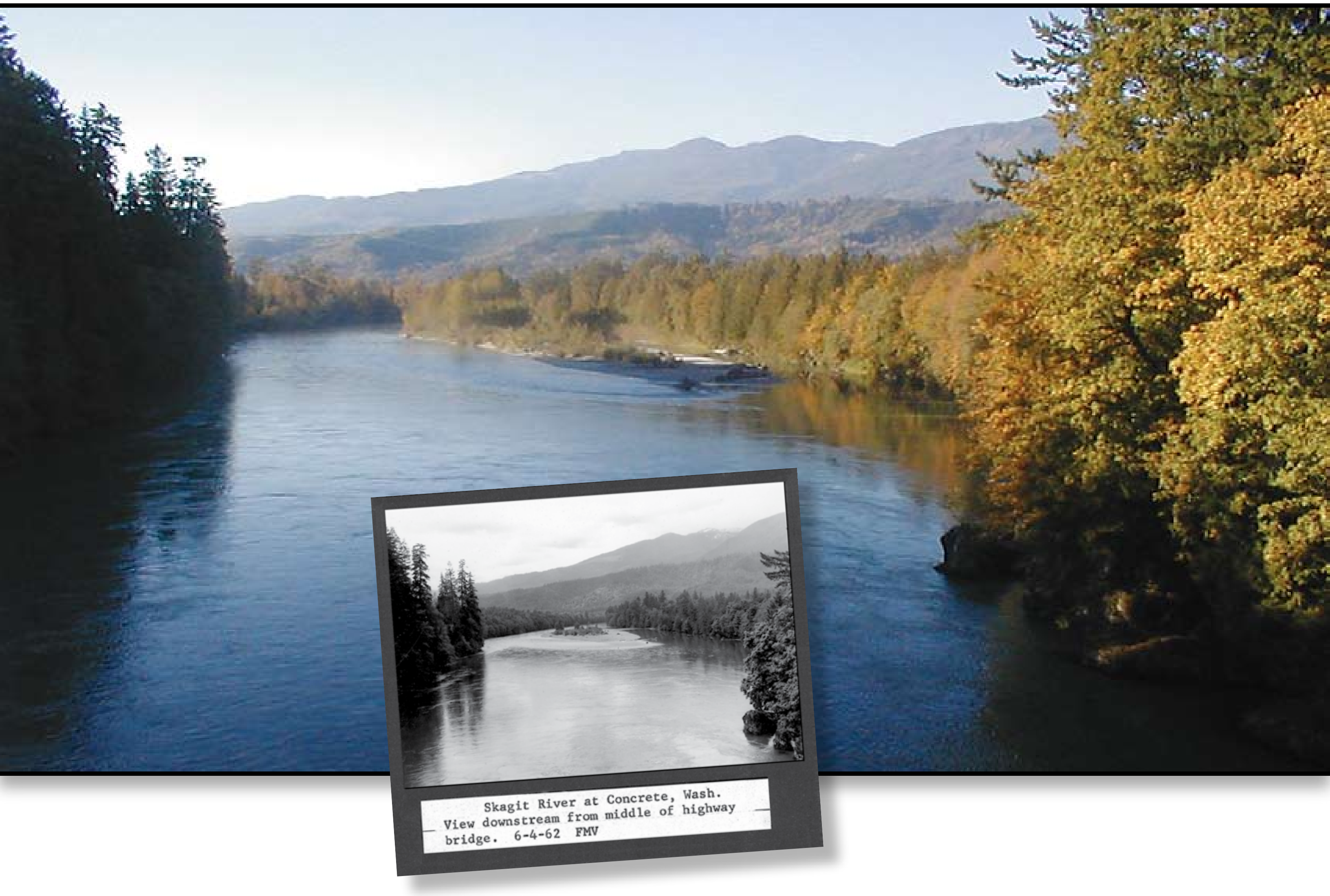
Verification of 1921 Peak Discharge at Skagit River near Concrete, Washington, Using 2003 Peak-Discharge Data



Scientific Investigations Report 2005–5029
Version 2.0, August 2005

U.S. Department of the Interior
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Cover: Photographs taken from the Dalles Bridge looking downstream at the slope-area study reach, Skagit River near Concrete, Washington. (Cover photo: D. Miller, U.S. Geological Survey, 2004; Inset, F. Veatch, U.S. Geological Survey, 1962)

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By M.C. Mastin and D.L. Kresch

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Gale A. Norton, Secretary

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Conversion Factors and Datum

Conversion Factors

Multiply	**By**	**To obtain**
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
foot per square second (ft/s^2)	0.3048	meter per square second
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Datum

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

Altitude, as used in this report, refers to distance above the vertical datum.

Verification of 1921 Peak Discharge at Skagit River near Concrete, Washington, Using 2003 Peak-Discharge Data

By M.C. Mastin and D.L. Kresch

Abstract

The 1921 peak discharge at Skagit River near Concrete, Washington (U.S. Geological Survey streamflow-gaging station 12194000), was verified using peak-discharge data from the flood of October 21, 2003, the largest flood since 1921. This peak discharge is critical to determining other high discharges at the gaging station and to reliably estimating the 100-year flood, the primary design flood being used in a current flood study of the Skagit River basin.

The four largest annual peak discharges used in the determination of the 100-year flood discharge at Skagit River near Concrete occurred in 1897, 1909, 1917, and 1921. The peak discharge on December 13, 1921, was determined by James E. Stewart of the U.S. Geological Survey using a slope-area measurement and a contracted-opening measurement. An extended stage-discharge rating curve based on the 1921 peak discharge was used to determine the peak discharges of the three other large floods. Any inaccuracy in the 1921 peak discharge also would affect the accuracies of the three other largest peak discharges.

The peak discharge of the 1921 flood was recalculated using the cross sections and high-water marks surveyed after the 1921 flood in conjunction with a new estimate of the channel roughness coefficient (*n* value) based on an *n*-verification analysis of the peak discharge of the October 21, 2003, flood. The *n* value used by Stewart for his slope-area measurement of the 1921 flood was 0.033, and the corresponding calculated peak discharge was 240,000 cubic feet per second (ft^3/s). Determination of a single definitive water-surface profile for use in the *n*-verification analysis was precluded because of considerable variation in elevations of surveyed high-water marks from the flood on October 21, 2003. Therefore, *n* values were determined for two separate water-surface profiles thought to bracket a plausible range of water-surface slopes defined by high-water marks. The *n* value determined using the flattest plausible slope was 0.024 and the corresponding recalculated discharge of the 1921 slope-area measurement was 266,000 ft^3/s. The *n* value determined using the steepest plausible slope was 0.032 and the corresponding recalculated discharge of the 1921 slope-area measurement was 215,000 ft^3/s. The two recalculated discharges were 10.8 percent greater than (flattest slope) and 10.4 percent less than (steepest slope) the 1921 peak discharge of 240,000 ft^3/s. The 1921 peak discharge was not revised because the average of the two recalculated discharges (240,500 ft^3/s) is only 0.2 percent greater than the 1921 peak discharge.

Introduction

Large-scale capital improvement projects currently (2004) are being planned to reduce flood impacts on the Skagit River basin. The size and cost of each of these projects are dictated by the size of the floods that can be expected based on historical floods. The 100-year flood, the primary design flood used for these projects, is based on the historical peak discharges at Skagit River near Concrete, Wash. (U.S. Geological Survey streamflow-gaging station 12194000) and any error in the calculation of these peak discharges could result in large, unnecessary expenditures, or inadequate protection measures. Station 12194000 is used to determine the design flood because it has a long period of record, has a stable stage-discharge rating curve, and is downstream of all major tributaries in the Skagit River basin. The peak discharge of the October 21, 2003, flood, the largest peak since 1921, offered an opportunity to verify the peak discharge of the 1921 flood that is critical to estimating the discharges of other large historical floods; and therefore, the magnitude of future flooding of the Skagit River.

The U.S. Army Corps of Engineers (USACE) manages two of the five major dams in the Skagit River basin for flood-control storage, and the other three are managed for power generation without any flood-control regulation. Pursuant to section 209 of the Flood Control Act of 1962, the USACE, with Skagit County as a local sponsor, recently completed a draft of a flood damage reduction study of the Skagit River basin. A critical element of that study was the determination of discharge on the mainstem of the Skagit

River for a flood with a 0.01 annual exceedance probability—the 100-year flood. A log-Pearson Type III flood-frequency analysis of all available unregulated annual peak discharges at Skagit River near Concrete was used to determine the 100-year flood discharge.

The Skagit River near Concrete gaging station was established as a continuous record station in 1924. However, because Skagit River flows have been regulated since 1924, all of the annual peak discharges determined since 1924 are affected by regulation. Estimates of the unregulated annual peak discharges for water years 1944–2004 were determined from the regulated annual peak discharges by USACE (Ted Perkins, U.S. Army Corps of Engineers, written commun., 2004) and used in the flood-frequency analysis. Unregulated annual peak discharges could not be determined for the 1925–43 water years because necessary streamflow data were not available. Also used in the flood-frequency analysis were peak discharges for historical floods in 1897, 1909, 1917, and 1921. Peak discharges for the 1815 (500,000 ft^3/s) and 1856 (350,000 ft^3/s) historical floods were downgraded to estimates and consequently not used in the flood-frequency analysis because the times and validity of the peak stages of these floods could not be validated (R.A. Kimbrough, U.S. Geological Survey, oral commun., 2004). The peak discharges of the 1897, 1909, 1917, and 1921 floods have the strongest influence on the magnitude of the 100-year flood discharge because they are the four largest discharges used in the flood-frequency analysis.

Procedures and cross-section properties used to determine the peak discharge of December 13, 1921 (240,000 ft^3/s), are documented in “Stage and Volume of Past Floods in Skagit Valley and Advisable Protective Measures Prior to the Construction of Permanent Flood Controlling Works” (J.E. Stewart, U.S. Geological Survey, written commun., 1923). Based on the 1921 flood peak, the upper end of the stage-discharge rating curve was extended and used to estimate peak discharges for the 1897, 1909, and 1917 floods. Therefore, any inaccuracy in the peak discharge of the 1921 flood would affect accuracies of the peak discharges of the other three largest floods used in the flood-frequency analysis.

The slope-area measurement of the 1921 peak discharge was based on (1) three surveyed cross sections along a reach of the river a short distance downstream of the Skagit River near Concrete streamflow-gaging station, (2) surveyed high-water marks used to define the slope of the water-surface profile along the reach, and (3) an estimated roughness coefficient (*n* value) of 0.033 for both subreaches [XS1 to XS2 and XS2 to XS3 (fig. 1)] of the measurement. This *n* value was based on an *n*-verification analysis of a reach near Skagit River near Sedro Woolley (gaging station 12199000), about 32 mi downstream from the gaging station near Concrete. The *n* value accounts for resistance to flood flows resulting from physical characteristics of a stream channel or floodplain. The most important factors that affect the *n* value of a stream channel are the type and size of materials that compose the bed and banks of the channel and the shape of the channel. Effects of depth of flow on the selection of an *n* value also must be considered. A relatively small inaccuracy in estimating or determining the actual *n* value of a stream reach can have a significant impact on the magnitude of the calculated discharge. The sensitivity of the recalculated peak discharges of the 1921 flood to the *n* values used (0.024 and 0.032) was evaluated by calculating discharge for several different *n* values between them. The resulting discharges decreased by about 2.5 percent for each 0.001 increase in the *n* value.

Purpose and Scope

Peak discharge for the 1921 flood at Skagit River near Concrete needed to be verified in order to determine the magnitude of the other three large floods (1897, 1909, and 1917) and therefore, the flood frequency discharges at the site. Specifically, the validity of the *n* value used by James E. Stewart (U.S. Geological Survey, written commun., 1923) to calculate peak discharge needed to be verified because of concerns about the river reach and discharge from which it was determined. The *n* value was determined by an *n*-verification analysis of a reach of the river near Skagit River near Sedro Woolley, which is about 32 mi downstream of Concrete. The *n* value at Concrete may be higher than the *n* value near Sedro Woolley because bed material in the reach near Concrete was somewhat coarser (J.E. Stewart, U.S. Geological Survey, written commun., 1923). The *n*-verification analysis was based on a discharge of only 40,200 ft^3/s measured on June 12, 1908, which is less than 20 percent of the magnitude of the peak discharge of the December 13, 1921, flood (210,00 ft^3/s) at the Sedro Woolley gaging station.

The flood peak on October 21, 2003, at Skagit River near Concrete (166,000 ft^3/s), the largest peak since 1921, offered an opportunity to calculate the *n* value for a much higher flow than the flow originally used by Stewart (40,200 ft^3/s), and for the study reach. The 1921 peak discharge was verified using *n* values determined from the peak discharge, cross-section data, and high-water marks for the flood peak on October 21, 2003, in conjunction with Stewart’s cross-section data and high-water marks for the 1921 flood. Only Stewart’s slope-area measurement reach downstream of Dalles Gorge was used for verification because hydraulics within the gorge, where several directions of flow and unusual flood profiles were observed, were considered too complicated to yield reliable results using the contracted-opening method. Furthermore, Stewart’s determination of peak discharge for the 1921 flood using the contracted-opening method (246,000 ft^3/s) was only 2.5 percent larger than the discharge determined by averaging results of the two methods.

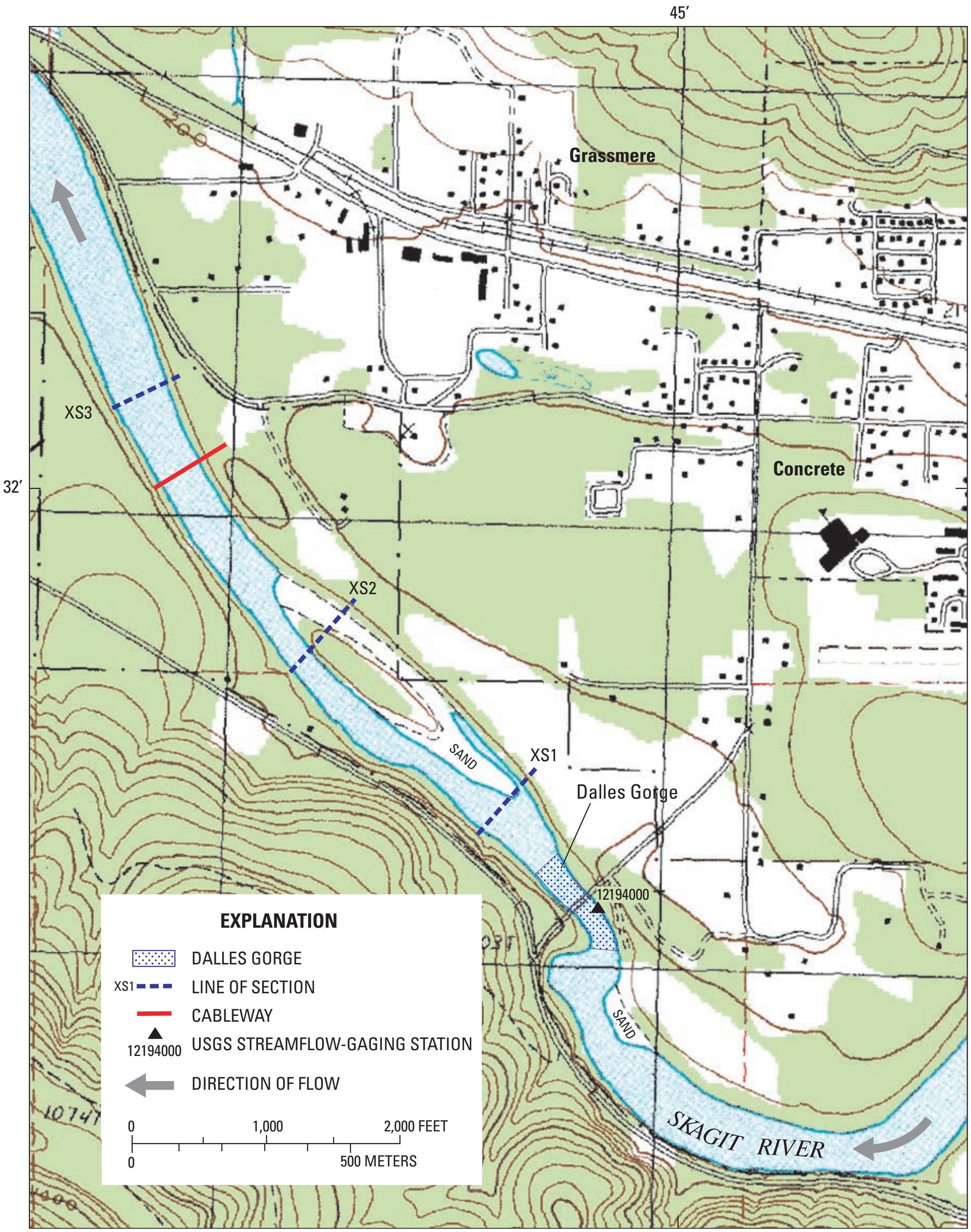

Figure 1. Location of cross sections, discharge measurement cableway, Dalles Gorge, and streamflow-gaging station Skagit River near Concrete, Washington.

Previous Investigations

The importance of knowing the actual peak discharge of the 1921 flood was recognized by the U.S. Geological Survey (USGS) in the 1950s when an *n*-verification analysis was done by H.C. Riggs and W.H. Robinson (U.S. Geological Survey, written commun., 1950). The peak discharge determined by Riggs and Robinson was later revised by F.J. Flynn and M.A. Benson (U.S. Geological Survey, written commun., 1951–52), whose analysis was given a final review by G.L. Bodhaine (U.S. Geological Survey, written commun., 1954).

The 1950s analyses were based on four surveyed cross sections, a water-surface profile of the November 27, 1949 flood, and a peak discharge of 153,000 ft^3/s, which was determined from a stage-discharge rating curve extension. The upper end of the rating used for the extension was defined by a series of high-flow measurements made in 1932. The highest measurement used to define the rating was a current-meter measurement made at a discharge of 135,000 ft^3/s. The upper end of this rating was essentially the same as the rating currently in use. The reach defined by the four cross sections used for the 1950s analyses was practically the same as the reach used for the slope-area measurement of the 1921 flood.

The *n* values determined by Riggs and Robinson for their upstream, middle, and downstream subreaches were 0.040, 0.0276, and 0.0325, respectively. They recalculated the peak discharge of the 1921 flood as 209,000 ft^3/s using an *n* value of 0.040 for Stewart's upstream reach and 0.033 for Stewart's downstream reach. They noted that there was a large expansion in the middle of the upstream reach and questioned whether the 50-percent energy recovery due to expansion that was assumed for that reach was too high. The general procedure used by the USGS assumes a 50-percent energy recovery in expanding reaches unless otherwise indicated (Dalrymple and Benson, 1984. p. 3).

Flynn and Benson revised Riggs and Robinson's analysis by not using their most upstream subreach because of the expansion problem and a poorly defined water-surface profile on the right bank at their most upstream cross section. They computed an average *n* value of 0.0305 for Riggs and Robinson's middle and downstream subreaches. Using only Stewart's downstream reach and an *n* value of 0.030, Flynn and Benson, using a two-section slope-area equation, recalculated peak discharge of the 1921 flood as 225,000 ft^3/s. Bodhaine did not revise the 1921 peak discharge of 240,000 ft^3/s because Flynn and Benson's revised peak discharge varied from Stewart's calculated discharge by only 6.2 percent. Several years later, a thorough history of flooding in the basin that included descriptions of high-water marks from the major floods and their discharges at gaging stations throughout the basin was documented in Stewart and Bodhaine (1961). The peak discharge listed in that report for the December 13, 1921, flood at Skagit River near Concrete gaging station is 240,000 ft^3/s.

Description of Skagit River Basin and Study Site

Skagit River near Concrete has an average discharge of 15,030 ft^3/s and drains a 2,737 mi^2 basin (Kimbrough and others, 2004) that extends to the Cascade Range divide and into Canada. Streamflow originates from rain, which falls primarily in late autumn to early spring and from glacier and snow melt that makes up a large percentage of the flow in late spring and summer. Precipitation ranges from 60 in. near Skagit River near Concrete to as much as 170 in. in the southeastern part of the Skagit River basin near Glacier Peak. Altitudes range from 190 ft at the gaging station to 10,773 ft at the highest point on Mount Baker (fig. 2). The basin, which is situated on the western slopes of the Cascade Range, lies in the path of the prevailing westerlies that bring moisture from the Pacific Ocean. About three-fourths of the annual peak discharges at Skagit River near Concrete occur in the rainy months of October through January. Typically, these floods are generated from heavy, long-duration rainfall sometimes augmented with snowmelt.

Since 1924, when Low Gorge Dam on the Skagit River was completed, flows on Skagit River have been regulated and flood discharges have been reduced by storage in reservoirs. Construction of dams continued with completion of Lower Baker River Dam in 1925, Diablo Dam in 1929, Ross Dam in 1949, 2nd Gorge Dam in 1950, Upper Baker Dam in 1959, and High Gorge Dam in 1961. The peak discharge on October 21, 2003, at Skagit River near Concrete (166,000 ft^3/s) is the largest discharge recorded since the dams were constructed.

The reach of Skagit River used for this analysis is essentially the same as the reach used by Stewart for his slope-area measurement (fig. 1, cross sections XS1-XS3). The Skagit River near Concrete gaging station is in Dalles Gorge, a steep-sided bedrock channel, where the river narrows as it enters from around a right-angle bend. Stewart referenced cross sections used in his slope-area measurement relative to the "lower end of the Dalles" (J.E. Stewart, U.S. Geological Survey, written commun., 1923). For this verification study, it was assumed that Stewart was referring to the downstream end of the prominent bedrock knob on the right bank (looking downstream) about 400 ft downstream of the streamflow-gaging station where the channel begins to abruptly widen along the right bank. Cross sections were field surveyed at the same distances downstream of this knob, as reported by Stewart, in order to place them as close as possible to his survey locations.

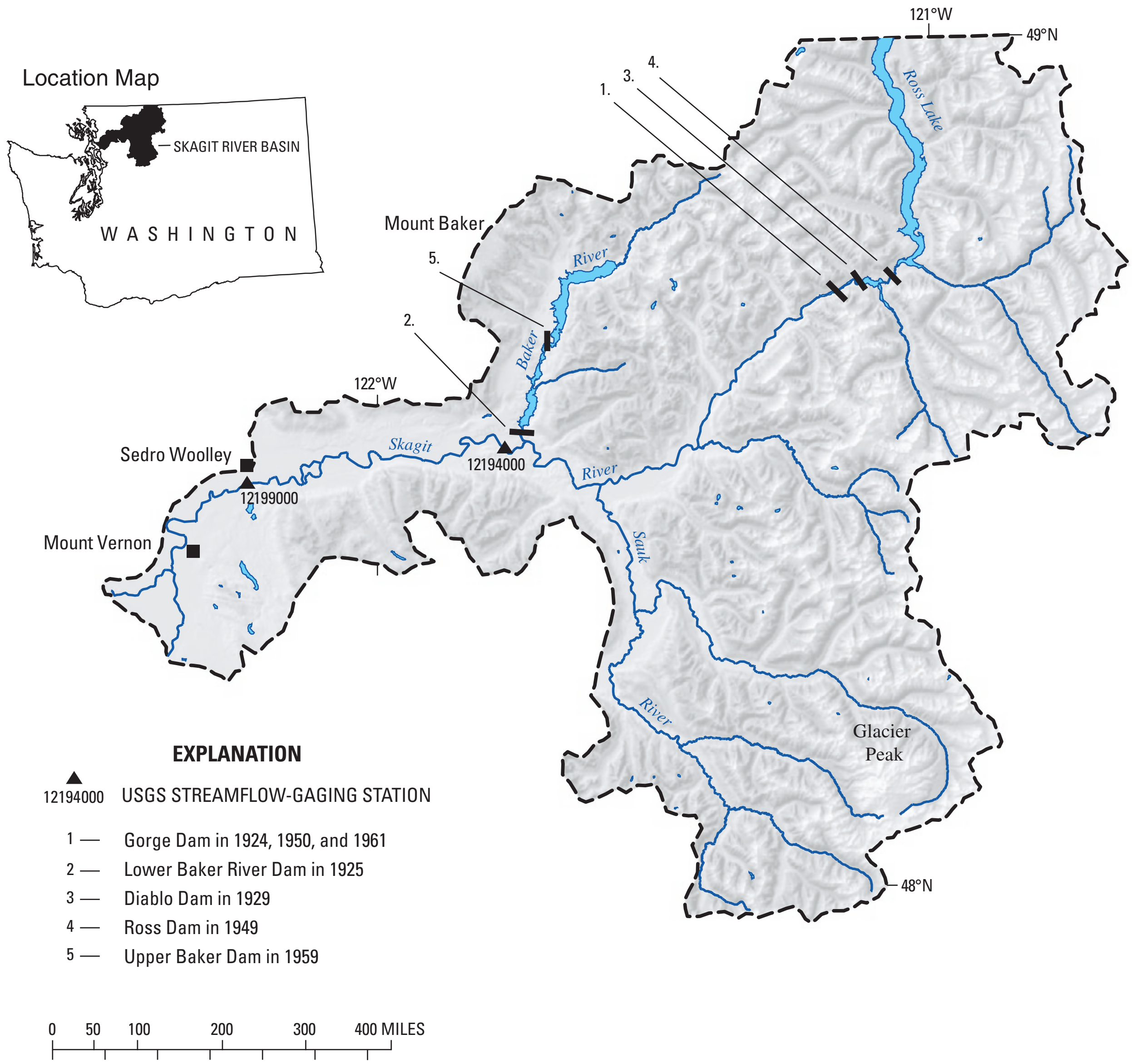

Figure 2. Skagit River basin and streamflow-gaging stations, Skagit River near Concrete, Washington.

Methods

USGS computer program NCALC v.2.6 (Jarrett and Petsch, 1985) was used in conjunction with peak discharge, cross-section data, and high-water marks for the October 21, 2003 flood, to determine the *n* value of the same reach of Skagit River that Stewart used to calculate peak discharge of the 1921 flood. That *n* value was used in conjunction with Stewart's cross-section and high-water mark data for the 1921 flood and a two-section slope-area equation to recalculate peak discharge of the 1921 flood. Although the peak stage of the 1921 flood (47.60 ft) was more than 5 ft higher than the peak stage of the 2003 flood (42.21 ft), *n* values for the two flood events are expected to be similar because in most stream channels, the *n* value does not vary much with depth once the ratio of depth of flow to the size of bed material exceeds 5, provided that flow width is large relative to flow depth (Benson and Dalrymple, 1967, p. 21). Streambed material of Skagit River near Concrete consists primarily of cobbles and small boulders with an estimated average size of about 10 in. The ratio of depth of flow to this size of material exceeds 5 at a flow depth of about 4 ft. Average flow depths at Skagit River near Concrete during the 1921 and 2003 floods were about 27 and 22 ft, respectively. Both flow depths are much smaller than the width of the channel, which was more than 700 ft during both floods.

NCALC and the slope-area method are based on the Manning equation:

$$Q = (1.486/n)AR^{\frac{2}{3}}S^{\frac{1}{2}}, \qquad (1)$$

where

Q is discharge, in cubic feet per second,

A is cross-sectional area, in square feet,

R is hydraulic radius, in feet,

S is friction slope, in feet per foot, and

n is Manning's roughness coefficient.

The Manning equation is used as shown in equation 1 to calculate discharge by the slope-area method. Using the Manning equation to calculate *n* values in NCALC requires that it be rearranged to solve for *n*.

The friction slope *S* between any two consecutive cross sections is defined as the total energy loss between them divided by the reach length *L*. Total energy at each cross section is determined as the sum of both the static head, represented by the water-surface elevation and the velocity head, which is a function of the flow velocity. Thus, the friction slope is determined by the equation:

$$S = (\Delta h + \Delta h_v - k(\Delta h_v))/L, \qquad (2)$$

where

Δh is difference in water-surface elevation (upstream minus downstream) between two consecutive cross sections, in feet,

L is length of the reach, in feet,

$h_v = \alpha v^2/2g$ is velocity head, in feet,

α is velocity head coefficient = 1.0 (for this study because the shapes of the cross sections are basically prismatic with minimal bank overflow),

v is flow velocity, in feet per second,

g is acceleration due to gravity = 32.2 (feet per square second),

S is friction slope, in feet per foot,

Δh_v is difference in velocity head (upstream minus downstream) between two consecutive cross sections, in feet, and

$k(\Delta h_v)$ is energy loss due to contraction or expansion of the channel in the reach, in feet, where k = energy loss coefficient varying from 0 to 1.

Stewart used the Chezy and Kutter equations (Corbett, 1962, p. 81-83) for his slope-area measurement of the peak discharge of the 1921 flood. However, the slope factor *S* used by Stewart in his application of these equations was the water-surface slope rather than the friction slope.

n-Verification Analyses

The peak discharge on October 21, 2003, at Skagit River near Concrete (166,000 ft^3/s) was determined from the recorded peak stage (42.21 ft) using the current stage-discharge rating curve for the gaging station. The accuracy of the upper end of the rating was verified by a current-meter discharge measurement made at a stage of 38.68 ft shortly after the river had crested on October 21, 2003. The measured discharge of 138,000 ft^3/s is only 1.2 percent greater than the discharge indicated by the rating for a stage of 38.68 ft.

Three cross sections and high-water marks along both banks were surveyed during July and August 2004 for the *n*-verification analysis of the peak discharge on October 21, 2003. A plan view of the entire survey and the reference line used to compute stationing of cross sections and high-water marks is shown in figure 3. The cross sections were placed as near as could be determined to the cross sections surveyed by Stewart for his 1921 slope-area measurement. However, only cross-sections XS2 and XS3 were used in the *n*-verification analysis. Cross-section XS1, the farthest upstream of the three cross sections, was not used in the *n*-verification analysis because the water-surface elevation at that cross section was not well defined by the surveyed high-water marks and because that cross section is about 600 ft downstream of a major river expansion where energy losses may not be fully dissipated and accounted for by the calculated energy slope. For the same reasons, a cross section in the same area was not used in the 1950's *n*-verification analysis by Flynn and Benson in their recalculation of the 1921 peak discharge.

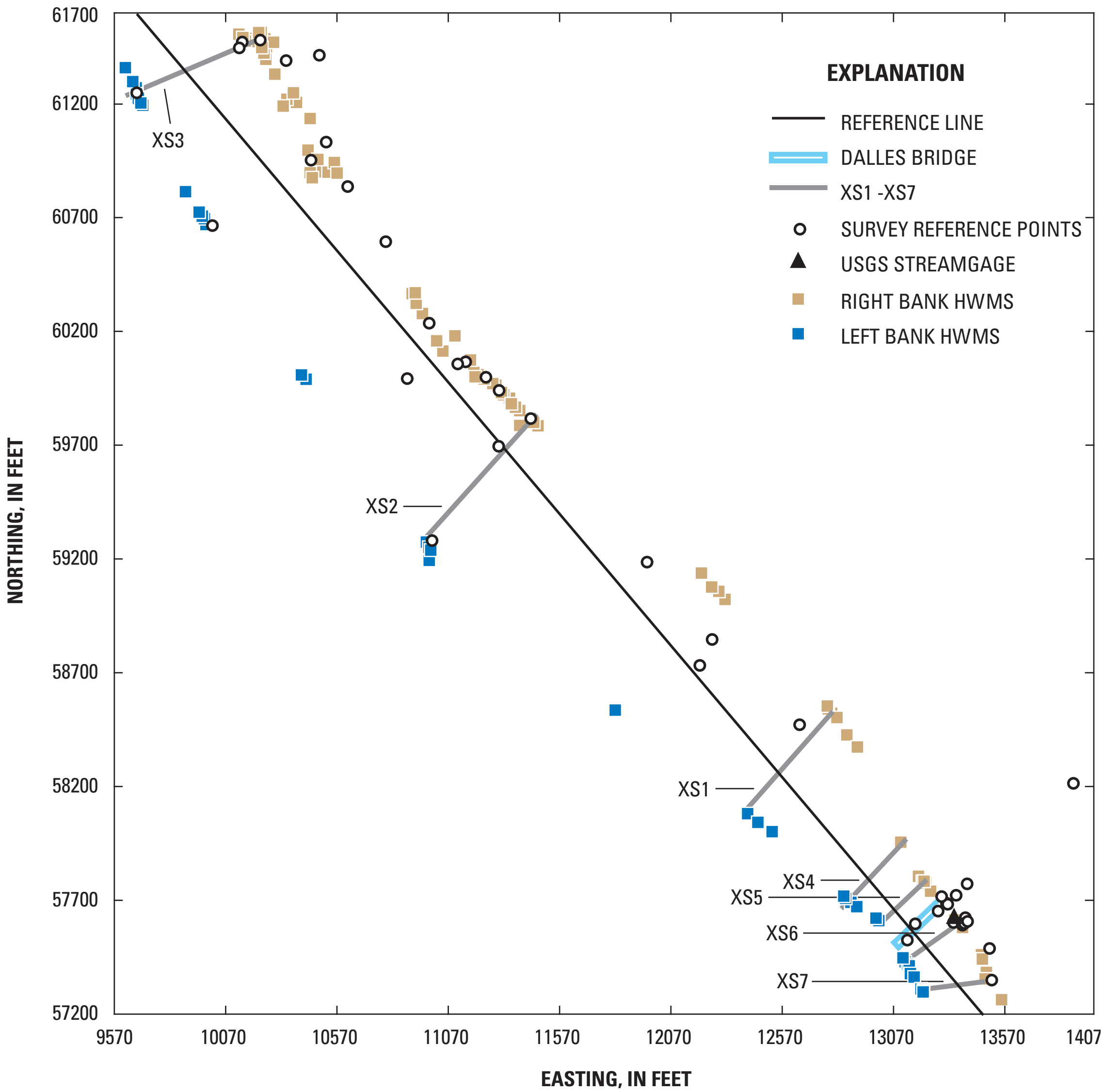

Figure 3. Plan view of cross sections, high-water marks, survey reference line, survey reference points, Dalles Bridge, and streamflow-gaging station, Skagit River near Concrete, Washington.

High-water marks from the October 21, 2003, flood were difficult to find and were of poor quality because they were not surveyed until about 9 months after the flood. Consequently, elevations of surveyed high-water marks varied considerably.

Cross-sections and high-water marks surveyed for the October 21, 2003, flood were processed and plotted using USGS software SAM 2.1 (Hortness, 2004). The peak flood elevation must be determined for each cross section in order to calculate the *n* value for each subreach. Water-surface profiles based on high-water mark elevations were plotted (fig. 4) to determine the peak flood elevation at each cross section. The high-water mark elevations near cross-section XS2 were in relatively close agreement, but those near cross-section XS3 were not, especially those along the right bank (the bank on the right when looking downstream). In addition, most high-water mark elevations along the left bank near cross-section XS3 were higher than most high-water mark elevations along the right bank near cross-section XS3. Consequently, two profiles were drawn in an attempt to bracket a plausible range of water-surface slopes for the actual water-surface profile, and *n* values were determined on the basis of both profiles. Both profiles began at the same elevation at cross-section XS2. However, the elevation at cross-section XS3 for the profile with the flattest plausible slope primarily was based on left bank high-water mark elevations, and the elevation at cross-section XS3 for the profile with the steepest plausible slope primarily was based on right bank high-water mark elevations.

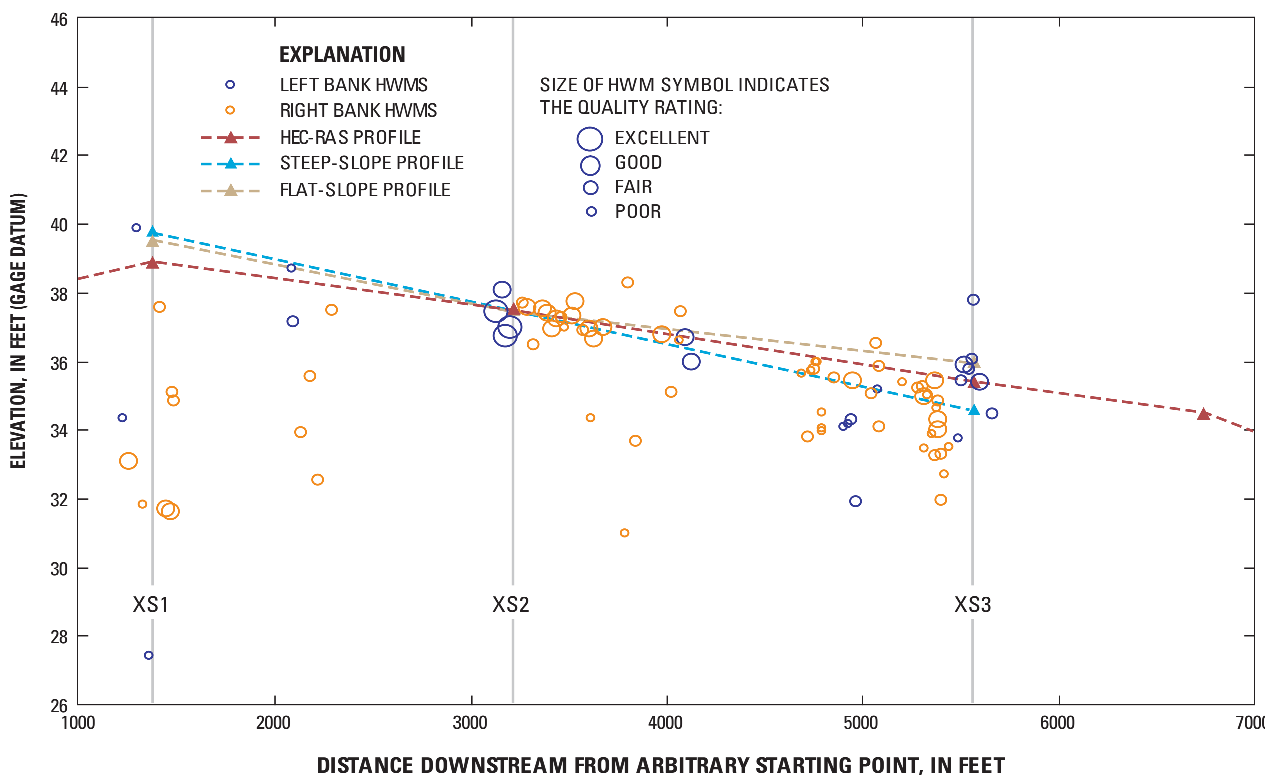

Figure 4. High-water marks (HWMs), flattest- and steepest-sloped water-surface profiles, and a HEC-RAS water-surface profile near cross sections XS1, XS2, and XS3, at Skagit River near Concrete, Washington.

The *n* values determined for the flattest and steepest of the two water-surface profiles are 0.024 and 0.032, respectively. Relative accuracy of these *n* values was considered fair because of the variability of high-water mark elevations near cross-section XS3. The average of the *n* values determined for the two water-surface profiles was 0.028.

A one-dimensional, steady-flow, step-backwater computer model, HEC-RAS version 3.1 (U.S. Army Corps of Engineers, 2002), was used to determine the reasonableness of the slopes for the two water-surface profiles. The HEC-RAS model contains 10 cross sections. Seven cross sections, beginning at river mile 50.05, 3.7 mi downstream of the study reach, were surveyed by USACE in 1975 (Ted E. Perkins, written commun., 2004), and the remaining three cross sections, XS1-XS3, were surveyed by the USGS in 2004. Discharge used in the HEC-RAS model was 166,000 ft^3/s, the same discharge used for the *n*-verification analysis of the peak discharge on October 21, 2003. The starting water-surface elevation at the most downstream cross section was obtained from the output of a USACE HEC-RAS model of Skagit River basin. The *n* value used for the first seven cross sections was changed from 0.040, as used in the USACE Skagit River basin model, to 0.036 so the simulated water-surface elevation at XS3 would most closely agree with high-water marks near that cross section. For the remaining three cross sections (XS1-XS3), the *n* value used was 0.028—the average of *n* values determined from the flattest- and steepest-sloped water-surface profiles. Coefficients for contraction and expansion losses were 0.0 and 0.5, respectively, at all cross sections. The HEC-RAS water-surface profile was plotted along with the flattest and steepest profiles determined based on surveyed high-water marks (fig. 4). The decline in water surface between cross-sections XS2 and XS3 is 2.90 ft for the steepest-sloped profile and 1.50 ft for the flattest-sloped profile. The average decline for these two profiles was 2.20 ft, which was within 0.08 ft of the 2.12 ft decline between the two cross sections in the HEC-RAS model profile.

The relative accuracy of the NCALC results was measured by comparing the mean velocities calculated at cross-sections XS2 and XS3 with the mean velocity of the discharge measurement made on October 21, 2003. Velocities calculated at XS2 and XS3 for the flattest (11.11 and 11.45 ft/s) and the steepest (11.11 and 12.20 ft/s) of the two water-surface profiles compare well with the mean velocity of 11.09 ft/s from the current-meter measurement of 138,000 ft^3/s on October 21, 2003. The accuracy of the average of the two calculated *n* values (0.028) can be evaluated by comparing it with verified *n* values on other rivers such as Clark Fork at St. Regis, Montana, where Barnes (1967) determined an *n* value of 0.028. The bed material and bank vegetation (fig. 5A) for Clark Fork at St. Regis appear to be similar to the channel characteristics of Skagit River near Concrete (fig. 5B), although vegetation along the banks of Skagit River probably is more dense.

Recalculating 1921 Peak Discharge

Two *n* values (0.024 and 0.032) were determined in the *n*-verification analysis of the October 21, 2003, flood peak for water-surface profiles thought to bracket the plausible range in the actual water-surface slope. These *n* values were used in conjunction with Stewart's cross section and high-water mark data for the 1921 flood and a two-section slope-area equation to recalculate peak discharge of the 1921 flood. Corresponding peak discharges of the 1921 flood calculated using these two *n* values are 266,000 and 215,000 ft^3/s, respectively. Although these two discharges were 10.8 percent greater than and 10.4 percent less than the peak discharge calculated by Stewart, respectively, the average of the two discharges (240,500 ft^3/s) was only 0.2 percent greater than the peak discharge of 240,000 ft^3/s calculated by Stewart.

USGS policy concerning revision of previously published peak discharges is to revise them only if the revised discharge is reliable and different from the original discharge by more than 10 percent (Novak, 1985, p. 103). Therefore, the peak discharge calculated by Stewart was not revised. Peak discharges of the 1897, 1909, and 1917 floods were not revised either because they were all determined from an extension of the stage-discharge rating curve based on the peak discharge of the 1921 flood.

A relatively small inaccuracy in estimating or determining the actual *n* value of a stream reach can have a significant impact on the magnitude of the calculated discharge. The sensitivity of the recalculated peak discharges of the 1921 flood to the *n* values used (0.024 and 0.032) was evaluated by calculating discharge for several different *n* values between them. The resulting discharges decreased by about 2.5 percent for each 0.001 increase in the *n* value.

A. Clark Fork at St. Regis, Montana, showing cobble bed material and fairly dense vegetation along the banks (Barnes, 1967, p. 24).

B. View from Dalles Bridge looking downstream at the upstream end of island at Skagit River near Concrete, Washington, August 2004. (Photograph taken by D. Miller, U.S. Geological Survey, 2004.)

Figure 5. Comparison of two *n*-verified river reaches with *n* values of 0.028.

Verification of the 1921 Peak Discharge

Use of an *n* value determined from October 21, 2003, flood data to verify peak discharge of the 1921 flood is valid only if the reach used for both analyses has not changed significantly since 1921. A comparison of historical and current aerial photographs of the reach (figs. 6 and 7) indicates that the reach has not significantly changed. The size and shape of an island near the right (north) bank of the river in the study area reach (left of center in the photographs) has not changed much over time, but the density of vegetation on the island has changed significantly. In the 1937 photograph (fig. 6), the island is bare of vegetation. Historical photographs from 1948 and 1962 show a gradual increase in vegetation on the downstream part of the island. As of 2004, the downstream part of the island is covered with a dense forest of mostly alders (many more than 2-ft diameter), maples, and cottonwoods.

The cross section at the cableway used for making discharge measurements appears to have changed little since the gaging station was established in 1924 (fig. 8). The cableway was replaced once, but information indicates that the current cableway is at the same location as the previous cableway. Discharge measurements 475 and 476 (fig. 8) made on October 21 and 22, 2003, indicate some scour in the deepest sections and fill on the right half of the cross section, but by May 13, 2004, when discharge measurement 479 was made, the cross section had adjusted back to its long-term shape.

Figure 6. Skagit River near Concrete, Washington, recording gage house and barren island/cobble bar in the study reach in 1937 (Skagit County, 2003).

Figure 7. Skagit River near Concrete, Washington, and vegetated island/cobble bar in the study reach in 2001 (Skagit County, 2003).

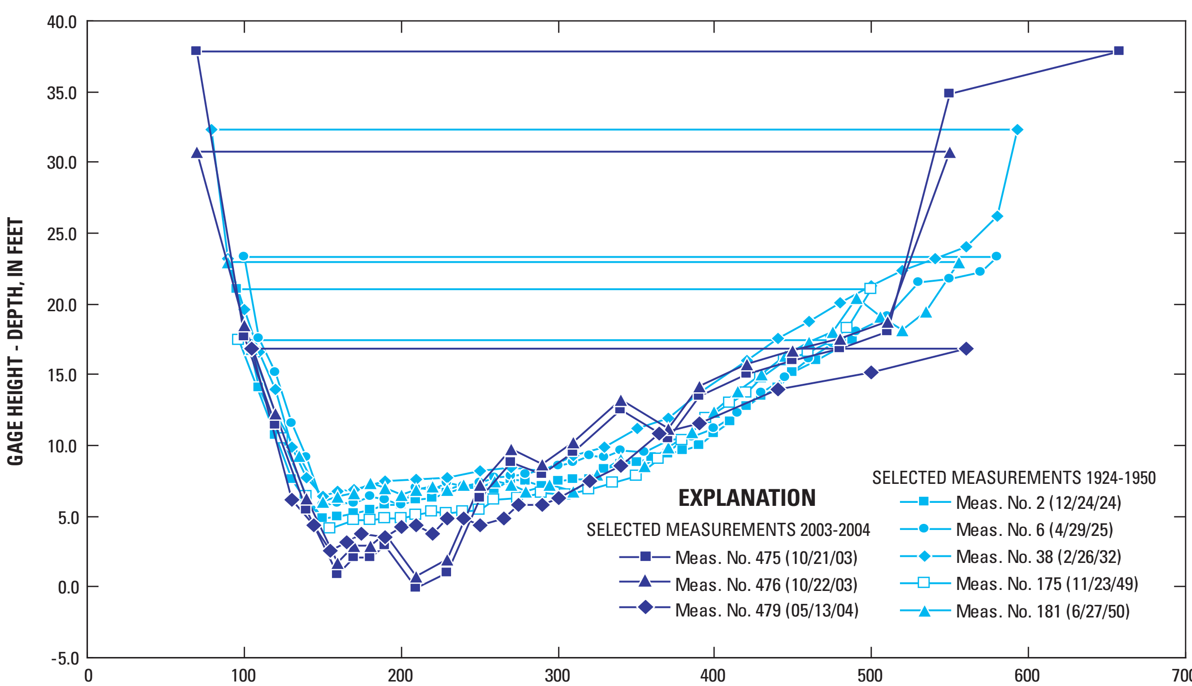

Figure 8. Historical and recent soundings made during discharge measurements at the cableway at Skagit River near Concrete, Washington, 1924-2004.

Stewart's cross-sections XS1, XS2, and XS3 were compared with cross sections surveyed after the peak discharge on October 21, 2003. The sizes and shapes of these cross sections compare well with each other as shown in figure 9.

The accuracy of recalculated peak discharge for the 1921 flood is contingent on accuracies of the *n* values determined from the *n*-verification analyses of the October 21, 2003, flood peak. A considerable amount of variation was observed in the elevations of the surveyed high-water marks, especially

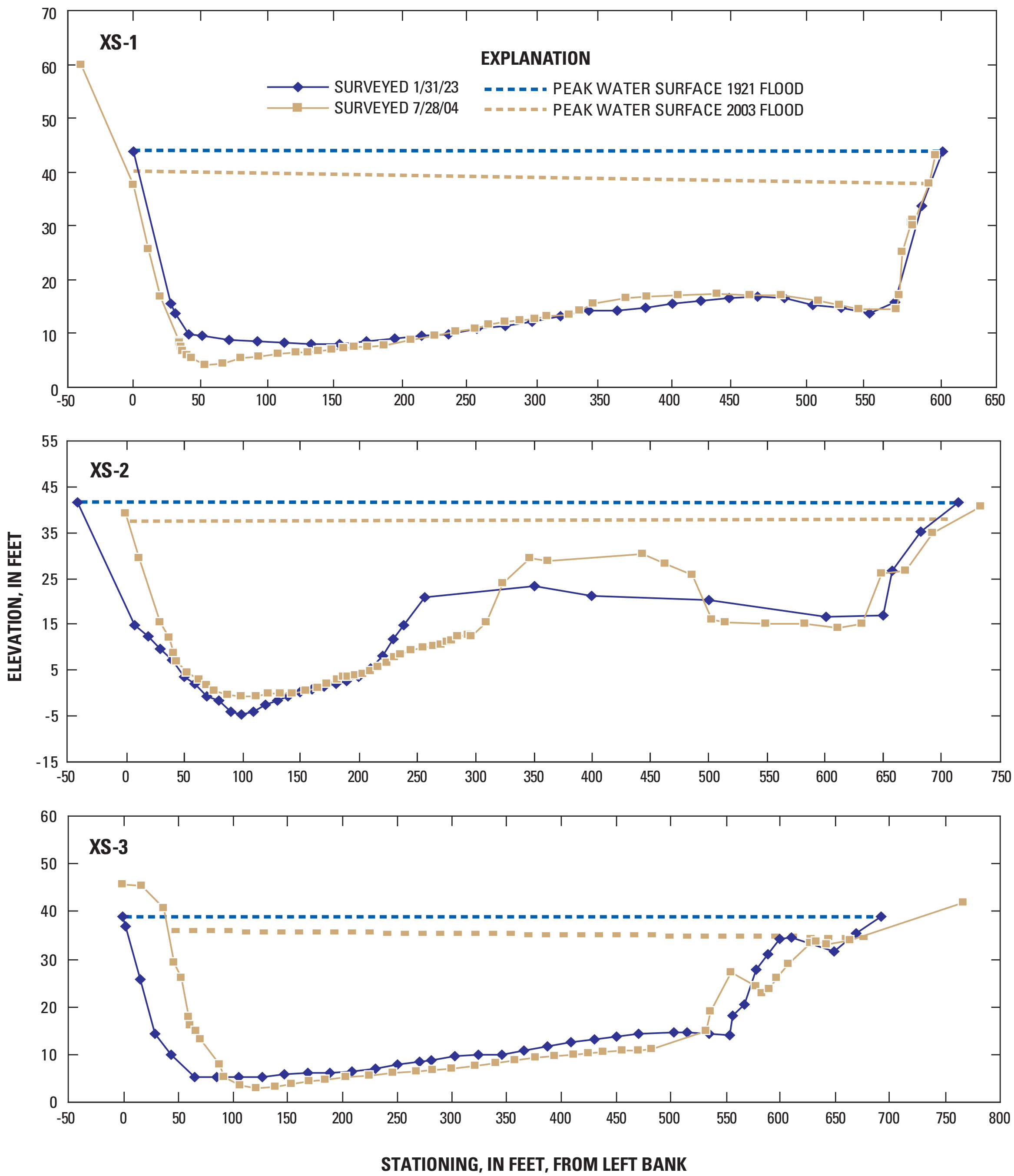

Figure 9. Comparison of three cross sections, XS1, XS2, and XS3, surveyed in 1923 and 2004, and peak water surfaces of the 1921 and 2003 floods at Skagit River near Concrete, Washington.
Peak water-surface elevations are based on high-water marks.

among those along the right bank near cross-section XS3, used to define water-surface profiles from which the *n* values were determined. Therefore, the accuracy of recalculated peak discharge is considered fair, which means that it may be in error by as much as 15 to 25 percent (Benson and Dalrymple, 1967, p. 30).

Because the island extending from cross section XS1 to a point downstream from cross section XS2 has significantly revegetated since the 1921 flood, the current channel roughness is undoubtedly greater than in 1921. The recalculation of Stewart's slope-area measurement of the 1921 flood peak does not take this into consideration. To accurately recalculate peak discharge of the 1921 flood, an *n* value less than 0.028—the average of the *n* values determined using the flattest and steepest plausible water-surface profiles—probably should be used. However, how much the *n* value should be decreased would be difficult to determine. A decrease in average *n* value would have the effect of increasing the recalculated peak discharge of the 1921 flood. Increased roughness of the island may explain why Stewart's calculated discharge measurement plots to the right of the relatively stable stage-discharge rating for the streamflow-gaging station (fig. 10). At river stages above the island's ground elevation, slightly higher gage heights are expected for a given peak discharge as the island's emerging forest resists flow.

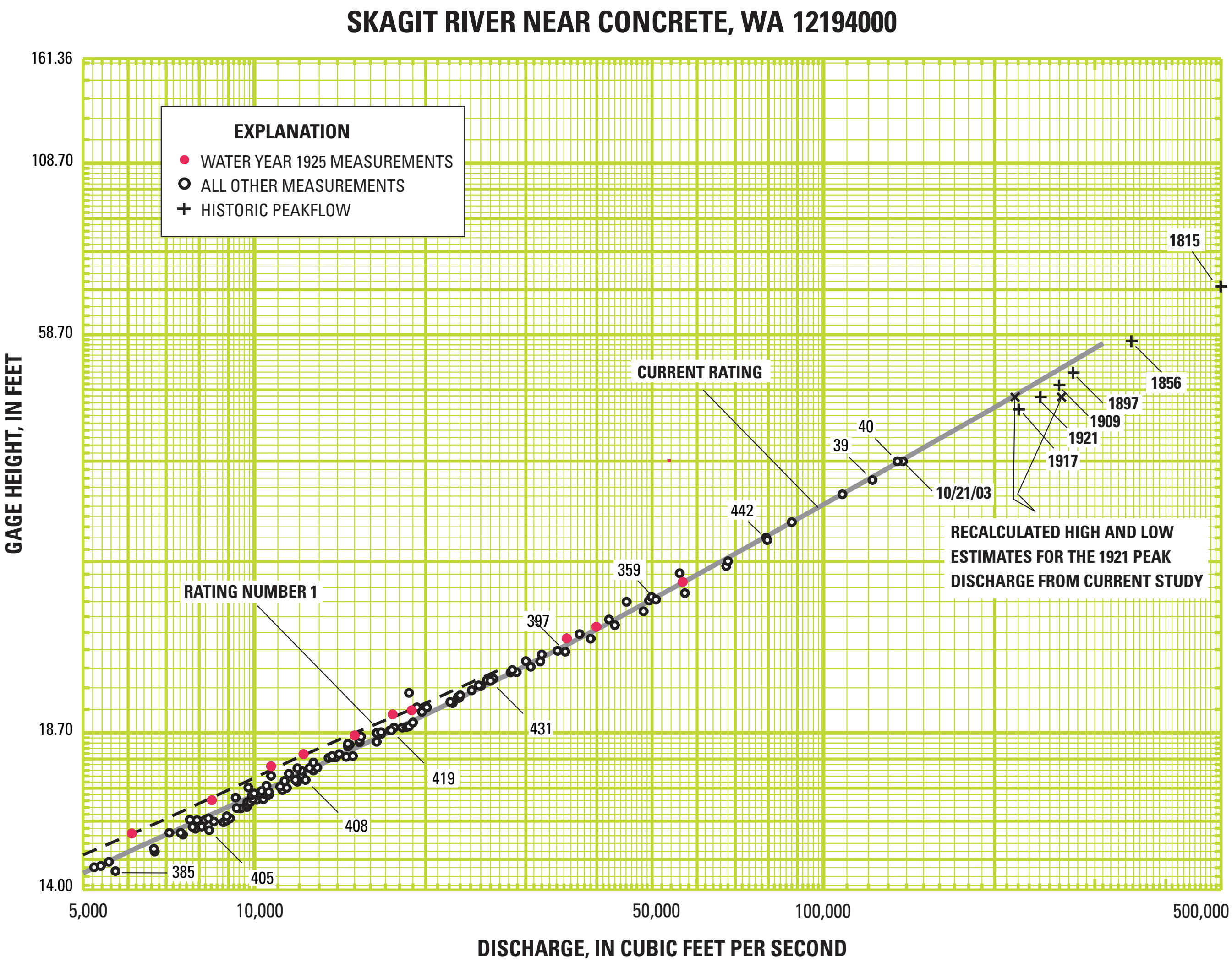

Figure 10. Current rating and rating No. 1 stage-discharge ratings for Skagit River near Concrete, Washington, with historical peak-flow discharges and recalculated high and low estimates of the peak discharge of the 1921 flood.

The effect of change in the island's roughness was tested by adding four more cross sections, each with an *n* value of 0.028, to the HEC-RAS model, which extended the model upstream beyond the gaging station. Contraction and expansion coefficients of 0.4 and 0.7, respectively, were used through Dalles Gorge so the simulated water-surface elevation at the gaging station would match the recorded peak stage of the 2003 flood. The *n* value at XS2 was decreased from 0.028 to 0.023 and the resulting simulated water surface at the gaging station decreased by 0.17 ft indicating that the island's roughness does affect the stage at the gaging station.

The relative influence of various estimates of the peak discharge of the December 13, 1921, flood on the determination of the 100-year flood discharge for Skagit River near Concrete gaging station was evaluated by comparing the 100-year flood discharges determined from those estimates.

Peak discharges for the historical floods of 1897, 1909, 1917, and 1921 are shown in table 1. Peak discharges determined in this analysis for the 1921 flood ranged from 10.8 percent greater than to 10.4 percent less than the discharge determined by Stewart. Assuming that the same approximate range in percentage of differences would apply to the other three historical peak discharges, discharges 10 percent greater than and 10 percent less than those determined by Stewart were calculated (table 1). Peak discharges for the 1921 flood determined by Riggs and Robinson and by Flynn and Benson were 12.5 and 6.2 percent less than the peak discharge determined by Stewart.

The 100-year flood discharges (table 2) were determined using a log-Pearson Type III flood-frequency analysis of the annual peak discharges for the historical floods of 1897, 1909, 1917, and 1921 and USACE estimates of unregulated annual peak discharges for water years 1944–2004. Using the historical peak discharges calculated by Riggs and Robinson and those calculated by Flynn and Benson in the flood-frequency analysis results in 100-year flood discharges 8.4 and 2.8 percent less than the 100-year flood discharge using Stewart's calculated peak discharges. Using Stewart's historical peak discharges plus or minus 10 percent results in 100-year flood discharges of 4.8 percent greater than and 6.2 percent less than the 100-year flood discharge determined using Stewarts unaltered historical peak discharges.

The poor quality of the surveyed high-water marks and the fact that channel conditions may have changed over 80 years precludes any definitive determination of the peak discharge of the December 13, 1921, flood. However, all the evidence from this investigation suggests that the discharge calculated by Stewart was reasonably accurate; therefore, neither the peak discharge of the 1921 flood nor the peak discharges of the 1897, 1909, or 1917 floods should be revised.

Table 1. Peak discharges for historical floods in Skagit River near Concrete, Washington.

Source of data	Peak discharge, in cubic feet per second			
	1897	1909	1917	1921
H.C. Riggs and W.H. Robinson (U.S. Geological Survey, written commun., 1950)	230,000	220,000	190,000	209,000
F.J. Flynn and M.A. Benson (U.S. Geological Survey, written commun., 1951-52)	265,000	240,000	205,000	225,000
James E. Stewart (U.S. Geological Survey, written commun., 1923)	275,000	260,000	220,000	240,000
Plus 10 percent	302,500	286,000	242,000	264,000
Minus 10 percent	247,500	234,000	198,000	216,000

Table 2. The 100-year flood discharges of Skagit River near Concrete, Washington, using annual peak discharges for 1897, 1909, 1917, and 1921 in conjunction with unregulated annual peak discharges for water years 1944-2004.

Source of data	100-year flood discharge, in cubic feet per second
H.C. Riggs and W.H. Robinson (U.S. Geological Survey, written commun., 1950)	256,700
F.J. Flynn and M.A. Benson (U.S. Geological Survey, written commun., 1951-52)	272,400
James E. Stewart (U.S. Geological Survey, written commun., 1923)	280,200
Plus 10 percent	293,700
Minus 10 percent	262,700

Summary and Conclusions

The 1921 peak discharge at Skagit River near Concrete, Washington (U.S. Geological Survey streamflow-gaging station 12194000), was verified using peak-discharge data from the flood of October 21, 2003—the largest flood since 1921. This peak discharge is critical to determining other high discharges at the gaging station and to reliably estimating the 100-year flood—the primary design flood being used in a current flood study of the Skagit River basin.

The four largest annual peak discharges used in the determination of the 100-year flood discharge at Skagit River near Concrete, Washington, occurred in 1897, 1909, 1917, and 1921. A peak discharge of 240,000 cubic feet per second (ft^3/s) for the flood on December 13, 1921, was determined by James E. Stewart of the U.S. Geological Survey by means of slope-area and contracted-opening measurements. Peak discharges of the other three largest floods were determined from a stage-discharge rating curve after extending the rating on the basis of the peak discharge of the 1921 flood. Therefore, any inaccuracy in the peak discharge of the 1921 flood also would affect the accuracies of the other three largest peak discharges.

The validity of the peak discharge of the 1921 flood was evaluated by recalculating the slope-area measurement using a channel roughness coefficient (*n* value) based on an *n*-verification analysis of the peak discharge on October 21, 2003. A U.S. Geological Survey computer program, NCALC was used in conjunction with peak discharge, cross-section data, and high-water marks for the flood on October 21, 2003, to determine the *n* value for the same reach of the Skagit River used by Stewart to calculate peak discharge for the 1921 flood. That *n* value then was used in conjunction with Stewart's cross-section and high-water mark data and a two-section slope-area equation to recalculate the 1921 peak discharge.

Peak discharge of the flood on October 21, 2003, at Skagit River near Concrete (166,000 ft^3/s) was determined from the recorded peak stage (42.21 ft) using the current stage-discharge rating curve for the gaging station. Accuracy of the upper end of the rating was verified by a current-meter discharge measurement made on the same day as the flood peak. The measured discharge of 138,000 ft^3/s is only 1.2 percent greater than the discharge indicated by the rating for a stage of 38.68 ft.

The *n* value used for Stewart's slope-area measurement was 0.033, and the corresponding calculated peak discharge was 240,000 ft^3/s. Because a considerable amount of variation was present in the elevations of high-water marks surveyed for the flood peak on October 21, 2003, two water-surface profiles were used in the *n*-verification analysis to bracket a plausible range of slopes for the actual water-surface profile. Analysis using the flattest-sloped profile resulted in an *n* value of 0.024 and a peak discharge of 266,000 ft^3/s. The *n*-verification analysis using the steepest-sloped profile resulted in an *n* value of 0.032 and a peak discharge of 215,000 ft^3/s. Although these two discharges are 10.8 percent greater than and 10.4 percent less than Stewart's 1921 peak discharge, respectively, the average of the two discharges (240,500 ft^3/s) is only 0.2 percent greater than Stewart's 1921 peak discharge.

U.S. Geological Survey's policy concerning the revision of previously published peak discharges is to revise them only if the revised discharge is reliable and different from the original discharge by more than 10 percent. Therefore, Stewart's 1921 peak discharge of 240,000 ft^3/s was not revised. The peak discharges of the 1897, 1909, and 1917 floods were not revised either because they were determined from an extension of the stage-discharge rating curve based on the peak discharge of the 1921 flood.

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USGS Publishing staff
Bill Gibbs
Debra Grillo
Ginger Renslow

For more information concerning the research in this report, contact the
Director, Washington Water Science Center,
U.S. Geological Survey,
1201 Pacific Avenue–Suite 600
Tacoma, Washington 98402
http://wa.water.usgs.gov

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Mastin and Kresch

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