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Estimation of Peak Discharges for Rural, Unregulated Streams in Western Oregon

Scientific Investigations Report 2005–5116

U.S. Department of the Interior
U.S. Geological Survey

Front cover: Flooding in January 1943 at West Salem, Oregon. The photograph was taken on Wallace Road near the Willamette River Bridge. (Photograph courtesy of the Salem, Oregon, Public Library Historic Photograph Collections.)

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Gale A. Norton, Secretary

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P. Patrick Leahy, Acting Director

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow Rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per day per square mile [(Mgal/d)/mi^2]	1,461	cubic meter per day per square kilometer [(m^3/d)/km^2]
foot per day (ft/d)	0.3048	meter per day (m/d)

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83).

Estimation of Peak Discharges for Rural, Unregulated Streams in Western Oregon

By Richard M. Cooper, Oregon Water Resources Department

Abstract

Methods for estimating the magnitudes of peak discharges at various frequencies were developed for rural unregulated streams in western Oregon. Development of these methods had two parts: (1) fitting observed peak discharges to a theoretical probability distribution and (2) developing equations to predict the magnitude of peak discharges at various frequencies. In the first part, logarithms of annual peak discharges were fitted to the Pearson Type III probability distribution for each of 376 gaging stations in the study area. For each gaging station, based on its fitted probability distribution, estimates were made of the magnitudes of the peak discharges for recurrence intervals of 2, 5, 10, 25, 50, 100, and 500 years. All annual series of peak discharges used in this analysis were from rural, unregulated streams.

In fitting the probability distributions, estimates of station skew were improved by adjustment with a "generalized" skew value based on the skews for long-term stations in the area. The areal distribution of the generalized logarithmic skew coefficients of annual peak discharge for Oregon was determined using geographic information systems (GIS) techniques. The actual areal distribution is a GIS grid but is represented in this report as an isoline map. In practice, generalized logarithmic skew coefficients are determined from the grid, not the isoline map.

Western Oregon was divided into three "flood regions." For each region, prediction equations were developed for estimating peak discharges at ungaged sites for the selected recurrence intervals. The equations relate peak discharge to physical and climatologic watershed characteristics such as drainage area and precipitation intensity. The equations were derived by generalized least-squares regression using data for the 376 gaged watersheds. Average standard error of prediction for the equations ranged from 25.3 to 39.1 percent. The accuracy of the equations and limitations on their use are discussed. Use of the prediction equations in various circumstances is illustrated with examples.

Use of the prediction equations requires estimates of watershed characteristics. Because of the reliance in this analysis on GIS techniques, making appropriate and reliable estimates of watershed characteristics may be inconvenient for many users. To make the prediction equations as widely available as possible, the Oregon Water Resources Department has developed an interactive Web site utility to facilitate the use of the equations:

http://www.wrd.state.or.us/OWRD/SW/peak_flow.shtml

Introduction

A study of the magnitude and frequency of peak discharges in western Oregon has been completed by the Oregon Water Resources Department with financial assistance from the Federal Emergency Management Agency, the Oregon Department of Transportation, and the Association of Oregon Counties, and with the cooperation of the U.S. Geological Survey. The study was undertaken to provide engineers and land managers with the information needed to make informed decisions about development in or near watercourses in the study area.

Much development takes place near rivers and streams and usually involves a variety of engineered structures. Some structures such as bridges and culverts, dams, levees, and floodways are within the stream banks and generally are exposed to streamflow at all times. Other structures such as homes, businesses, or agricultural buildings are exposed to streamflow only during times of flooding. Safe and economical design of these structures and correct assessment of the hazards of development in flood plains requires knowledge of the magnitude and frequency of the peak discharges of nearby streams.

Peak discharges have the potential to extensively damage any structure exposed to them. The extent to which a structure is designed to withstand the impacts of peak discharges depends on the risk that failure of the structure poses to life and property. In some cases, failure of the structure is unacceptable. For example, a dam upstream of a populated area will be designed to withstand and function properly under the probable maximum flood.

Usually the failure of a structure is more likely to cause property damage than loss of life. In these cases, it may make economic sense to replace the structure periodically rather than build it to withstand any extreme flood. For example, a remote, rarely traveled road may be designed with the expectation that culverts under the road will wash out on average once in 10 to 25 years. As another example, homes on flood plains typically are required to be built above the elevation of the flood likely to occur on average once in 100 years. Because risk assessment is an important part of planning and design, the magnitude of peak discharges at various frequencies is needed.

This report provides techniques for estimating the magnitudes of peak discharges at various frequencies or "return intervals." A return interval is the number of years expected to pass "on average" between peak discharges of a given magnitude. For example, consider the gaging station Umpqua River near Elkton, Oregon (14321000). Annual peak discharges have been observed at this site for 94 years through 2001. A magnitude and frequency analysis, described later, estimates the 2-year peak discharge to be 94,200 cfs (cubic feet per second). The largest peak each year is expected to exceed this value half the time, that is, every 2 years on average. In fact, for the 94 years of record, the annual peak discharge exceeded 94,200 cfs 46 times. Similarly, the 100-year peak discharge is 261,000 cfs and is expected to be exceeded 1 percent of the time or once in 100 years on average. For the 94 years of record, one annual peak discharge exceeded 261,000 cfs.

Purpose and Scope

This report describes the results of an analysis of the peak discharges of rural streams in Oregon west of the crest of the Cascade Range (fig. 1). The results of this study include (1) the magnitude of annual peak discharges for selected frequencies at 376 gaging stations, (2) the areal distribution within Oregon of generalized logarithmic skew coefficients for annual peak discharges, and (3) sets of equations relating the magnitude of peak discharges at selected frequencies to physical and climatological watershed characteristics such as drainage area and mean January precipitation. A set of frequency-specific prediction equations was developed for each of three hydrologically similar regions within western Oregon. The prediction equations may be used at ungaged sites to make estimates of peak discharges.

The selected peak discharge frequencies are described by the recurrence interval at which the peak discharge is likely to recur. The selected recurrence intervals are the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year peak discharges. A 10-year peak discharge has a probability of exceedance in any year of 0.10 or 10 percent, and a 100-year peak discharge, a probability of exceedance of 0.01 or 1 percent.

The study described in this report is based on annual series of peak discharge for 376 gaging stations in western Oregon, southwestern Washington, and northwestern California. Of these stations, 294 are located in western Oregon.

The study had two parts: (1) a magnitude and frequency analysis and (2) a derivation of the prediction equations. In the magnitude and frequency analysis, a frequency distribution was fitted to the annual series of peak discharges at each gaging station. The fitted distribution was used to estimate the magnitude of annual peak discharges at selected frequencies. Determining the areal distribution of the generalized skew coefficients was part of this analysis and is described in the section titled "Generalized Skew." The prediction equations were derived using generalized least-squares regression analysis.

Although the analysis described in this report was based in part on gaging stations located in southwestern Washington and northwestern California, the resulting prediction equations are to be applied only to western Oregon. The out-of-State gaging stations were included to increase the information used in the derivation of the prediction equations, to reduce any edge effects in developing the generalized skew coefficients, and in some cases, because parts of the out-of-State gaging station watersheds lie in Oregon.

The prediction equations may be used to estimate peak flows for any stream. Be aware, however, that the prediction equations do not account for reservoir operations, diversion or urbanization. Many streams are affected by these factors. In these cases, the estimates of peak flow represent a hypothetical condition of the watershed, not the actual condition.

For peak discharges for urban watersheds, it is recommended that the prediction equations developed by Laenen (1980 and 1983) or Sauer and others (1983) be used. Laenen's work is specific to the Portland, Oregon – Vancouver, Washington, area (1980) and to the Willamette Valley (1983). Sauer and others developed prediction equations applicable anywhere in the United States. Sauer and other's equations are included in the National Flood Frequency Program (Sauer, 2002).

The prediction equations require estimates of several physical characteristics of the watershed of interest. Most of these characteristics are estimated from regionalized data. These data are described later in the report and only the versions of the regionalized data described there should be used with the prediction equations. Sources for these data sets are listed elsewhere in the report. The best estimates of watershed characteristics are achieved by analyzing the regionalized data with geographic information systems (GIS) techniques rather than making the estimates manually from plotted isoline maps.

For these reasons, making appropriate and reliable estimates of watershed characteristics may be inconvenient for many users. To make the prediction equations as widely available as possible, the Oregon Water Resources Department has developed an interactive Web site utility to facilitate the use of the equations. The Web site and the options available there are described in a later section of the report.

Acknowledgements

This study was completed in part due to generous financial support from the Federal Emergency Management Agency (from both the National Dam Safety Program and the Federal Insurance and Mitigation Division), the Oregon Department of

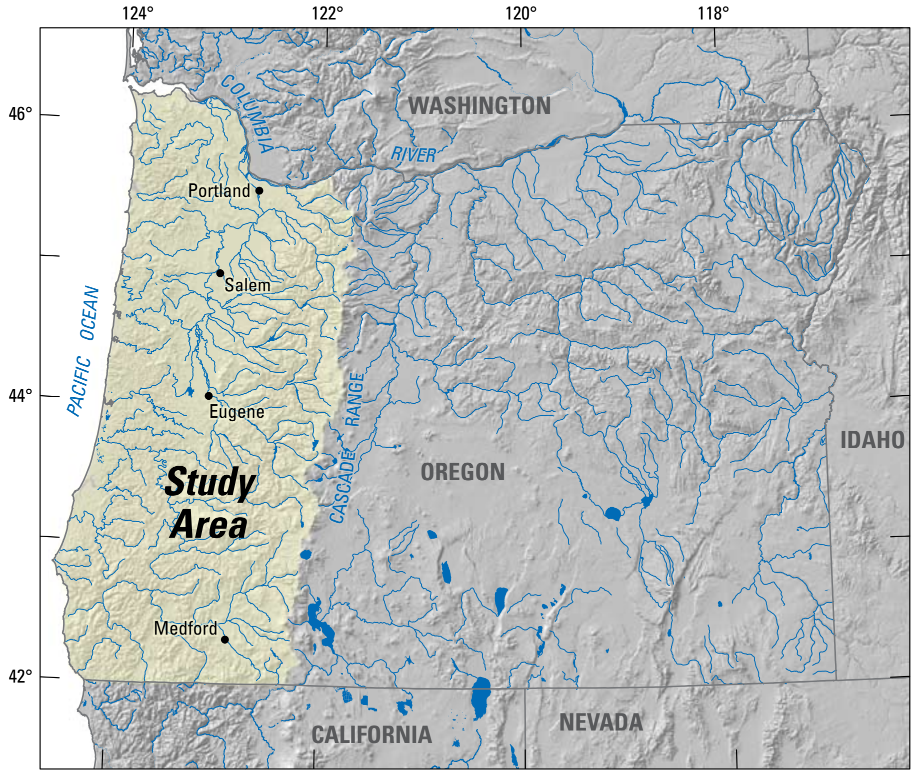

Figure 1. Location of the study area.

Transportation, and the Association of Oregon Counties. Their contributions are gratefully acknowledged.

Many thanks are due Ken Stahr, who made numerous contributions. He has done the bulk of the GIS work. He delineated and digitized most of the watersheds, he managed all the various coverages and grids used to calculate watershed characteristics and calculated those characteristics, and he created several of the figures in this report. He is also largely responsible for developing a method for auto-delineation of watersheds. This method is used in a Web utility available from the Oregon Water Resources Department's Web site for estimating peak discharges at ungaged sites.

Bob Harmon is lead worker for GIS work in the Oregon Water Resources Department. He acquired the watershed characteristic grids and coverages used for this analysis and wrote the computer programs that calculate watershed characteristics.

Rich Marvin and Jonathan La Marche (Oregon Water Resources Department), John Risley (U.S. Geological Survey, Portland Office), Dennis Lettenmaier (University of Washington), Bo Miller (Oregon Department of Transportation), Rob Allerman (Pacific Corps), and Catilino Cecilio (Consulting Engineer) reviewed early drafts of the report and made many valuable observations and criticisms. The report was greatly improved through their efforts.

Previous Studies

Hulsing and Kallio (1964) reported a method for determining the probable magnitude of peak discharges of any return period between 1.1 and 50 years for Pacific slope basins in Oregon and Columbia River tributaries below the Snake River. West of the Cascade crest, the method applies to any watershed greater than 0.5 square miles. East of the crest, watersheds must be greater than 10 square miles.

The peak discharge estimates were based on a correlation of watershed characteristics with mean annual peak discharges. Characteristics used were drainage area, percent area of lakes and ponds, and average annual runoff. Also used was a "geographic factor" based on the residuals resulting from the regression of the mean annual peak discharges on the other three characteristics. Composite frequency curves for nine subregions over the study area gave the relationship between frequency and the ratio of the peak discharge of that frequency to the mean annual peak discharge. Frequency curves for individual stations were fitted visually to the annual peaks plotted on log-probability paper.

The analysis was based on annual peaks for 391 gaging stations. Each site had more than 5 years of record and was unaffected by significant reservoir operations, diversions, or urbanization. The annual peaks and the characteristics for each watershed are included in Hulsing and Kallio's report.

Lystrom (1970) evaluated the streamflow-data program in Oregon. As part of that analysis, Lystrom developed equations for estimating peak discharge magnitudes for recurrence intervals of 2, 5, 10, 25, and 50-years. There are two sets of equations: one for western Oregon and one for eastern Oregon. Lystrom did not explicitly limit the use of the equations, but good practice would limit their application to the range of values exhibited by the characteristics of the watersheds used to develop the equations.

Lystrom's equations were derived by regressing peak discharges of a given frequency on watershed characteristics. Logarithms of annual peaks were fitted to the Pearson Type III distribution to obtain peak discharges of specified frequency. The regressions were developed by ordinary least-squares regression analysis. Standard errors of estimate ranged from 40 to 46 percent. The characteristics considered by Lystrom were drainage area, main-channel slope, percent area of lakes and ponds, mean watershed elevation, percent area of forest cover, mean annual precipitation, 2-year 24-hour precipitation intensity, mean minimum January temperature, and a soils index developed by the Soil Conservation Service. Of these, all but channel slope and percent forest cover appear in the prediction equations Lystrom developed for western Oregon.

Lystrom's analysis was based on annual peaks for 222 gaging stations with more than 10 years of record and unaffected by significant reservoir operations, diversions, or urbanization. The watershed characteristics for each of the gaging stations used in the regressions are included in Lystrom's report.

The Oregon Water Resources Department (1971) developed curves relating mean annual peak discharges to drainage area for 29 hydrologically similar regions in the State. Multipliers related the mean annual peak discharges to peak discharges for recurrence intervals of 1.01, 1.05, 1.25, 2, 5, 20, and 100 years. The analysis applies to all of western Oregon and parts of eastern Oregon. The curves are to be used for watersheds of less than 100 square miles.

The curves were developed from methods described by Hazen (1930). The only watershed characteristic required to use the curves is drainage area. The analysis was based on annual peaks for 120 gaging stations, most of which had more than 20 years of record.

Harris and others (1979) reported a method for estimating peak discharge magnitudes for unregulated streams in western Oregon for recurrence intervals of 2, 5, 10, 25, 50, and 100 years. Four subregions were defined: coast, Willamette, Rogue-Umpqua, and High Cascades. A set of equations was developed for each region. Harris and others did not explicitly limit the use of the equations, but, again, good practice would limit their application to the range of values exhibited by the characteristics of the watersheds used to develop the equations.

The equations were derived by regressing peak discharges of a given frequency on watershed characteristics. Logarithms of annual peaks were fitted to the Pearson Type III probability distribution to obtain peak discharges of specified frequency. The regressions were developed by ordinary least-squares regression analysis. Standard errors of estimate ranged from 32 to 72 percent. The characteristics considered were drainage area, main-channel slope, main-channel length, mean watershed elevation, percent area of lakes, percent forest cover, a soils index developed by the Soil Conservation Service, azimuth, latitude of the gaging station, longitude of the gaging station, mean annual precipitation, 2-year 24-hour precipitation intensity, and mean minimum January temperature. Of these, only drainage area, percent area of lakes, precipitation intensity, and percent forest cover were used in the equations.

The analysis was based on annual peaks for 230 gaging stations with more than 10 years of record and unaffected by significant reservoir operations, diversions, or urbanization. The watershed characteristics for each of the gaging stations used in the regressions are included in Harris and others' report.

Campbell and others (1982) developed a method for predicting peak discharges on small, unregulated watersheds in Oregon for recurrence intervals of 10, 25, 50 and 100 years. Six subregions were defined. The four subregions in western Oregon were the same as those used by Harris and others (1979). In eastern Oregon, one subregion was defined by watersheds in or near the upper Klamath River Basin. A second subregion was defined by watersheds in or near the John Day, Umatilla, Grande Ronde, and Powder River Basins. Watersheds used in the study ranged in size from 0.21 to 10.6 square miles.

In each region, annual peak discharges from gaging stations with more than 20 years of record were fitted to four frequency distributions: Gumbel, two-parameter log-normal, three-parameter log-normal, and log-Pearson Type III. The log-Pearson Type III distribution was determined to be best suited to all regions of the State.

The prediction equations were developed using an ordinary least-squares regression of peak discharges of a given frequency on watershed characteristics. Standard errors of estimate ranged from 21 to 67 percent for western Oregon. The characteristics considered were drainage area, mean watershed elevation, gage datum, main-channel slope, main-channel length, percent forest cover, latitude of the gaging station, longitude of the gaging station, mean annual precipitation, 2-year 24-hour precipitation intensity, and mean minimum January temperature. Of these, only drainage area, mean watershed elevation, mean annual precipitation, latitude of the gaging station, and mean minimum January temperature were used in the equations for western Oregon.

The analysis was based on annual peaks for 80 gaging stations with more than 10 years of record and unaffected by significant reservoir operations, diversions, or urbanization. The watershed characteristics for each of the gaging stations used in the regressions are included in Campbell and others' (1982) report.

Current Study

The current study improves on previous work in several ways. Because of these improvements, the prediction equations developed for this study are considered more reliable than prediction equations previously reported for use in western Oregon and should be used in lieu of equations from previously published reports for western Oregon.

First, more gaging stations were used in this study than in other studies. Most other studies have used only peak discharge record published by the U.S. Geological Survey. This study includes peak discharge record published by the U.S. Geological Survey and the Oregon Water Resources Department.

Second, more than 20 years of streamflow record has been collected since the last comprehensive study for western Oregon (Harris and others, 1979). This new record includes continuation of record at existing stations and addition of record at new stations by both the U.S. Geological Survey and the Oregon Water Resources Department.

Third, generalized logarithmic skew coefficients for Oregon have been developed specifically for this study. The most recent previous study (Harris and others, 1979) used the generalized logarithmic skew coefficients provided by the U.S. Water Resources Council in Bulletin 17A (1977). The new generalized skew coefficients are based on more peak discharge data than the previous analysis of generalized skew. In the 25 years since the previous analysis, new stations have been established and records at many previously existing stations have been extended.

Fourth, more watershed characteristics and better methods to estimate them are now available. Many physical and climatological characteristics of watersheds have been regionalized and put into digital formats in recent years. By using these regionalized characteristics in conjunction with GIS techniques, estimation of watershed characteristics is easier, more precise, more accurate, and more readily reproduced than previously possible.

Finally, other studies in Oregon have used ordinary least-squares regression to develop the prediction equations. This study uses a generalized least-squares analysis that accounts for unequal lengths and variances of streamflow records and cross-correlation between series of streamflow characteristics where ordinary least-squares regression does not.

Description of the Study Area

The study area includes all of Oregon west of the crest of the Cascade Range (fig. 1). Some of the gaging stations used in the analysis lie outside of the study area. These stations are located adjacent to the study area in southwestern Washington and northwestern California. In Washington, gaging stations within about 50 miles of the State line were considered, and in California, gaging stations within about 25 miles of the State line. By physiography and climate, these out-of-State areas are extensions of the adjacent regions of the study area.

Western Oregon has wet winters and dry summers. Annual precipitation varies from less than 20 inches in the interior valleys of southern Oregon to nearly 200 inches at some locations in the coastal mountains. Coastal Oregon is drained by numerous small rivers and streams. Interior parts of western Oregon are drained almost entirely by just three rivers: the Willamette, Umpqua, and Rogue Rivers. Western Oregon is heavily vegetated with thick conifer forests in mountain regions and grasslands and oak woodlands in the valleys.

Physiography

Principal physiographic features of the study area are the Coast and Cascade mountain ranges, the Klamath Mountains, and the Willamette Valley (fig. 2). The Coast Range parallels the coastline from the Olympic Mountains in Washington south to the Klamath Mountains in Oregon. The elevation of the crest line of the Coast Range averages about 1,500 feet with a few peaks near 4,000 feet. Marys Peak, elevation 4,097 feet, is highest. In Oregon, the Coast Range provides a continuous hydrologic divide except where the Umpqua River crosses it. A narrow coastal plain extends to the west of the Coast Range varying in width from less than a mile to around 20 miles. Numerous river valleys extend into the Coast Range from the ocean.

The Cascade Range also parallels the coastline, extending from British Columbia across both Washington and Oregon and into California to the Sierra Nevada. The elevation of the crest line of the Cascades is generally over 4,000 feet with several peaks exceeding 10,000 feet in elevation. In Oregon, Mount Hood is highest at 11,239 feet. Mount Jefferson and the Three Sisters are all over 10,000 feet. In southern Oregon, Mount McLoughlin is the highest peak at 9,495 feet.

In Oregon, the Cascades provide a continuous hydrologic divide along their length. In some areas, the surface water and ground water divides do not coincide. Very permeable volcanic rocks allow movement of ground water across the surface water divides (Gannett and others, 2000). Almost all watersheds draining the west side of the Cascades are tributary to just three rivers: the Willamette, Umpqua and Rogue Rivers.

The Klamath Mountains occupy most of Oregon south of the Umpqua River and west of the Cascade Range. The terrain here is much more rugged and is higher in elevation than other parts of western Oregon. There is not a clear separation between the coastal mountains and the Cascades as there is between the Coast Range and the Cascades to the north. Near the coast, Brandy Peak is the highest peak at 5,316 feet. In the central Klamath Mountains, near the California border, Grayback Mountain has an elevation of 7,048 feet and Mount Ashland an elevation of 7,553 feet. On the divide between the Rogue and Umpqua River Basins, King Mountain reaches 5,265 feet.

The Willamette Valley lies between the Coast and Cascade Ranges. It extends from Eugene in the south to Portland

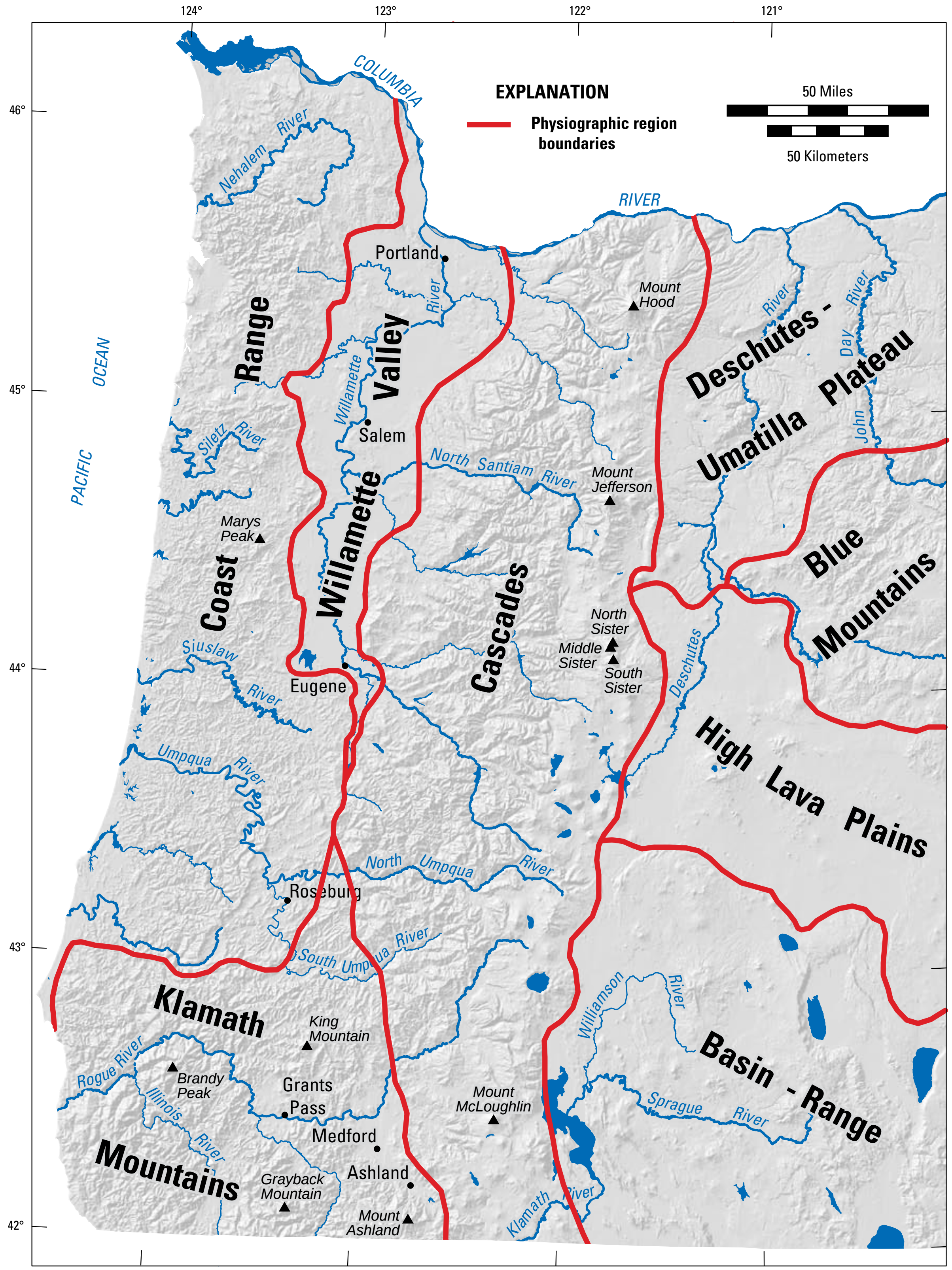

Figure 2. Physiographic features of western Oregon. Physiographic regions are based on Dicken (1965) and Baldwin (1981).

in the north. It varies in width from 10 to 30 miles. Near Eugene, elevations of the valley floor are around 500 feet. The valley slopes gently to the north with elevations at Salem around 130 feet, and at Portland, near sea level. Other features of note are the Umpqua and Rogue River Valleys of southern Oregon. The Umpqua Valley lies directly south of the Willamette Valley. It is less well defined and separates the Coast Range from the Cascades to a lesser extent than does the Willamette Valley. The Umpqua Valley is roughly encompassed by a circle having a radius of 15 to 20 miles centered on the City of Roseburg. It includes the downstream parts of the watersheds draining to Lookingglass, Calapooya and Sutherlin Creeks and the North and South Umpqua Rivers. Elevations on the valley floor average around 500 feet.

The Rogue River Basin has three broad alluvial valleys that are within the Klamath Mountains of southwestern Oregon. The first is along the mainstem of the Rogue River from the town of Shady Cove to the Rogue's confluence with Bear Creek. It includes the lower parts of the watersheds draining to Bear Creek, Little Butte Creek, and Elk Creek. The second is along the mainstem Rogue River from Grants Pass downstream to the Rogue's confluence with Jumpoff Joe Creek. It includes the lower parts of the watersheds draining the Applegate River and Jumpoff Joe Creek. The third is centered near the confluence of the East and West Forks of the Illinois River. The valley extends about 5 miles up each fork and down along the mainstem about five miles. It ranges from about 2 to 5 miles wide. Valley floor elevations among the three valleys range from about 1,000 to 1,500 feet.

Climate

Almost all precipitation in the study area occurs from October to May and is due to frontal storms originating over the Pacific Ocean and moving from west to east over the area. Because these storms originate over the ocean, they are relatively warm, and significant snowfall is confined to higher elevations in the Cascade Range and the Klamath Mountains. Summers, in contrast, are usually dry with only occasional fronts moving across the area. Summertime convective storms (i.e., thunderstorms) occur regularly only in the Cascade and Klamath Mountains and are rare elsewhere.

The mountains receive most of the precipitation because of orographic effects. Annual precipitation in the coastal mountains ranges from about 50 inches to almost 200 inches (G.H. Taylor, Oregon State Climatologist, written commun., 2002). Snowmelt typically is not a significant factor contributing to peak discharges in the Coast Range. Annual precipitation on the west slope of the Cascade Range varies from about 50 inches to over 140 inches. Precipitation amounts are much less in the south Cascades (50 to 60 inches) than in the north (80 to 100 inches). Much of this precipitation falls in winter as snow, and peak discharges are often the result of heavy rain on snow, frozen ground, or both. Annual precipitation in the eastern parts of the Klamath Mountains is less than about 45 inches. Higher elevations in the Klamath Mountains may receive significant snowfall.

The interior valleys lie in the rain shadow of the coastal mountains and receive significantly less precipitation. Annual precipitation ranges from 30 to 50 inches in the Willamette Valley and from 35 to 45 inches in the Umpqua Valley. The valleys of the Rogue River Basin are drier, with 20 to 35 inches of precipitation annually.

Characteristics of Peak Discharges

Peak discharges in the study area result primarily from three hydrological processes: (1) rainfall from frontal storms moving eastward from the Pacific Ocean, (2) snowmelt, and (3) rainfall from convective storms. Very rarely a peak discharge results from a glacial outburst. The most recent of these occurred in September 1998 from the White River Glacier on Mount Hood.

Frontal storms occur mostly in winter and are regional in affect. Precipitation from these storms falls mostly as rain in the Coast Range and interior valleys, but often falls as snow in the Cascades and the Klamath Mountains. Rainfall intensities for these storms tend to be low, but storms may last for several days. Where the precipitation falls as rain, streamflow usually increases rapidly and then, after the front has passed, decreases gradually over several days. Maximum flows are sustained for only a short time—perhaps a few hours. Where the precipitation falls as snow, streamflow is unaffected.

Snowmelt usually occurs in spring and affects watersheds with headwaters at higher elevations in the Cascades and the Klamath Mountains. As the weather warms in the spring, as a general trend, streamflow from snowmelt increases gradually over several weeks or months. Eventually, as the snowpack diminishes, streamflow begins a gradual decline to base flow levels. The maximum streamflows associated with this general trend may be sustained for a week or more. Superimposed on this general trend are numerous short duration peaks due to diurnal temperature variation and to short periods of either rain or high temperatures. Maximum flows associated with these superimposed peaks are sustained only briefly. The overall peak discharge for the period will result from one of these superimposed peaks.

Convective storms usually occur in summer and are most likely to occur in the Cascade Range and the Klamath Mountains. Convective storms tend to be small in area and their effects local. Rainfall intensities for these storms may be high, but their durations are short. Streamflows associated with convective storms rise and then decrease rapidly. Maximum flows are not sustained.

In western Oregon, convective storms may produce no precipitation at all (G.H. Taylor, Oregon State Climatologist, written commun., 2004). These storms result from air masses originating over the Gulfs of Mexico and California. As these air masses move north, they lose much of their moisture over the mountains of Arizona, New Mexico, Nevada, and California. By the time they arrive here, they are relatively dry. They produce lightening over Oregon's mountains, but little rain.

Mixed Processes

Often storms from the subtropical Pacific bring warm temperatures and rain to western Oregon. In these cases, rain may fall on snow and frozen ground at higher elevations and saturated soils at lower elevations. High rainfall amounts, rapidly melting snow, and impervious or saturated soils combine to produce the largest peak events to occur in western Oregon. The floods of December 1964 and February 1996 are examples.

Rain-on-snow events may occur at higher elevations anytime from about November through May. Peaks due only to rainfall usually occur at low elevation, or if at higher elevations, only in the fall or early winter. In western Oregon, annual peaks due only to snowmelt are probably uncommon, occurring only at the highest elevation stations in late spring or early summer.

Whether a peak event is the result of rain only or rain-on snow is a function of elevation. Higher elevation watersheds are more likely to have accumulated snow than low elevation watersheds. Many watersheds, of course, have areas of both high and low elevation. In addition, depending on season or the year, the same watershed may experience both kinds of events.

As will be shown later in the section on flood regions, the relationship between peak discharge and elevation changes abruptly at about 3,000 feet. This observation is best explained by the fact that snow generally does not accumulate at elevations below about 3,000 feet in western Oregon. For purposes of this study, it is assumed that for watersheds with mean elevations below 3,000 feet that most peak events are the result of rain only. For watersheds with mean elevations above 3,000 feet, it is assumed most peak discharges are the result of mixed processes—some combination of rain, rain on snow, and snowmelt.

Relative Importance of Hydrologic Processes

An analysis was done to determine the relative importance of the hydrologic processes contributing to peak discharges. Although it is difficult to classify an individual peak as to the types of hydrologic processes it resulted from, some general conclusions about all peaks can be made. First, we assume that the hydrologic processes associated with a peak discharge are related to its season of occurrence. For example, rain or rain on snow events are most likely in winter, snowmelt in spring, and thunderstorms in summer. Unfortunately, none of these classifications is definitive, only likely. Still, an analysis of this type indicates the relative importance of the hydrologic processes contributing to peak discharges.

In order to see how peak discharges in western Oregon are distributed in time, they were grouped by their month of occurrence (fig. 3). All west side peaks unaffected by regula-

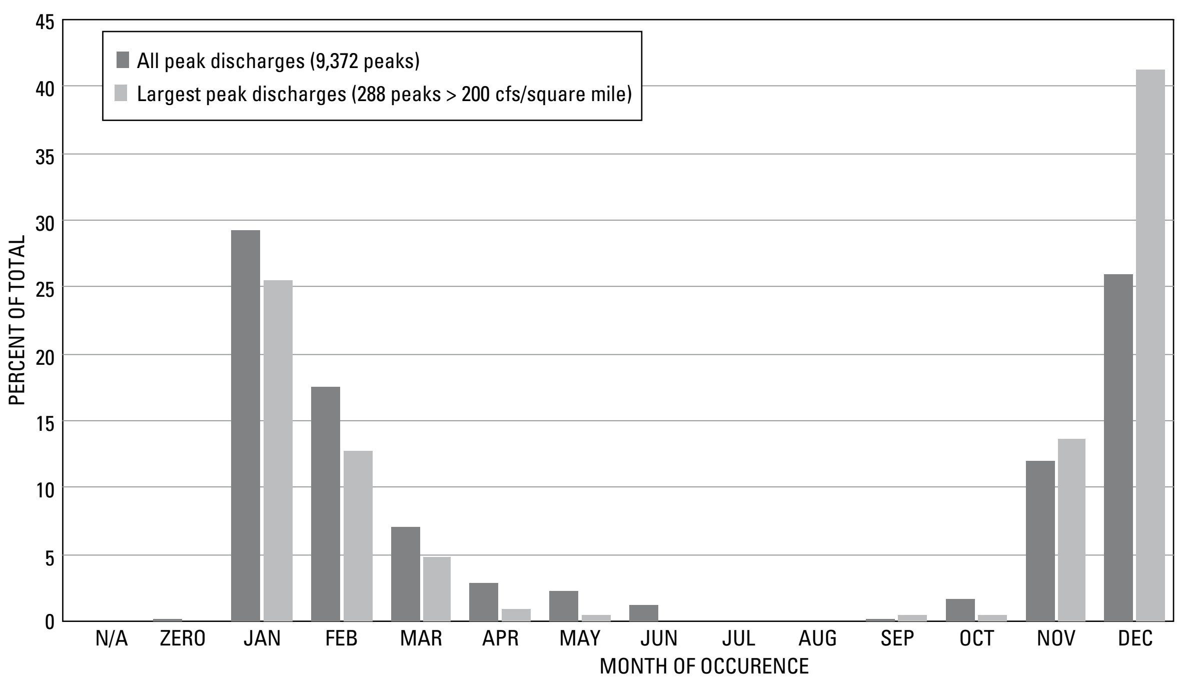

Figure 3. Distribution of the monthly occurrence of 9,372 observed peak discharges for western Oregon. Zero is the percentage of zero peaks (0.10 percent). N/A is the percentage of peaks that are not zero, but for which the date of occurrence is unknown (0.03 percent). Also shown is the distribution of the monthly occurrence of the 288 largest peak discharges, i.e., peak discharges larger than 200 cubic feet per second (cfs) per square mile.

tion or urbanization were included even if the associated gaging station did not qualify for inclusion in the flood frequency analysis. (Gaging stations excluded from the flood frequency analysis included those with fewer than 10 years of record or with too many zero peaks or peaks below the gage threshold.) In all, 9,372 peaks representing 418 gaged sites were identified.

The peak discharges then were grouped by season, with winter defined as October through March, spring as April through June, and summer as July through September. Table 1 shows these summary results. It is clear that most annual peaks occur in the winter, some occur in spring, and a very few in summer. This result suggests that most annual peak discharges in western Oregon are the result of rain or rain-on-snow, a minor part are due to snowmelt, and a negligible number are due to thunderstorms.

A similar analysis was done for the peak discharges with the largest unit discharges (the peak discharge divided by the watershed area). Two hundred eighty-eight peak discharges had unit discharges greater than 200 cfs per square mile. The distribution of these peak discharges is also shown (fig. 3 and table 1). The results are similar to those for all peak discharges, but with an even greater part of the annual peaks occurring in winter.

Historic Floods

The first documented flood in western Oregon occurred in the fall of 1813. For the Willamette River Basin, this flood was on the order of later floods in 1861 and 1890, but its magnitude remains unknown. Information about this flood came from records of the Northwest Fur Company. Other major, but poorly documented, floods are known to have occurred in 1843, 1844, 1849, and 1853 (Brands, 1947).

The largest documented flood on the Willamette River occurred in December 1861. Along the Willamette River, two towns were washed away and all other towns were at least partly submerged. Discharge at Salem on December 4 was 500,000 cfs (Brands, 1947). At Salem, a flood of this magnitude has a recurrence interval of about 100 years. Coastal rivers were also affected. The 1861 flood was also the largest known on the Rogue River (Hubbard, 1991).

The second largest historical flood on the Willamette River peaked at Salem on February 5, 1890, with a discharge of 450,000 cfs (Brands, 1947). At Salem, a flood of this magnitude has a recurrence interval of about 50 years. The third largest known flood on the Willamette River occurred just 9 years earlier, peaking at Salem on January 16, 1881. The discharge was 428,000 cfs (Brands, 1947).

The greatest flood to occur in the Willamette Basin prior to construction of the flood-control reservoirs and for which rainfall and runoff records were generally available occurred in January 1923. Brands (1947) discusses this flood in detail. Discharge at Salem was 348,000 cfs. Hubbard (1991) gives recurrence intervals of from 10 to 100 years for peak discharges for streams in the basin.

Heavy rain and mild temperatures brought flooding to western and northeastern Oregon March 31 to April 1, 1931 (Taylor and Hatton, 1999). The recurrence intervals for flood peaks on the Salmon River at Welches and Willamina Creek near Willamina exceeded 50 years. Recurrence intervals for other streams in the Sandy and Yamhill River Basins were from 10 to 30 years.

A large storm brought heavy rain, wind, and warm temperatures to northwestern Oregon, Washington, Idaho and British Columbia December 21–24, 1933 (Taylor and Hatton, 1999). Recurrence intervals for peak discharges in the Sandy, Clackamas, and Santiam River Basins and along the north coast were from 5 to 20 years.

Heavy rain December 26–30, 1937, caused flooding along the north coast and in the Willamette Valley (Taylor and Hatton, 1999). Generally, recurrence intervals for peak discharges were from 5 to 20 years, but exceeded 40 years for the Pudding River at Aurora and 80 years for the Tualatin River at West Linn.

Rain falling on snow and very warm temperatures caused flooding in northwestern Oregon December 26–29, 1945 (Taylor and Hatton, 1999). Flooding was most severe in the Willamette Valley. Recurrence intervals for many streams were greater than 10 years. The McKenzie River at Vida was about 45 years and the Willamette River at Springfield exceeded 90 years.

Table 1. The seasonal occurrence of 9,372 observed peak discharges for western Oregon. Also shown is the seasonal occurrence of the 288 largest peak discharges, i.e., peak discharges larger than 200 cfs (cubic feet per second) per square mile.

[Spring, April to June; Summer, July to September; Winter; November to March]

Peak discharges	Spring	Summer	Winter	Unknown	Total
	Percent of total				
All 9,372	6.2	0.2	93.5	0.1	100.0
288 largest	1.3	0.4	98.3	0.0	100.0

The floods of October 27–30, 1950, were confined to southwestern Oregon and northwestern California. These floods were almost entirely the result of rainfall, as little snow had accumulated so early in the season. Generally, the floods resulting from this storm were not the greatest known in the area, though peak discharges on the Smith and Umpqua Rivers may have been as great as the flood of 1861 (Paulsen, 1953).

The floods of January 17–21, 1953, affected all of western Oregon, but the most serious flooding occurred in southwestern Oregon and northwestern California. Peak discharges were generally greater than for the floods of October 1950. Snowmelt was not a factor in flooding in the Coast Range, but contributed to flooding on streams heading in the Cascades (Rantz, 1959).

A series of storms from December 1955 to January 1956 caused widespread flooding in most of California, western Nevada, western Oregon and parts of Idaho. In Oregon, the Willamette River and its tributaries and all coastal rivers were affected. Warm temperatures and rain at high elevation melted much of the accumulated snowpack, resulting in record-breaking streamflows for many streams (Hofmann and Rantz, 1963). Recurrence intervals varied from 10 to 50 years, depending on location (Hubbard, 1991).

Heavy rains falling over southwestern Oregon on December 2, 1962, caused severe flooding in some areas of the Rogue Valley (Taylor and Hatton, 1999). Recurrence intervals for peak discharges for the two forks of Ashland Creek exceeded 30 years, for the Rogue River at Raygold, 25 years, and for the South Fork Little Butte Creek, 100 years.

The storm of December 19–23, 1964, was extreme. The recurrence interval for floods in some areas was in excess of 100 years (Hubbard, 1991). All of Oregon, northern California, and parts of Idaho and southern Washington were affected. Peak discharges were substantially increased due to warm rain falling on accumulated snow. Many areas of the State experienced severe flooding. Flooding in the Willamette Valley, however, was significantly reduced because of the flood control reservoirs built in the previous two decades. The peak discharge on the Umpqua River at Elkton of 265,000 cfs exceeded the 1861 peak discharge of 220,000 cfs (Waananen and others, 1971).

The flood of January 1972 affected a limited area in the lower Willamette Valley, the Sandy River, and rivers of the northern Oregon coast. Peak discharges on some coastal streams exceeded those of the December 1964 flood. Recurrence intervals varied from 10 to 100 years for affected streams (Hubbard, 1991).

During January 13–17, 1974, a series of storms with mild temperatures and intense rain followed a period of heavy snow and freezing rain (Taylor and Hatton, 1999). The resulting snowmelt and rapid runoff caused widespread flooding in western Oregon. Recurrence intervals for peak discharges on several steams in the Umpqua and Rogue River Basins exceeded 50 years, with the West Branch of Elk Creek well in excess of 100 years.

Heavy rain fell over much of Oregon February 22–23, 1986. The rain combined with melting snow to bring flooding to many areas (Taylor and Hatton, 1999). In the Sandy River Basin, many streams had peak discharges with recurrence intervals from 10 to 30 years. The recurrence interval for the Middle Santiam River exceeded 80 years.

The storm of January 9–11, 1990, affected coastal streams of northwest Oregon and parts of southwestern Washington. Flooding was exacerbated by high tides and high winds. Recurrence intervals ranged from 25 to 100 years (Hubbard, 1996).

During the period February 5–9, 1996, warm temperatures and intense rain falling on a deep snowpack combined to create severe flooding throughout the northern part of Oregon (Taylor and Hatton, 1999). In many areas, flood magnitudes were generally comparable to or greater than those of the 1964 flood. The peak on the Nehalem River near Foss was the greatest on record, greatly exceeding the 100 year event. In the Willamette Valley, flood control reservoirs minimized flooding.

From November 18–20, 1996, warm, moist air from the tropical Pacific brought record-breaking precipitation to much of Oregon (Taylor and Hatton, 1999). Melting snow exacerbated flooding in some areas. The recurrence interval for the flood peak for the South Fork Coquille River was nearly 50 years and for the Chetco River nearly 70 years. Recurrence intervals for many streams in the interior valleys and the Cascades were on the order of 10 to 30 years.

From December 30, 1996, to January 5, 1997, warm moist air from the subtropical Pacific passed over the entire northwest (Taylor and Hatton, 1999). Heavy rain, warm temperatures, and rapid snowmelt caused flooding over much of the region. In western Oregon, estimated recurrence intervals in a few areas in the south exceeded 15 years. Hard hit was the town of Ashland, which experienced severe flooding. The flood was extreme, but its recurrence interval at Ashland is unknown.

Magnitude and Frequency Analysis

For a site where peak discharges have been systematically measured, the magnitude of peak discharges can be related to frequency by fitting the observed peaks to a theoretical probability distribution. From the probability distribution, the magnitude of the peak discharge for any return interval can be estimated. In practice, however, it is seldom reasonable to make estimates of flood magnitudes for return intervals greater than about 500 years.

For this study, the logarithms of annual series of peak discharges at 376 streamflow gaging stations in western Oregon, southwestern Washington, and northwestern California (Appendix A) were fitted to the Pearson Type III distribution following guidelines established by the Interagency Advisory Committee on Water Data (1982). These guidelines are commonly known as Bulletin 17B. Where the logarithms of the