The Hydrology of Four Streams in Western Washington as Related to Several Pacific Salmon Species

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THE HYDROLOGY OF FOUR STREAMS IN WESTERN WASHINGTON AS RELATED TO SEVERAL PACIFIC SALMON SPECIES

By M. R. COLLINGS, RONALD W. SMITH, and G. T. HIGGINS

ABSTRACT

Enhancement—or possibly even preservation—of the Pacific salmon hinges on the careful planning and proper management of the streamflow upon which they depend for spawning. Most spawning activity occurs on reaches of streams where specific hydraulic conditions exist and where stream-channel characteristics and water-quality criteria are met. The present report is the first of a series and is used to present the method of determining preferred spawning conditions and results of the investiagtion of 129 measurements on 14 study reaches of the Dewatto, Cedar, Kalama, and North Fork Nooksack Rivers. Subsequent reports, using the same method will present analyses and preferred spawning and rearing discharges for other streams used by salmon.

The method consists of measuring water depth and velocities to designate, from area—(spawnable) discharge curves, peak, preferred spawning discharges for fall chinook, spring chinook, sockeye, and coho salmon at each reach on each river. Also, streambed gravels, water temperature, suspended sediment, dissolved oxygen, and specific conductance are used to help evaluate river conditions during spawning.

In examining the repeatability of the method, tested by analyzing independently each of selected pairs of adjacent reaches on the Cedar River, it was found that the preferred peak discharges from the comparisons varied 4.6 percent for the average of four species and two pairs of reaches.

Peak spawning discharges ranged, for the four salmon species on each of the three study reaches of each river, from 50 to 140 cfs (cubic feet per second) on Dewatto River, from 230 to 510 cfs on Cedar River, from 245 to 800 cfs on Kalama River, and from 195 to 710 cfs on North Fork Nooksack River.

The results indicate that the methods used and the probable discharge values determined are reasonable and, if economically justified, may be used to select discharges, for salmon spawning and rearing.

INTRODUCTION

The Pacific salmon is an anadromous fish, living in the sea and ascending rivers and streams for spawning, incubation, and early rearing. Five salmon species of Pacific salmon frequenting the Washington streams are sockeye (*Oncorhynchus nerka*), chinook (*O. tsawytscha*), coho (*O. Kisutch*), pink (*O. gorbuscha*), and chum *O. keta*). Sockeye, coho, and the spring and fall chinook were investigated in this study; for simplicity, in the rest of this report these three salmon species (with two races of one species) will be referred to as four species.

The Pacific salmon utilizes most of the streams in western Washington for spawning and rearing. The most productive spawning activity occurs on reaches of streams where specific hydraulic conditions exist and where certain stream-channel characteristics and water-quality criteria are met. Each salmon species has specific hydraulic prerequisities—ranges of water depths and bottom velocities—for spawning. The critical channel characteristics include streambed composition and compactness infiltration of water through the gravels, cover and concealment, and the amount of habitation along the streambanks (Royce, 1959). Some factors of water quality which influence spawning are water temperature, suspended sediment, dissolved oxygen, and dissolved-solids concentration.

Anadromous fish usually spawn in pool-riffle streams, where the water slope alternates between comparatively level reaches (pools) and comparatively steep segments (riffles). Sand is the predominant bed material in the pools, whereas the bed material of the riffles, where the salmon form their redds (nests), is generally much coarser. Smolt production is highest in stream channels composed of 50-percent riffles and 50-percent pools (Ruggles, 1966). The pools, with proper food production and volume of water, serve as rearing areas for the fry and fingerlings of some salmon species. Riffles also serve as food-production and rearing areas.

At present, the streams of western Washington have an abundant supply of water; however, the increasing population and industrial growth is accompanied by an ever-growing demand for water for hydroelectric power generation and other beneficial uses, such as irrigation and municipal supply. Therefore, if the Pacific salmon is to be enhanced or even preserved, the allocation of streamflow, careful planning, and proper management will be necessary.

PURPOSE AND SCOPE

The major purpose of this study was to develop a suitable method for designating the most desirable streamflow or flows for spawning and rearing of various salmon species in the major salmon-producing streams in Washington. The preferred rates of streamflow are based on optimum salmon propagation at the minimum suitable flow. The ultimate objective of the study, after a sufficient sample is obtained, is regionalization which will allow a determination of the minimum acceptable flow at any desired location on a river. The relationships developed—minimum acceptable discharge versus easily obtained significant basin and channel parameters—may provide a basis for future allocation of water for salmon.

The present report is the first of a series on a study of streams used by salmon. On four streams (fig. 1)—the Dewatto, Cedar, Kalama, and North Fork Nooksack Rivers—at 14 sites, 129 determinations of velocity, depth, discharge and water-quality parameters have been made. These data are used to determine rearing and spawning discharges for sockeye, coho, spring chinook, and fall chinook salmon, species for which the preferred spawning depths and velocities are known. Spring and fall chinook are races of the species *Oncorhynchus tshawytscha*. Each stream and each site is discussed independently, each having varying degrees of analysis, depending on the amount of data available at this time (1969).

ACKNOWLEDGMENTS

This study was made under a cooperative agreement between the U.S. Geological Survey and the Washington State Department of Fisheries. The assistance of biologists from the Department of Fisheries in selecting river study reaches is gratefully acknowledged. The constructive criticism and suggestions from colleagues Prof. Milo C. Bell of the Fisheries Center, University of Washington, M. A. Benson and S. E. Rantz of the Geological Survey, and Stanley G. Jewett, Jr., of the U.S. Fish and Wildlife Service were of benefit to the final report.

APPROACH

The methods used for collection and analysis of these data are, with a few modifications, a combination of the methods used by

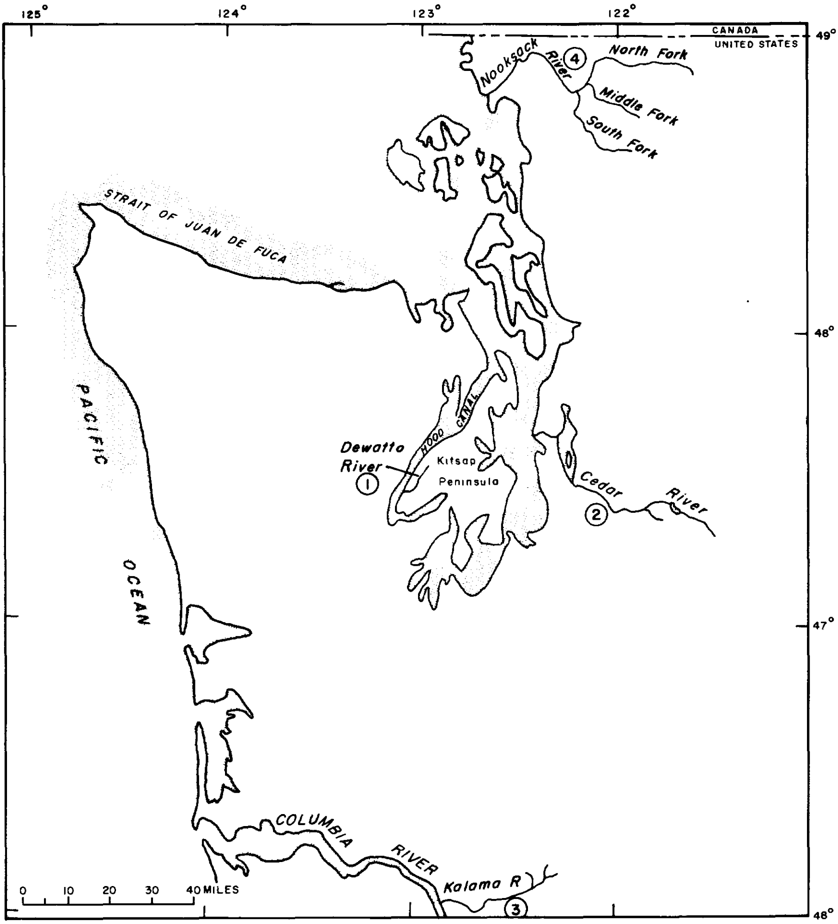


FIGURE 1.—Location of streams studied in western Washington: (1) Dewatto River, (2) Cedar River, (3) Kalama River, and (4) North Fork Nooksack River.

Rantz (1964), Westgate (1958), and the Washington State Department of Fisheries (Deschamps and others, 1966).

SELECTION OF SITES

Three major factors were considered in the selection of streams for this study: (1) The streams must have known salmon-spawning areas; (2) because obviously not all streams can be studied, streams must be selected on the basis of being representative of varying geographic locations, such as highland or lowland streams, and of differing runoff characteristics; and (3) a priority must be given to streams where future water development projects are imminent.

Three to five reaches were selected on each river to obtain replications of the sample in order to analyze the variance of the sample within a particular river or for error evaluation. Selection of the reaches was based on the following criteria: (1) The reach must exhibit observable spawning activity, and (2) the reach must have a fairly stable streambed to enable sampling of a range of flows without major channel shifting. At each reach four cross sections were established, the reach was mapped by planetable methods, and a river-stage reference point or gage was established.

HYDRAULIC CRITERIA

To obtain a sample, the discharge was measured, the river stage noted, and the depth and bottom velocity were measured at 10–25 points on each cross section. The bottom velocity was measured at a distance of 0.4 foot above the streambed (Chambers and others, 1955, p. 43). After a number of samples were obtained, the stage-discharge relation was established and used to detect any major streambed shifting. The cross-sectional depth and bottom-velocity data for each discharge were plotted on the planetable map of the reach, and lines of equal depth and velocity were drawn.

Chambers and others (1955) have supplied ranges of "preferred" depth and bottom velocity of the water for spawning of fall chinook, spring chinook, sockeye, and coho salmon, which are given in table 1. The table shows a range of water velocities from 1.75 to 1.8 fps (feet per second) for sockeye spawning. Chambers gives the preferred water velocity for sockeye as 1.75 fps, and Clay (1961, p. 232) presents the velocity range from 1.75 to 1.8 fps. For purposes of analyses, to define an area of spawning, Clay's range of preferred velocity for sockeye spawning is used. No preferred water-depth

TABLE 1.—*Preferred depth and velocity criteria for salmon spawning from Chambers and others, 1955*

Salmon species	Depth (feet)	Velocity[1] (feet per second)
Fall chinook	1.0–1.5	1.0 –2.25
Spring chinook	1.5–1.75	1.75–2.25
Sockeye	1.0–1.5	1.75–1.8
Coho	1.0–1.25	1.20–1.80

[1]Measured 0.4 ft above streambed

and water-velocity values have yet been determined for chum and pink salmon.

On the depth and velocity maps for a particular discharge, and using the preferred velocity and depth criteria from table 1, the areas of preferred velocity, preferred depth, and preferred spawning (where overlapping occurs), are delineated and measured for each of the salmon species investigated. After determination of preferred areas (expressed in square feet), the relation of discharge versus preferred area is plotted, a trend analysis using a three-point moving average is made, and a curve is fitted to the data.

The curves of the original data, as plotted, are jagged because, as discharge in the low-water channel increases beyond an optimum value, the velocity-depth criteria are exceeded and preferred area begins to decrease. When water depth increases sufficiently to just cover a medium-stage berm, the preferred area increases sharply. This sequence may be repeated as the depth continues to increase, depending on the number of berms that progressively become submerged. In a long reach, however, not all berms would be simultaneously submerged, and the pattern of increasing or decreasing favorable area would not be uniform throughout the reach. Consequently, the tendency would be for a smoother area-discharge curve. The authors obtained this smoothing effect by using moving averages.

From the highest point on the area-discharge curve, or the point where the spawnable area (determined from the preferred criteria in table 1) is greatest, the most preferred discharge for salmon spawning will occur. This point is referred to as the "peak preferred discharge." Most preferred area-discharge curves have a plateau rather than a peak because the discharge is diminishing at a faster rate than the area preferred for spawning. Thus, possibly at some point below the peak preferred discharge, there may be only a small decrease in spawning area, although the discharge is appreciably smaller than the peak.

To investigate the shape of the curves and determine the breaking or inflection point on the lower side of the peak, the peak spawning discharge is reduced by selected percentages of 5, 10, 15, and 25 percent. Using these reduced discharges the comparable reduction in spawnable area is picked from the area-discharge relations. These discharge and area values are given in table 15.

The repeatability of the method used to determine the preferred spawning discharges was investigated by selecting adjacent reaches on the Cedar River; that is, the riffle about 250 feet below reach B, referred to as reach B1 and the riffle about 200 feet above reach C, referred to as C1, were sampled and analyzed independent of reaches B and C and the results were compared. The period of sampling for reaches B and C extended from April 1968 through October 1968, and that of reaches B1 and C1 extended from September 1968 through August 1969. The comparisons of the five selected area-reduction points and comparable discharges from each of the four discharge-preferred-area curves are shown in table 2.

TABLE 2.—*Comparison of spawnable areas and of variations of discharges for adjacent reaches on the Cedar River*

[Numbers in parentheses are values obtained by extrapolation. All areas in square feet. All discharges in cubic feet per second]

Reach	Preferred parameter	Salmon species									
		Fall chinook					Spring chinook				
		Percentage reductions of spawnable area from the peak					Percentage reductions of spawnable area from the peak				
		Peak	2	5	10	15	Peak	2	5	10	15
B	Area	1,050	1,029	998	945	892	170	167	162	153	144
	Discharge	275	250	230	210	190	510	500	490	460	440
B1	Area	4,080	3,998	3,876	3,672	3,468	525	514	499	472	446
	Discharge	250	230	220	(210)	(200)	480	440	430	(390)	(370)
C	Area	960	941	912	864	816	420	412	399	378	357
	Discharge	320	(310)	(300)	(290)	(280)	420	400	380	365	360
C1	Area	1,920	1,882	1,824	1,728	1,632	630	617	598	567	536
	Discharge	290	270	250	(230)	(210)	420	400	360	(340)	(320)
		Percentage differences in discharges									
B/B1		+10.0	+8.7	+4.5	0	—5.0	+6.2	+13.6	+14.0	+18.0	+18.9
C/C1		+10.3	+14.8	+20.0	+26.1	+33.3	0	0	+5.6	+7.4	+12.5

Reach	Preferred parameter	Salmon species									
		Coho					Sockeye				
		Percentage reductions of spawnable area from the peak					Percentage reductions of spawnable area from the peak				
		Peak	2	5	10	15	Peak	2	5	10	15
B	Area	320	314	304	288	272	255	250	242	230	217
	Discharge	270	255	235	220	205	440	420	400	330	290
B1	Area	767	752	729	690	652	275	270	261	248	234
	Discharge	285	260	250	(240)	(230)	430	410	400	(385)	(370)
C	Area	360	353	342	324	306	170	167	162	153	144
	Discharge	450	440	430	410	(300)	510	500	485	465	450
C1	Area	285	279	271	256	242	130	127	124	117	110
	Discharge	450	430	390	(370)	(350)	490	460	440	(420)	(400)
		Percentage differences in discharges									
B/B1		—5.3	—1.9	—6.0	—8.3	—10.9	+2.3	+2.4	0	—14.3	—21.6
C/C1		0	+2.3	+10.2	+10.8	—14.3	+4.1	+8.7	+10.2	+10.7	+12.5

Table 2 also shows that, at all discharges used in calculations, the areas spawnable are greater for reach B1 than for reach B. The same is true for reach C1 compared to reach C, except for the sockeye and coho salmon, where reach C has slightly greater spawning areas than reach C1.

The lower part of table 2 shows the ratios of discharges, expressed as percentages, of reaches B divided by B1 and reaches C divided by C1 for each species at the peak and the four reductions of discharge. These percentage ratios may be used to show the consistency of the method used to determine preferred discharges. Some of the errors involved in the discharge percentages would result from measuring discharge, plotting of the hydraulic criteria, measuring the areas preferred for spawning, and slight shifts in streambed configuration. The peak spawning discharges between compared reaches for the four salmon species vary as much as 10.3 percent, are as small as 0.0 percent, and average 4.6 percent for all points on both reaches.

Flows for rearing are determined from curves (for example, fig. 8*A*) showing how the perimeter of the average study reach that is wetted increases as the discharge increases. This relationship is shown by wetted-perimeter-discharge curves. At lower discharges the typical curve is steep, indicating that wetted perimeter increases at a rate equal to, or greater than, the increase in flow. Where the curve breaks, or at the point where, for a unit increase in discharge the wetted perimeter increases considerably less than a unit, the greatest perimeter of the stream would be covered by water at the lowest discharge. Above the break the wetted perimeter increases very little with increasing discharge. This point is picked as representing the rearing discharge. To aid in determining this breaking point a second curve (see fig. 8*B*) is drawn showing the percentage of bankfull area wetted versus the discharge. The bankfull area was defined along each particular study reach as the last definite change in slope of either bank of the river—beginning at the lowest point in stream cross section. The bankfull area, as defined, is generally very discernible from aerial photographs. The curves of percentage of bankfull area wetted versus discharge and that of wetted perimeter versus discharge generally break at nearly the same discharge.

STREAMBED GRAVELS

The bed material of spawning areas must consist of gravel of such size that the salmon which is ready to spawn can excavate redds in which their eggs may be deposited, fertilized, and hatched.

Gravel size and stream velocity are interrelated. Spawning salmon prefer specific gravel sizes as well as hydraulic criteria. The excess fines, to a certain extent, may be washed out during the course of spawning by the action of the fish. The water velocities also may be important to ensure covering of the eggs by hydraulic action on the gravel during spawning and in determining the size of the gravel present at a particular location.

In each of the 14 reaches selected for this study spawning salmon were observed, indicating that the gravels for the observed species must have been acceptable. No attempt was made to establish criteria for streambed composition preferred by the various species. However, gravel samples were taken within the preferred spawning areas, and curves of the percentage by weight of gravel passing a range of sieve sizes are shown for each reach.

The streambed samples were obtained with a cylindrical tooth-edged "cookie cutter" that was 2 feet in length and 14 inches in diameter (patterned after Rantz, 1964, p. AA5). The cylinder was forced into the streambed as far as possible (usually 1 ft), the material within was removed by hand, sorted in sieves, and each fraction weighed. Four to five samples were obtained on each reach.

WATER TEMPERATURE

The temperature of the stream influences the rate of production of aquatic life (food for the rearing salmon), the amount of dissolved oxygen in the water, and the length of time for salmon egg incubation. Fish affected by a rise of water temperature respond by increased metabolic rates, higher oxygen requirements, greater sensitivity to toxic materials, and reduced swimming speed.

For maximum productivity of the Pacific salmon the fresh-water temperature requirements range from 7.2° to 15.6°C (45°–60°F) for upstream migration, from 5.8° to 12.8°C (42.5°–55°F) for maximum survival at spawning, from 0° to 12.8°C (32°–55°F) for egg incubation, and from 10° to 15.6°C (50°–60°F) for the fingerling salmon development (Burrows, 1963). The four rivers investigated in this report are covered by thermograph records that have been analyzed; these data are presented with the discussion and analysis of each river.

SALMON AND SPAWNING

When spawning, the salmon excavates a pit in the bottom of the streambed in which ova are deposited. This pit and the resulting downstream pile of disturbed gravel is called a redd. The two major parts of a redd are the "pot," or excavated pit, and the "tail spill," or the downstream gravel (Burner, 1951, fig. 4, p. 101). Where mass spawning of salmon occurs, however, the outlines of the individual redds are completely obliterated because of the close proximity in which the salmon spawn. After spawning, the territorial behavior of the individual salmon, in the vicinity of the redd, forces other salmon to spawn at other locations in the reach. At times, where preferred areas are limited or mass spawning occurs, spawning may take place in locations within the reach, which may not meet the preferred hydraulic criteria. The average sizes of redds for the four salmon species of this study are fall chinook, 6.1 sq yd (square yards); spring chinook, 3.9 sq yd; coho, 3.4 sq yd; and sockeye, 2.1 sq yd (Burner, 1951, p. 110).

Certain streams are noted for their production of a particular salmon species (discussed under the analysis of each stream)—generally, the Cedar River is noted for sockeye; the Nooksack River, for pink; the Dewatto River, for chum; and the Kalama River, for coho and chinook. Some of the other salmon species also spawn to a lesser degree in these rivers, but, conversely, not all species spawn in significant numbers in any one of these rivers. Each reach analysis in this report was made from preferred hydaulic criteria for the four species given in table 1, even though some of these species and races do not frequent that particular stream.

Among the many reasons that all salmon species do not spawn in a particular river, where one, two, or three species now spawn, are (1) the flow may not be acceptable for spawning and (or) rearing during the desirable interval of time, (2) the streambed materials may not be satisfactory, (3) the strength or size of the members of a species may limit their upstream migration, (4) nonavailability of rearing areas or the rearing habits of a species may render the stream unacceptable, (5) sea-migration patterns may not be compatible with the location of the river, and (or) (6) susceptibility to certain water-quality characteristics may be prohibitive to some species. Some of these conditions have only minor or negligible relation to the hydraulics (depth and velocity) of a reach of a river; others have no relation at all. For the purposes of this report the assumption is made that the reach hydraulics, from which the discharge-preferred spawning-condition relation is obtained, would theoretically be acceptable for spawning by all species if the other criteria were met. Therefore, the same hydraulic parameters are used for all species studied and for all stream reaches, regardless of whether fish are present or not. The hydraulic criteria are applied as independent variables that can be considered even though the total environment might not support a specific species—or fish life at all. In this context, they would be considered, for example, for a reach of river upstream from a dam or high waterfall, even though the downstream barrier might effectively prevent fish from ever entering the study reach.

DEWATTO RIVER

The Dewatto River is on the southwestern lobe of the Kitsap Peninsula and drains into Hood Canal (fig. 1). The basin lithology consists of unconsolidated sand and gravel of varying thicknesses underlain by sandy clay. Swamp deposits (peat) also are found in abundance in the upper parts of the basin.

The Dewatto River, with a source altitude of 360 feet, may be classified as a lowland stream. The flow of the river reflects the precipitation of the area (fig. 2), high during the wet winter months and low during the late summer and early fall months when rainfall is least. September is generally the month with the lowest mean monthly discharge, and January has the highest discharges. Winter snowfall is negligible, and there is little, if any, effect on the streamflow from snowmelt; however, a small amount of ground-water storage is provided by the permeable nature of the sand and gravels and the water-holding capacity of the clay and swamp materials. This storage helps maintain stream flows during the dry season.

A thermograph was installed on the stream near reach A. Daily stream temperature maximums, means, and minimums were evaluated for the 1968 calendar year using a harmonic fitting (Collings, 1969). The resulting curves (fig. 3) have 91, 93, and 92 percent of

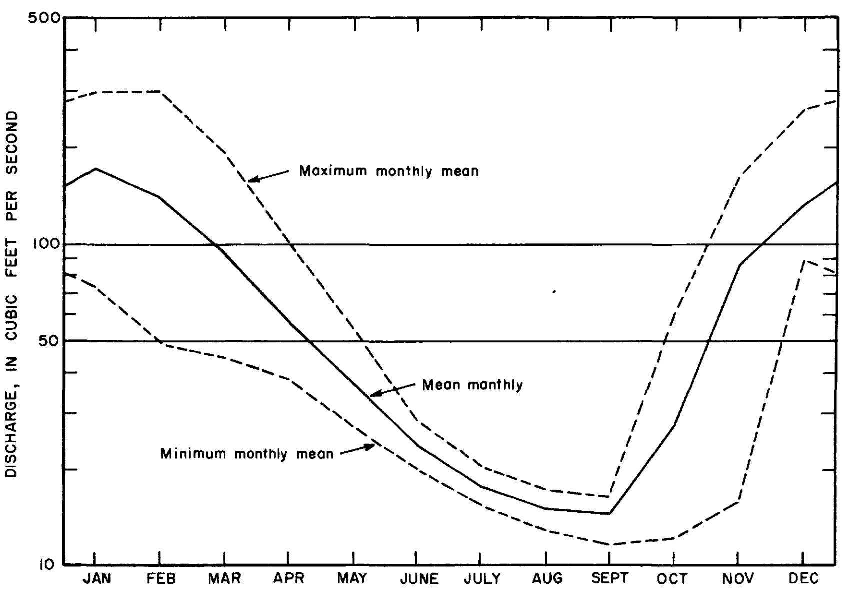


FIGURE 2.—Mean monthly discharge and maximum and minimum monthly mean discharges, Dewatto River near Dewatto, 1947–54 and 1958–67.

their variance defined, and the standard errors of estimate are 1.1°, 0.9° 0.9°C (degrees Celsius) for maximum, mean, and minimum temperatures, respectively. The temperature of the stream generally reflects the season, being high during the summer and low in the winter, which is the inverse of the flow hydrograph (fig. 2).

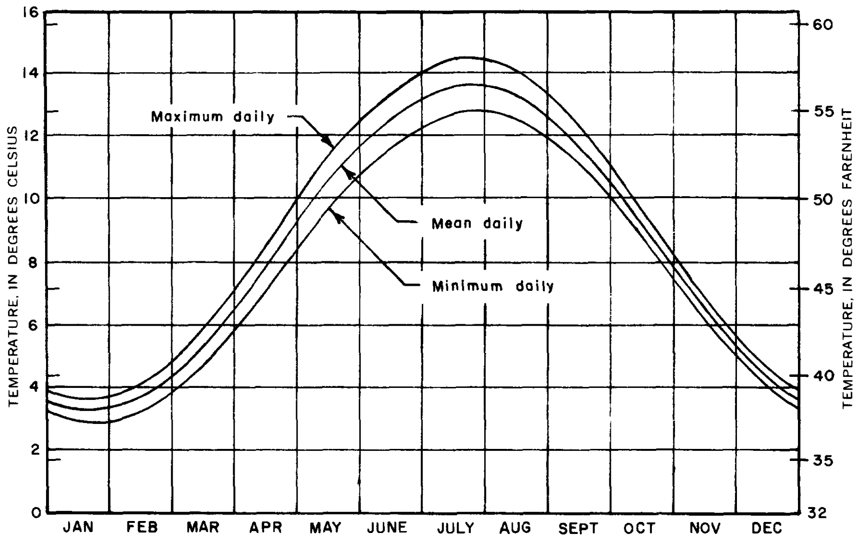


FIGURE 3.—Maximum, minimum, and mean daily water temperatures, Dewatto River near Dewatto. Data from harmonic fitting of thermograph record for 1968.

The major salmon species that frequent Dewatto River are coho and two races of chum. The period of spawning for these species, depending on various factors which include flow conditions, will range from September through January. After hatching, the chum go almost immediately to salt water, but the coho will rear for about 1 year in the stream before migrating to salt water.

Three reaches were selected for study on the Dewatto River (fig. 4). The average grading of the gravels in the three reaches is shown in figure 5. The curves are best explained by an example: 40 percent of the gravels of reach A are less than 1 inch in size (40 percent by weight will pass the 1-in. sieve). Also, 51 percent of reach B gravels and 43 percent of reach A–1 gravels will pass the 1-inch sieve. Generally, as seen by the curves, reach A has gravels that are slightly coarser than those of reach B. Reach A–1 has gravel of sizes more or less between those of reaches A and B.

DEWATTO RIVER REACH A

The Geological Survey gaging station (Dewatto River near Dewatto) is just above reach A. This gage was used for the river-stage reference and also for discharge determinations. The stream above reach A drains 18.4 square miles and has a main-stem length of 7.6 miles. The altitude at the gage is 55 feet, and the mean basin altitude is 376 feet; the channel slope above the reach is 36 feet per mile. The reach has a surface area of 7,690 square feet at bankfull stage.

On reach A, 14 measurements of depth and bottom velocity were made at each cross section, with flows ranging from 19 to 225 cfs.

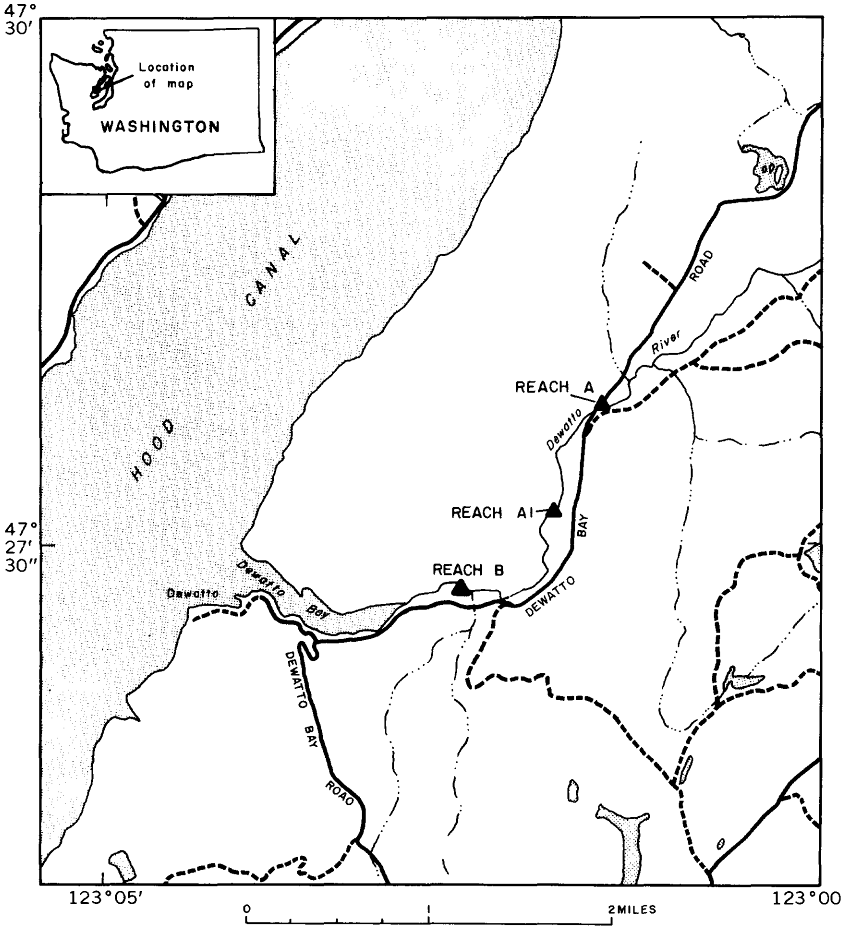


FIGURE 4.—Study reaches on Dewatto River.

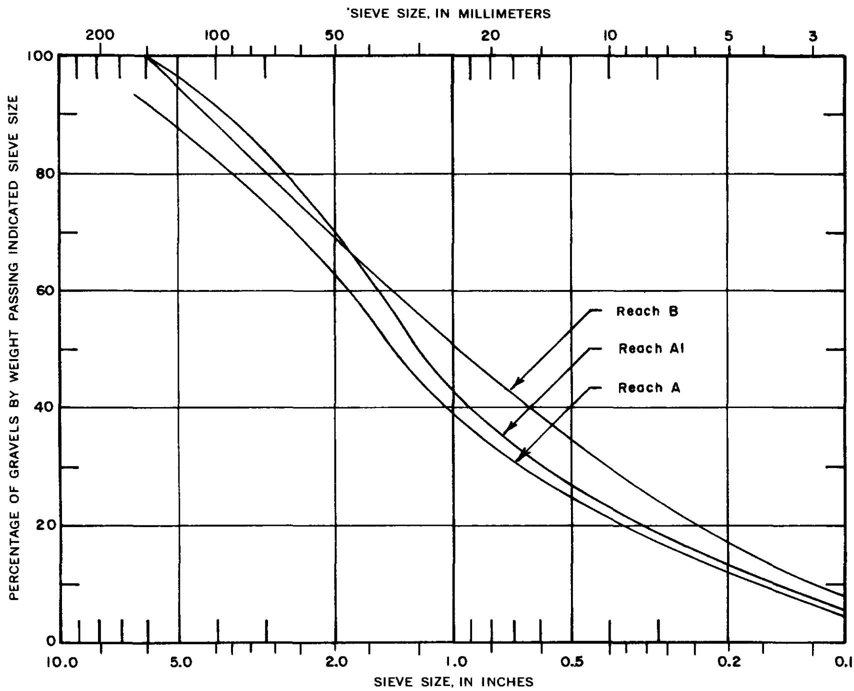
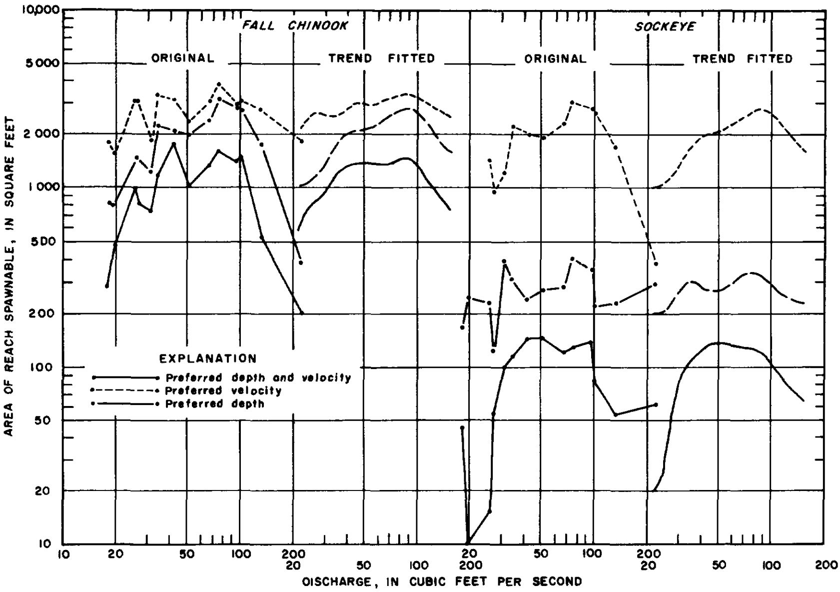


FIGURE 5.—Curves showing average grading of several samples of gravel found on natural spawning grounds on Dewatto River.

The relation between preferred depth, velocity and spawnable area (the area where both preferred depth and velocity criteria are met) versus discharge, for each salmon species is shown in figure 6. Also, a trend-fitted curve of the data was obtained by using a three-point moving average.

The peaks (from fig. 6), the spawning-discharge values for the selected reductions of 5, 10, 15, and 25 percent, and the comparable spawnable areas are given in table 15.

Table 15 shows that at the 10-percent discharge reduction (from 87 to 78 cfs) the spawnable area for fall chinook is only 1 percent less than the spawnable area at the peak (from 1,440 to 1,420 sq ft). The spawnable area for spring chinook decreases at a greater rate than the discharge at the 15-percent discharge reduction (table 16), and the 25-percent discharge reduction shows a 35-percent reduction in area. Compared with the other species, sockeye has the least amount of spawnable area, 140 square feet at a peak preferred discharge of 50 cfs.



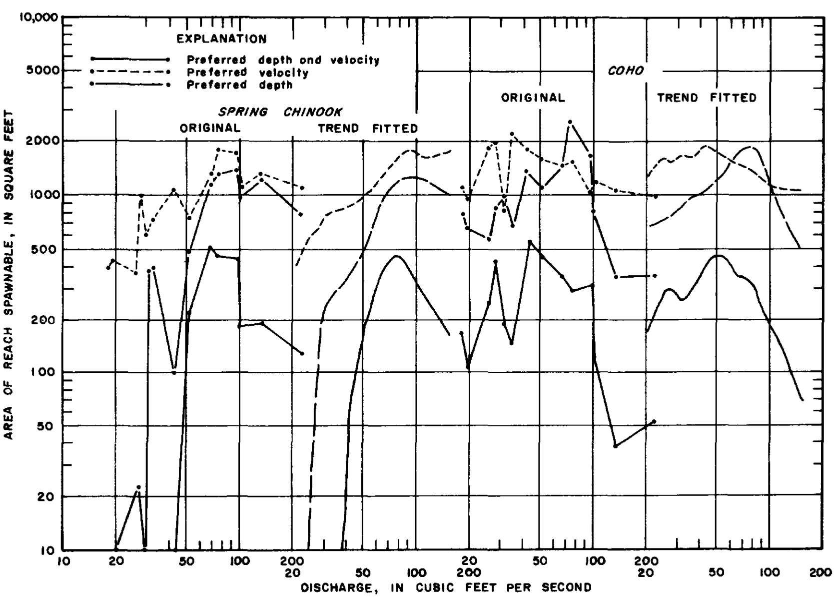
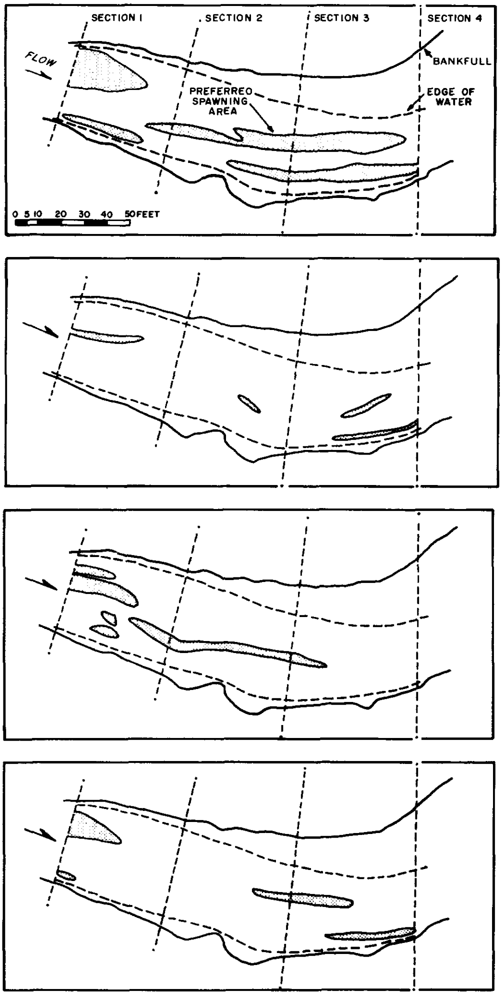


FIGURE 6.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of four salmon species, Dewatto River reach A. Curves show the original and the trend-fitted data based on a three-point moving average. Total area of the reach is 7,690 square feet.



Species: Fall Chinook
Discharge: 68 cfs
Percentage preferred spawning: 17.1
Percentage preferred velocity: 39.8
Percentage preferred depth: 30.9

Species: Sockeye
Discharge: 68 cfs
Percentage preferred spawning: 1.6
Percentage preferred velocity: 3.7
Percentage preferred depth: 30.9

Species: Spring Chinook
Discharge: 98 cfs
Percentage preferred spawning: 5.9
Percentage preferred velocity: 22.7
Percentage preferred depth: 18.3

Species: Coho
Discharge: 52 cfs
Percentage preferred spawning: 6.0
Percentage preferred velocity: 21.0
Percentage preferred depth: 14.3

FIGURE 7.—Plain-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Dewatto River reach A.

The areas within the reach which would be preferred for spawning are shown in figure 7 for the four salmon species. The data for figure 7 were obtained from flows selected near the peak spawning conditions shown by the curves in figure 6. The most preferred areas (fig. 7) tend to be in the same general locations in the reach because of the general overlap of the preferred data of table 1.

Obviously, the most important criteria for salmon rearing in a stream is that water has to be present during the period of rearing,

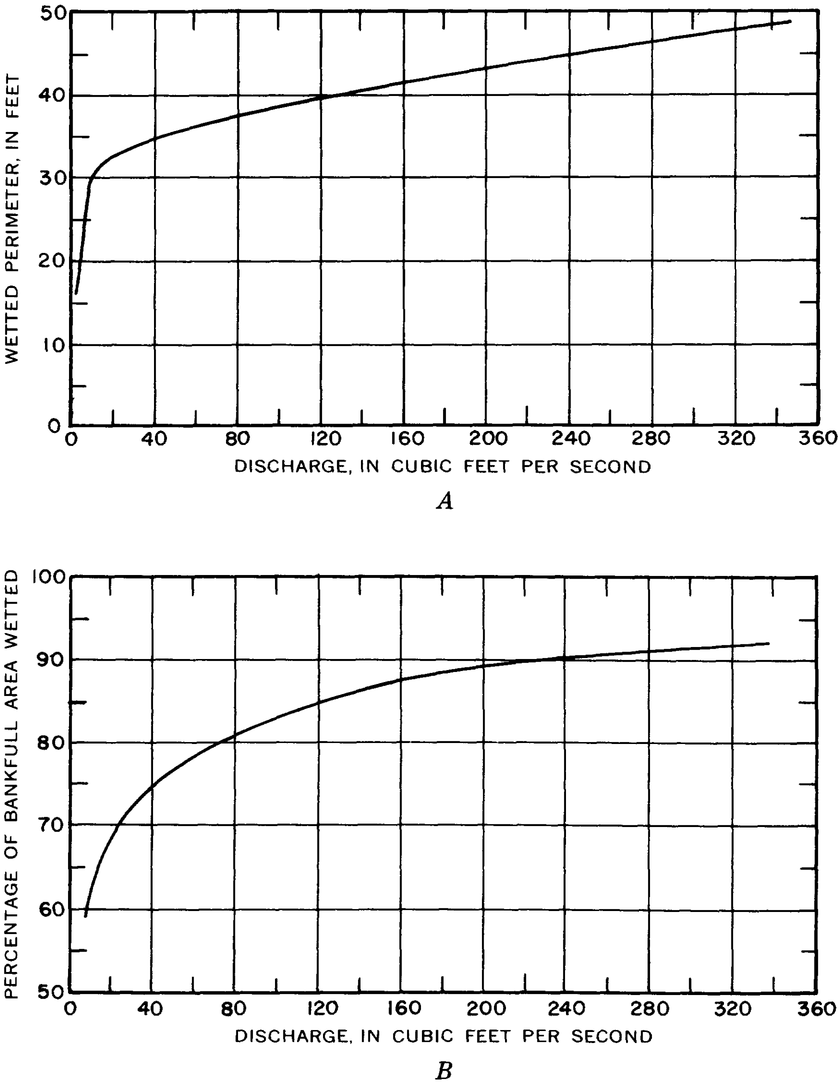


FIGURE 8.—Relation between curve of wetted perimeter versus discharge (graph *A*) and curve of percentage of bankfull area wetted versus discharge (graph *B*), Dewatto River reach A. The point at which the curve in *A* changes slope indicates the most advantageous discharge for rearing. The curve in *B* is used in conjunction with figure 9.

but other important rearing criteria are stream temperature, area of pools, water velocity, and food production. The curves of figure 8 show how the wetted perimeter and wetted reach area increase with increasing discharges. After the first break in the curves, at about

20 cfs (fig. 8*A*), the wetted perimeter increases relatively little with increasing discharge.

By joint use of figure 8*B* and figure 9, we can determine area-velocity relations in the study reach, and from those relations, select optimal discharge for rearing in the reach. For example, at a discharge of 20 cfs, 20 percent of the area of reach A will be covered by water moving at a velocity of 1.2 fps or more. At the same discharge, 30 percent of the area is dry (fig. 8B). Over the remaining 50 percent of the area of reach A—3,845 square feet of the total 7,690 square feet—the velocity of the water will be equal to or less than 1.2 fps. The curves in figure 9 are linear only in the part shown, and they should not be extrapolated for higher or lower discharges without further data.

Stream velocity is an important factor influencing rearing potential. Food production as well as the capability of fry and fingerlings to exist in a stream is partly dependent upon the velocity. A study made by the Bureau of Sport Fisheries and Wildlife (Kennedy,

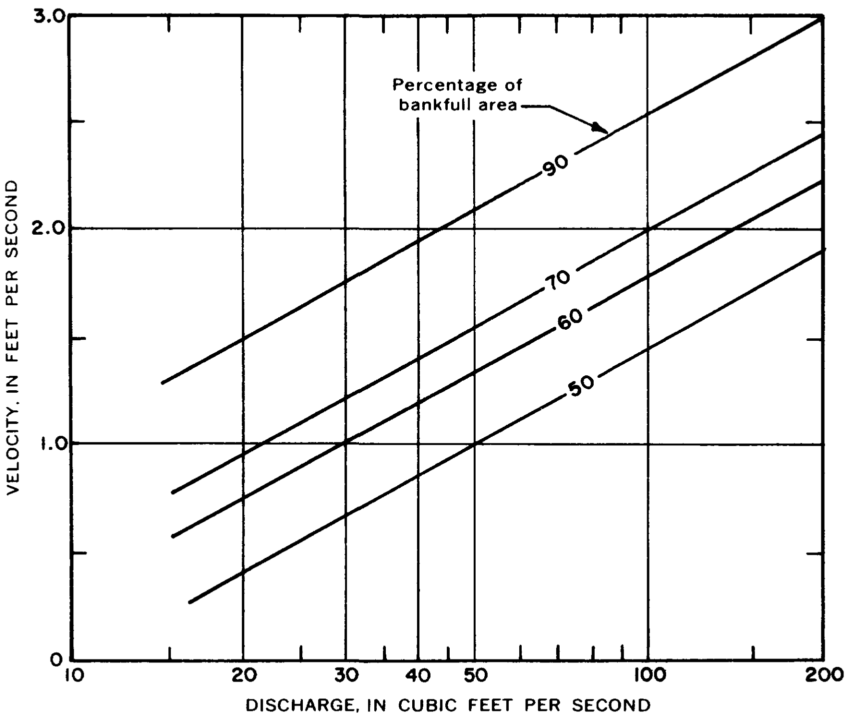


FIGURE 9.—Family of curves showing relation between velocity, discharge, and percentage of bankfull area, Dewatto River reach A. Shows selected percentages of reach which have velocities equal to or less than that indicated at a selected discharge.

1967) discloses that the greatest concentration of food organisms occurs at velocities from 1.0 to 1.2 fps, with the majority (79 percent) occurring in the range 1.0–1.7 fps. The optimal depth is in the 3–6-inch range.

The occurrence of sufficient discharges at the desired time of the year is one criterion for determining whether a salmon species is able to frequent a particular stream or reach of a stream for spawning and rearing. The hydrographs (fig. 2) indicate when high and low streamflows occur on the average; however, a more useful evaluation of occurrence of flows is presented by the monthly and annual flow-duration curves (fig. 10). These curves are computed

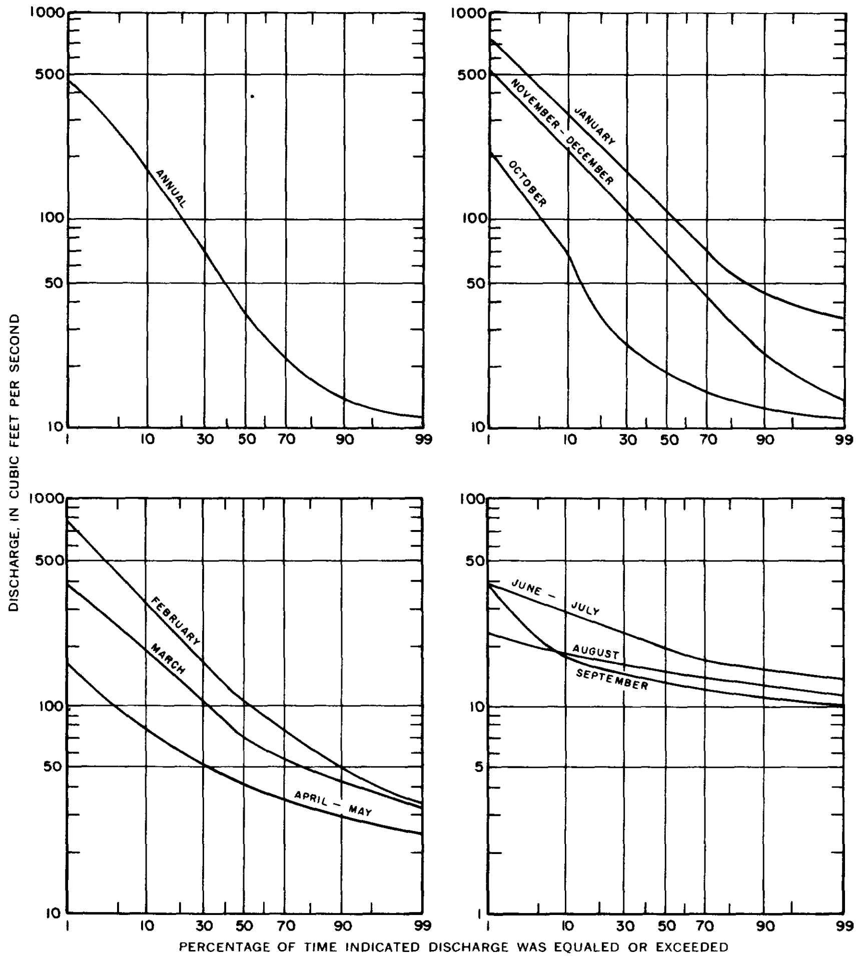


FIGURE 10.—Monthly and annual flow durations, Dewatto River reach A.

from mean daily discharges for Dewatto River near Dewatto for the period 1948–66 and indicate the percentage of time a selected discharge can be expected to be equaled or exceeded. For example, using the peak preferred spawning discharge of 51 cfs for coho, a discharge of 51 cfs will be exceeded 15 percent of the time in October, 66 percent during the November–December period, and 86 percent in January (fig. 10). Inversely, this means that during 85 percent of the time in October the discharge will be below 51 cfs.

Similar computations show that the rearing discharge of 20 cfs is exceeded 72 percent of the time annually (fig. 10).

Some water-quality characteristics of reach A are given in table 3. The dissolved-oxygen content was derived from a relation with stream temperature, assuming 100-percent saturation which was checked by taking dissolved-oxygen samples. The suspended sediment, for the few samples taken, was very low, the largest concentration being 14 mg/l (milligrams per liter) at 20 cfs.

TABLE 3.—*Characteristics of water quality, Dewatto River reach A, March–December 1968*

Date	Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/l)	Suspended sediment (mg/l)	Specific conductance (micromhos per cm at 25°C)
Mar. 14	225	7.2	45	11.7	----	----
Apr. 2	98	8.9	48	11.2	----	----
9	68	----	----	----	----	----
17	52	6.7	44	11.8	----	----
29	43	8.9	48	11.2	6	----
May 15	32	10.0	50	11.0	7	----
31	27	10.0	50	10.9	----	----
July 8	20	13.9	57	10.0	14	----
Sept. 16	19	11.7	53	10.5	----	----
Oct. 10	26	8.9	48	11.2	0	----
18	35	8.0	46.5	11.4	----	----
Nov. 13	101	6.9	44.5	11.7	1	----
26	76	7.8	46	11.5	0	45
Dec. 13	134	5.3	41.5	12.2	0	30

DEWATTO RIVER REACH A–1

Reach A–1 on the Dewatto River is between reaches A and B (fig. 4), and encompasses 2,920 square feet. Above this reach, which has an altitude of 40 feet, the stream is 8.1 miles long, has a drainage area of 19.1 square miles, and a channel slope of 32.9 feet per mile. For the analysis of this reach, nine streamflow measurements were made with discharges ranging from 19 to 247 cfs. A stage discharge relation was established from a staff gage, near the downstream end of the reach, at the time of each discharge measurement. No major shifting in the reach was evident over the period of measurements.

The analyses conducted on reach A data also were conducted on reach A–1 data, except for determination of the flow-duration curves (fig. 10). A regression analysis of discharge at reach A–1 versus that at reach A shows a relation defined by

$$Q_{A-1}=0.99(Q_A)^{1.00}$$

where Q_{A1} is the discharge at reach A–1 and Q_A is the discharge at reach A. The standard error of estimate of the relation is ±1.4 percent. The regression constant is not significantly different from 1.0, at the 95-percent significance level; therefore, the discharges of the two reaches are not significantly different ($Q_{A1}=Q_A$), and the flow-duration curves of figure 10 apply to both reaches.

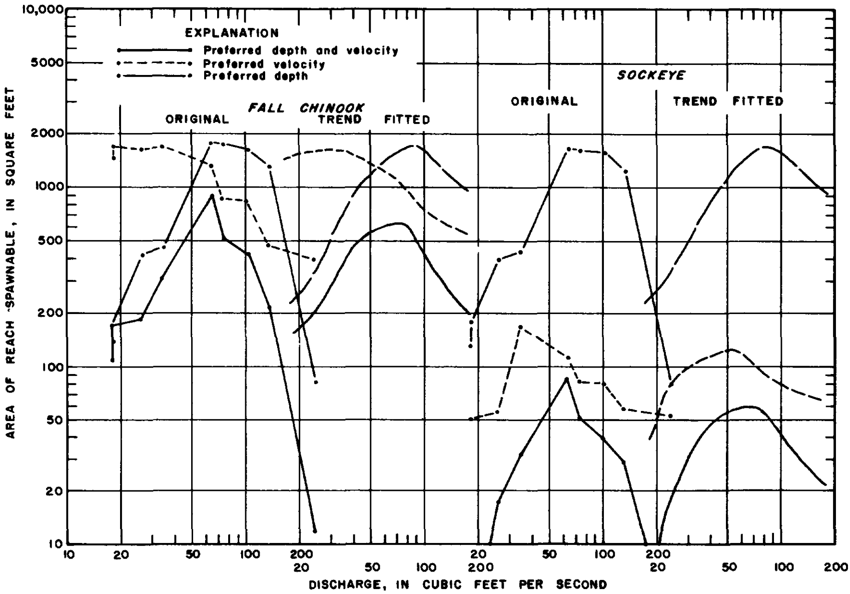
The curves of figure 11 show the relations between discharge and spawnable area for the four species groups. The discharges for the peak and the four defined discharge reductions and comparable areas are given in table 15. The preferred-velocity curves for coho and fall chinook are open ended at the lower discharges, indicating a general maintenance of a minimum velocity (about 1 fps), governed by the channel slope.

The plan views (fig. 12) of reach A–1 show the preferred areas of spawning for the four species. The spawning areas are well distributed over the entire reach. Figure 13 shows the relation between the curve for the wetted perimeter versus discharge and the curve for the percentage of bankfull area wetted versus discharge. This latter curve may be used in conjunction with figure 14 to obtain information on the rearing conditions of the reach. The preferred rearing discharge occurs at the break in the wetted perimeter versus discharge curve (fig. 13*A*), or at about 20 cfs.

The water-quality characteristics of reach A–1 are given in table 4.

TABLE 4.—*Characteristics of water quality, Dewatto River reach A–1 September–December 1968*

Date		Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/l)	Suspended sediment (mg/l)	Specific conductance (micromhos per cm at 25°C)
Sept.	16	19	11.7	53	10.5	----	----
	25	19	----	----	----	----	----
Oct.	10	26	9.4	49	11.1	0	----
	18	34	8.9	48	11.2	----	----
Nov.	13	101	7.2	45	11.7	0	----
	15	65	6.1	43	12.0	0	----
	26	76	7.8	46	11.5	1	46
Dec.	11	247	6.7	44	11.8	2	33
	13	134	5.3	41.5	12.2	0	30



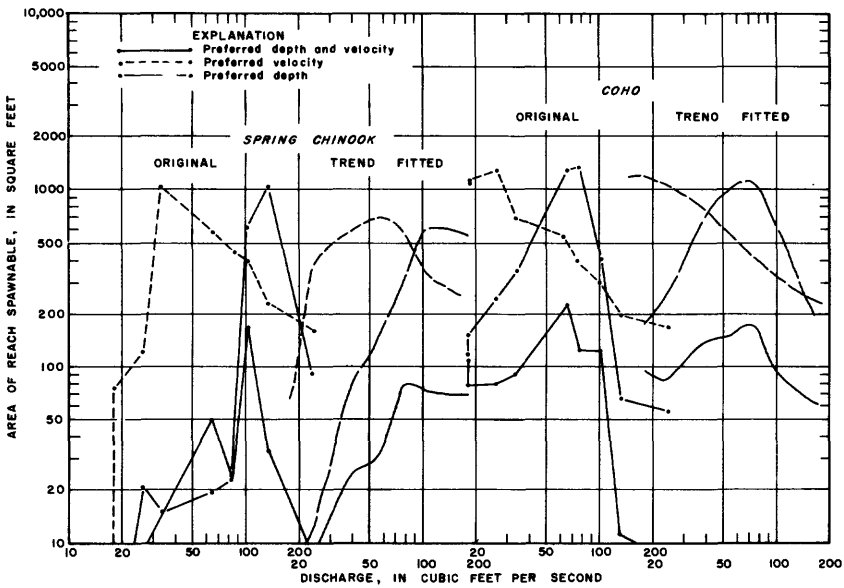


FIGURE 11.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of four salmon species, Dewatto River reach A-1. Curves show the original and the trend-fitted data based on a three point moving average. Bankfull area of reach covers 2,920 square feet.

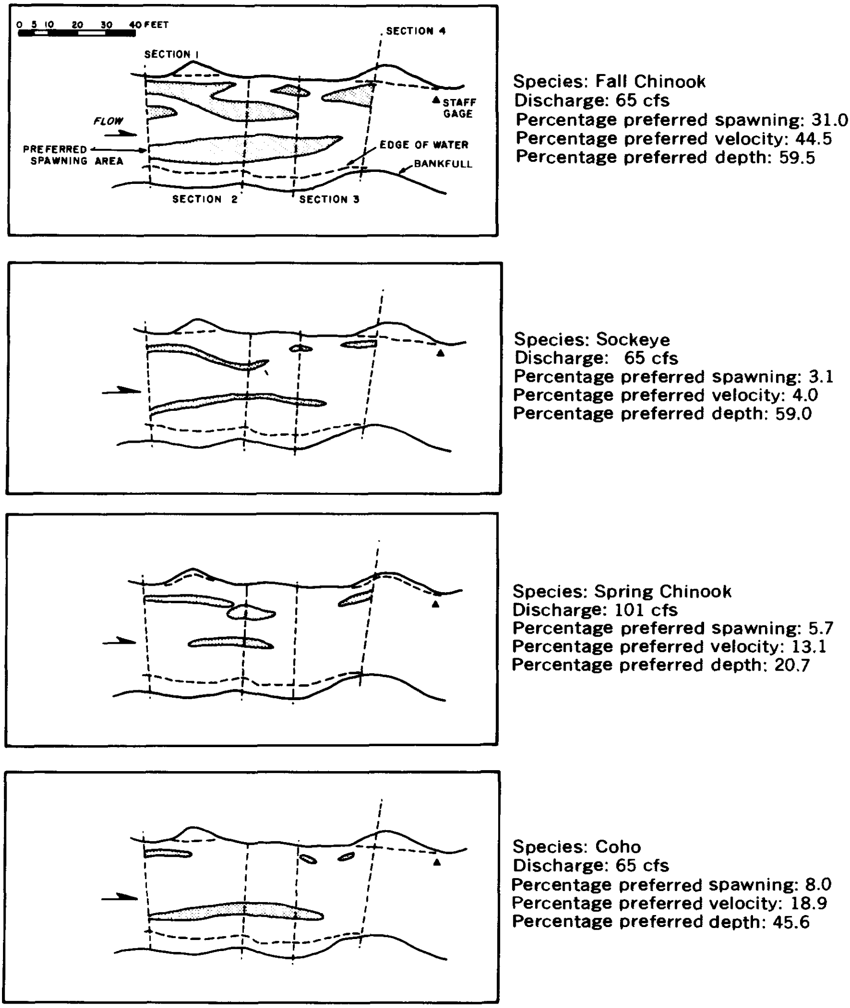
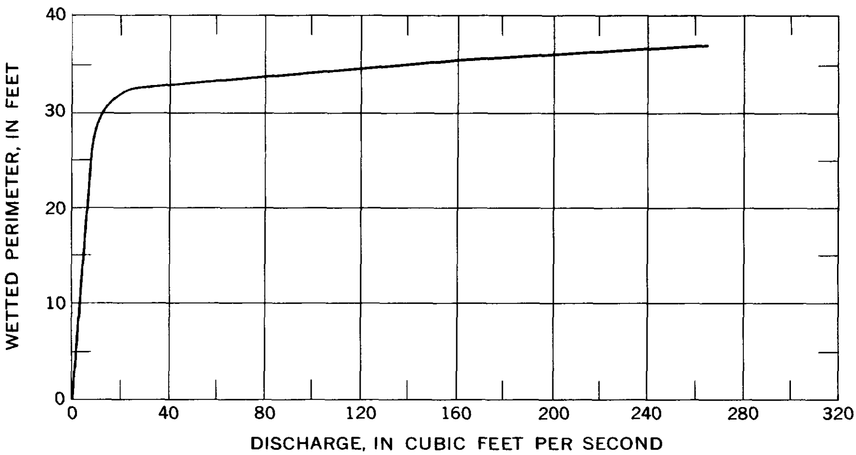


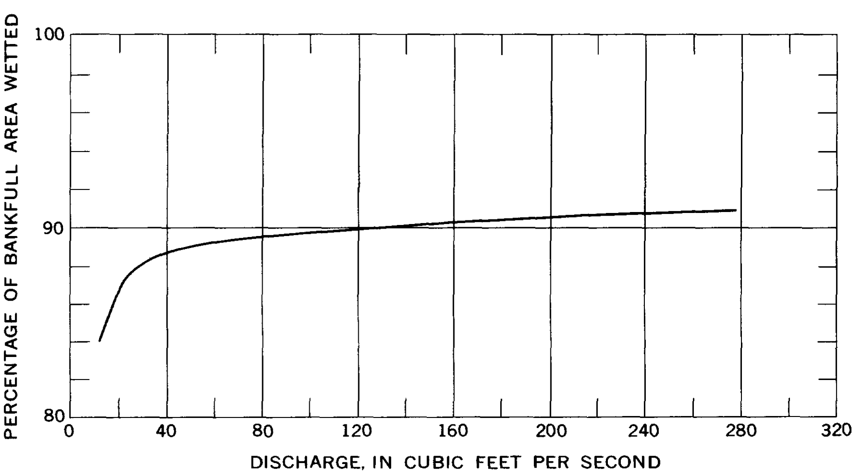
FIGURE 12.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Dewatto River reach A–1.

DEWATTO RIVER REACH B

Dewatto River reach B is the lowest study reach on the river (fig. 4), having an altitude of 10 feet. Above the reach the stream is 9.0 miles long, and has a drainage area of 21.7 square miles and a channel slope of 32.6 feet per mile. Fourteen flow measurements, ranging from 22 to 274 cfs, were used to analyze the reach.



A



B

FIGURE 13.—Relation between curve of wetted perimeter versus discharge (graph *A*) and curve of percentage of bankfull area wetted versus discharge (graph *B*), Dewatto River reach A–1. The inflection point of the curve on graph *A*, where it begins to flatten, denotes the most advantageous rearing discharge. Curve on graph *B*, which is similar in shape to that in graph *A*, is used in conjunction with figure 14.

Reach B, which covers 8,250 square feet, is above a section of the river where the stream divides into two channels at flows greater than 45 cfs. During low discharges about 25 cfs, and discharges above 45 cfs, the riffle area extends over parts of the entire reach.

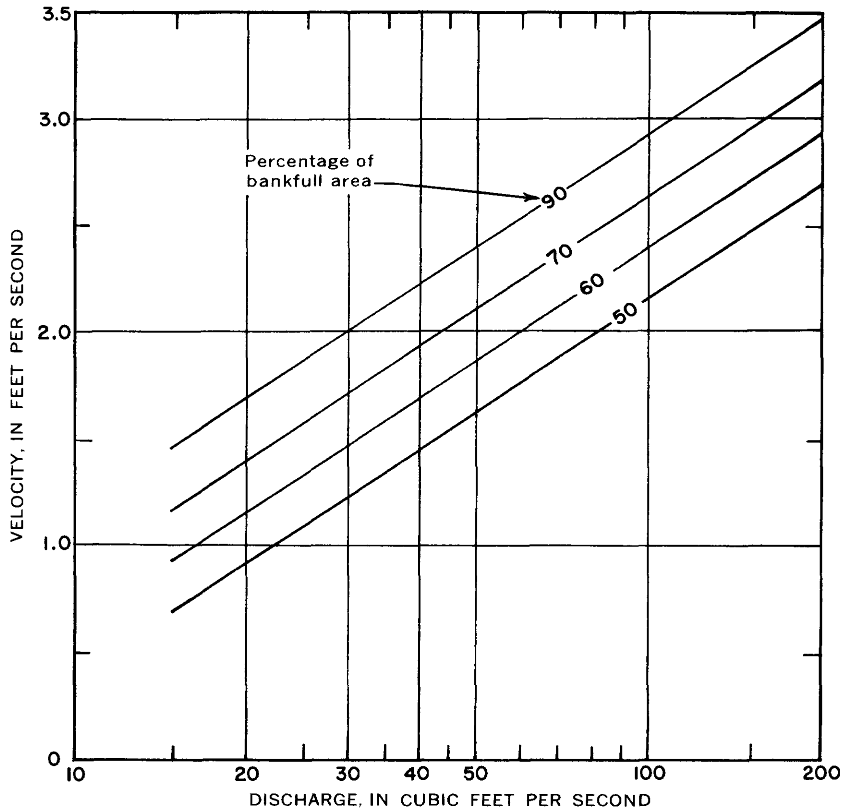


FIGURE 14.—Family of curves showing relation between velocity, discharge, and percentage of bankfull area, Dewatto River reach A-1. Shows selected percentages of reach which have velocities equal to or less than that indicated at a selected discharge.

For discharges between 25 and 45 cfs, the riffle is confined mainly to an area in the vicinity of cross section 3. The area of the reach having preferred spawning versus discharge for each of the species is shown in figure 15. The trend-fitted preferred-velocity curves have a tendency toward double peaks. One peak occurs near the discharge where the stream splits and the riffle area lengthens, and another peak occurs at a lower flow. The trend-fitted curves for preferred depth versus discharge have either an open end or peak at the higher discharges, indicating only slight increases in depth as discharge increases, again because of the splitting channel control. However, the preferred depth and velocity combine to produce well-defined peaks for the preferred spawning versus discharge curves. The areas and discharges for the peak and the four selected

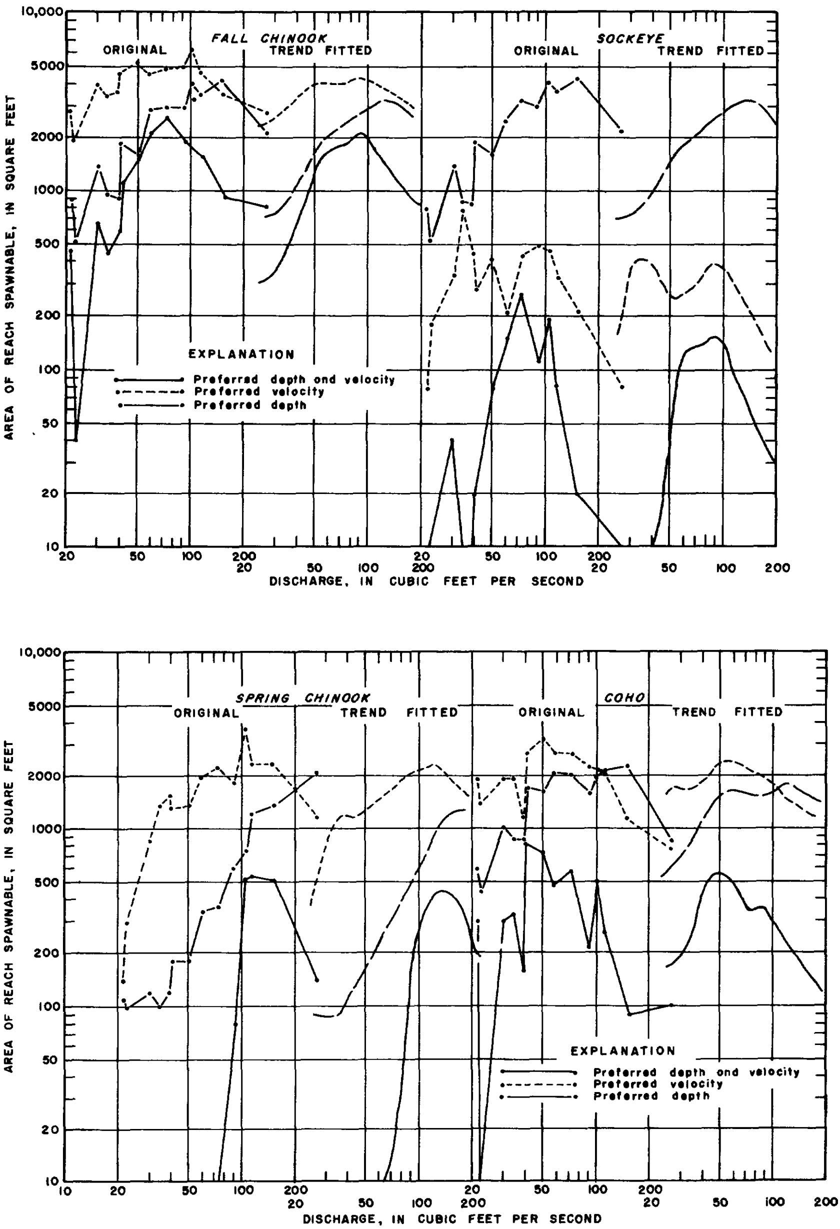


FIGURE 15.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of four salmon species, Dewatto River reach B. Curves show the original and the trend-fitted data based on a three-point moving average. Bankfull area of reach covers 8,250 square feet.

percentage discharge reductions for each of the four salmon species are given in table 15. The higher preferred depth and velocity ranges (table 1) may be the cause of the higher peak discharges for spring chinook.

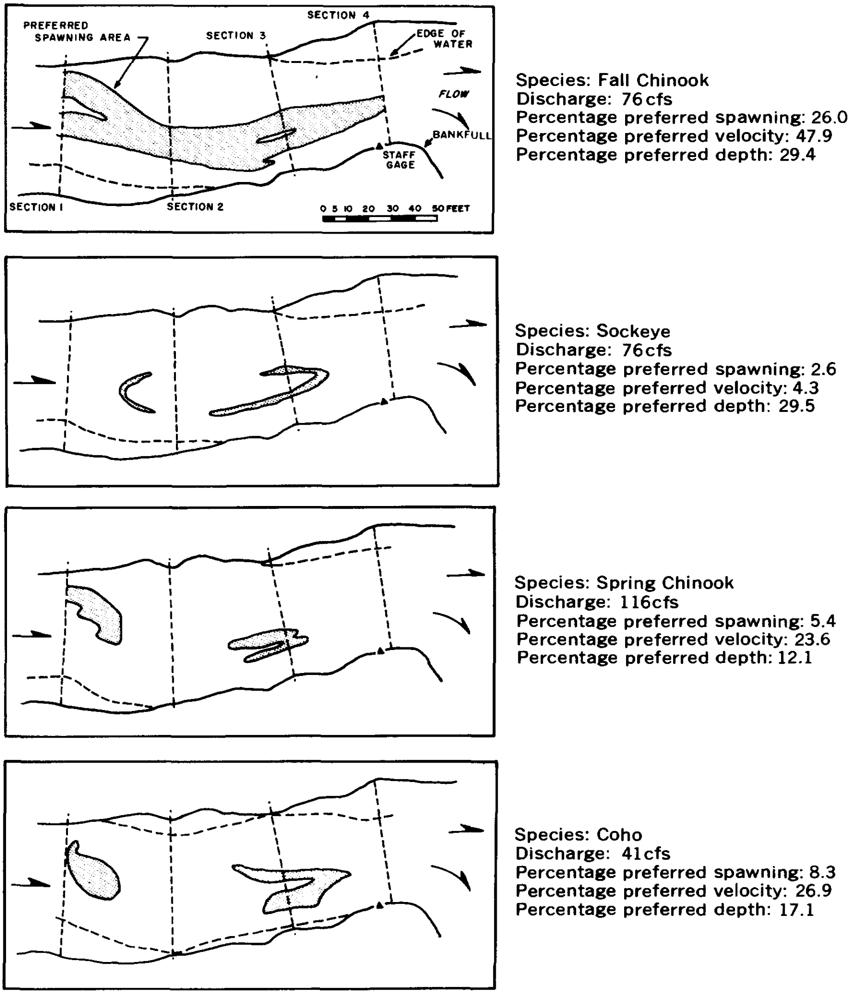


FIGURE 16.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Dewatto River reach B.

The plan views (fig. 16) show the areas of preferred spawning, at selected discharges, for each salmon species studied. Shallow pool areas occur on the left side of section 2 and on the right side of

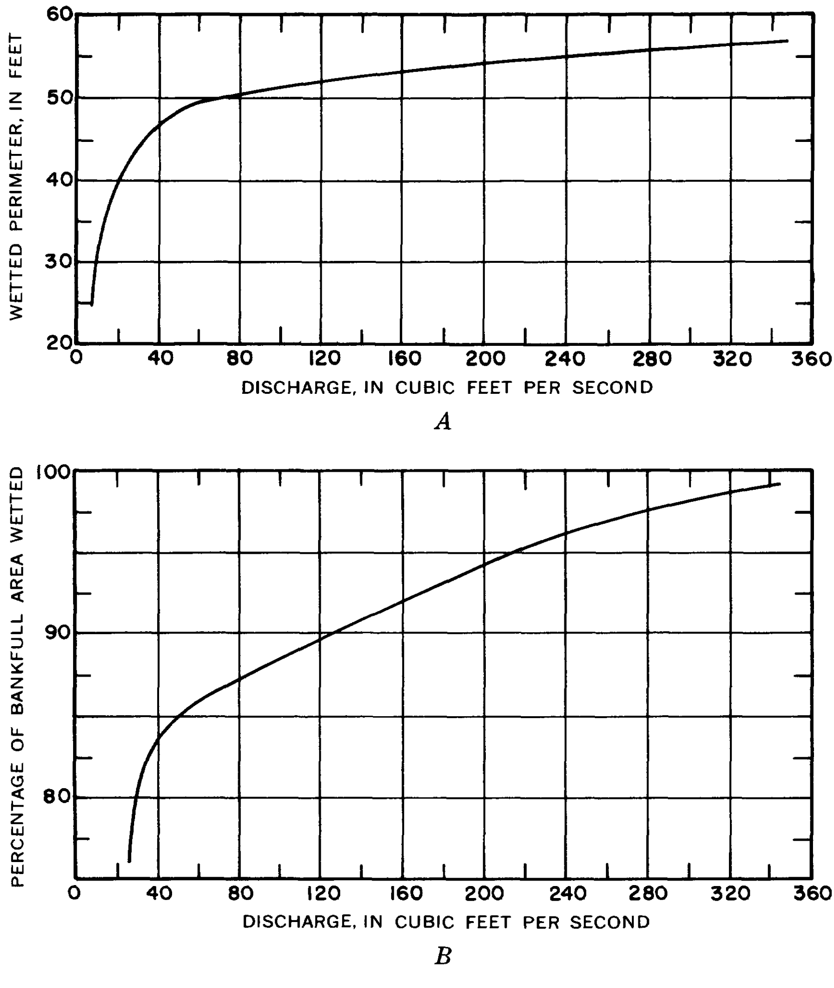


FIGURE 17.—Relation between curve of wetted perimeter versus discharge (graph *A*) and curve of percentage of bankfull area wetted versus discharge (graph *B*), Dewatto River reach B.

section 4. The shallow pools act as resting areas for salmon migrating upstream and also as possible rearing areas.

Figure 17 shows the relation between the curve for the wetted perimeter versus discharge and the curve for the percentage of bankfull area wetted versus discharge. The break in the wetted perimeter discharge curve (fig. 17*A*) occurs at about 40 cfs. Figure 18 shows the relation between the velocity, discharge, and percentage of bankfull area for reach B.

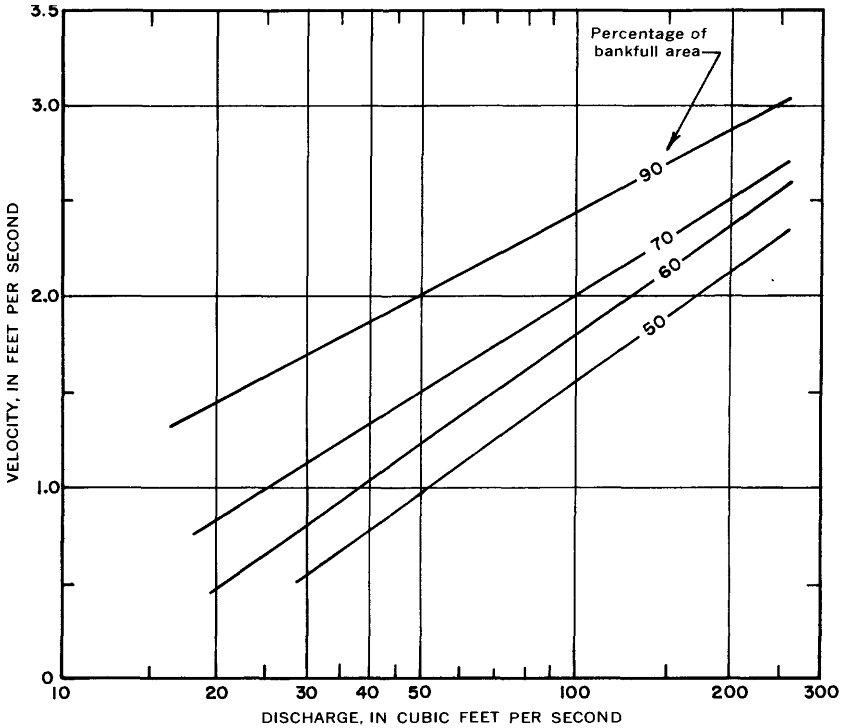


FIGURE 18.—Family of curves showing relation between velocity, discharge, and percentage of bankfull area, Dewatto River reach B. Shows selected percentages of reach which have velocities equal to or less than that indicated at a selected discharge.

Flow-duration curves (fig. 19) for reach B were obtained from an analysis of discharge at reach B (Q_B) versus discharge at reach A (Q_A), which is at the gaging station Dewatto River near Dewatto. The relation is shown by the equation

$$Q_B = 1.33 (Q_A)^{0.97}$$

and has a standard error of estimate of ±4.5 percent. The regression coefficient and constant are significantly different from 1.0 at the 95-percent testing level.

The peak spawning discharge for coho is 50 cfs and has an exceedance percentage from the flow-duration curves (fig. 19) of 20 percent for October, 72 percent for the November–December period, and 92 percent for January. The rearing discharge of 40 cfs has an annual exceedance percentage (fig. 19) of 53 percent.

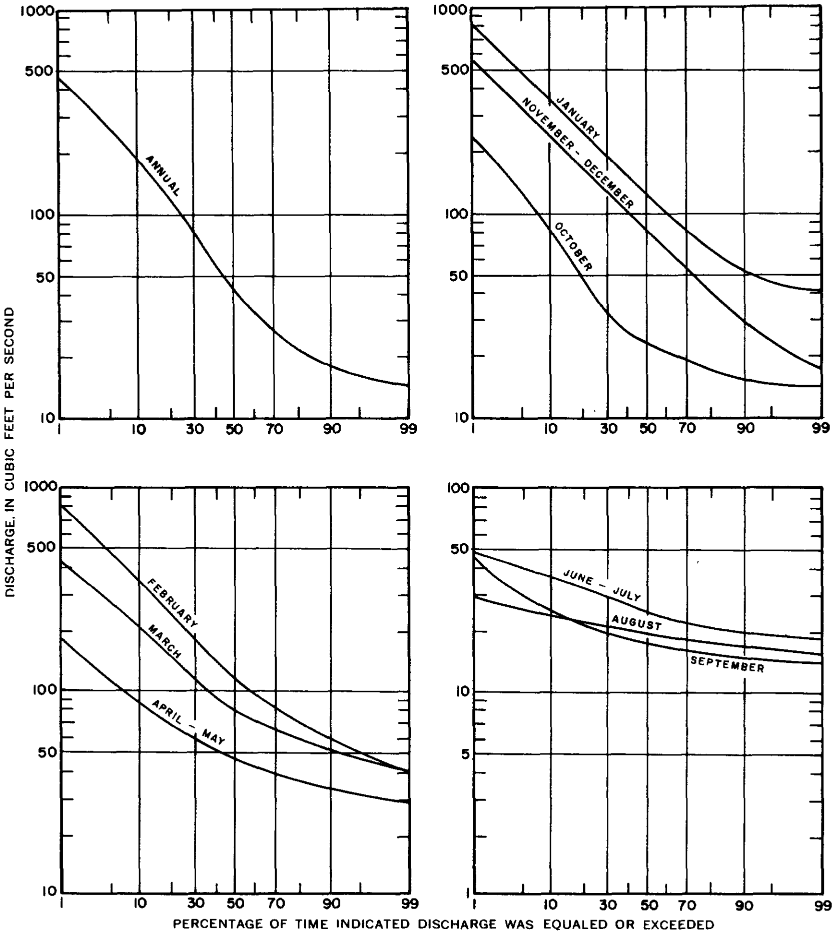


FIGURE 19.—Monthly and annual flow duration, Dewatto River reach B.

The water-quality characteristics of reach B are given in table 5 and show uniformity with upstream reaches A and A–1.

CEDAR RIVER

The Cedar River, with a drainage that heads in the west Cascade foothills at an altitude of 3,600 feet, flows across the Puget Sound lowland and empties into Lake Washington. The mean annual precipitation ranges from more than 100 inches in the uppermost parts of the basin to about 32 inches near the mouth of the river.

TABLE 5.—*Characteristics of water quality, Dewatto River reach B, April–December 1968*

Date		Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/1)	Suspended sediment (mg/1)	Specific conductance (micromhos per cm at 25°C)
Apr.	2	107	8.3	47	11.4	----	----
	9	76	----	----	----	----	----
	17	61	7.8	46	11.5	----	----
	29	52	9.4	49	11.1	4	----
May	15	40	9.4	49	11.1	16	----
	31	35	10.6	51	10.8	10	----
July	8	23	12.8	55	10.3	2	----
Sept.	16	22	11.7	53	10.5	----	----
Oct.	10	31	10.0	50	11.0	4	----
	18	41	8.3	47	11.4	----	----
Nov.	13	116	7.2	45	11.7	1	----
	26	94	7.5	45.5	11.6	1	50
Dec.	11	274	6.4	43.5	11.9	1	35
	13	156	5.3	41.5	12.2	1	40

The flow of the river is regulated both by powerplant operation at Chester Morse Lake and by continuous diversion of between 200 and 300 cfs farther downstream by the city of Seattle. The hydrograph of streamflow of the Cedar River at Renton (fig. 20), which is below the study reaches, shows high flows during the winter and low flows in late summer, typical characteristics of a lowland stream. However, in the spring months some snowmelt runoff does occur. The flow-duration curves (fig. 21), based on records for 1946–67, show the effect of the city of Seattle's diversion by the very steep lower end on the summer-month curves; also shown is the small effect of snowmelt by the general flatness of the upper parts of the April–May curve. Flow-duration curves for the long-term gage, Cedar River at Renton, are related to each of the study reaches on the Cedar River by regression methods.

Stream temperatures were determined by analysis of thermograph records from the Cedar River near Landsburg gaging station, for the years 1954–66. The median temperature and the 95-percent-probability extremes of maximum and minimum temperatures were fitted by harmonic curves (fig. 22). The fitted curves define 90 percent of the temperature variance and have a standard error of estimate of 0.4°C. Stream temperatures will be within the outer two curves 90 percent of the time, and there is a 95-percent chance that the minimum stream temperature in January will exceed 2.2°C and the maximum stream temperature in July will be less than 17.6°C.

As an aid in determining potential rearing and possible spawning areas, stereo pairs of aerial photographs were obtained for the

Cedar River from Landsburg to the mouth, a distance of 20.9 miles. From these photographs, the pool-and-riffle relation was established by delineating areas of each, then planimetering each area to determine the total area of riffles and of pools. The discharge when the photographs were taken was 185 cfs at the lower study reach (reach C, fig. 23). The stretch of river photographed showed 57.8 percent about 2.4×10^5 sq ft per mi) as pool area and 42.2 percent (about 1.7×10^5 sq ft per mi) as riffle area.

Five study reaches were selected on the Cedar River. Reaches B1 and C1 (fig. 23) were established to supplement data collected at reaches B and C and to evaluate repeatability of the methods and the sampling error by comparison with reaches B and C, respectively. This comparison is evaluated on page 6.

The major spawning areas in the Cedar River extend from Maple Valley to below reach C (fig. 23). The major salmon species which frequent the Cedar River are sockeye and fall chinook. The sockeye rear in Lake Washington for about a year, whereas the fall chinook return to salt water in the spring.

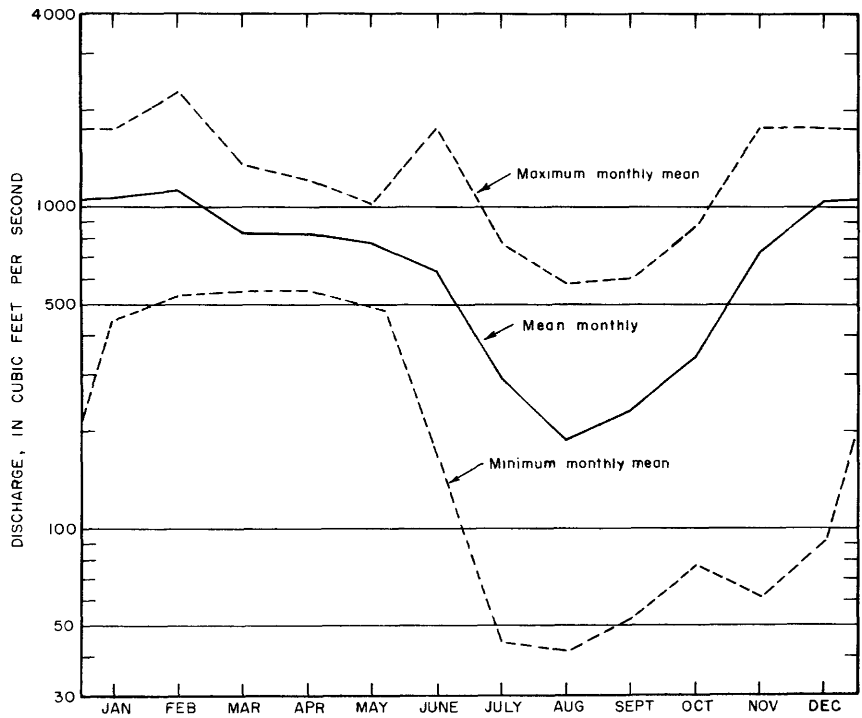


FIGURE 20.—Mean monthly discharge and maximum and minimum monthly mean discharges of Cedar River at Renton, 1950–67.

Figure 24 shows curves of the average grading of gravels for the five study reaches. Reach B1 has a greater amount of fines than the other reaches. Reaches A, B, C, and C1 have a similar grading of gravels, with 35–40 percent by weight passing the 1-inch sieve. Only 8 percent or less of the gravels pass the 0.1-inch sieve on all reaches.

CEDAR RIVER REACH A

Study reach A is a typical Cedar River spawning area. Above the reach, which is at an altitude of 260 feet, the mean basin altitude is 2,010 feet. The river is 41.4 miles long, drains an area of 160 square

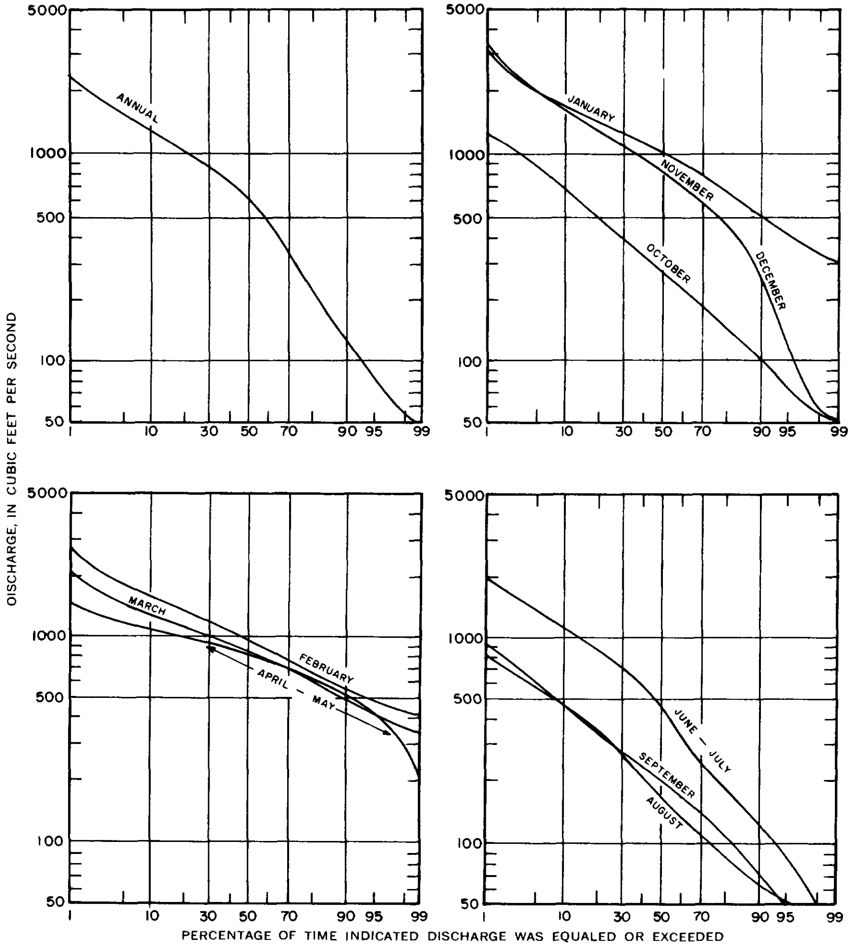


FIGURE 21.—Monthly and annual flow durations, Cedar River at Renton. Upstream diversions account for the steepness of the lower end of the summer-month curves.

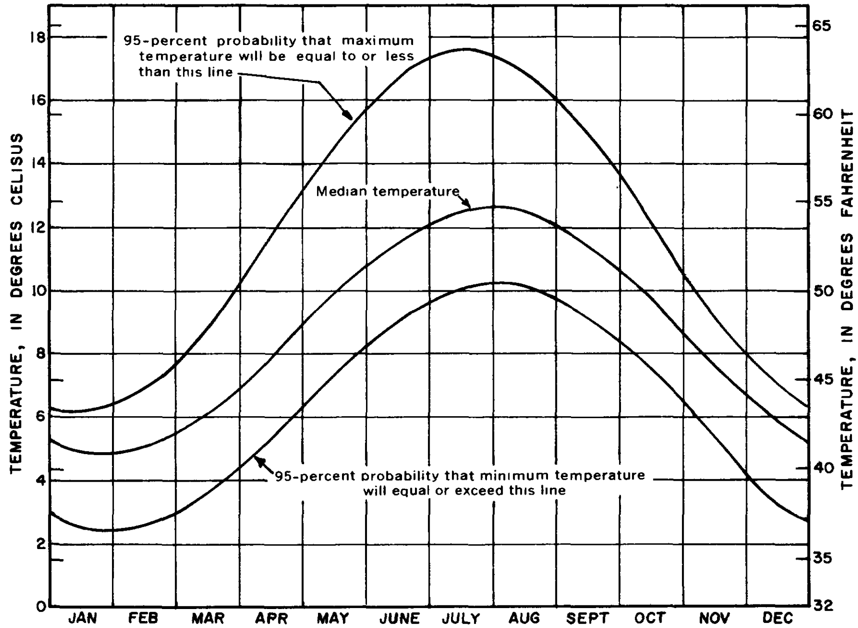


FIGURE 22.—The 90-percent probability range of stream temperatures, Cedar River near Landsburg, 1954–66.

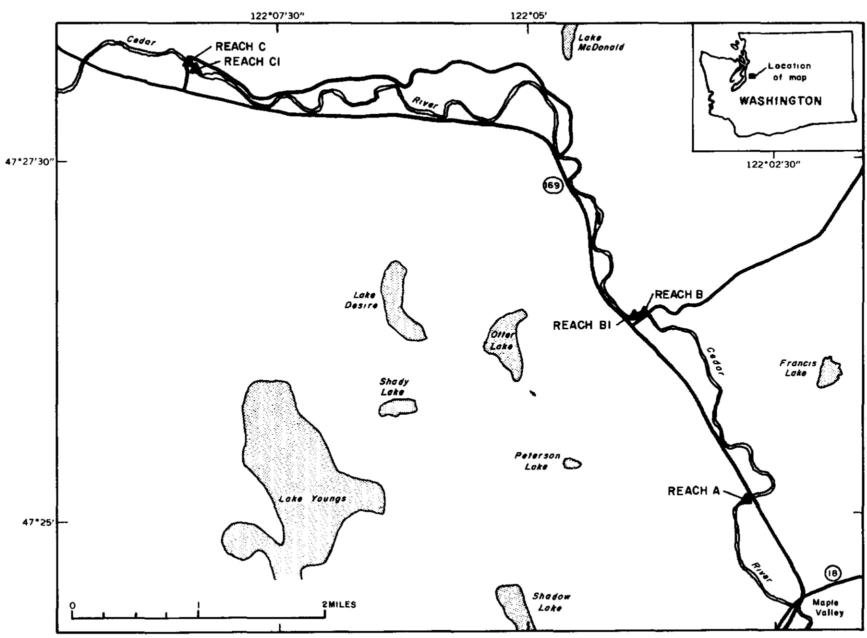


FIGURE 23.—Study reaches on Cedar River.

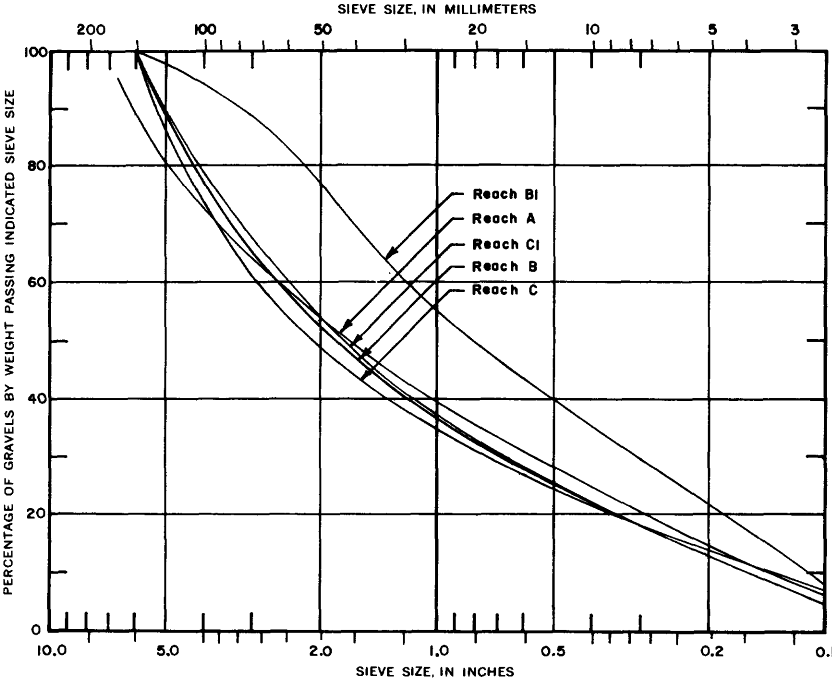


FIGURE 24.—Curves showing average grading of several samples of gravels found on natural spawning grounds of Cedar River.

miles, and has a channel slope of 50 feet per mile. Reach A, which covers 22,240 square feet at bankfull stage, is located just upstream from a bridge on State Highway 169, a little less than 1 mile below Maple Valley. The main channel of reach A is just left of center and spawning tends to be heaviest on the right bank (fig. 25).

Figure 26 shows plots of the original and the trend-fitted data for discharge versus spawning area preferred for each of the four salmon species studied. The curves tend toward double peaks, since powerplant regulation has established two fairly well defined gradational terraces by releasing relatively constant flows for long periods of time. At the lower flows, one terrace is inundated. As the river stage increases, water overflows onto the second terrace, thus establishing a second preferred spawning area at the higher discharge. Ten discharge measurements ranging from 76 to 1,050 cfs were made for the analysis. The preferred spawning discharges and areas for the peaks and the discharges and areas for the four percentage discharge reductions for the species studied are given in table 15. The discharges for the peaks are uniform for the four species, varying only 10 cfs (230–240 cfs).

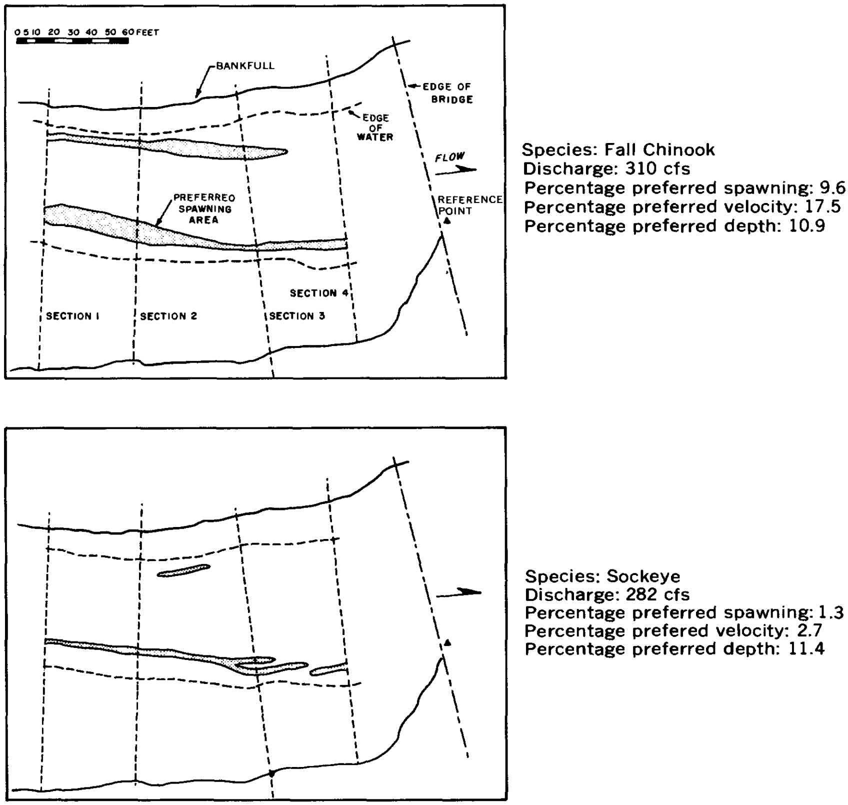


FIGURE 25.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Cedar River reach A. The bankfull area of the reach covers 22,240 square feet.

Rearing potential at reach A may be examined by referring to figures 27 and 28 and using them in the same way that the preferred relations of wetted perimeter versus discharge, wetted area versus discharge, and velocity versus discharge versus percent area were used on the Dewatto River reaches (p. 18). Figure 27 shows the double-terrace effect by the slight double break in the curve. The first break in the wetted perimeter curve occurs at about 75 cfs; this may be referred to as the rearing discharge.

The duration of flows was determined at reach A by relating discharges at reach A (Q_A) to equivalent discharges at the gaging station, Cedar River at Renton (Q_R). The relation is shown by the equation

$$Q_A = 0.45 (Q_R)^{1.10}$$

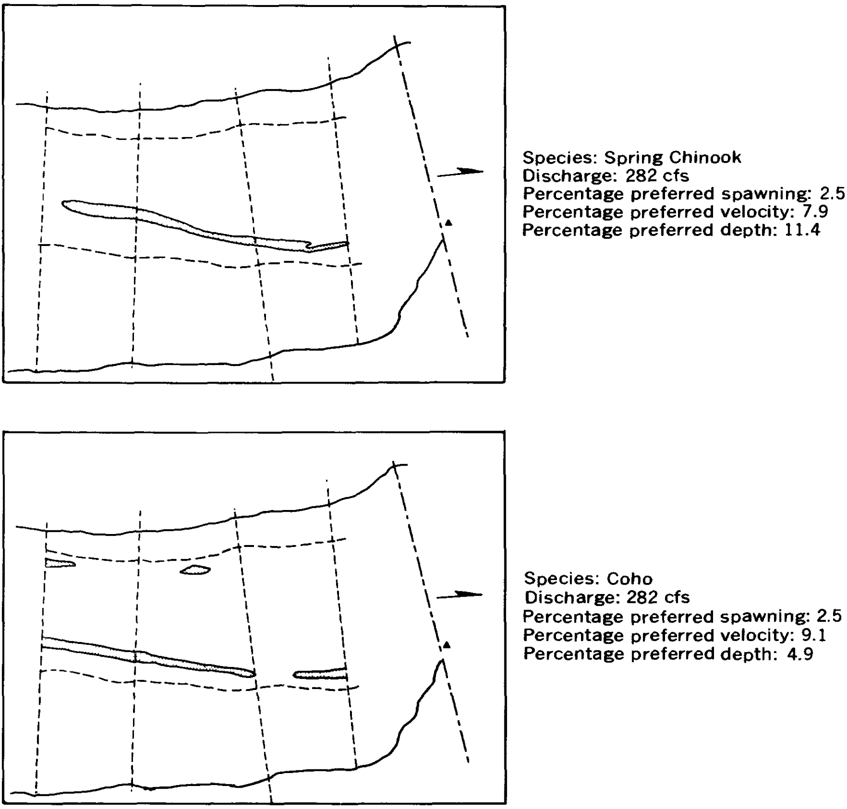


FIGURE 25.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Cedar River reach A. The bankfull area of the reach covers 22,240 square feet—Con.

and has a standard error of estimate of ±8.2 percent. The above equation was used to reconstruct flow-duration curves (fig. 29) from the gaging-station records.

Water-quality parameters obtained at reach A are given in table 6. The dissolved-oxygen content given is from a relation with stream temperature which was checked by sampling. Oxygen saturation of the water exists at or near 100 percent most of the time.

CEDAR RIVER REACH B

Reach B of the Cedar River is downstream from a highway bridge and just below a river channel island. Above the reach, which is at an altitude of 225 feet, the river is 43.5 miles long, drains an

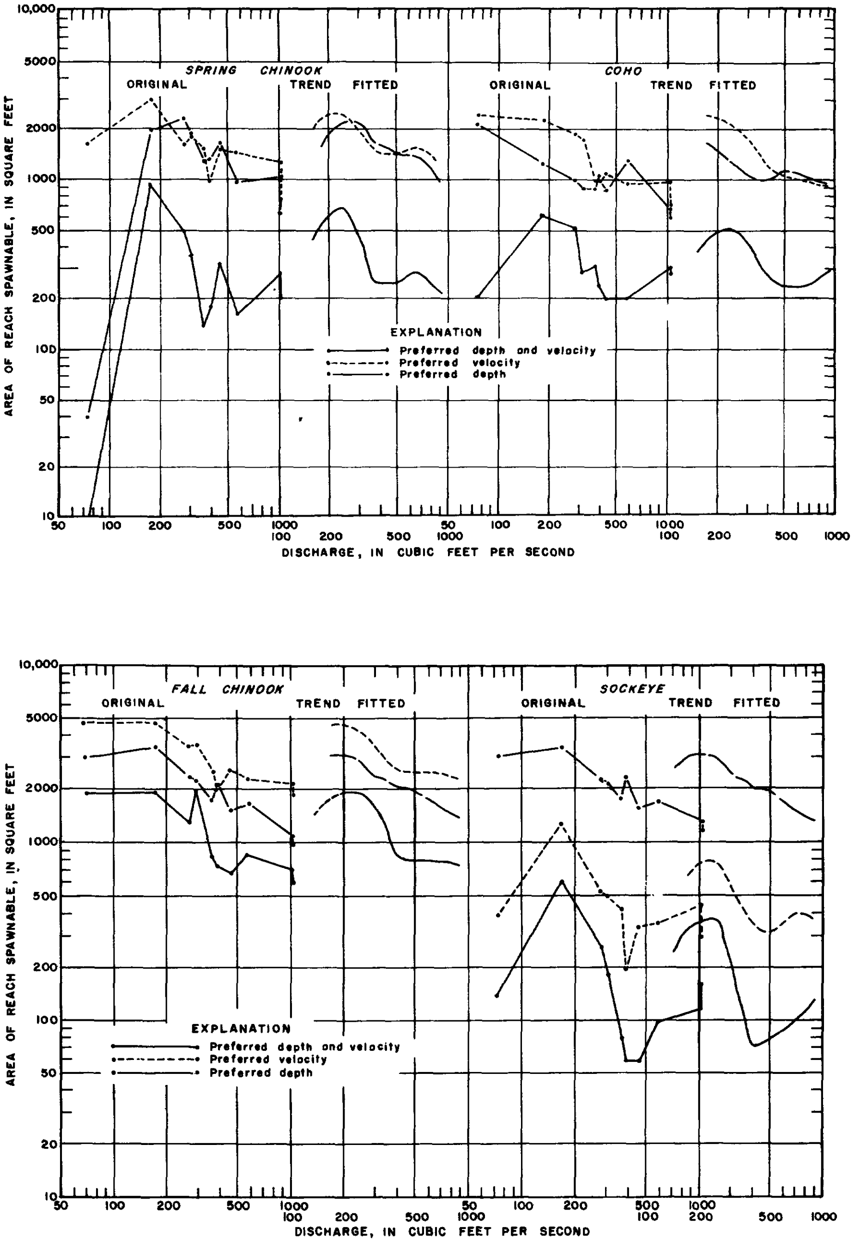
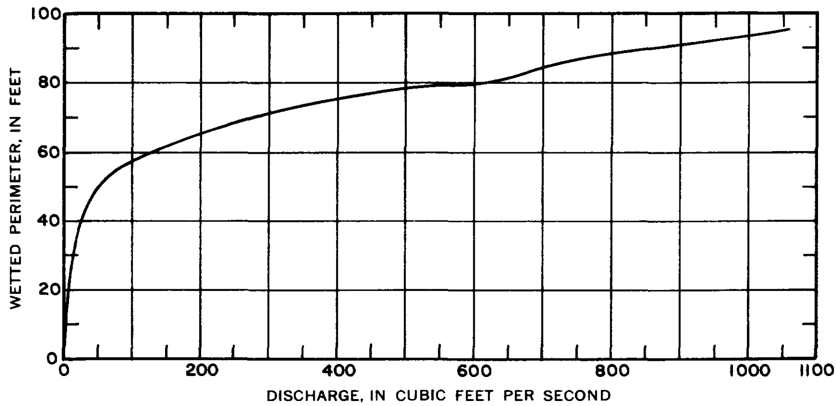
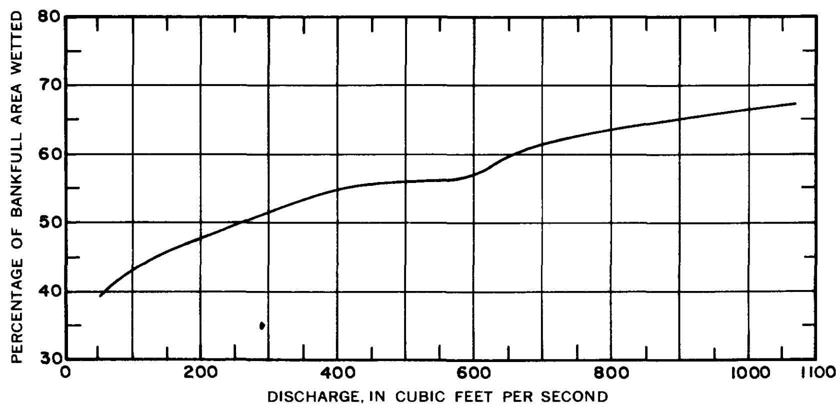


FIGURE 26.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of four salmon species, Cedar River reach A. Curves show the original and the trend-fitted data based on a three-point moving average. The bankfull area of the reach contains 22,240 square feet.



A



B

FIGURE 27.—Relation between curve of wetted perimeter versus discharge (graph *A*) and curve of percentage of bankfull area wetted versus discharge (graph *B*), Cedar River reach A. The first break in the curve of graph *A* denotes the most advantageous rearing discharge, whereas the second break is caused by the high terrace of the channel. The curve in graph *B* is used in conjunction with figure 28.

area of 169 square miles, and has a channel slope of 48 feet per mile. Reach B covers 23,420 square feet. The main channel flow is centered in the upper sections but veers to the right at the lower end of the reach. Both banks have been stabilized by rock riprap. The preferred spawning areas occur just below and to the left of the upstream channel island and under overhanging bushes on the right bank (fig. 30).

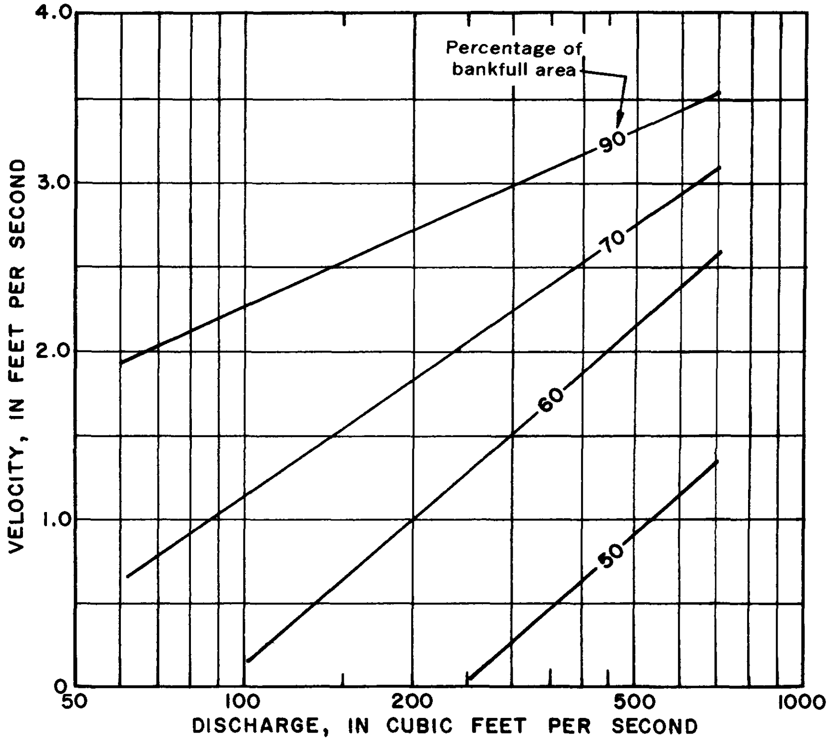


FIGURE 28.—Family of curves showing relation between velocity, discharge, and percentage of bankfull area, Cedar River reach A. Shows selected percentages of reach which have velocities equal to or less than that indicated at a selected discharge.

TABLE 6.—*Characteristics of water quality, Cedar River reach A, April–October 1968*

Date		Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/l)	Suspended sediment (mg/l)	Specific conductance (micromhos per cm at 25°C)
Apr.	11	1,050	----	----	----	----	----
	22	1,050	9.4	49	11.1	4	----
May	1	394	8.3	47	11.4	19	----
	29	370	11.1	52	10.7	10	----
June	5	459	11.1	52	10.7	2	----
July	2	183	18.3	65	9.1	----	----
	10	76	14.7	58.5	9.9	0	----
Aug.	30	282	12.8	55	10.3	2	----
Sept.	30	310	11.7	53	10.5	----	----
Oct.	16	584	9.4	49	11.1	6	----

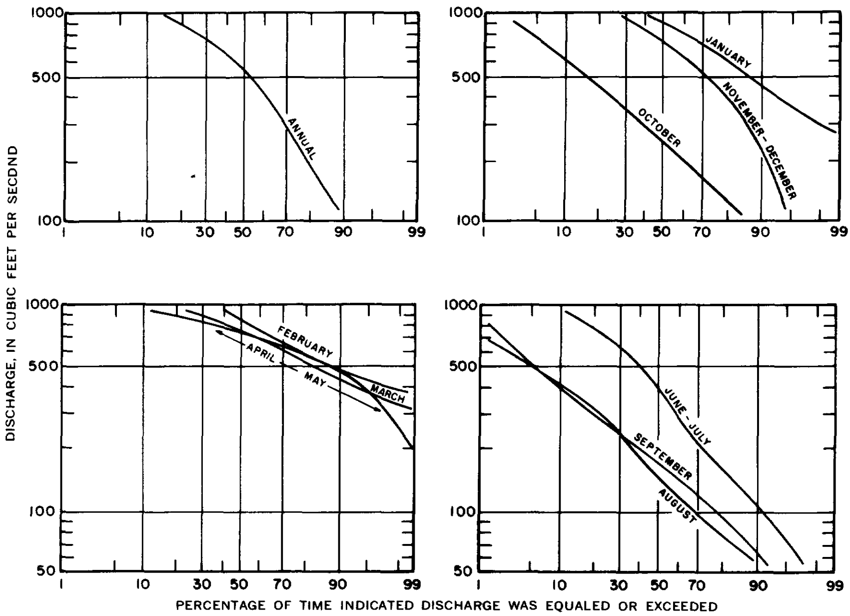
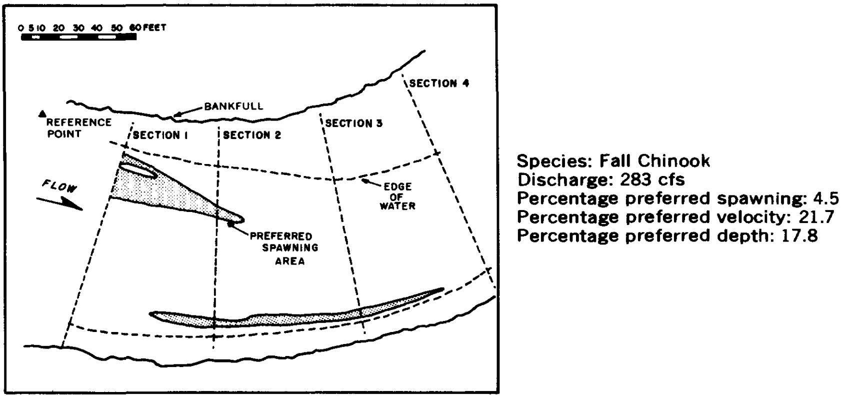


FIGURE 29.—Monthly and annual flow durations, Cedar River reach A.

The double terracing of the channel at reach B is not so well developed as it is at reach A, as indicated by the curves in figure 31. The lower peak (fig. 31) is much more definite, probably because of the bank riprap. The peak preferred spawning discharges and areas, and discharges and areas for the selected percentage reductions in discharge for the four salmon species are given in table 15. Using table 15 with the above discharges it may be noted that on reach B for a reduction in sockeye spawning discharge of 25 percent from the peak (from 440–330 cfs) the spawnable area decreases only 8 percent (from 255–235 sq ft). Similar evaluations may be made for the other species. Ten discharge measurements, ranging from 89 to 1,540 cfs, were available for this analysis.

Figures 32 and 33 are used to evaluate the hydraulics of rearing conditions on reach B. The double-terrace effect is evidenced in graph A of figure 32 by the double break in the curve. The lower break, used to indicate the rearing discharge, occurs at about 90 cfs.

Flow-duration curves for discharges of Cedar River reach B (Q_B) were obtained by relating Q_B to the discharge of the Cedar River



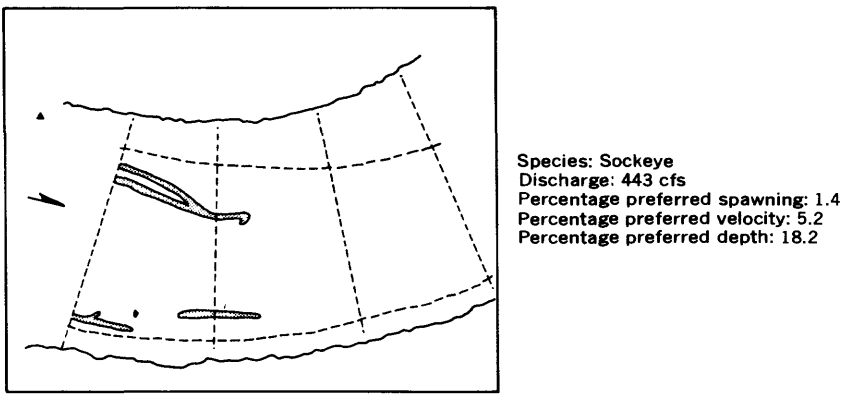


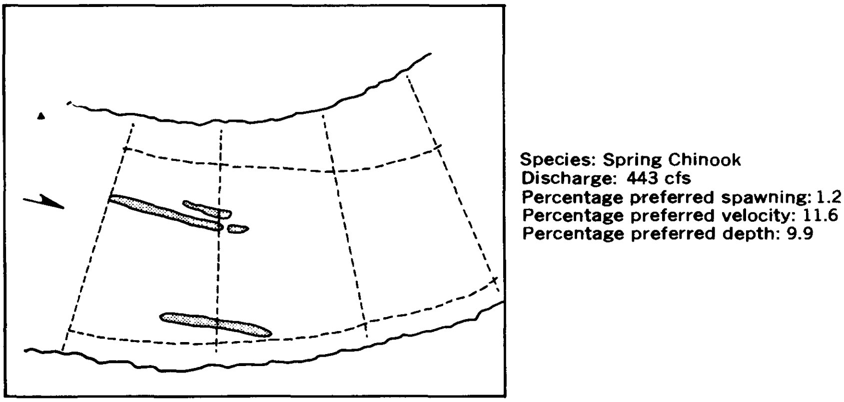
FIGURE 30.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Cedar River reach B.

at the Renton gaging station (Q_R), after adjustment of discharge for time of travel between the two sites. The relation is shown by the equation

$$Q_B = 0.59 (Q_R)^{1.07},$$

which has a standard error of estimate of ±3.5 percent. The flow-duration curves obtained from this relation are shown in figure 34.

The water-quality characteristics of reach B (table 7) are not significantly different from those for reach A (table 6).



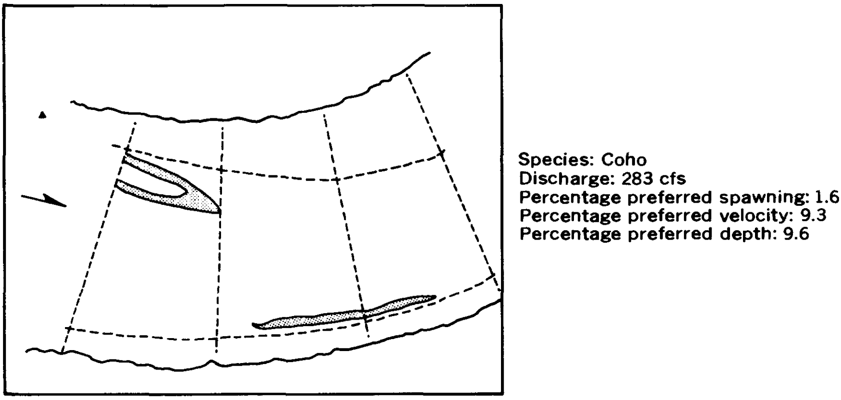


FIGURE 30.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Cedar River reach B—Continued.

CEDAR RIVER REACH C

Cedar River reach C (alt 90 ft) is the lowest site studied on the river. The river above the reach is 49.4 miles long, drains an area of 177 square miles, and has a channel slope of 44 feet per mile. The bankfull area of the reach encompasses 17,620 square feet. The left bank is stabilized by riprap, and the main flow is also on the left side of the channel. The preferred spawning area is on the right side of the channel (fig. 35).

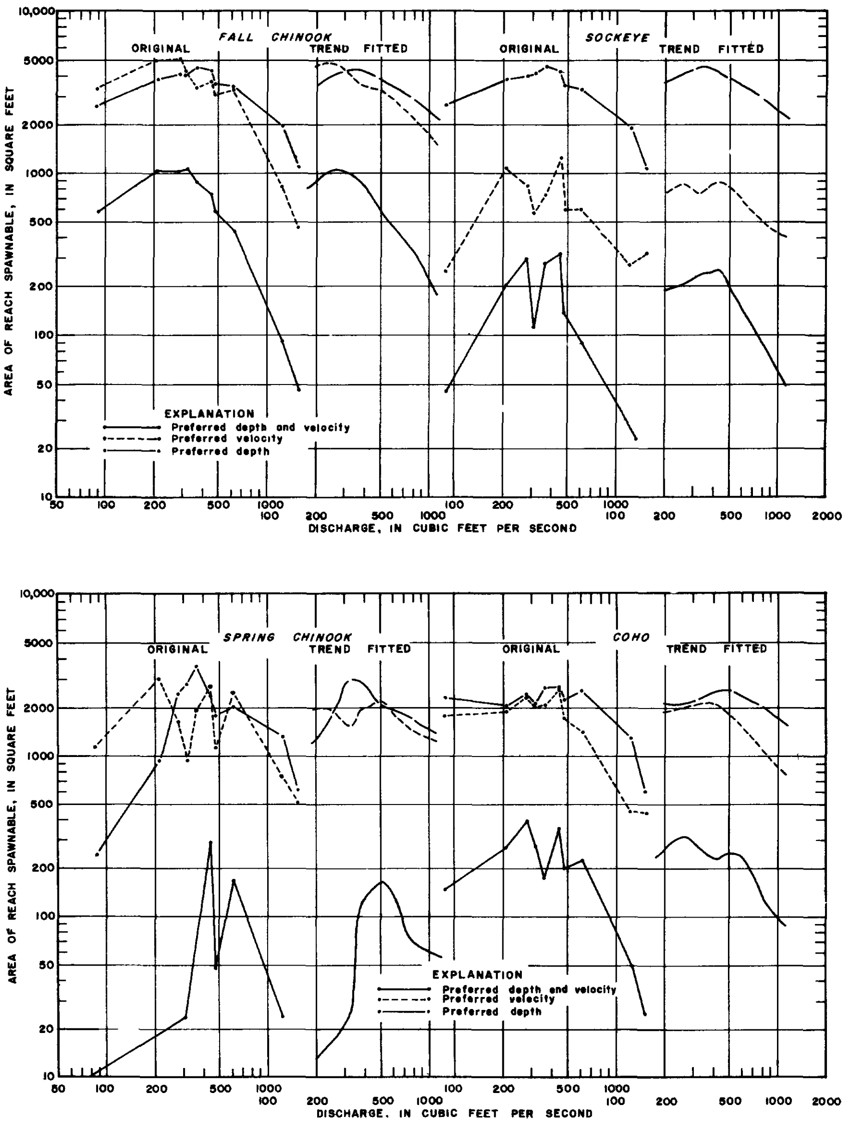


FIGURE 31.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of four salmon species, Cedar River reach B. Curves show the original and the trend-fitted data based on a three-point moving average. The bankfull area of the reach covers 23,420 square feet.

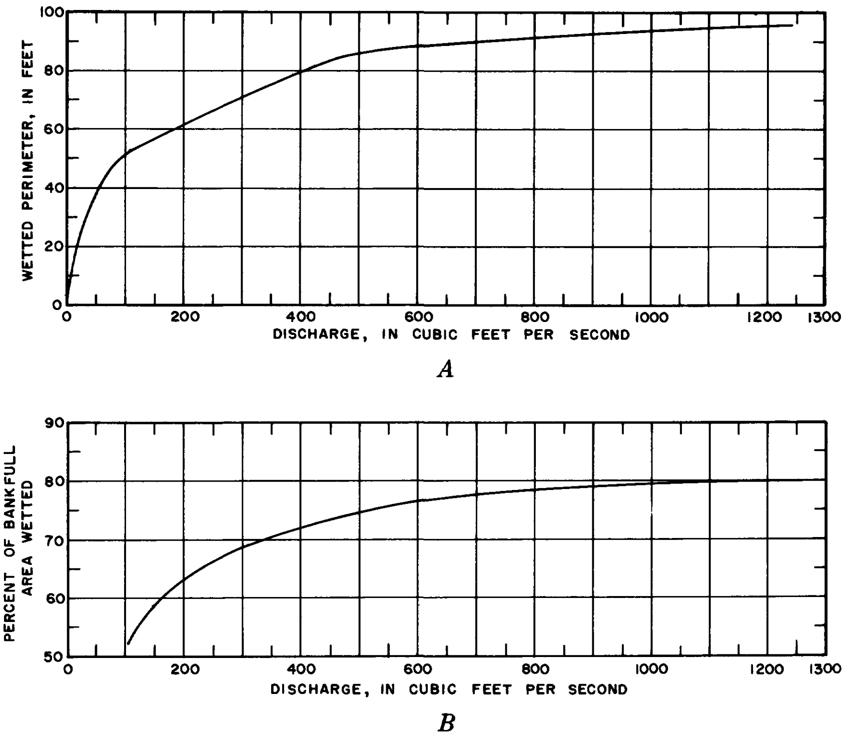


FIGURE 32.—Relation between curve of wetted perimeter versus discharge (graph *A*) and curve of percentage of bankfull area wetted versus discharge (graph *B*), Cedar River reach B.

TABLE 7.—*Characteristics of water quality, Cedar River reach B, April 1968–August 1969*

Date	Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/l)	Suspended sediment (mg/l)	Specific conductance (micromhos per cm at 25°C)
Apr. 15	1,540	6.4	43	12.0	----	----
22	365	9.4	49	11.1	6	----
May 1	1,240	9.4	49	11.1	18	----
29	443	11.1	52	10.7	10	----
June 5	474	13.9	57	10.2	4	----
July 2	212	15.6	60	9.7	0	----
10	89	16.4	61.5	9.5	1	----
Aug. 30	283	15.6	60	9.7	2	----
Sept. 30	319	12.2	54	10.4	----	----
Oct. 16	607	9.4	49	11.1	5	----
Nov. 3	306	9.2	48.5	11.5	----	----
Mar. 21	452	8.3	47	11.4	2	59
Aug. 1	170	12.8	55	10.3	----	66

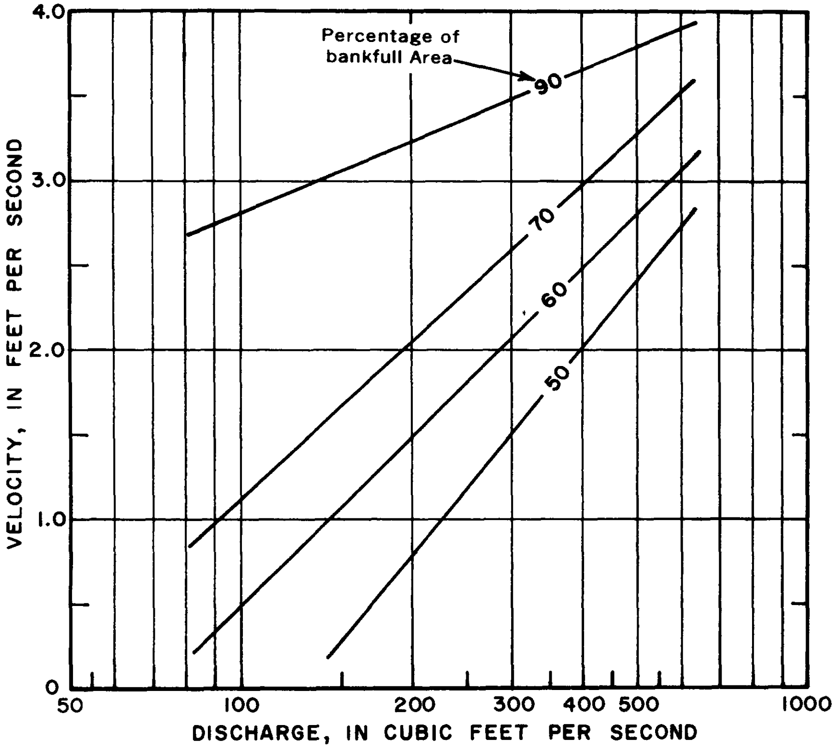


FIGURE 33.—Family of curves showing relation between velocity, discharge, and percentage of bankfull area, Cedar River reach B. Shows selected percentages of reach which have velocities equal to or less than that indicated at a selected discharge.

Seven discharge measurements, ranging from 290 to 900 cfs, were made during the period of investigation. At the time of low flows, a temporary unauthorized rock dam was constructed below the study reach and was used to impound water for swimming. Therefore, the lower end of the discharge curves for preferred spawning conditions (fig. 36) for fall chinook could not be defined properly. However, the preferred discharges and areas for the peaks and for the selected percentage reductions in discharge for the four salmon species are given in table 15. The spawnable area values in parenthesis were extrapolated by using the original and trend-fitted depth, velocity, and depth and velocity curves (fig. 36) as guides.

In order to evaluate the flow duration at reach C relations were determined between discharges at reach C (Q_C) and discharges at

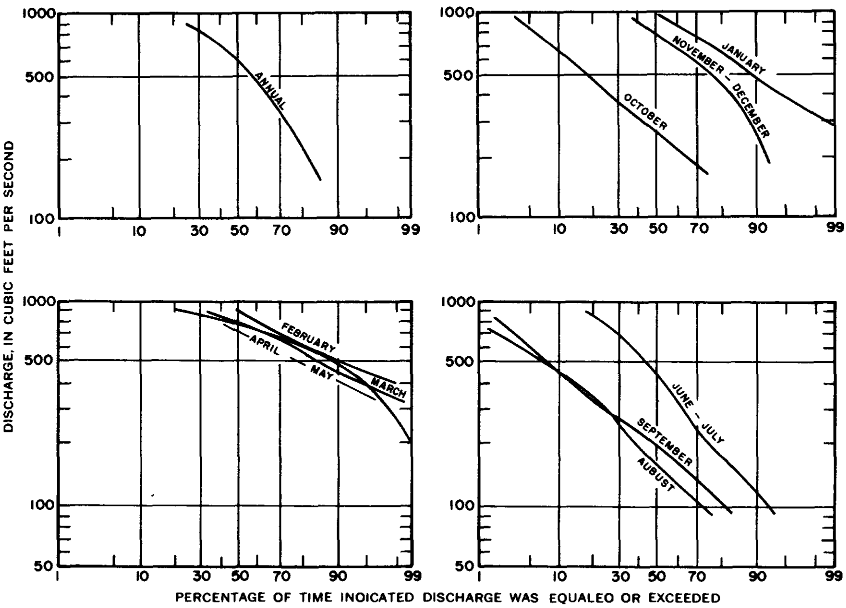


FIGURE 34.—Monthly and annual flow durations, Cedar River reach B.

the long-term recording gage, Cedar River at Renton (Q_R). The discharges of the Cedar River at Renton were adjusted for discharge time of travel between the two sites. The relation is shown by the equation

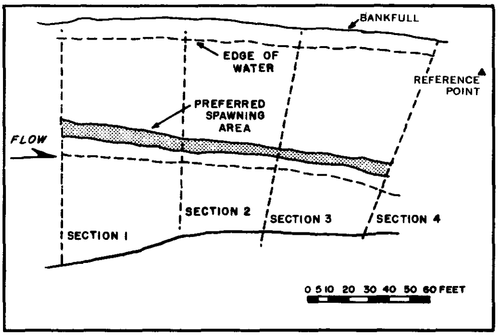
$$Q_C = 0.78 (Q_R)^{1.03},$$

which has a standard error of estimate of ±2.5 percent and at the Renton gage is valid only over a discharge range from 200 to 900 cfs. By use of the equation, the flow-duration curves in figure 37 were constructed.

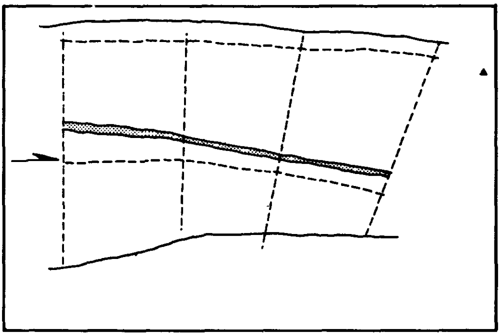
Table 8 gives the water-quality measurements on reach C.

KALAMA RIVER

The Kalama River drains a part of the western foothills (source alt 2,900 ft) of Mount St. Helens and flows westward into the lower Columbia River. The river receives flow from snowmelt during the spring; however, most peak flows occur because of the winter rains. The low flows of late summer are maintained largely by considerable ground-water inflow from alluvium and from permeable vol-



Species: Fall Chinook
Discharge: 443 cfs
Percentage preferred spawning: 6.0
Percentage preferred velocity: 9.5
Percentage preferred depth: 6.1



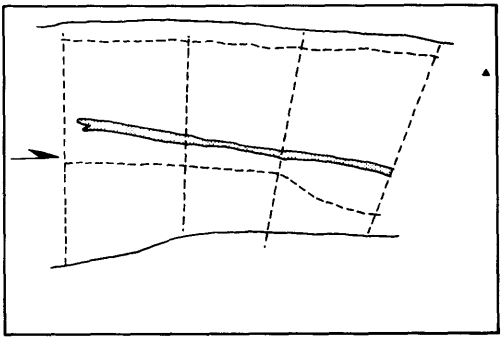
Species: Sockeye
Discharge: 489 cfs
Percentage preferred spawning: 1.5
Percentage prefered velocity: 1.5
Percentage preferred depth: 3.2

FIGURE 35.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Cedar River reach C.

canic rocks—predominantly basalt flows and flow breccia—which include some pyroclastics and andesitic rocks (Huntting and others, 1961). The mean monthly hydrograph of discharge (fig. 38) shows that the streamflow diminishes continuously from January

TABLE 8.—*Characteristics of water quality, Cedar River reach C, April 1968–March 1969*

Date	Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/l)	Suspended sediment (mg/l)	Specific conductance (micromhos per cm at 25°C)
Apr. 22	571	7.8	46	11.5	4	----
May 13	489	9.4	49	11.1	8	----
28	443	14.7	58.5	9.9	----	----
June 4	900	11.7	53	10.6	7	----
Aug. 26	327	13.3	56	10.2	----	----
Sept. 24	290	13.9	57	10.0	----	----
Oct. 16	657	8.6	47.5	11.3	6	----
Nov. 3	327	8.9	48	11.2	----	----
Mar. 21	537	7.2	45	11.7	4	63



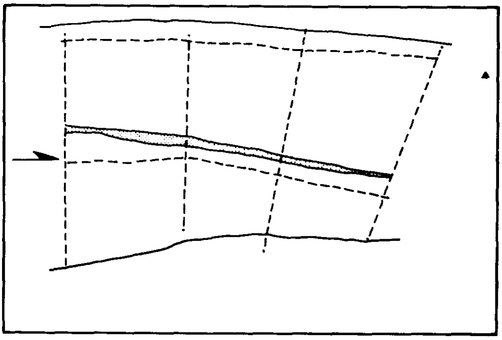


FIGURE 35.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Cedar River reach C—Continued.

to August. Flow stabilization occurs during the base-flow period in August and September; then discharge increases as the winter rains begin.

The majority of the salmon that frequent the Kalama River are coho, spring chinook, and fall chinook. The study reaches (fig. 39) are above two hatcheries of the Washington State Department of Fisheries. These hatcheries collect fall chinook and coho for their operations.

A thermograph has been operated since 1955 in the gaging station (Kalama River below Italian Creek, near Palama) located below the study reaches. The thermograph records were analyzed and time-temperature relations computed and drawn (fig. 40). The fitted curves show the median temperature and the 95-percent probability extremes of maximum and minimum temperatures. The outer curves indicate that for the average year, at the end of July, there is a 90-percent chance that the maximum temperature will not

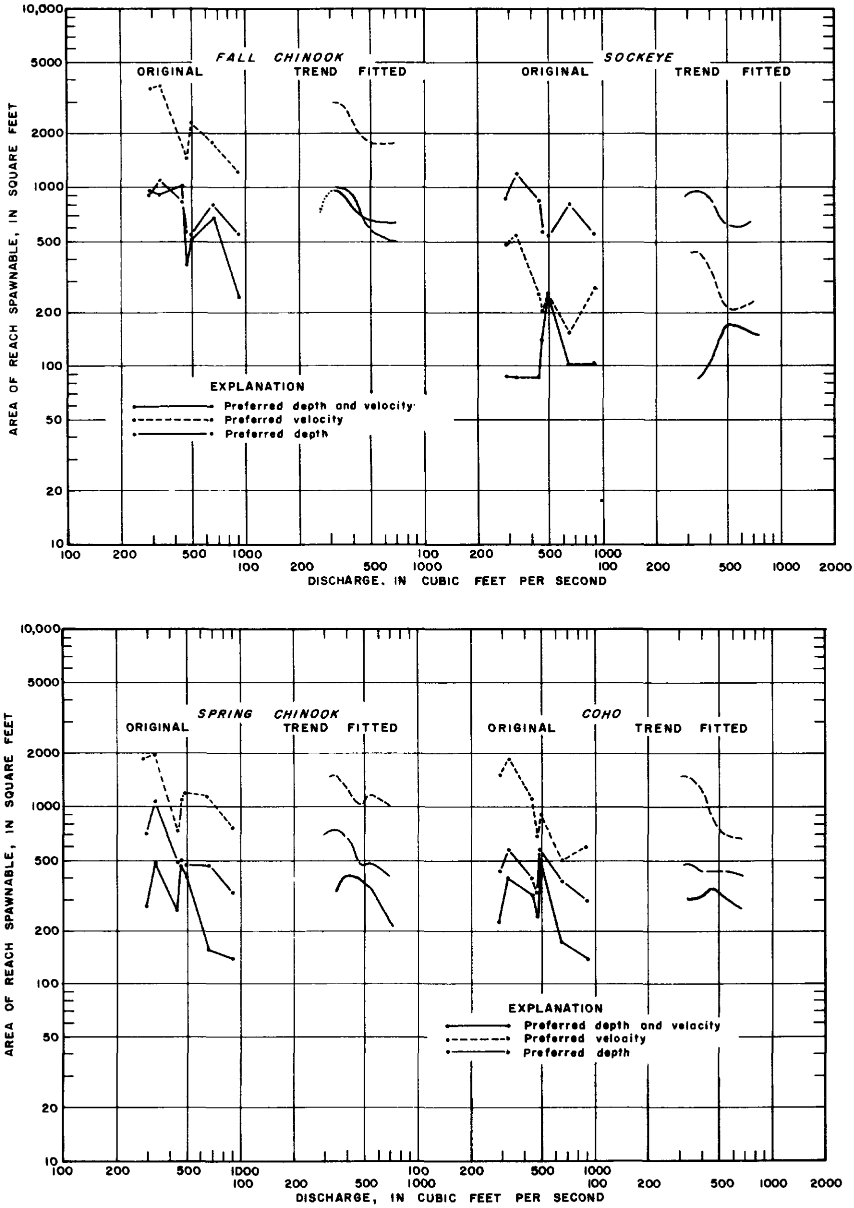


FIGURE 36.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of the four salmon species, Cedar River reach C. Curves show the original and the trend-fitted data based on a three-point moving average. The bankfull area of the reach covers 17,620 square feet.

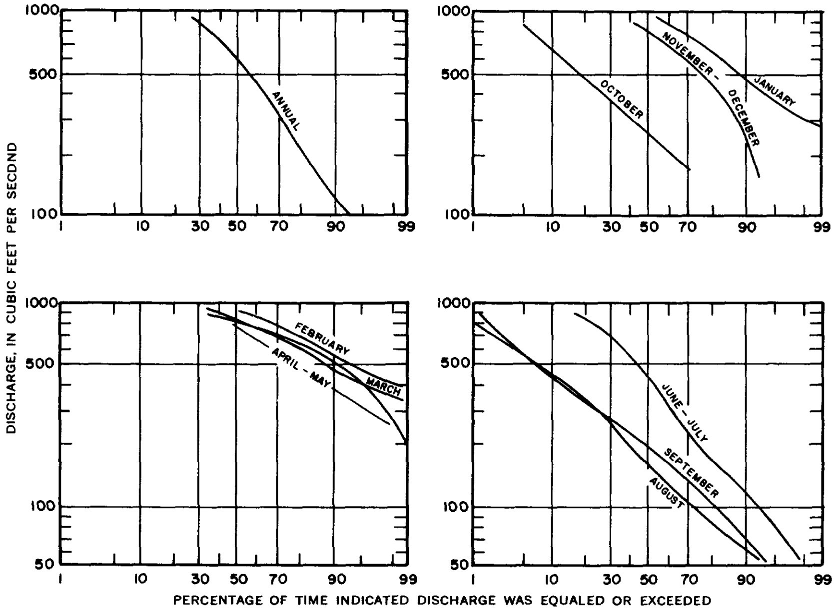


FIGURE 37.—Monthly and annual flow durations, Cedar River reach C.

exceed 19.2°C (about 66°F) and that the minimum temperature at the end of January will not be less than 0.9°C (about 33°F). The fitted curves in figure 40 define an average of 86 percent of the stream-temperature variance; the standard error of estimate of the fittings is 1.1°C.

Aerial photographs of the Kalama River were obtained during a discharge of about 400 cfs at the gaging station. From the stereo pairs of photographs, the pool-and-riffle areas from Pigeon Springs (fig. 39) to the river mouth were delineated and planimetered. Of the 21.1 miles of river photographed, 29.7 percent (1.928×10^5 sq ft per mi) of the stream is riffle area, and 70.3 percent (6.485×10^5 sq ft per mi) is pool area. The lower 3 miles of the Kalama River is mainly pool area, being on the reentrant flood plain of the Columbia River.

To investigate the section of upper river where the study reaches are located, relations were established between the pools and riffles of the reaches. The percentage of area of pools and riffles was determined over a length of stream extending from halfway between reaches A and B to an equidistant point above reach A, which is within the photographed part of the river. This length of

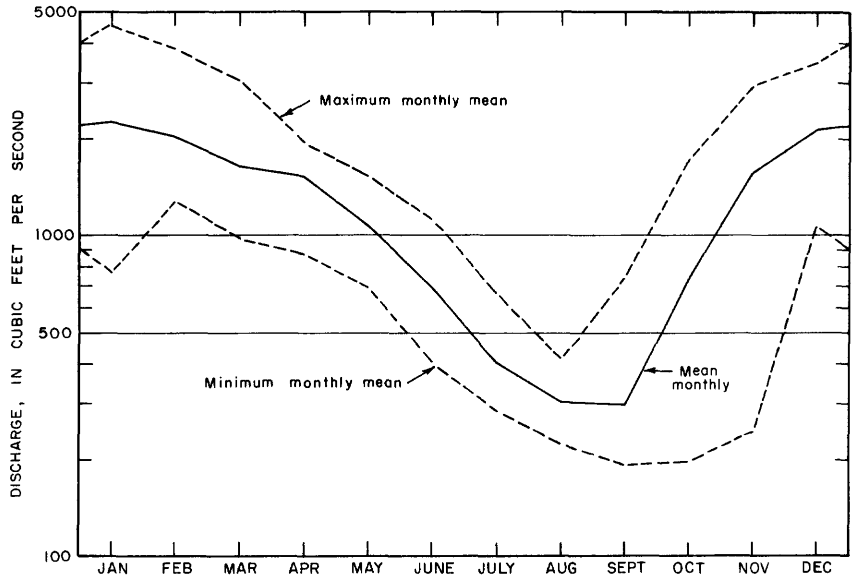


FIGURE 38.—Mean monthly discharge and maximum and minimum monthly mean discharge of Kalama River (Kalama River below Italian Creek, near Kalama), 1950–67.

stream through reach A contained 54.1 percent riffle area; the slope of the channel here is 113 feet per mile. The next stretch of river examined was from a point halfway between reaches A and B to a point halfway between reaches B and C. This length of stream through reach B had 37.6 percent riffle area; the channel slope to this point has decreased to 102 feet per mile. The third stretch of river examined was from a point halfway between reaches B and C to an equidistant point below reach C. This length of river through reach C had 42.7 percent riffle area, the channel slope being 94 feet per mile. The riffle areas over the three study reaches averaged 44.8 percent of their lengths.

The average grading of gravels on the three Kalama River study reaches is shown by the curve in figure 41. Compared to other streams studied in this report, the gravels on the three reaches are fairly coarse, with from 20 to 26 percent of the gravels passing through the 1-inch screen. The three reaches have generally similar gravels, and the difference in curve shapes and spread between curves is small.

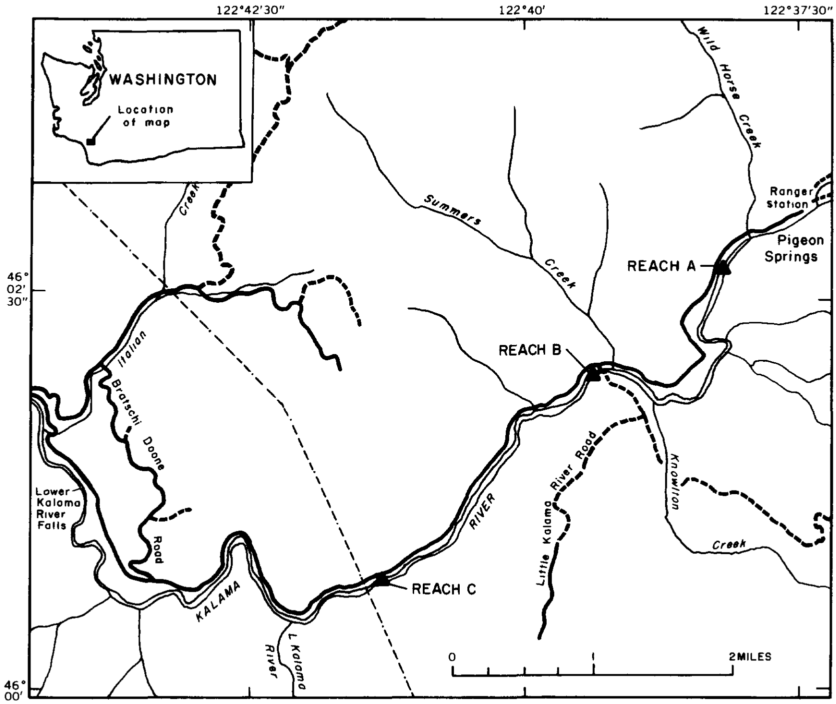


FIGURE 39.—Study reaches on Kalama River.

KALAMA RIVER REACH A

The Kalama River above reach A is 29.0 miles long, has a mean basin altitude of 2,350 feet, and drains 142 square miles. Reach A, at an altitude of 400 feet, is on a straight channel of the river and encompasses 23,140 square feet at the upstream part of a riffle. Water is distributed over the entire width of the reach, but the main flow at lower stages is near the left bank, especially in the lower part of the reach. Slightly upstream from the uppermost part of the reach, and on the right side of the channel, bedrock is exposed and the channel is deeper; also evident is a higher percentage of fine material (sand) in the streambed.

Discharge measurements, covering a range of 270 to 1,280 cfs, have been used in the analysis. The curves in figure 42 show hydraulic relations in the reach for preferred conditions for spawning. The peak preferred spawning discharges and areas and the discharge reductions and areas for each species are given in table 15.

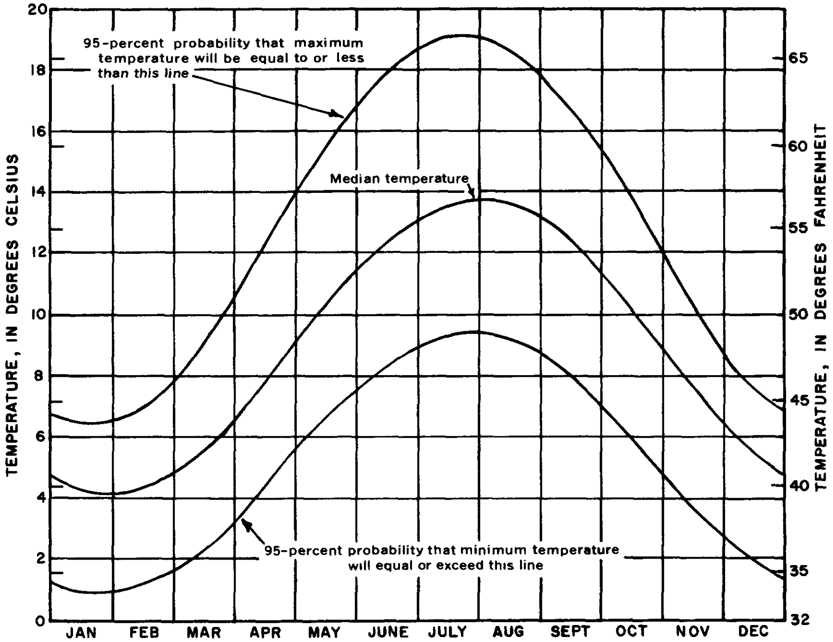


FIGURE 40.—The 90-percent probability range of stream temperatures, at station Kalama River below Italian Creek, near Kalama, 1955–66.

Under favorable discharge conditions, the preferred spawning areas are near the lower three sections (fig. 43), tending toward the left bank at section 2. The small tributary from the right bank (fig. 43), between sections 1 and 2, drains logged areas and unpaved roadways and carries some sediment during rainstorms. The hydraulic criterion of spawning depth, and probably the physical criterion of suspended sediment, are the major reasons for the lack of spawning on the right side of the channel between sections 1 and 2, which indicates that hydraulic and physical criteria are related.

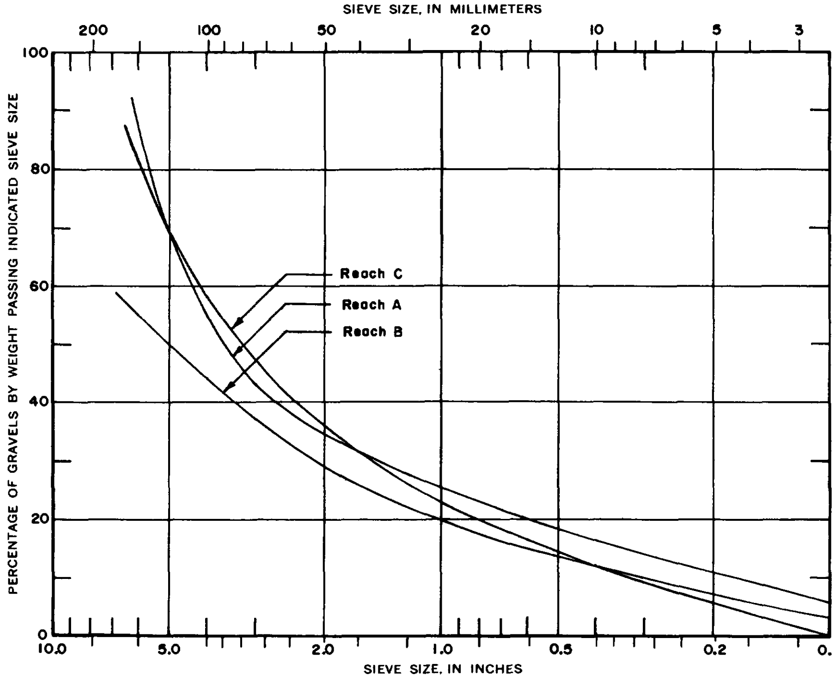


FIGURE 41.—Curves showing average grading of several samples of gravels found on natural spawning grounds of Kalama River.

Data on rearing capacity at reach A may be obtained by using the wetted perimeter versus discharge relation, the percentage wetted area versus discharge relation (fig. 44 *A*, *B*, respectively), and the velocity versus discharge versus percentage of bankfull reach curves (fig. 45) in the same way as figures 8 and 9 were used on the Dewatto River reach A. For instance, the curve in figure 44*A* tends to flatten at about 350 cfs, the minimum discharge for maximum rearing area. At this discharge, about 99 percent (fig. 44*B*) of the bankfull area is wetted—or 1 percent is dry. As shown in figure

45, a velocity of 1.2 fps and a discharge of 350 cfs intersect at the 50 percent bankfull area curve. However, 1 percent of the bankfull area is dry (fig. 44*B*) and, therefore, 49 percent, or 11,340 square feet, of the bankfull area of the reach is wetted.

Flow-duration curves for reach A (fig. 46) were obtained by computing the relation between reach A discharge (Q_A) and the discharge (Q_G) at the long-term (1947–66) gaging station Kalama River below Italian Creek, near Kalama, which is downstream. The relation is shown by the equation

$$Q_A = 1.59\,(Q_G)^{0.19},$$

which has a standard error of estimate of ±7.8 percent.

Both coho and spring chinook rear in the river for a little more than 1 year after hatching. From the annual flow-duration curve (fig. 46), the rearing discharge of 350 cfs (fig. 44*A*) will be equaled or exceeded 80 percent of the time—or during 20 percent of the time, discharges will be less than the most advantageous rearing discharge for the species.

Data on discharge, water temperature, dissolved-oxygen content, and suspended-sediment concentration for reach A are given in table 9.

TABLE 9.—*Characteristics of water quality, Kalama River reach A, June 1968–August 1969*

Date	Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/1)	Suspended sediment (mg/1)	Specific conductance (micromhos per cm at 25°C)
June 19	555	10.6	51	10.8	2	----
July 17	352	12.2	54	10.4	2	----
Aug. 15	270	11.1	52	10.7	1	----
29	1,280	9.4	49	11.1	4	----
Sept. 3	528	10.0	50	11.0	----	----
Oct. 29	754	9.4	49	11.1	2	----
Aug. 8	297	10.6	51	10.8	----	52

KALAMA RIVER REACH B

Study reach B is at an altitude of 330 feet and about a quarter of a mile below the confluence of the Kalama River with Summers Creek (fig. 39). Above reach B the river is 31.0 miles long and drains an area of 154 square miles.

The surface area of reach B encompasses 16,800 square feet. Just above the reach the streambed is bedrock, and just below the reach

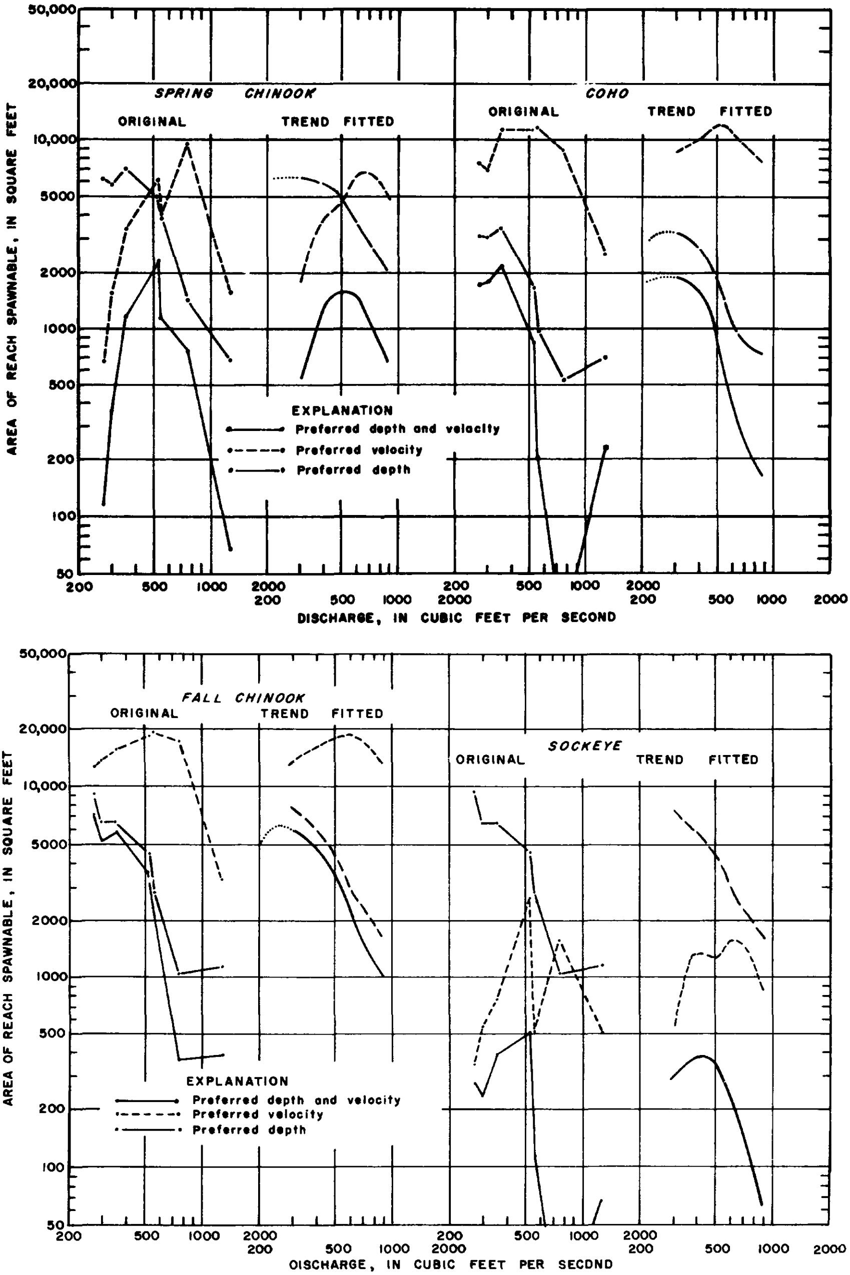


FIGURE 42.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of four salmon species, Kalama River reach A. Curves show the original and the trend-fitted data based on a three-point moving average. The bankfull area of reach covers 23,140 square feet.

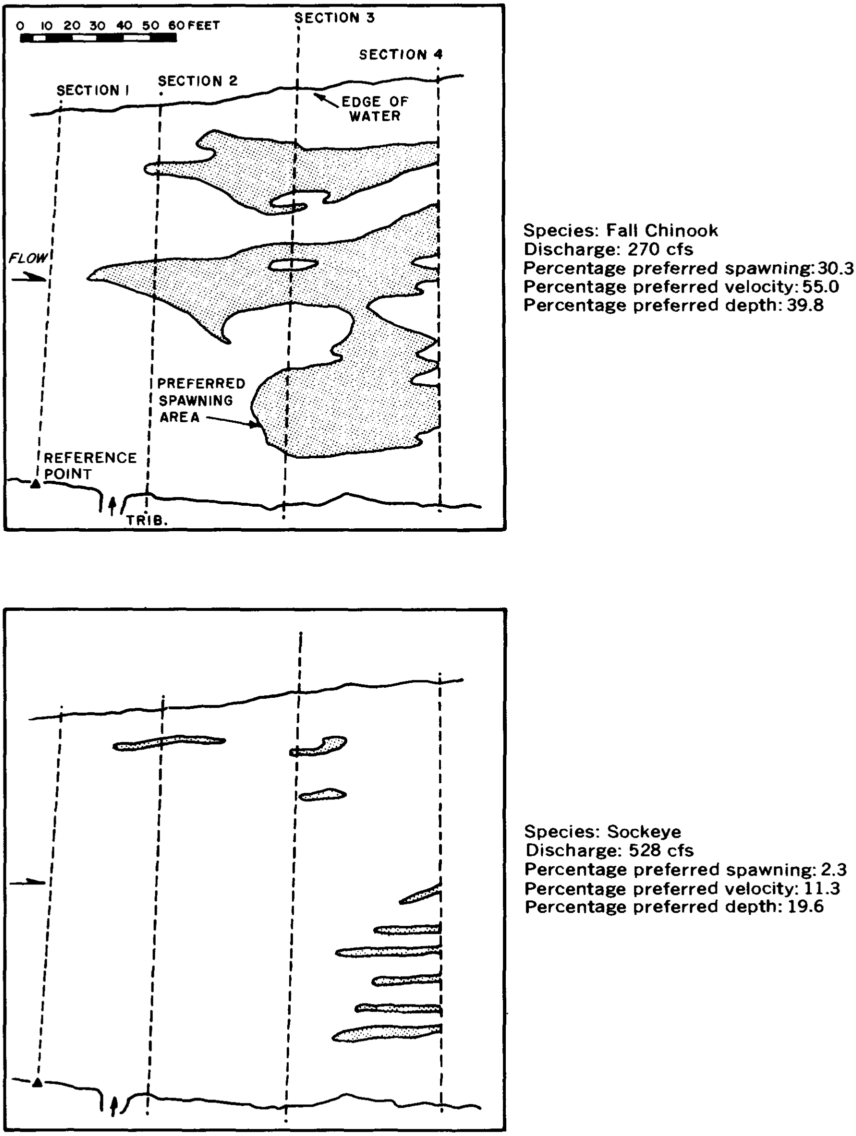
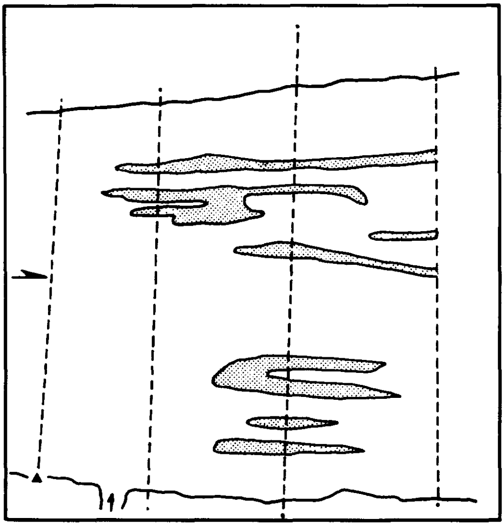
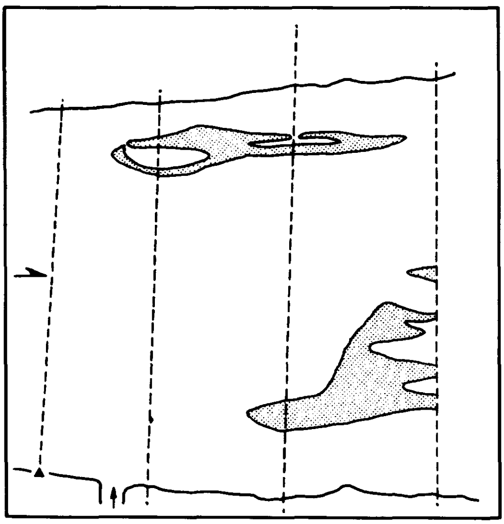


FIGURE 43.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Kalama River reach A.

the channel splits into two channels, the main flow being on the left side. The pool above the riffle at reach B is considerably smaller in volume than the pool at reach A, but it has higher velocities and is slightly deeper. The channel bank on the left side of reach B is steep,



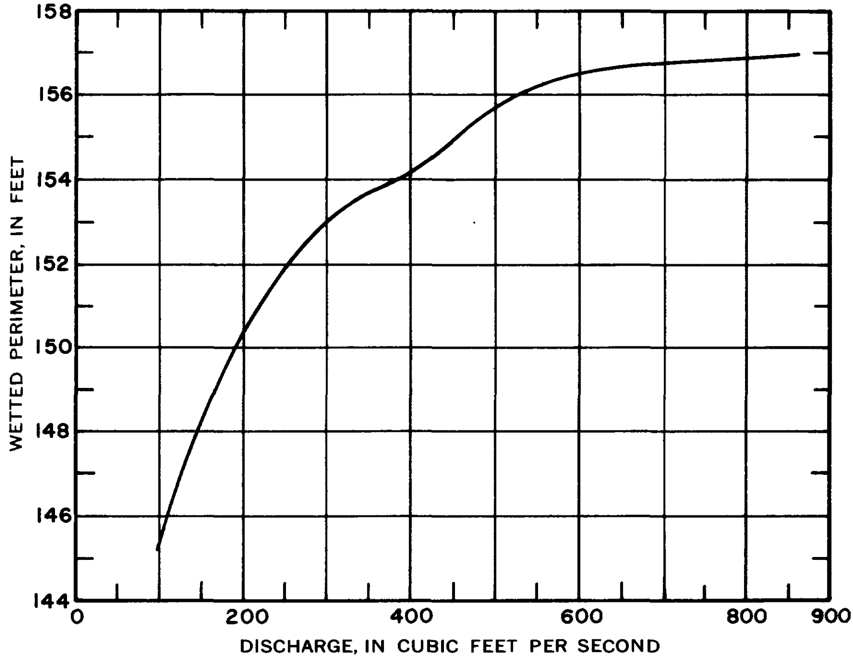
Species: Spring Chinook
Discharge: 528 cfs
Percentage preferred spawning: 10.0
Percentage preferred velocity: 26.5
Percentage preferred depth: 21.8



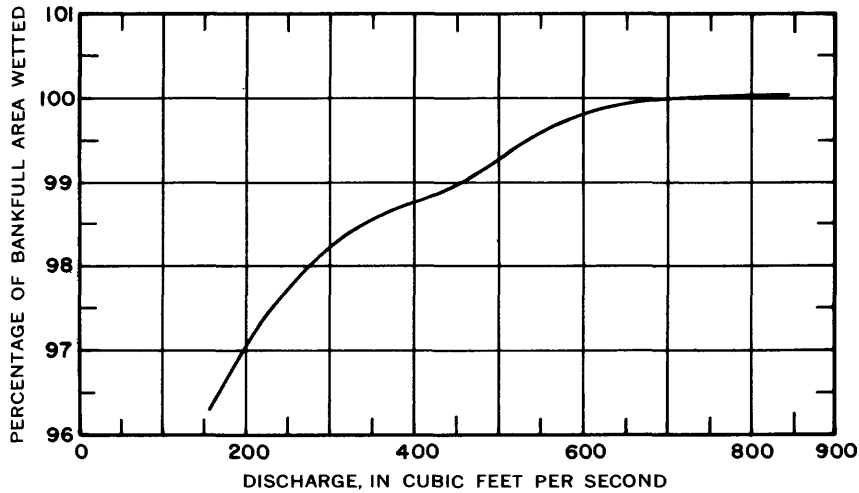
Species: Coho
Discharge: 352 cfs
Percentage preferred spawning: 9.6
Percentage preferred velocity: 49.7
Percentage preferred depth: 14.9

FIGURE 43.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Kalama River reach A—Continued.

but on the right side a poorly defined flood plain exists; this plain is inundated by high flows that build up behind the downstream channel island. At lower flows the riffle area extends well into the study area.



A



B

FIGURE 44.—Relation between curve of wetted perimeter versus discharge (graph *A*) and curve of percentage of bankfull area wetted versus discharge (graph *B*), Kalama River reach A.

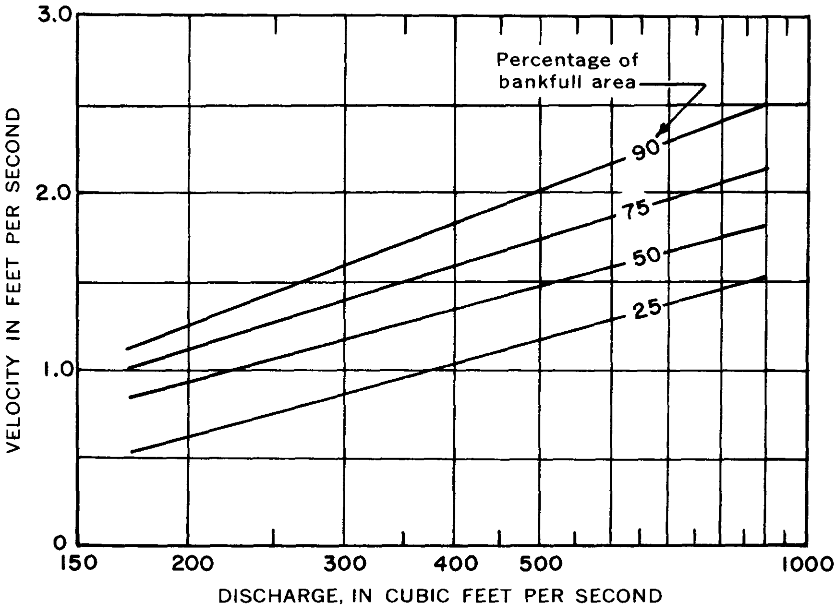


FIGURE 45.—Family of curves showing relation between velocity, discharge, and percentage of bankfull area, Kalama River reach A. Shows selected percentages of reach which have velocities equal to or less than that indicated at a selected discharge.

Discharge measurements covering the range 287–1,690 cfs were used in the analysis. The curves of preferred spawning parameters versus discharge are shown in figure 47. The spawning discharges and areas for the trend-fitted peaks and the selected discharge reductions for the four species are given in table 15.

The preferred spawning areas of reach B (fig. 48) occur mainly on the left side of sections 2 through 4 and on the right side of the channel over sections 3 and 4. The greater depth and, for most discharges, the higher velocities in midchannel limit spawning at section 1.

A discharge of about 400 cfs (fig. 49*A*) is the most advantageous discharge for rearing on reach B. The relation between wetted perimeter and discharge shows the effect of the branching channel by the break in the curve at about 450 cfs. As would be expected, the channel branching also causes a break in the relation between percentage of bankfull area wetted and discharge, shown in figure 49*B*. This graph is used in conjunction with the velocity versus discharge versus percentage of bankfull area curves (fig. 50) for

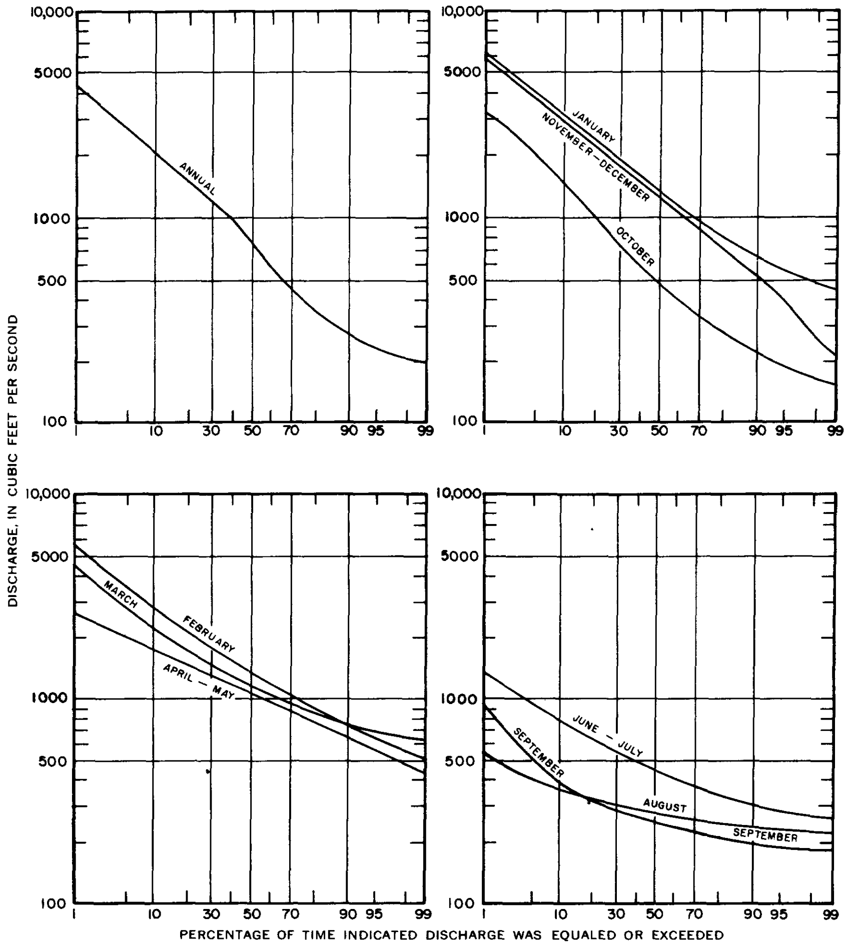
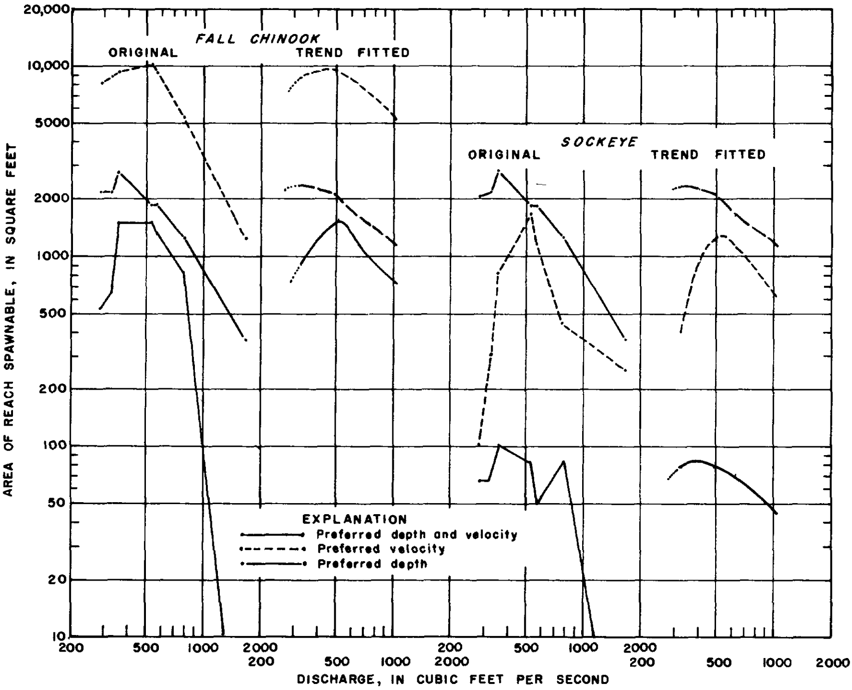
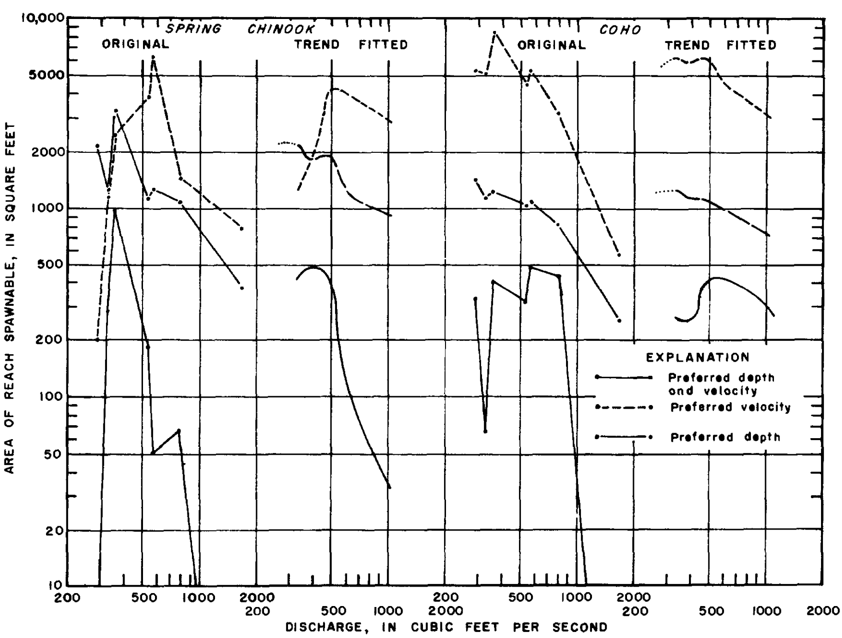


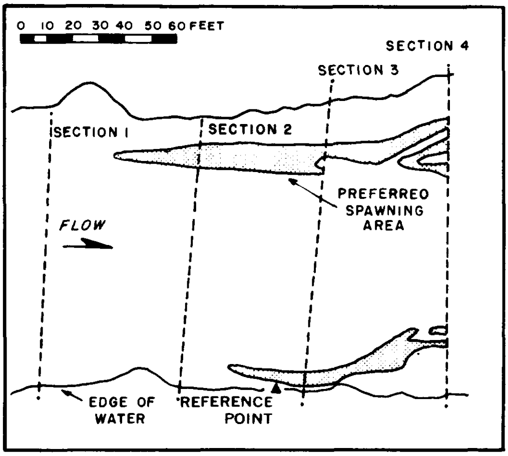
FIGURE 46.—Monthly and annual flow durations, Kalama River reach A.

determining the area of the reach with velocities equal to or less than a certain magnitude at a specified discharge. For the rearing discharge of 400 cfs, 96 percent of the bankfull area is wetted (fig. 49*B*), or 4 percent is dry. Also at 400 cfs, 50 percent of the reach has velocities equal to or less than 1.5 fps (fig. 50), but since 4 per-

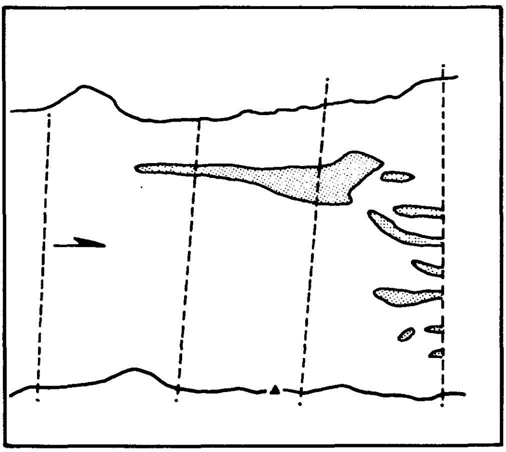
FIGURE 47.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of four salmon species, Kalama River reach B. Curves show the original and the trend-fitted data based on a three-point moving average. The bankfull area of the reach is 16,800 square feet.


FALL CHINOOK
ORIGINAL
TREND FITTED
SOCKEYE
ORIGINAL
TREND FITTED
AREA OF REACH SPAWNABLE, IN SQUARE FEET
20,000
10,000
5000
2000
1000
500
200
100
50
20
10
EXPLANATION
Preferred depth and velocity
Preferred velocity
Preferred depth
200 500 1000 2000
200 500 1000 2000
200 500 1000 2000
200 500 1000 2000
DISCHARGE, IN CUBIC FEET PER SECOND


SPRING CHINOOK
ORIGINAL
TREND FITTED
COHO
ORIGINAL
TREND FITTED
AREA OF REACH SPAWNABLE, IN SQUARE FEET
10,000
5000
2000
1000
500
200
100
50
20
10
EXPLANATION
Preferred depth and velocity
Preferred velocity
Preferred depth
200 500 1000 2000
200 500 1000 2000
200 500 1000 2000
200 500 1000 2000
DISCHARGE, IN CUBIC FEET PER SECOND



Species: Fall Chinook
Discharge: 355 cfs
Percentage preferred spawning: 9.1
Percentage preferred velocity: 55.7
Percentage preferred depth: 16.6

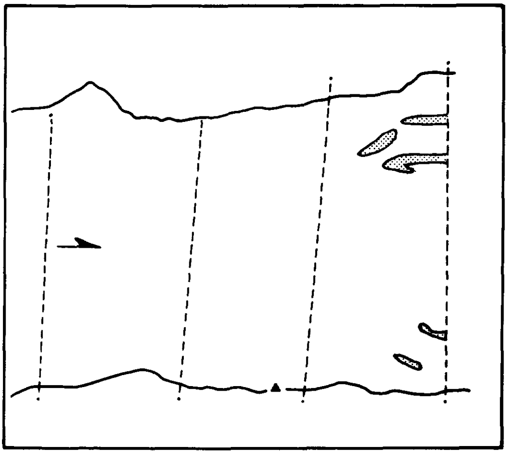


Species: Spring Chinook
Discharge: 355 cfs
Percentage preferred spawning: 5.9
Percentage preferred velocity: 14.3
Percentage preferred depth: 19.6

FIGURE 48.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Kalama River reach B.

cent of the 50 percent bankfull area is dry, 46 percent of the bankfull area of the reach is wetted and has velocities less than or equal to 1.5 fps. It must be remembered that the error involved in this determination is at least equal to the sum of the errors of each of the curves used to derive the values.

Flow-duration curves for reach B were determined by relating discharges at reach B (Q_B) to discharges at the gaging station Kalama River below Italian Creek, near Kalama (Q_G). The relation



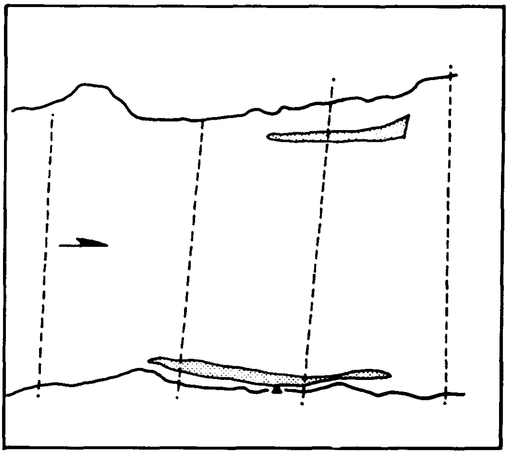


FIGURE 48.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Kalama River reach B—Continued.

is shown by the equation

$$Q_B = 1.11 (Q_G)^{0.97},$$

which has a standard error of estimate of ±7.8 percent. The relation is not significantly different (tested at the 95-percent confidence level) from the relation between reach A and the gaging station; therefore, the duration curves of reach A (fig. 46) also may be used for discharges at reach B. For the most advantageous rearing discharge at reach B (fig. 49*A*), the annual duration curves (fig. 46) show that 400 cfs will be equaled or exceeded 72 percent of the time.

The water-quality characteristics at reach B (table 10) are similar to those at reach A (table 9).

TABLE 10.—*Characteristics of water quality, Kalama River reach B, June 1968–August 1969*

Date	Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/l)	Suspended sediment (mg/l)	Specific conductance (micromhos per cm at 25°C)
June 19	546	10.6	51	10.8	3	----
July 17	355	11.7	53	10.5	1	----
Aug. 16	287	11.1	52	10.7	1	----
28	1,690	10.6	51	10.8	5	----
Sept. 3	518	11.7	53	10.5	1	----
Oct. 29	790	8.9	48	11.2	5	----
Aug. 8	329	12.2	54	10.4	----	51

KALAMA RIVER REACH C

Reach C is the lowest study site (alt is 260 ft) on the Kalama River (fig. 39). Above reach C, the river is 33.0 miles long and drains 157 square miles. Reach C, which covers an area of 22,090 square feet, differs from reaches A and B in that the latter two encompass riffle areas, whereas reach C does not. Reach C is located above a slight bend and also above a bedrock outcrop. Behind the outcrop—and mainly on the inside of the bend (left bank)—gravel has been deposited. The water flows through the gravel behind the bedrock and emerges at the impermeable rock barrier. Thus, the gravel in the bar is well oxygenated and provides an acceptable spawning area for salmon.

From the measurements of depth and velocity for a range of discharges (264–1,660 cfs), the curves showing preferred spawning hydraulic parameters versus discharge were fitted for each of the salmon species studied (fig. 51). These plots show peaks for the original as well as for the trend-fitted data. The spawning discharges and areas for the trend-fitted peaks (fig. 51) and the four discharge reductions and areas for the four species are given in table 15.

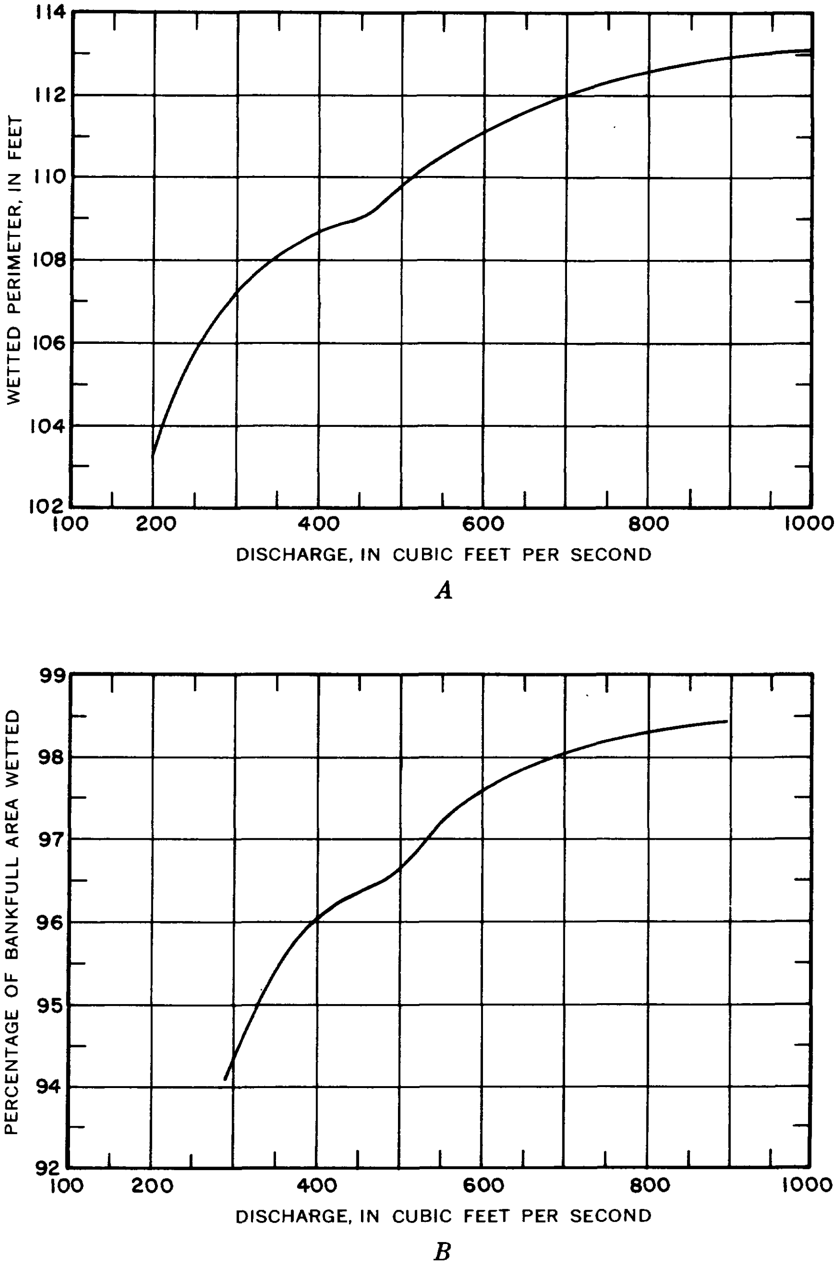


FIGURE 49.—Relation between curve of wetted perimeter versus discharge (graph *A*) and curve of percentage of bankfull area wetted versus discharge (graph *B*), Kalama River reach B.

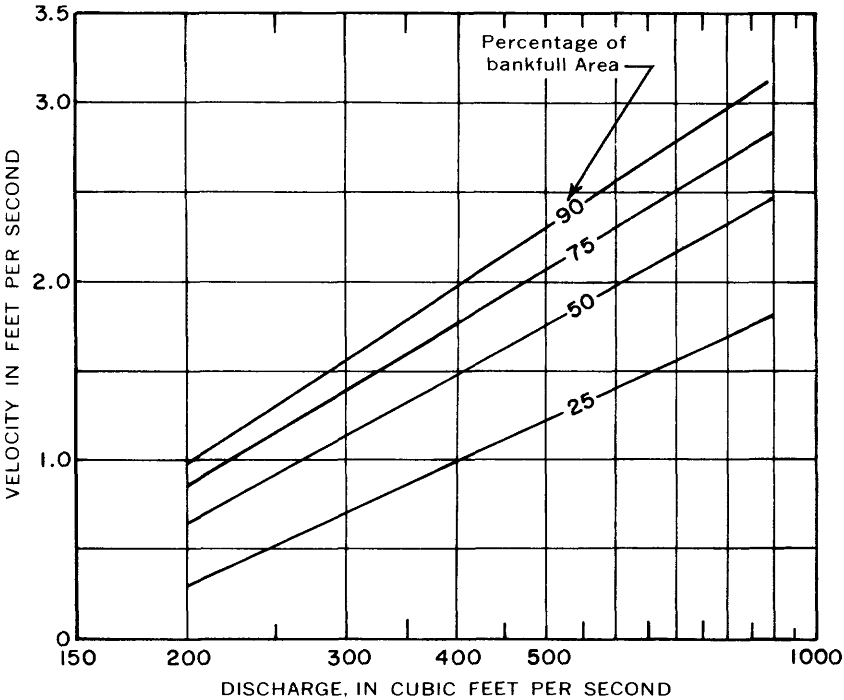


FIGURE 50.—Family of curves showing relation between velocity, discharge, and percentage of bankfull area, Kalama River reach B. Shows selected percentages of reach which have velocities equal to or less than that indicated at a selected discharge.

From the curves in figure 51, measured discharges in the vicinity of the preferred discharge were selected, and the preferred spawning areas (areas where preferred depth overlaps preferred velocity) were delineated on maps of the reach (fig. 52). The map plots (fig. 52) show that the major preferred spawning area is on the left side of the channel which, as mentioned on page 66, is also preferred for spawning because of the flow through the gravel.

Because of the nearly vertical banks, which are 2–3 feet and higher, on either side of the study reach channel, the bankfull area (fig. 52) is covered by water for discharges greater than 300 cfs. At a discharge of 300 cfs, an inflection in the wetted perimeter versus discharge curve (fig. 53*A*) also occurs. Thus, the most advantageous discharge for rearing is at 300 cfs, above which the wetted perimeter increases only a small amount with increases in discharge.

For the rearing discharge of 300 cfs, 75 percent of the bankfull area of the reach has velocities of 1.2 fps or less (fig. 54). However,

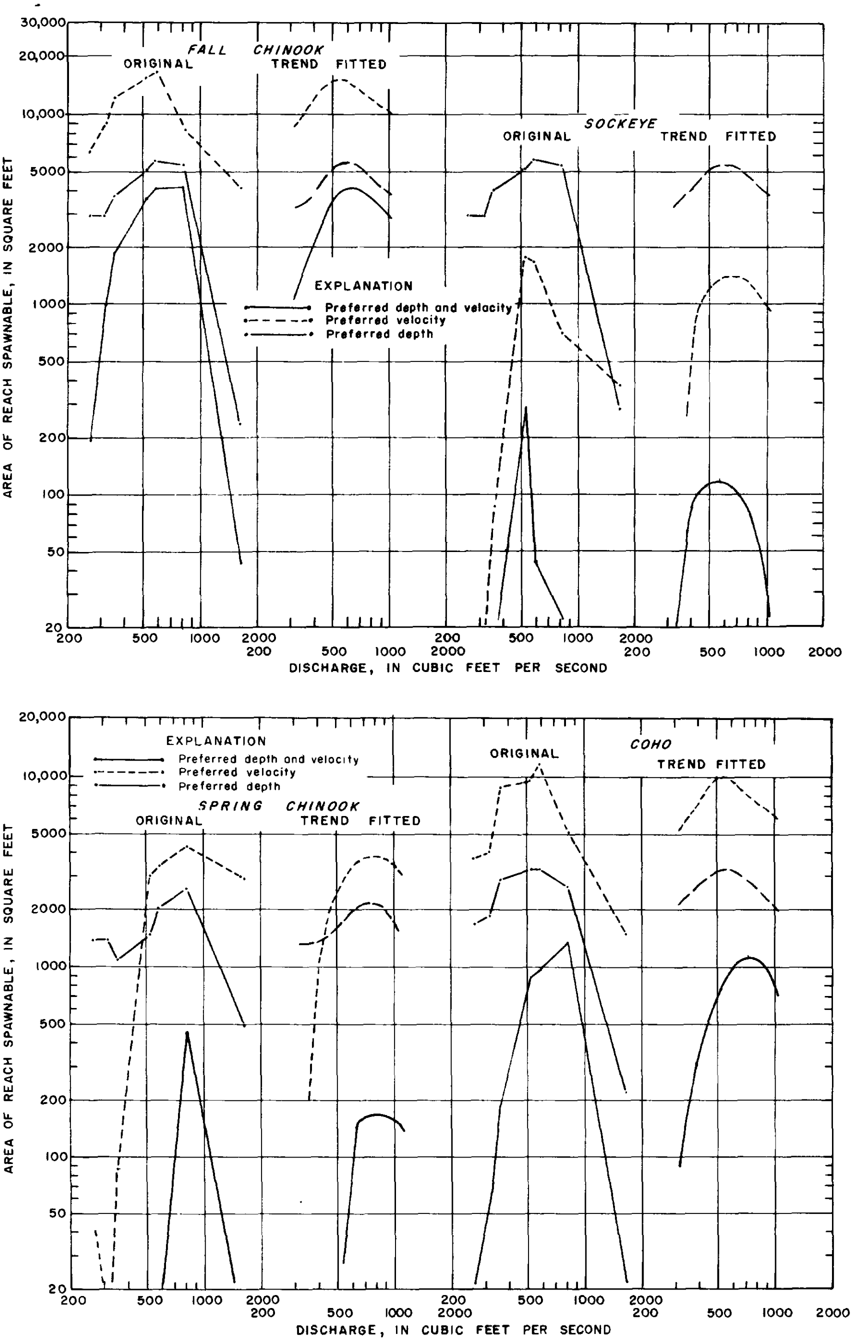
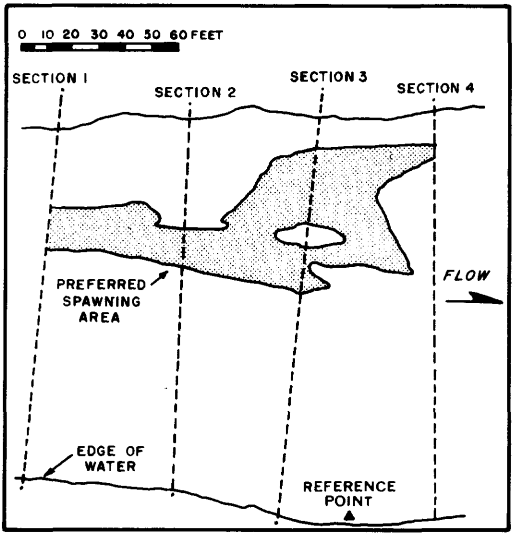
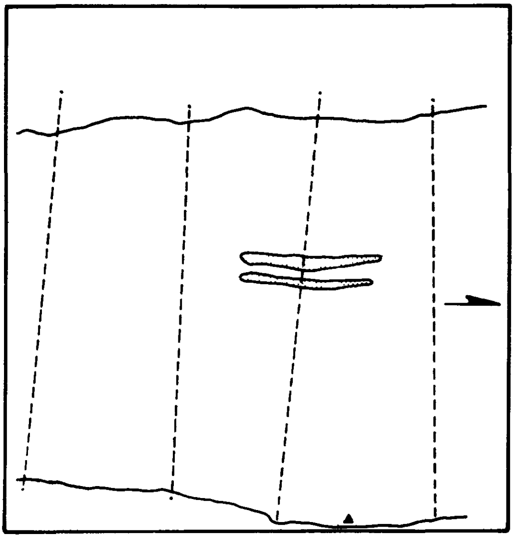


FIGURE 51.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of four salmon species, Kalama River reach C. Curves show the original and the trend-fitted data based on a three-point moving average. The bankfull area of the reach covers 22,090 square feet.

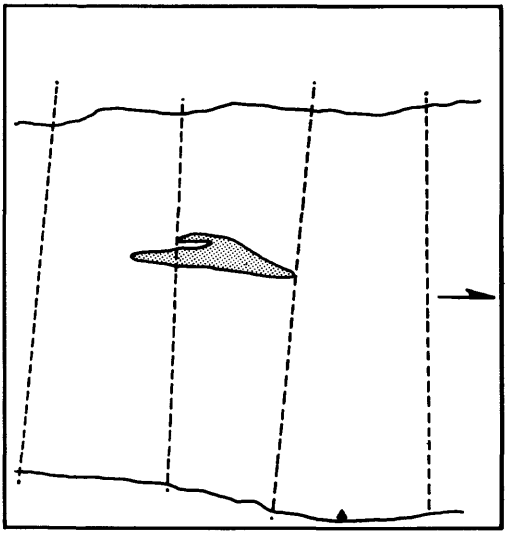


Species: Fall Chinook
Discharge: 583 cfs
Percentage preferred spawning: 18.5
Percentage preferred velocity: 17.1
Percentage preferred depth: 26.1

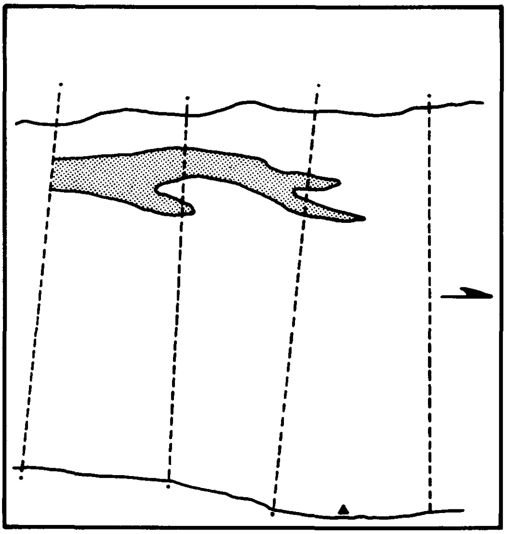


Species: Sockeye
Discharge: 528 cfs
Percentage preferred spawning: 1.3
Percentage preferred velocity: 8.1
Percentage preferred depth: 23.8

FIGURE 52.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Kalama River reach C.

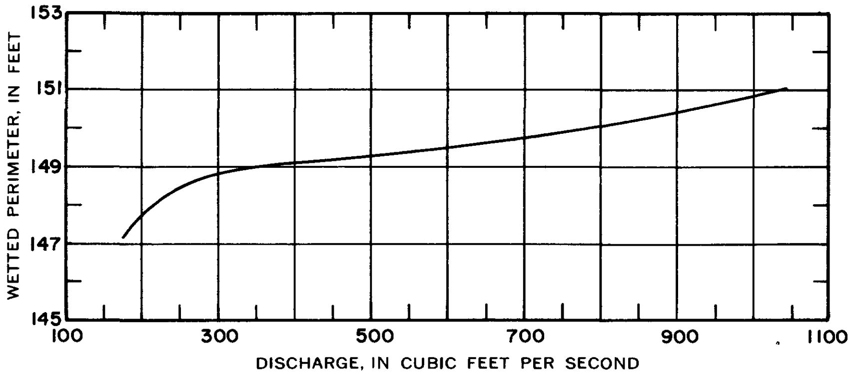


Species: Spring Chinook
Discharge: 822 cfs
Percentage preferred spawning: 2.06
Percentage preferred velocity: 18.6
Percentage preferred depth: 11.8

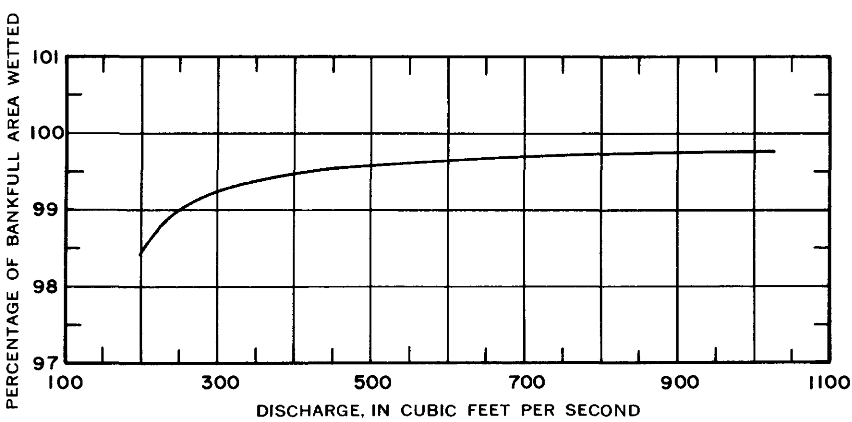


Species: Coho
Discharge: 822 cfs
Percentage preferred spawning: 8.2
Percentage preferred velocity: 27.8
Percentage preferred depth: 11.8

FIGURE 52.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, Kalama River reach C—Continued.



A



B

FIGURE 53.—Relation between curve of wetted perimeter versus discharge (graph *A*) and curve of percentage of bankfull area wetted versus discharge (graph *B*), Kalama River reach C.

99 percent of the bankfull areas is wetted and 1 percent is dry (fig. 53*B*); therefore, 74 percent of the wetted area (16,350 sq ft) has velocities less than 1.2 fps.

The flow-duration curves for reach C (fig. 55) were determined by relating the discharge at reach C (Q_C) to the discharge downstream

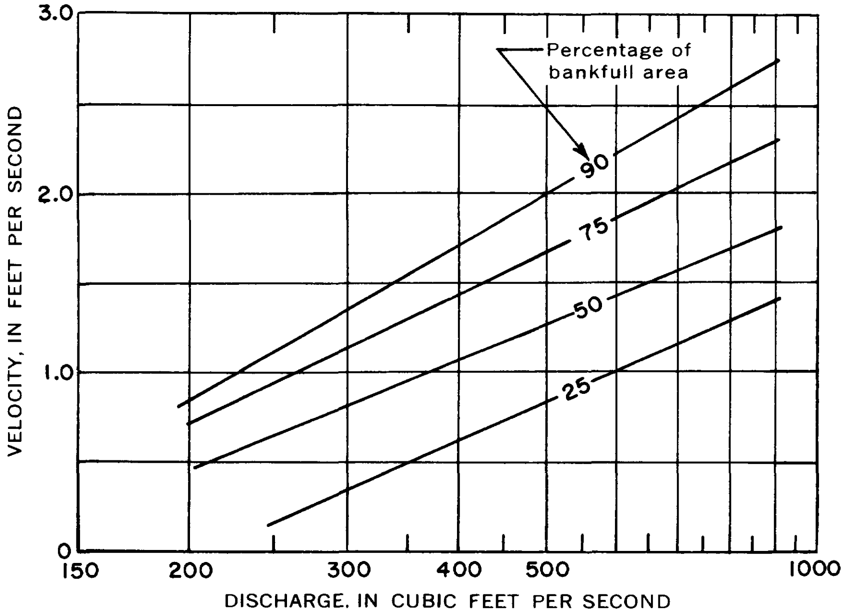


FIGURE 54.— Family of curves showing relation between velocity, discharge, and percentage of bankfull area, Kalama River reach C. Shows selected percentages of reach which have velocities equal to or less than that indicated at a selected discharge.

(Q_G), gaging station Kalama River below Italian Creek, near Kalama. The relation was found to be

$$Q_C = 1.08 (Q_G)^{0.98}$$

and had a standard error of estimate of ±6.8 percent. From the flow-duration curves (fig. 55), the occurrence of 800 cfs, the peak spawning flow for spring chinook (fig. 51), will be equaled or exceeded 3 percent of the time in September, 30 percent in October, and 76 percent of the time for the November–December period. The rearing discharge of 300 cfs (from fig. 53*A*) will be equaled or exceeded 85 percent of the time annually (fig. 55).

Table 11 gives water-quality measurements obtained over a range of discharges in the summer and fall of 1968. The suspended-sediment-concentration average is slightly higher for reach C (7 mg/l) than for reach A (2 mg/l) and reach B (3 mg/l), but it is not excessive at any reach.

TABLE 11.—*Characteristics of water quality, Kalama River reach C, June 1968–August 1969*

Date	Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/l)	Suspended sediment (mg/l)	Specific conductance (micromhos per cm at 25°C)
June 19	583	11.4	52.5	10.6	11	----
July 17	358	12.8	55	10.2	1	----
Aug. 15	264	12.2	54	10.4	1	----
28	1,660	10.6	51	10.8	8	----
Sept. 4	528	11.1	52	10.7	5	----
Oct. 29	822	8.9	48	11.2	18	----
Aug. 8	320	13.3	56	10.2	----	52

NORTH FORK NOOKSACK RIVER

The Nooksack River basin is in the northwestern part of the State. Streamflow originates on the western slope of the northern Cascade Range and terminates in Lummi Bay on the Strait of Georgia, west of Bellingham.

The salmon study was conducted on the North Fork Nooksack River (fig. 1). Some of the tributaries in the headwaters have their source at altitudes of about 6,500 feet. The main-stem source altitude is about 3,600 feet. During melting periods several large glaciers on Mounts Baker and Shuksan contribute to the flow of the river. The bed of the North Fork Nooksack River is heavily charged with gravel, and in many places the stream has numerous small interlacing, or braided, channels. The braiding of the stream is caused by the waters passing through the streambed gravels and subsequently dropping their load, which clogs the channel. The gravel-bar dams that are constantly being deposited force frequent position changes in the channel by splitting it into anabranches which reunite downstream with the main stem. Other reaches of the channel are controlled by bedrock and have little or no definite flood plain. At these places, if the channel slope is steep enough, rapids are present; if the channel slope is not steep, there is one gravel-filled channel—generally a riffle. The three reaches selected for study on the Nooksack (fig. 56) experienced shifting of bed material during the investigation period, but they are probably as stable, or more stable, than any other spawned section that could be chosen on this river.

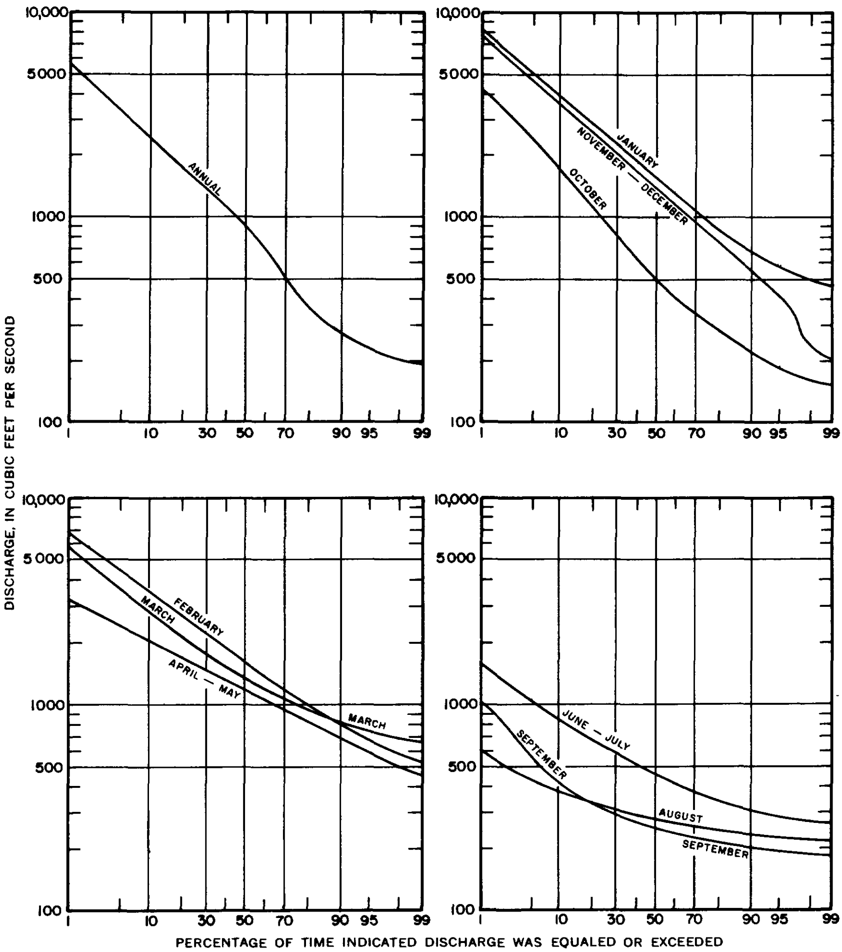


FIGURE 55.—Monthly and annual flow durations, Kalama River reach C.

Curves of average grading of gravels on study reaches of the North Fork Nooksack River are shown in figure 57. Reach B gravel sizes are similar to those of the Dewatto and Cedar River study reaches, but gravels of reaches A and C approximate those of the study reaches on the Kalama River.

Aerial photographs were taken of the North Fork Nooksack River from the powerplant at Excelsior, about 1.5 miles above reach A (fig. 56), to the confluence with the South Fork—a distance of 33 river miles with 28.3×10^6 square feet of river surface (8.54×10^5 sq ft per mi). From the stereo pairs of aerial photographs, the areas of pools and riffles were delineated and measured. Examination

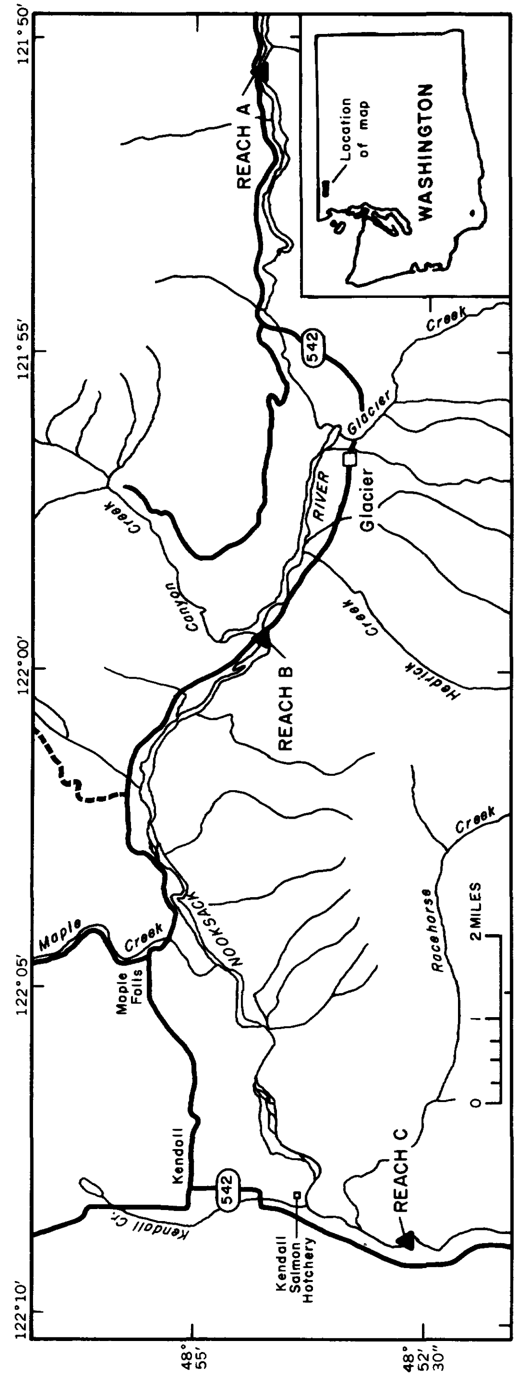


FIGURE 56.—Study reaches on North Fork Nooksack River.

shows that the photographed part has 52.5-percent pool area and 47.5-percent riffle area.

The percentage of riffle area was determined for reach A by using the distance from the powerplant at Excelsior to a point midway between reaches A and B; for reach B, by using the distance from the point midway between reaches A and B to a point midway between reaches B and C; and for reach C, by using the distance from the midway point between B and C to the confluence with the South Fork. Reach A contains 64.2 percent riffles, and the channel slope for the total main stem above A is 106 feet per mile; reach B has 56.7 percent riffle area with the slope of the total main stem above B being 97 feet per mile; and reach C has 26.1 percent riffles, with the slope of the main stem above having decreased to 71 feet per mile.

Flows of the river during the winter-early spring period (fig. 58) are typical of a glacier-fed stream; however, at these low flows there is some minor regulation from the operation of a powerplant at Excelsior. During the winter, the glacier flow will decrease because of freezing, and the lowest discharges of the year occur at

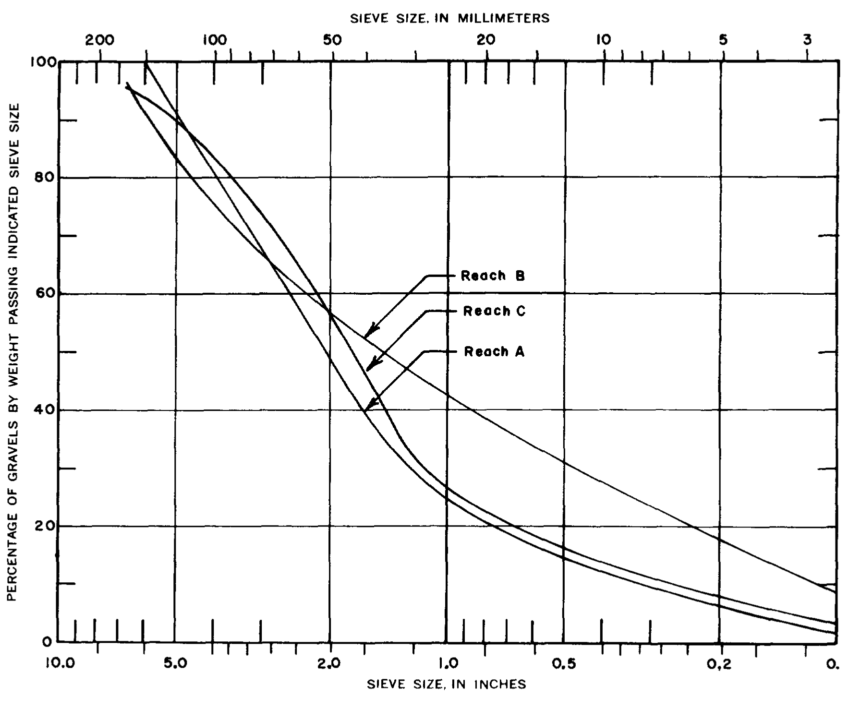


FIGURE 57.—Curves showing average grading of several samples of gravels found on natural spawning grounds of North Fork Nooksack River.

this time. With spring snowmelt and increased flow from the glaciers as the air temperature rises, the river stage rises to a peak in June. Streamflow at the upper station, North Fork Nooksack River below Cascade Creek near Glacier (fig. 58*A*), the site of reach A, does not reflect the winter rains (October through January) as much as the discharge at the lower station, North Fork Nooksack River near Deming, the site of reach C (fig. 58*B*), because precipitation above reach A occurs more often as snow.

The annual cycle of river temperatures (fig. 59) reflects the seasonal climate; lows occur in February and highs occur in July. The curves in figure 59 were computed from 365 values each for maxi-

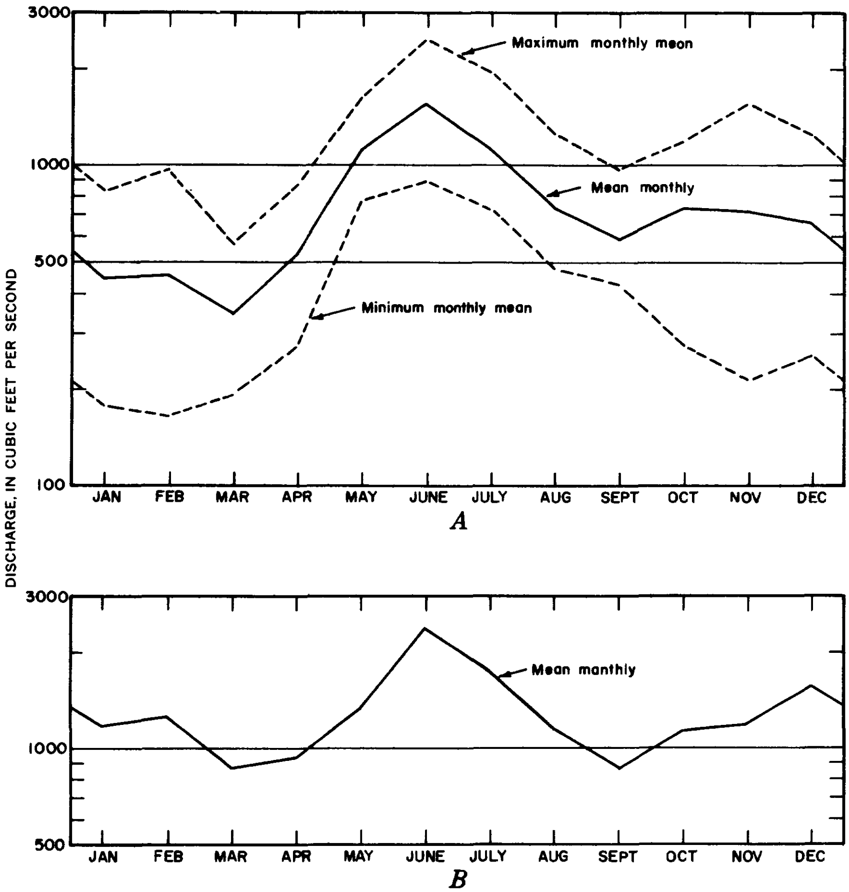


FIGURE 58.—Mean monthly discharge and maximum and minimum monthly mean discharges, North Fork Nooksack River below Cascade Creek near Glacier, 1950–67 (graph *A*), and mean monthly discharge, North Fork Nooksack River near Deming, 1965–67 (graph *B*).

mum, mean, and minimum water temperatures in the calendar year 1968. The curve fitting the maximum daily water temperatures defines 84 percent of the variance of the data and has a standard error of estimate of ±1.4°C. The mean daily water-temperature curve defines 89 percent of the variance of the data and has a standard error of estimate of 1.0°C. The curve defining the minimum daily temperatures accounts for 89 percent of the variance and has a standard error of estimate of 0.9°C.

The diurnal fluctuations of stream temperature during the summer months, at times, amount to as much as 6°C (11.0°F). These diurnal fluctuations are due to a larger contribution of cooler melt waters from glaciers during the daylight hours and to the reduction of this colder-water flow at night, when most of the streamflow is from lower-altitude snowmelt and ground-water inflow. Although the lower-altitude snowmelt water is at about the same temperature as the glacier melt water, the latter occurs at the sources of the streams, whereas snow after melting generally becomes overground runoff, which is warmed before it enters the stream.

The major salmon species frequenting the North Fork Nooksack River and its tributaries are the coho, chum, pink, and fall chinook. Typically, spawning occurs later (about December–March) in the North Fork than in non-glacier-fed streams. The winter and early

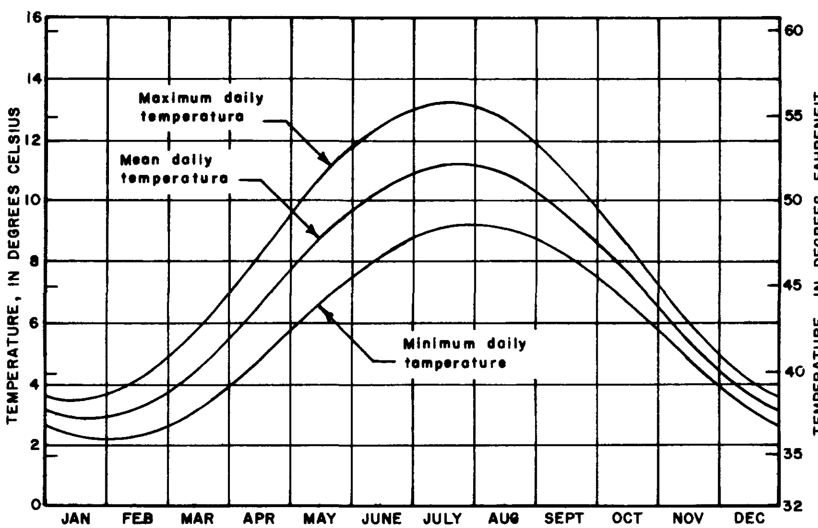


FIGURE 59.—Maximum, minimum and mean daily water temperatures, North Fork Nooksack River near Deming. Data from harmonic fitting of thermograph record for 1968.

spring months are the low-flow period (fig. 58). Discharges are low because precipitation is in the form of snow and the glaciers are contributing little or no water, resulting in clearer water (without "glacier flour") and a more stable streambed. Also, the water temperature begins to rise in March (fig. 59), facilitating hatching and food growth for later rearing.

NORTH FORK NOOKSACK RIVER REACH A

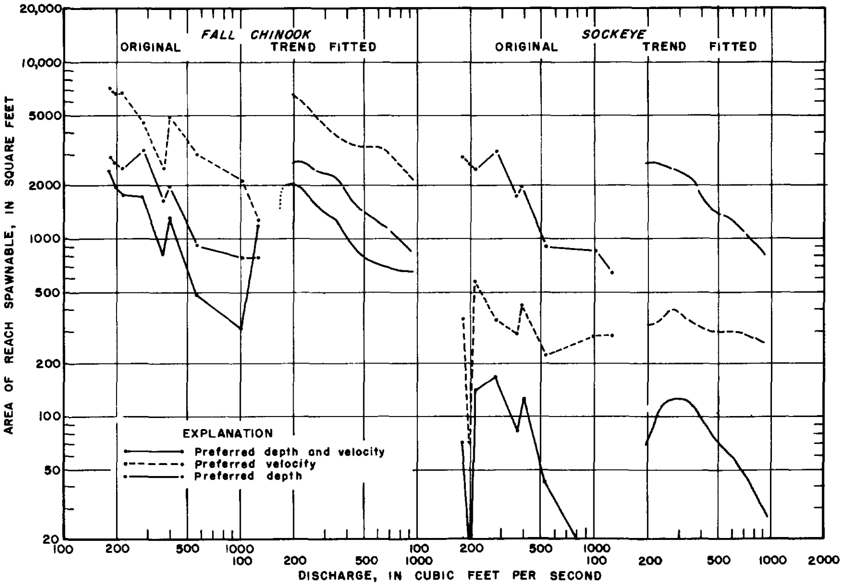
Reach A is located (fig. 56) just below the gaging station (North Fork Nooksack River below Cascade Creek, near Glacier) and encompasses 13,880 square feet. Reach A is the highest study reach on the river, having an altitude of 1,245 feet. Above reach A, the main river stem is 17.6 miles long and drains a 105-square-mile area that has a mean altitude of 4,300 feet.

Bedrock is exposed in the channel just above the study reach, and large boulders are randomly distributed in the channel below the reach. The right bank of the reach is very steep and rises more than 15 feet above the channel bed. The left side of the reach has a shallow cross-sectional gradient for a short distance, then rises about 4 feet and flattens toward a Forest Service picnic ground away from the reach.

The peaks for spawnable areas and discharges and the values for the selected percentages of reduction of discharge and area are given in table 15. These discharge values were obtained from the trend-fitted curves in figure 60. In two of the four plots, the trend-fitted curves are not well defined on the low discharge side; however, by extrapolating between the original curves and the trend-fitted velocity and depth curves, the breakover is estimated (estimated values in table 15 are given in parentheses). Also, the exceedance percentage of the peaking discharge (fig. 64) is very high, indicating that preferred spawning discharges will be available most of the time under natural conditions.

The preferred spawning areas within reach A (fig. 61) tend to be located on the left side of the reach. This probably is due to the midstream velocities being slowed by the upstream bedrock outcrop; also, the river bends to the left below the reach, and its greatest flow is forced onto the steep right bank. The streambed lithology also is more desirable on the left side of the river because it consists of more gravel and fewer large rocks.

The curve for the relation of wetted perimeter versus discharge (fig. 62*A*) is representative mainly of the left side of the channel, the right side being very steep. Two breaks in the curve are noted;



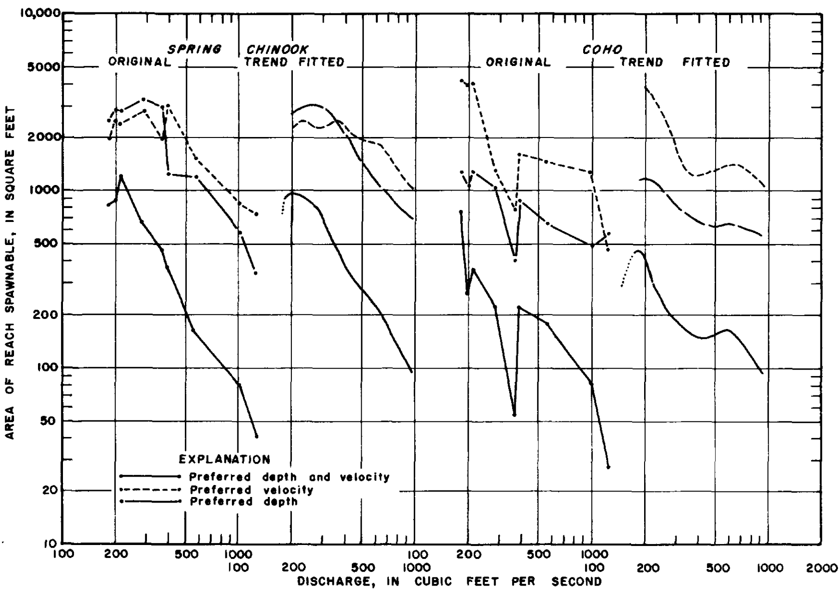
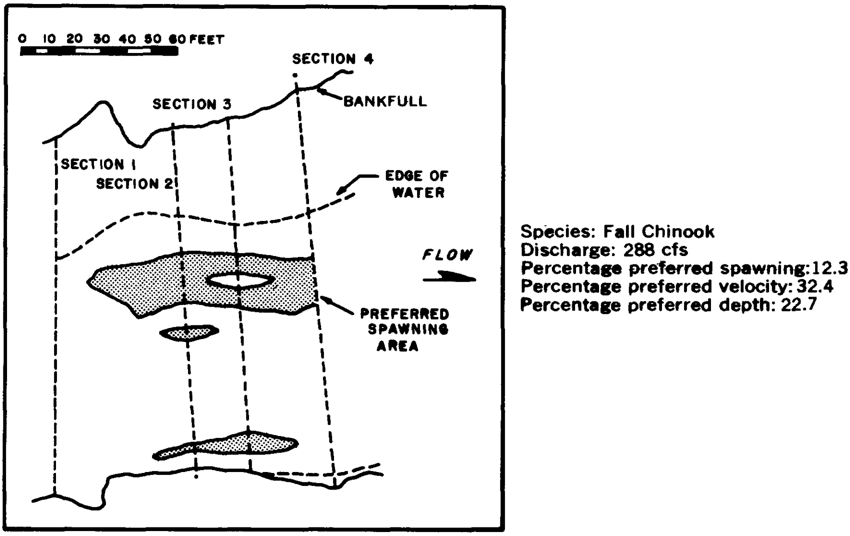


FIGURE 60.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of four salmon species, North Fork Nooksack River reach A. Curves show the original and the trend-fitted data based on a three-point moving average. The bankfull area of reach covers 13,880 square feet.



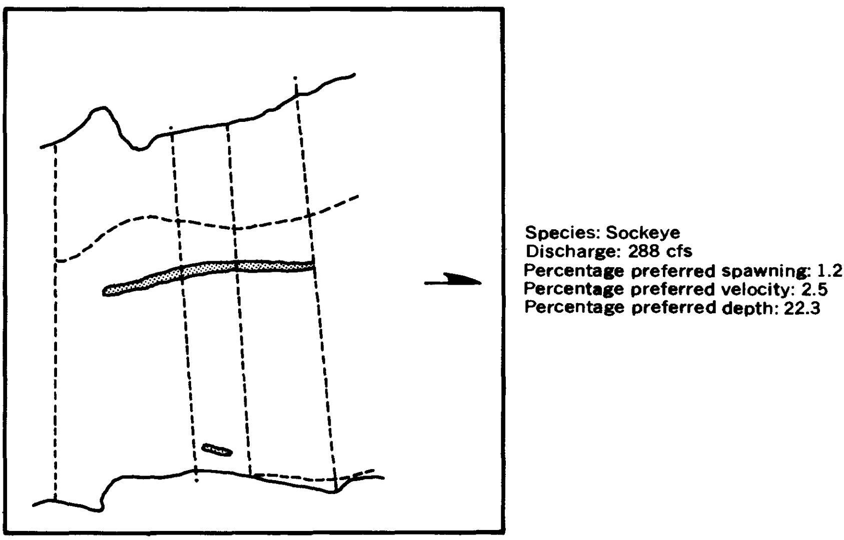
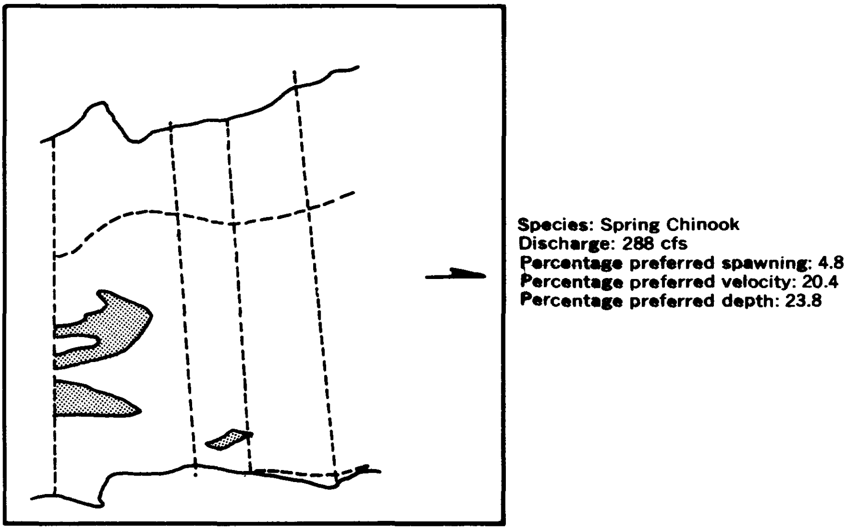


FIGURE 61.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, North Fork Nooksack River reach A.

one break occurring at a little less than 200 cfs (near the minimum preferred spawning discharge) and the other more definite break occurring at about 750 cfs. The wetted perimeter increases 35 feet, from 95 feet at 200 cfs to 130 feet at 750 cfs. Either of these curve



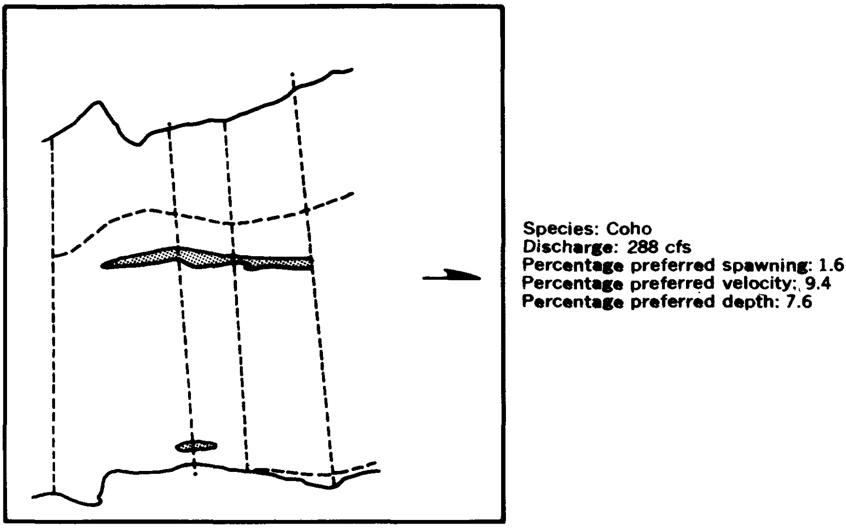
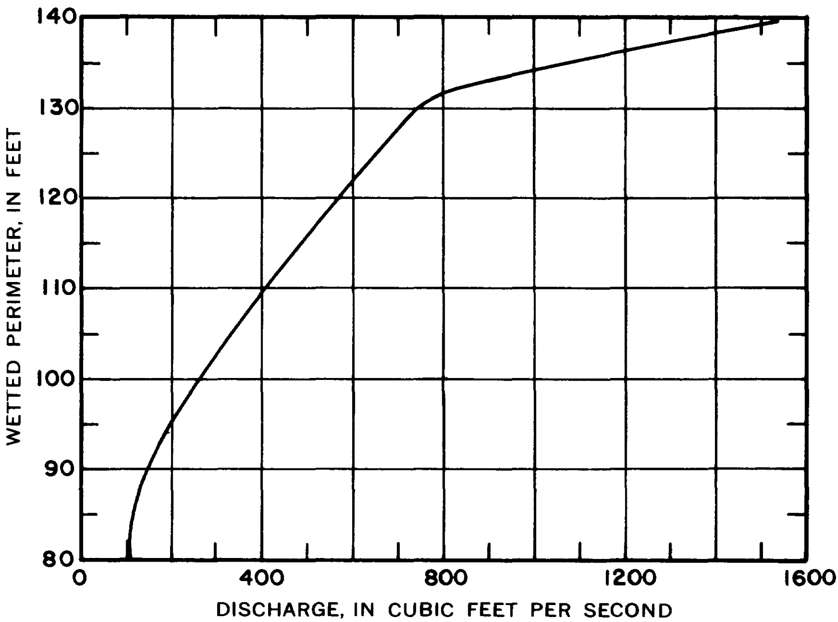
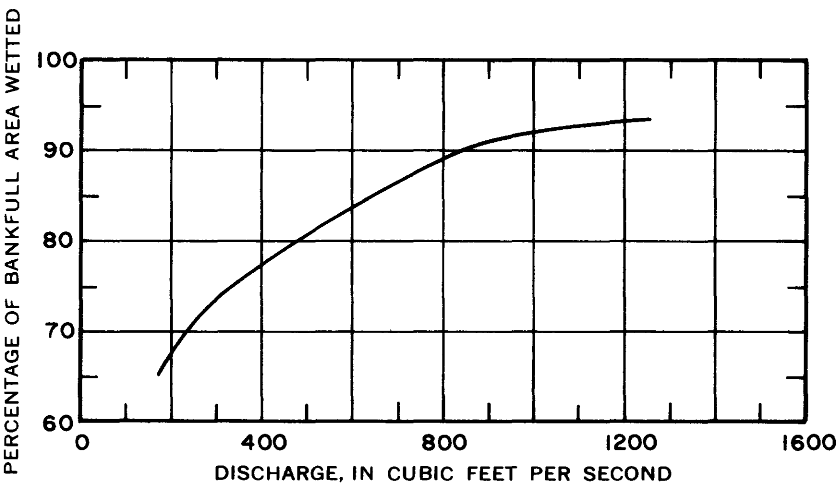


FIGURE 61.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, North Fork Nooksack River reach A—Continued.

breaks could be considered the point for the preferred rearing discharge; as would be expected, however, the exceedance percentage of the lower discharge is much greater than that of the upper flow (fig. 64).



A



B

FIGURE 62.—Relation between curve of wetted perimeter versus discharge (graph *A*) and curve of percentage of bankfull area wetted versus discharge (graph *B*), North Fork Nooksack River reach A.

Figure 62*B* shows the percentage of bankfull area wetted versus discharge. This percentage was used in conjunction with the percentage of bankfull area versus velocity versus discharge curves (fig. 63) to evaluate the velocities over the reach at the preferred rearing flows.

Duration curves showing the percentage of time that annual and monthly discharges are equaled or exceeded at reach A (fig. 64) were

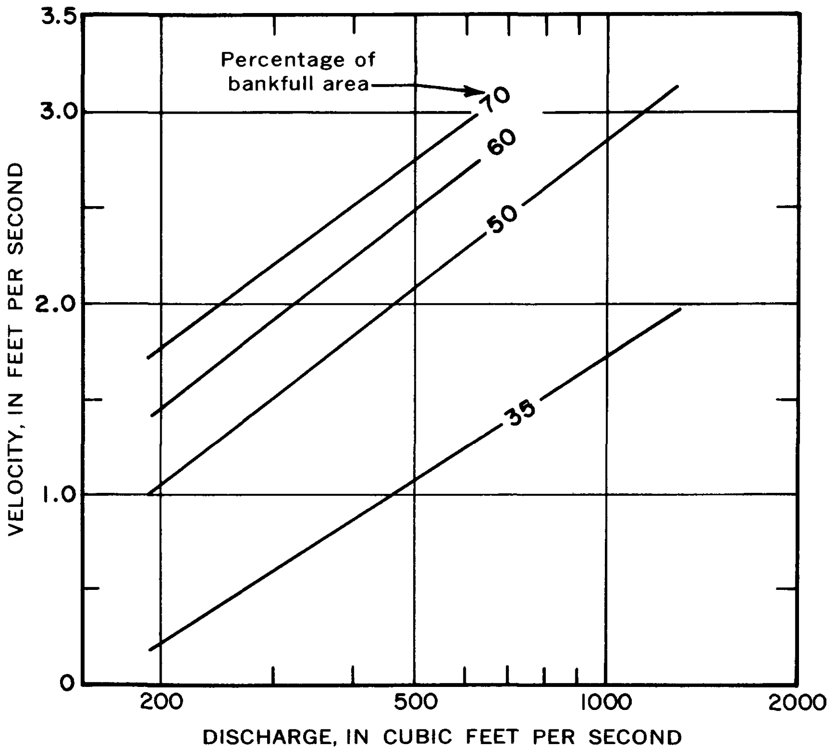


FIGURE 63.—Family of curves showing relation between velocity, discharge, and percentage of bankfull area, North Fork Nooksack River reach A. Shows selected percentages of reach which have velocities equal to or less than that indicated at a selected discharge.

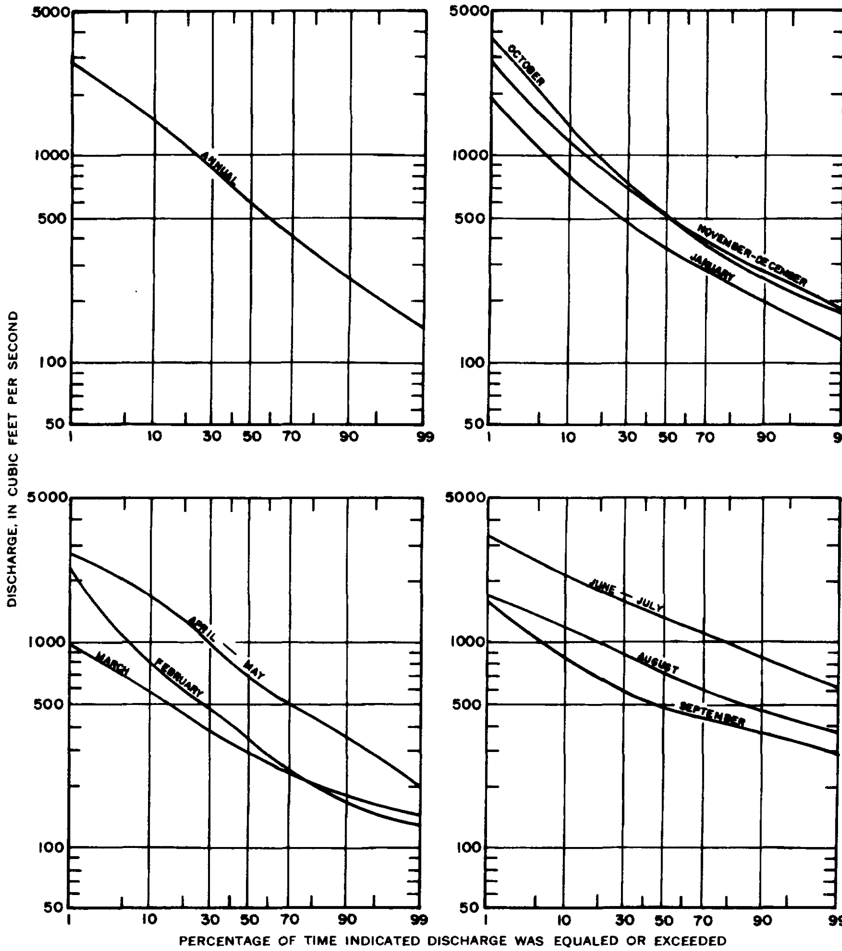


FIGURE 64.—Monthly and annual flow durations, North Fork Nooksack River reach A.

computed from records of the North Fork Nooksack River above Cascade Creek for the period 1938–66. The preferred spawning discharges at the peak (fig. 60) for all species except sockeye are within the 180–200 cfs range. A discharge of 190 cfs will be equaled or exceeded 98 percent of the time in the November–December period, 91 percent of the time in January, 82 percent of the time in February, and 85 percent of the time in March. As seen by the exceedance percentages, a discharge of 190 cfs could be realistically maintained by the natural discharge of the stream during the spawning period.

The lowest rearing flow (200 cfs), will be exceeded annually 96 percent of the time (fig. 64), but the higher rearing discharge (750 cfs) will be exceeded annually only 37 percent of the time. Thus, the chances of obtaining the lowest rearing discharge (200 cfs) are much more favorable, even though there is 35 feet less wetted perimeter for the lower discharge than for the higher rearing discharge.

Water-quality parameters collected at reach A are listed in table 12. As would be expected for glacial streams, both the suspended-sediment concentration and specific conductivity are higher than for the other streams studied. However, for the measurements made, neither is excessive and, by observation, does not seem to be detrimental to fish life.

TABLE 12.—*Characteristics of water quality, North Fork Nooksack River reach A, April 1968–October 1969*

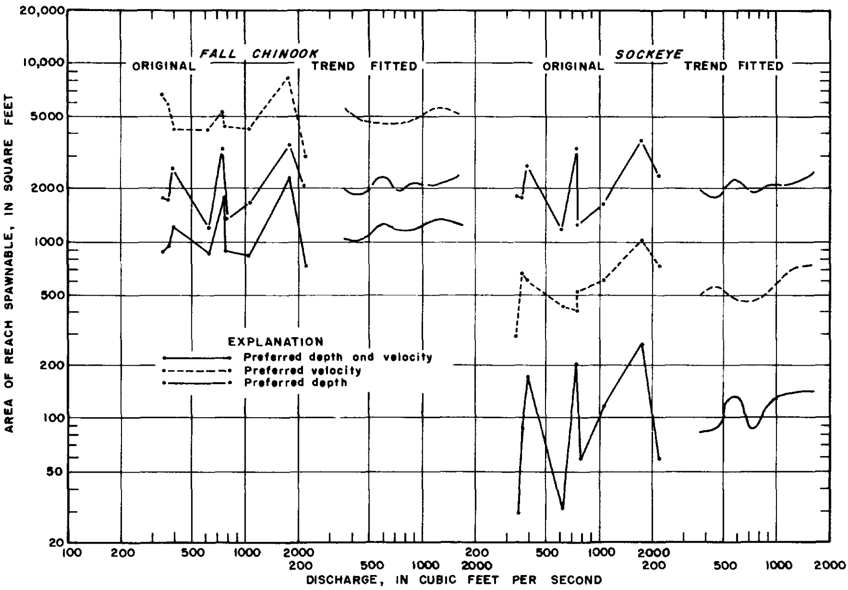
Date		Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/l)	Suspended sediment (mg/l)	Specific conductance (micromhos per cm at 25°C)
Apr.	4	370	4.4	40	12.5	----	----
	18	288	4.4	40	12.5	----	----
May	3	570	4.4	40	12.5	7	----
	27	1,010	5.8	42.5	12.1	30	----
June	24	1,270	8.9	48	11.3	30	----
Oct.	9	397	5.6	42	12.2	0	----
Dec.	23	360	2.8	37	13.1	----	91
Feb.	5	200	.8	33.5	13.8	3	85
	18	213	1.9	35.5	13.4	0	97
	25	185	2.2	36	13.3	1	98
Oct.	8	1,800	6.7	44	11.9	----	46

NORTH FORK NOOKSACK RIVER REACH B

The middle study reach on the North Fork Nooksack River is denoted as reach B and is located about a quarter of a mile below the inflow of Canyon Creek (fig. 56). Above reach B (alt 720 ft), the main river is 25.5 miles long and drains an area of 193 square miles.

Reach B covers a surface area of 28,750 square feet. At flows greater than 2,500 cfs, the stream below the reach is divided into two channels. At lower discharges, the main flow is on the right at the upper end of the reach and moves to the left at the lower end. The right bank is riprapped with large boulders near the upper end of the reach, and abandoned railroad-bridge abutments stand on both banks near the center of the reach.

The relations between discharge and area of reach with preferred spawning conditions (fig. 65) were trend fitted to smooth out any peaks or outlier measurements (one-point peaks) which do not



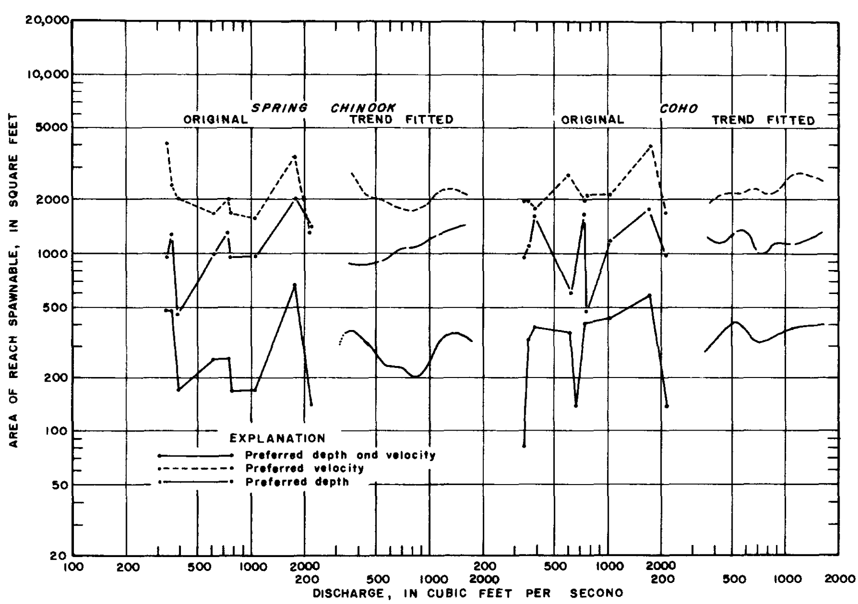


FIGURE 65.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of four salmon species, North Fork Nooksack River reach B. Curves show the original and the trend-fitted data based on a three-point moving average. Bankfull area of reach covers 28,750 square feet.

have enough data to be substantiated or do not conform to the trend. The original plots (fig. 65) show several peaks, in most places, three; but after trend fitting, one peak is defined and another, at a higher discharge, is open ended. This higher discharge peak is the result of the gravel bar on the left side of sections 1 and 2 being inundated at higher stages. The peak spawnable areas and discharges for the lowest peak of the preferred spawning curves (fig. 65), and the areas and discharges for the percentage discharge reductions are given in table 15.

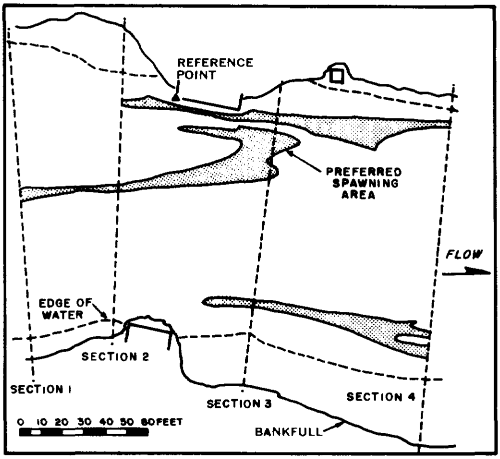
The preferred spawning areas in reach B (fig. 66) tend to be located near the left side of the channel between sections 2 and 4 and on the right side of the channel between sections 3 and 4. The area on the right side between sections 1 and 2 is too deep and fast for spawning, and the left side between sections 1 and 2 is generally too shallow for spawning. Also, the boulder riprap on the right bank at the upper end of the reach makes this section undesirable for spawning.

The curve showing the relation between wetted perimeter and discharge (fig. 67*A*) is used to determine the preferred rearing discharge. The preferred rearing discharge was selected at the first break in the wetted perimeter curve, which occurs at a discharge of 560 cfs. Figure 67*B*, showing percentage of bankfull area wetted versus discharge, is used in conjunction with figure 68 to evaluate the velocity over the reach for the preferred rearing discharge. For example, at 560 cfs, 64 percent of the bankfull area is wetted (fig. 67*B*), or 36 percent is dry. Also, at this discharge, 60 percent of the bankfull area has velocities equal to or less than 1.3 fps; thus, 24 percent (60—36) of the bankfull area of the reach is wetted and has velocities less than 1.3 fps.

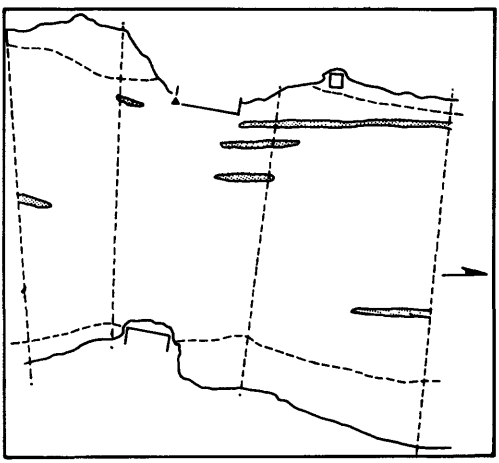
The annual and monthly flow-duration curves (fig. 69) were determined by relating the discharges of reach B (Q_B) to the discharges (Q_A) at the long term gaging station (North Fork Nooksack River above Cascade Creek, near Glacier). The relation is shown by the equation

$$Q_B = 4.84\,(Q_A)^{0.85},$$

which has a standard error of estimate of ±4 percent. The peak preferred spawning discharge for fall chinook (620 cfs) will be equaled or exceeded 87 percent of the time during the November-December period, 61 percent of the time in January, and 55 percent of the time in February. The preferred rearing discharge of 560 cfs will be equaled or exceeded annually 88 percent of the time.



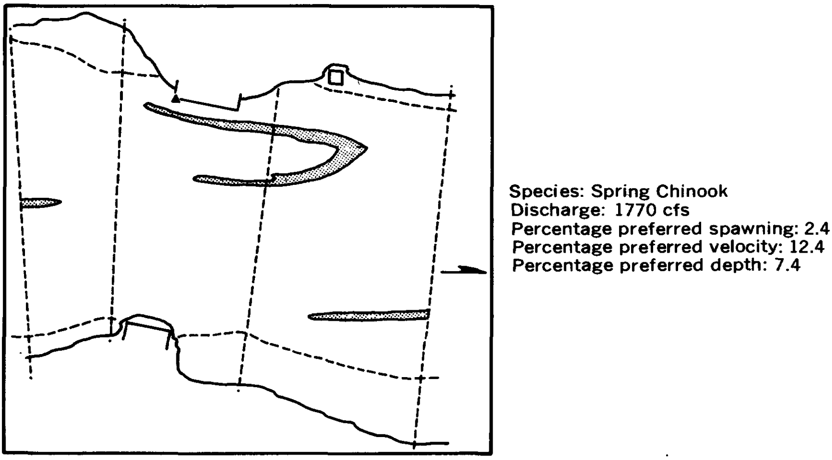
Species: Fall Chinook
Discharge: 1770 cfs
Percentage preferred spawning: 8.1
Percentage preferred velocity: 28.9
Percentage preferred depth: 12.0



Species: Sockeye
Discharge: 1770 cfs
Percentage preferred spawning: 0.9
Percentage preferred velocity: 3.5
Percentage preferred depth: 12.2

FIGURE 66.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, North Fork Nooksack River reach B.

The water-quality characteristics of reach B that were measured are given in table 13. They do not vary substantially from those at reach A, except the specific conductivity (a function of dissolved solids in the water) seems to have increased slightly. The average conductivity at reach A is 93 micromhos per centimeter, and the average at reach B is 107 micromhos per centimeter. The samples were taken during the same time period.



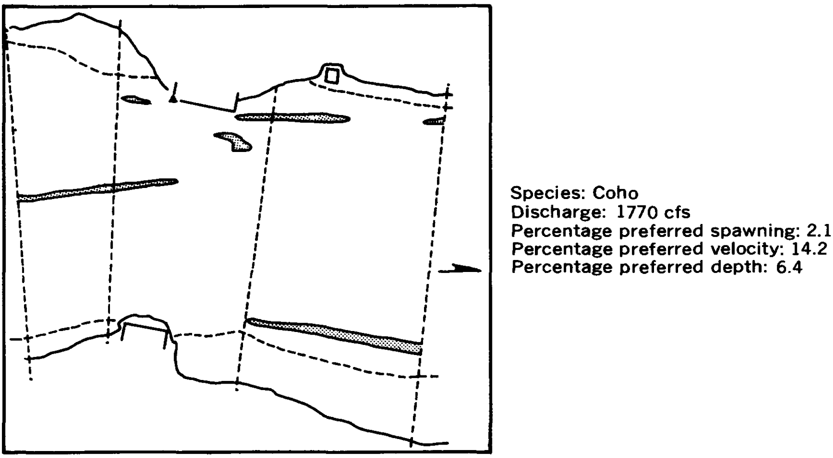


FIGURE 66.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, North Fork Nooksack River reach B—Continued.

NORTH FORK NOOKSACK RIVER REACH C

Reach C, at an altitude of 345 feet, is the lowest study reach on the river (fig. 56). Above the reach the main river is 36.7 miles long and has a drainage area of 282 square miles.

Reach C covers 54,940 square feet and has a channel which, for the most part, is wide and uniform, and which virtually exhibits no

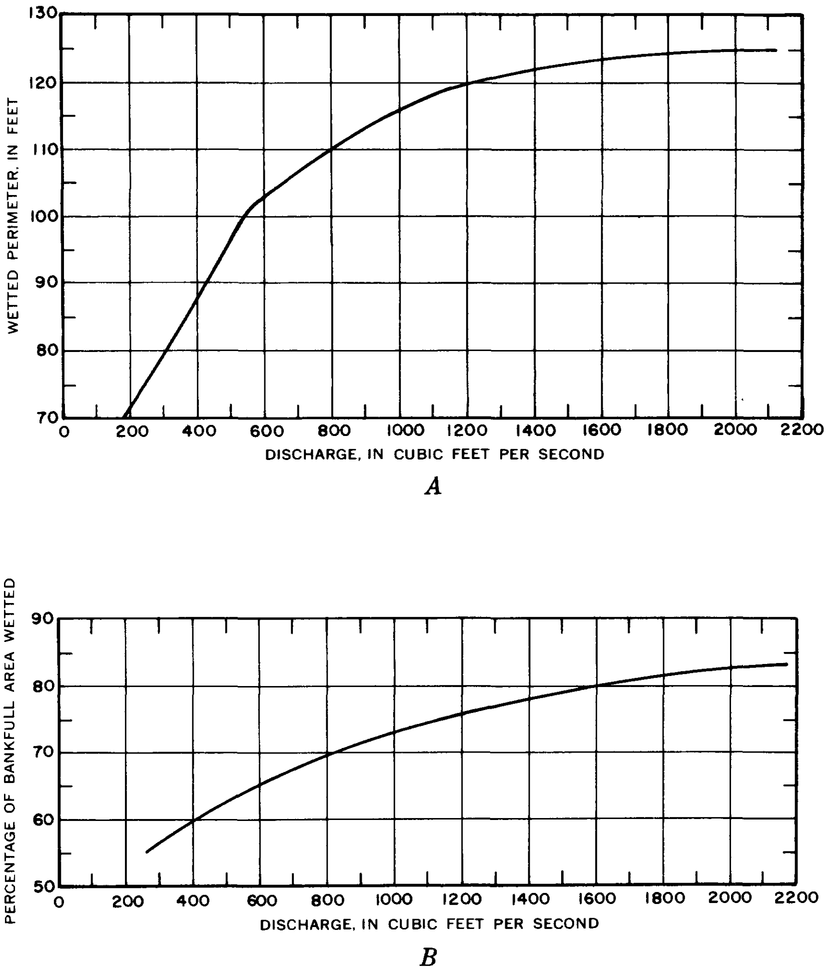


FIGURE 67.—Relation between curve of wetted perimeter versus discharge (graph *A*) and curve of percentage of bankfull area wetted versus discharge (graph *B*), North Fork Nooksack River reach B.

flood plain. Gravel bars migrate through the reach, but the water depth at any one section remains fairly uniform. About 100 yards above the reach is a bend where the river narrows from a braided stream into one channel; about 100 yards below the reach, the channel again becomes braided.

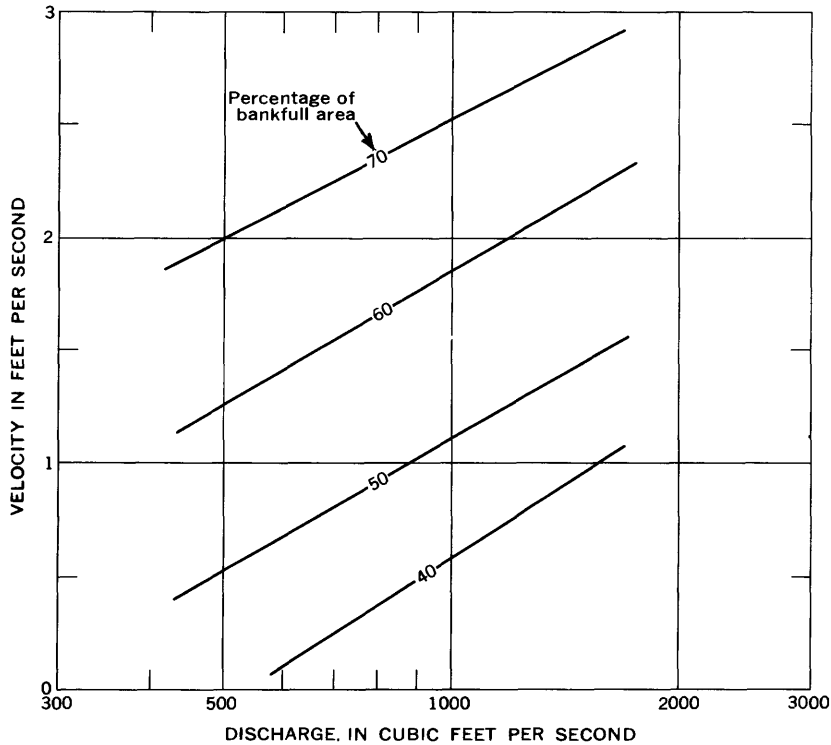


FIGURE 68.—Family of curves showing relation between velocity, discharge, and percentage of bankfull area, North Fork Nooksack River reach B. Shows selected percentages of reach which have velocities equal to or less than that indicated at a selected discharge.

TABLE 13.—*Characteristics of water quality, North Fork Nooksack River reach B, April 1968–October 1969*

Date		Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/l)	Suspended sediment (mg/l)	Specific conductance (micromhos per cm at 25°C)
Apr.	4	767	5.0	41	12.3	----	----
	18	620	5.6	42	·12.2	----	----
May	2	1,050	8.9	48	11.2	6	----
	27	1,770	7.2	45	11.7	6	----
June	24	2,160	10.6	51	10.8	39	----
Oct.	9	754	5.6	42	12.2	7	----
Dec.	23	730	----	----	----	----	100
Feb.	5	365	1.1	34	13.7	1	109
	18	392	3.3	38	12.9	1	109
	25	342	3.6	38.5	12.8	2	112
Oct.	8	----	7.2	45	11.7	----	42

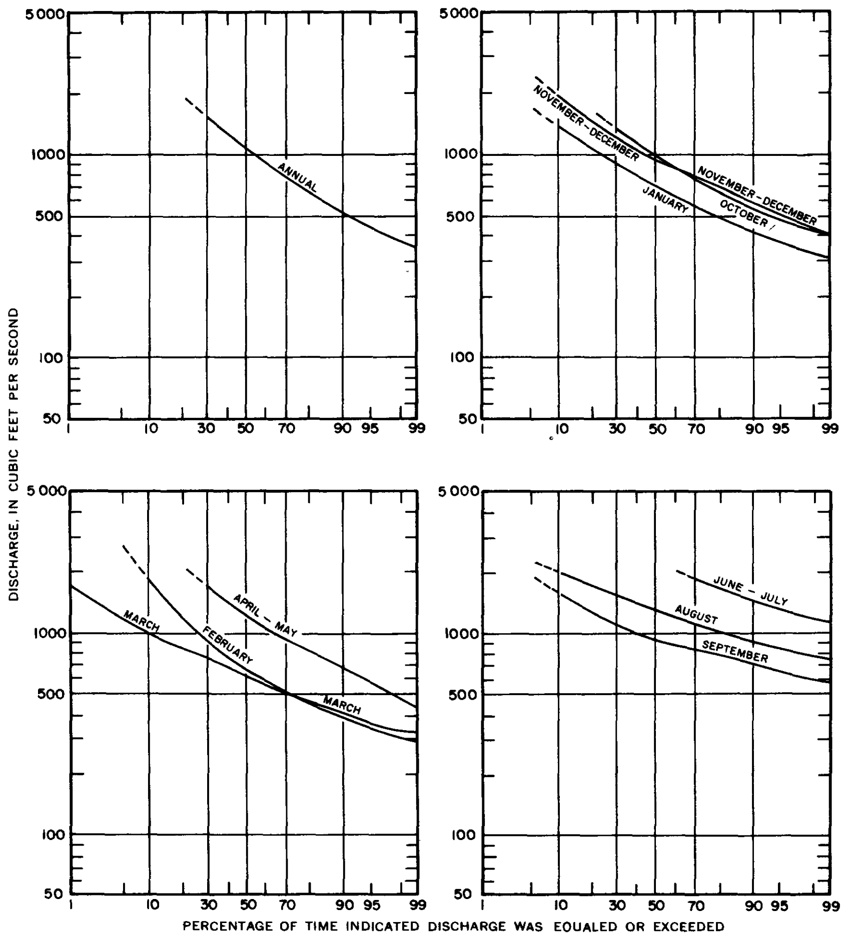


FIGURE 69.—Monthly and annual flow durations, North Fork Nooksack River reach B.

The peaks for spawning discharges and areas (fig. 70) and the values for the selected percentages of reduction of discharge are given in table 15. The original and the trend-fitted curves for depth, velocity, and depth and velocity (fig. 70) were used as guides to extrapolate the spawnable area values (shown in parentheses).

The locations within the reach of preferred spawning areas, generally, are confined to edges of the channel with no spawning occurring in midchannel (fig. 71). At discharges near the preferred discharge, the center of the channel has depths slightly greater

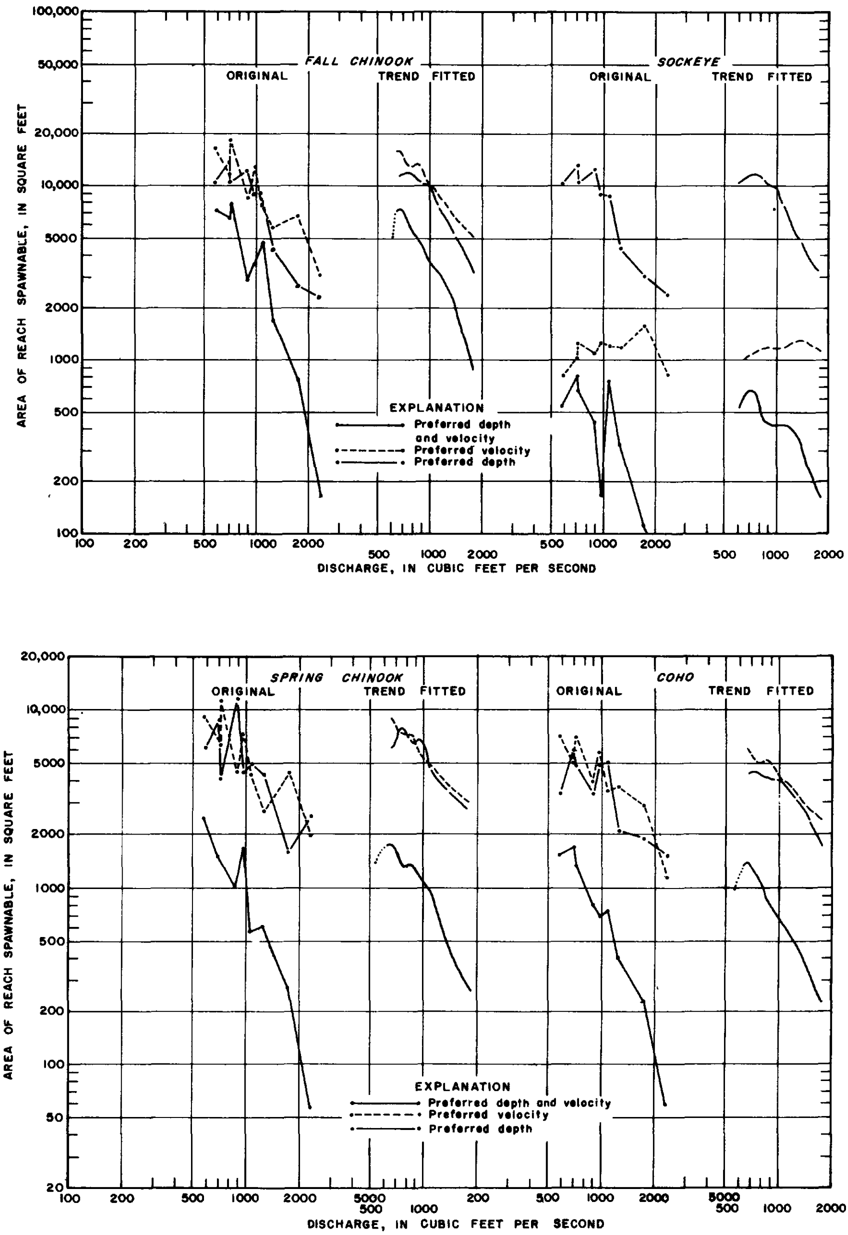


FIGURE 70.—Relations between area of reach and discharge, for preferred velocity, depth, and depth and velocity, for each of four salmon species, North Fork Nooksack River reach C. Curves show the original and the trend-fitted data based on a three-point moving average. Bankfull area of reach covers 54,940 square feet.

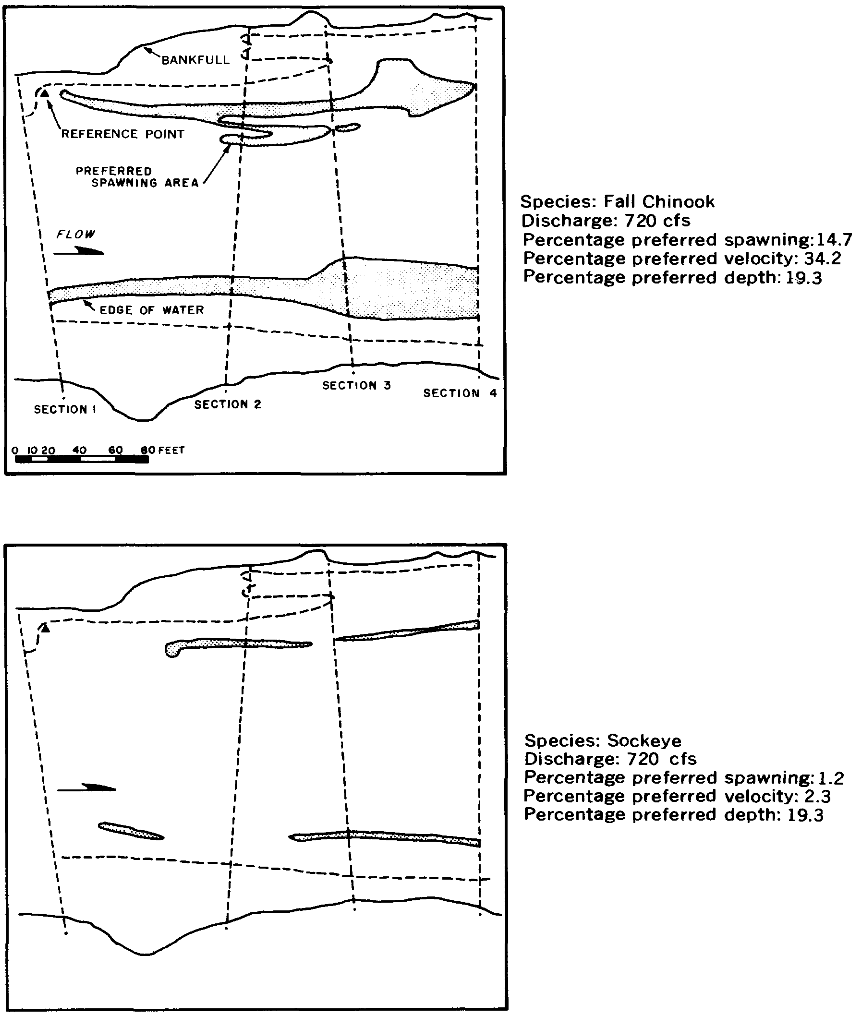
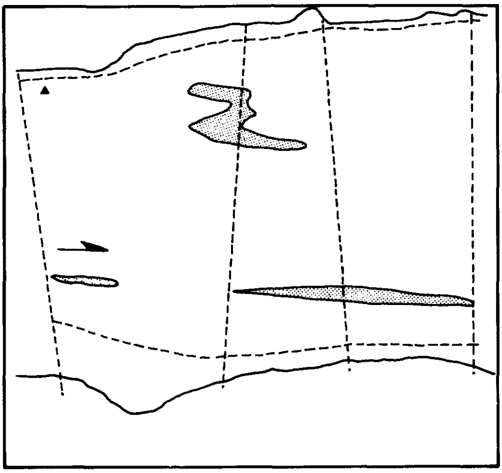


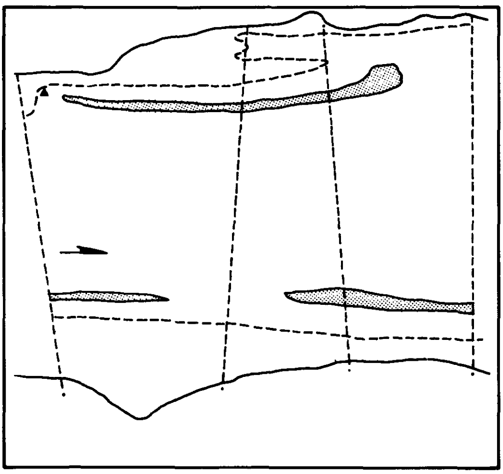
FIGURE 71.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, North Fork Nooksack River reach C.

than those preferred for spawning, and the velocities are generally much too great.

The preferred rearing discharge in reach C (570 cfs) was determined from the first break in the curve of wetted perimeter versus



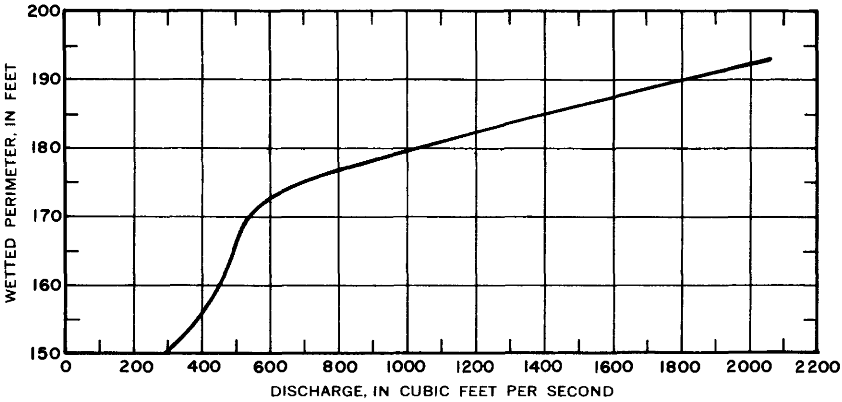
Species: Spring Chinook
Discharge: 970 cfs
Percentage preferred spawning: 3.1
Percentage preferred velocity: 13.1
Percentage preferred depth: 7.9



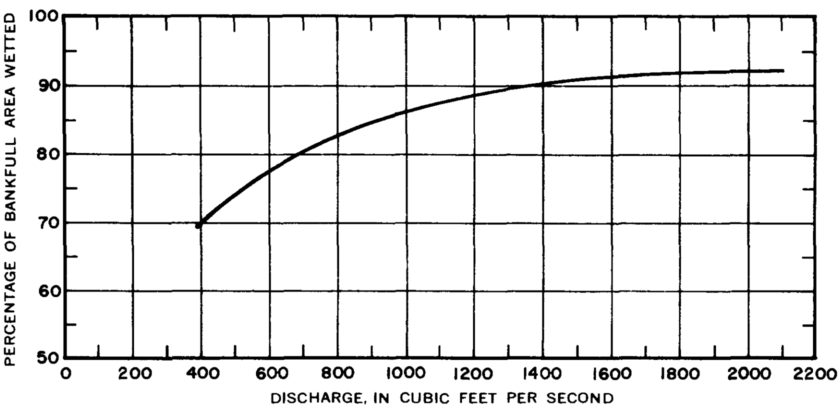
Species: Coho
Discharge: 720 cfs
Percentage preferred spawning: 3.3
Percentage preferred velocity: 12.5
Percentage preferred depth: 8.8

FIGURE 71.—Plan-view locations of cross sections and preferred spawning areas for each of four salmon species studied at selected discharges, North Fork Nooksack River reach C—Continued.

discharge (fig. 72*A*). At 570 cfs, 76 percent of the bankfull area is wetted (fig. 72*B*), and 24 percent is dry. From the relations of percentage of bankfull area versus velocity versus discharge (fig. 73) it was determined that, at 570 cfs, there is 40 percent of the bankfull



A



B

FIGURE 72.—Relation between curve of wetted perimeter versus discharge (graph *A*) and curve of percentage of bankfull area wetted versus discharge (graph *B*), North Fork Nooksack River reach C.

area—or 16 percent (40—24) of the wetted bankfull area—with velocities equal to or less than 1.2 fps. In reach C, 16 percent of the wetted area encompasses 8,790 square feet.

The annual and monthly flow-duration curves (fig. 74) were determined by relating mean daily discharges from reach C (Q_C), the site of the gaging station, North Fork Nooksack River, near Deming, to the flows at reach A (Q_A), North Fork Nooksack River below Cascade Creek, near Glacier. Reach A has 30 years of flow data, whereas reach C has only 3 years of data. The relation is shown by the equation

$$Q_C = 22.0\,(Q_A)^{0.64},$$

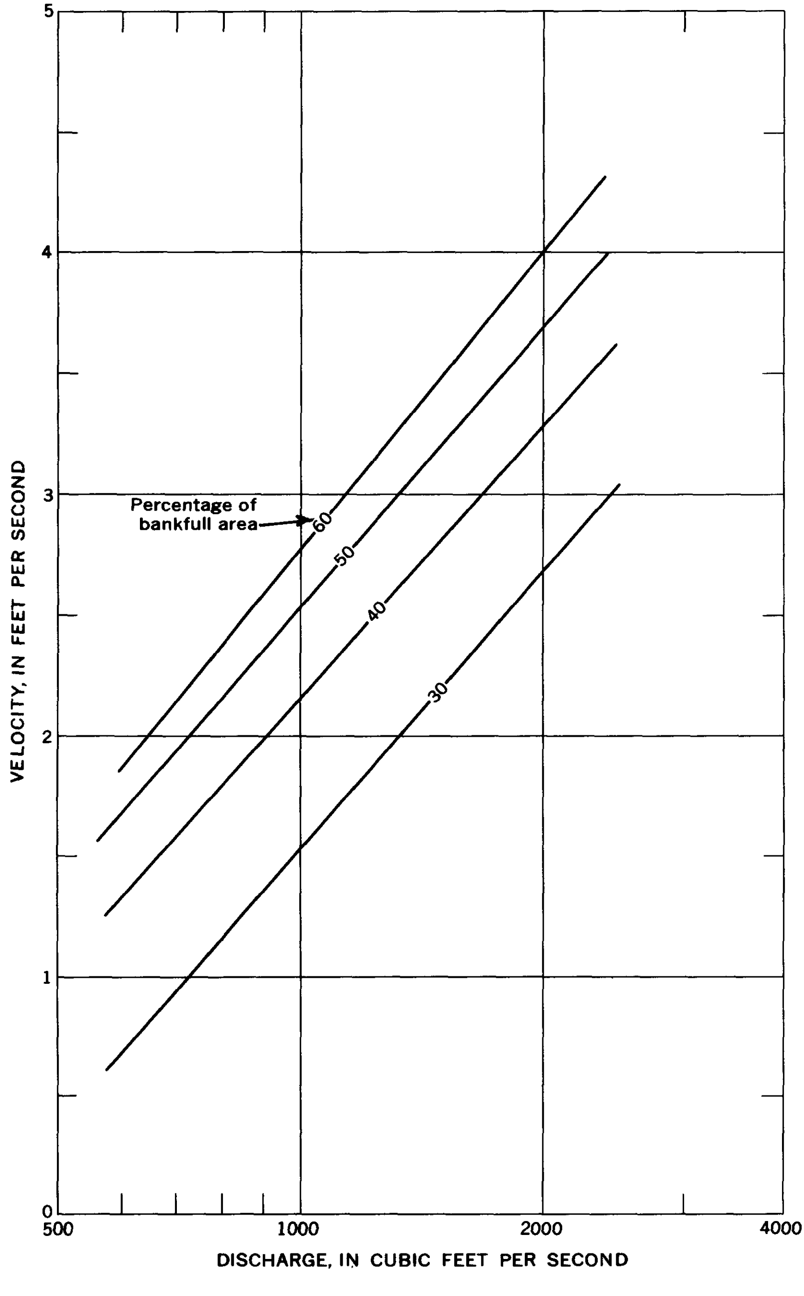


FIGURE 73.—Family of curves showing relation between velocity, discharge, and percentage of bankfull area, North Fork Nooksack River reach C. Shows selected percentages of reach which have velocities equal to or less than that indicated at a selected discharge.

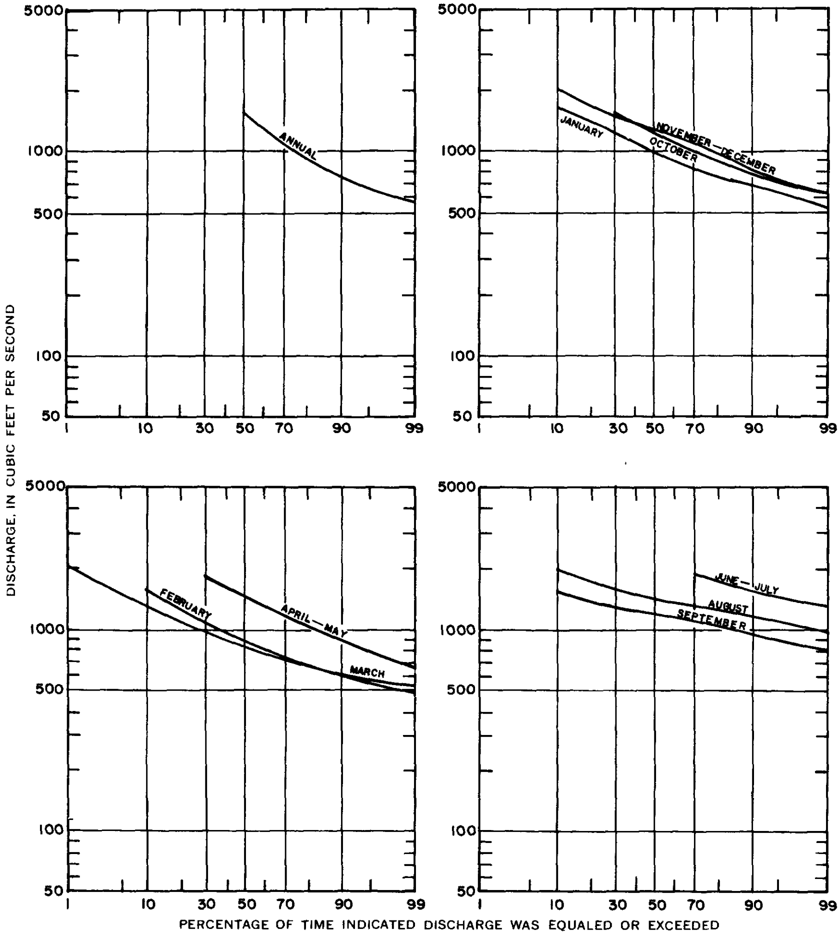


FIGURE 74.—Monthly and annual flow durations, North Fork Nooksack River reach C.

which has a standard error of estimate of ±30 percent. The standard error is very large and, above a discharge of 1,700 cfs at reach C, the curve breaks and the equation does not hold. However, the lower discharges for spawning and rearing are the major concern of this analysis, and the equation is valid over this range. The large magnitude of the standard error is probably caused by the difference in elevation between reaches A and reach C, the latter being 900 feet lower. Much of the fall, winter, and spring precipitation occurs as snow at reach A and as rain at reach C.

From the flow-duration curves (fig. 74), the peak preferred spawning discharge of 680 cfs for fall chinook is equaled or exceeded 96 percent of the time in the November–December period, 91 percent of the time in January, and 80 percent of the time in February. The preferred rearing discharge (570 cfs) is equaled or exceeded 98 percent of the time annually—or only 2 percent of the time will the discharge be less than the preferred rearing discharge. The flow-duration curves (fig. 74) are no better than the relation from which they were derived, which has a standard error of ±30 percent.

The water-quality characteristics for reach C are given in table 14. The specific conductivity shows, as it did between reaches A and B, a downstream increase; the average conductivity for reach C is 115 micromhos per centimeter. Thus, between reaches A and C there is an increase of 22 micromhos per centimeter in specific conductivity. This is a relatively small amount, however, and by no means would it be detrimental to aquatic life at any of the reaches.

TABLE 14.—*Characteristics of water quality, North Fork Nooksack River reach C, April 1968–October 1969*

Date	Discharge	Temperature (°C)	Temperature (°F)	Dissolved oxygen (mg/l)	Suspended sediment (mg/l)	Specific conductance (micromhos per cm at 25°C)
Apr. 3	1,080	7.8	46	11.5	----	----
18	900	6.1	43	12.0	----	----
May 2	1,260	8.9	48	11.2	----	----
28	1,730	7.8	46	11.5	32	----
June 25	2,320	9.4	49	11.1	71	----
Oct. 9	970	6.9	44.5	11.8	6	----
Dec. 23	1,040	3.3	38	12.9	----	104
Jan. 22	720	.6	33	13.9	3	122
Feb. 18	710	5.0	41	12.3	1	115
26	585	3.3	38	12.9	13	120
Oct. 8	2,700	8.3	47	11.4	----	47

GENERALIZATION OF PEAK PREFERRED SPAWNING DISCHARGES

One of the principal objectives of the study is the generalized definition of spawning discharges in all salmon-producing streams in Washington, whether or not the streams have field determination of spawning discharges. This generalization of preferred spawning discharges would enable allocation of streamflows for salmon spawning and thus would aid the designer in making economic feasibility studies on rivers where projects for diversion or storage are planned.

There are many possible ways of generalizing preferred spawning discharges, starting with the determination by sampling at specific sites. All the known hydrologic techniques of generalization were examined, and it was concluded that the most promising method was by statistical correlation of spawning discharges with basin and stream-channel characteristics.

Only a relatively small sampling of spawning discharges are available or will be available, and definition of spawning discharge at any desired site, requires a method of transferring and extending available discharge information. The transfer methods range from simple extrapolation or interpolation at two sites to complex statistical methods that simultaneously consider a population of discharges and related environmental characteristics. The selected multiple-regression technique seems to be the most effective.

A study was made, using the data in this report, for the purpose of testing the feasibility of using the multiple-regression method for a spawning-discharge generalization. Peak preferred spawning discharge were related to several easily measured stream-channel and basin parameters individually, as well as in combinations and ratios with each other. Some of the parameters tested were stream length, in miles, from the source to the sampling site; channel slope, in feet per mile, of the river upstream from the site; mean altitude of the drainage basin, in feet; the drainage area, in square miles; and the average width and depth of the stream channel for the bankfull stage at the study reach.

Even though there are 12 samples (four rivers—each with three reaches) only four data sets, with the reaches as replications, could be used in this preliminary investigation, because of the interrelation of reaches on a given river. Also, no more than three parameters could be related to spawning discharges in any one regression because of the small sample size and the loss of one degree of freedom for each parameter used. Several of the regressions were not significant when only two parameters were used.

There are 2^4 or 16 possible combinations of relations between the spawning discharges of three reaches on each of the four rivers and the basin and channel parameters. To expedite this preliminary generalization, however, relations were developed using spawning discharges from the upper reach, the middle reach, and the lower reach of each of the four rivers. Thus, regressions were computed and tested using upper-reach spawning discharges versus basin and channel parameters; then, the same regressions were computed for the spawning discharges from the middle reaches; and, finally, the lower-reach spawning discharges were used to derive the regressions. Coefficients of correlation were high, and all three sets of regressions showed the same general tendency for the most significant parameters to be (1) drainage area, (2) channel slope, and (3) stream width and depth. Also, regression coefficients were found to be similar on each of the parameters. The standard errors of estimate of the relations (before adjustment for sample size) ranged from ±18 to ±42 percent. After adjustment for sample size the error range increased considerably, ranging from ±28 to ±62 percent, which shows the need for an increased sample size. The resultant equations of this generalization are of only academic interest with little usable value, because of the small sample size, and are therefore not shown. At present, other study reaches on additional streams are being sampled and the spawning discharges determined so that the generalization method herein presented may be refined and more reliable relations obtained.

In summary, this initial attempt by generalization of spawning discharges shows that—

(1) Multiple-regression methods may lead to reasonably accurate relations for predicting peak preferred spawning discharges from basin and channel characteristics.

(2) The most significant basin and channel characteristics of those investigated were drainage area, channel slope, and stream width and depth.

(3) A larger sample of spawning discharges is needed in order to investigate interrelations between the physical characteristics and improve the standard error of estimate of the relations.

(4) Even though results from this generalization produce only rough estimates of peak preferred spawning discharges, data being collected in the present continuing program seem to follow the trends and relations indicated by this initial study.

CONCLUSIONS

The curves, graphs, and values in this report are all subject to a certain amount of error inherent in field measuring, streambed shifts, manmade controls of flow, plotting of maps, and fitting of curves. Wherever feasible, the errors involved are stated as errors or a confidence interval is shown. However, some errors were not evaluated because time limited obtaining replications of samples, which would have enabled definition of the sampling errors.

Table 15 gives the preferred spawning areas and discharges, for the four salmon species studied, at the maximum or peak condition and at each of the 5-, 10- 15-, and 25-percent discharge-reduction levels for the 14 study reaches on the four rivers investigated.

Table 16 gives the percentage reductions of spawning area for each of the four salmon species, at the four percentage reductions from the peak spawning discharge, for the 14 river study reaches. For example, table 16 shows that for fall chinook on the Dewatto River reach A, for a 25-percent reduction from the peak in spawning discharge, there is only a 6-percent reduction from the peak in spawning area.

A more general presentation of table 16 is obtained by a plot of the reduction data as shown in figure 75. Here, the regression line for a river is indicative of the average of the study reaches and of the salmon species. Three of the regression lines (for the Dewatto, Cedar, and Kalama Rivers) shows that for a selected percentage reduction of spawning area the percentage reduction in discharge

TABLE 15.—*Summary of peak preferred corresponding reductions of spawnable areas*

[Numbers in parentheses are values obtained by extrapolation.

River	Reach	Preferred parameter	Salmon Species: Fall chinook: Peak	Fall chinook: Percentage reduction from peak spawning discharge: 5	10	15	25	Spring chinook: Peak	Spring chinook: Percentage reduction from peak spawning discharge: 5	10
Dewatto	A	Area	1,440	1,440	1,420	1,400	1,350	460	450	420
		Discharge	87	83	78	74	65	77	73	69
	A1	Area	640	630	625	620	590	80	79	72
		Discharge	74	70	67	63	56	83	79	75
	B	Area	2,100	2,100	1,950	1,900	1,800	440	440	435
		Discharge	92	87	83	78	69	140	135	125
Cedar	A	Area	1,900	1,900	1,900	1,870	1,800	680	660	640
		Discharge	230	218	207	196	172	240	228	216
	B	Area	1,050	1,040	1,030	1,010	930	170	160	150
		Discharge	275	261	248	234	206	510	484	459
	B1	Area	4,080	4,050	3,950	(3,700)	(3,300)	525	520	505
		Discharge	250	238	225	212	188	480	456	432
	C	Area	960	(920)	(860)	(780)	(650)	420	410	400
		Discharge	320	304	288	272	240	420	399	378
	C1	Area	1,920	1,900	1,850	(1,800)	(1,650)	630	620	610
		Discharge	290	276	261	246	218	420	399	378
Kalama	A	Area	6,100	6,100	6,000	5,900	4,700	1,640	1,620	1,610
		Discharge	260	246	234	221	195	580	504	476
	B	Area	1,560	1,520	1,450	1,380	1,200	510	500	490
		Discharge	520	495	468	442	390	375	356	338
	C	Area	4,100	4,100	4,050	4,000	3,450	160	160	155
		Discharge	650	617	585	552	487	800	760	720
North Fork Nooksack	A	Area	2,050	2,000	1,950	....	....	960	950	900
		Discharge	195	185	175	166	146	200	190	180
	B	Area	1,250	1,250	1,220	1,150	1,040	360	360	350
		Discharge	620	589	557	527	465	370	352	333
	C	Area	7,400	7,300	6,000	(4,700)	....	1,720	1,700	1,690
		Discharge	680	646	612	578	510	670	636	603

is greater. This is indicated by the relative positions of the "average" line and the line of equal reduction. The North Fork Nooksack River average line intersects the equal reduction line at about 23-percent reduction in area and discharge. Below this intersection, reduction in area is less than the reduction in discharge; above 23 percent, the inverse is true. In figure 75 the average line slope for the North Fork Nooksack is greater than 1.0 indicating a steep recession on the area-discharge relations (for example, see fig. 65 for sockeye). The assumption of linearity for the average lines of figure 75 should not be extended beyond the ranges shown.

The standard error of estimate (fig. 75) is not an error term, but an index of the deviation of the data about the average line for the river; in essence, it indicates the magnitude of differences between

spawning areas and discharges and of
at 5, 10, 15, and 25 percent reduction of discharge

All areas in square feet. All discharges in cubic feet per second]

Salmon species—Continued													
Spring chinook—Con.													
Percentage reduction from peak spawning Discharge—Continued			Coho					Sockeye					
			Percentage reduction from peak spawning discharge					Percentage reduction from peak spawning discharge					
15	25	Peak	5	10	15	25	Peak	5	10	15	25		
390	300	460	450	430	390	320	140	135	130	130	120		
66	58	51	48	46	43	38	50	48	45	42	38		
60	36	170	170	165	160	150	62	60	58	57	55		
71	62	70	66	63	60	52	65	62	58	55	49		
420	410	550	550	540	480	380	150	150	140	135	130		
120	105	50	48	45	42	38	88	84	79	75	66		
620	530	520	515	510	500	460	370	370	360	355	335		
204	180	235	223	212	200	176	240	228	216	204	180		
140	115	320	315	310	300	260	255	250	240	235	235		
434	382	270	256	243	230	202	440	418	396	374	330		
(485)	(440)	767	760	750	(700)	(440)	275	265	250	(230)	(185)		
408	360	285	271	256	242	214	430	408	387	366	322		
350	(280)	360	340	320	315	315	170	160	150	125	95		
357	315	450	428	405	382	338	510	484	459	434	382		
(595)	(530)	285	280	275	(265)	(225)	130	125	120	(115)	(95)		
357	315	450	428	405	382	338	490	466	441	416	368		
1,550	1,250	2,130	2,110	2,090	2,010	1,800	390	380	370	365	320		
450	398	245	232	220	208	183	420	398	378	366	315		
410	210	430	425	410	400	280	86	84	83	82	73		
318	281	540	512	485	468	405	390	370	351	332	292		
150	100	1,140	1,100	1,060	1,010	870	115	115	113	110	100		
680	600	725	688	652	615	544	570	542	514	485	428		
(800)	....	460	440	(380)	(340)	....	130	130	125	120	100		
170	150	180	171	162	153	135	300	285	270	255	225		
(310)	....	405	400	385	365	315	135	130	125	95	87		
315	278	515	490	464	438	386	570	541	512	485	427		
(1,550)	....	1,400	1,350	(1,150)	(1,000)	....	690	670	600	(550)	...		
568	502	660	626	594	560	495	710	674	639	604	532		

TABLE 16.—*Percentage reductions of spawnable area for selected reductions of the peak spawning discharge*

[Numbers in parentheses are values obtained by extrapolation]

Reach	Salmon species															
	Fall chinook				Spring chinook				Coho				Sockeye			
	Selected percentage reductions of peak spawning discharge															
	5	10	15	25	5	10	15	25	5	10	15	25	5	10	15	25
	Dewatto River, percentage reductions of spawnable area															
A	0	1	3	6	2	9	15	35	2	6	15	30	4	7	7	14
A1	2	2	3	8	1	10	25	45	0	3	6	12	3	6	8	11
B	0	1	2	3	0	1	4	7	0	2	13	31	0	7	10	13
	Cedar River, percentage reduction of spawnable area															
A	0	0	2	5	3	6	9	22	1	2	4	12	0	3	4	10
B	1	2	4	11	6	12	18	32	2	3	6	19	2	6	8	8
B1	1	3	(9)	(19)	1	4	(8)	(16)	1	2	(9)	(43)	4	9	(16)	(33)
C	(4)	(10)	(19)	(32)	2	5	17	(33)	6	11	12	12	6	12	26	44
C1	1	4	(6)	(14)	2	3	(6)	(16)	2	4	(7)	(21)	4	8	(12)	(27)
	Kalama River, percentage reductions of spawnable area															
A	0	2	3	23	1	2	5	24	1	2	5	15	2	5	6	18
B	2	7	11	23	2	4	20	59	1	4	7	35	2	4	5	15
C	0	1	2	16	0	3	6	38	3	7	11	24	0	2	4	13
	North Fork Nooksack River, percentage reductions of spawnable area															
A	2	5	..	..	1	6	(17)	..	4	(17)	(26)	..	0	4	8	23
B	0	2	8	17	0	1	(4)	..	1	5	10	22	4	7	30	35
C	1	19	(36)	..	1	2	(10)	..	4	18	28	..	3	13	(20)	..

species and between reaches. The standard error should not be used as an index between streams because of the differences in sizes of peak spawning flows and spawnable areas between rivers. For example, a reduction of 5 cfs will be 50 percent if the reduction is from 10 to 5 cfs but only 5 percent with a reduction from 100 to 95 cfs.

By using table 15 in conjunction with table 16, it is possible to select reasonable discharge to allocate for salmon spawning at the reaches studied.

The timing of discharges, as shown by the hydrographs of streamflows, plays an important part in the survival of anadromous fish, not only for spawning discharges but for egg incubation, rearing, and up-and-down stream migration. Unnatural changes in discharge, and shifts in timing or movement of water in a river system may have an adverse effect on velocity which could cause warming or cooling of certain water areas.

In the future, after a sampling of rivers deemed large enough for reliable analysis, a regionalization will be attempted by testing and then relating the most significant basin and channel parameters to the preferred discharges. Then, if the attempt succeeds, at river lo-

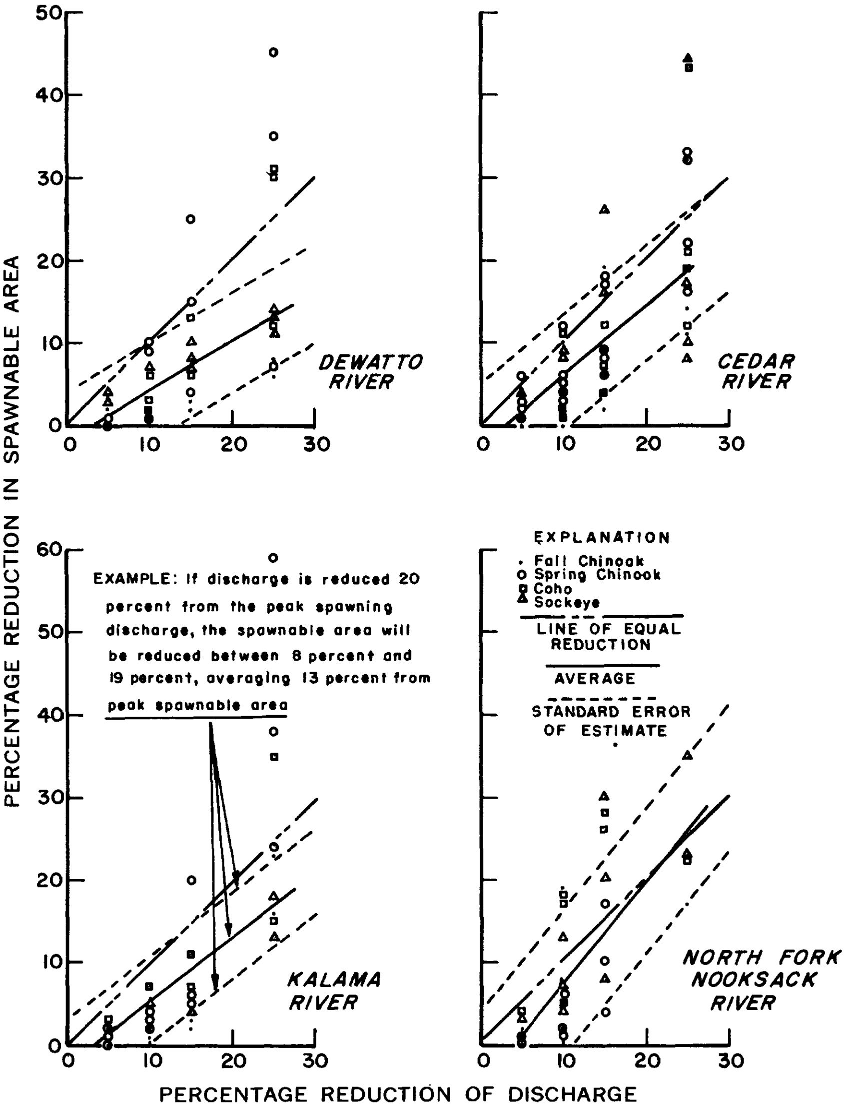


FIGURE 75.—Relations between selected percentage reductions of the peak spawning discharge and comparable percentage reductions of spawnable area. The assumption of linearity for the average line should not be extended beyond the ranges shown.

cations where the preferred spawning discharge is desired, the specified parameters can be obtained and the preferred discharge computed. The parameters used to derive the regionalized equation must be pertinent as well as related to the dependent variable. These parameters also must be easily obtained to expedite derivation of the relation; they may be used for predicting the preferred discharge in practical applications. If the parameters are more difficult to determine than the preferred discharge, the relation has lost its usefulness. Some of the basin parameters that will be tested are drainage area, length of stream, mean altitude of basin, percentage of basin covered by lakes, altitude of the site, altitude of the river source, and the slope of the main stem channel. Some of the channel parameters, using bankfull stage as a reference, may be wetted perimeter, average area, average width, average depth, and channel slope over the reach. The basin parameters can be evaluated from topographic maps, and the channel parameters can be evaluated easily at the site where the preferred discharge is to be determined.

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