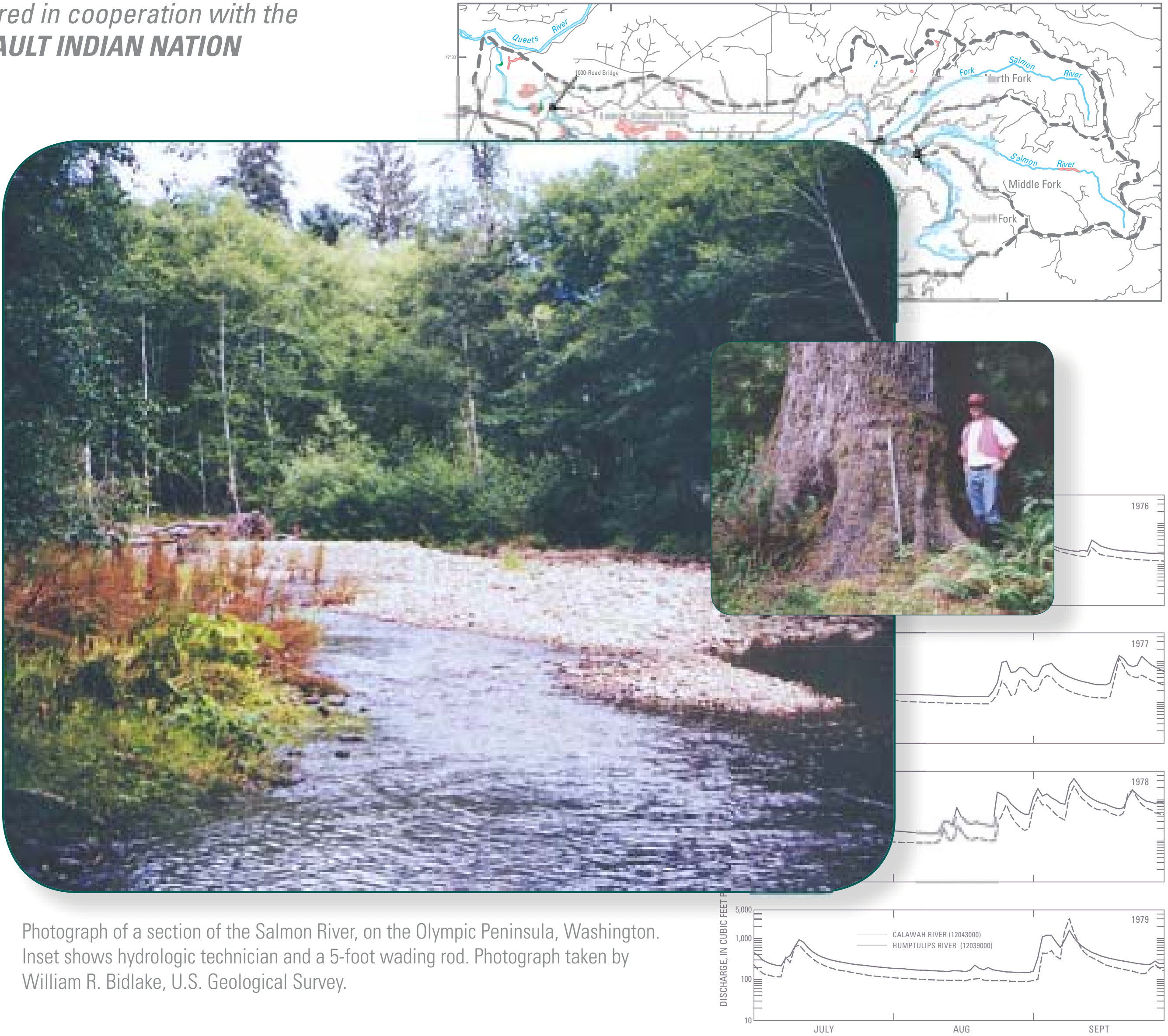
# Watershed Analysis of the Salmon River Watershed, Washington: Hydrology

## Water-Resources Investigations Report 03-4204

*Prepared in cooperation with the*
***QUINAULT INDIAN NATION***



Photograph of a section of the Salmon River, on the Olympic Peninsula, Washington. Inset shows hydrologic technician and a 5-foot wading rod. Photograph taken by William R. Bidlake, U.S. Geological Survey.

**U.S. DEPARTMENT OF THE INTERIOR**
**U.S. GEOLOGICAL SURVEY**

# Watershed Analysis of the Salmon River Watershed, Washington: Hydrology

*By* William R. Bidlake

---

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 03-4204

Prepared in cooperation with the

QUINAULT INDIAN NATION

Tacoma, Washington
2003

**U.S. DEPARTMENT OF THE INTERIOR**
GALE A. NORTON, *Secretary*

**U.S. GEOLOGICAL SURVEY**
Charles G. Groat, *Director*

For additional information write to:

Director, Washington Water Science Center
U.S. Geological Survey
1201 Pacific Avenue – Suite 600
Tacoma, Washington 98402
http://wa.water.usgs.gov

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Building 810
Box 25286, Federal Center
Denver, CO 80225-0286

Suggested citation:

Bidlake, W.R., 2003, Watershed analysis of the Salmon River Watershed, Washington–Hydrology: U.S. Geological Survey Water-Resources Investigations Report 03-4204, 34 p.

# CONTENTS

# FIGURES

# TABLES

# CONVERSION FACTORS AND DATUM

## CONVERSION FACTORS

| Multiply | By | To obtain |
|---|---|---|
| **Length** | | |
| inch (in) | 2.54 | centimeter |
| foot (ft) | 0.3048 | meter |
| mile (mi) | 1.609 | kilometer |
| **Area** | | |
| acre | 4,047 | square meter |
| acre | 0.4047 | hectare |
| acre | 0.004047 | square kilometer |
| square mile ($mi^2$) | 259.0 | hectare |
| square mile ($mi^2$) | 2.590 | square kilometer |
| **Volume per unit time** | | |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second |
| cubic foot per second per square mile [$(ft^3/s)/mi^2$] | 0.01093 | cubic meter per second per square kilometer |

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{o}C=(^{o}F-32)/1.8.$$

## DATUM

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 29).

# Watershed Analysis of the Salmon River Watershed, Washington: Hydrology

*By* William R. Bidlake

## ABSTRACT

The U.S. Geological Survey analyzed selected hydrologic conditions as part of a watershed analysis of the Salmon River watershed, Washington, conducted by the Quinault Indian Nation. The selected hydrologic conditions were analyzed according to a framework of hydrologic key questions that were identified for the watershed. The key questions were posed to better understand the natural, physical, and biological features of the watershed that control hydrologic responses; to better understand current streamflow characteristics, including peak and low flows; to describe any evidence that forest harvesting and road construction have altered frequency and magnitude of peak and low flows within the watershed; to describe what is currently known about the distribution and extent of wetlands and any impacts of land management activities on wetlands; and to describe how hydrologic monitoring within the watershed might help to detect future hydrologic change, to preserve critical ecosystem functions, and to protect public and private property.

## INTRODUCTION

An analysis of the Salmon River watershed, on the western Olympic Peninsula in Washington (fig. 1), was conducted by the Quinault Indian Nation in 1999. The analysis was initiated to better understand and document the state of natural and cultural resources and selected ecosystem components within the watershed. The U.S. Geological Survey (USGS) participated in the watershed analysis by performing analyses of selected hydrologic conditions, and by writing and contributing a chapter (termed a "module report") for the hydrologic analysis to the overall Salmon River watershed analysis report (Salmon River Watershed Analysis Team, 2002).

The purpose of this report is to present the hydrology module report that was prepared for the Salmon River watershed analysis report. The hydrology module report is organized around the key questions for the hydrology issues that were developed through consensus among participants in the Salmon River watershed analysis.

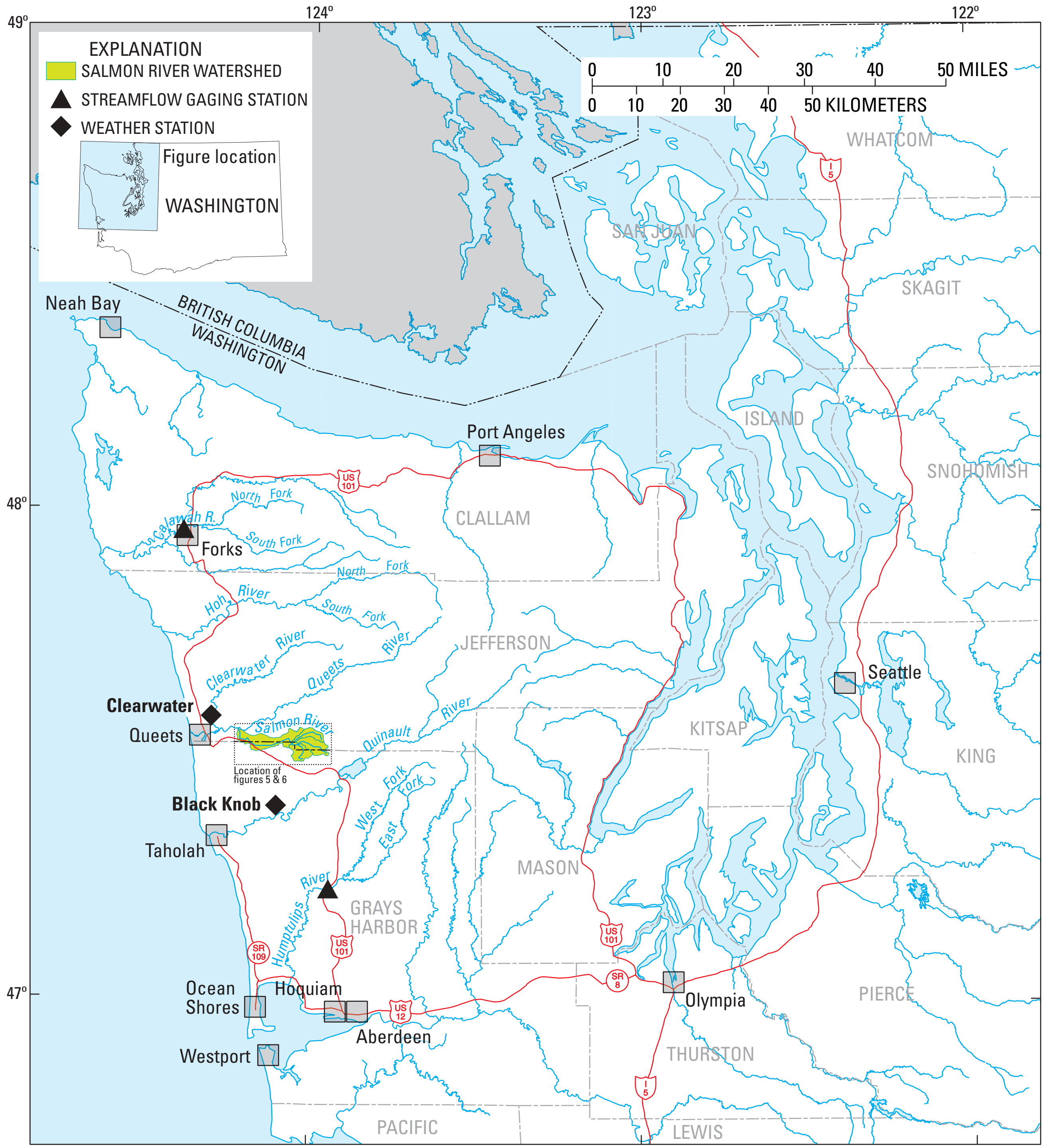


**Figure 1.** Location of the Salmon River watershed in western Washington.

# KEY HYDROLOGY ISSUES AND KEY QUESTIONS

Watershed analysis of the Salmon River watershed was conducted using the guide "Ecosystem Analysis at the Watershed Scale Federal Guide for Watershed Analysis," hereafter, "Federal Guide" (Regional Interagency Executive Committee, 1995). Watershed analysis by the Federal Guide is a flexible, issue-driven analysis that is focused on specific issues or concerns for maintenance or restoration of important watershed processes or functions. The key hydrologic issues for the Salmon River watershed are:

A. Maintaining flows in the Salmon River and its tributaries that are, to the degree possible, beneficial to human uses and that promote maintenance or restoration of critical ecosystem functions; and

B. Effects of management on wetland form and function.

These issues were addressed through a key-question process, which is the principal vehicle prescribed by the Federal Guide for advancing through watershed analysis. The key questions are:

1. What are the natural, physical, and biological features of the watershed that control hydrologic responses?
2. What is known about current streamflow characteristics, including peak and low flows?
3. What evidence exists that forest harvesting and road construction have altered frequency and magnitude of peak and low flows?
4. What is currently known about the distribution and extent of wetlands, and what have been the impacts of land management activities on wetlands?
5. How might existing hydrologic monitoring be maintained or augmented to help detect future hydrologic change, to preserve critical ecosystem functions, and to protect public and private property?

The key questions were researched using the scientific literature, a brief field investigation, and hydrologic, climatic, and resource mapping databases maintained by tribal and governmental agencies. The Quinault Indian Nation furnished all watershed maps and associated geographical statistics presented in this hydrology module report to the author. Data for precipitation and air temperature at Clearwater were read from a CD-ROM (compact disk-read-only medium) produced by Hydrosphere Data Products, Inc. (1999). Streamflow data from the gaging station near the 1000-Road Bridge were provided by George C. Onwumere, Quinault Indian Nation, Taholah, Washington (written and electronic commun., August 1999), and by Don Richardson of Gig Harbor, Washington (written commun., August 1999).

# RESPONSES TO KEY QUESTIONS

## 1. What Are the Natural Physical and Biological Features of the Watershed That Control Hydrologic Responses?

For this report, hydrologic response is defined as a change in a hydrologic variable as a result of changes in rates at which water is added to or taken away from a hydrologic system. Hydrologic variables include streamflow, overland flow rate, water yield, stream and lake stage, hydraulic head, hydraulic gradient, ground-water recharge and discharge, evaporation, transpiration, ground-water flow rate, soil water content, and snow and ice water equivalent.

### Climate

Variations of weather and climate are probably the most important determinants of hydrologic responses in most watersheds. Weather refers to meteorological conditions, such as precipitation or air temperature, as they occur at any given instant, and climate refers to the average weather conditions or to recurrent seasonal weather variations during some number of years. The location of the Salmon River watershed on the west coast of North America at a latitude of about 47 degrees N. subjects it to strong maritime influences. Westerly trending winds bring moist air to the west coast of North America from the Pacific Ocean along pathways that vary with the season of the year (Hirschboeck, 1991). During summers, the pathways are shifted as far north as 60 degrees N. latitude and during winter they are shifted as far south as 35 degrees N. latitude. Summers are dry as a result of the northerly pathways of moisture delivery, combined with the proximity of a persistent area of high atmospheric pressure in the North Pacific Ocean, and the stabilizing effects of the cold California Current. During fall and winter, major rain and windstorms are brought onto the west coast of North America at mid-latitudes by strong westerly winds that have shifted to more southerly pathways. These large winter storms typically approach the Olympic Peninsula from the Pacific Ocean following a southwest-to-northeast track because they are spawned by systems of low atmospheric pressure over the ocean and driven by winds that circulate counterclockwise around the pressure systems.

Seasonal variations of precipitation can be seen by examining long-term average monthly precipitation. Average monthly precipitation measured at nearby Clearwater (fig. 1) for water years 1932 to 1998 ranged from approximately 3 inches for June to August to 18 inches for December (fig. 2). The water year begins October 1. The annual total of the monthly averages is 118 inches, which can be considered to be the average annual precipitation at Clearwater for the 1932-to-1998 period.

January was the coldest month at Clearwater from the time of the earliest available air-temperature recordings in 1939 to 1998 (fig. 3). The average of daily maximum and minimum air temperatures during January was 40 degrees Fahrenheit (°F). August was the warmest month with an average of daily maximum and minimum air temperatures of 60°F. The long-term (1939 to 1998) monthly average of daily maximum air temperature ranged from 46°F in December and January to 71°F in August, which was a seasonal span of 25 degrees. The long-term monthly average of daily minimum air temperature ranged from 34°F in January to 49°F in July and August, which was a season span of 15 degrees.

Superimposed on seasonal variations of weather in the Pacific Northwest are year-to-year variations and variations due to long-term regional climate shifts. Year-to-year variations of precipitation at Clearwater are depicted in figure 4. In addition, the U. S. Geological Survey (1996) has identified two long-term climate shifts for Washington State during the twentieth century. A relatively dry climate period ended in the late 1940s and was followed by a relatively wet climate period that ended in 1977. Since 1977, a relatively dry climate has persisted. The climate shifts were determined from analysis of the long-term precipitation record, and they reflect multi-year climate trends that might or might not be reflected by the amount of precipitation in any given year. For example, total precipitation during any given year of a relatively dry period could be larger or smaller than the long-term average precipitation, but average annual precipitation for the entire dry period will be smaller than the long-term average annual precipitation.

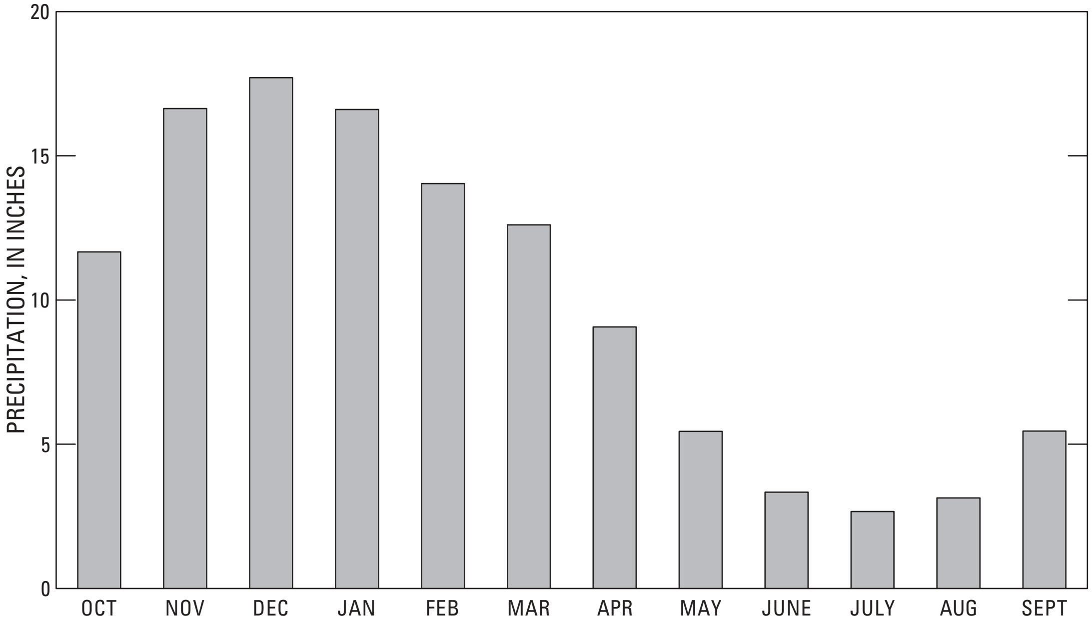


**Figure 2.** Average monthly precipitation at Clearwater, Washington, during water years 1932 to 1998.

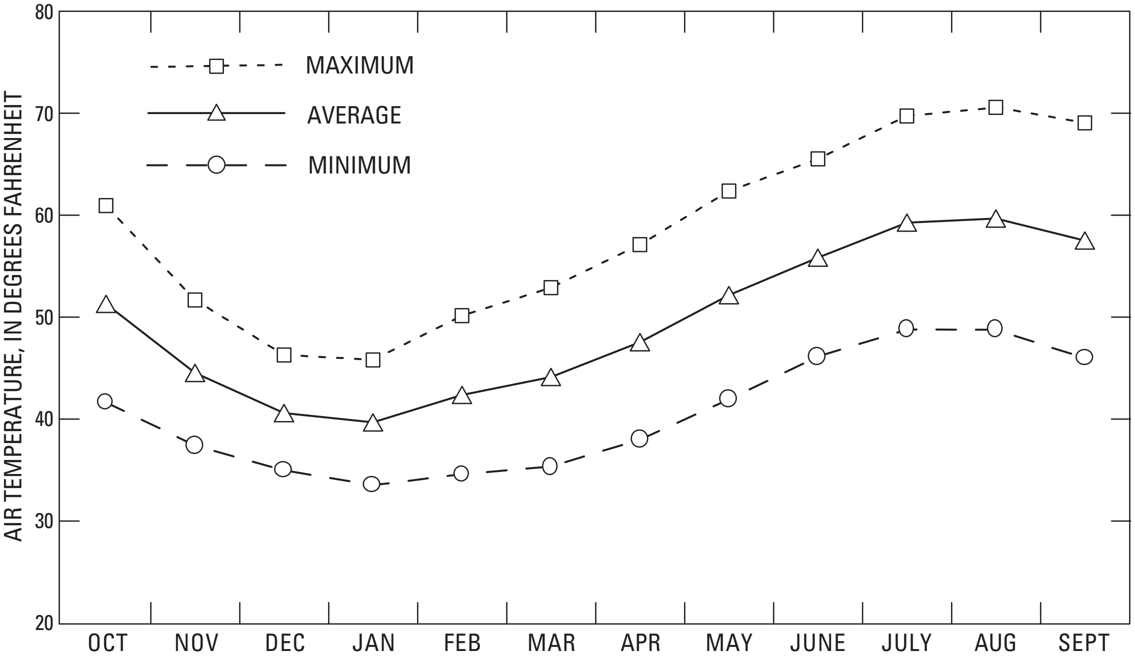


**Figure 3.** Monthly average of daily maximum and minimum air temperature and average of maximum and minimum air temperature at Clearwater, Washington, during water years 1939 to 1998.

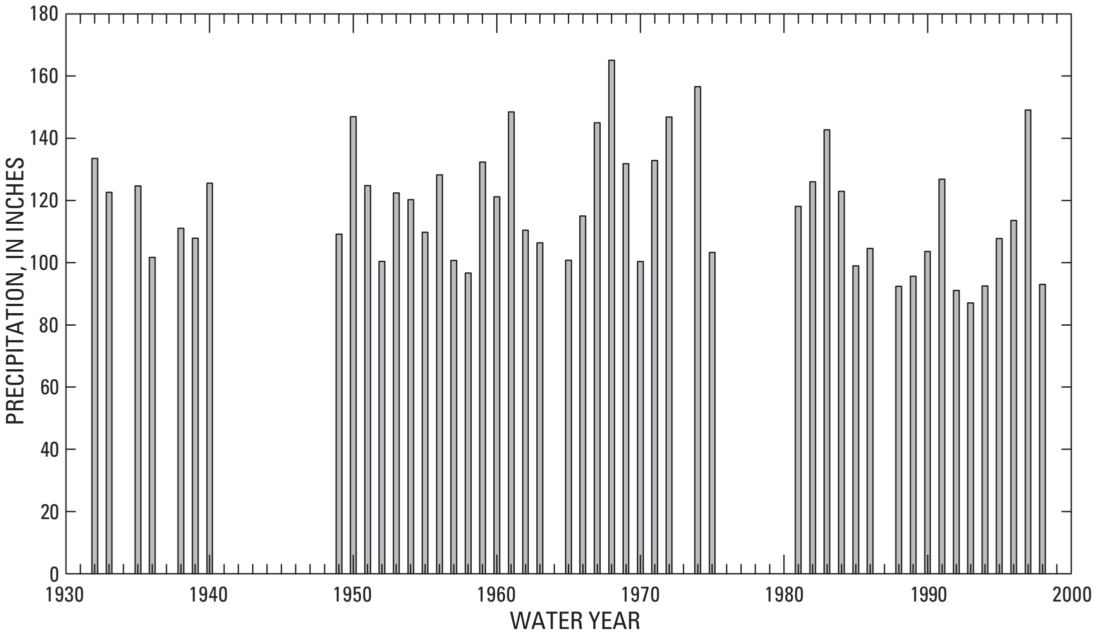


**Figure 4.** Annual precipitation at Clearwater, Washington, during water years 1932 to 1998. Gaps (for example, 1941 to 1948) indicate sufficient data are not available.

Precipitation at Clearwater reflected the climate shift of the late 1970's. Annual (water-year) precipitation at Clearwater from 1950 to 1977 averaged 123 inches, whereas annual precipitation from 1978 to 1998 averaged 110 inches. Measured annual precipitation at Clearwater from 1932 to 1949 averaged 130 inches, which suggests the climate there became drier in the late 1940's instead of wetter as the U. S. Geological Survey reported (1996); however, much of the precipitation record for Clearwater from 1932 to 1949 is missing (fig. 4) and this confounds detection of the late 1940's climate shift.

### Physiographic Influences on Local Climate of the Salmon River Watershed

The mountainous nature of the Salmon River watershed contributes to the abundant precipitation and to the accumulation and melt of snow. The higher mountain ridges in the watershed reach altitudes of approximately 2,700 feet. When weather systems moving in from the ocean encounter such high-relief terrain, some of the moisture-laden air within the systems is forced to higher altitudes, a process termed "orographic lifting," where total atmospheric pressure and density decrease. When the pressure on a parcel of moist air decreases, temperature of the parcel decreases. As temperature of a parcel decreases, its ability to hold moisture decreases. For example, a parcel of air at a temperature of 40°F can hold only about one half as much moisture as can a parcel with a temperature of 60°F (Campbell, 1977, p. 150). As a result of the lifting and cooling of air, some of the water condenses to form clouds and precipitation (Wallace and Hobbs, 1977, p. 232). Owing to orographic lifting, precipitation amounts probably vary considerably within the Salmon River watershed; however, precipitation records for the ridges and valleys with which to confirm this are not available.

One source for estimates of spatially varying precipitation for the Salmon River watershed is PRISM (Parameter-elevation Regressions on Independent Slopes Model; Oregon Climate Service, 2000). PRISM-produced maps of precipitation for 1961 to 1990 indicate that average annual (calendar year) precipitation ranged from 117 inches for most of the Lower Salmon River subwatershed to 165 inches for the highest terrain of the North Fork and Middle Fork subwatersheds. The watershed-average annual precipitation from PRISM for 1961 to 1990 was 132 inches.

Some of the terrain in the Salmon River watershed is at high enough altitude that some of the winter precipitation falls as snow. Snowmelt can contribute to flooding, particularly during winter when infiltrability of soils, the ability of soils to accept water, is small because the soils are saturated or partially frozen. Evaporative demand is small during winter months, and much of the water from snowmelt can become available for runoff. Some of the water from melt in deep snowpacks is stored within the interstitial spaces of the pack and is therefore not immediately available for runoff. Shallow, transient snowpacks, which can melt completely during rain and wind storms, are the most efficient snowpacks for yielding water for runoff because water from melt is applied directly to the soil surface. Water from melt contributes to the water available for runoff during rain-on-snow events, and the Washington State Department of Natural Resources (WADNR) (Washington State Department of Natural Resources, 1995) indicates that rain-on-snow events are a major cause of flooding in Washington State.

The likelihood of rain-on-snow events apparently varies with site altitude, and the WADNR has mapped the State of Washington according to 5 altitude zones of varying likelihood of rain-on-snow events. The altitude zones are termed "precipitation zones." Rain-on-snow events, according to the WADNR (1995), are most likely in the peak rain-on-snow precipitation zone. The rain-dominated and snow-dominated precipitation zones, which are immediately below and above the peak rain-on-snow zone, have the second highest likelihood for rain-on-snow events. Collectively, the rain-dominated, peak rain-on-snow, and snow-dominated precipitation zones are the three precipitation zones with the greatest likelihood for flood-producing rain-on-snow events. Finally, the lowland and highland zones have the smallest likelihood for rain-on-snow events.

Precipitation zones for the Salmon River watershed are shown in figure 5. Sixty-six percent of the terrain of the Salmon River watershed lies at altitudes that encompass the peak rain-on-snow or rain-dominated precipitation zones (table 1). Of the 13,600 acres within zones susceptible to rain-on-snow events, approximately 18 percent are within the Lower Salmon River subwatershed, approximately 21 percent are within the North Fork subwatershed, approximately 33 percent are within the Middle Fork subwatershed, and approximately 27 percent are within the South Fork subwatershed (table 1).

### Geology and Soils

The geology of the Salmon River watershed affects hydrologic responses in the watershed insofar as it controls bed surface slopes and gradients in stream channels and as it affects substrate materials that control or mediate subsurface flow. Ridges within the North Fork, Middle Fork, and South Fork subwatersheds are composed of rocks of sedimentary origin, such as sandstone and shale (Tabor and Cady, 1978). The sides of the ridges are very steep. As a result, the hydrologic response to storms of many smaller, steep-gradient tributaries is prompt. In contrast, most of the Lower Salmon River

**Table 1.** Precipitation zone area, in acres rounded to the nearest 100 acres, by subwatershed

| Subwatershed | Precipitation zone | | | | | Total |
|---|---|---|---|---|---|---|
| | Lowland | Rain dominated | Peak rain-on-snow | Snow dominated | Highland | |
| Lower Salmon River | 6,900 | 2,100 | 400 | 0 | 0 | 9,400 |
| North Fork | 0 | 1,200 | 1,700 | 0 | 0 | 2,900 |
| Middle Fork | 0 | 1,700 | 2,800 | 0 | 0 | 4,500 |
| South Fork | 0 | 2,400 | 1,300 | 0 | 0 | 3,700 |
| Percentage of total area | 34 | 36 | 30 | 0 | 0 | 20,500 |

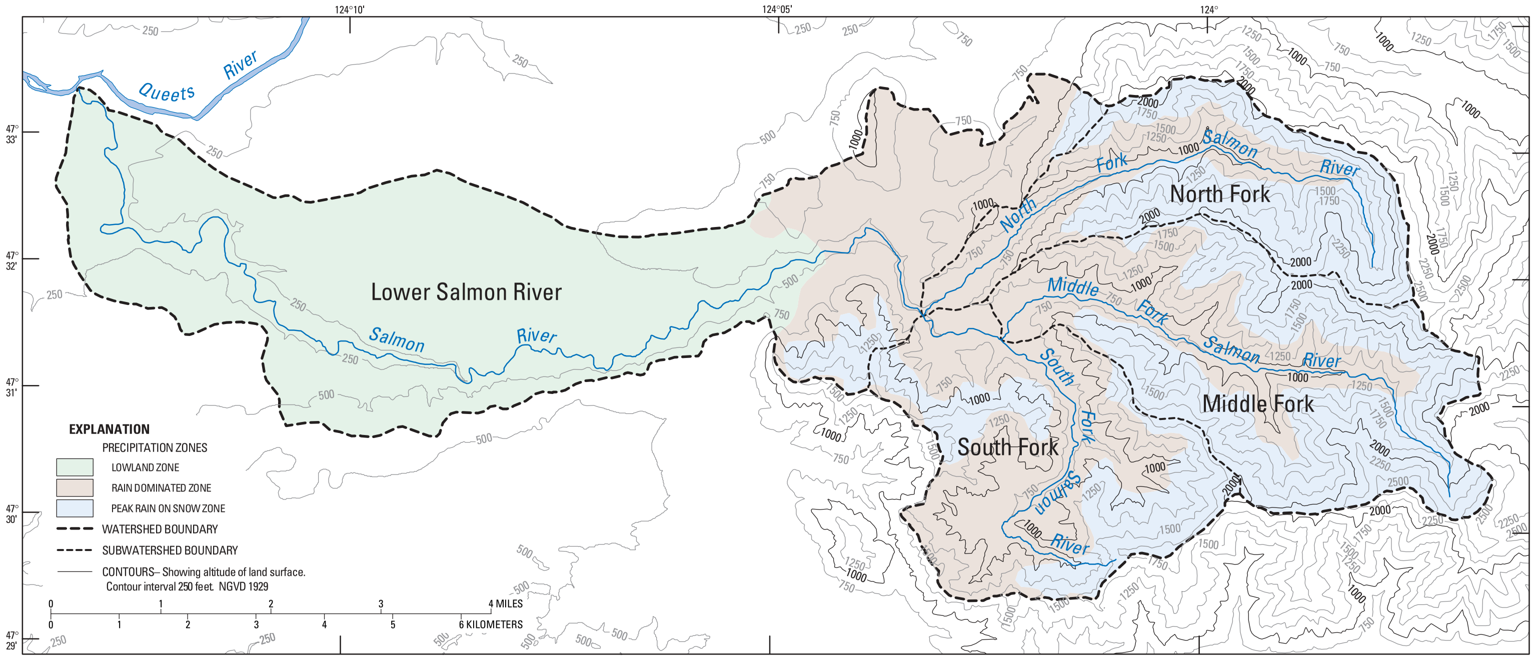
subwatershed is coastal piedmont consisting of porous, unconsolidated deposits of Olympic alpine glaciers, including gravels, sands, silts, and clays (Tabor and Cady, 1978). As a result of the decreased bed gradient and the larger capacity for bank storage in the porous materials of the piedmont, the hydrologic response of streams in that subwatershed can generally be expected to be relatively slow compared to streams of the more mountainous subwatersheds, except for isolated reaches in the lowlands where the channel is incised to sedimentary bedrock, such as between river miles 3.7 and 4.0 (James E. O Connor, U.S. Geological Survey, written commun., December 1999). The composition and spatial distribution of geologic materials obviously have a major influence on ground-water flow and recharge and on interactions between ground- and surface-water bodies. Little is known about ground water within the Salmon River watershed because, apparently, no investigations have been conducted to document occurrence, recharge, quality, or flow of ground water.

### Vegetation

The physical environment of the Salmon River watershed, particularly its temperate maritime climate, makes it suitable for the establishment and growth of stands of long-lived evergreen conifers such as Sitka spruce, western hemlock, and Douglas fir. Prior to the beginning of logging during the 1900s, the watershed was thickly covered with late-successional conifer stands, with relatively small patches of younger stands that had established following destruction wrought by wind storms and fires. Riparian areas that were frequently subjected to destructive floods or debris flows were inhabited by stands of deciduous hardwood trees, primarily red alder. Coniferous forests occupy greater than 80 percent of the watershed and the remaining watershed area is occupied by hardwood forest and by such features as non-forest wetland, rock outcrops, human developments, and recent clear-cuts (Rodney F. Mayte, U.S. Forest Service, written commun., February 2001).

Vegetation performs a number of functions that can influence hydrologic responses. First, terrestrial vegetation mediates the exchange of water and energy between the atmosphere and the soil and thereby exerts control on the amount of water that is stored in the soil and available to recharge streams or ground water. For example, vascular plants can absorb water from the soil through their roots and transport it to their leaves, where the receipt of energy from the atmosphere causes the water to evaporate. The nature of the leaf surface, such as how efficiently it absorbs down welling solar radiation, in part determines the magnitude of evaporation and, ultimately, the amount of water withdrawn from the soil. During rainfall, some of the precipitation is intercepted and stored on the surfaces of the vegetation. Some of the intercepted water can drip from the vegetation to the soil, and some of the water evaporates into the atmosphere. The process by which water evaporates from wetted vegetation is termed "interception loss." In some situations, the presence of vegetation can lead to increased inputs of water to the soil surface. Vegetation can intercept some of the moisture from fog and some of that intercepted moisture can drip onto the soil surface.

A second function of vegetation that influences hydrologic responses is protection and augmentation of soils that can store water and retard runoff. Vegetation absorbs impact energy from raindrops that otherwise could fall on the soil surface and detach soil particles. Vegetation contributes large amounts of fibrous materials to the soil, such as leaves, twigs, and stems. These materials, by contributing to the overall erosion resistance of the soil and to the total volume of the soil, can increase capacity of the watershed to store water from storms.



Base map modified from
Quinault Indian Nation's Department of Natural Resources,
Environmental Protection Division, Watershed Analysis Team
UTM Zone 10, NAD 27, 1:50,000

**Figure 5.** Precipitation zones in the Salmon River watershed, delineated by the Washington Department of Natural Resources.

## 2. What Is Known About Current Streamflow Characteristics, Including Peak and Low Flows?

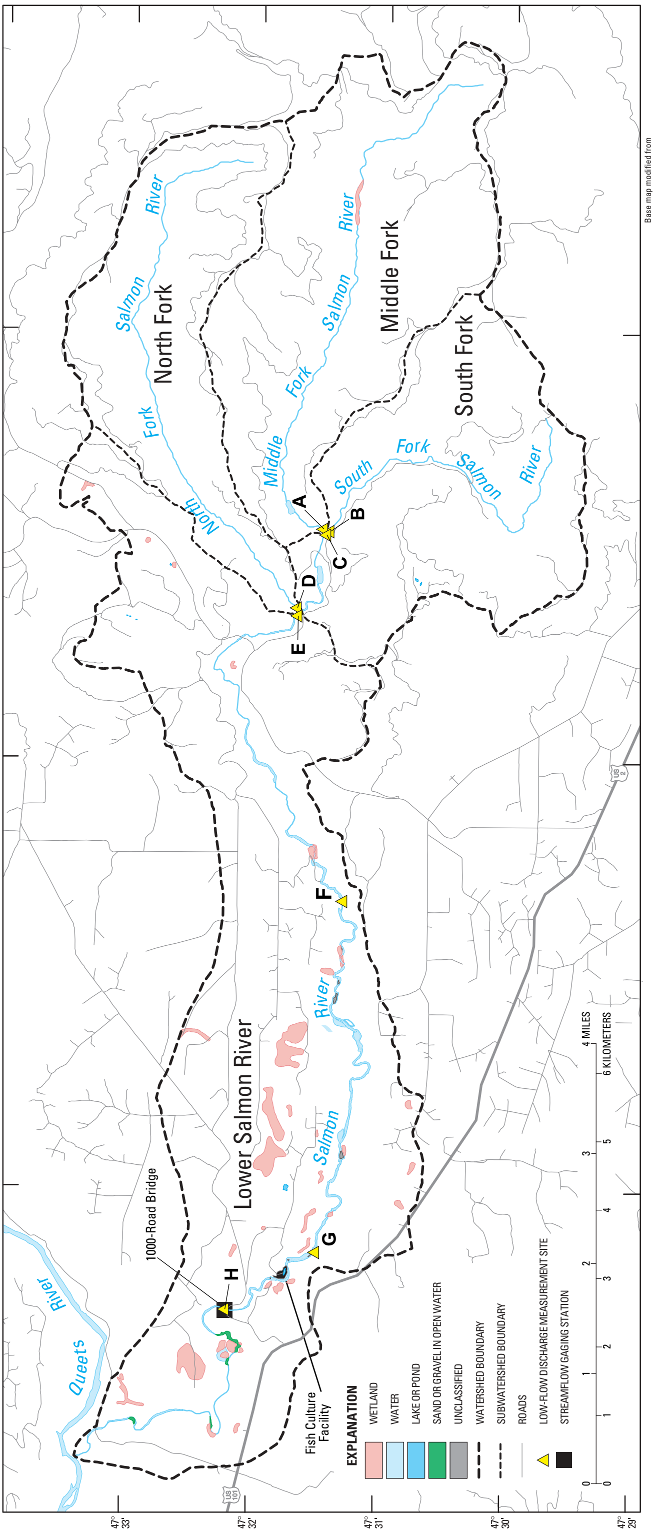
A streamflow gaging station on the Salmon River near the 1000-Road Bridge (fig. 6) has been operated since 1994, and streamflow data from that station for water years 1995 to 1998 were used for computing average monthly and average annual discharge. Seasonal variations of discharge near the 1000-Road Bridge were grossly similar to seasonal variations of precipitation at Clearwater during water years 1995 to 1998 (figs. 7 and 8), although the extremes of average monthly discharge and precipitation occurred during different months. The minimum average monthly discharge of 40 $ft^3/s$ (cubic feet per second) occurred during August, which was one month later than the precipitation minimum. The maximum of average monthly discharge of 595 $ft^3/s$ occurred during December, which was one month later than the precipitation maximum during water years 1995 to 1998. Average annual discharge near the 1000-Road Bridge for water years 1995 to 1998 was 288 $ft^3/s$.

Annual unit-area discharge from the drainage area upstream of the gage near the 1000-Road Bridge averaged 134 inches for water years 1995 to 1998, and annual precipitation at Clearwater averaged 116 inches during the same period. Unit-area discharge is computed as mean discharge divided by the contributing drainage area and can be expressed in the same units of measurement as precipitation is commonly expressed-inches per unit time. The contributing drainage area upstream of the gage site is 29.2 $mi^2$ (square miles). Annual unit-area discharge was correlated with annual precipitation at Clearwater during water years 1995 to 1998 (fig. 9). The trend line that is given in figure 9 was developed by a statistical analysis that also produced the coefficient of determination ($r^2$). The coefficient of determination indicates the fraction of the variation of annual discharge that was explained by precipitation. Given that precipitation falling in the watershed is a major source for water that appears in the river, the strong explanatory power of precipitation related to discharge is in accordance with expectations. The fact that annual unit-area discharge averaged 16 percent greater than annual precipitation at Clearwater was consistent with spatially averaged precipitation in the Salmon River watershed being greater than precipitation at Clearwater, as was discussed previously.

### Peak-Flow Characteristics of the Salmon River

The magnitude and frequency of peak flows bear important implications for the design of manmade structures in the floodplain, and potentially for fish habitat and survival of juvenile fish. Thus, the characterization of peak-flow magnitude and frequency is important for resource management in the Salmon River watershed. The annual peak flow at a point on the stream is the maximum instantaneous stream discharge at the point during a given water year. Annual peak flow of the Salmon River near the 1000-Road Bridge for water years 1995 to 1999 is shown in figure 10.

Annual peak flow is a hydrologic event that can be amenable to statistical description and characterization. One statistical characterization is the frequency curve of annual peak flows-the peak-flow frequency curve. A peak-flow frequency curve, which relates the magnitude of the annual peak-flow event to its frequency of occurrence, can be used to estimate the average time interval between occurrences of an annual peak flow of a given magnitude or larger. An N-year peak flow read from a frequency curve developed for a given site is an estimate of the peak-flow magnitude to be expected or exceeded on average at the site every N years. A peak-flow event with an N-year recurrence interval has a probability of 1/N of occurring during any year. Development and use of a peak-flow frequency curve for annual peak flows at a given site assumes those events are statistically independent and that the underlying physical factors that lead to peak flows remain constant from year to year. Few sites have peak flows that strictly meet these statistical assumptions because of such factors as climate trends or shifts; however, the assumptions are met well enough for many sites to make the curves useful tools in hydrologic assessment of surface waters. The peak-flow frequency curve is the foundation for making probabilistic statements concerning magnitude and frequency of peak flows at sites with many years of flow data. Other peak-flow estimation techniques have been developed for estimating N-year events at sites, such as the 1000-Road Bridge site, where streamflow data are not sufficient to develop a peak-flow frequency curve.



Base map modified from
Quinault Indian Nation's Department of Natural Resources,
Environmental Protection Division, Watershed Analysis Team
UTM Zone 10, NAD 27, 1:50,000

**Figure 6.** Hydrologic measurement sites, wetlands, and selected cultural features in the Salmon River watershed and vicinity.

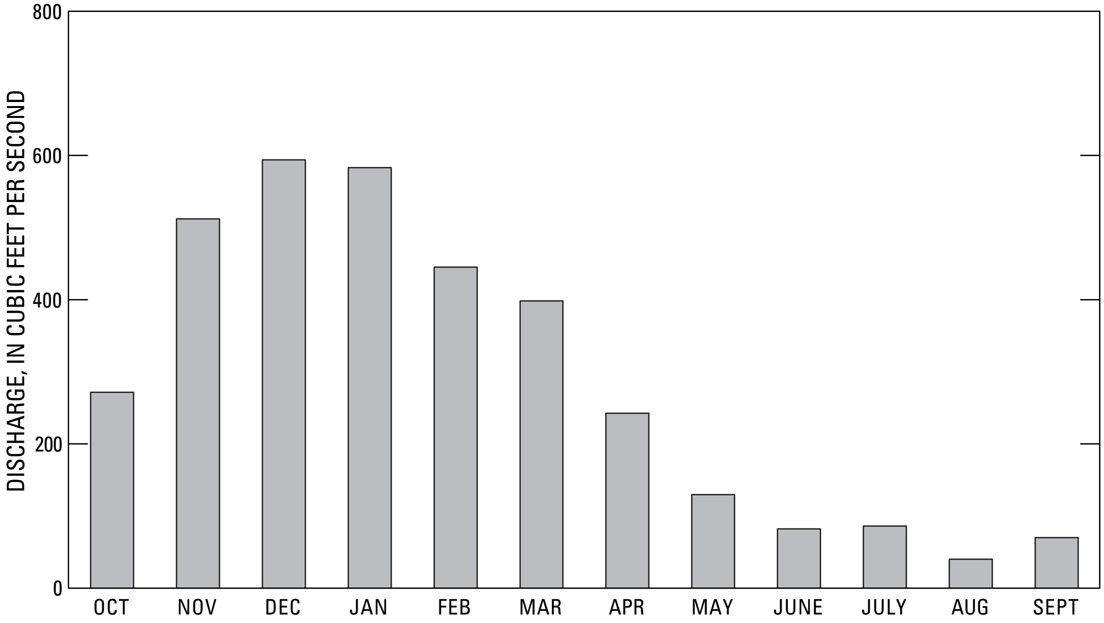


**Figure 7.** Average monthly discharge of the Salmon River near the 1000-Road Bridge during water years 1995 to 1998.

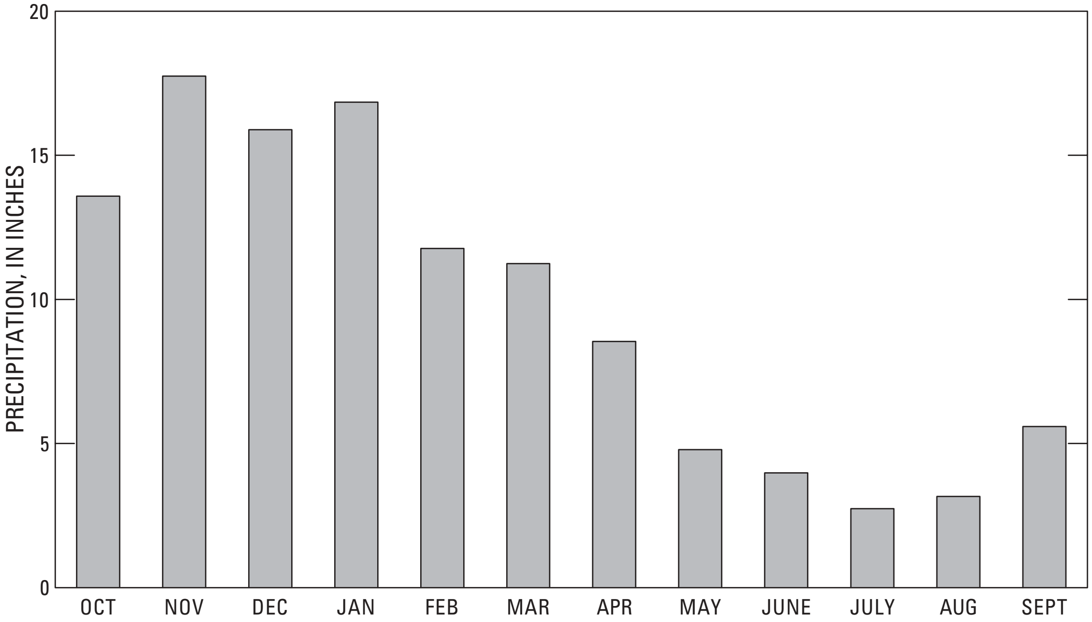


**Figure 8.** Average monthly precipitation at Clearwater, Washington, during water years 1995 to 1998.

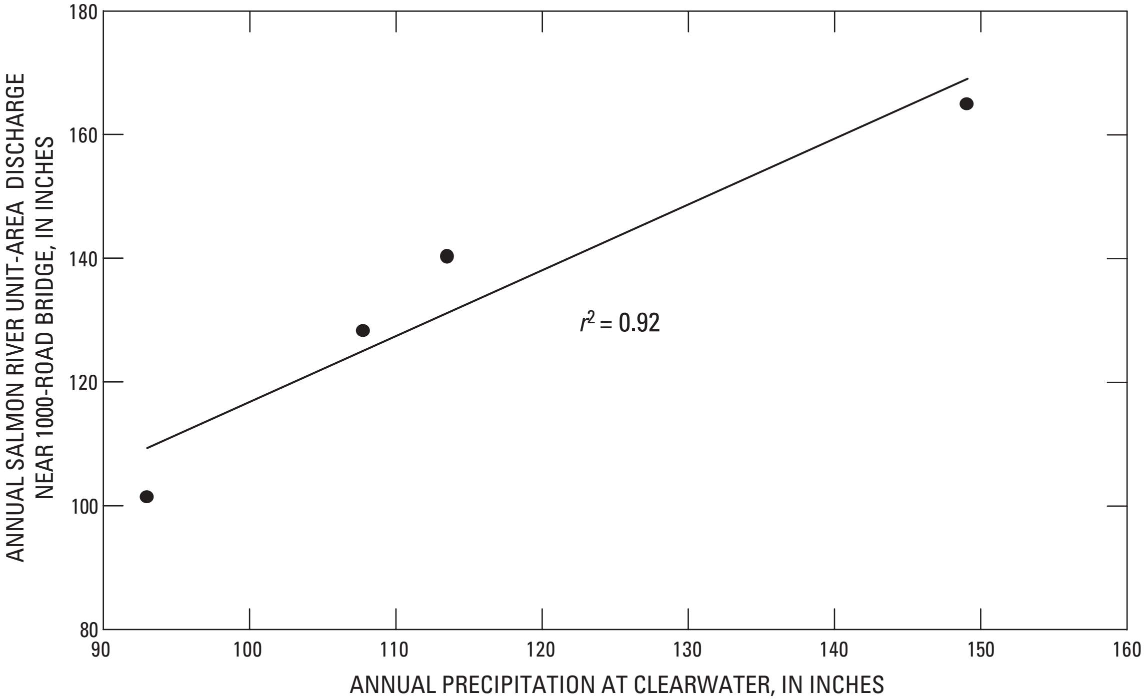


**Figure 9.** Relation between annual unit-area discharge of the Salmon River near the 1000-Road Bridge and annual precipitation at Clearwater, Washington, during water years 1995 to 1998.

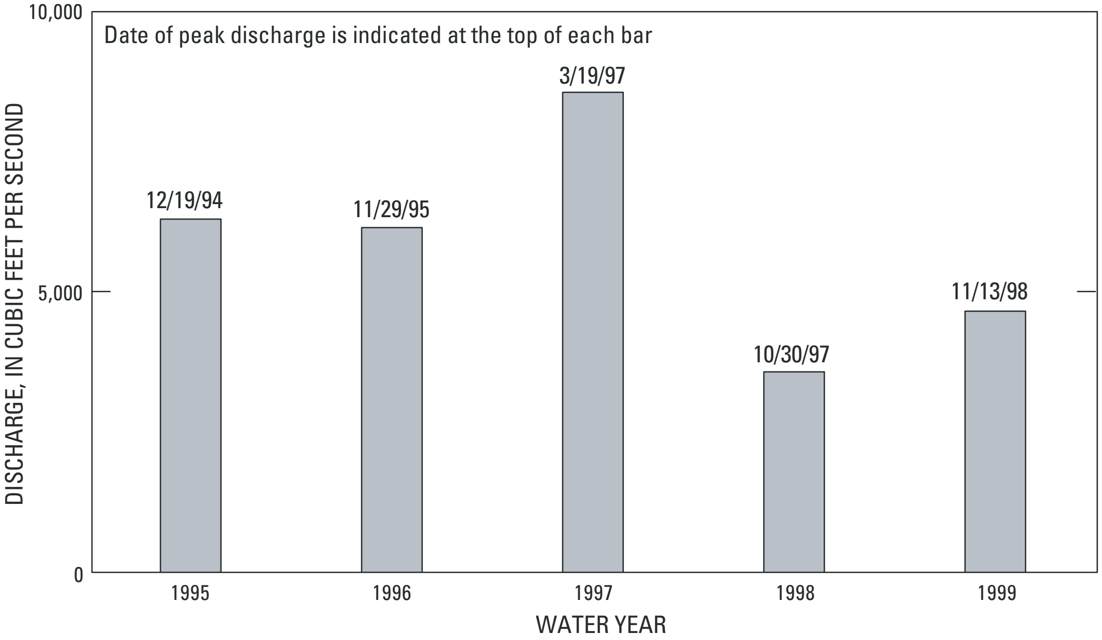


**Figure 10.** Annual instantaneous peak discharge of the Salmon River at the gaging station near the 1000-Road Bridge for water years 1995 to 1999.

One such technique is described by Sumioka and others (1998), who correlated magnitudes of selected N-year peak-flow events from frequency analysis of Washington gaging station records with quantifiable watershed characteristics (termed "explanatory watershed variables"), such as drainage area and mean annual precipitation. They developed peak-flow regression equations to enable estimates of selected N-year peak flows to be made for sites where streamflow records are not available or not of sufficient duration to compute peak-flow frequency curves. Sumioka and others' peak-flow regression equations were applied to estimate the magnitude of selected N-year peak flows at the streamflow gaging site near the 1000-Road Bridge. According to the applicable peak-flow regression equations from Sumioka and others (1998), the largest gaged peak flow at the 1000-Road Bridge site, that of March 19, 1997, was approximately a 100-year event. The regression-predicted, 100-year peak flow was 8,300 $ft^3/s$, and the gaged peak flow on March 19, 1997 was 8,550 $ft^3/s$. The annual peak flows for water years 1995 and 1996 that are also presented in figure 10 were approximately 25-year events, according to the applicable peak-flow regression equation from Sumioka and others (1998). The regression-predicted, 25-year peak flow was 6,550 $ft^3/s$, and the gaged annual peak flows for water years 1995 and 1996 were 6,290 and 6,140 $ft^3/s$, respectively.

It is considered unlikely that the 5 years of available record of annual peak flow at the 1000-Road Bridge site captured two 25-year peak-flow events and a 100-year peak-flow event as is indicated by the peak-flow regression equations. More likely, the peak flows were specified as 25- and 100-year events because of such factors as the Salmon River peak-flow characteristics being statistically aberrant among the watersheds that were used to develop the equations or because of errors in the gaged peak flows at the 1000-Road Bridge site. This argument is bolstered by the observation that the event of March 19, 1997, was approximately a 25-year event, both at the streamflow gaging station on the nearby Quinault River at Lake Quinault (USGS station 12039500) and at the gaging station on the Queets River near Clearwater (USGS station 12040500; U.S. Geological Survey, 1998). Peak-flow events at these latter two sites were characterized by frequency analysis of long-term streamflow gaging records (Sumioka and others, 1998).

Peak-flow frequency analysis of long-term streamflow gaging records is in itself subject to errors caused by violation of the statistical assumptions that were discussed previously and that could be caused by such factors as climate shifts or trends. The implication of this is the peak-flow magnitudes from frequency analysis and the peak-flow regression equations that were derived from those magnitudes are sources for uncertainty that ultimately could reduce the accuracy of the regression-predicted peak flows at the 1000-Road Bridge site. The detailed hydrologic analysis that could be made to evaluate applicability of those equations for the 1000-Road Bridge site, which could include analysis for possible precipitation trends or anomalies or testing of the regression equations for nearby rivers for water years 1995 to 1999, is beyond the scope of this report. Uncertainties concerning magnitudes of recurring peak-flows at the 1000-Road Bridge site could in the future be addressed by additional hydrologic analysis. Such an analysis would be aided by data from the continued operation of the gaging station at that site.

### Low-Flow Characteristics of the Salmon River

Stream low-flow magnitude and frequency bear potentially important implications both for the uninterrupted operation of the fish culture facility and for the survival and growth of juvenile fish in the Salmon River and its tributaries. Watershed analysis was taken as an opportunity to develop a better hydrologic understanding of low-flow characteristics of the Salmon River. The three objectives of a brief low-flow investigation that was conducted during summer and autumn 1999 were:

1. Estimate the magnitudes of the annual 7-day low flows for the 5-year and 20-year recurrence intervals at the streamflow gaging station that is near the 1000-Road Bridge by correlating streamflow at that station with streamflow at a long-term gaging station on the Calawah River (fig. 1);
2. Test the low-flow estimation procedure employed for objective (1) using streamflow records from long-term stations on the Calawah and Humptulips Rivers (fig. 1);
3. Measure and describe low flows at selected sites on the Salmon River and its tributaries by conducting and interpreting seepage runs during the low-flow season.

A seepage run is a series of near-simultaneous measurements of stream discharge that are made at different points on a stream. The annual 7-day low flow at any point on a stream is the smallest average discharge at the point among any 7 consecutive days during a single "low-flow" year. The annual 7-day low flow is a hydrologic event that is amenable to statistical treatment in much the same manner as are events such as the annual peak flow. A low-flow recurrence interval is a probabilistic statement of how often an N-day low flow of a given magnitude or smaller would be expected to occur, on average, during a period of many years. The low-flow year begins on April 1 and thus is distinct from the water year or from the calendar year.

### *Estimating the 5- and 20-Year 7-Day Low-Flow Discharges at the 1000-Road Bridge Gage Site*

The magnitudes of recurring N-day low-flows at a given site, such as the annual 7-day low flow, can be estimated using low-flow frequency curves that have been developed for the site (Riggs, 1972). A low-flow frequency curve can be developed for a site where a streamflow gaging station exists by statistical analysis of the streamflow records. For a curve to be reliable for estimating magnitudes of low flows at a site, the low flows should meet certain statistical assumptions and streamflow records for the site should be of a sufficient duration. Two important statistical assumptions are (1) the individual N-day low flows are statistically independent of each other from time to time and the population of those low flows does not change with time, and (2) the probability distribution of the N-day low flows is compatible with the theoretical distribution upon which the frequency curve is based. Few populations of low flows strictly meet both of these assumptions because of such factors as climate shifts or trends that potentially can cause the low flows to be correlated from time to time. Nonetheless, statistically derived low-flow frequency curves, if they are interpreted with the statistical assumptions in mind, can be useful tools for estimating frequency and magnitude of low flows.

Generally, 10 or more years of discharge records are needed to develop reliable low-flow frequency curves for a given station. Riggs (1972) describes a procedure that can be used to estimate low-flow discharges for a site with less than 10 years of record if gaged low flows at the site correlate with concurrent flows at a long-term station for which the needed low-flow frequency curves can be developed. The specific steps of Riggs' procedure for estimating low-flow characteristics for gaging stations with less than 10 years of discharge record can be summarized as follows.

1. Develop a relation line or equation for predicting low flow at the station of interest from low flow at an alternative gaging station where a long-term record of discharge is available.
2. For the long-term station, compute a low-flow frequency curve for each annual N-day low-flow event that is of interest, where N could be any integer from 1 to 365 but that was 7 for this investigation. Use the low-flow frequency curves to compute the appropriate annual N-day low flows at the long-term station and at the desired recurrence intervals.
3. Use the relation line or equation of concurrent low flows with the N-day flows from the long-term station to estimate the N-day low flows at the appropriate recurrence intervals for the station of interest.

The gaging station near the 1000-Road Bridge, the site of interest, had been operated for less than 10 years at the time of this analysis, and the technique of Riggs was used to estimate the magnitudes of the 5- and 20-year 7-day low-flows at that site. The alternative long-term station selected for this purpose (USGS station 12043000) was on the Calawah River near Forks (fig. 1). The area of the Calawah River watershed upstream of station 12043000 is 129 mi$^2$, approximately four times that of the Salmon River watershed upstream of the 1000-Road Bridge.

The Calawah station was selected because of physical similarities between the Calawah and Salmon River watersheds. The Calawah River watershed, like the Salmon River watershed, lies on the Pacific slope of the Olympic Peninsula and comprises low- to mid-altitude forested terrain. The two watersheds are also similar in that neither river drains large permanent snowfields or glaciers that could augment low flows during late summer or autumn.

Flows gaged near the 1000-Road Bridge and on the Calawah River near Forks during July through September of years 1995, 1996, and 1998 were selected for developing a relation line of concurrent flows. The time series of daily mean discharge for the two stations for July to September is presented in figure 11. No estimated record was used in the analysis, and because discharge at the gaging station near the 1000-Road Bridge was almost entirely estimated during 1997, data from that year were not used in the analysis. One pair of daily mean flows was selected from each month July through September, and each pair was selected such that the Calawah River member was the smallest daily mean discharge for that station for the month. This selection procedure provided a degree of selection objectivity and repeatability that would not have been realized had the flow pairs been selected, for example, from visual inspection of figure 11.

Graphical techniques (Riggs, 1972) were used to develop a relation line of low flows at the 1000-Road Bridge and the Calawah River gaging stations (fig. 12). Daily mean discharge averaged 21 $ft^3/s$ for the Salmon River site among the 9 days that were selected, whereas daily mean discharge averaged 82 $ft^3/s$ for the Calawah River site. That the average low flow of the Calawah River near Forks was roughly four times larger than the average low flow at the 1000-Road Bridge site could be explained by the fact the drainage area for the former site is roughly four times larger than the drainage area for latter site.

For the second step, that of computing the low-flow frequency curve for the annual 7-day low flow for the Calawah River near Forks, the U.S. Geological Survey computer program Surface-Water Statistics (SWSTAT; Lumb and others, 1990) was used to compute a frequency curve for the annual 7-day low flow by fitting a log-Pearson Type III probability distribution to the available data for that station. Data were excluded from the analysis for years when the gaging station records were not complete. Riggs (1968) describes the log-Pearson Type III probability distribution, and Riggs (1972) describes the application of that distribution to the study of stream low flows. The computer program SWSTAT is available at this time (2003) on the World Wide Web at the universal resource locator (URL): http://water.usgs.gov/software/swstat.html. The particular low-flow years for which data from the Calawah River station were used for fitting the frequency curve, plus the annual 7-day low flows for the 5- and 20-year recurrence intervals from the fitted frequency curve are presented in table 2. The series of annual 7-day low flows was tested for the presence of a trend, but no trend was detected. Annual 7-day low flows computed from the gaged stream flow record and the fitted frequency curve for the 7-day low flow are presented in figure 13. The low flows specified by the frequency curve are themselves estimates of the recurring low flows. The specified flows are subject to errors that are due to such factors as lack of conformance of the gaged low flows to the statistical assumptions that were discussed previously, and errors of sampling or measurement in the gaged, annual 7-day low flows.

For the third step, the relation line for concurrent low flows was applied to yield estimates of the annual 7-day low flow near the 1000-Road Bridge site for the 5- and 20-year recurrence intervals. The estimates are presented in table 2. The estimates appear to be plausible. For example, the smallest gaged daily mean discharge at the 1000-Road Bridge site during 1995, 1996, and 1998 was 14.2 $ft^3/s$. This gaged, annual 1-day low flow was 2 percent larger than the estimated annual 7-day low flow at the 5-year recurrence interval (13.9 $ft^3/s$) that is presented in table 2.

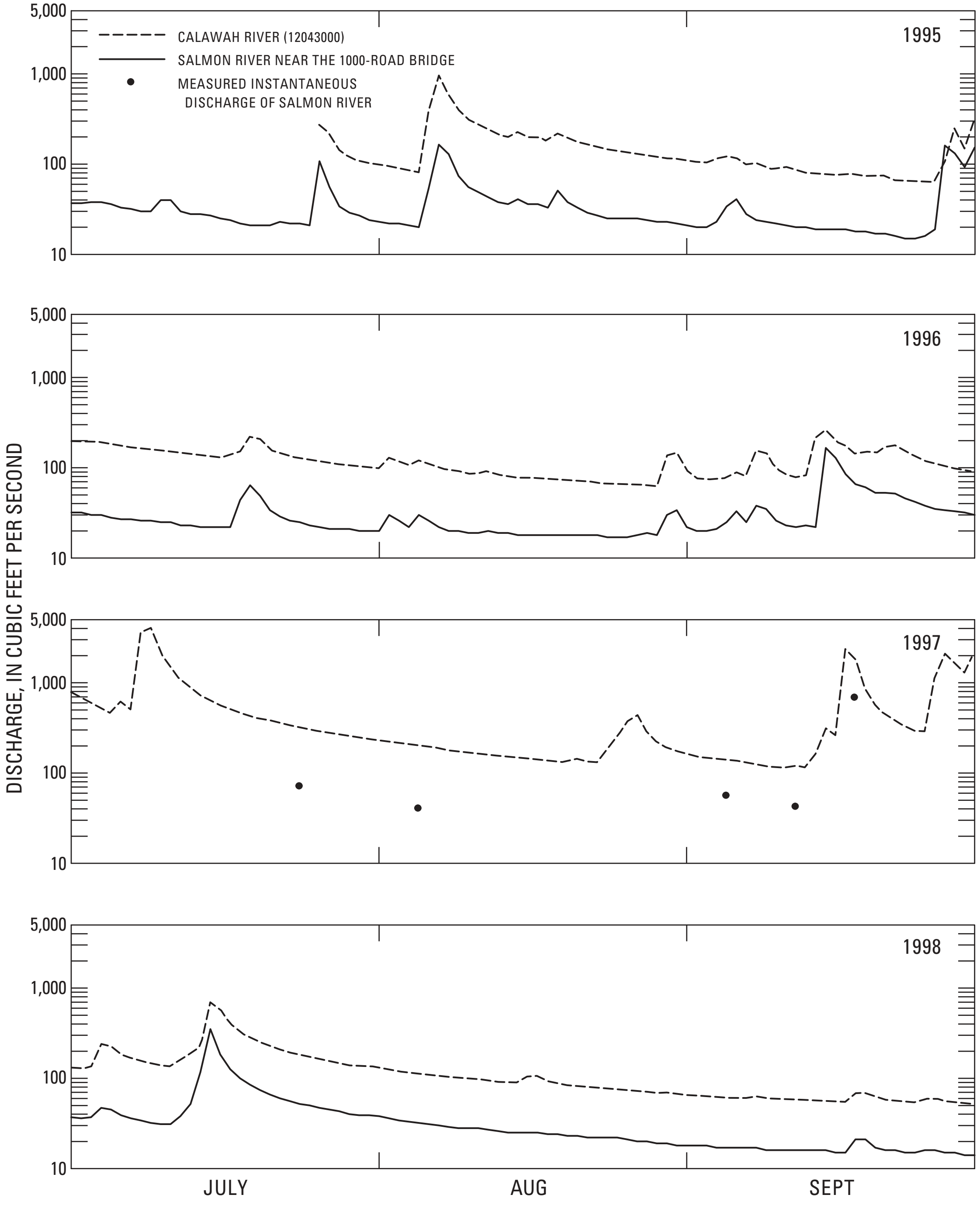


**Figure 11**. Daily mean discharge of the Calawah River near Forks, Washington, (USGS station 12043000) and of the Salmon River near the 1000-Road Bridge during July to September of 1995 to 1998 and for which sufficient data are available.

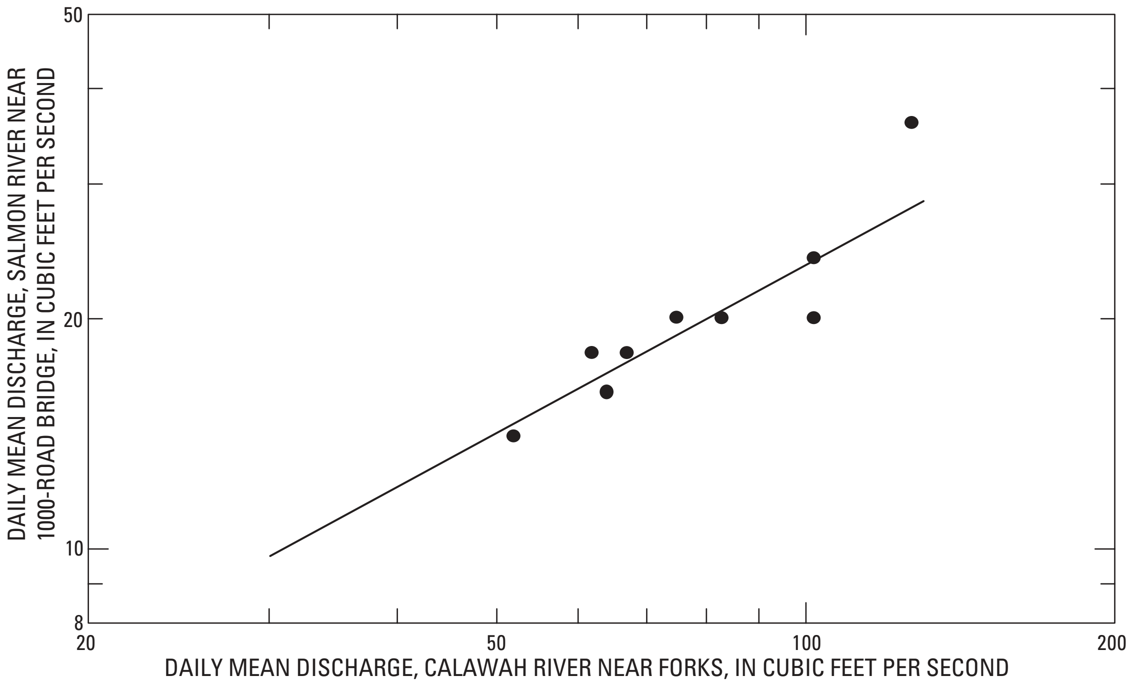


**Figure 12.** Relation between monthly minimum of daily mean discharge of the Calawah River near Forks, Washington, (USGS station 12043000) and concurrent discharge of the Salmon River near the 1000-Road Bridge during July to September of 1995, 1996, and 1998.

**Table 2.** Contributing drainage area and computed and estimated 7-day low flow discharge for stream gaging stations on the Salmon, Calawah, and Humptulips River

| Station | Contributing drainage area (square miles) | Period(s) of station record used to develop low-flow frequency function | Annual 7-day low flow computed from frequency function (cubic feet per second) | | Annual 7-day low flow estimated using correlation with alternative, long-term station (cubic feet per second) | |
|---|---|---|---|---|---|---|
| | | | Recurrence interval (years) | | Recurrence interval (years) | |
| | | | 5 | 20 | 5 | 20 |
| Salmon River near the 1000-Road Bridge | 29.2 | None | Not computed | Not computed | [1]13.9 | [1]10.8 |
| Calawah River near Forks (USGS station 12043000) | 129 | Low-flow years 1899 to 1901, 1977 to 1980, 1985 to 1998 | 48.6 | 34.4 | Not estimated | Not estimated |
| Humptulips River near Humptulips (USGS station 12039000) | 130 | Low-flow years 1944 to 1979 | 118.3 | 95.5 | [1]64.2 | [1]40.8 |

[1] Alternative station was Calawah River near Forks (USGS station 12043000).

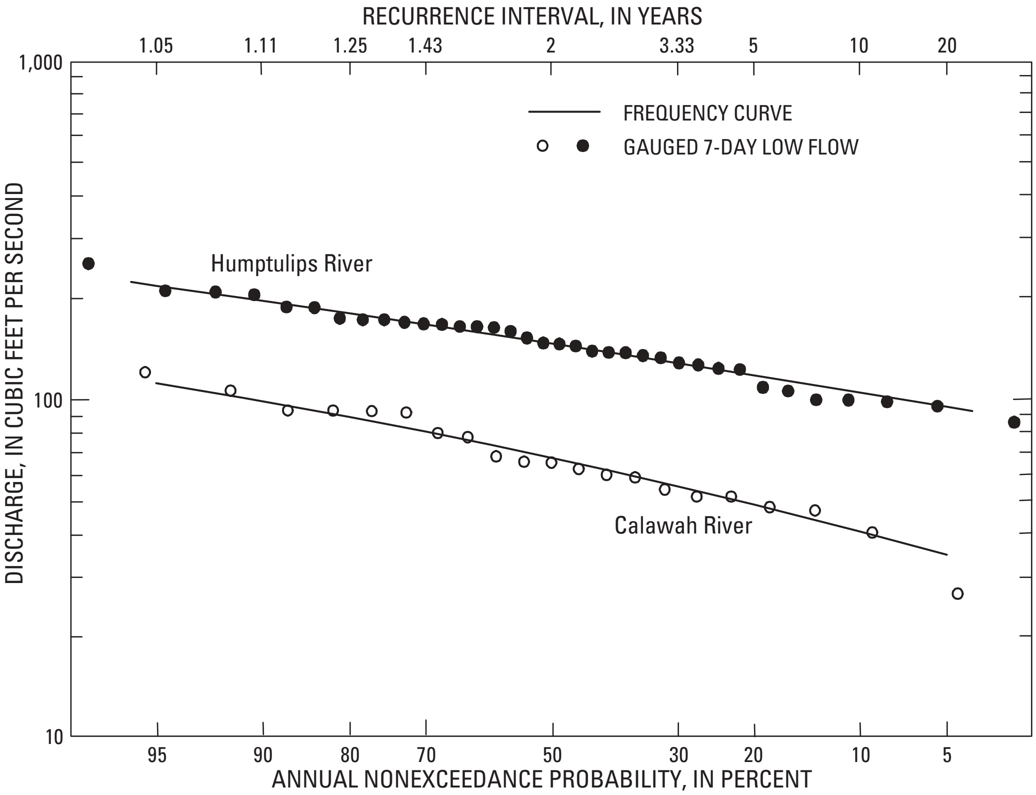


**Figure 13.** Annual 7-day low flows of the Calawah River near Forks, Washington, (USGS station 12043000) and of the Humptulips River near Humptulips, Washington, (USGS station 12039000), as computed from gaging station records and as depicted by frequency curves based on the log-Pearson Type III probability distribution.

### *Testing the Low-Flow Estimation Procedure Using Long-Term Stations on the Calawah and Humptulips Rivers*

To provide a sense of how reliably the annual 7-day low flows in mid-altitude, forested watersheds on the Pacific slope of the Olympic Peninsula can be estimated for short-term stream flow stations using the Riggs (1972) procedure, the procedure was tested for two long-term stream flow gaging stations on different rivers in the vicinity. The alternate station was again on the Calawah River near Forks (USGS station 12043000), and the station for which the 7-day low flow was estimated was a discontinued gaging station on the Humptulips River near Humptulips (USGS station 12039000; fig. 1) that was last operated during water year 1979. Testing was done using the long-term station on the Humptulips River because this permitted the low flows estimated by the Riggs procedure to be compared with low flows from the more reliable frequency curve for that station. Selection of concurrent flows and development of a relation line for those flows were performed as was described previously. The Humptulips River watershed upstream of station 12039000 is a forested, low- to mid-altitude watershed of 130 mi$^2$ on the Pacific slope of the Olympic Peninsula. The Humptulips River, like the Salmon and Calawah Rivers, does not drain large permanent snowfields or glaciers that would augment low flows during late summer. The time series of daily mean discharge for the Calawah and Humptulips River stations overlap for July to September of years 1976 to 1979. The overlapping time series are presented in figure 14.

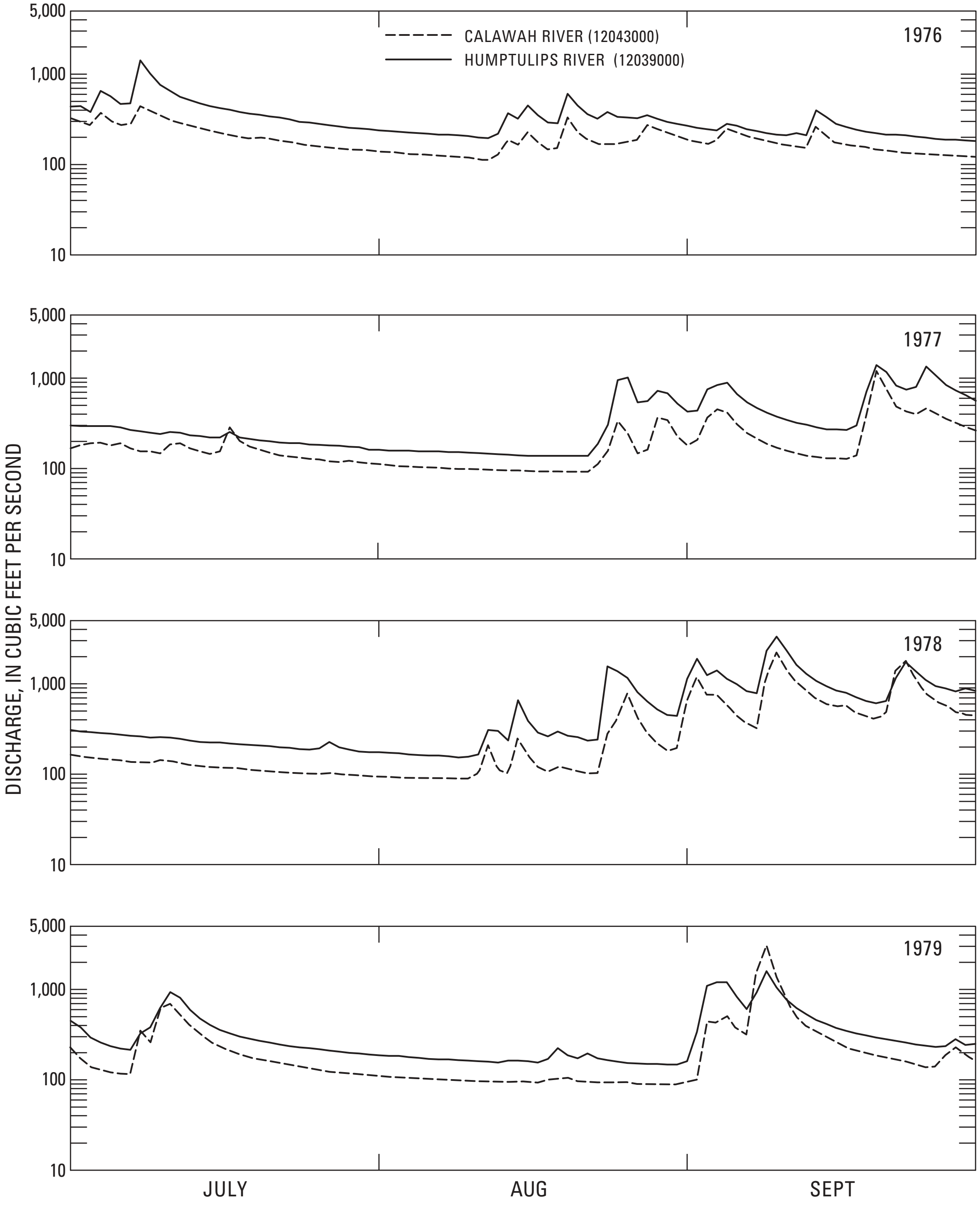


**Figure 14.** Daily mean discharge of the Calawah River near Forks, Washington, (USGS station 12043000) and of the Humptulips River near Humptulips, Washington, (USGS station 12039000) during July to September of years 1976 to 1979.

The annual 7-day low flows for the period of record for the Humptulips River station, exclusive of data from years when the gage record was not complete, were used to develop a frequency curve in the manner that was described previously. The series of annual 7-day low flows also was tested for the presence of a trend, but no trend was detected. The particular low-flow years for which data from the Humptulips River station were used for fitting the low-flow frequency curve, plus the curve-specified annual 7-day low flows for the 5- and 20-year recurrence intervals are presented in table 2. Annual 7-day low flows computed from the gage record and the fitted frequency curve for the annual 7-day low flow are plotted in figure 13.

The relation between concurrent flows at the Calawah River and Humptulips River gaging stations is presented in figure 15. The Riggs procedure produced estimates of the annual 7-day low flows of the Humptulips River near Humptulips for the 5- and 20-year recurrence intervals that compared poorly with flows prescribed by the low-flow frequency curve (table 2). The low-flow estimate for the 5-year recurrence interval (64.2 $ft^3/s$) was 46 percent smaller than the corresponding low flow prescribed by the frequency curve (118.3 $ft^3/s$), and the low-flow estimate for the 20-year recurrence interval (40.8 $ft^3/s$) was 57 percent smaller than the corresponding flow prescribed by the frequency curve (95.5 $ft^3/s$).

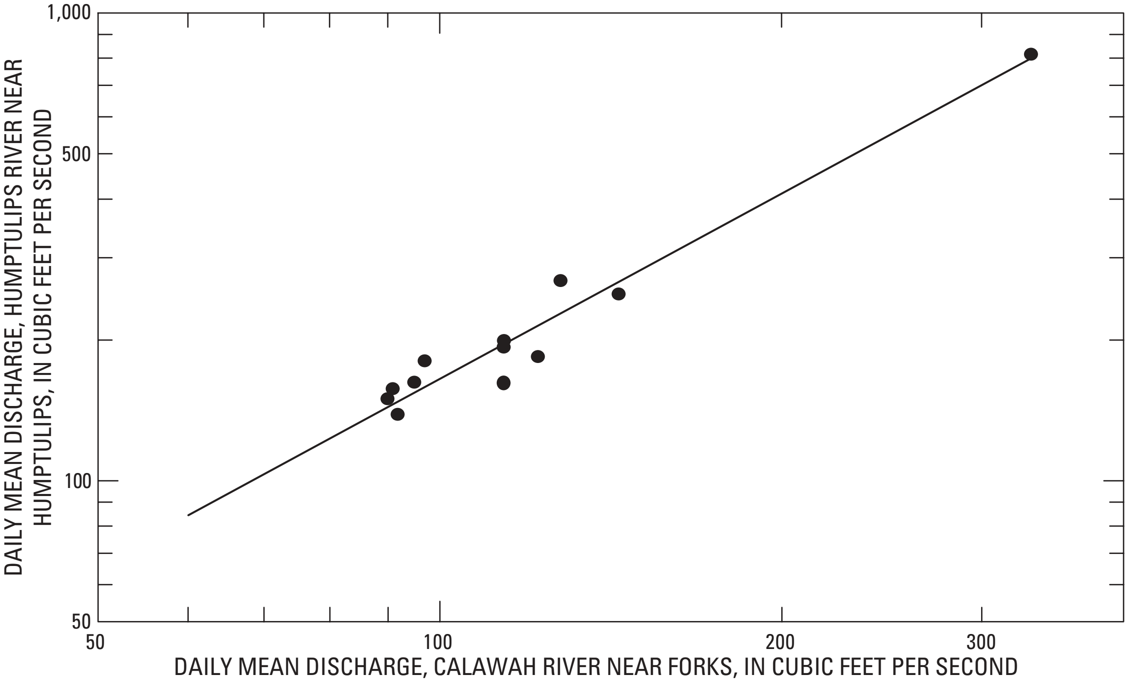


**Figure 15.** Relation between monthly minimum of daily mean discharge of the Calawah River near Forks, Washington, (USGS station 12043000) and concurrent discharge of the Humptulips River near Humptulips, Washington, (USGS station 12039000) for July to September of years 1976 to 1979.

That the estimates of low flows for the Humptulips River near Humptulips that were computed by the Riggs procedure agreed poorly with the low-flow estimates from the frequency curve for that site could have been caused by at least two factors. The first of these potential factors is the lack of data for flows small enough to accurately define the relation between concurrent flows at the two sites at the magnitudes of the 5- and 20-year low-flow events. Another possible factor is climatically induced differences in the low-flow frequency curves for the Calawah River and the Humptulips River sites. The low-flow frequency curve for the Humptulips site was computed from a period (table 2) that encompassed the relatively wet period of the late 1940s to 1977 that was described previously. Conversely, most of the years (17 out of 21 years) used to compute the low-flow frequency curve for the Calawah River site were during the relatively dry 1978-to-1998 period. Thus, the underestimation of low flows at the Humptulips River site could have resulted from estimating those flows using the frequency curve for the Humptulips River that was developed based on a relatively wet climatic regime.

### *Low Flows at Selected Sites on the Salmon River and Its Tributaries During August and September 1999*

Understanding temporal and spatial variations of the evolution of low flows is important for understanding the relative importance of various stream reaches in contributing to low flows and for describing and understanding interactions among ground water and surface waters. Seepage runs were made on the main stem of the Salmon River and its major tributaries during August and September 1999 to describe variations of flow gains or losses on selected reaches of the river. Four seepage runs were conducted during which discharge was measured at 6 to 8 sites from the mountainous subwatersheds to near the 1000-Road Bridge (sites A-H, fig. 6, table 3). Discharge at each site was measured with a vertical-axis type current meter (Smoot and Novak, 1968). An attempt was made to complete each seepage run during a relatively brief period of 24 hours and during a period without precipitation; however, precipitation occurred during the seepage runs of August 24-25 and September 22-23. Although the rain on September 23 probably had minimal effect on discharge (fig. 16), the flows measured on August 25 on the Middle and South Forks near the confluence of those streams and on the main stem immediately downstream of the confluence appeared to have been affected by rain that fell the previous night, and those flows likely consisted of surface runoff as well as low flow. Despite the difficulties in interpreting flows that were affected by precipitation, the seepage runs provided information about low flows for some major streams in the Salmon River watershed.

**Table 3**. Salmon River watershed low-flow discharge measurement sites and measurement dates

| Point on Figure 6 | Description | Discharge measurement dates |
|---|---|---|
| A | South Fork Salmon River at a point approximately 150 feet upstream of its confluence with the Middle Fork | Aug. 9 and 25, 1999<br>Sept. 9 and 23, 1999 |
| B | Middle Fork Salmon River at a point approximately 200 feet upstream of its confluence with the South Fork | Aug. 9 and 25, 1999<br>Sept. 9 and 23, 1999 |
| C | Main stem Salmon River approximately 50 feet downstream of confluence of the South and Middle Forks | Aug. 9 and 25, 1999<br>Sept. 9 and 23, 1999 |
| D | North Fork Salmon River approximately 200 feet upstream of its confluence with the Main stem | Aug. 9 and 24, 1999<br>Sept. 9 and 22, 1999 |
| E | Main stem Salmon River approximately 250 feet downstream of its confluence with the North Fork | Sept. 22, 1999 |
| F | Main stem Salmon River near Forest Road Number 040 | Aug. 10 and 24, 1999<br>Sept. 9 and 21, 1999 |
| G | Main stem Salmon River near fish culture facility | Aug. 10 and 24, 1999<br>Sept. 10 and 22, 1999 |
| H | Main stem Salmon River approximately 300 feet downstream of the 1000-Road Bridge | Aug. 24, 1999<br>Sept. 10 and 22, 1999 |

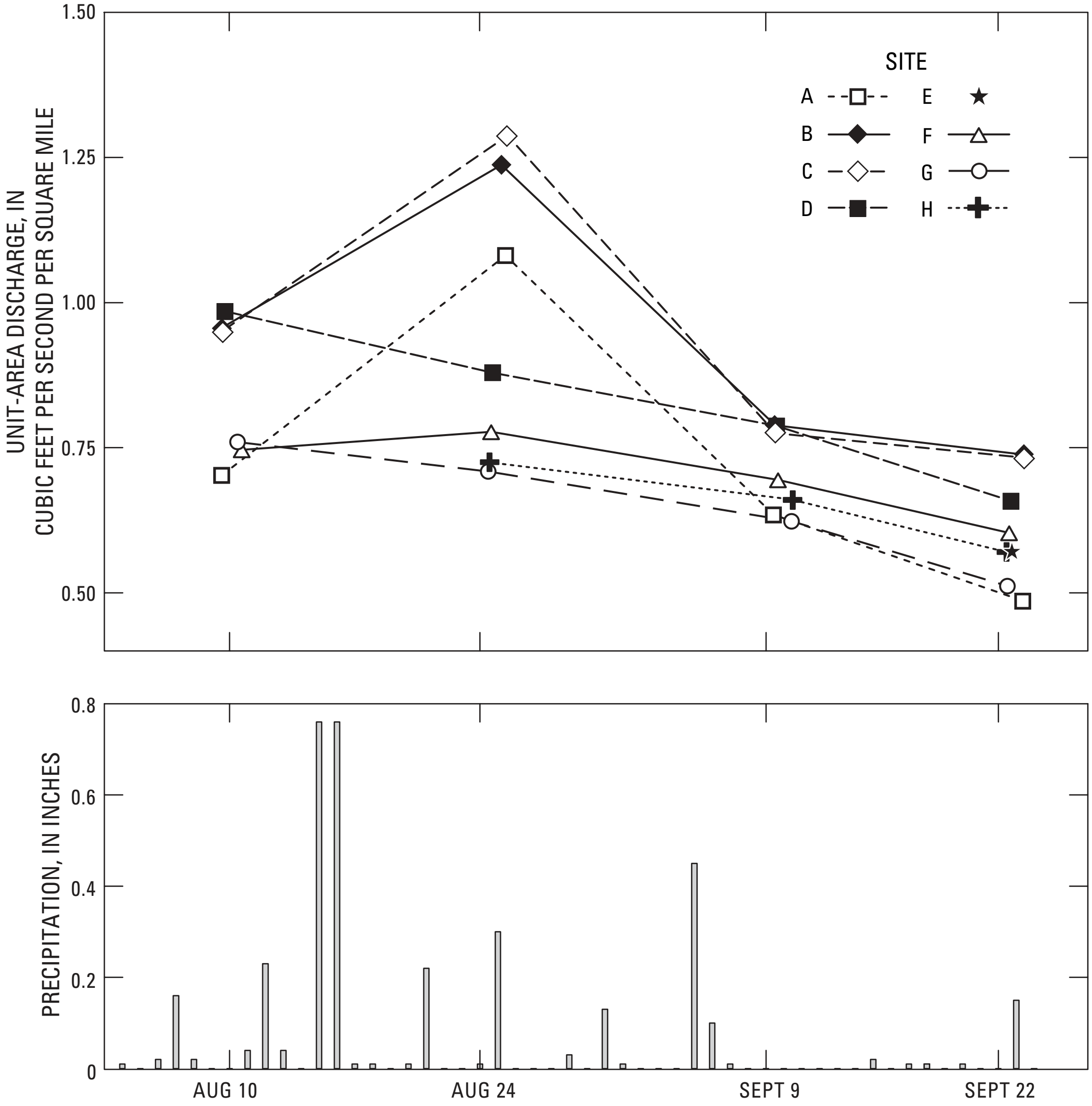


**Figure 16.** Unit-area discharge of the Salmon River and its tributaries at the low-flow measurement sites (table 3), and 24-hour precipitation totaled at 1:00 P.M. on the indicated day, at Black Knob, Washington.

Firstly, the South Fork contributed substantially less flow per unit drainage area than did the other two mountainous forks, the Middle and North Forks. For example, on August 9, the unit-area discharge of the South Fork near its confluence with the Middle Fork was 27 percent less than the unit-area discharge of the Middle Fork, and it was 29 percent less than the unit-area discharge of the North Fork near the confluence of that fork with the main stem (fig. 16). On September 9, the unit-area discharge of the South Fork was 20 percent less than the unit-area discharge of the Middle Fork, and it was 19 percent less than the unit-area discharge of the North Fork. The underlying causes of the relatively small contribution by the South Fork are not known at this time but could be related to variations of geologic composition or to variations of road construction or timber harvesting practices or harvest extent among the mountainous subwatersheds. Additional investigation of contrasting road construction or timber harvesting practices or harvest extent in the uppermost reaches could help identify whether or not low-flow yields are controllable through forest management practices.

Secondly, low-flow discharge increased with but was not linearly related to drainage area throughout the Salmon River and its tributaries, and trends of low-flow gains with drainage area changed with discharge. Excluding the precipitation-affected seepage run of August 24 and 25, and given that measured discharge was subject to errors of approximately 10 percent, discharge between low-flow measurement sites A and F increased in roughly fixed proportion to drainage area (fig. 17). During the two final seepage runs, when flows overall were smallest, discharge between sites F and G increased relatively little, and discharge between sites G and H increased sharply.

The causes of the variations of low flows in the upper and lower reaches of the Salmon River are not known with certainty; however, variations of watershed geology and physiography are consistent with the following possible explanations. Most of the mountainous reaches of the Salmon River are probably gaining reaches during the low-flow season because precipitation amounts are relatively large at the higher altitudes, soil moisture stores are depleted later in the season, and flows tend to remain in the channel due to the confining bedrock. A gaining reach of a stream is one where the flow is greater at the downstream end of the reach than it is at the upstream end. Thus, low flows in the Salmon River and its tributaries probably accumulate in the headwater reaches during late summer. As was stated previously in this report, the lower Salmon River channel lies mostly within porous unconsolidated deposits where the potential for the surface waters to exchange with the regional ground-water flow system is high. Thus, reaches in these deposits, such as are found between sites F and G (fig. 6), can be either gaining or losing reaches depending on the degree of hydrologic connectivity and hydrologic gradients between the surface- and ground-water systems. Finally, between sites G and H the river becomes confined by bedrock. The increases in low flows that were observed in that reach might have been caused by the river's encounter with the bedrock. For example, the bedrock might have prevented channel losses to the regional ground-water system and inflows from tributaries therefore remained in the channel and increased the river's flow.

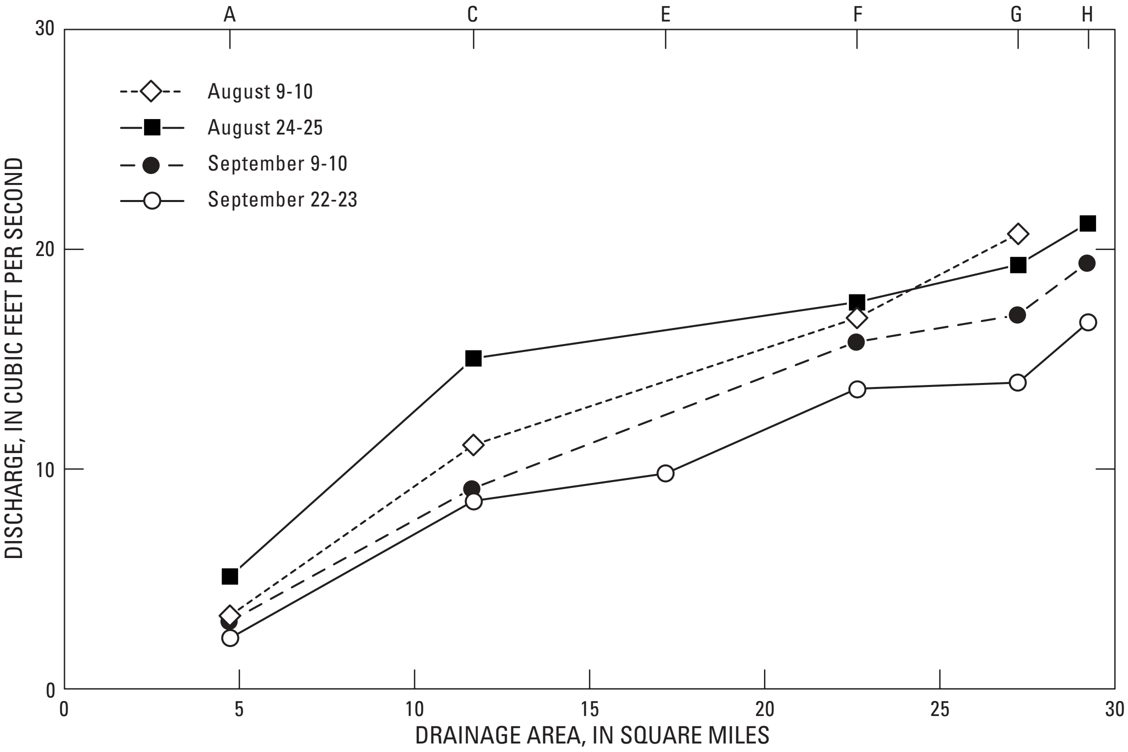


**Figure 17.** Discharge of the Salmon River and selected tributaries at selected low-flow measurement sites, as related to drainage area.

Letters on upper X-axis refer to low-flow measurement sites given in table 3.

## 3. What Evidence Exists That Forest Harvesting and Road Construction Have Altered Frequency and Magnitude of Peak and Low Flows?

Timber harvesting and associated road construction might have affected one or more hydrologic responses in the Salmon River watershed. The Salmon River watershed has been extensively harvested throughout, although the timing of harvesting has varied for different parts of the watershed. Clearcut logging began in the easily accessed Lower Salmon River subwatershed during the 1930's (Rodney F. Mayte, U.S. Forest Service, written commun., February 2001). Clearcut logging began in the mountainous North Fork, Middle Fork, and South Fork subwatersheds during the 1960s. The resulting mosaic of forest stands represent different stages of forest succession. Almost all of the conifer stands and many of the hardwood stands that currently are at early to middle successional stages likely resulted from forest harvesting and related human activities of the twentieth century. Stands at early to middle successional stages occur in approximately 90 percent of the Lower Salmon River subwatershed, approximately 50 percent of the North Fork subwatershed, approximately 60 percent of the Middle Fork subwatershed, and approximately 80 percent of the South Fork subwatershed (Rodney F. Mayte, U.S. Forest Service, written commun., February 2001).

Available hydrologic data for the watershed are currently not sufficient to document the possible effects of timber harvesting and associated road construction on any hydrologic variables. Given the relatively short record from the streamflow gaging station near the 1000-Road Bridge and the lack of streamflow data for preharvest conditions, statistical examination of timber-harvesting effects on hydrologic responses was not possible during this watershed analysis. Because of the lack of hydrologic data for impacted areas within the watershed, no attempt was made in this analysis to quantify effects of timber harvesting on hydrologic responses.

Instead, questions concerning effects of vegetation manipulation can be addressed qualitatively to provide insight into the possible change mechanisms for hydrologic responses and to point out the types of investigations and hydrologic data that will be needed to determine effects of forest clearing and associated road construction on hydrologic responses. The primary resource for making qualitative evaluations of effects of timber harvesting and road construction on hydrologic response is the scientific literature describing investigations in other impacted watersheds. The brief review of that literature that follows is not intended to be comprehensive, but rather to give the reader some examples of documented harvest effects from the Pacific Northwest and to provide insights into how questions about the possible hydrologic effects of harvesting and road construction in the Salmon River watershed can be addressed through site-specific investigations.

Numerous scientifically rigorous investigations of forest hydrology and of hydrologic effects of forest harvesting and road construction have been conducted on the forested lands of the Pacific Northwest during the past century. The particular hydrologic response variables that have been investigated most commonly in conjunction with harvest and road construction are total watershed surface-water yield; magnitude of stream peak flows; and duration and magnitude of stream low flows. Surface-water yield is the unit-area surface-water discharge from a given watershed or subwatershed, and it is commonly expressed in inches per month or inches per year.

Investigations of surface-water yield conducted in small, low- to mid-altitude mountain watersheds in the western Oregon Cascades and the Oregon Coast Range indicated that annual and summer yield generally increased immediately following extensive harvesting of dense forest stands (Harris, 1977, Harr, 1982, 1983; Hicks and others 1991). Harr (1983) and Hicks and others (1991) reported that most of the increase in annual water yield occurred during the winter rainy season. Postharvest increases in surface-water yield have been attributed to reductions in evapotranspiration caused by clear-cutting (Hicks and others, 1991). The magnitude of yield changes, expressed in inches per year, has varied somewhat among the studied watersheds. For example, annual water yield for the first eight years following 100-percent harvesting of a small (0.27 mi$^2$), hardwood-dominated watershed on the west slope of the Oregon Coast Range averaged 57 inches, which was 19 inches larger than the yield predicted from a control watershed (Harris, 1977). Annual precipitation for that watershed was about 95 inches. Annual water yield of a nearby watershed with forest cover that initially was about 60 percent Douglas-fir and 40 percent red alder averaged

52 inches following patch-clear-cut harvesting of about 25 percent of the watershed. Annual postharvest water yield from this latter watershed was not statistically different from the annual yield of 48 inches that was predicted from the control watershed. In another study, annual water yield of a small (0.37 $mi^2$) watershed in the western Oregon Cascades increased by an average of 14 inches as compared to water yield predicted from a control watershed for the eight years following the beginning of 100 percent harvesting of dense stands of mature Douglas-fir (Hicks and others, 1991). Some of the variability among the watersheds in the change of annual water yield was probably caused by variations in composition of the preharvest forests, by the extent and type of watershed harvest and roads, and by differences among the watersheds with respect to local geological, soil, or climate conditions.

Increases in annual surface-water yield following harvesting, where they occurred, generally decreased during the decade following harvesting (Harris, 1977; Harr, 1983; Hicks and others, 1991). Recovery (decrease) of surface-water yield toward the preharvest yield was attributed by Hicks and others (1991) to regrowth of vegetation that reestablished evaporative water losses from the watershed toward preharvest amounts. Timing and extent of postharvest yield recovery varied considerably among the watersheds, and although specific causes for these variations are elusive, they may be related to differences in geological conditions or climate or to differences in water-use characteristics of the dominant postharvest plant species in the watersheds.

Although changes in annual surface-water yield are an integrated measure of the effects of harvesting and road construction, it is probably the extreme low- and peak-flow events that are of most interest in the management of watersheds such as the Salmon River watershed. Decreased stream discharge and changes in channel geometry during low flows could pose a threat to the fishery resource, and increased peak flows can cause flooding. Scientifically rigorous investigations of the effects of timber harvesting and road construction on low and peak flows have been conducted for a number of watersheds in the Pacific Northwest, including those watersheds discussed previously. For the small, low- to mid-altitude mountain watersheds in the western Oregon Cascades, forest harvesting generally was associated with postharvest increases in summer low flows (Rothacher, 1965, Hicks and others, 1991), at least during the initial postharvest years. In contrast, Harris (1977) reported that no statistically significant changes in summer low flows occurred following clear-cut harvesting in two low-altitude mountain watersheds in the Oregon Coast Range. Also, Harr (1982) reported a small decrease in summer low flows as a consequence of clear-cut harvesting in a small, high-altitude watershed in the Oregon Cascades. Harr proposed that eliminating trees decreased interception of fog and subsequent drip to the soil, and thereby removed a summer source of water to augment low flows. Some investigations in coastal forests of Oregon (Isaac, 1946) and northern California (Azevedo and Morgan, 1974) have indicated that fog drip can be a significant water-balance component. Fog does occur over the low-lying coastal terrain of the Pacific slope of the Olympic Peninsula (Capoeman, 1990, p. 24), and removal of fog-intercepting conifers might reduce the amount of water that is available to augment low flows of the Salmon River, at least for a few years following harvesting. The effects of timber harvesting on fog drip and summer low flows in the Salmon River watershed can be known only if appropriate investigations of streamflow, fog drip, and related water-balance components are conducted in the watershed.

The literature describing investigations of effects of harvesting and road construction on peak flows in the Pacific Northwest is more difficult to interpret than that for surface-water yield and low flows. Part of the reason for this is that different investigators have used different techniques for classifying and analyzing peak-flow events. Some have considered all peaks above an arbitrary base, some have classified peaks as being either "high" or "low" peaks, while others have attempted to classify peaks based on whether or not they were associated with rain-on-snow events. In addition, the runoff-generating mechanisms for peak flows appear to be more variable in time and space than those for yield and low flows. For example, rain-on-snow might be the runoff-generating mechanism for major flow events in a watershed consisting largely of mid-altitude terrain, whereas rain without snow might be the major flood producer in low-altitude watersheds. One result of these complications is that general conclusions about whether or not forest harvesting increases peak flows are difficult to reach.

One of the most recent published investigations of peak flows in the Pacific Northwest at the date of this literature review (2000) employed inferential statistics to examine effects of forest harvesting and road construction on stream peak-discharge in eight small (<1 $mi^2$) and large (20 to 250 $mi^2$) watersheds in the western Cascades of Oregon (Jones and Grant, 1996). Specifically, Jones and Grant examined 34 years of streamflow records for three small research watersheds. The small watersheds included a control, where no timber harvesting or road construction was conducted, a treated watershed that was entirely clear-cut and slashed-burned during 1962 to 1966 without construction of roads, and a treated watershed in which 1.7 miles of road were constructed in 1959 and 25 percent of the area of which was patch clear-cut during 1963. Baseline comparisons of peak discharges among the control and treated watersheds were made during 1955 to 1961 and prior to the treatments. Jones and Grant classified peak discharge magnitudes according to ranges in the statistically derived event recurrence interval. For example, they classified peaks (events) with a recurrence interval of less than 0.125 year as "small," and they classified peaks with a recurrence interval of from 0.4 to 100 years as "large."

Jones and Grant (1996) developed a statistical model to compare paired peak-discharge events among the control and treated watersheds. They then used inferential statistics and probability theory to judge whether or not the magnitudes of peak-discharges from each treated watershed changed relative to peak discharge from the control watershed by more than could be explained by random chance. If the treatment-related changes were larger than could be explained by chance, Jones and Grant reasoned, the treatments (forestry operations) must have been the cause of the changes.

Among Jones and Grants' conclusions were (1) the average magnitude of all events increased significantly following 25 percent patch clear-cutting with roads; (2) the average magnitude of small events and all events increased significantly following 100 percent clear-cutting without roads; however, the average magnitude of large events did not increase significantly following 100 percent clear cutting without roads; (3) the largest percentage increase in peak discharge was as much as 50 percent; and (4) increases in the magnitude of peak discharge were persistent for up to 25 years following 25 percent patch clear-cutting with roads and for up to 16 to 22 years after 100 percent clear-cutting without roads.

Experimental conditions in the large watersheds studied by Jones and Grant were not as carefully controlled as were conditions in the small research watersheds because the former were managed for multiple uses, including fiber production, rather than for research. As a result, Jones and Grant (1996) developed a statistical regression model to examine whether or not relative differences in paired-event, peak discharges among the large watersheds were statistically linked to differences in cumulative percentage of harvested watershed area. Their regression analyses indicated the difference between the paired watersheds in magnitude of peak discharge was significantly correlated with the difference between cumulative percentage of the watershed area that had been harvested. Furthermore, Jones and Grant concluded that forest harvesting had increased the magnitude of peak discharge from the large watersheds by as much as 100 percent during the 50 years prior to their investigation.

In a subsequent investigation that employed much or all of the same data used by Jones and Grant (1996), Thomas and Megahan (1998) criticized the methods and conclusions of the former investigators. As for the small watersheds, Thomas and Megahan rejected both the statistical model and the rationale that Jones and Grant applied in choosing the model. Thomas and Megahan selected and applied a different, regression-based statistical model, termed an "analysis of covariance model," that allowed them to group all events together regardless of magnitude. Among the conclusions reached by Thomas and Megahan for the small watersheds was that the magnitude of peak discharge was significantly increased for 20 years following harvest in the watershed that was 100 percent clear-cut without roads and for 10 years following harvest in the watershed that was 25 percent patch clear-cut with roads. Secondly, the percentage increase in peak discharge decreased with peak-discharge magnitude. For example, for the 100 percent clear-cut watershed, the smallest peaks were increased by 90 percent, whereas the largest peaks with statistically detectable increases were increased by 25 percent. Thirdly, the magnitude of the peak-flow increase decreased exponentially with time in both watersheds.

Thomas and Megahan (1998) also were critical of the methods and conclusions presented by Jones and Grant (1996) for the large watersheds. Thomas and Megahan questioned Jones and Grants' choice for the dependent variable (differences in paired-event, peak discharges among watersheds) and for the independent variable (difference in cumulative percentage of watershed area harvested). Thomas and Megahan also objected to the statistical regression model that Jones and Grant employed. As was the case with the small watersheds, Thomas and Megahan analyzed the peak-discharge data for the large watersheds using a statistical model of their own derivation. Thomas and Megahan concluded that the data for one watershed pair failed to show that magnitude of peak discharge responded to harvesting. As for the other two large-watershed pairs, where harvest effects were small but statistically significant, Thomas and Megahan stated, "the 'usefulness' of these relationships is questionable." (p. 3401). The conclusions of Thomas and Megahan for the large watersheds stand in contrast to the conclusion stated by Jones and Grant (1996) that forest harvesting has caused large percentage increases in the magnitude of peak flows both in small and large watersheds.

The contrasting findings reported by Jones and Grant (1996) and Thomas and Megahan (1998) point to some of the difficulties in attempting to predict the effects of forest harvesting and road construction on hydrologic responses in the Pacific Northwest. One point of agreement between the two pairs of investigators is that more information and investigation of the potential hydrologic effects of forest harvesting are needed to identify when hydrologic changes caused by harvesting have occurred and to identify the important mechanisms of those changes.

Results of the above investigations of hydrologic effects of forest harvesting and road construction in Pacific Northwest watersheds, taken as a whole, do not support a conclusion that these practices have resulted in long-term or large-magnitude changes in annual water yield, low flows, or peak flows in the studied watersheds. As for the Salmon River watershed, it is considered probable that periods of extensive harvesting have yielded low flows and peak flows on the Salmon River and its impacted tributaries that were of slightly larger magnitude than would have occurred had the forest been left intact. This statement is qualified by the observation that hydrologic responses to forest practices on the Pacific slope of the Olympic Peninsula might differ substantially from documented responses in investigated watersheds, owing principally to climatic differences, and lessons taken from investigations of remote watersheds are best accepted cautiously as they are applied to the specific case of the Salmon River watershed.

## 4. What Is Currently Known About the Distribution and Extent of Wetlands, and What Have Been the Impacts of Land Management Activities on Wetlands?

A preliminary map of current wetlands and related hydrologic features of the Salmon River watershed was produced by the staff of the U.S. Forest Service, Olympic National Forest (fig. 6). The staff combined spatial wetland and hydrology databases (layers) from several sources, including the National Wetlands Inventory (NWI) layer (U.S. Fish and Wildlife Service, 1979; and U.S. Fish and Wildlife Service, 2000), the WADNR Hydrology Layer, and the U.S. Forest Service Geometronics Service Center (GSC) hydrology layer (Robin Stoddard, U.S. Forest Service, written commun., March 1997). Area of current wetlands is shown in table 4. Almost all of the wetland area (96 percent) is in the Lower Salmon River subwatershed. The inventory of current wetlands indicates the Middle Fork subwatershed accounts for the remaining 4 percent of the wetland area.

The preliminary map of current wetlands provides a good starting point for discussion of wetlands issues within the watershed. Because the map was derived by combining different wetland surveys, the uniformity of wetland mapping and classification throughout the watershed has not been established. Classification and mapping uniformity could be established by conducting a single, comprehensive survey of wetlands within the watershed.

Description of the change of the distribution and extent of wetlands would require a map of historical wetlands against which the current map could be compared. A map of historical wetlands was not found during this watershed analysis, and a sufficiently detailed historical wetland map probably does not exist. Whether or not a sufficiently accurate and detailed map of historical wetlands could be produced from historical aerial photographs is not known, and the investigation and application of the requisite photogrammetric techniques for producing such a map is beyond the scope of this report.

Forest harvesting, if it alters the water balance by reducing evaporative loss, could increase wetland water depth or the duration of inundation of seasonal wetlands. Construction and use of the transportation network have impacted wetlands within the Salmon River watershed. Roads have the potential for impacting wetlands by altering wetland hydrology (water depth and velocity, and duration of inundation for seasonally flooded wetlands), by disrupting wetland wildlife habitat, and by occupying lands that have previously been wetlands. An attempt was made in this analysis to provide a sense of the scope of wetland disruption related to the construction and use of the transportation network. To accomplish this, a map of existing roads was drawn on the map of current wetlands and the number of intersections of roads with wetlands and the total mileage of roads within wetlands were computed. The results of this analysis are presented in table 5. The only known impacts of roads on wetlands have occurred in the Lower Salmon River subwatershed (fig. 6).

**Table 4.** Wetland area, in acres, for each subwatershed of the Salmon River watershed

| Subwatersheds | | | | |
|---|---|---|---|---|
| Lower Salmon River | North Fork | Middle Fork | South Fork | Total |
| 298 | 0 | 11 | 0 | 309 |

**Table 5.** Number of intersections of roads with wetlands and mileage of roads within wetlands in the Salmon River watershed

| Subwatershed | Number of intersections | Mileage within wetlands |
|---|---|---|
| Lower Salmon River | 12 | 0.7 |
| North Fork | 0 | 0 |
| Middle Fork | 0 | 0 |
| South Fork | 0 | 0 |

## 5. How Might Existing Hydrologic Monitoring Be Maintained or Augmented to Help Detect Future Hydrologic Change, to Preserve Critical Ecosystem Functions, and to Protect Public and Private Property?

Many opportunities exist for monitoring to increase overall understanding of and predictive capability for hydrologic responses and processes within the Salmon River watershed. These include:

1. Maintaining the streamflow gaging station near the 1000-Road Bridge. This station had been operated for about 5 years at the time this hydrologic analysis was conducted. Continued operation will, in time, yield sufficient data for refining estimates of peak- and low-flow magnitudes and frequencies that are described in this report.
2. Measuring precipitation at high and low altitudes. Precipitation is quantitatively the most important hydrologic input to the Salmon River watershed, and understanding and prediction of hydrologic responses, such as flows measured at the 1000-Road Bridge gaging station, could be enhanced by determining precipitation within the watershed. Because precipitation probably varies with land-surface altitude, precipitation-measurement stations at both low and high altitudes would be useful for detecting onset, duration, and intensity of precipitation events that drive many of the watershed's hydrologic responses.
3. Describing the evolution of water available for runoff throughout the watershed. Hydrologic change due to forest harvesting and road construction in the Pacific Northwest has been linked to changes in the quantity and timing of water available for runoff during rain-on-snow-events (WADNR, 1995). Water available for runoff is the quantity of water per unit time or per storm that is applied to the soil surface from snowmelt and precipitation. Apparently, little is known about distribution of water available for runoff during these events in Pacific Northwest watersheds because watershed-scale surveys to compute water available for runoff have not been made. Such a survey in the Salmon River watershed for one or more storms could enhance understanding of runoff-generating rain-on-snow events in the Salmon River watershed and similar watersheds.

A survey of water available for runoff for a single storm would consist of measurements to compute water available for runoff at several different sites that vary with respect to altitude, vegetation type, or aspect direction. The snowpack snow-water equivalent would be measured before and after the storm, as would the amount of water from precipitation that is applied to the snow surface or bare soil (no snow) surface during the storm. Total storm water available for runoff at each site would then be computed from an equation for the site water balance. An equation for the water balance is

$$WAR = P - \Delta SWE - E, \qquad (1)$$

where

$WAR$ is the total water available for runoff for the storm, in inches;
$P$ is the quantity of water from precipitation that is input to the snow or bare soil surface during the storm, in inches;
$\Delta SWE$ is the change of snow water equivalent during the storm, in inches; and
$E$ is the total evaporative loss during the storm, in inches.

If the magnitude of $E$ is small compared to the magnitude of ($P$ - $\Delta SWE$) during rain-on-snow events (van Heeswijk and others, 1996), water available for runoff could be estimated from the equation

$$WAR \approx P - \Delta SWE. \qquad (2)$$

A survey of water available for runoff would be an intensive effort that would require several teams of people to react to an incoming storm in time to make the necessary pre-storm measurements and preparations and to return to the survey sites to make post-storm measurements. The number of sites to be incorporated would be decided upon as part of the survey design. Potentially, the following types of questions could be addressed by properly designed and conducted surveys.

  A. Where in the watershed is most of the water available for runoff generated during rain-on-snow events?
  B. How do precipitation and water available for runoff amounts vary with land-surface altitude during rain-on-snow events?
  C. How important is pre-storm snow-water equivalent on the generation of water available for runoff during rain-on-snow events?
  D. How much of the water available for runoff is derived from precipitation and how much is from snowmelt during rain-on-snow events? Do the relative contributions of precipitation and snowmelt vary with land-surface altitude?
  E. What is the effect of clear-cutting on prestorm snow-water equivalent and on generation of water available for runoff during rain-on-snow events?
  F. Is site directional aspect important for determining prestorm snow-water equivalent?
  G. Do the deepest snowpacks contribute to water available for runoff during rain-on-snow events?

4. Enhance the existing, preliminary map of wetlands through wetland surveys. An intensive mapping and classification of wetlands in the Salmon River watershed would be useful for checking and updating the preliminary map of current wetlands (fig. 6). The preliminary map of current wetlands could be compared to future wetland inventories for the purpose of evaluating status and trends in wetland resources.

## SUMMARY

The U.S. Geological Survey analyzed selected hydrologic conditions of the Salmon River watershed on the western Olympic Peninsula, Washington, as part of a watershed analysis conducted by the Quinault Indian Nation. The analysis of selected hydrologic conditions was motivated by five key questions that were developed by watershed analysis participants.

1. What are the natural, physical, and biological features of the watershed that control hydrologic responses?
2. What is known about current streamflow characteristics, including peak- and low-flows?
3. What evidence exists that forest harvesting and road construction have altered frequency and magnitude of peak and low flows?
4. What is currently known about the distribution and extent of wetlands, and what have been the impacts of land management activities on wetlands?
5. How might existing hydrologic monitoring be maintained or augmented to help detect future hydrologic change, to preserve critical ecosystem functions, and to protect public and private property?

The key questions were researched using the scientific literature, a brief field investigation, and hydrologic, climatic, and resource mapping databases maintained by tribal and governmental agencies.

The natural, physical, and biological characteristics that control hydrologic responses in the Salmon River watershed include the climate, the watershed physiography, geology, and vegetation. Climate is influenced by the watershed's location on the west coast of North America at a latitude of about 47 degrees N. Westerly trending winds bring moist air to the west coast of North America from the Pacific Ocean. The strong maritime influence results in abundant precipitation. Annual precipitation measured at nearby Clearwater, Washington, averaged 118 inches during 1932 to 1998, most of it falling as rain during the winter months.

The mountainous nature of the Salmon River watershed contributes to the abundant precipitation and to the accumulation and melt of snow. The higher mountain ridges in the watershed reach altitudes of approximately 2,700 feet. Average annual precipitation in the Salmon River watershed during 1961 to 1990 was estimated to range from ranged from 117 inches for low-altitude parts of the watershed to 165 inches for the highest terrain.

The terrain of the Salmon River watershed was classified according to system of five precipitation zones intended to portray the likelihood for flood-producing rain-on-snow events. Sixty-six percent of the terrain of the Salmon River watershed lies at altitudes that encompass the peak rain-on-snow or rain-dominated precipitation zones, which are two of the three precipitation zones with the greatest likelihood for rain-on-snow events. The remainder of the watershed terrain is in the lowland precipitation zone, which has a relatively small likelihood for rain-on-snow events.

The geology of the Salmon River watershed affects hydrologic responses in the watershed insofar as it controls bed surface slopes and gradients in stream channels and as it affects substrate materials that control or mediate subsurface flow. Vegetation potentially performs a number of functions that can influence hydrologic responses, including taking up and transpiring soil water, intercepting water in precipitation that is then evaporated back into the atmosphere, intercepting water in fog that drips to the soil surface, and protecting and augmenting soils that can store water and retard runoff.

Current streamflow characteristics of the Salmon River were investigated by examining the streamflow record from a gaging site on the river, by estimating stream peak flows using a regional regression equation, by estimating low flows by correlating flows at the Salmon River gage site with flows of a nearby river for which a low-flow frequency curve could be developed, and by measuring and interpreting flow of the Salmon River at selected points during the low flow season.

Annual unit-area discharge from the drainage area upstream of the gage near the 1000-Road Bridge averaged 134 inches for water years 1995 to 1998, and annual precipitation at Clearwater averaged 116 inches during the same period. The contributing drainage area upstream of the gage site is 29.2 mi$^2$. Annual unit-area discharge was correlated with annual precipitation at Clearwater during water years 1995 to 1998.

Annual peak discharge at the gage near the 1000-Road Bridge ranged from 3,570 to 8,550 ft$^3$/s during water years 1995 to 1999. One of the five gaged annual peak discharges was greater than the 100-year peak discharge for the site that was predicted using a regional regression equation, and two of the gaged annual discharges were almost as large as the predicted 25-year event. It is considered unlikely that the 5 years of available record of annual peak flow at the 1000-Road Bridge site captured three such rare events. More likely, the peak flows were specified as 25- and 100-year events because of such factors as the Salmon River peak-flow characteristics being statistically aberrant among the watersheds that were used to develop the equations or because of errors in the gaged peak flows at the 1000-Road Bridge site.

Annual low flows at the 1000-Road Bridge site were estimated by correlating flows at that site during 1995, 1996, and 1998 with flows at a long-term site on the nearby Calawah River for which a low-flow-frequency curve could be developed. The estimated 5- and 20-year 7-day low flows at the 1000-Road Bridge site were 13.9 and 10.8 ft$^3$/s, respectively.

Discharge of the Salmon River and its tributaries were measured during four seepage runs made during August and September 1999. The seepage runs indicated the South Fork of the Salmon River contributed substantially less flow per unit drainage area than did the other two mountainous forks, the Middle and North Forks. On August 9, the unit-area discharge of the South Fork near its confluence with the Middle Fork was 27 percent less than the unit-area discharge of the Middle Fork, and it was 29 percent less than the unit-area discharge of the North Fork near the confluence of that fork with the main stem. Also, low-flow discharge increased with but was not linearly related to drainage area throughout the Salmon River and its tributaries, and trends of low-flow gains with drainage area changed with discharge.

Timber harvesting and associated road construction might have affected one or more hydrologic responses in the Salmon River watershed. The Salmon River watershed has been extensively harvested throughout, although the timing of harvesting has varied for different parts of the watershed. Available hydrologic data for the watershed are currently not sufficient to document the possible effects of timber harvesting and associated road construction on any hydrologic variables. Therefore, the primary resource for making qualitative evaluations of effects of timber harvesting and road construction on hydrologic response is the scientific literature describing investigations in other impacted watersheds in the Pacific Northwest. Based on a brief review of such scientific literature, it is considered probable that periods of extensive harvesting have yielded low flows and peak flows on the Salmon River and its impacted tributaries that were of slightly larger magnitudes than would have occurred had the forest been left intact. This conclusion is qualified by the observation that hydrologic responses to forest practices on the Pacific slope of the Olympic Peninsula might differ substantially from documented responses in investigated watersheds, and lessons taken from investigations of remote watersheds are best accepted cautiously as they are applied to the specific case of the Salmon River watershed.

A preliminary map of current wetlands that was produced by staff of the U.S. Forest Service indicates wetlands area in the Salmon River watershed totals 309 acres, with 96 percent of the wetlands area in the Lower Salmon River subwatershed. Impacts of land management activities on wetlands are generally not known, except analysis of current wetlands and roads indicates there currently are 12 intersections of roads with wetlands within the Lower Salmon River subwatershed and a total of 0.7 mile of roads within wetlands.

Many opportunities exist for monitoring to help detect future hydrologic change, to preserve critical ecosystem functions, and to protect public and private property. Monitoring opportunities discussed in this report include (1) maintaining and operating the streamflow gaging station that is near the 1000-Road Bridge, (2) measuring precipitation at high and low altitudes within the watershed, (3) investigating the storm-driven evolution of water available for runoff throughout the watershed, and (4) enhancing the existing, preliminary map of wetlands through intensive mapping and classification of wetlands in the watershed.

## LITERATURE CITED

Azevedo, J., and Morgan, D.L., 1974, Fog precipitation in coastal California forests: Ecology, v. 55, p 1135-1141.

Campbell, G.S., 1977, An introduction to environmental biophysics: New York, Springer-Verlag, 159 p.

Capoeman, P.K., ed., 1990, Land of the Quinault: Taholah, Washington, Quinault Indian Nation, 316 p.

Harr, R.D., 1982, Fog drip in the Bull Run Municipal Watershed, Oregon: American Water Resources Association, Water Resources Bulletin, v. 18, p. 785-789.

Harr, R.D., 1983, Potential for augmenting water yield through forest practices in western Washington and western Oregon: American Water Resources Association, Water Resources Bulletin, v. 19, p. 383-393.

Harris, D.D., 1977, Hydrologic changes after logging in two small Oregon coastal watersheds: U.S. Geological Survey Water-Supply Paper 2037, 31 p.

Hicks, B.J., Beschta, R.L., and Harr, R.D., 1991, Long-term changes in streamflow following logging in western Oregon and associated fisheries implications: American Water Resources Association, Water Resources Bulletin, v. 27, p. 217-226.

Hirschboeck, K.K., 1991, Climate and floods, in National water summary 1988-89- Hydrologic events and floods and droughts: U.S. Geological Survey Water Supply Paper 2375, p. 67-88.

Hydrosphere Data Products, Inc., 1999, ClimatedataTM, v. 10.3, NCDC Summary of the Day, West 2: Boulder, Colorado, Hydrosphere Data Products, Inc., CD-ROM.

Isaac, L.A., 1946, Fog drip and rain interception in coastal forests: U.S. Department of Agriculture, Forest Service Pacific Northwest Forest Experiment Station, Forest Research Notes, no. 34, p. 15-16.

Jones, J.A., and Grant, G.E., 1996, Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: Water Resources Research, v. 32, p. 959-974.

Lumb, A.M., Kittle, J.L., Jr., and Flynn, K.M., 1990, Users manual for ANNIE, a computer program for interactive hydrologic analyses and data management: U.S. Geological Survey Water-Resources Investigations Report 89-4080, 236 p.

Oregon Climate Service, 2000, The PRISM Climate Mapping Program: World Wide Web Universal Resource Locator (URL): http://www.ocs.orst.edu/prism/prism_new.html, accessed February 2000.

Regional Interagency Executive Committee, 1995, Ecosystem analysis at the watershed scale Federal guide for watershed analysis: Portland, Oregon, U.S. Forest Service Regional Ecosystem Office, version 2.2, 26 p.

Riggs, H.C., 1968, Frequency curves: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 4, chap. A2,15 p.

Riggs, H.C., 1972, Low-flow investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 4, chap. B1,18 p.

Rothacher, J., 1965, Streamflow from small watersheds on the western slope of the Cascade Range of Oregon: Water Resources Research, v. 1, p. 125-134.

Salmon River Watershed Analysis Team, 2002, Salmon River watershed analysis: Tahola, Washington, Quinault Indian Nation/Washington Department of Natural Resources, chapters individually paginated.

Smoot, G.F., and Novak, C.E., 1968, Calibration and maintenance of vertical-axis type current meters: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 8, chap. B2, 15 p.

Sumioka, S.S., Kresch, D.L., and Kasnick, K.D., 1998, Magnitude and frequency of floods in Washington: U.S. Geological Survey Water-Resources Investigations Report 97-4277, 91 p., 1 pl.

Tabor, R.W., and Cady, W.M., 1978, Geologic Map of the Olympic Peninsula, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-994, 2 pl.

Thomas, R.B., and Megahan, W.F., 1998, Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon-- A second opinion: Water Resources Research, v. 34, p. 3393-3403.

U.S. Fish and Wildlife Service, 1979, Classification of wetlands and deepwater habitats of the United States: U.S. Fish and Wildlife Service, Office of Biological Services publication FWS/OBS-79-31, 131 p.

U.S. Fish and Wildlife Service, 2000, National Wetlands Inventory: World Wide Web Universal Resource Locator (URL): http://www.nwi.fws.gov, accessed January 2000.

U.S. Geological Survey, 1996, U.S. Geological Survey programs in Washington: U.S. Geological Survey Fact Sheet FS-047-96, 4 p.

U.S. Geological Survey, 1998, Water resources data, Washington, water year 1997: U.S. Geological Survey Water-Data Report WA-97-1, 528 p.

van Heeswijk, M., Kimball, J.S., and Marks, D., 1996, Simulation of water available for runoff in clear-cut forest openings during rain-on-snow events in the western Cascade Range of Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 95-4219, 67 p.

Wallace, J.M., and Hobbs, P.V., 1977, Atmospheric science: Orlando, Florida, Academic Press, 467 p.

Washington State Department of Natural Resources, 1995, Standard methodology for conducting watershed analysis under Chapter 222-22 WAC: Olympia, Washington, v. 3.0, variously paginated.

Bidlake

**Watershed Analysis of the Salmon River Watershed, Washington: Hydrology**

WRIR 03–4204