with flows at the Sulphur Creek gaging station, which is the closest station and measures flow from the same side of Mount Baker as most of the eight streams. Historic records for Sulphur Creek show that it has lower spring runoff from snowmelt than nearby stations, but a higher base flow during the summer months. This is probably due to geologic factors that allow the spring snowmelt to enter the ground and then drain more slowly during the summer.

Table 7 also shows that the standard error of estimate is much higher for the Rocky Creek relation than for the others. One possible explanation for this could be that the stream channels of Rocky and Sulphur Creeks may have moved and changed their drainage areas, both in 1981 and in the past. The fieldman who made the discharge measurements on August 14, 1981, noted a sudden rise of very muddy water in Rocky Creek on that date. Rocky Creek had been very clear when earlier discharge measurements were made. There were no rises on other streams in the area. It is possible that melt water from Easton Glacier, which normally flows into Sulphur Creek, may have risen suddenly and cut a new channel into the Rocky Creek drainage. Reconnaissance of the area indicated that the channel also may have shifted in the past.

TABLE 7.--Relations for estimating flows at the selected streams from correlations with flows from nearby gaging stations

Equation	Average standard error in percent	Correlation coefficient
Jackman Creek = 0.038 (North Fork Stillaguamish River)$^{1.08}$	23	0.98
Swift Creek = 5.35 (Stetattle Creek)$^{0.82}$	22	.96
Park Creek = 0.043 (North Fork Nooksack River)$^{1.20}$	35	.90
Sandy Creek = 0.15 (Sauk River above Whitechuck)$^{0.92}$	24	.95
Rocky Creek = 0.00017 (North Fork Nooksack River)$^{1.86}$	61	.90
Bear Creek = 0.0042 (North Fork Stillaguamish River)$^{1.26}$	18	.99
North Fork Bear Creek = 0.0014 (North Fork Stillaguamish River)$^{1.26}$	24	.98
Thunder Creek = 0.20 (South Fork Nooksack River)$^{1.00}$	30	.96

TABLE 8.--Estimates of mean monthly flows for the selected streams, using the correlations of table 7 and using long-term mean monthly flows from records at the gaging stations

[Flows, in cubic feet per second]

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Jackman Creek	110	180	220	200	170	150	150	160	120	59	29	47
Swift Creek	340	350	330	270	240	240	370	620	680	540	310	250
Park Creek	110	110	100	71	63	52	78	190	290	240	130	96
Sandy Creek	73	95	110	87	75	66	91	160	180	120	56	47
Rocky Creek	32	33	29	17	14	10	19	79	150	110	44	26
Bear Creek	45	83	100	91	75	65	68	70	51	22	10	17
North Fork Bear Creek	14	26	32	28	23	20	21	22	16	7	3	5
Thunder Creek	130	190	210	180	160	130	160	220	180	93	44	59

Riggs Method

In the third method estimates of long-term mean monthly flows for the eight ungaged stream sites also were made by adjusting the estimates of monthly mean flows for 1981 calculated by the Riggs' method (p. 22). The monthly mean flows for 1981 estimated by the Riggs' method are shown in table 9. To adjust the monthly flows of table 9 to long-term mean monthly flows, it was necessary to compute the relations between the monthly flows at nearby gaging stations and their long-term mean monthly flows. The monthly relations for the five gaging stations used in the correlations of table 7 were averaged to give a regionalized value for the area. Table 10 shows the monthly and average relations for the five nearby gaging stations. By applying the average adjustment factors from table 10 to the estimated monthly mean flows from table 9, estimated long-term mean monthly flows for the eight sites were calculated and listed in table 11.

Table 11 summarizes the estimated mean monthly flows that were calculated by the three methods. In general, the three methods provide estimates that compare reasonably well with each other. The estimated flows for Park Creek and North Fork Bear Creek from the regressions seem too low when compared to the estimates from the other two methods. This may be because their effective drainage areas may well include more area than the surface contour lines indicate. For those two stations the estimated mean monthly flows by correlations and by Riggs' method adjusted are probably more nearly correct.

Gaging stations were operated for short periods at three of the eight stream sites, and their records can be used in a generalized comparison to help judge the accuracy of the mean monthly flows estimated by regression, correlation, and Riggs' method. Jackman Creek was gaged for 4 water years (1944 to 1947), and the average monthly flows for those years are shown plotted on figure 2. For comparison, the estimated mean monthly flows by regression, correlation, and Riggs methods are also plotted. In general the comparison is favorable with perhaps the estimates by Riggs' method appearing most favorable.

The Bear Creek and Sandy Creek gaging stations operated for only one complete water year, 1954. The monthly mean flows for that year are shown plotted on figures 3 and 4, respectively, along with estimates by correlation, regression, and Riggs' method. For the first half of the water year the recorded monthly mean flows plot somewhat higher than the estimated values, and the values estimated by correlation plot higher than those estimated by regression. However, the comparison seems reasonable because average discharge for the 1954 water year was 125 percent of average for the North Fork Stillaguamish River and 128 percent of average for the Sauk River above White Chuck River, the two streams used to correlate with Bear Creek and Sandy Creek, respectively.

TABLE 9.--Monthly mean flows for 1981 estimated by Riggs method

[Flows, in cubic feet per second]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Jackman Creek	124	273	74	207	181	192	56	23	44	197	137	186
Swift Creek	268	254	110	382	599	941	399	228	147	466	365	283
Park Creek	51	211	42	111	129	257	191	255	80	142	102	64
Sandy Creek	57	135	36	122	121	170	62	50	44	94	100	105
Rocky Creek	14	133	14	12	73	143	20	40	19	23	52	18
Bear Creek	41	167	28	122	52	92	20	8.0	12	87	67	101
North Fork Bear Creek	13	42	9.3	36	17	26	7.3	2.3	2.9	26	24	34
Thunder Creek	103	117	87	175	230	169	71	27	44	170	117	135

TABLE 10.--Ratios of 1981 monthly mean flows to long-term mean monthly flows at nearby gaging stations

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
North Fork Stillaguamish River	0.48	1.59	0.64	1.63	0.84	1.49	0.92	1.05	0.93	1.64	0.86	1.05
Stetattle Creek	.74	1.91	.51	1.12	.76	.88	.80	.73	.70	1.08	.71	.68
Sauk River above White Chuck	.91	1.77	.66	.97	.81	.98	.71	.69	.82	1.26	.83	.76
North Fork Nooksack River	1.23	1.55	.81	1.20	.89	.78	.77	.96	.92	1.22	1.28	1.21
South Fork Nooksack River	.46	1.48	.79	1.42	.71	1.14	.82	.60	.89	1.33	.78	.81
Average	.76	1.66	.68	1.27	.80	1.05	.80	.81	.85	1.31	.89	.90

TABLE 11.--Summary of estimated long-term mean monthly flows for the selected sites

[flows, in cubic feet per second]

		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Jackman Creek	1.	140	150	140	120	110	86	140	250	270	170	79	81
	2.	110	180	220	200	170	150	150	160	120	59	29	47
	3.	150	150	210	160	160	110	160	230	180	70	28	52
Swift Creek	1.	210	230	220	180	160	130	200	370	440	290	140	140
	2.	340	350	330	270	240	240	370	620	680	540	310	250
	3.	360	410	310	350	150	160	300	750	900	500	280	170
Park Creek	1.	71	71	57	50	44	33	47	110	160	130	71	61
	2.	110	110	100	71	63	52	78	190	290	240	130	96
	3.	110	110	71	67	130	62	87	160	240	240	315	94
Sandy Creek	1.	67	67	55	48	42	31	57	120	160	110	49	45
	2.	73	95	110	87	75	66	91	160	180	120	56	47
	3.	72	110	120	75	81	53	96	150	160	78	62	52
Rocky Creek	1.	47	47	38	33	29	21	42	92	110	72	31	28
	2.	32	33	29	17	14	10	19	79	150	110	44	26
	3.	18	58	20	18	80	21	9	91	140	25	49	22
Bear Creek	1.	61	66	59	53	48	36	60	99	99	58	28	31
	2.	45	83	100	91	75	65	68	70	51	22	10	17
	3.	66	75	112	54	101	41	96	65	88	25	10	14
North Fork	1.	7	10	6	6	5	4	7	13	13	8	3	4
Bear Creek	2.	14	26	32	28	23	20	21	22	16	7	3	5
	3.	20	27	38	17	25	14	28	21	25	9	3	3
Thunder Creek	1.	130	140	130	110	100	80	140	240	250	160	74	75
	2.	130	190	210	180	160	130	160	220	180	93	44	59
	3.	130	130	150	140	70	130	140	290	160	89	33	52

1. By regression of basin characteristics.
2. By correlation with nearby gaging stations.
3. By Riggs method adjusted.

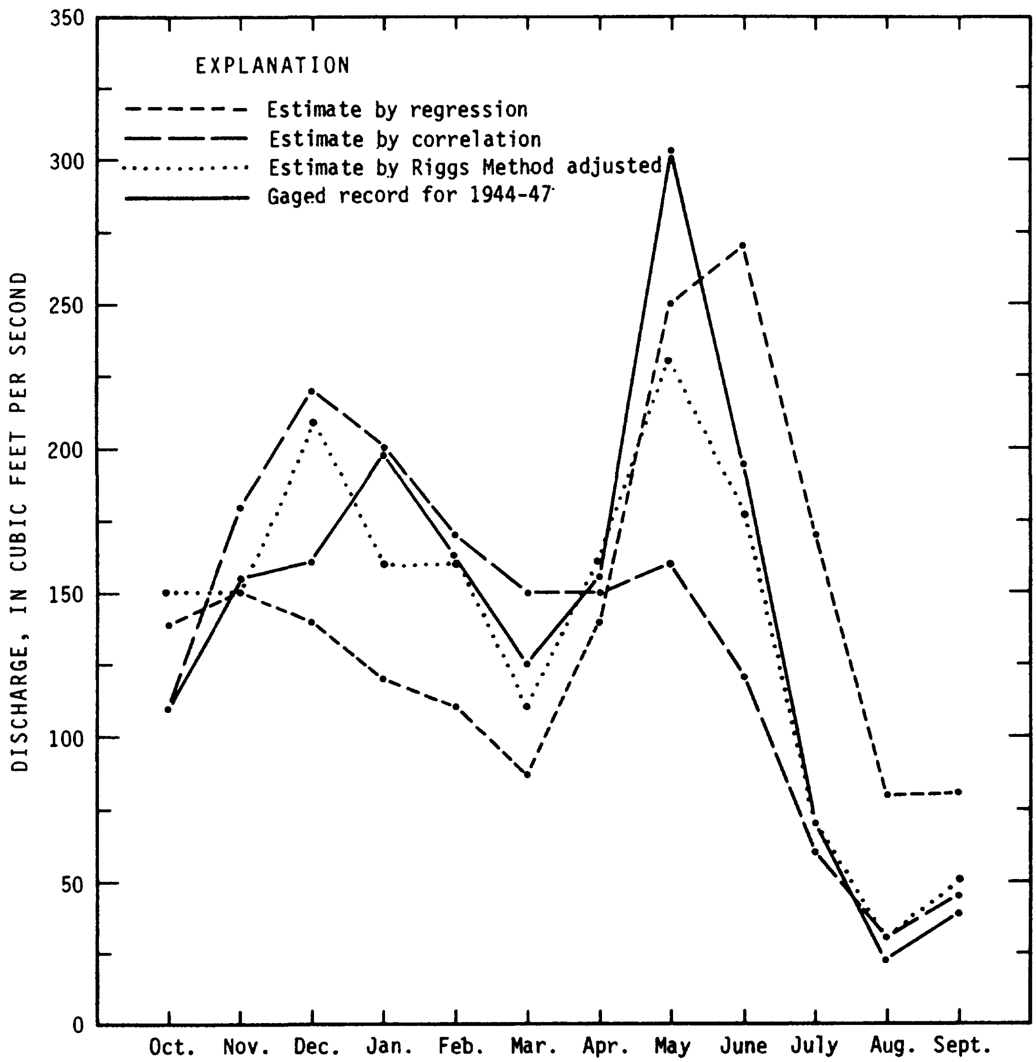

Figure 2.--Mean monthly flows for a typical water year at Jackman Creek.

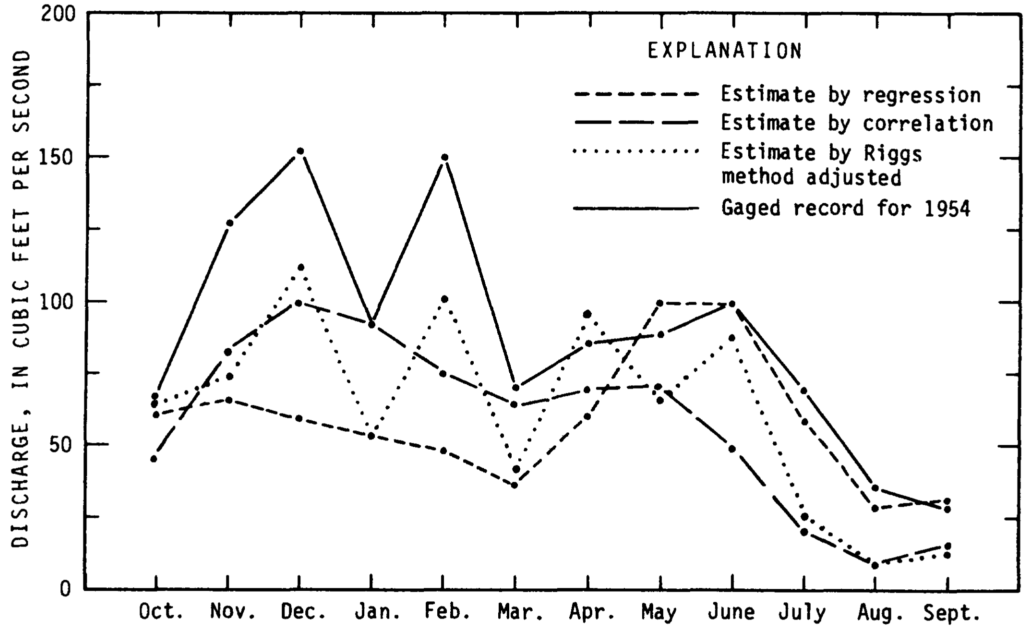

Figure 3.--Mean monthly flows for a typical water year at Bear Creek.

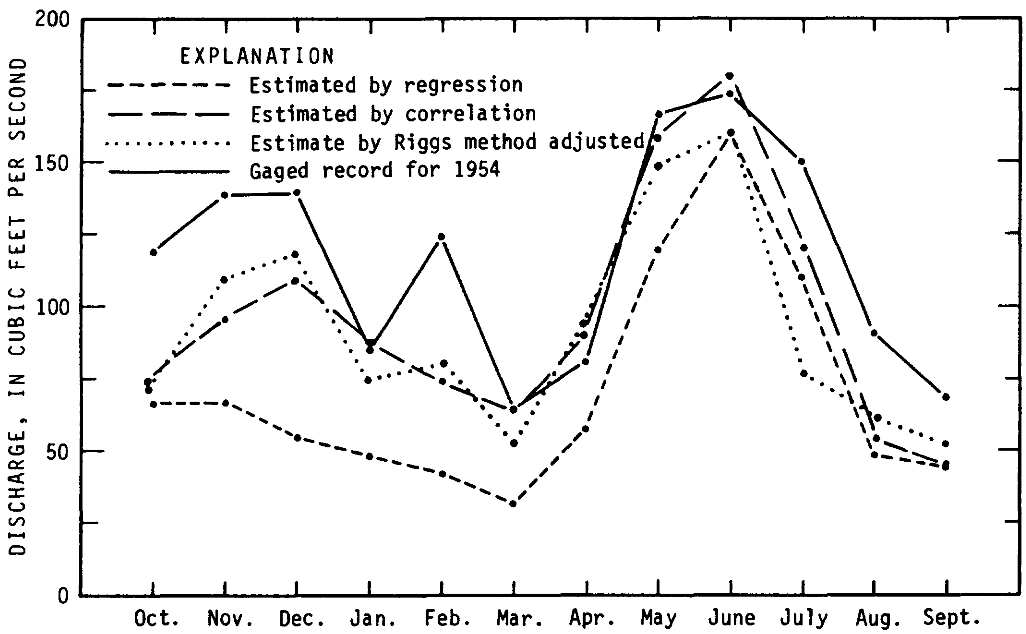

Figure 4.--Mean monthly flows for a typical water year at Sandy Creek.

High flows may also be of importance in the consideration of safety in the development of hydropower at some locations. Annual peak flows for several recurrence intervals for streams in Washington may be computed using a regression analysis of floodflows of nonregulated streams (Haushild, 1978). Regression equations are given for streams in western and eastern Washington and for streams whose annual peak flows usually occur at several times during the year, such as during winter or spring. The eight streams studied in this report are assumed to fall in Haushild's category of "winter and spring peaks: winter peak dominant." The regression equations for peak discharges with various recurrence intervals are given as follows:

$$P_{10} = 1.54\ (DA)^{0.89}\ (P)^{1.06}$$
$$P_{25} = 1.94\ (DA)^{0.89}\ (P)^{1.05}$$
$$P_{50} = 2.21\ (DA)^{0.89}\ (P)^{1.04}$$
$$P_{100} = 2.49\ (DA)^{0.89}\ (P)^{1.04}$$

In the above regression equations P_{10} is a peak flow with a recurrence interval of 10 years, which means that it could be expected to be equaled or exceeded on the average about once in 10 years; this should not be construed to mean it could be expected to occur on a regular basis. DA is the drainage area, in square miles, and P is the mean annual precipitation on the basin, in inches. All of the regression equations have a standard error of estimate of 33 percent and a multiple-correlation coefficient of 0.984. The peak flows calculated for the various recurrence intervals for the eight selected streams are shown in table 12.

TABLE 12.--Annual peak floodflows for indicated recurrence intervals for the selected stream

Stream	Floodflow, in cubic feet per second, for indicated recurrence intervals			
	10 years	25 years	50 years	100 years
Jackman Creek	3,800	4,600	5,000	5,600
Swift Creek	5,800	6,900	7,500	8,500
Park Creek	2,100	2,500	2,700	3,100
Sandy Creek	2,100	2,600	2,800	3,140
Rocky Creek	1,600	1,900	2,000	2,300
Bear Creek	1,600	1,900	2,100	2,300
North Fork Bear Creek	240	290	320	360
Thunder Creek	3,600	4,300	4,700	5,300

SUMMARY

When additional hydropower is needed in the State of Washington, it will have to be obtained from the many small, steep streams in the mountains, because most sites suitable for large powerplants have been developed. There are few historic streamflow data available for such streams, since few have been gaged.

In this study, regression equations were used to estimate streamflow characteristics at eight ungaged sites on small streams in the Baker River basin in the North Cascade Mountains, Washington, that could be suitable for run-of-the-river hydropower development. The regression equations were obtained by relating known streamflow characteristics at 25 gaging stations in nearby basins to several physical and climatic variables that could be measured easily in gaged or ungaged basins. The most significant variables in all the regression equations were drainage area and mean annual precipitation. The known streamflow characteristics were mean annual flows, 1-, 3-, and 7-day low flows and high flows, mean monthly flows, and flow duration. Variance in the low flows and the summer mean monthly flows was reduced by including an index of glacierized area within the basin as an additional variable. The standard errors of estimate of the regression equations ranged between 25 and 88 percent, with the larger errors associated with the low-flow characteristics.

Two other methods were used to estimate discharges at the ungaged sites. In one method, discharges measured at an ungaged site were correlated with the concurrent daily mean discharges at a gaging station with a similar geologic and climatic setting. The resulting equation was applied to mean monthly discharges at the gaging stations to provide an estimate of the mean monthly discharge at the ungaged site. In the other method monthly means were computed by a procedure based on the assumption that the ratio of concurrent daily mean flows of two streams near the middle of the month equals the ratio of their means for that month.

The estimates of the various streamflow characteristics obtained by the three methods compared reasonably well with each other. Additional studies in other areas of the Cascade Range are needed to determine if similar estimates of streamflow characteristics can be obtained with reasonable accuracy in those areas.

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